Title: Oscillation/Rare Decay Experiments 1

Date: Jul 16, 2018 02:30 PM

URL: http://pirsa.org/18070025

Abstract:

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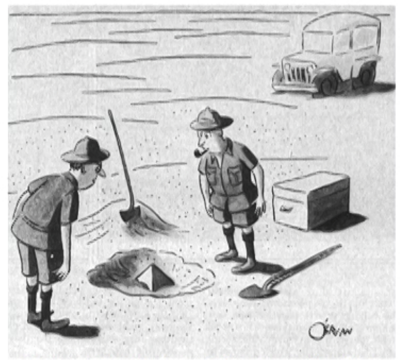
Fakultät Mathematik und Naturwissenschaften, Institut für Kern- und Teilchenphysik

Experimental neutrino physics and rare event searches



"This could be the discovery of the century. Depending, of course, on how far down it goes."

Kai Zuber

TU Dresden, Atomki Debrecen

16-20. 7. 2018, Perimeter Institute

PI · SNOLAB · TRIUMF TRISEP

DRESDEN concept

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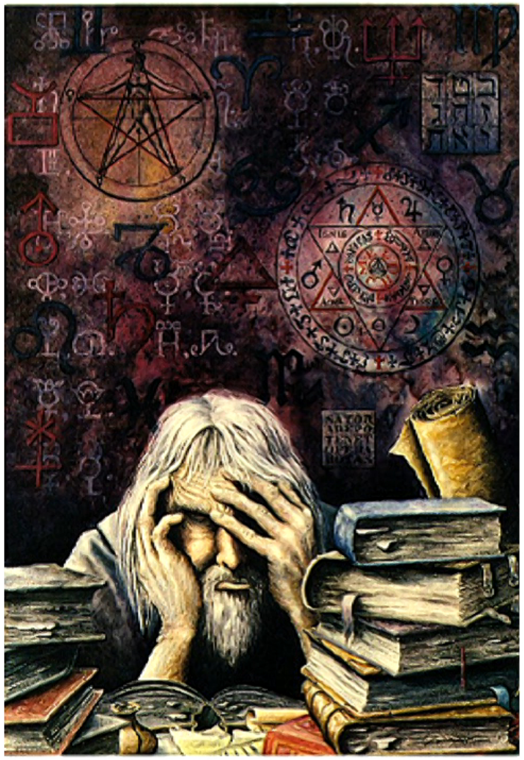

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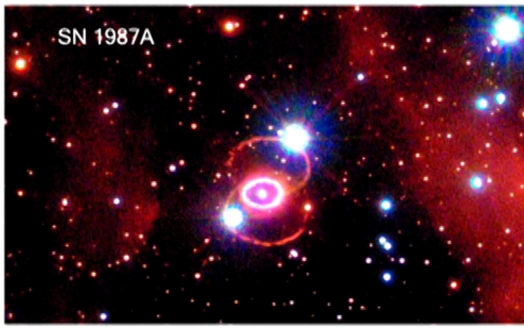
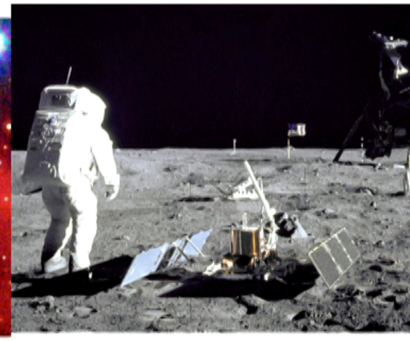
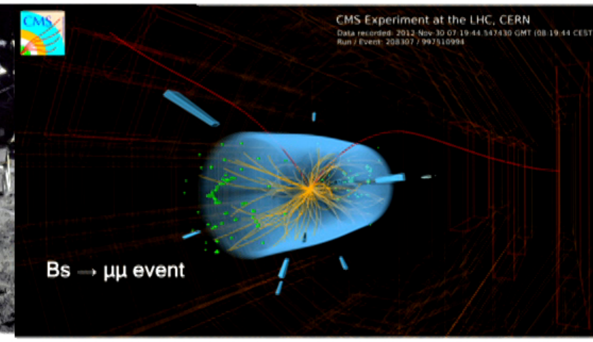
What are rare events? The needle in a haystack approach







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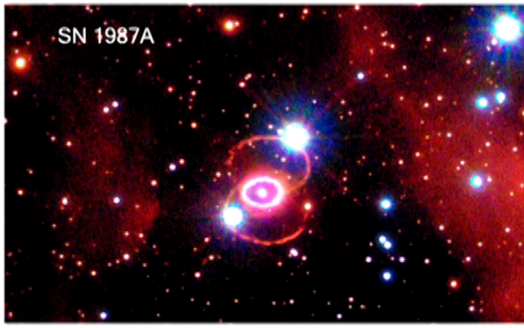

