Tribute to Milla and her legacy to Physics

Padova, 20th November 2012
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Milla and the heroic years of the weak interactions

or

Milla’s sense of particle physics

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Milla and Particle Physics

Milla was in her twenties when the basic discoveries were made:

- the identification of a second lepton family (Conversi, Pancini, Piccioni, 1945-1947);
- the observation of the Yukawa meson (Lattes, Occhialini, Powell, 1947).

In her long career, Milla has been a protagonist in the search for the basic laws of particle physics and the formation of the Standard Theory.

After the great fathers (Fermi, Rasetti, Majorana, Rossi, Segre, Occhialini, Amaldi..) Milla has been among those who have demonstrated that doing great physics in Italy ***was possible***, on par with what was happening in the US, Russia and Europe:

Touschek, Gatto, Cabibbo, Radicati, Regge, Fubini, Fiorini, Rubbia, Picasso, U. Amaldi, Zichichi (a surely incomplete list)

... who have been the teachers and friends of my generation.

Matching technology to frontier physics

As an experimental physicist, Milla has been always at the front of observation technologies:

- emulsions exposed to cosmic rays → identification of the strange particles, the θ-τ puzzle;

Late fifties

- emulsions exposed to accelerator beams → anti-Lambda
- bubble chamber (Berkeley and CERN) → properties of weak decays, $K_0 - \bar{K}_0$ oscillations, determination of δm_{12} ;
- spark chambers → ν-e neutral current couplings;
- bubble chamber (BEBC-deuterium) → ν-quark neutral current couplings;
- drift chambers (NOMAD) → ν-oscillations search;
- streamer tubes and scintillation counters → neutron-antineutron oscillations;
- large volume liquid argon (ICARUS) → limits on ν-velocity and e^+e^-pair emission *in vacuo*.

2011

Milla Baldo Ceoli

2. The heroic Weak Interaction era

Annu. Rev. Nucl. Part. Sci. 2002. 52:1–21
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The Discreet Charm of the Nuclear Emulsion Era

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Io stimo più il trovar un vero
benchè di cosa leggiera
che 'l disputar lungamente
delle massime questioni
*senza conseguir verità nissuna.**

Galileo Galilei, *Opere*

Milla's recollections, Venice Conference 1957 (Adv. in Nucl.& Part. Phys.)

Figure 5 The Padova-Venice Conference in 1957. A rest in the area of the San Giorgio isle in Venice. From left to right: B. Touschek, T.D. Lee, W. Pauli, and R. Marshak.

At the Venice Conference, .. Jack Steinberger presented evidence for parity nonconservation in Λ^0 decay...in purely hadronic interactions.
A large theoretical participation...
T.D. Lee gave a talk on weak interactions...the two-component ...neutrino theory and ... lepton conservation; Bruno Touschek, ...proposed that a suitable gauge transformation of the neutrino field, imposed to keep $m_\nu = 0$, leads to two-component neutrinos; moreover, he elaborated on the equivalence of two-component and Majorana neutrinos.
One of the most successful theoretical models...was the one presented by Robert Marshak and George Sudarshan, leading to the universal *V-A* theory—another triumph for the Fermi theory.

Marshak & Sudarshan stated, contrary to the then-current experimental evidence, that all weak interactions are of type *V-A* with $G_V \simeq G_A$, ..lepton conservation is incorporated, neutrinos are two-component spinors and all particles participate in the weak interactions in the same two-component manner.
Here also came the suggestion that the weak interactions arose from the exchange of charged vector bosons, the $W^\pm$.

Feynman’s perplexities

- In his 1961 book, Richard Feynman vividly described his and Murray Gell-Mann’s satisfaction at explaining the close equality of the muon’s and neutron’s beta decay Fermi constants.
- They and, independently, other authors (notably C. G. Sudarshan and R. Marshak) had discovered the ***universality*** of the weak interactions, closely similar to the universality of the electric charge and a tantalising hint of a common origin of the two interactions.
- But Feynman recorded also his disconcert following the discovery that the Fermi constants of the strange particles, e.g. the Λ beta decay constant, turned out to be smaller by a factor of 4-5.
- It was up to Nicola Cabibbo to reconcile strange particle decays with the universality of weak interactions, paving the way to modern electroweak unification (for a recent account of the origin of Cabibbo Theory, see L. Maiani, Rivista del Nuovo Cimento, **34** (2011) 679).

