The Young Cabibbo

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NICOLA CABIBBO Memorial Symposium
Laboratori Nazionali di Frascati dell'INFN
15 Dicember 2020

Particle Physics in transition

Accelerators take over

THE DISCREET CHARM OF THE NUCLEAR EMULSION ERA

Annu. Rev. Nucl. Part. Sci. 2002. 52:1–21

1953. Cosmic Rays Conference in France

The news, just arrived, of recent experiments at the Cosmotron did not create surprise or preoccupation… C. F. Powell (who had discovered the true Yukawa meson, the pion) commented, "Gentlemen, we have been invaded . . . the accelerators are here,"

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.

1957. Padua-Venice Conference, Italy

... ***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…elaborated on the equivalence of two-component and Majorana neutrinos. .

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, two component neutrinos (***R. Feynman***: *after 23 years, we come back to Fermi, except for the factor* $(1-\gamma_5)$!… and for the suppression of $\Delta S = 1$ decays)

The suggestion was made that weak interactions are mediated by charged vector bosons, $W^{\pm}$.

1. The beginning

- graduated in 1958, mentor Bruno Touschek
- meets Raoul Gatto (5 years elder) in Roma who was coming back from Berkeley, at Physics Institute, Roma, 1959;
- first thoretical physicist in Frascati, hired by G. Salvini, continues to work with Gatto, Director of the Frascati theory group;
- exciting times in Frascati: e^+ e^- collider AdA, later Adone, new particles (the eta meson), SU(3), etc.
- Cabibbo & Gatto author an important article on e^+ e^- physics (the Bible)
- in 1961, they investigated the weak interactions of hadrons in the framework of the newly discovered SU(3) symmetry

Nicola Makes a Shining Start in Theoretical Physics

***Cabibbo……adornment of Physics* (Ezio Ferrari)**

- Cabibbo, N. and Gatto, R. *Symmetry between Muon and Electron*, PRL 5, 114 (1960)
- N. Cabibbo, R. Gatto and C. Zemach – *A Theorem on the Elimination of Contact Muon-Electron Interactions*, NC 16, 168 (1960)
- N. Cabibbo and R. Gatto – *Consequences of Unitary Symmetry for Weak and Electromagnetic Transitions*, NC 21, 872 (1961)
- N. Cabibbo and R. Gatto – *Electron-Positron Colliding Beam Experiments*, PR 124, 1577 (1961)
- N. Cabibbo and E. Ferrari – *Quantum Electrodynamics with Dirac Monopoles*, NC 23, 1147 (1962)
- N. Cabibbo, G. Da Prato, G. De Franceschi, U. Mosco, *Circular Polarization of High-Energy γ Rays by Birefringence in Crystals*, PRL 9, 435 (1962)
- A. Zichichi, S. M. Berman, N. Cabibbo and R. Gatto – *Proton-Antiproton Annihilation into Electrons, Muons and Vector Bosons*, NC 24, 170 (1962)
- N. Cabibbo – *Unitary Symmetry and Leptonic Decays*, PRL 10, 531 (1963)
- ……..
- N. Cabibbo, G. Parisi and M. Testa – *Hadron Production in e+e− Collisions*, Lett. NC 4, 35 (1970)

Two neutrinos

No $\mu - e$, γ_5 mass terms

Weak currents in SU(3)

The *Bible*

Monopoles

γ Rays in crystals

$p\bar{p}$ annihilation

The Angle !!

Partons in e^+e^- annihilation @ADONE

- 1962-63. CERN: Cabibbo angle and quark mixing
- 1963. Marries Paola Iandolo, then assistant in English Literature, their son, Andrea, was born in 1965
- 1963-64. Berkeley
- 1964-66 at CERN
- 1965. Nicola (at his best!) lectures on Weak Interactions at the Brandeis Summer School. This was my first travel to the US, with several other italians (Preparata, De Franceschi, Buccella, Velo…). Giuliano's brother was a University friend of Nicola. In Brandeis, Giuliano introduced me to Nicola and Paola, several friendly conversations.
- 1966-67 Chair in Theoretical Physics at L'Aquila
- From 1967 in Roma. La Sapienza, then Tor Vergata (1976), then back to Sapienza.
- 1967. Our first theoretical paper: N. Cabibbo, L. Maiani, G. Preparata, *Radiative corrections to leptonic decays and composite models for strong interactions*, PL B 25", 135 (1967).

2. SU(3) Symmetry and weak interactions

Gatto & Cabibbo (1961) and others had observed that the Noether currents associated to the newly discovered SU(3) symmetry includes 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):

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

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

$$V_\lambda^4 + iV_\lambda^5,\ (\Delta S = 1, \Delta Q = 1)$$

The identification implied the rule $\Delta S = \Delta Q$ in the decays, in conflict with some alleged evidence: there was a single event $\Sigma^+ \rightarrow \mu^+ + n + \nu$ reported in an emulsion experiment by Barbaro Gualtieri *et al* (1962).
In addition, the problem remained how to formulate correctly the concept of CVC and muon-hadron universality in the presence of three weak Noether currents.

Enters Cabibbo

- In his 1963 paper, Nicola made a few decisive steps.
- decided to ignore the evidence for a $\Delta S = -\Delta Q$ component (the fact that Paolo Franzini had a larger statistics without seeing any such event was important);
- ignored the problem of non-leptonic decays and the I=1/2 enhancement;
- formulated a new notion of universality with the *leptonic current:* there is ***one, and only one hadron current***, a combination of the SU(3) currents with $\Delta S=0$ and $\Delta S=1$: the hadron current has to be *equally normalized* to the lepton current:

$$V_\lambda^{(\text{hadron})} = \cos\theta\ V_\lambda^{(1+i2)} + \sin\theta\ V_\lambda^{(4+i5)}$$

- Axial currents are inserted via the V-A hypothesis.

- Currents belong to chiral SU(3)xSU(3)
- Partial conservation of the vector and axial vector currents protects the normalization of strenght
- Gatto-Ademollo theorem (1965): vector current is not 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. This was understood later as a renormalization group effect (K. Wilson) due to QCD (B.W. Lee and M.K. Gaillard, G. Altarelli and L. Maiani, 1974).

The agreement has been but reinforced by the more recent data from Frascati, FermiLab and CERN, as will be discussed by L. Sivestrini in the next talk.