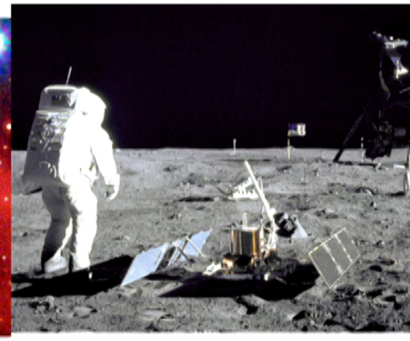

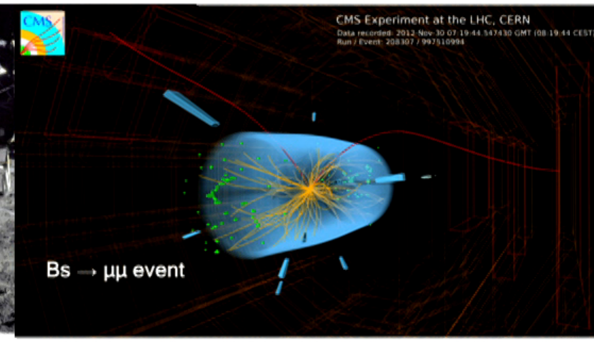

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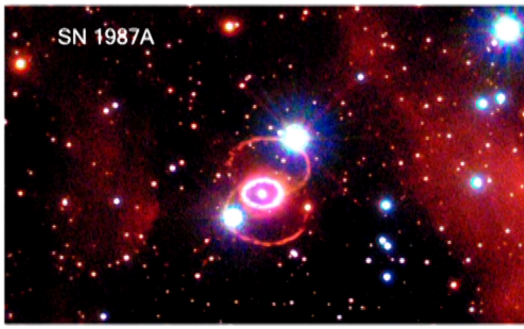

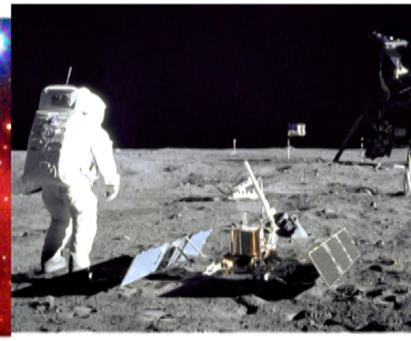

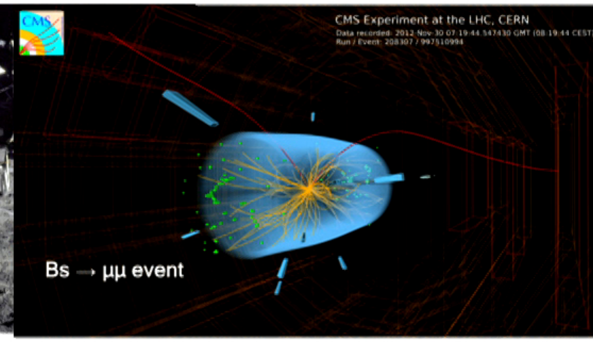

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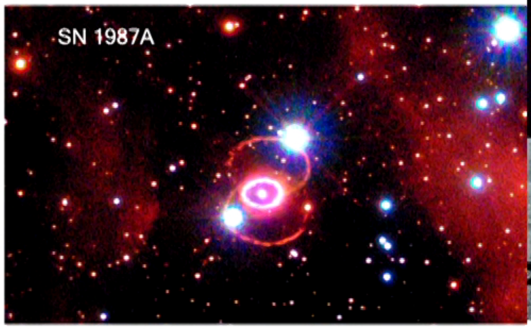

