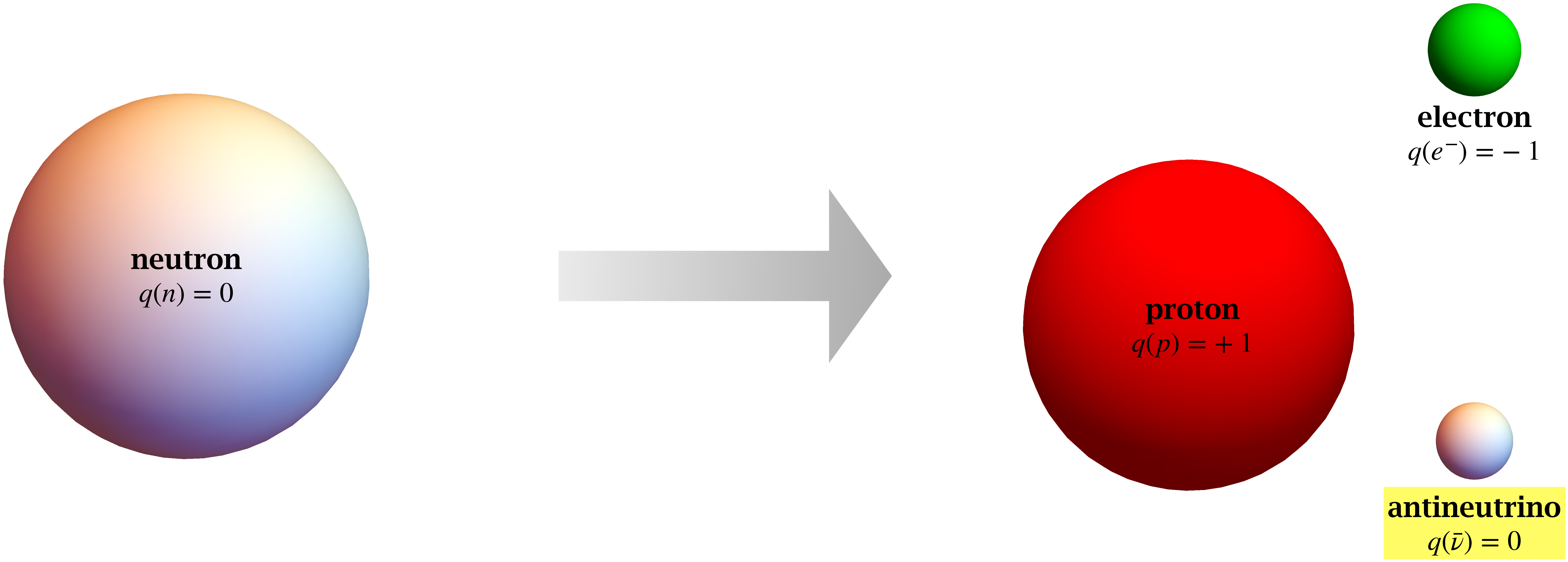
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

cross section and error updates

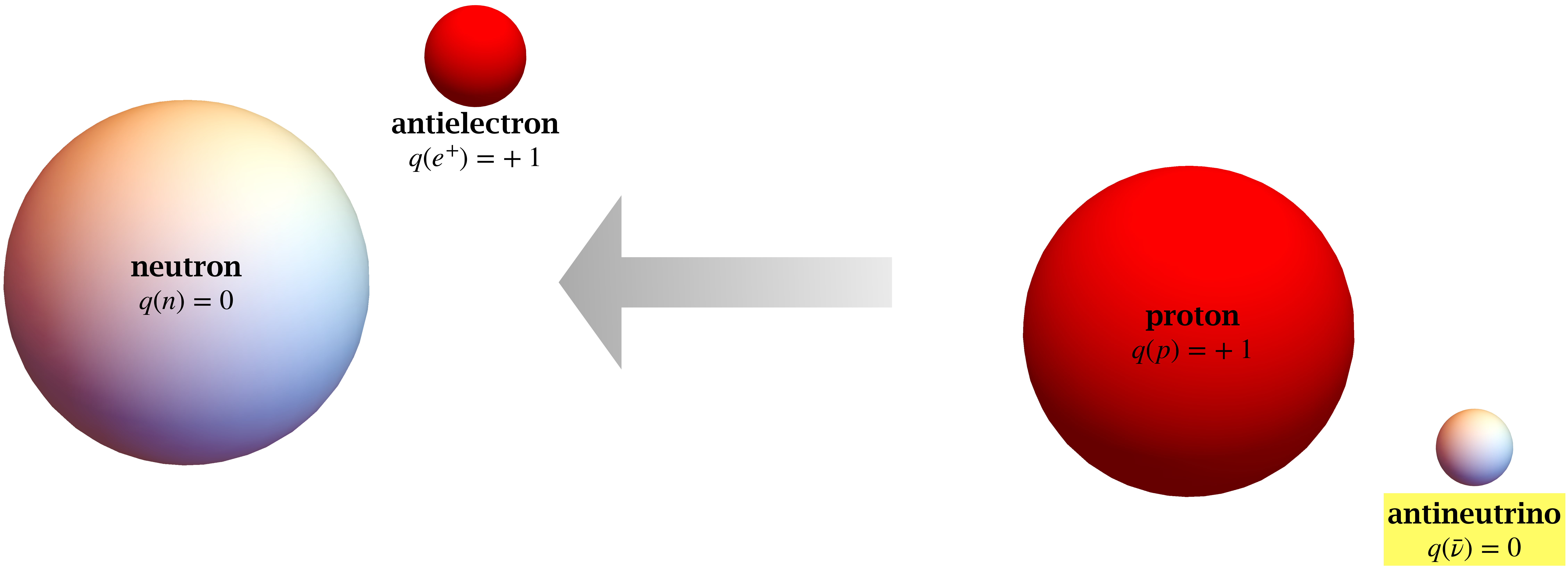
Francesco Vissani,
INFN - Laboratori Nazionali del Gran Sasso