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

PDG02, CKMwg use

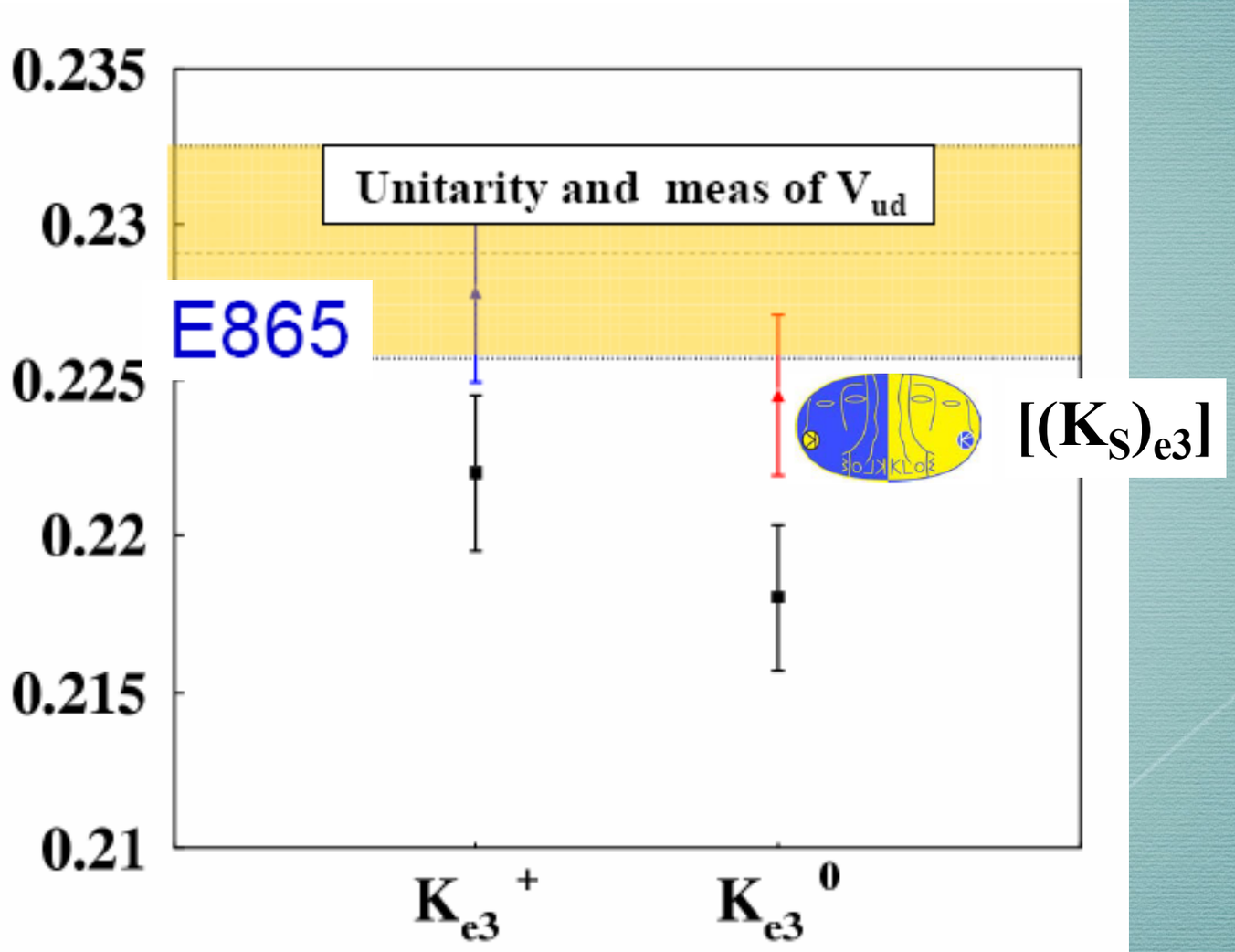
$$f_+^{K^0\pi^-}(0) = 0.961 \pm 0.008$$

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

Hyperon decays: NA48 data!

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

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



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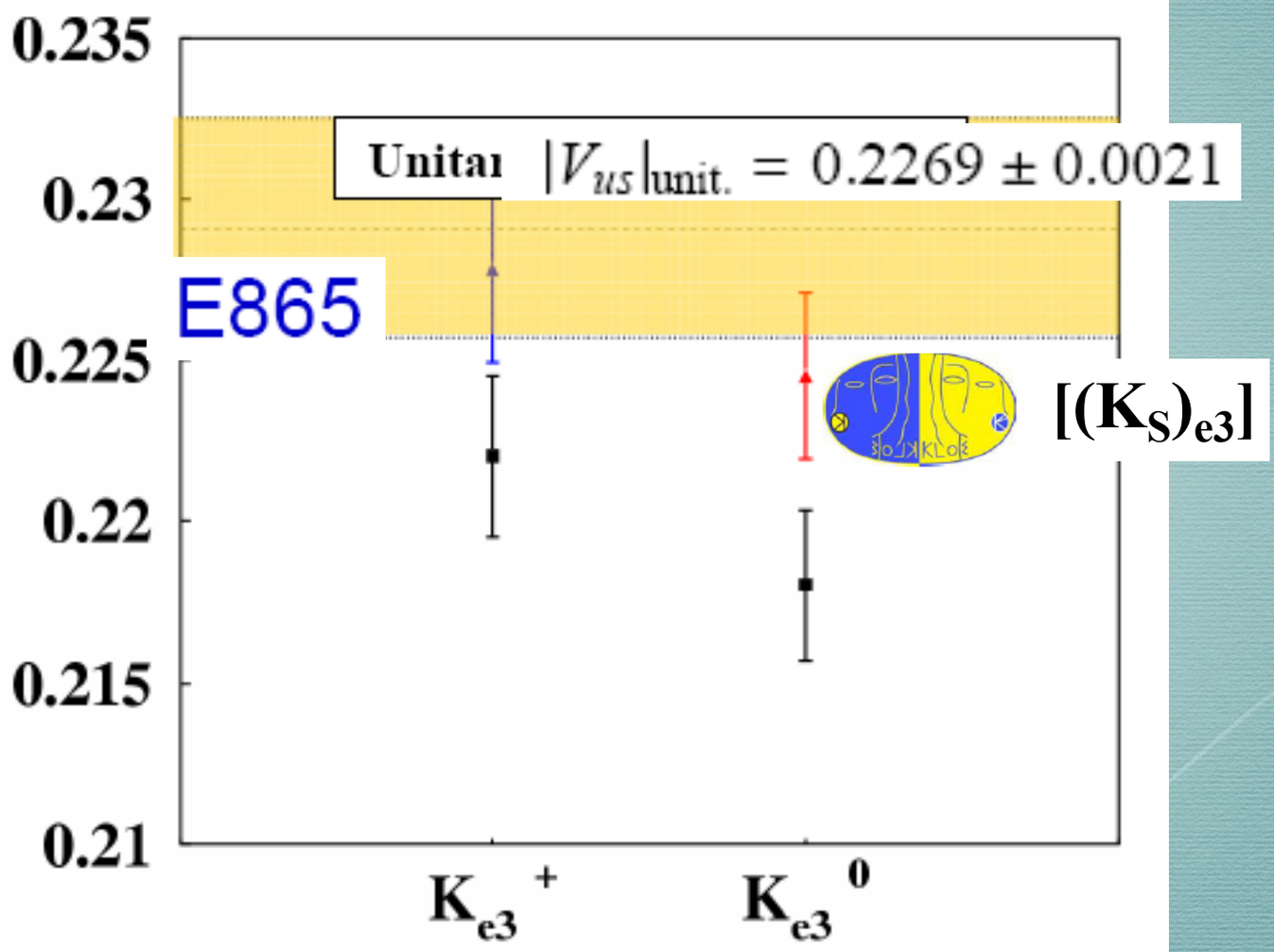