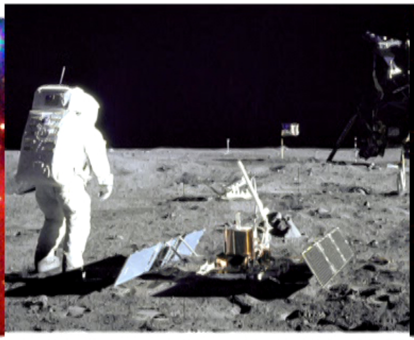

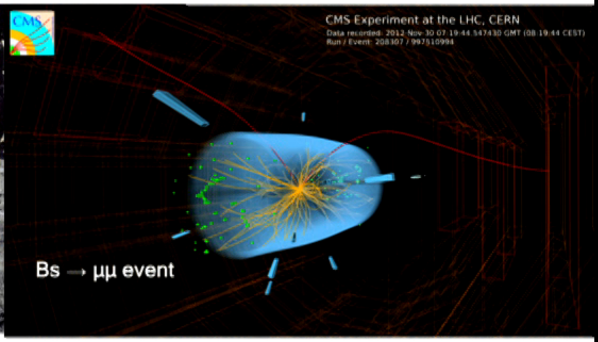

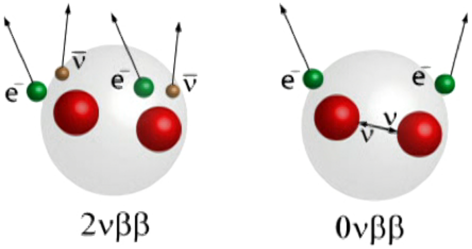

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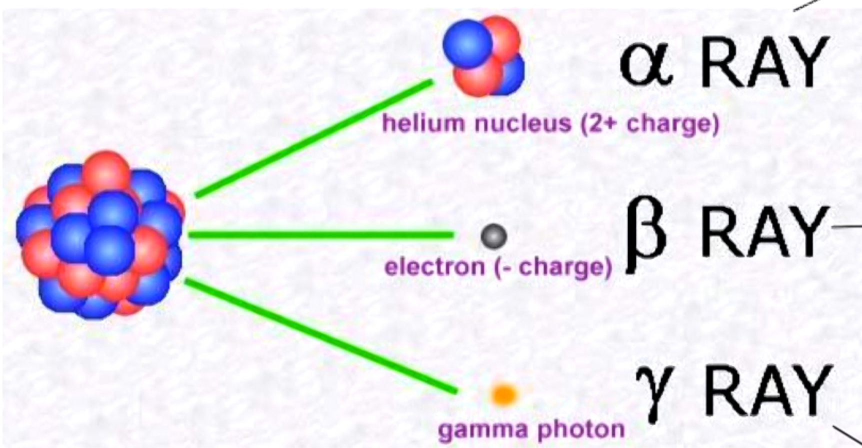
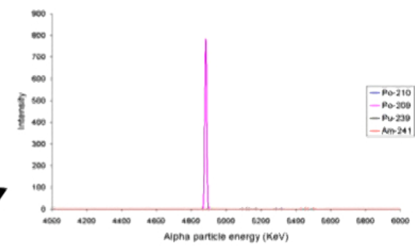
History - Radioactivity

Three kinds of radioactivity





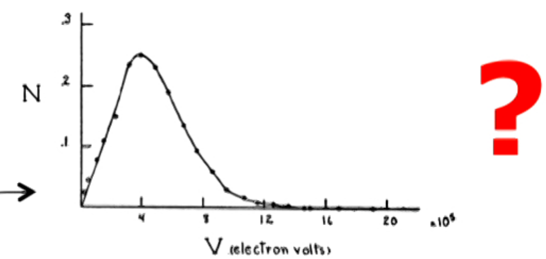
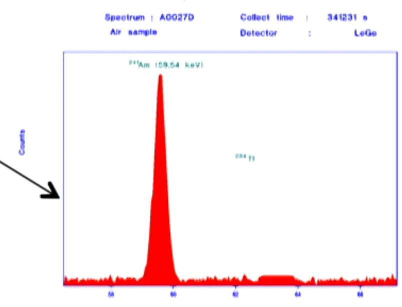


FIG. 5. Energy distribution curve of the beta-rays.



Why neutrinos?

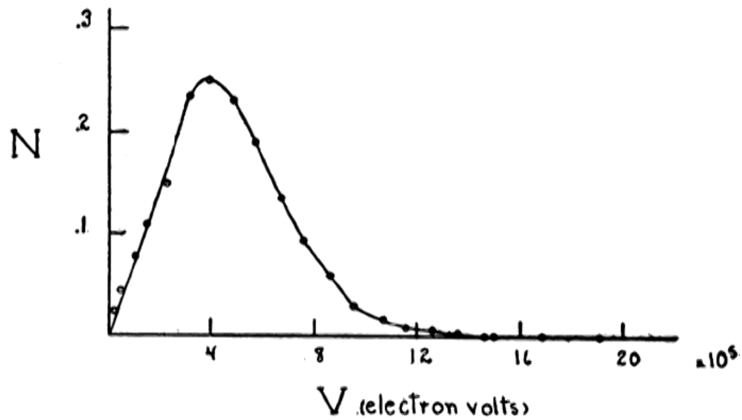


FIG. 5. Energy distribution curve of the beta-rays.

Why do beta decays show a continuous energy spectrum of electrons?

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Why neutrinos?

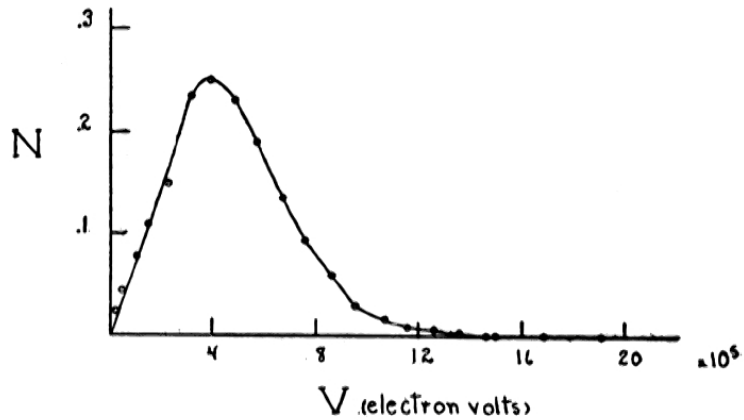

FIG. 5. Energy distribution curve of the beta-rays.