MAYORANA Workshop – Modica, July 13, 2023

β decay



inverse β decay



Masatoshi Koshiba

Yogi Totsuka

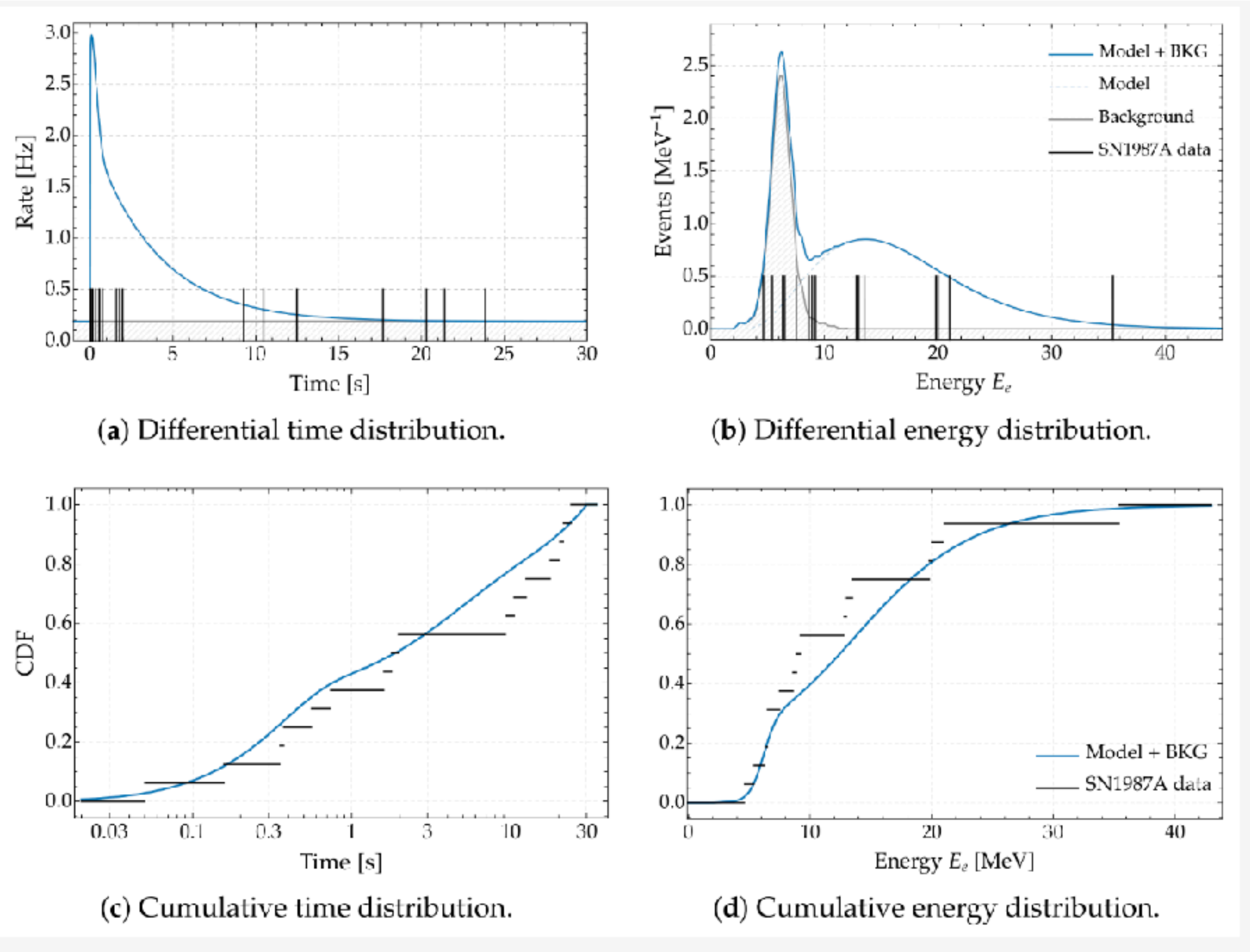
Takaaki Kajita

water Cherenkov detectors

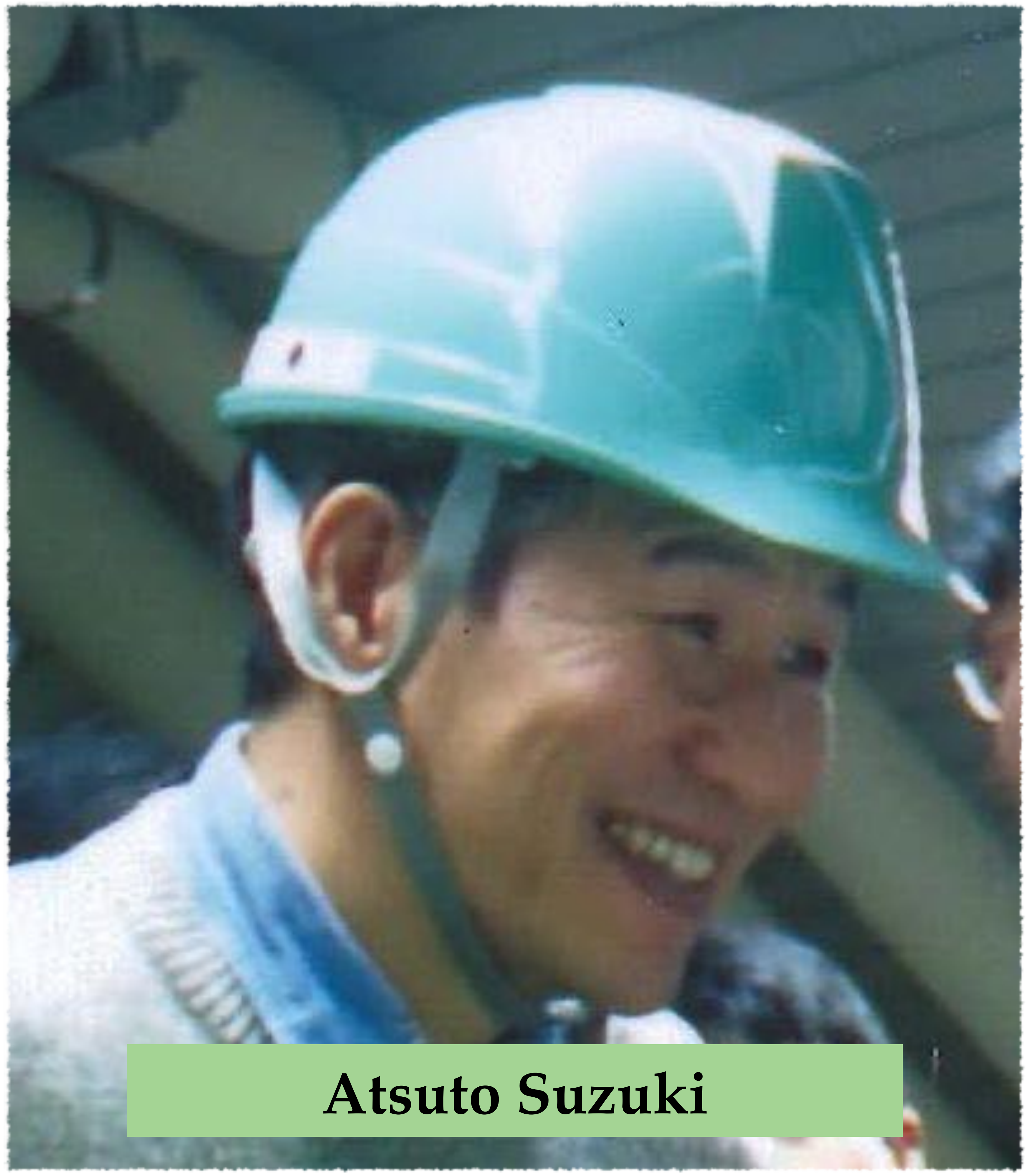
Kamiokande, Super-Kamiokande, Hyper-Kamiokande

core collapse supernovae

detection of electron antineutrinos



http://www.sns.ias.edu/~jnb/Galleries/Some_Solar_Neutrino_Researchers/index.htm



liquid scintillators with ultra-high radio purity

Borexino, KamLAND, ...

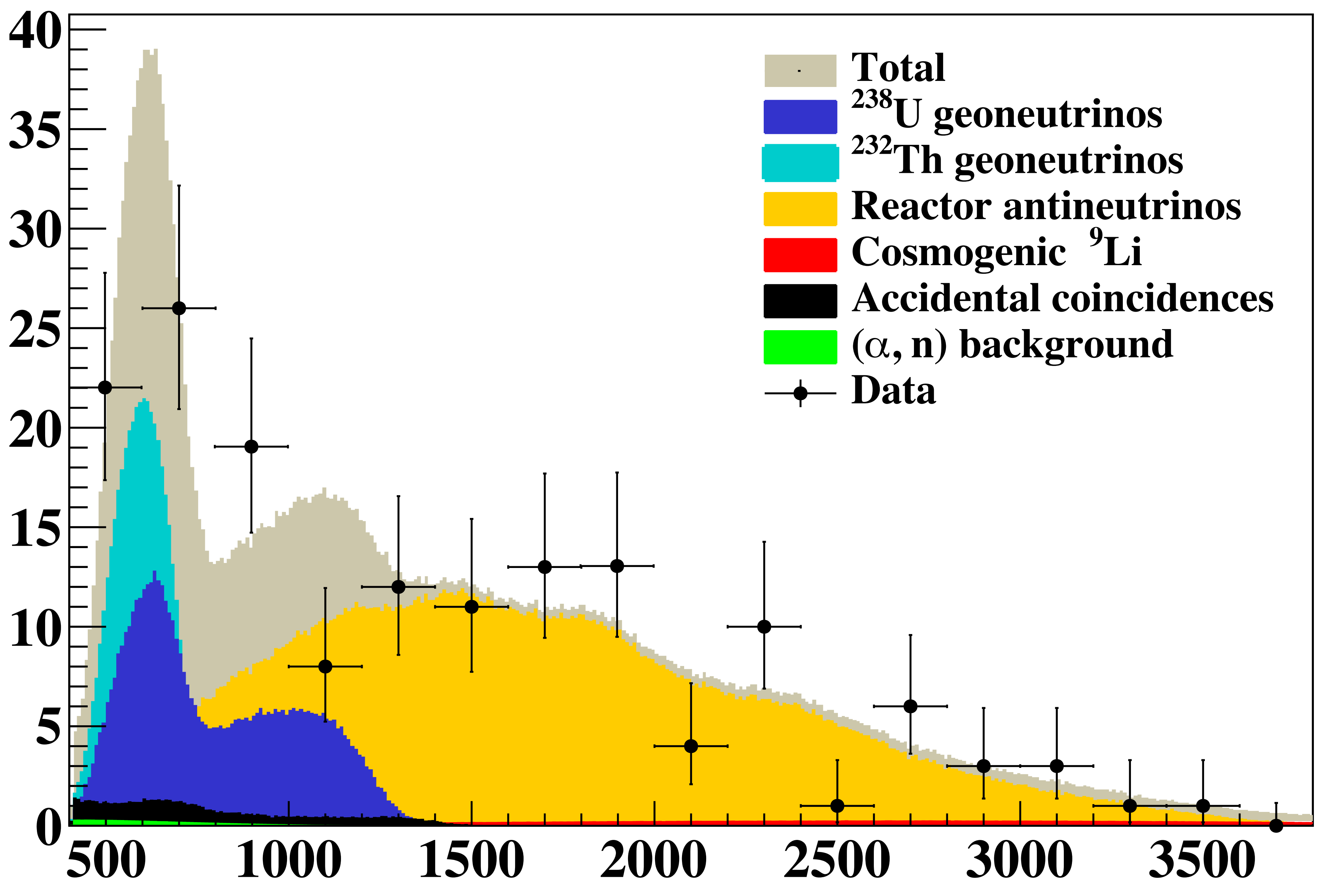
reactor antineutrinos

today very important for neutrino oscillations studies

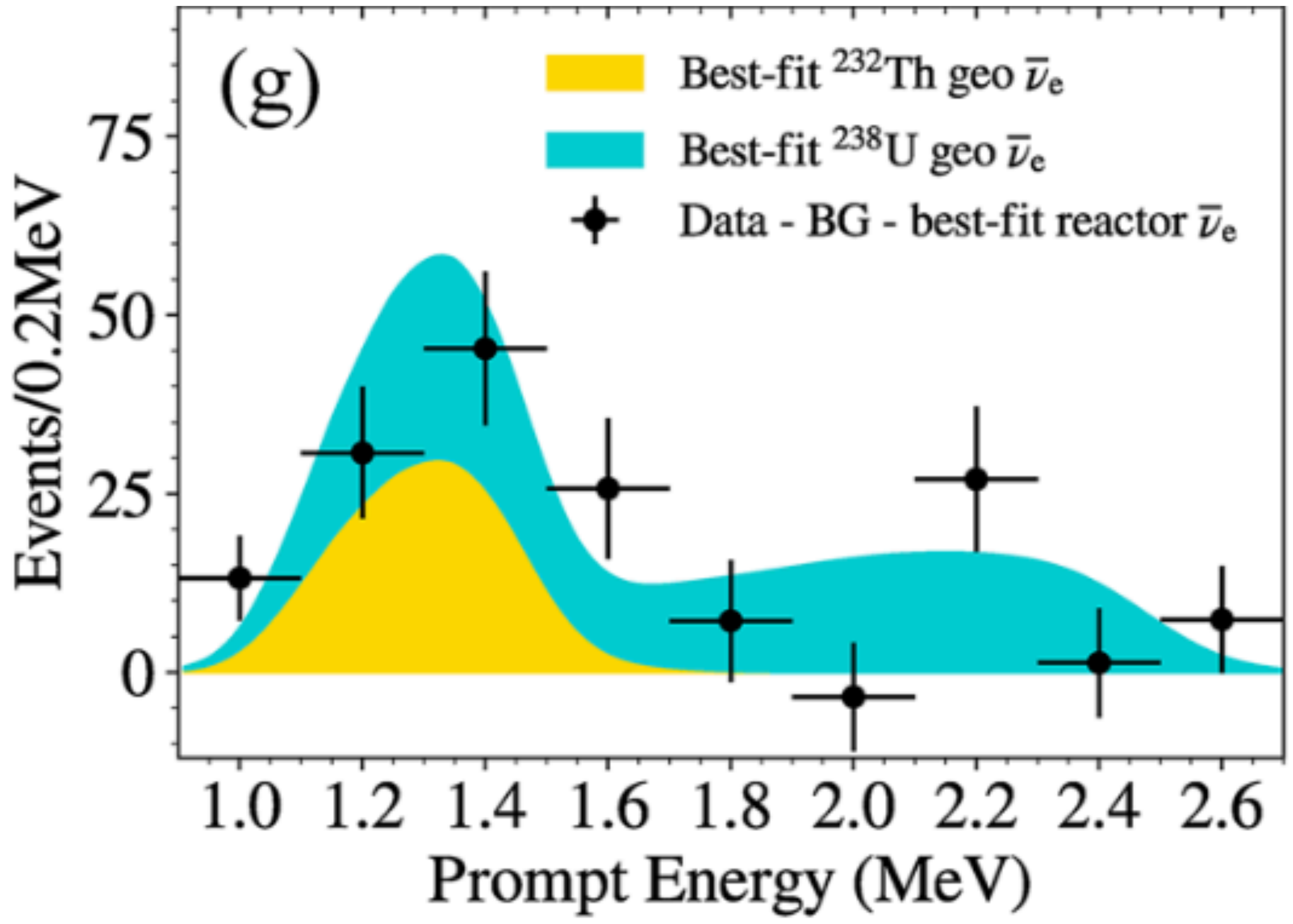
geoneutrinos

important for geophysics, planetology, etc

Borexino



Kamland



energy ranges

geoneutrinos... till 2.5 MeV
reactor............... till 10 MeV
supernovae..... till 50 MeV
inside PNS.... till 200 MeV

recent evaluations of IBD

Characteristics, mutual agreement, IBD cross section values

1999

Vogel-Beacom

a systematic inclusion of small effects, relevant in the region below $E_\nu < 60$ MeV as, weak magnetism and recoil (first discussed in 30s, till Gell-Mann, PR 1958).

several useful analytical results; discussion of supernova pointing

PHYSICAL REVIEW D, VOLUME 60, 053003

Angular distribution of neutron inverse beta decay, $\bar{\nu}_e + p \to e^+ + n$

P. Vogel* and J. F. Beacom†
Physics Department 161-33, California Institute of Technology, Pasadena, California 91125

(Received 1 April 1999; published 27 July 1999)

The reaction $\bar{\nu}_e + p \to e^+ + n$ is very important for low-energy ($E_\nu \lesssim 60$ MeV) antineutrino experiments. In this paper we calculate the positron angular distribution, which at low energies is slightly backward. We show that weak magnetism and recoil corrections have a large effect on the angular distribution, making it isotropic at about 15 MeV and slightly forward at higher energies. We also show that the behavior of the cross section and the angular distribution can be well understood analytically for $E_\nu \lesssim 60$ MeV by calculating to $\mathcal{O}(1/M)$, where M is the nucleon mass. The correct angular distribution is useful for separating $\bar{\nu}_e + p \to e^+ + n$ events from other reactions and detector backgrounds, as well as for possible localization of the source (e.g., a supernova) direction. We comment on how similar corrections appear for the lepton angular distributions in the deuteron breakup reactions $\bar{\nu}_e + d \to e^+ + n + n$ and $\nu_e + d \to e^- + p + p$. Finally, in the reaction $\bar{\nu}_e + p \to e^+ + n$, the angular distribution of the outgoing neutrons is strongly forward peaked, leading to a measurable separation in positron and neutron detection points, also potentially useful for rejecting backgrounds or locating the source direction. [S0556-2821(99)04015-1]