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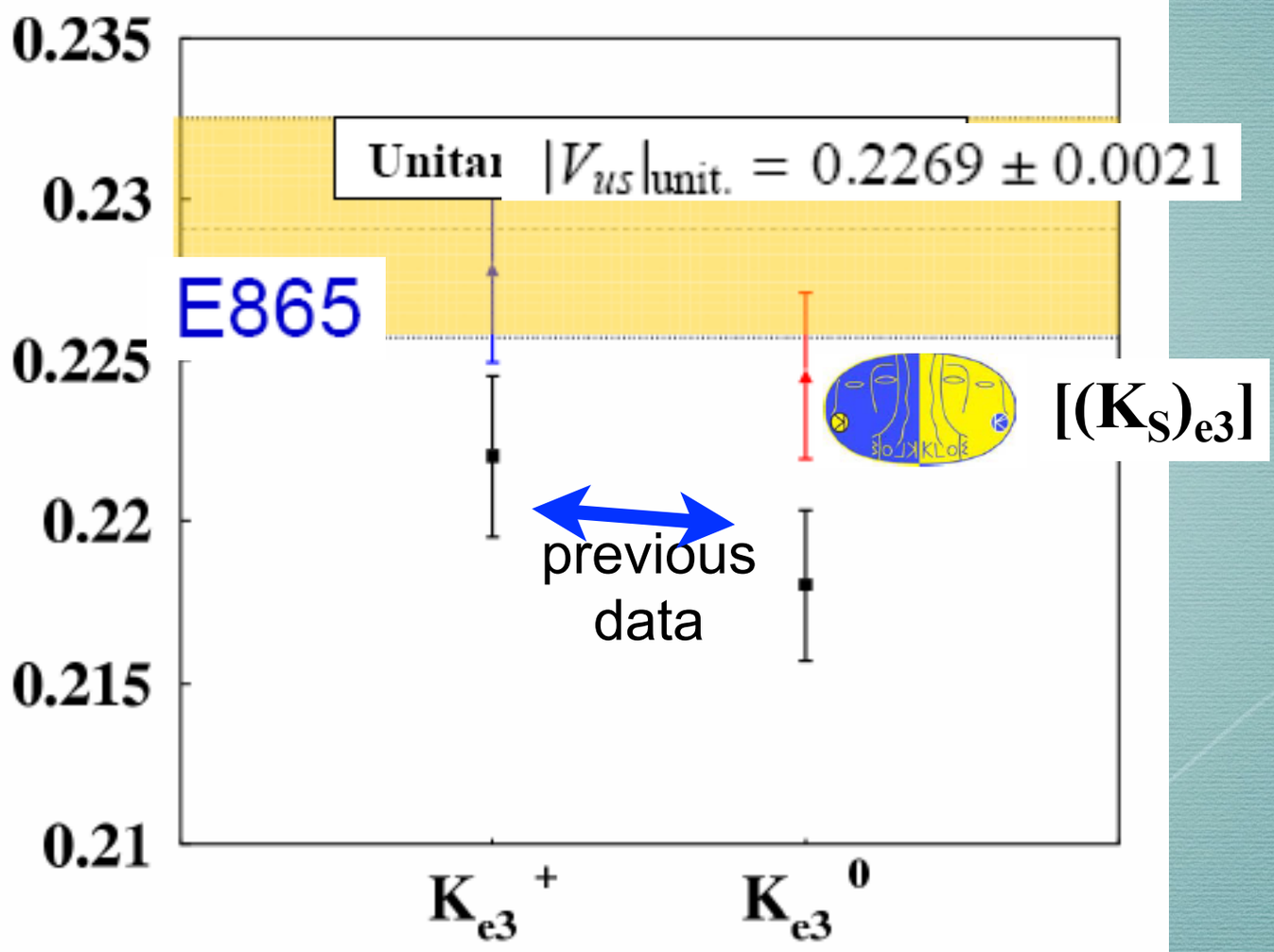

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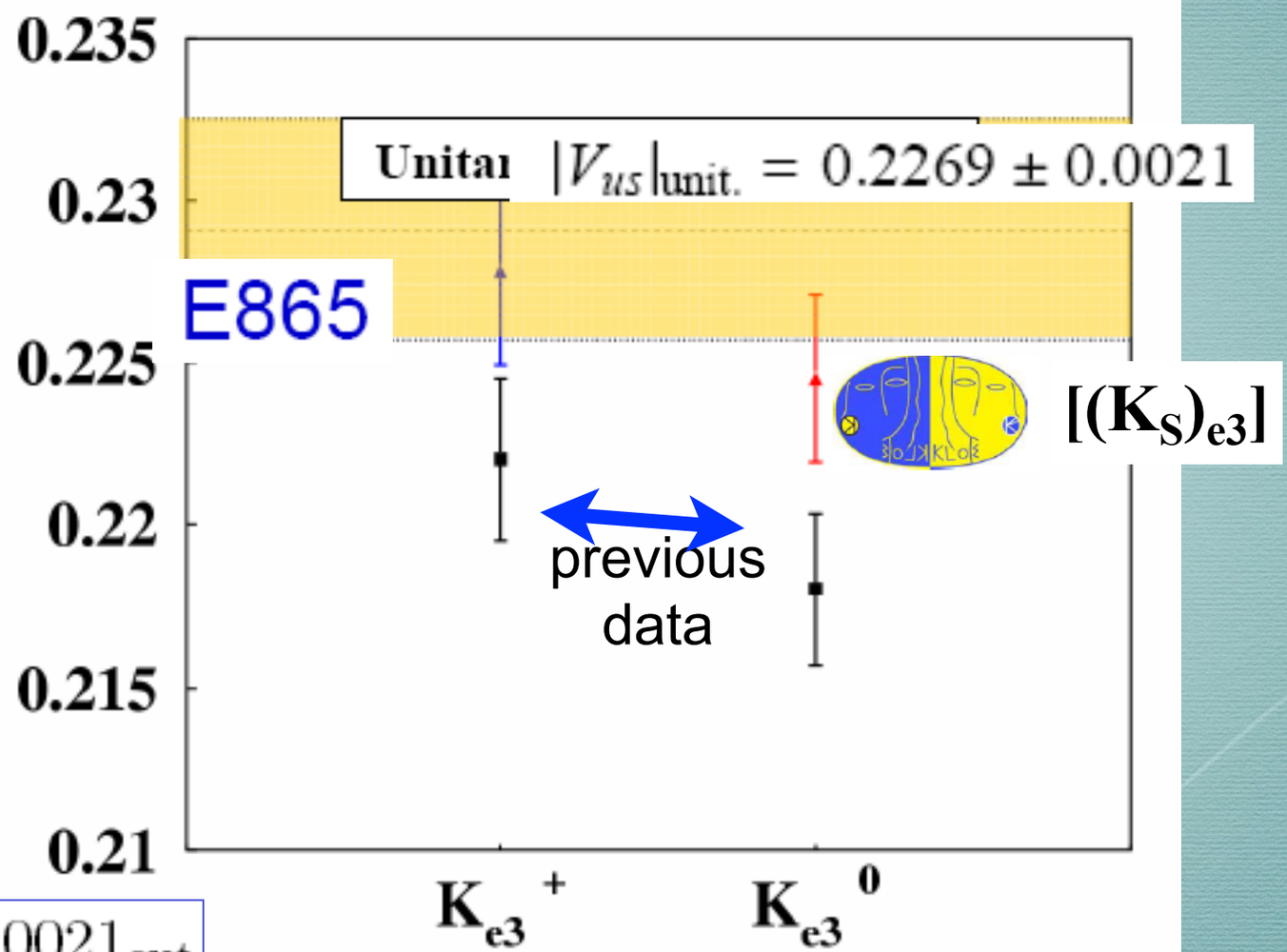
$$|V_{us}| = 0.2252 \pm 0.0008_{\rm KTeV} \pm 0.0021_{\rm ext}$$