V-A (from R. P. Feynman, Theory of Fundamental Processes)

Some quotations from this fundamental book

$$a = \frac{1-\gamma_5}{2}$$

Since $\bar{a}\gamma_\mu = \gamma_\mu a$ and $aa = a$, this can be simplified to

$$G(\bar{\Psi}_P \gamma_\mu a \Psi_N)(\bar{\Psi}_e \gamma_\mu a \Psi_\nu)$$

After 23 years we come back to Fermi!

Fermi's rule is just modified by replacing $a\Psi$ for every Ψ. It took 23 years to find the a. It is easy to verify that if one applies this substitution to all the β couplings, then the scalar, tensor, and pseudoscalar components vanish, and the vector and the axial vector give the above result. Historically, Salam, and Landau, and Lee and Yang, proposed that the neutrino wave function be always multiplied by a. Afterward I proposed the same for the electron and muon, but hesitated to apply it to neutron and proton because I believed there were some wrong experiments. Finally Marshak and Sudarshan, and Gell-Mann and I, proposed the general rule, every Ψ replaced by $a\Psi$.

Let us find out now what is the physical content of this theory. For this purpose we look at the decay of a polarized neutron. For simplicity we

Current x Current theory and the Strange Particle decay puzzle

natural from one assumption. That is that the Fermi couplings are of the nature of the interaction of a kind of current with itself:

$$J \longleftrightarrow J \tag{12-4}$$

and the problem is to find the composition of the current J, the sum of several parts. The couplings (6-4), (6-5), and (6-6) described previously result if J is written

$$J = (\bar{\nu}e) + (\bar{\nu}\mu) + (\bar{p}n) + X \tag{12-5}$$

Experimentally the coefficient of all first three terms are equal. All our three new couplings will result if we add to J just one term, say X, which changes strangeness. Above we have suggested solely as an example what X might be but we shall now have to consider more seriously what properties the term X might have.

An immediate consequence of this idea is that the coefficients of X to each of the three currents $(\bar{\nu}e)$, $(\bar{\nu}\mu)$, and $(\bar{p}n)$ are equal. That is, the couplings (12-1), (12-2), and (12-3) must all have the same coefficient [although it need not equal the coefficient of (6-4), (6-5), and (6-6)].

electron-muon universality well obeyed in Strange Particle decays

What is the strenght of X ?

4. *Leptic decays with change of strangeness are relatively much slower than those without change of strangeness* (although the $K^+ \to \mu^+ + \nu$ is a possible violation).

But if the coefficients in X are of the order of 0.1 for lepton coupling, we should expect them to be exactly the same for the $(\bar{p}n)$ coupling. This is uncomfortable because the nonleptic decays seem too fast for this. They seem to require coefficients of order unity, but we cannot be sure, for we cannot really calculate these processes because of the virtual states of strongly interacting particles that are involved.

- In the JxJ theory, the ***suppression of leptonic strange particle decays*** got mixed with the so called ***I=1/2 enhancement*** of non-leptonic decays.

A real mess !!

3. The modern era, following the SU(3) Symmetry

Gatto & Cabibbo (1961) and others observed that the Noether currents associated to the newly discovered SU(3) symmetry include a *strangeness changing current* that could be associated with strangeness changing decays, in addition to the *isospin current* responsible for strangeness-non-changing beta decays (CVC).

The identification, however, implied the rule ΔS= ΔQ in the decays, in conflict with some alleged evidence from $K^0 - \bar{K}^0$ oscillations of a ΔS= -Δ Q component of strangeness changing weak interactions (Padua-Winsconsin).