A. Differential cross section: expansion in powers of $1/M$

We begin with the matrix element of the form

$$\mathcal{M} = \frac{G_F \cos\theta_C}{\sqrt{2}} \left[\bar{u}_n \left(\gamma_\mu f - \gamma_\mu \gamma_5 g \boxed{- \frac{i f_2}{2M} \sigma_{\mu\nu} q^\nu} \right) u_p \right] \times \left[\bar{v}_{\bar{\nu}} \gamma^\mu (1 - \gamma_5) v_e \right] , \quad (4)$$

2002

Strumia-FV

an "exact" expression based on the 4 known form factors. virtually valid at all energies

includes a pedantic comparison with previous calculations and an estimate of the uncertainty

Physics Letters B
Volume 564, Issues 1–2, 3 July 2003, Pages 42-54

Precise quasielastic neutrino/nucleon cross-section

Alessandro Strumia [a], Francesco Vissani [b]

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https://doi.org/10.1016/S0370-2693(03)00616-6

Abstract

Quasielastic antineutrino/proton and neutrino/neutron scatterings can be well approximated by simple formulae, valid around MeV or GeV energies. We obtain a single expression valid in the whole range, and discuss its relevance for studies of supernova neutrinos, which reach intermediate energies.

Table 2
Percentage difference between our full result and various approximations for $\bar{\nu}_e$ (above) and ν_e (below) total cross-sections. A negative (positive) sign means that a certain cross-section is an over(under)-estimate. It is easy to implement approximations made with ⋆⋆⋆, while implementing those marked with a ⋆ is not much simpler than performing a full computation

E_ν, MeV		ease	2.5	5	10	20	40	80	160
			Percentage difference in $\sigma(\bar{\nu}_e p \to n\bar{e})$						
(1)	Naïve	⋆⋆⋆	−3.9	−5.8	−9.9	−19	−38	−84	−210
(2)	Naïve+	⋆⋆⋆	0	0.3	−0.2	0.4	0.2	0.5	−0.9
(3)	Vogel and Beacom	⋆⋆	0	0	0.3	1.2	5.6	28	150
(4)	NLO in E_ν/m_p	⋆	0	0	0	0	0.1	1.5	13
(5)	Horowitz	⋆⋆	−370	−83	−32	−14	−6.4	−3.0	−1.3
(6)	Llewellyn-Smith+	⋆	−13	−2.1	−0.5	−0.1	0	0	0
(7)	LS + VB	⋆	0.5	0.1	0	0	0	0	0

Very good agreement with Vogel and Beacom for $E_\nu < 60$ MeV; note that the two implementations are equally demanding.

estimated uncertainty

low energy region - high energy region

3.2. Overall uncertainty

We now discuss how accurate our full expressions for the cross-sections are.

The axial coupling $g_1(0)$ is measured from neutron decay.[4] Different experimental determinations do not fully agree, therefore we conservatively increased the error. Newer measurements, performed with a higher neutron polarization than older ones, are consistent and agree on $g_1(0)/f_1(0) = -1.272 \pm 0.002$ when older determinations are discarded—a value slightly different from the one quoted in Section 2. Isospin-breaking corrections to $f_1(0) = 1$ are negligible [15].

In conclusion, at low energy $\sigma(\bar{\nu}_e p)$ has an overall 0.4% uncertainty, which is adequate for present experiments. The ratio between the measured and the no-oscillation reactor $\bar{\nu}_e$ flux is $1.01 \pm 2.8\%$ (stat) $\pm 2.7\%$ (syst) at

The above discussion shows why it is difficult to assess the uncertainty on g_1 and g_2. Optimistically assuming that (1) or (2) is right, it is negligible. On the other side, a pessimistic estimate can be obtained by using M_{A_1} in place of M_A: the total $\bar{\nu}_e p$ cross-section increases by $0.4\% \times (E_\nu/50\ \mathrm{MeV})^2$ for $E_\nu \lesssim 200$ MeV. The shift remains relatively small because, as shown in Section 2, the t-dependence of the form factors affects $\bar{\nu}_e p$ only at NNLO in E_ν/m_p.

why an updated cross-section and error assessment?

the two cross sections are in good agreement and they are quite accurate: an error of 0.4% as PLB2002 matches the statistical error of a sample of **60,000** *events*

- however, Daya Bay has collected already **3.5 million** events *(60 times)* and similarly, other reactor antineutrino experiments
- JUNO will collect **180,000** events after 6 years *(3 times)*
- Super-Kamiokande (and JUNO) will collect **5,000** events from a future galactic supernova, a number that scales as $(\,10\,\mathbf{kpc}\,/\,D\,)^2$. For Hyper-Kamiokande, multiply by a factor of **10**

2022

Ricciardi-Vignaroli-FV

objective: assess better the **uncertainty** of expectations

updating of relevant parameters, testing with the neutron decay rate

verification of the significance of “second-class currents”

Regular Article - Theoretical Physics | Open Access | Published: 22 August 2022

An accurate evaluation of electron (anti-)neutrino scattering on nucleons

Giulia Ricciardi, Natascia Vignaroli & Francesco Vissani

Journal of High Energy Physics **2022**, Article number: 212 (2022) | Cite this article

Abstract

We discuss as accurately as possible the cross section of quasi-elastic scattering of electron (anti-)neutrinos on nucleons, also known as inverse beta decay in the case of antineutrinos. We focus on the moderate energy range from a few MeV up to hundreds of MeV, which includes neutrinos from reactors and supernovae. We assess the uncertainty on the cross section, which is relevant to experimental advances and increasingly large statistical samples. We estimate the effects of second-class currents, showing that they are small and negligible for current applications.

2.1.1 The six form factors

One possible formulation of the most general matrix element of the charged weak current between proton and neutron states, of 4-momenta p_p and p_n respectively, is

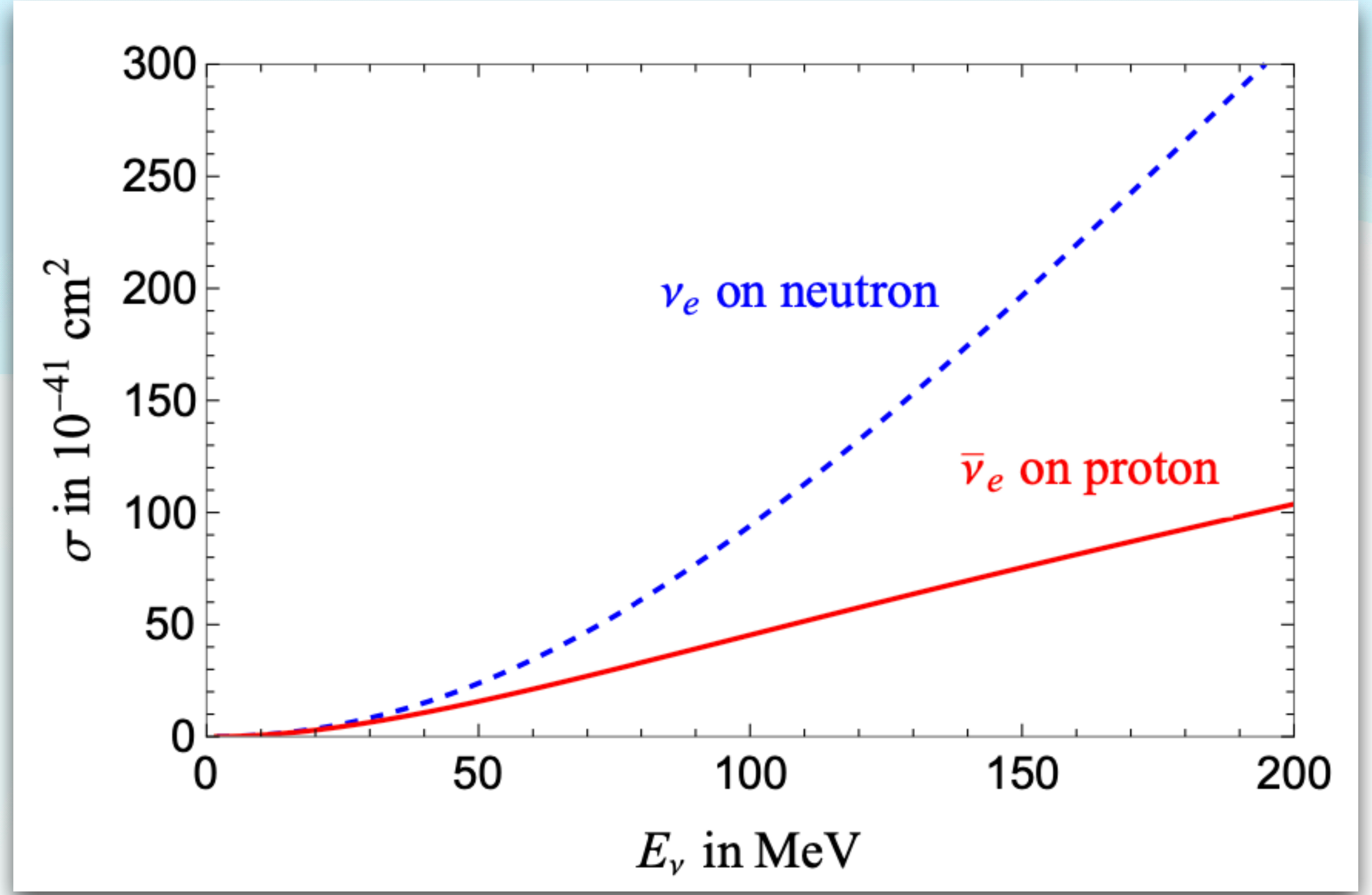
$$\mathcal{J}_\mu = \bar{u}_n \left(f_1 \gamma_\mu + g_1 \gamma_\mu \gamma_5 + i f_2 \sigma_{\mu\nu} \frac{q^\nu}{2M} + g_2 \frac{q_\mu}{M} \gamma_5 + f_3 \frac{q_\mu}{M} + i g_3 \sigma_{\mu\nu} \frac{q^\nu}{2M} \gamma_5 \right) u_p \tag{2.1}$$

The normalisation mass scale is $M = (m_n + m_p)/2$. The form factors f_1, f_2 and f_2 are generally referred to, respectively, as vector, weak magnetism and scalar. The terms including them represent the vector part of the current. The terms including g_1, g_2 and g_2 represent the axial part of the current. These six dimensionless form factors are Lorentz invariant, and in general depend upon the four-momentum transfer squared $t = q^2 = -Q^2$, where $q = p_n - p_p$.