Why do beta decays show a continuous energy spectrum of electrons?

Bohr: ***At the present stage of atomic theory, however, we may say that we have no argument, either empirical or theoretical, for upholding the energy principle in the case of β-ray disintegrations***

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The solution?

4th December 1930

Dear Radioactive Ladies and Gentlemen,

As the bearer of these lines, to whom I graciously ask you to listen, will explain to you in more detail, how because of the "wrong" statistics of the N and Li^6 nuclei and the continuous beta spectrum, I have hit upon a desperate remedy to save the "exchange theorem" of statistics and the law of conservation of energy. Namely, the possibility that there could exist in the nuclei electrically neutral particles, that I wish to call neutrons, which have spin 1/2 and obey the exclusion principle and which further differ from light quanta in that they do not travel with the velocity of light. The mass of the neutrons should be of the same order of magnitude as the electron mass and in any event not larger than 0.01 proton masses. The continuous beta spectrum would then become understandable by the assumption that in beta decay a neutron is emitted in addition to the electron such that the sum of the energies of the neutron and the electron is constant...

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The discovery

C. Cowan, F. Reines 1953,1956

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

Project Poltergeist

Herr Auge

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The discovery

C. Cowan, F. Reines 1953,1956

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

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Herr Auge

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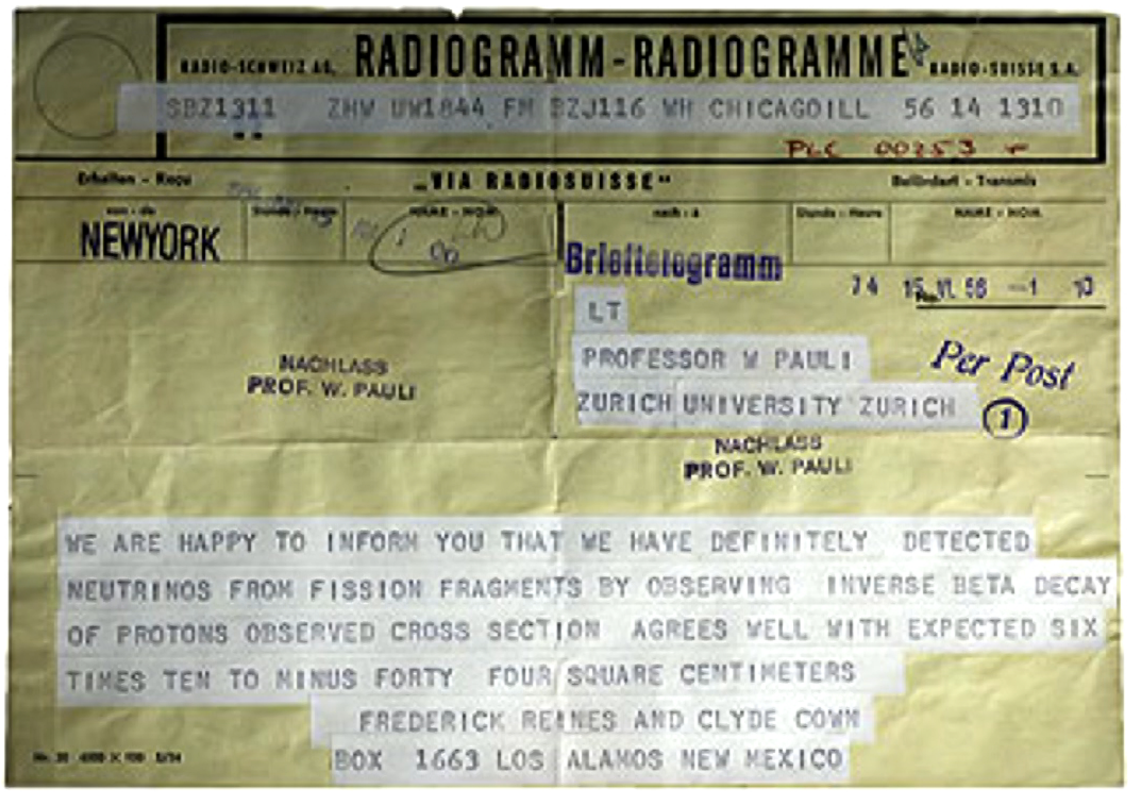
„Texting“ Pauli...



RADIO-SCHWEIZ AG. RADIOGRAMM-RADIOGRAMME RADIO-SUISSE S.A.