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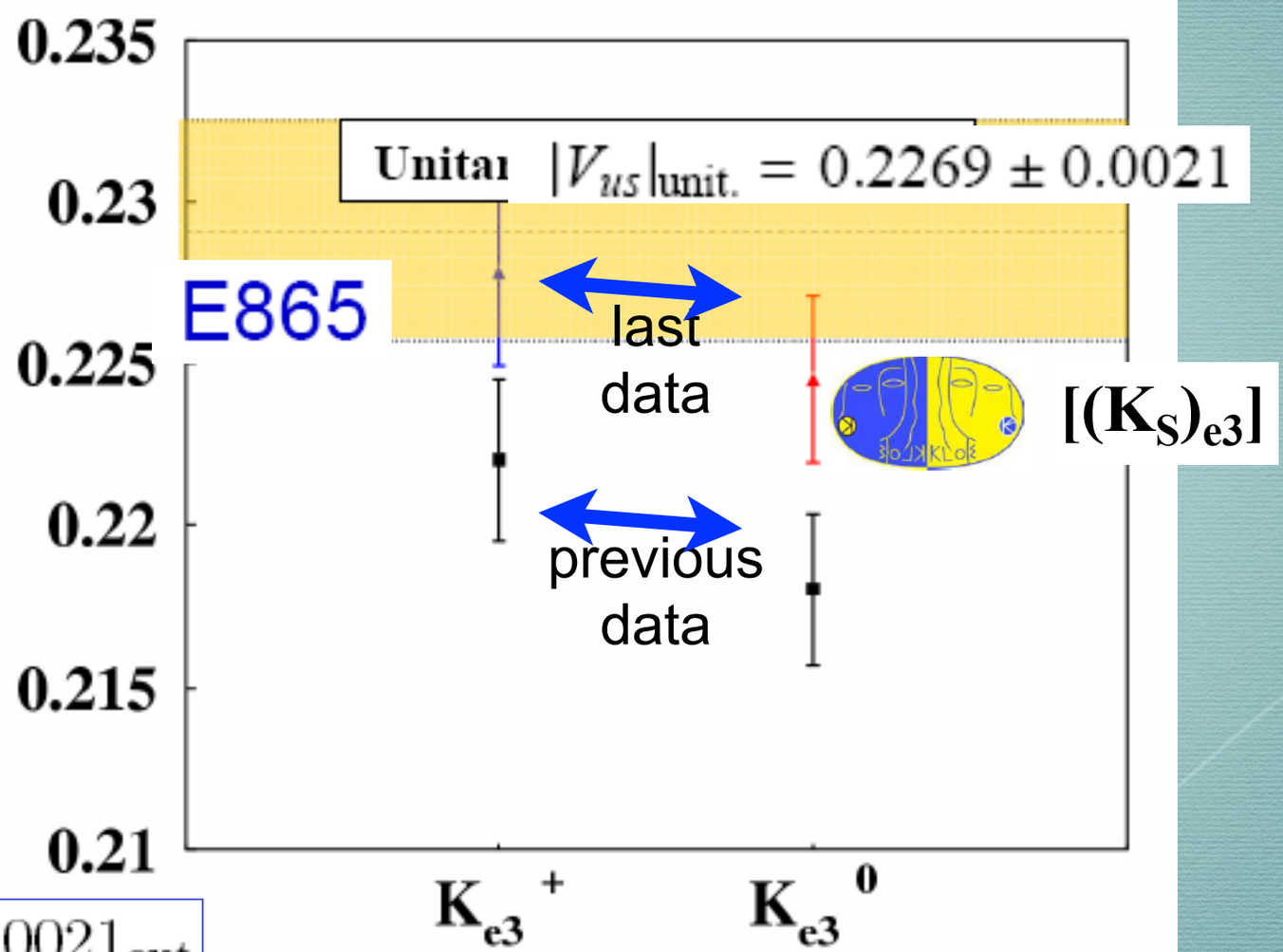

3. Cabibbo Theory and quarks

•The earlier formula proposed (1960) by Gell-Mann& Levy in the Sakata model *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 form:

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

which coincides with the Gell-Mann and Levy formula, with: (P, N, Λ) → (u, d, s).

• θ is seen as the mixing angle expressing the weak interacting down-quark, d_C, in terms of the mass-eigenstates d, s.

The weak current of baryons

•Gell-Mann-Levy: $J_\mu^{had} = \bar{p}\gamma_\mu(1-\gamma_5)\ (n+\epsilon\Lambda)$

•Cabibbo: the form of $J_\lambda^{(had)}$, in terms of the SU(3) symmetry, takes a remarkably complicated form in terms of individual baryon fields (F and D are phenomenological coefficients related to axial current renormalization):

$$J_\mu^{(had)} = \cos\theta\ \bar{p}\left[\gamma_\mu - (F+D)\gamma_5\right] n + \sin\theta \left\{ -\sqrt{\frac{3}{2}}\bar{p}\left[\gamma_\mu - (F+\frac{1}{3}D)\gamma_5\right]\Lambda \right\} +$$

$$+\sin\theta\left\{ -\bar{n}\left[\gamma_\mu - (F-D)\gamma_5\right]\Sigma^- - \bar{\Sigma^+}\left[\gamma_\mu - (F+D)\gamma_5\right]\Xi^0 + \sqrt{\frac{3}{2}}\bar{\Lambda}\left[\gamma_\mu - (F-\frac{1}{3}D)\gamma_5\right]\Xi^- \right\} + \cdots$$

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$$F \sim 0.46$$

$$D \sim 0.80$$

$$\sin\theta \sim 0.22$$

Cabibbo Universality vs. Quark-Lepton Symmetry

•Cabibbo universality is evident in quark language: there is only one quark weak doublet

• Quarks:

-one doublet only: $(u, d_C)_L$

-singlets: $(s_C)_L$, u_R, d_R, s_R

•Leptons:

-doublets: $(\nu_e, e)_L$, $(\nu_\mu, \mu)_L$

-singlets e_R, μ_R, ν_R (?)

•the quark doublet is oriented by the Cabibbo angle in SU(3) triplet space, with respect to the isospin direction chosen by the strong interactions. This notion fascinated Nicola and many other people, including myself, who tried unsuccesfully to "compute the angle" from some self-consistency condition.

•full quark-lepton symmetry was later restored by the GIM mechanism (1970), to explain the suppression of flavour changing neutral current processes, which require a charm quark with the structure

-doublets: $(u, d_C)_L$, $(c, s_C)_L$

-singlets: u_R, d_R, s_R

•quark-lepton symmetry was shown to be necessary for the renormalizability of the unified electroweak theory, Bouchiat, Iliopopulos and Meyer (1972).

• CP violation requires three weak doublets, Kobayashi and Maskawa (1973).

Closing up on Cabibbo-theory

•From its very publication, the Cabibbo theory has been seen as a crucial development:

• indicating the correct way to embody lepton-hadron universality

• enjoying a heartening phenomenological success, which indicated that we could be on the right track towards the fundamental theory of the weak interactions.

•The authoritative book *Inward Bound* by A. Pais, quotes the Cabibbo theory among the most important developments in Particle Physics after the war.

•In the book *History of CERN*, J.Iliopoulos writes:

There are very few articles in the scientific literature in which one does not feel the need to change a single word and Cabibbo's is definitely one of them. With this work he established himself as one of the leading theorists in the domain of weak interactions.