- There are various way to rewrite this current, due to Gordon identity.
- f_3 and g_3 are second class currents, expected to be small; we use *Day & McFarland, PRD 86, 2012* to estimate the phenomenologically maximum value.

results 1: the updated cross section

result: second-class currents, even at maximum value, give a **negligible** contribution



what is the accuracy of the IBD cross section?

quantitative discussion of the uncertainty; neutron decay as a test; axial radius *leading uncertainties are due to input parameters:*

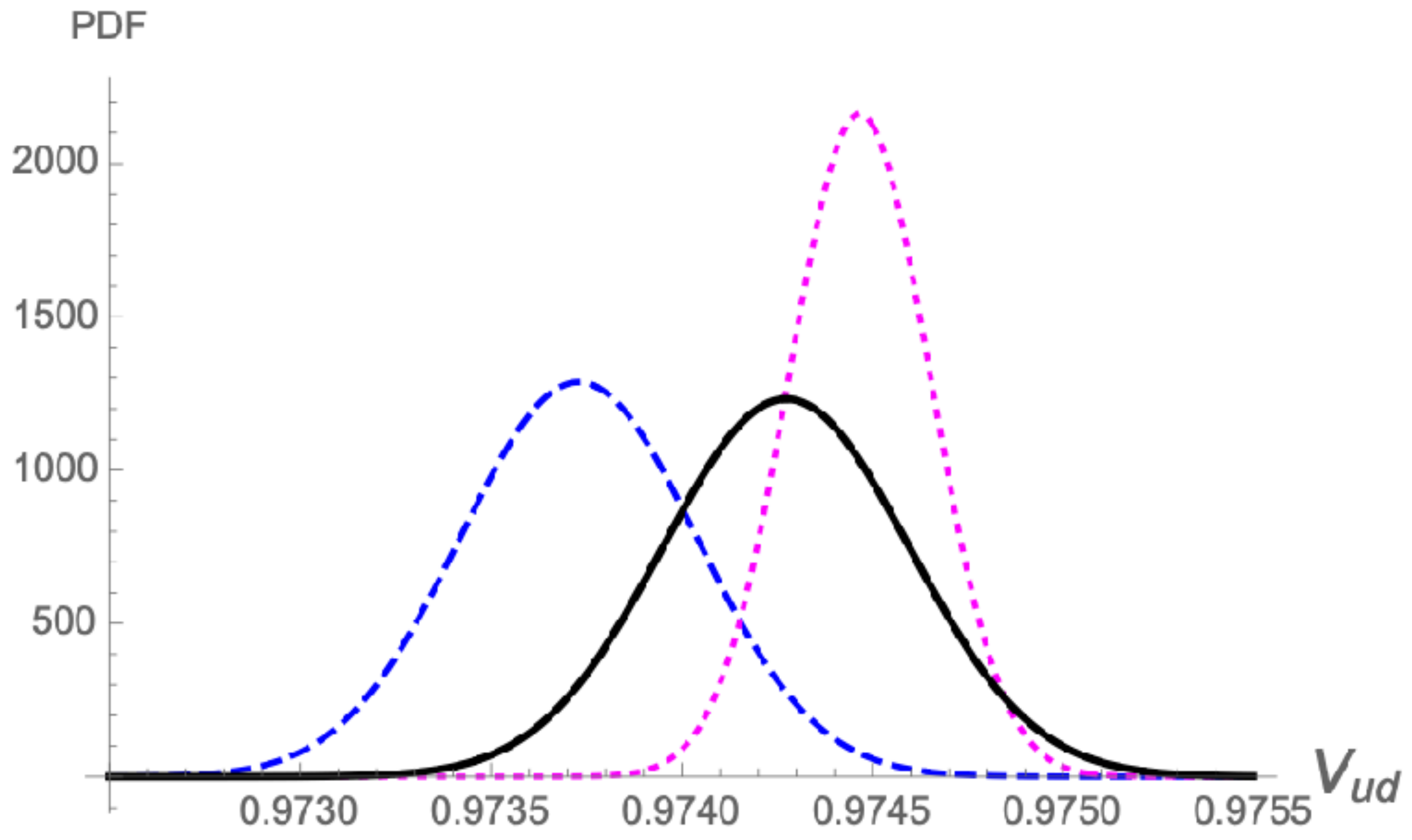
- V_{ud} - **namely,** $\cos\theta_C$ - **and the parameter** λ ,
- **the axial mass - or, the axial radius,**

at low and high energies, respectively.

V_{ud}

=the cosine of the Cabibbo angle

- For the **superallowed transitions**, we use *Hardy & Towner, PRD 102 (2020)*
- Using the **unitarity of CKM matrix**, we can estimate V_{ud} from V_{us} and V_{ub}, following *PDG 2020*
- The two results are not in perfect agreement; thus, we include the scale factor $S = \sqrt{\chi^2/(N-1)} = 2.0$ for a conservative estimation of the uncertainty



λ

=the zero momentum transfer $g_1(q^2)$

★eight measurements with polarized neutron decay

★most recent one (PERKEO-III) is very precise

★*Czarnecki, Marciano & Sirlin, PRL 120 (2018)*

suggest to omit pre-2002 ones

★we prefer to include them, enlarging $S = 2$

result within 1σ from most recent & global average

the neutron decay constraint

compatibility test

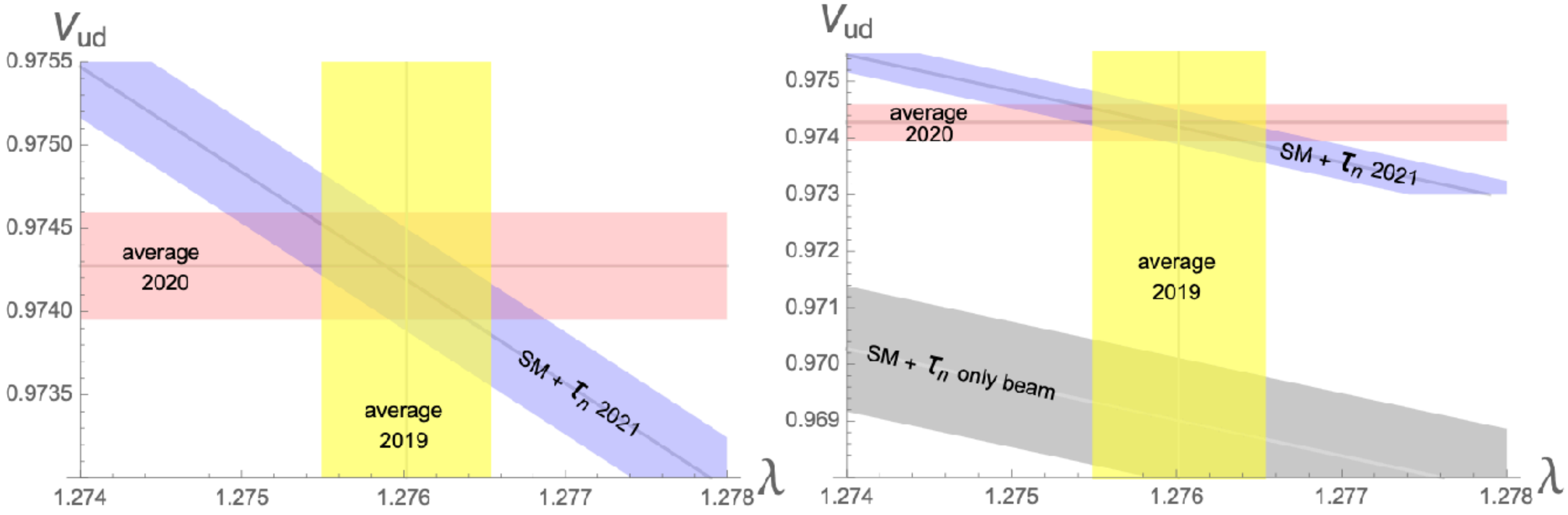


Figure 2. Left: illustration of the compatibility, within the SM, among the determinations of λ, $V_{\rm ud}$ and $\tau_{\rm n}$(tot). Right: enlargement of the parameter region to include the prediction of the correlation $\lambda - V_{\rm ud}$ (gray band) that follows from the SM assuming the correctness of measurement $\tau_{\rm n}$(beam): this is incompatible with the determinations of λ and $V_{\rm ud}$.

“A priori, it would be possible to hypothesize an **additional neutron decay channel** into undetected particles, which would shorten the total average lifetime — a possible way out, recently attempted.

This would require an agreement between the prediction and the **exclusive** measurement, namely τ_n(beam).

This is not what is observed: the predicted value τ_n(SM) - a function of V_{ud} and λ - agrees with the **inclusive** measurement τ_n(tot) instead.”

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This is not what is observed: the predicted value τ_n(SM) - a function of V_{ud} and λ - agrees with the **inclusive** measurement τ_n(tot) instead.”

there is no simple theoretical way out; the first suspect becomes an unknown systematic error

summary of low energy uncertainties

conservative and standard error propagation

3.1.4 Procedures for assessing the uncertainty on the cross section

At this point in the discussion, we can evaluate the uncertainty on the σ cross section. By calculating the derivatives with respect to the parameters of interest, at the point of maximum likelihood,

$$\vec{\xi} = \left(\frac{\partial\sigma}{\partial V_{\rm ud}} , \frac{\partial\sigma}{\partial\lambda} \right) \Big|_{\substack{\rm best \\ \rm fit}} \tag{3.8}$$

we find the uncertainty from the formula

$$\delta\sigma = \sqrt{\vec{\xi}^{\,t}\, \Sigma^2\, \vec{\xi}} \quad \text{where} \quad \Sigma^2 = \begin{pmatrix} (\delta V_{\rm ud})^2 & , \rho\, \delta V_{\rm ud}\, \delta\lambda \\ \rho\, \delta V_{\rm ud}\, \delta\lambda\, , & (\delta\lambda)^2 \end{pmatrix} \tag{3.9}$$

We conclude that $\delta\sigma = 0.1\,\%$, i.e. 4 times better than 2002

(or half as much if we had included the neutron decay data, that we prefer to use as a test)

r_A or M_A

parameterization of $g_1(q^2)/g_1(0)$

★ at GeV energies, $g_1(t)/g_1(0) = 1/(1 - t/M_A^2)^2$ gives good results. But at low energies, it is more unbiased to use the linear expansion: $g_1(t)/g_1(0) = 1 + (r_A^2 \cdot t)/6$