In addition, the problem remained how to formulate correctly the concept of CVC and muon-hadron universality, in the presence of the three Noether currents:

$$V_\lambda^{lept} = \bar{\nu}_\mu \gamma_\lambda \mu + \bar{\nu}_e \gamma_\lambda e \ (\Delta \mathrm{Q} = 1);$$

$$V_\lambda^{(1)} + iV_\lambda^{(2)} \ (\Delta \mathrm{S} = 0, \ \Delta \mathrm{Q} = 1)$$

$$V_\lambda^{(5)} + iV_\lambda^{(6)} \ (\Delta \mathrm{S} = \Delta \mathrm{Q} = 1)$$

Enters Cabibbo

- In his 1963 paper, Nicola made few decisive steps.
- he decided to ignore the evidence for a ΔS= -ΔQ component, which indeed was later disconfirmed (P. Franzini had a role on this).
- he ignored also the problem of the normalization of non-leptonic processes and of the ΔI=1/2 enhancement (see later)
- he formulated a notion of universality between the *leptonic current* and *one, full hadronic current*, a combination of the SU(3) currents with ΔS=0 and ΔS=1, such as to be *equally normalized* to the lepton current. Axial currents are inserted via the V-A hypothesis. In formulae:

$$V_\lambda^{(hadron)} = a\left[V_\lambda^{(1)} + iV_\lambda^{(2)}\right] + b\left[V_\lambda^{(5)} + iV_\lambda^{(6)}\right]$$

$$a^2 + b^2 = 1$$

$$J_\lambda^{lept} = \bar{\nu}_\mu \gamma_\lambda (1-\gamma_5)\mu + \bar{\nu}_e \gamma_\lambda (1-\gamma_5) e;$$

$$J_\lambda^{(hadron)} = \cos\theta\left[J_\lambda^{(1)} + iJ_\lambda^{(2)}\right] + \sin\theta\left[J_\lambda^{(5)} + iJ_\lambda^{(6)}\right];$$

$$J_\lambda^{(i)} = V_\lambda^{(i)} - A_\lambda^{(i)}$$

The angle θ is a new constant of Nature, since known as *the Cabibbo angle*.

- Currents belong to SU(3)xSU(3)
- Partial conservation of the vector and axial vector currents protects the normalization of strenght
- Gatto-Ademollo theorem: vector current is non renormalized to first order in SU(3) breaking

The phenomenological success of the Cabibbo theory for semileptonic decays has made it clear that the ***I=1/2 enhancement of non-leptonic decays*** must have a different origin than the normalization of the strange particle current, X.

The agreement has been but reinforced by the most recent data from Frascati, FermiLab and CERN.