4. Pointlike Partons in ADONE

- In spring 1970, ADONE had found strong indications of a substantisl multi hadron production in ADONE events.
- This was at odd with the idea that form factors would damp hadron production with respect to muon pair production.
- The phenomenon was already known in deep inelastic scattering, was considered by Drell and Yan for high mass muon pairs in hadron collisions (1970) and had been the basis of the GIM mechanism
- Coming back from Harvard, in spring 1970, I found Nicola very excited by the multihadron production in ADONE (Tousheck was absolutely delighted !)

- Nicola and his present and former students, Giorgio Parisi and Massimo Testa, described the process as the production of point like partons and derived the simple formula

$$R = \frac{\sigma(e^+e^- \to hadrons)}{\sigma(e^+e^- \to \mu^+\mu^-)} = \sum_{\text{parton i}} Q_i^2$$

- Experimental errors were still big, but the formula seemed to be inconsistent with the value corresponding to u, d, and s quarks

$$\sum_{\text{parton i}} Q_i^2 = (\frac{4}{9}) + 2(\frac{1}{9}) = \frac{2}{3}$$

- Nicola and coll. examined more fancy hypotheses, such as point like mesons…

Three colors for Muster Mark

- In 1972, the theory of fractionally charged quarks endowed with a 3-fold color quantum number was formulated by Bardeen, Gell-Mann and Fritzsch, called Quantum ChromoDynamics (QCD). Asymptotic Freedom of QCD came in immediately after, by Gross & Wilczeck and Politzer.
- Gell-Mann visited Roma in spring 1972 and was present in a seminar where Conversi illustrated ADONE results of multihadrons.
- Conversi, quoting the formula by Cabibbo, Parisi and Testa: *quarks would give R= 2/3…*
- Gell-Mann: *w,ith color one has rather* $R = 2/3 \cdot 3 = 2$
- Conversi: *hummm….indeed we find 2….*
- that was how QCD appeared in ADONE. The formula with color was later used by Mario Greco to prove that the increase in R after the J/Ψ was indeed consistent with the production of charm quark pairs of charge +2/3 following the Cabibbo et al. formula (and GIM) and supporting the proposal that $J/\Psi = (\bar{c}c)$ (De Rujula, Gergi and Glashow).

5. Science Manager, teacher and friend

- Nicola played an overall important role in the Italian scientific life of the turn of the century, as:
- Member of Academia Nazionale dei Lincei and of the American Academy of Science
- President of Istituto Nazionale di Fisica Nucleare: 1983-1992
- President of Ente Nazionale Energie Alternative: 1993 -1998
- President of the Pontifical Academy of Science: from 1993
- He held these important positions with vision, managerial skill and universally appreciated integrity.

- Nicola liked to teach and continued to do so until the very last period of his life.
- Like all great minds, he could find simple arguments to explain the most difficult concepts.
- His students were fascinated by his simplicity, gentle modes and sense of humour.
- So we did, all of us who had the privilege to be his collaborators and friends.

Erice School started in 1963…
it gave great impetus to Italian particle physics

Weak and electromagnetic currents

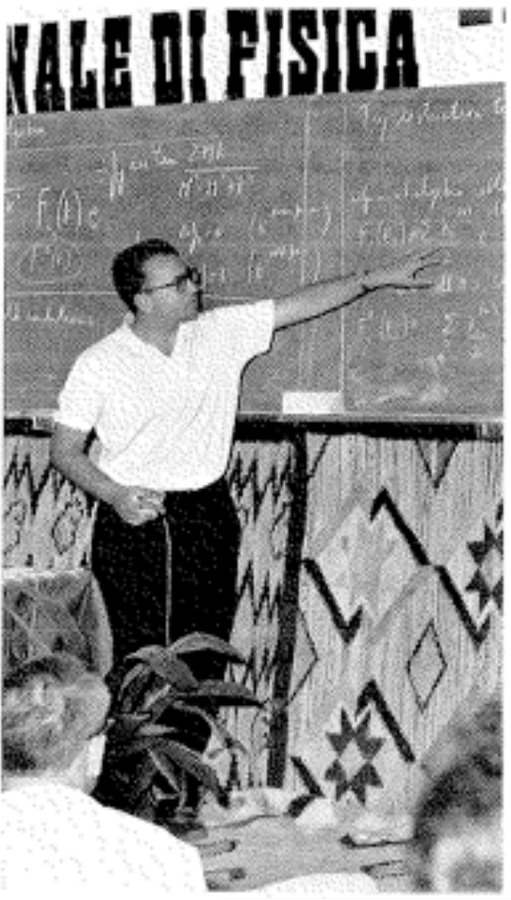
Professor Cabibbo of CERN described some recent work on the computation of radiative corrections to beta decay, done in collaboration with L. Maiani and G. Preparata.

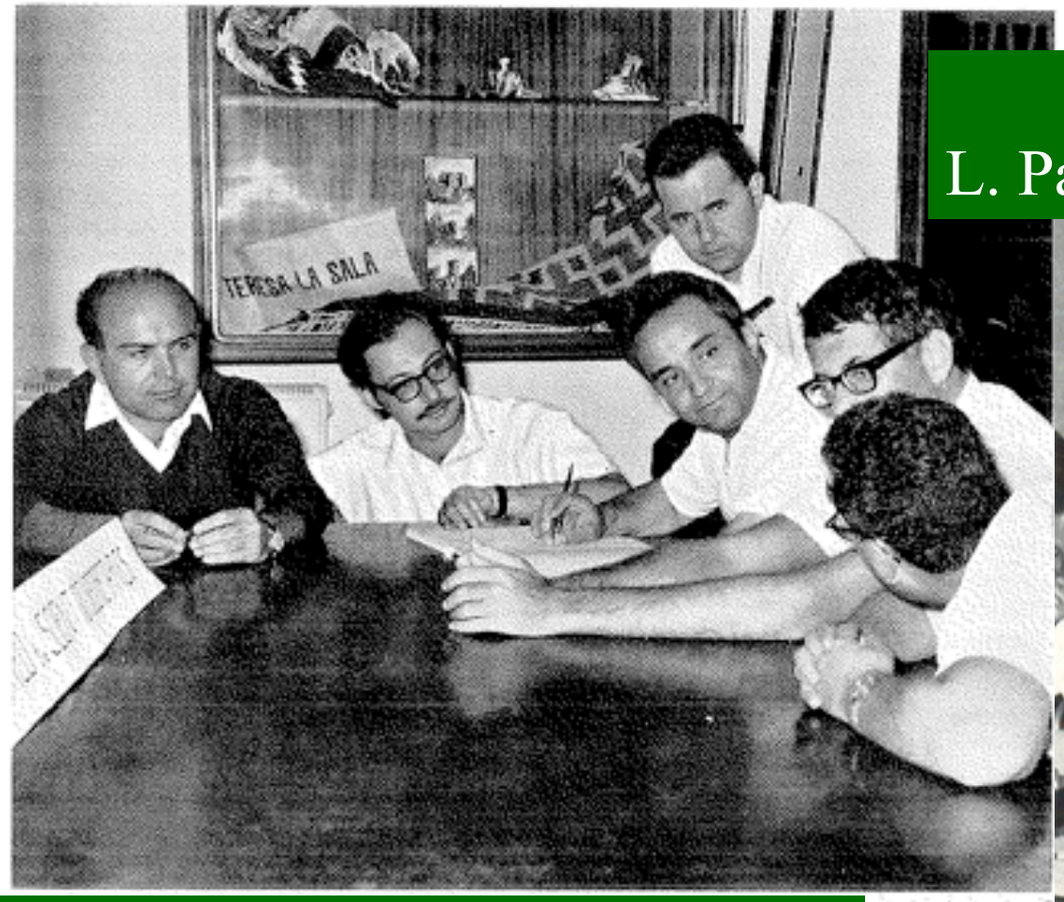
versions of the quark model with fractional charges. However, this requirement is easily met in models with only integrally charged particles. Professor Cabibbo discussed in detail one such model, which reproduces most of the desirable results of the quark model.

scattering lengths, and the Callan-Treiman relations for K_{l3} and K_{l4} decays.