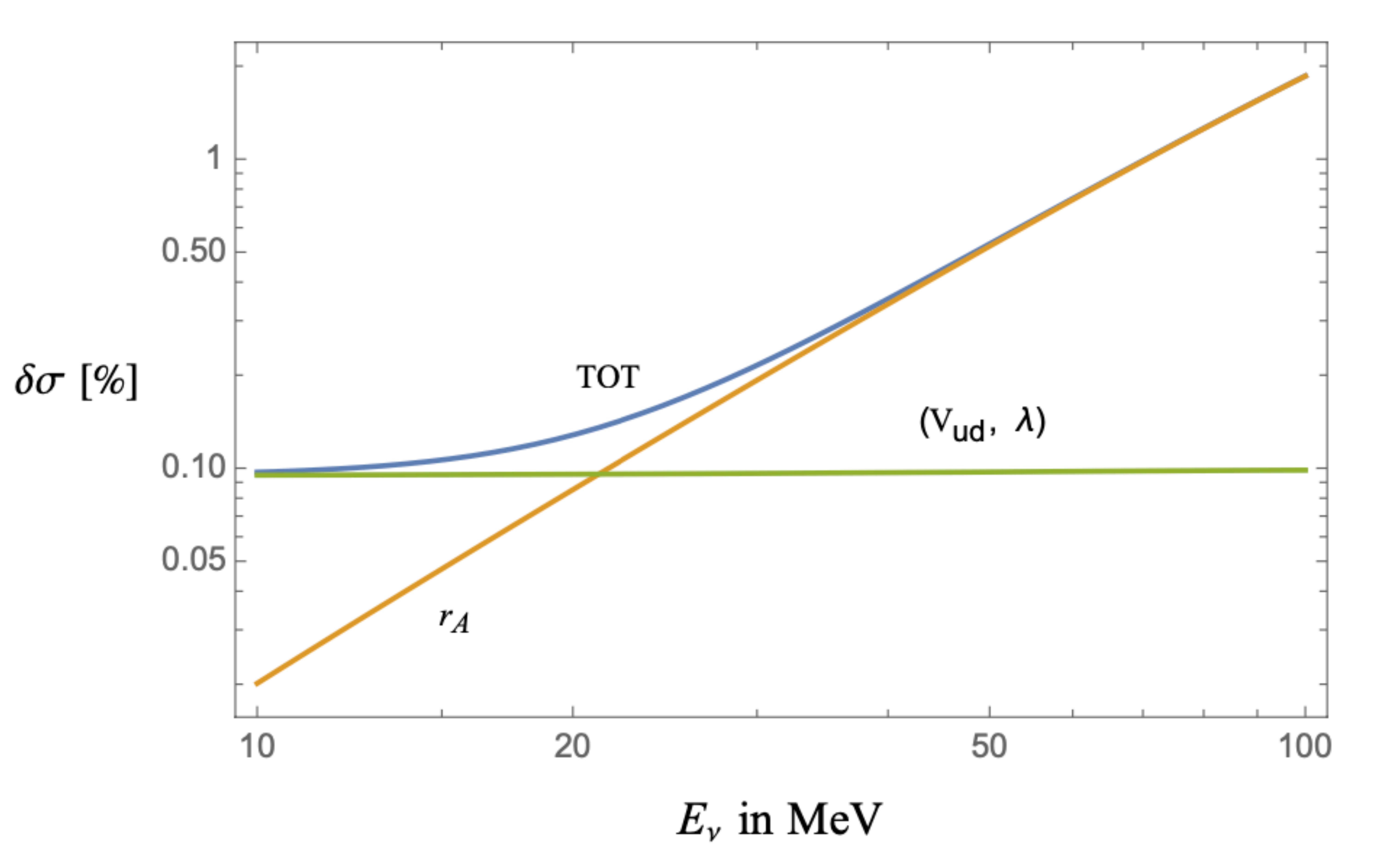
★ a global fit, based on the assumed double-dipole, gives $M_A = 1014 \pm 14$ MeV. This corresponds to $r_A^2 = 0.455 \pm 0.013\ \mathrm{fm}^2$, supported by electro-pion production data

★ an analysis **that does not assume double-dipole** finds instead $r_A^2 = 0.46 \pm 0.12\ \mathrm{fm}^2$. We use this to estimate a conservative error on the cross section

compare Bodek et al EPJC 2008 and Hill et al, PRD 2018

results 2: the cross section uncertainty

the low energy and the high energy uncertainties sum in quadrature



summary and discussion

The cross section of the IBD is well known.

To perform its maintenance, all we need is a set of consolidated theoretical concepts

and, most importantly, reliable measurements of the key parameters.

summary and discussion

The cross section of the IBD is well known.

To perform its maintenance, all we need is a set of consolidated theoretical concepts

and, most importantly, reliable measurements of the key parameters.

- **the cross section depends critically upon** $V_{ud} = \cos\theta_C$, $g_1(0) = \lambda$, $r_A^2 \sim 12/M_A^2$;
- **the uncertainty is small** $(0.1\ \%)$ **at low energies,** $1.1\ \% \left(\dfrac{E_\nu}{50\ \mathbf{MeV}}\right)^2$ **at high ones;**
- **second class currents are not expected to give a significant contribution.**

summary and discussion

The cross section of the IBD is well known.

To perform its maintenance, all we need is a set of consolidated theoretical concepts

and, most importantly, reliable measurements of the key parameters.

how to clarifiy / improve?

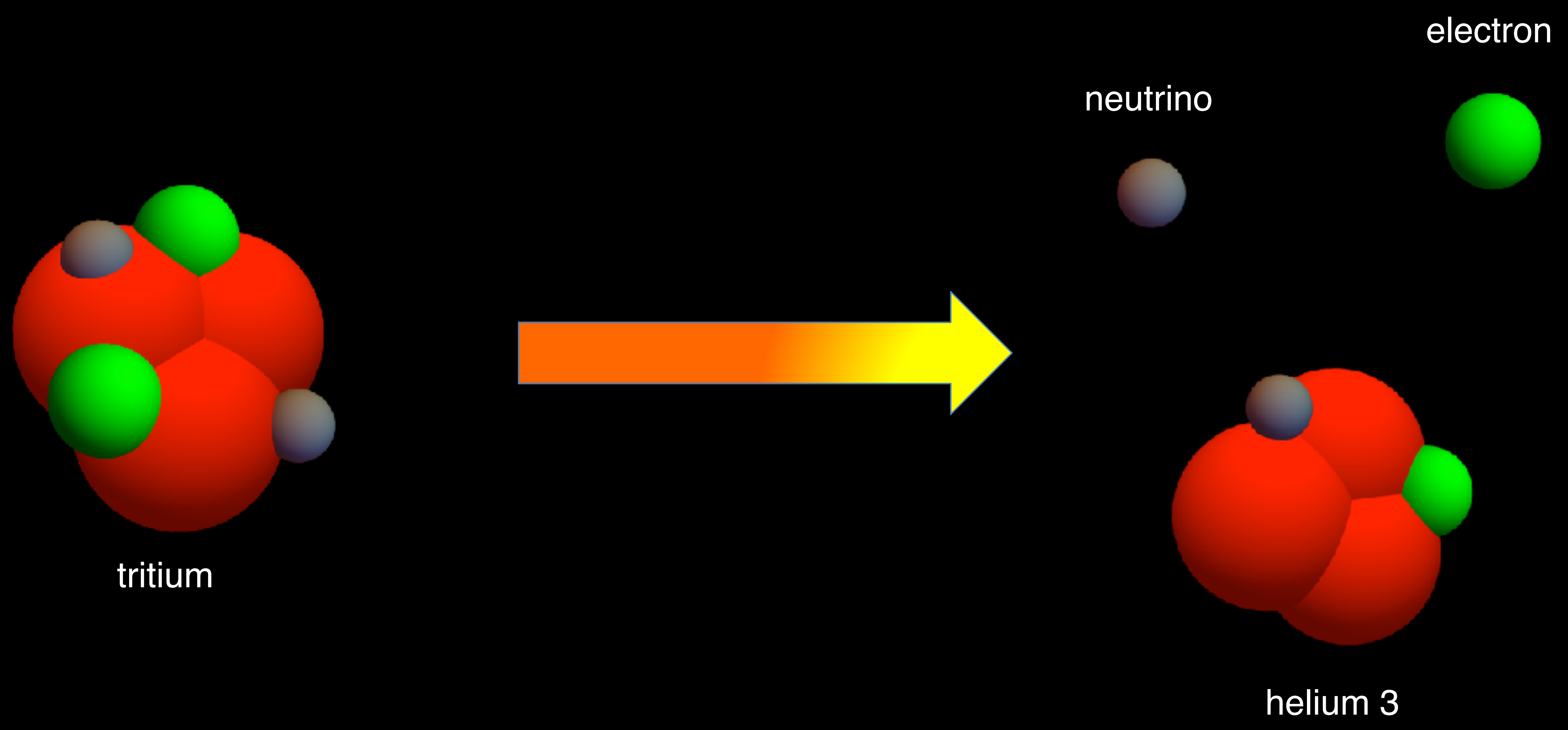
- ⭐ **need to understand the reason of discrepancy in τ_n - measurements.**
- ⭐ **need to decrease the uncertainty due to r_A^2 — i.e. we need refine the description of the axial form factor in the 100 MeV range.**

Thanks for the attention!

history of IBD cross-section

for aficionados, students, and/or historians

Pauli's model (1930)



**the nucleus contains electrons, protons & <u>neutrinos</u>;
the neutrino takes away some energy**

American Journal of Physics

ARTICLE NAVIGATION

DECEMBER 01 1968

Fermi's Theory of Beta Decay

Fermi's Theory of Beta Decay

Fred L. Wilson

American Journal of Physics 36, 1150–1160 (1968)

https://doi.org/10.1119/1.1974382 Article history

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Only the positive eigenvalues are to be considered. The negative eigenvalues are removed by an artifice analogous to the Dirac hole theory.

Dirac sea - ground state

American Journal of Physics

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(a) The total number of electrons, as well as neutrinos, is not necessarily constant. Electrons (or neutrinos) can be created or annihilated. This possibility, however, is not analogous to the creation or annihilation of an electron–positron pair.

creation of 1 positive enegy electron as in β decay

creation of 1 positive enegy electron as in β decay

extraction of one electron - formation of Dirac' hole

extraction of one electron - formation of Dirac' hole

American Journal of Physics

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(a) The total number of electrons, as well as neutrinos, is not necessarily constant. Electrons (or neutrinos) can be created or annihilated. This possibility, however, is not analogous to the creation or annihilation of an electron–positron pair.

As is well known, the meaning of the probability amplitudes ψ and φ, when interpreted as operators, is the following: let $\psi_1\psi_2\cdots\psi_s\cdots$ be a system of individual quantum states for the electrons. One then can write

$$\psi=\sum_s \psi_s a_s, \qquad \psi^*=\sum_s \psi_s^* a_s^*. \qquad (2)$$

first approach (neglect spin)

If we first neglect relativistic corrections and spin interaction, the simplest choice for Eq. (9) would probably be the following:

$$H = g[Q\psi(x)\varphi(x) + Q^*\psi^*(x)\varphi^*(x)], \qquad (10)$$

where g represents a constant with dimensions l^5mt^{-2}, and x represents the coordinates of the heavy particles. ψ, φ, ψ^*, φ^* are given by Eqs. (2) and (4), and are to be evaluated at the position (x, y, z) of the heavy particles.

first approach (neglect spin)

If we first neglect relativistic corrections and spin interaction, the simplest choice for Eq. (9) would probably be the following:

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where g represents a constant with dimensions l^5mt^{-2}, and x represents the coordinates of the heavy particles. ψ, φ, ψ^*, φ^* are given by Eqs. (2) and (4), and are to be evaluated at the position (x, y, z) of the heavy particles.

$$Q = \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix}$$

converts p -> n,

whereas

$$Q^* = \begin{pmatrix} 0 & 0 \\ 1 & 0 \end{pmatrix}$$

converts n->p

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$[Q]$ = pure number (p->n)

$[H]$ = energy

$[\psi^2] = [\varphi^2] = 1/\text{volume}$

$\Rightarrow [g] = \text{energy} \times \text{volume}$

(i.e., $[g] = 1/\text{mass}^2$ in natural units)

refinement (inclusion of the spin)

Here, we meet a difficulty originating in the fact that the relativistic wave equation of the heavy particles is unknown. If the velocity of the heavy particles is small relative to c, one can limit oneself to the term analogous to eV, where V is the scalar potential, and write

$$H = g[Q(-\psi_1\varphi_2 + \psi_2\varphi_1 + \psi_3\varphi_4 - \psi_4\varphi_3) + Q^*(-\psi_1^*\varphi_2^* + \psi_2^*\varphi_1^* + \psi_3^*\varphi_4^* - \psi_4^*\varphi_3^*)]. \quad (12)$$

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refinement (inclusion of the spin)

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the relativistic current is the zero-component of

$$\bar\psi\gamma^\mu\gamma^5 C\bar\varphi^t$$

where C=charge conjug.

and γ^5=chirality

(Dirac representation of γ-matrices and modern notations)

positive energy electrons & neutrinos are created

$$n \rightarrow p + e + \nu$$

NB: At the time Fermi thought of bound neutrons. With today's knowledge, we can conveniently talk of *neutron decay*: notice, neutron instability was conjectured by Chadwick 1932, but neutron lifetime was measured only 16 years later.

it was soon realized that there is much more than neutron decay in Fermi' theory

$$p \rightarrow n + \bar{e} + \bar{\nu}$$

$$p + e \rightarrow n + \bar{\nu}$$

Atti della Reale Accademia Nazionale dei Lincei (1934) Vol. XIX, p.319

Fisica. — *Sugli elementi radioattivi di F. Joliot e I. Curie*[1]. Nota di G. C. WICK presentata[2] dal Corrisp. E. FERMI.