$K_S \to \pi e \nu$ decay: V_{us} determination

PDG02, CKMwg use

$$f_+^{K^0\pi^-}(0) = 0.961 \pm 0.008$$

From **Leutwyler, Roos**
Z.Phys. C 25 1984

- p^4 contr. in χPT

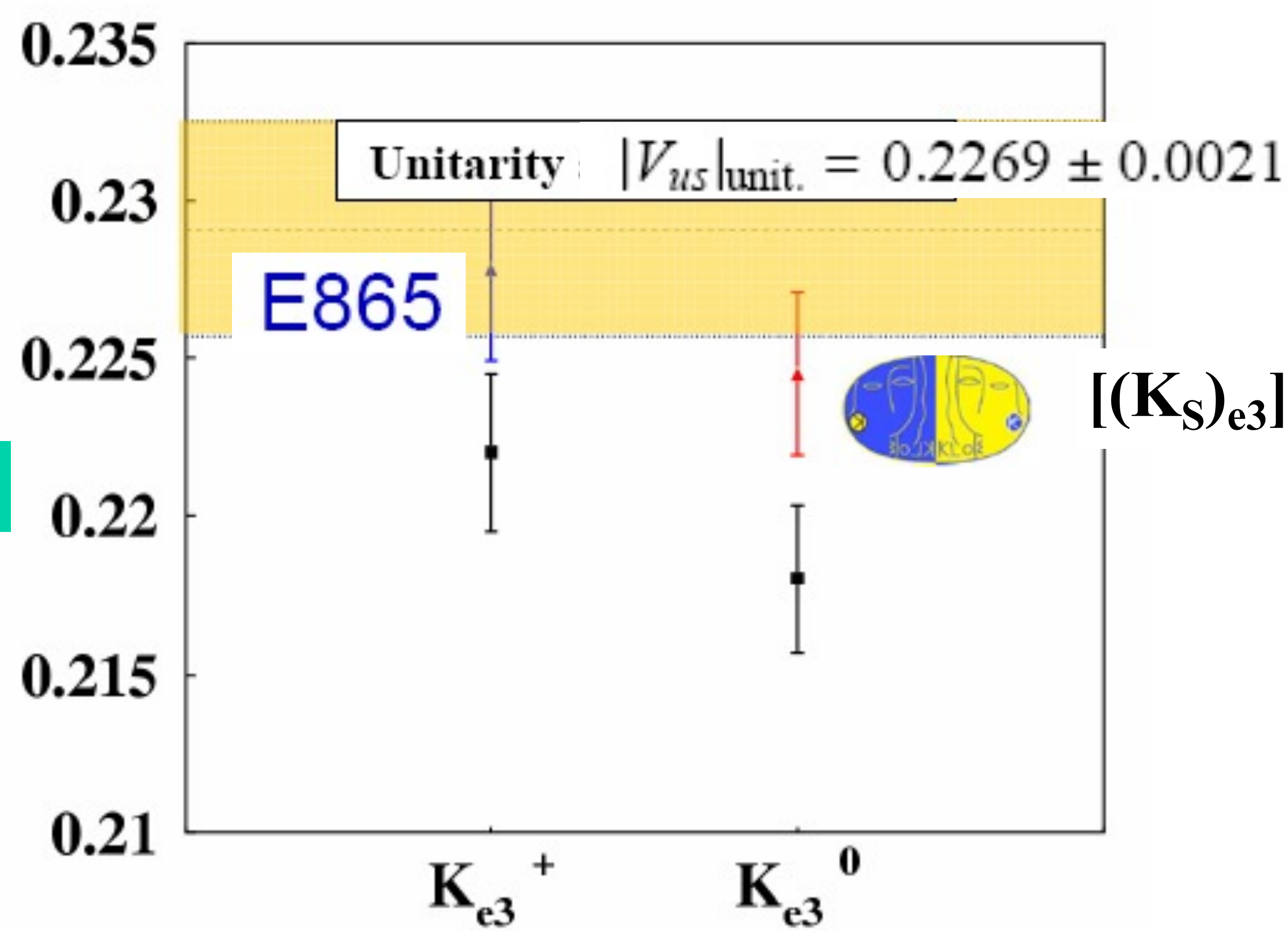
Hyperon decays: NA48 data!

N. Cabibbo, E. C. Swallow and R. Winston, hep-ph/0307214, hep-ph/0307298.

$$|V_{us}|_{\text{Hyp}} = 0.2250 \pm 0.0027_{\text{exp}}$$

New!!! KTeV (K_Ll3):

$$|V_{us}| = 0.2252 \pm 0.0008_{\text{KTeV}} \pm 0.0021_{\text{ext}}$$



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Cabibbo Theory with quarks

An observation made in a 1960 by M. Gell-Mann and M. Levy is often quoted as a precursor or source of inspiration for Cabibbo. This is justified to some extent, but the role of Gell-Mann and Levy's observation needs not to be overestimated. The Gell-Mann and Levy's paper is quoted by Cabibbo and was well known to all those working in the field.

In G-M & L paper, the weak current is written in the Sakata model, with elementary P, N and Λ. All hadrons are supposed to be made by these three fundamental fields.

G-M & L observe that one could relate the reduction of the Λ w.r.t. the muon coupling by assuming the following form of the weak vector current:

$$V_\lambda = \frac{1}{\sqrt{1-\epsilon^2}} \left[\bar{P}\gamma_\lambda \left(N + \epsilon\Lambda\right)\right]$$

But:

nobody knew how to proceed from the G-M&L formula to a real calculation of meson and baryon decays, for two reasons:

- The Sakata model was already known to be substantially wrong, due to the absence of the positive-strangeness hadrons. Thus the inclusion of the decays of the S=-1 and S=-2 hyperons was completely out of reach.

- The important point of the non-renormalisation was missed. In Gell-Mann and Levy's words: *There is, of course, a renormalization factor for that decay*, (i.e. Λ decay) *so we cannot be sure that the low rate really fits in with such a picture*.