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„VIA RADIOSUISSE"

NEWYORK

Brieftelegramm

LT

PROFESSOR W PAULI

ZURICH UNIVERSITY ZURICH

Per Post

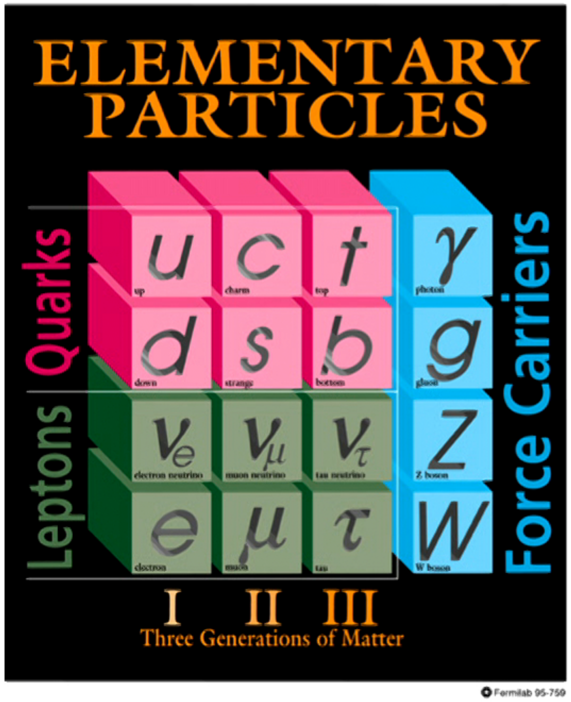
NACHLASS PROF. W. PAULI

WE ARE HAPPY TO INFORM YOU THAT WE HAVE DEFINITELY DETECTED NEUTRINOS FROM FISSION FRAGMENTS BY OBSERVING INVERSE BETA DECAY OF PROTONS OBSERVED CROSS SECTION AGREES WELL WITH EXPECTED SIX TIMES TEN TO MINUS FORTY FOUR SQUARE CENTIMETERS

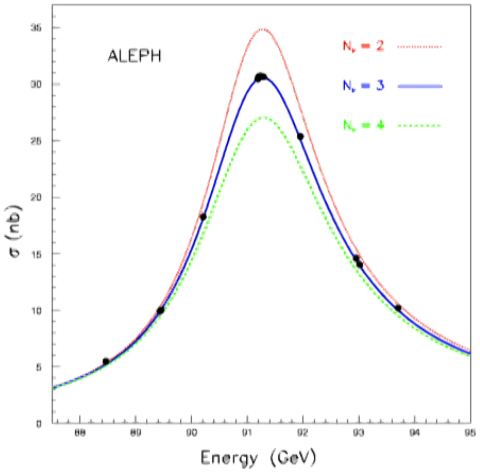
FREDERICK REINES AND CLYDE COWN

BOX 1663 LOS ALAMOS NEW MEXICO

Neutrinos – The prototype for rare events (very low cross section)



Neutrinos in the Standard Model are massless particles



Major progress of last 20 years: Neutrinos have a non-vanishing rest mass

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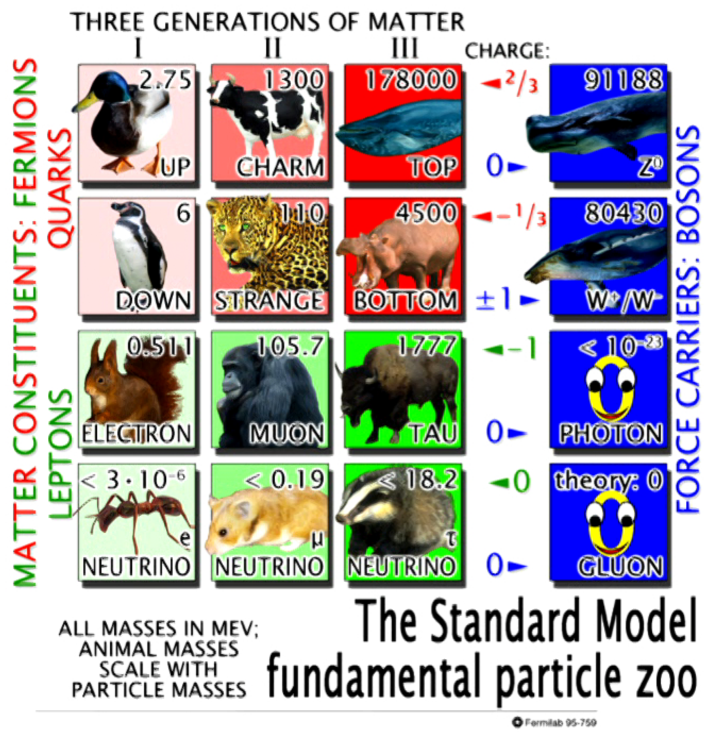
Neutrinos – The prototype for rare events (very low cross section)



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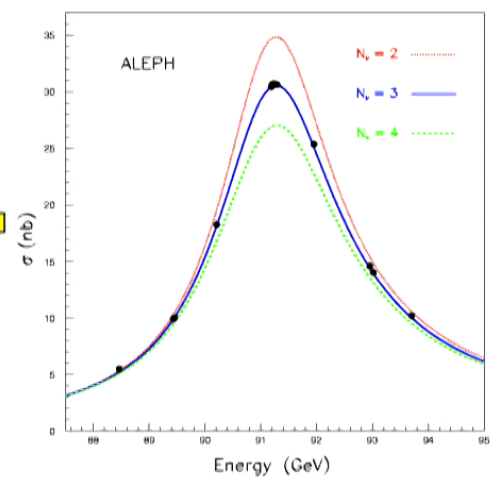