Questa Nota contiene un'applicazione della teoria della disintegrazione β, recentemente proposta da E. Fermi[3], ai fenomeni di radioattività provocata osservati da F. Joliot e I. Curie[4].

considerazioni di invarianza relativistica[1]. La teoria contiene naturalmente anche la possibilità del processo inverso: trasformazione di un protone in un neutrone, e distruzione di un elettrone e un neutrino. Perchè un tale processo possa avvenire è però essenziale che nelle vicinanze del nucleo vi sia una certa densità di neutrini. Questa densità è fornita precisamente dai neutrini di energia negativa; la distruzione di uno di questi neutrini equivale alla formazione di una particella (buco di neutrino) perfettamente analoga al neutrino. Se l'elettrone che viene assorbito è un elettrone di energia cinetica negativa, si ha emissione di un positrone. È naturale identificare questo fenomeno con quello osservato da Curie e Joliot[2]. Se invece l'elettrone è un elettrone atomico, si ha il fenomeno di cui si è detto. Valutiamo

ELECTRON CAPTURE PROVED

the momentum of the final state nucleus is measurable and opposite to the one of the neutrino

thus, neutrinos carry momentum; but this is not a direct observation

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Experimental Evidence for the Existence of a Neutrino

James S. Allen
Phys. Rev. **61**, 692 – Published 1 June 1942

ABSTRACT

Radioactive Be^7 was deposited on a platinum foil by means of a new evaporation technique. An electron multiplier tube was employed to count the recoil nuclei produced in the reaction, $\mathrm{Be}^7+e_{\mathrm{K}}\rightarrow\mathrm{Li}^7+\eta+Q$. The maximum energy of the recoils was about 40 to 45 electron volts compared with the value of 58 electron volts to be expected for a neutrino of zero rest mass. An attempt was made to detect coincidences caused by the emission in opposite directions of a gamma-ray and a recoil nucleus. The observed coincidences were less than two percent of those expected for gamma-ray recoils. Apparently the recoils were caused by the emission of a neutrino and not by the emission of a gamma-ray.

here is our friend, the IBD!

$$p + \nu \rightarrow n + e^{+}$$

first discussed by **Bethe & Peierls 1934**

Bethe & Peierls

Nature 133, 532 (1934)

- A nice estimate the IBD cross section with dimensional arguments…
- … & recourse to "crossing symmetry"

The cross section σ for such processes for a neutrino of given energy may be estimated from the lifetime t of β-radiating nuclei giving neutrinos of the same energy. (This estimate is in accord with Fermi's model but is more general.) Dimensionally, the connexion will be

$$\sigma = A/t$$

where A has the dimension cm.^{2} sec. The longest length and time which can possibly be involved are $\hbar/mc$ and $\hbar/mc^2$. Therefore

$$\sigma < \frac{\hbar^3}{m^3c^4t}$$

For an energy of $2 \cdot 3 \times 10^6$ volts, t is 3 minutes and therefore $\sigma < 10^{-44}$ cm.^{2} (corresponding to a penetrating power of 10^{16} km. in solid matter). It is therefore absolutely impossible to observe processes of this kind with the neutrinos created in nuclear transformations.

one can conclude that there is no practically possible way of observing the neutrino.

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R. Peierls.

Physical Laboratory,
University,
Manchester.
Feb. 20.

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- (Funnily, this pessimistic paper was published, while Fermi's was rejected)

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???
Reines

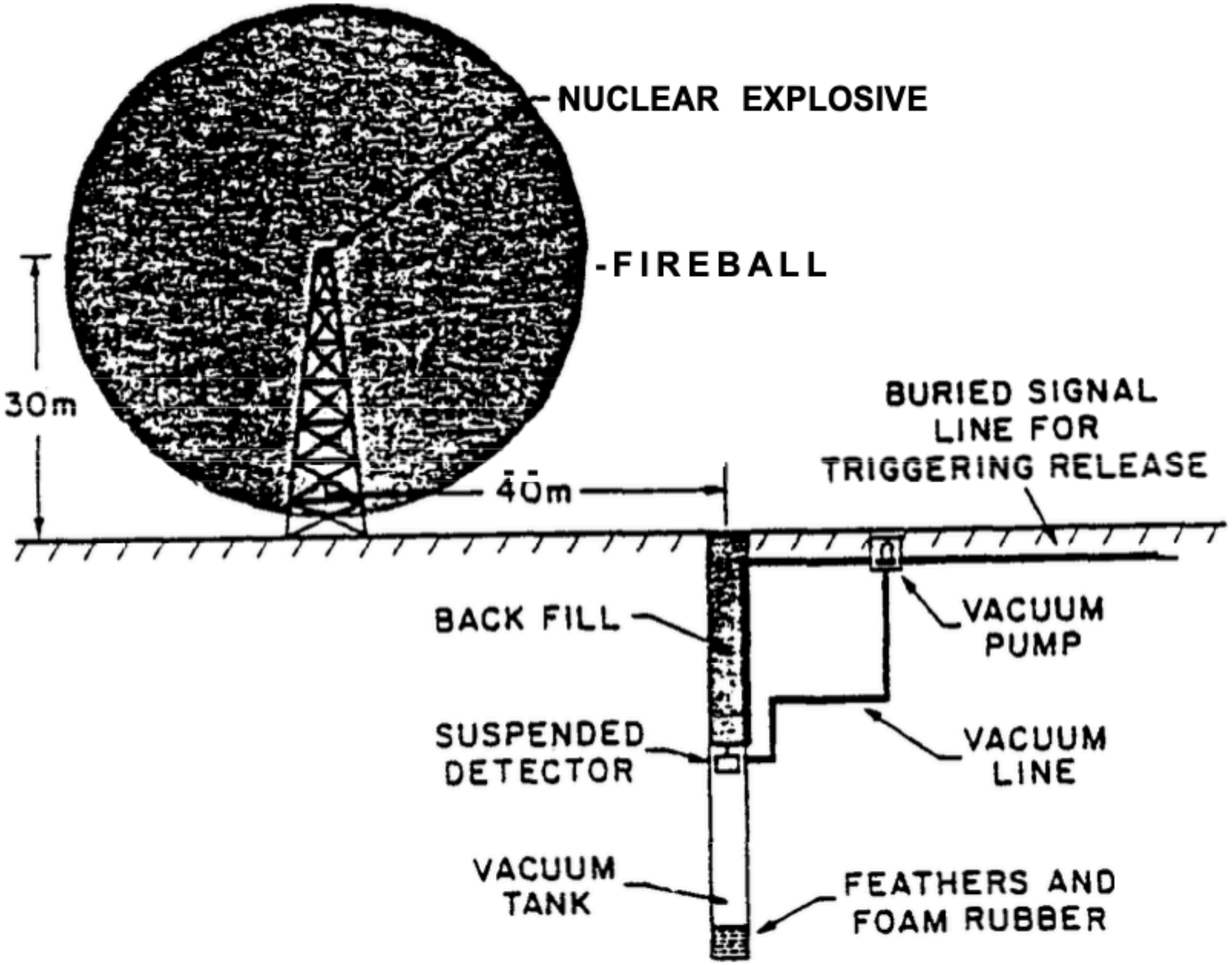

you shouldn't believe everything you read in the papers
Pauli
Reines

THE NEUTRINO: FROM POLTERGEIST TO PARTICLE

Nobel Lecture, December 8, 1995

by

FREDERICK REINES



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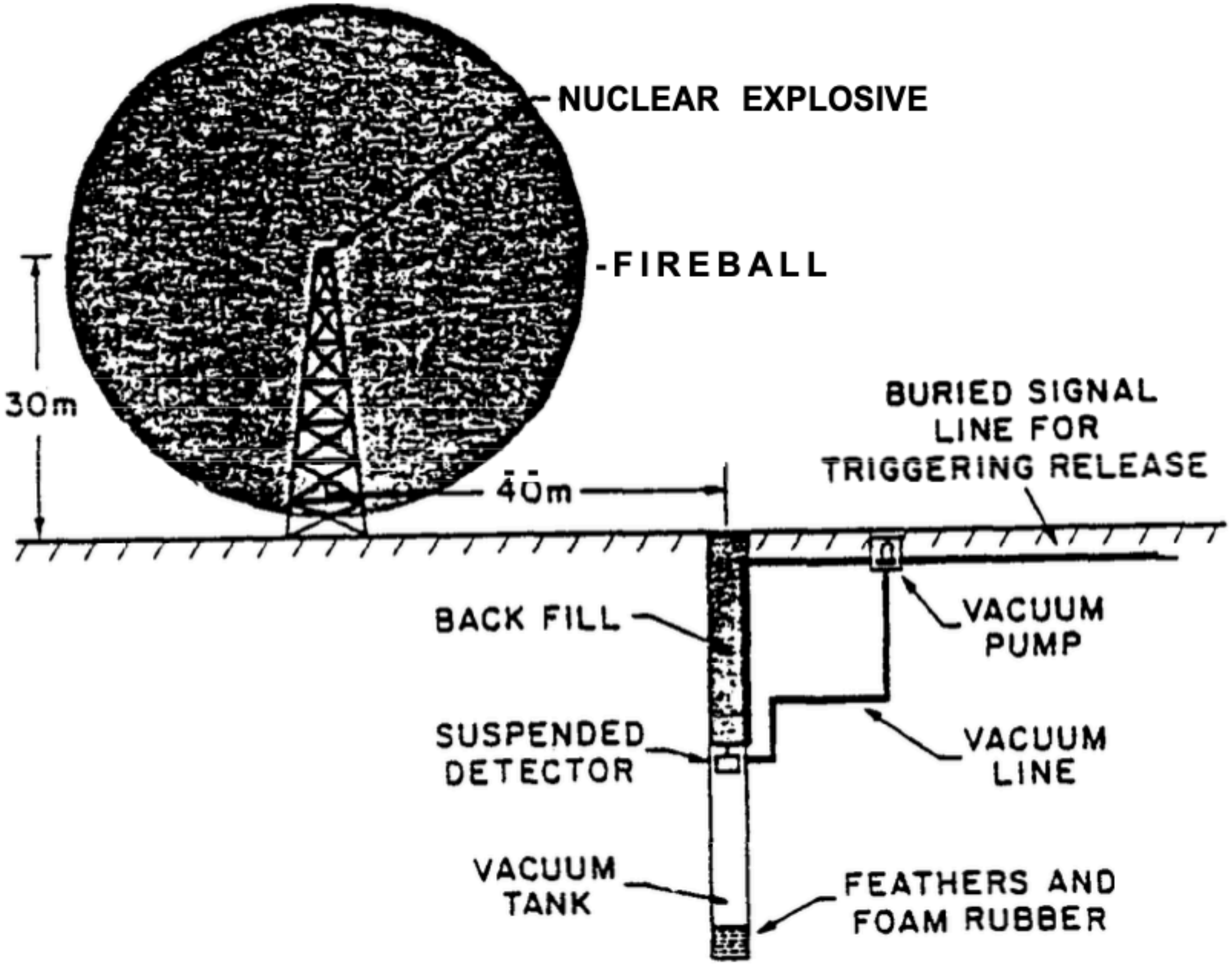

THE UNIVERSITY OF CHICAGO
CHICAGO 37 · ILLINOIS
INSTITUTE FOR NUCLEAR STUDIES

October 3, 1952

Dr. Fred Reines
Los Alamos Scientific Laboratory
P.O. Box 1663
Los Alamos, New Mexico

Dear Fred:

Thank you for your letter of October 4th by Clyde Cowan and yourself. I was very much interested in your new plan for the detection of the neutrino. Certainly your new method should be much simpler to carry out and have the great advantage that the measurement can be repeated any number of times. I shall be very interested in seeing how your 10 cubic foot scintillation counter is going to work, but I do not know of any reason why it should not.