Cabibbo Theory with quarks (cont'd)

•The Gell-Mann-Levy formula *was given a new life* after the consolidation of the Cabibbo theory, *in the context of the quark model*. If quarks and flavor-singlet gluons are the fundamental particles, as we know today, beta decays of baryons simply reflect the two transitions

$$d \to u, \quad s \to u$$

•(this is similar to Fermi's idea that beta decays of nuclei are simply the manifestation of the $n \to p$ transition)

•in the quark picture, the Cabibbo weak current takes the simple form:

$$J_\lambda = \cos\theta \left[\bar{u}\gamma_\lambda(1-\gamma_5)\left(d + \tan\theta s\right)\right] =$$
$$= \bar{u}\gamma_\lambda(1-\gamma_5)d_C$$

4. The ΔI=1/2 rule

- The first time I met Milla, she raised the issue with me with her characteristic Padova accent: *dopotutto, 1⊗1/2 fa 1/2 ⊕3/2…*, she told me, walking in a corridor of Istituto Superiore di Sanità, where we had invited her to give a seminar, circa 1965.
- The object of innumerable speculations, it was believed by many that the dominance of ΔI=1/2 amplitudes in non-leptonic weak decays carried an important message for the structure of the weak interactions;
- with SU(3), ΔI=1/2 became "octet dominance" and higher symmetry model were tested against non-leptonic amplitudes;
- in Florence, the Gatto school was very efficient in this game, we tried SU(6), $SU(6)_W$, U(12)…
- very prominent in baryon and K meson decays, the fact that the rule was not built-in in Cabibbo Theory, casted some doubt on the current x current hypothesis.

suggestions

$$H_{nl} = \frac{G \sin\theta_C}{\sqrt{2}} \left[\bar{s}\gamma_\mu(1-\gamma_5)u\right]\left[\bar{u}\gamma^\mu(1-\gamma_5)d\right] \;+\; h.c.$$

- With the progress of quark model, several suggestions were advanced towards the solution of the problem.
- Without quark color:
  - H_{nl} is symmetric under the exchange u $\Longleftrightarrow$ d: one minus sign for the gamma matrices, one minus sign for Fermi statistics
  - so I(ud)=1 and H has ΔI=1/2, 3/2 in similar amounts
- Feynman put it this way: should quarks be bosons, ΔI=1/2 rule would be exact.
- Quarks are fermions, of course, but a similar problem arises for the statistics of the baryon wave function...could the two things be related?

enters color

$$H_{nl} = \frac{G\sin\theta_C}{\sqrt{2}}\,[\bar{s}^{\alpha}\gamma_{\mu}(1-\gamma_5)u_{\alpha}]\left[\bar{u}^{\beta}\gamma^{\mu}(1-\gamma_5)d_{\beta}\right] + h.c.$$

$$< n\pi^0|H_{nl}|\lambda > \approx < n|H_{nl}|\lambda >$$

- with color, both I(ud)=0,1 are allowed
- J.Pati:
  - baryons are antisymmetric in color...then only the antisymmetric combination of ud can contribute,
  - hence I(ud)=0 and ΔI=1/2 is exact for baryons...but what about Kaons?
- K. Wilson, about 1970, prompted a revival of renormalization group:
  - strong interactions may give different anomalous dimensions to $H_{nl,1/2}$ and $H_{nl,3/2}$,
  - if $d_{nl,1/2} > d_{nl,3/2}$ the result would follow for all amplitudes
- but...if?

final round, with QCD

- M.K.Gaillard and B.W.Lee, G.Altarelli and L. Maiani (1974)
  - the components with I(ud)=1(0) are (anti)symmetric in color and therefore do not mix under renormalization group scaling;
  - the anomalous dimensions can be computed in asymptotically free QCD;
  - $d_{nl,1/2} > 0$ (enhanced), $d_{nl,3/2} < 0$ (suppressed) !!
- further contribution found by M. Shifman et al. :
  - penguin diagrams below charm threshold

$$A_i(QCD) = \left(\frac{\alpha_S(\mu)}{\alpha_S(M_W)}\right)^d A_i(tree)$$

$$i = 1/2, 3/2, \;\; \mu = m_c \; ?$$

- semiquantitatively: it works;
- lattice QCD calculation would give an exact answer, but are still inconclusive
- heavier flavors show less differences among the different channels

All in all, the current x current hypothesis with the Cabibbo current survives the test and the road to Unification is viable.