Major progress of last 20 years: Neutrinos have a non-vanishing rest mass

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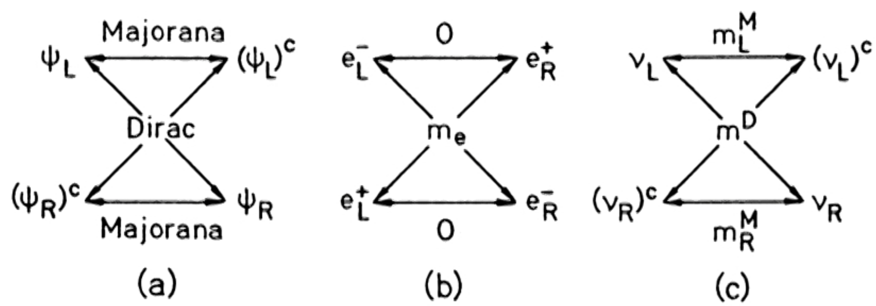
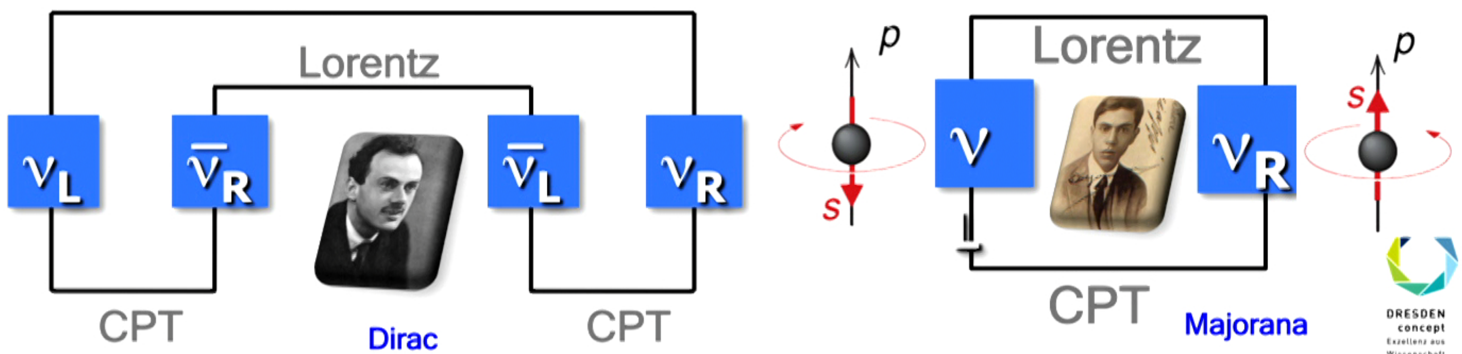
Another unique feature

Option: Couple neutrino to its charge conjugate,
consequence lepton number violation - Majorana neutrinos





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Hence there are a bunch of questions

- What is the mass of the neutrinos?
- Why is the mass so much smaller than for all other elementary particles?
- Are neutrinos their own antiparticles? If so, can they create the baryon-asymmetry in the Universe?
- Can they transform into each other?
- Are there more than 3 neutrinos states?
- What are sources of neutrinos?
- What about decay, magnetic moment...? .....????

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Nobel prices for neutrinos

- L. Lederman, M. Schwartz, J. Steinberger 1988
  Discovery of two different neutrinos
- F. Reines 1995
  Discovery of the neutrino
- M. Koshiba, R. Davis 2002
  Discovery of cosmic neutrinos
- T. Kajita, A. McDonald 2015
  Discovery of neutrino oscillations