Good luck.

Sincerely yours,

Enrico

Enrico Fermi

EF:vr

1952

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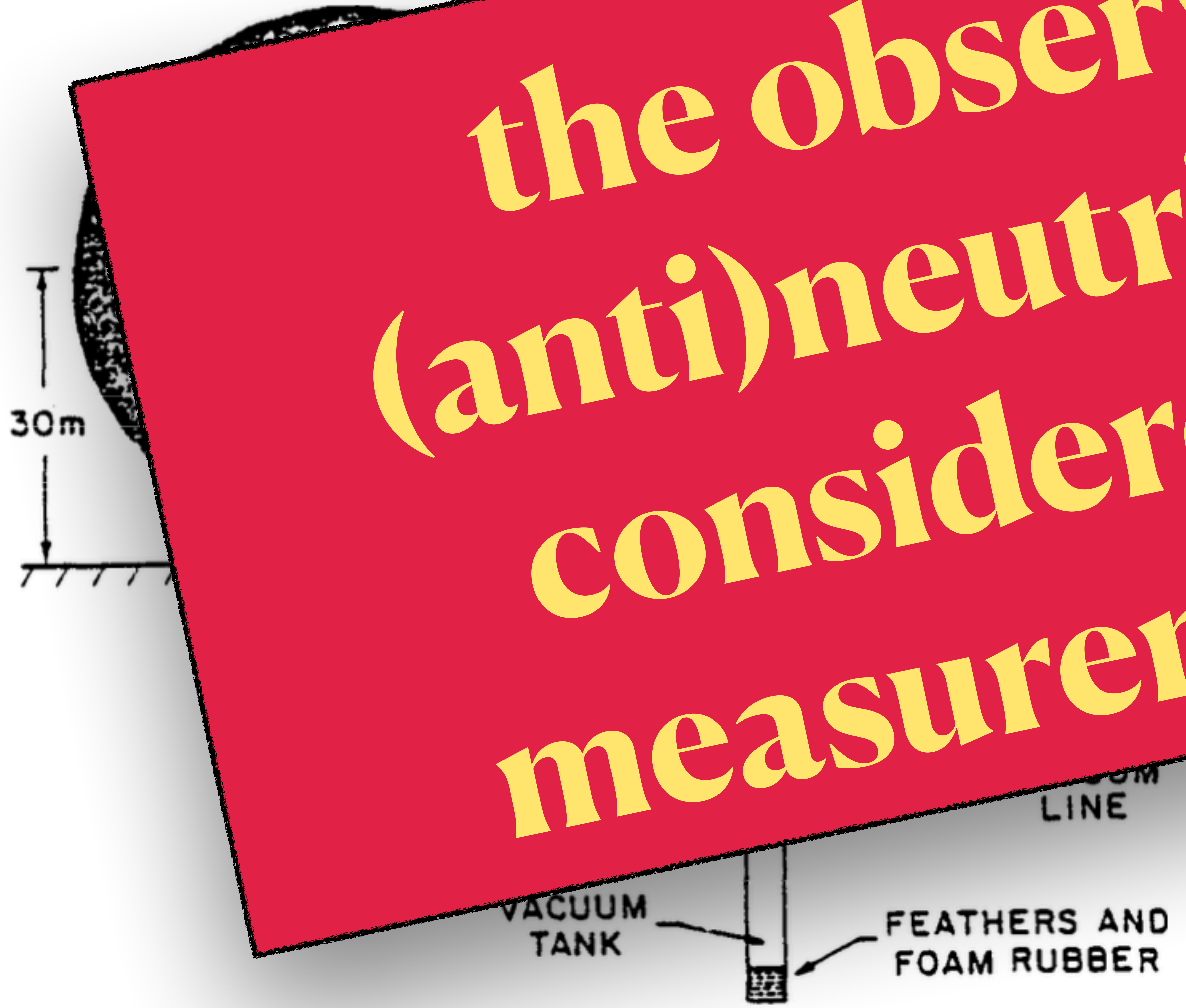
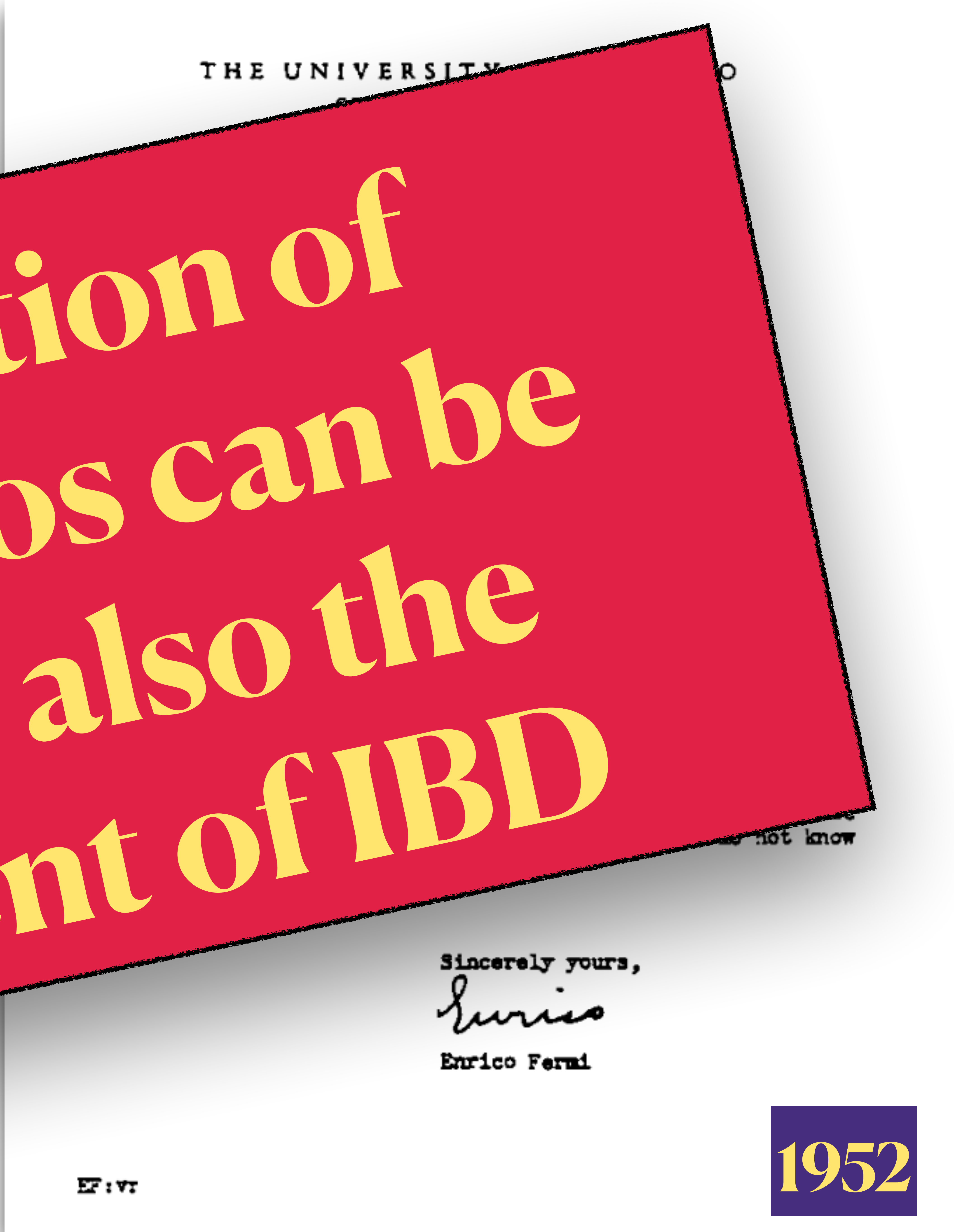


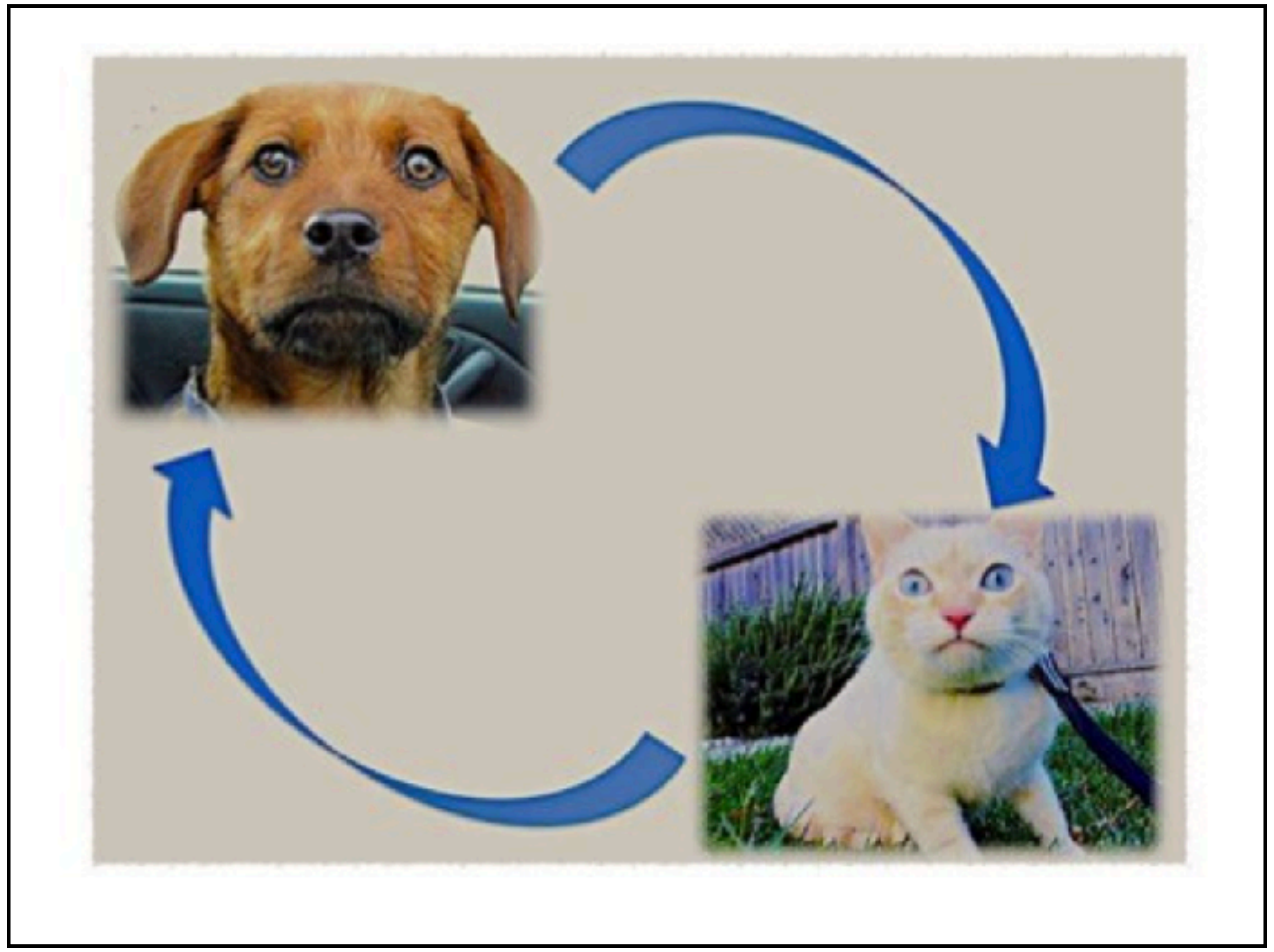
the observation of (anti)neutrinos can be considered also the measurement of IBD



1952

Early on it had been suggested by Pontecorvo and by Nakagawa et al. [18] that the neutrino may oscillate from one flavor to another as it travels from its place of origin. A graphic analogy is the change of character from dog to cat: Imagine at time zero a dog leaving his house to walk down the street to another dog house at the end of the block. As he progresses down the street a transformation takes place - his appearance gradually changes (à la Escher) from that of a dog to that of a cat! Halfway down the block the transformation is complete and the erstwhile dog - now a cat - continues on its feline journey. But the transformation goes on and, mirabile dictu, upon arrival at the dog house the erstwhile dog turned cat is once again a dog.