5. Towards Electroweak Unification

- After the discovery of the neutral currents, Milla has actively articipated in the experimental determination of the basic parameter of the $SU(2)_L \otimes U(1)_Y$ theory, the Glashow-Weinberg-Salam angle, for leptons and quarks

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Measurement of Muon-Neutrino and -Antineutrino Scattering off Electrons

H. Faissner, H. G. Fasold,[a] E. Frenzel, T. Hansl,[b] D. Hoffmann, K. Maull,[c] E. Radermacher, H. Reithler, and H. de Witt
III. Physikalisches Institut, Technische Hochschule, Aachen, Germany

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Istituto di Fisica Galileo Galilei dell'Università di Padova, Padova, Italy, and
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(Received 6 April 1978)

$$A = g_L^2 = (-\frac{1}{2} + \sin^2\theta_W)^2$$

$$B = g_R^2 = (\sin^2\theta_W)^2$$

(3) Pure V or pure A currents are improbable at about 90% C.L. (4) The results indicate dominant $V+A$, with some $V-A$ mixed in; an estimate of their ratio is $a = A/B = (15^{+25}_{-15})\%$. (5) The data are in good agreement with the Salam-Weinberg model with

$$\sin^2\theta_W = 0.35 \pm 0.08.$$

Electroweak Unification (cont'd)

NIKHEF

NATIONAAL INSTITUUT VOOR KERNFYSICA EN HOGE-ENERGIEFYSICA

July 1983 NIKHEF-H/83-12

Measurement of the neutral current coupling constants in neutrino and antineutrino interactions with deuterium

Amsterdam-Bergen-Bologna-Padova-Pisa-Saclay-Torino collaboration

D. Allasia[7], C. Angelini[5], A. Baldini[5], M. Baldo-Ceolin[4], S. Barlag[1], L. Bertanza[5], A. Bigi[5], V. Bisi[7], F. Bobisut[4], T. Bolognese[6], A. Borg[6], E. Calimani[4], P. Capiluppi[3], R. Casali[5], S. Ciampolillo[4], J. Derkaoui[3], M.L. Faccini-Turluer[6], R. Fantechi[5], V. Flaminio[5], A.G. Frodesen[2], D. Gamba[7], G. Giacomelli[3], A. Halsteinslid[2], A. Hornaes[2], H. Huzita[4], B. Jongejans[1], I. Lippi[6], M. Loreti[4], C. Louedec[6], G. Mandrioli[3], A. Marzari-Chiesa[7], A. Nappi[5], R. Pazzi[5], G.M. Pierazzini[5], L. Riccati[7], A. Romero[7], A.M. Rossi[3], P. Serra-Lugaresi[3], A. Tenner[1], G.W. van Apeldoorn[1], P. van Dam[1], D. Vignaud[6], C. Visser[1], R. Wigmans[1].

Abstract:

We have measured neutral and charged current interactions of ν_μ and $\bar{\nu}_\mu$ on proton and neutron. From a combination of ratios we determine the neutral current chiral coupling constants. The results are $u_L^2 = 0.13 \pm .03$, $d_L^2 = 0.19 \pm .03$, $u_R^2 = 0.02 \pm .02$ and $d_R^2 = 0.00 \pm .02$. These results agree with the predictions of the standard $SU(2) \times U(1)$ model. The corresponding value of $\sin^2\Theta_W$ is $0.20 \pm .04$.

6. Beyond the Standard Model

- BSM, for Milla has meant neutrino masses and oscillations (NOMAD, ICARUS)
- and the very successfull Neutrino Telescopes conferences in Venice, started in 1988 until the last one, March 2011, see http://www.slac.stanford.edu/spires/find/conf/wwwbrief?rawcmd=FIND+t+neutrino+telescopes&FORMAT=WWWBRIEF
- I have been there several times, as guest, as speaker or simply to enjoy seeing Milla again and to have the pleasure of her conversation.

Many thanks, Milla, we are missing you !!!!