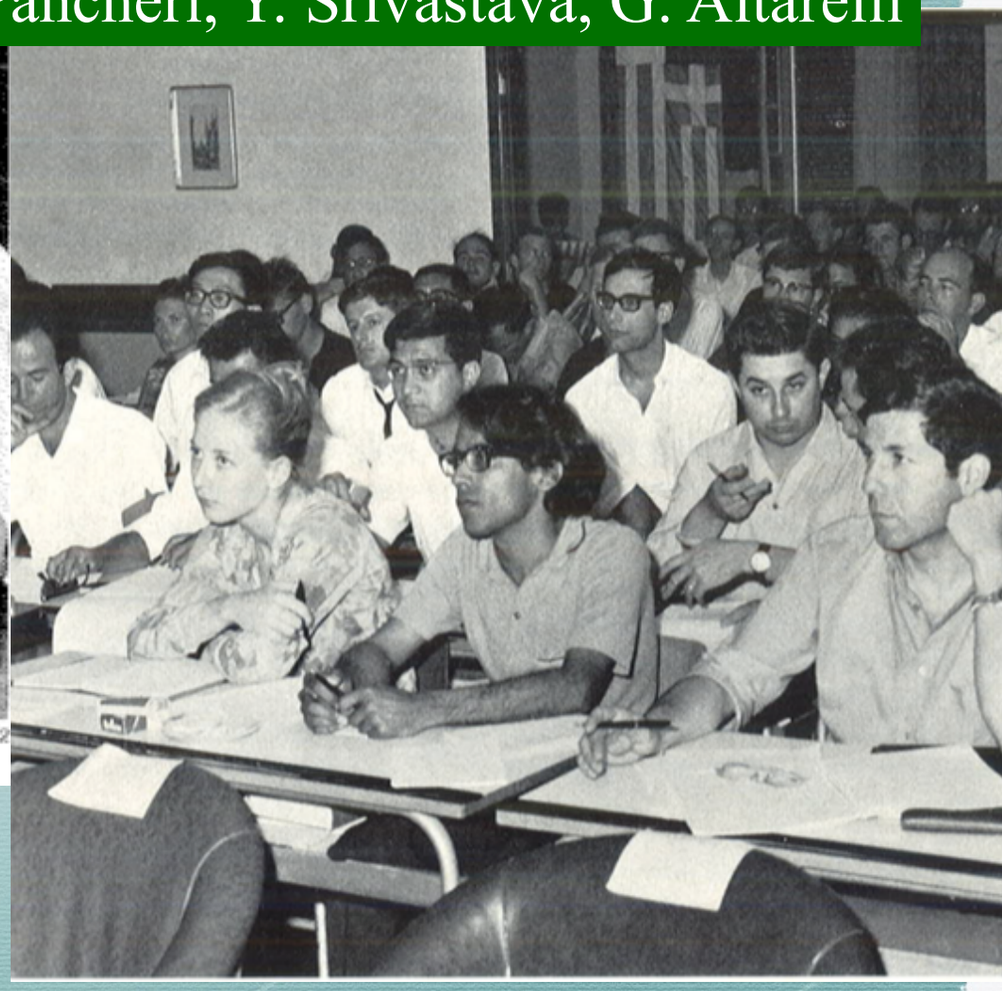
Relativistic quark model of baryons and mesons

The course given by Professor Gell-Mann, from California Institute of Technology,