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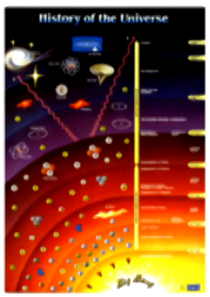
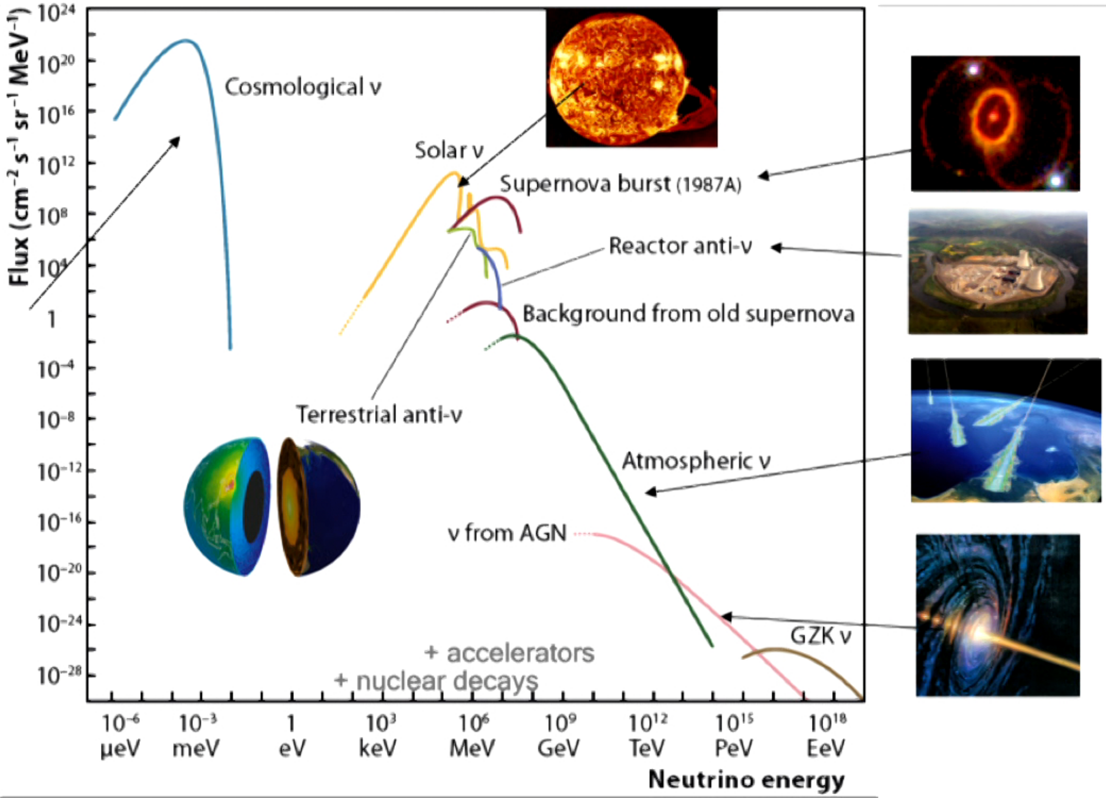
Universal neutrino spectrum



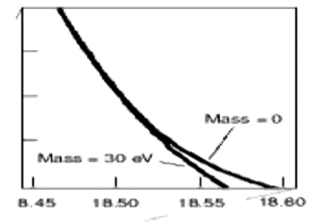
1.95 K neutrino background



How can we learn about the neutrino mass?

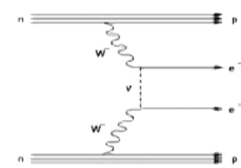
Beta decay:

$$m_\beta = \left[c_{13}^2 c_{12}^2 m_1^2 + c_{13}^2 s_{12}^2 m_2^2 + s_{13}^2 m_3^2\right]^{\frac{1}{2}}$$



Double beta decay:

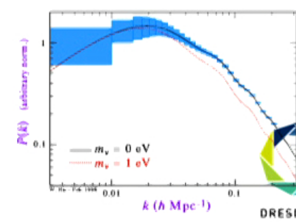
$$m_{\beta\beta} = \left|c_{13}^2 c_{12}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3 e^{i\phi_3}\right|$$



Cosmology: $\Sigma = m_1 + m_2 + m_3$

$$\Omega_\nu h^2$$

+ oscillation parameters



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The (anti-)electron neutrino mass