A last, curious passage of Reines' Nobel speech



many advances took place in fifties

- ⋆ Neutrinos and antineutrinos are different *(Davis 1955);*
- ⋆ Parity violation in weak interactions (*Lee & Yang, 1956*);
- ⋆ Left-handed neutrinos (*Landau; Salam; Lee & Yang; 1957*)

(this can be called “the second WIN revolution”)

advances relevant to IBD

- **Radiative corrections** (from *Fermi 1933* to *Kurylov, Ramsey-Musolf & Vogel 2003*)
- **Hadronic form factors** (morally, begun with *Yukawa 1934*; see e.g., reviews in *Riazuddin, Marshak & Ryan 1969* or *Llewellyn-Smith 1972 for modern treatment)*
- **V-A structure** of weak charged current *(Marshak & Sudarshan; Feynman & Gell-Mann 1958)*
- **Cabibbo angle** (*Gell-Mann & Lévy 1960; Sakata et al 1962; Cabibbo 1963*)

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Yukawa 1934

Inspired by Fermi's paper, Yukawa reformulated: $G_F = \dfrac{4\pi g g'}{\lambda^2}$

- The propagator in ordinary space time is short range $\sim \exp(-\lambda r)/r$
- With $\lambda = 0.5$ fm, this is $m_U c^2 = (\hbar c)\lambda = 100$ **MeV**
- Dimensions of g, g' is $\sqrt{\textbf{erg cm}}$ as for the electric charge
- The couplings of hadrons and leptons are very different

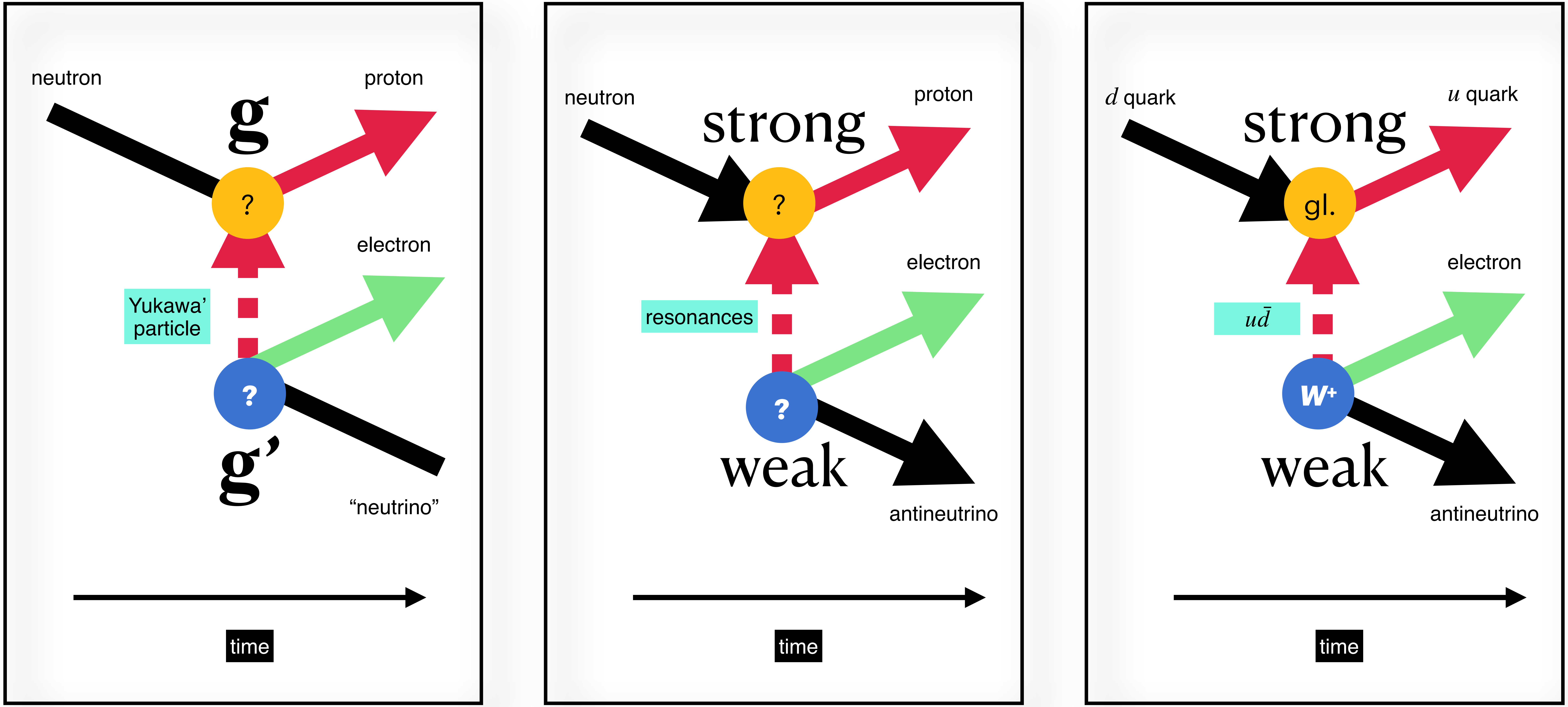
Thus the result is the same as that of Fermi's theory, in this approximation, if we take

$$\frac{4\pi g g'}{\lambda^2} = 4 \times 10^{-50}\text{cm}^3.\ \text{erg},$$

from which the constant g' can be determined. Taking, for example, $\lambda = 5 \times 10^{12}$ and $g = 2 \times 10^{-9}$, we obtain $g' \simeq 4 \times 10^{-17}$, which is about 10^{-8} times as small as g.

This means that the interaction between the neutrino and the electron is much smaller than that between the neutron and the proton so that the neutrino will be far more penetrating than the neutron and consequently more difficult to observe. The difference of g and g' may be due to the difference of masses of heavy and light particles.

evolution of ideas: 30s, 50s, 70s



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1960

The Axial Vector Current in Beta Decay (*).

M. GELL-MANN (**)

Collège de France and Ecole Normale Supérieure - Paris (***)

M. LÉVY

Faculte des Sciences, Orsay, and Ecole Normale Supérieure - Paris (*•*)

(*) *Note added in proof.* - Should this discrepancy be real, it would probably indicate a total or partial failure of the conserved vector current idea. It might also mean, however, that the current is conserved but with $G/G_\mu < 1$. Such a situation is consistent with universality if we consider the vector current for $\Delta S = 0$ and $\Delta S = 1$ together to be something like:

$$GV_\alpha + GV_\alpha^{(\Delta S=1)} = G_\mu \bar{p}\gamma_\alpha(n + \varepsilon\Lambda)(1+\varepsilon^2)^{-\frac{1}{2}} + \dots ,$$

and likewise for the axial vector current. If $(1+\varepsilon^2)^{-\frac{1}{2}} = 0.97$, then $\varepsilon^2 = .06$, which is of the right order of magnitude for explaining the low rate of β decay of the Λ particle. There is, of course, a renormalization factor for that decay, so we cannot be sure that the low rate really fits in with such a picture.

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1962

Progress of Theoretical Physics, Vol. 28, No. 5, November 1962

Remarks on the Unified Model of Elementary Particles

Ziro MAKI, Masami NAKAGAWA and Shoichi SAKATA

Institute for Theoretical Physics
Nagoya University, Nagoya

$$p = \langle B^+ \nu_1 \rangle, \quad n = \langle B^+ e^- \rangle, \quad \Lambda = \langle B^+ \mu^- \rangle, \qquad (2\cdot5)$$

and $\langle B^+ \nu_2 \rangle$ corresponds no baryons.**) We call this correspondence *the modified B-L symmetry*. The baryonic weak current J_λ obtained from (2·1′) is written as

$$J_\lambda \equiv \langle j_\lambda \rangle_B = (\bar{n}p)_\lambda \cos\delta + (\bar{\Lambda}p)_\lambda \sin\delta. \qquad (2\cdot6)$$

The weak interaction Hamiltonian is obviously

$$H_w = \frac{G}{\sqrt{2}} \mathcal{J}_\lambda \cdot \mathcal{J}_\lambda^+, \qquad (2\cdot7)$$

where $(\bar{a}b)_\lambda = (\bar{a}\gamma_\lambda(1+\gamma_5)b)$.

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1963

UNITARY SYMMETRY AND LEPTONIC DECAYS

Nicola Cabibbo
CERN, Geneva, Switzerland

(Received 29 April 1963)

We present here an analysis of leptonic decays based on the unitary symmetry for strong interactions, in the version known as "eightfold way,"[1] and the V-A theory for weak interactions.[2,3] Our basic assumptions on J_μ, the weak current of strong interacting particles, are as follows:

(1) J_μ transforms according to the eightfold representation of SU_3. This means that we neglect

able to treat the complex of K or $\Sigma^+ \to n + e^+ + \nu$ in which $\Delta S =$ a role. For the other proces hypothesis that the main contr that part of J_μ which is in the tation.

(2) The vector part of J_μ is the electromagnetic current.

$$\Gamma(K^+ \to \mu\nu)/\Gamma(\pi^+ \to \mu\nu)$$
$$= \tan^2\theta M_K(1 - M_\mu^2/M_K^2)^2/M_\pi(1 - M_\mu^2/M_\pi^2)^2. \qquad (3)$$

From the experimental data, we then get[5,6]

$$\theta = 0.257. \qquad (4)$$

For an independent determination of θ, let us consider $K^+ \to \pi^0 + e^+ + \nu$. The matrix element for this process can be connected to that for $\pi^+ \to \pi^0 + e^+ + \nu$, known from the conserved vector-current hypothesis (2nd assumption). From the rate[6] for $K^+ \to \pi^0 + e^+ + \nu$, we get

$$\theta = 0.26. \qquad (5)$$

Table I. Predictions for the leptonic decays of hyperons.

Decay	Branching ratio From reference 2	Branching ratio Present work	Type of interaction
$\Lambda \to p + e^- + \bar{\nu}$	1.4 %	0.75×10^{-3}	$V - 0.72\,A$
$\Sigma^- \to n + e^- + \bar{\nu}$	5.1 %	1.9×10^{-3}	$V + 0.65\,A$
$\Xi^- \to \Lambda + e^- + \bar{\nu}$	1.4 %	0.35×10^{-3}	$V + 0.02\,A$
$\Xi^- \to \Sigma^0 + e^- + \bar{\nu}$	0.14 %	0.07×10^{-3}	$V - 1.25\,A$
$\Xi^0 \to \Sigma^+ + e^- + \bar{\nu}$	0.28 %	0.26×10^{-3}	$V - 1.25\,A$