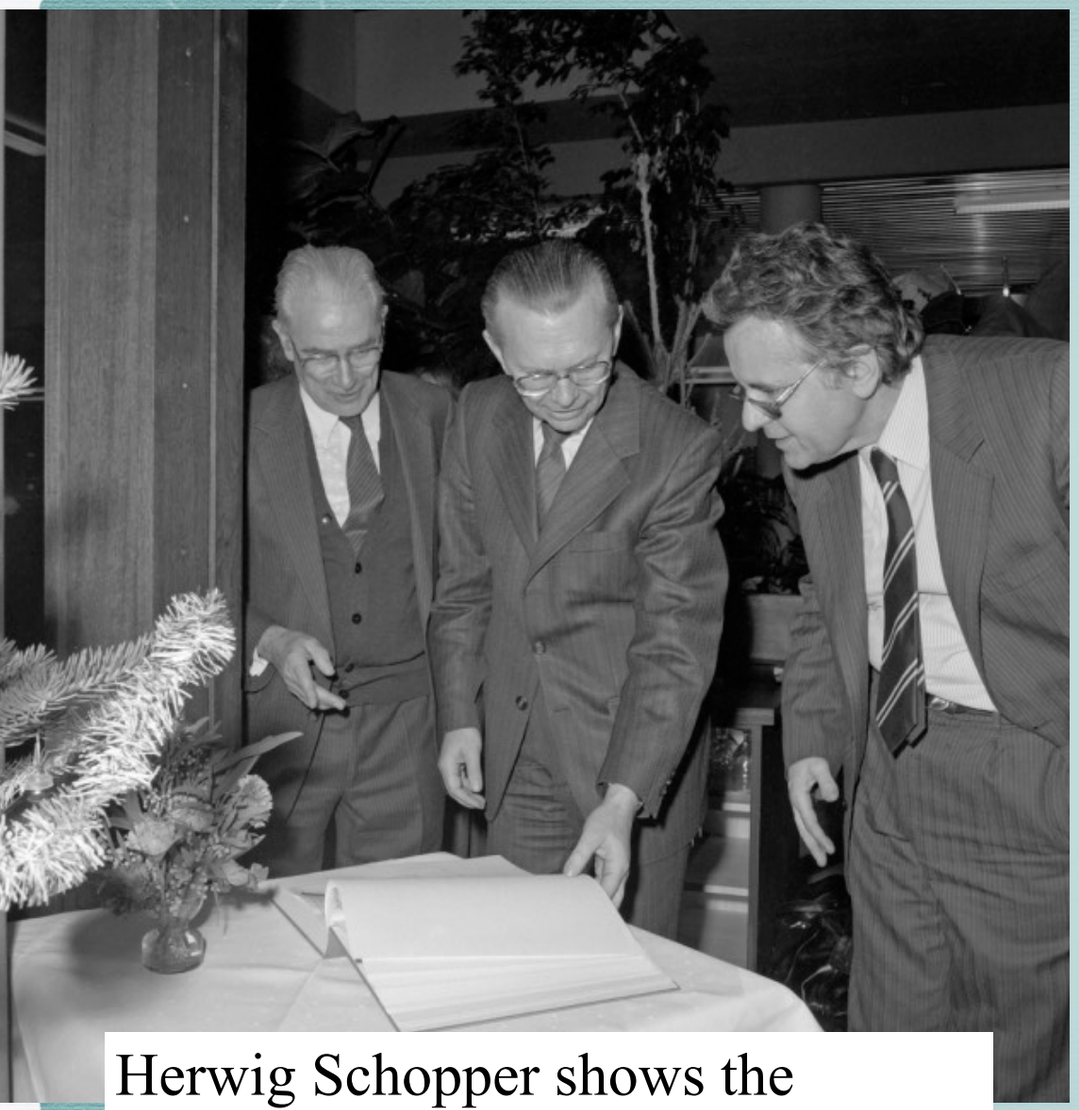




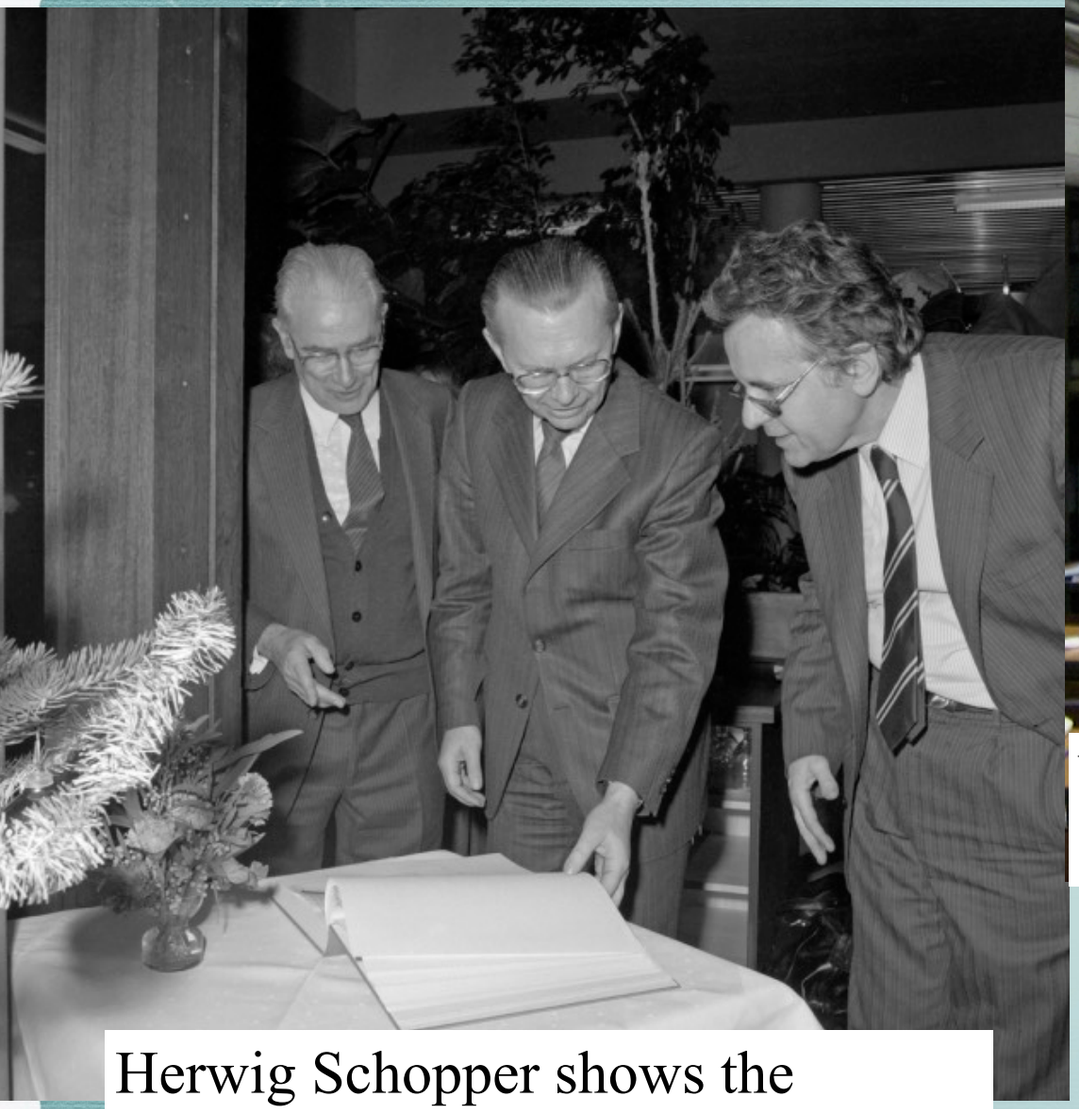
Erice 1967
L. Pancheri, Y. Srivastava, G. Altarelli



Erice 1967: making the Standard Model...
B. Zumino, S. Coleman, A. Zichichi, N. Cabibbo, S. Glashow, M. Gell-Mann



Herwig Schopper shows the Golden Book to Nicola Cabibbo (right, just after his nomination to Chair INFN) and Gordon Munday (left), 75th Council Session, December 1983. Photo CERN.



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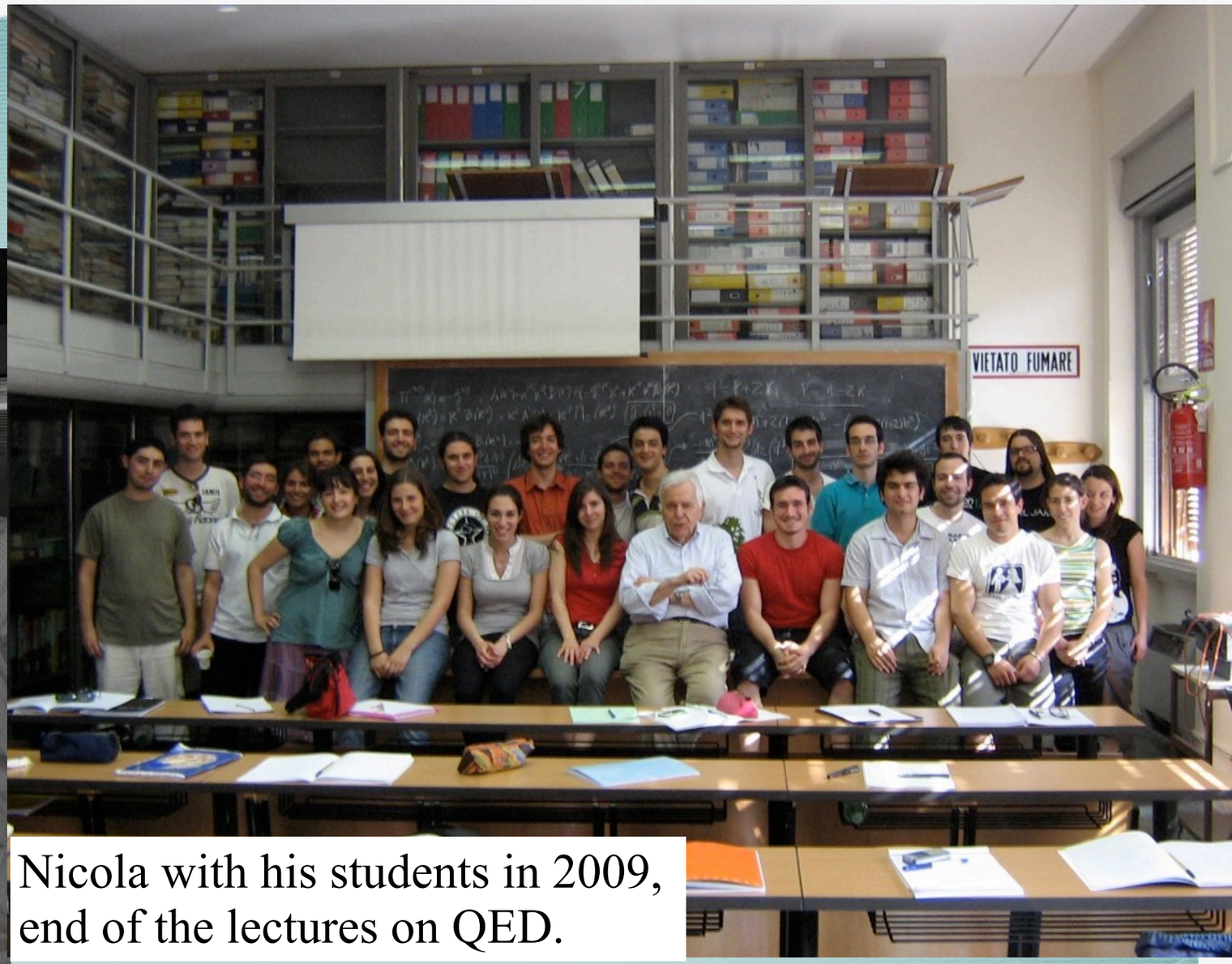
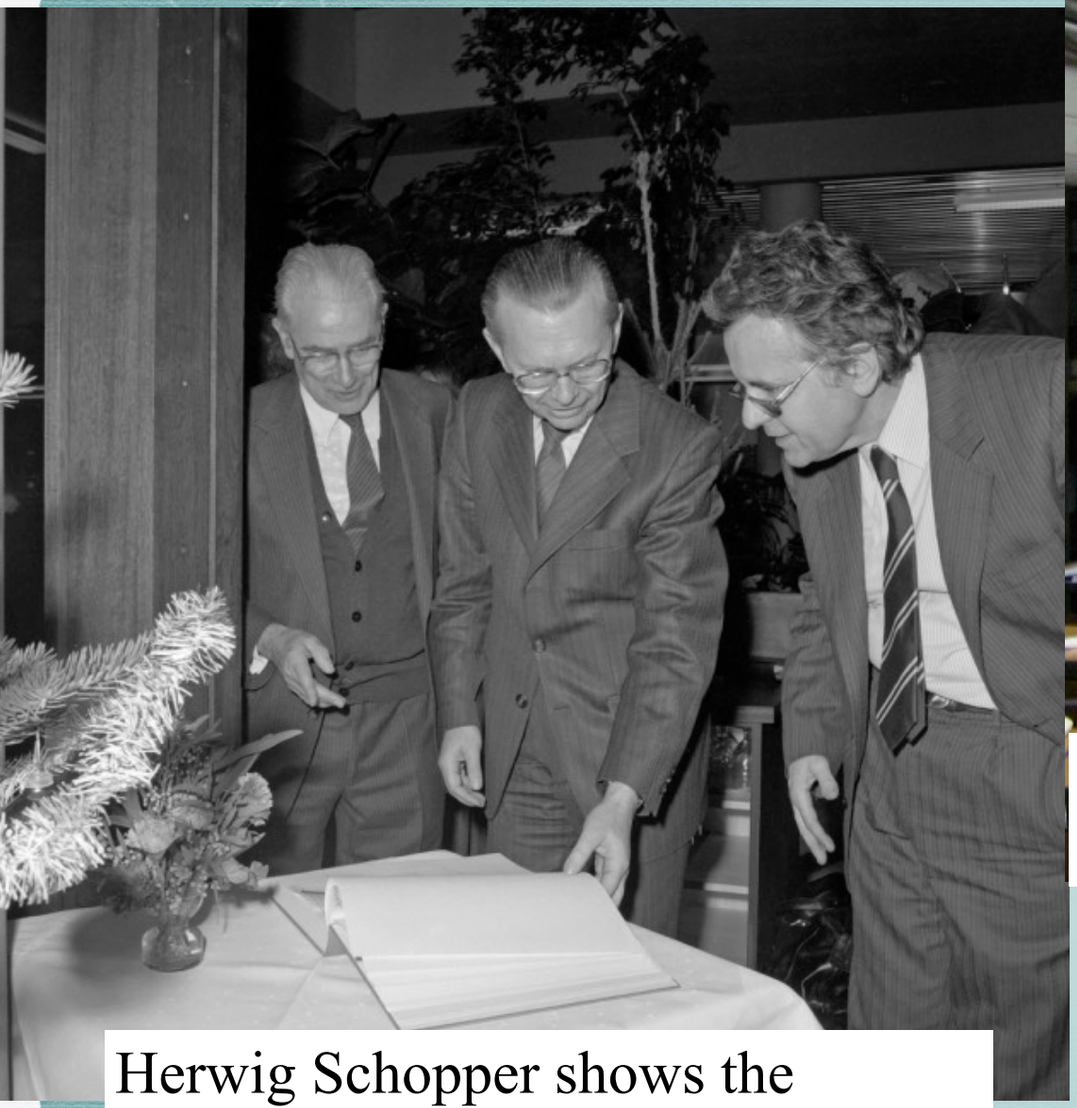


Nicola with his students in 2009, end of the lectures on QED.



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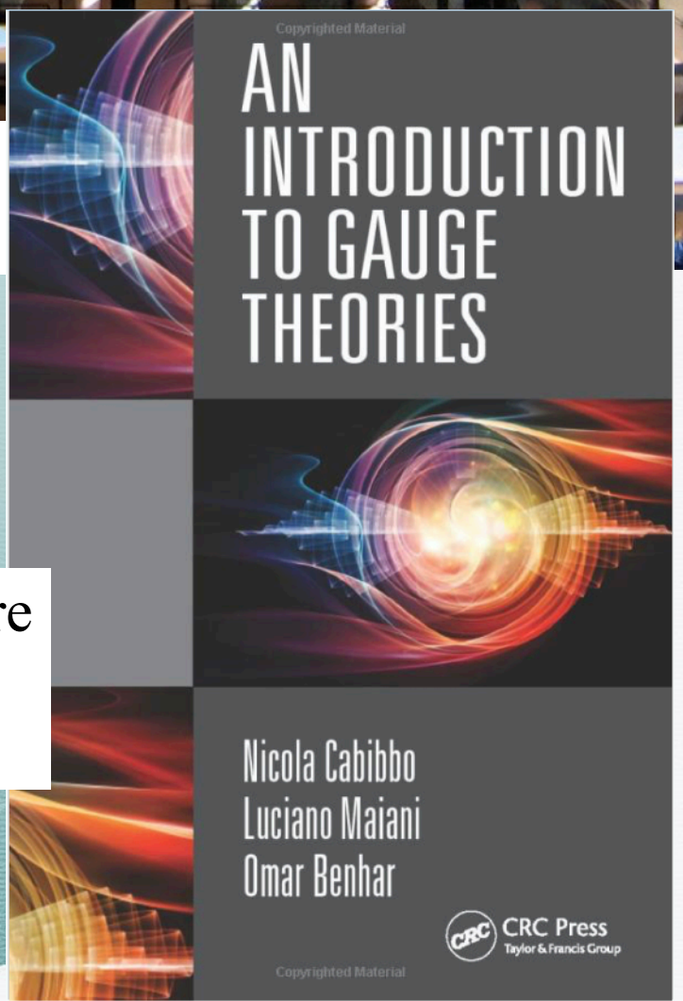

Large parts of Nicola's Lecture Notes, edited by Benhar and myself, are in this book.