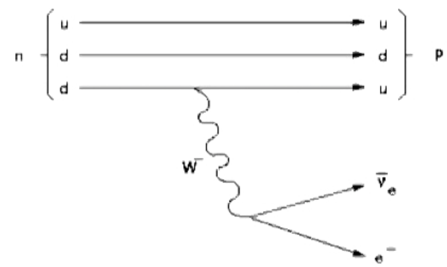
We need nuclear physics

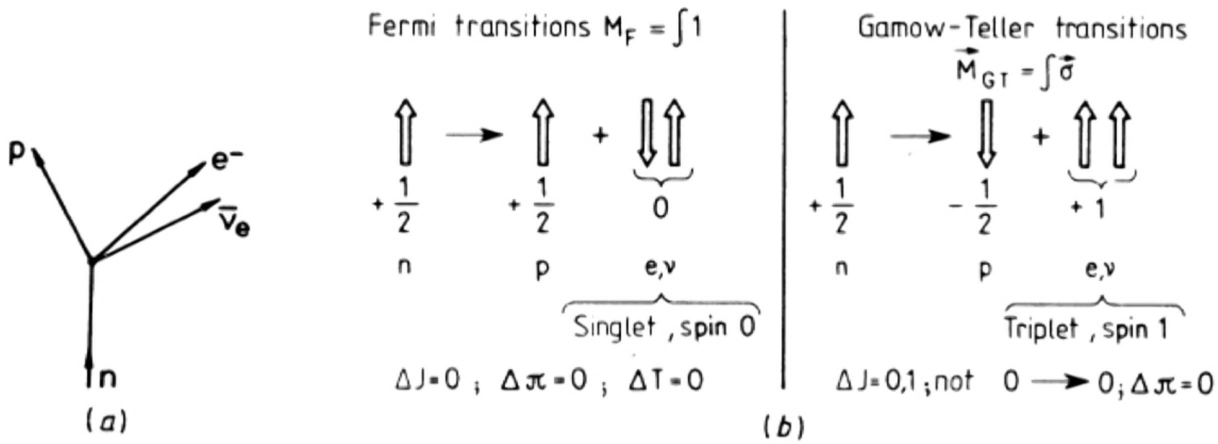
The mass of the neutrino - beta decay

$$(Z,A) \rightarrow (Z+1,A) + e^- + \bar{\nu}_e \qquad (\beta^-\text{-decay})$$

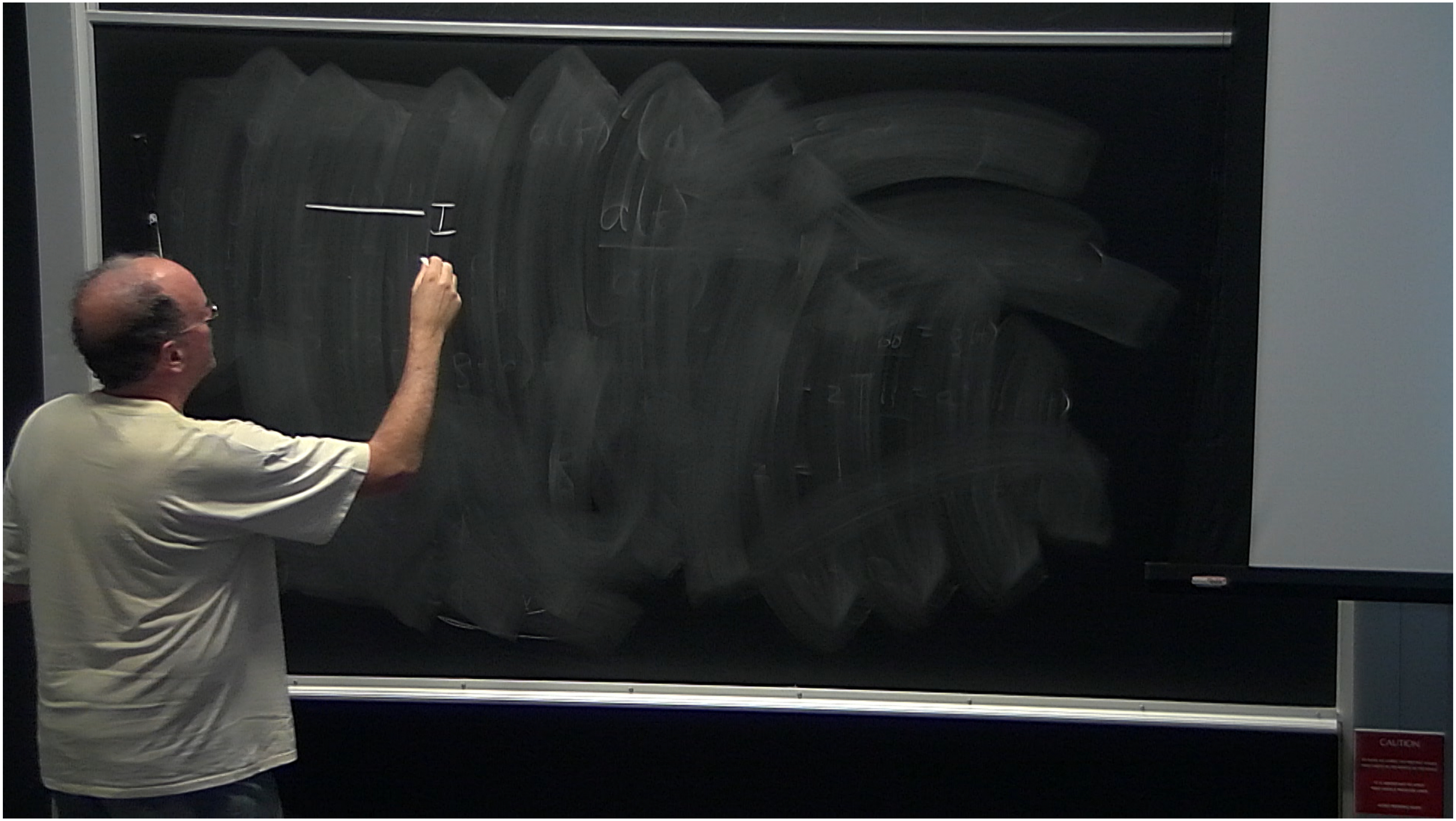
$$(Z,A) \rightarrow (Z-1,A) + e^+ + \nu_e \qquad (\beta^+\text{-decay})$$

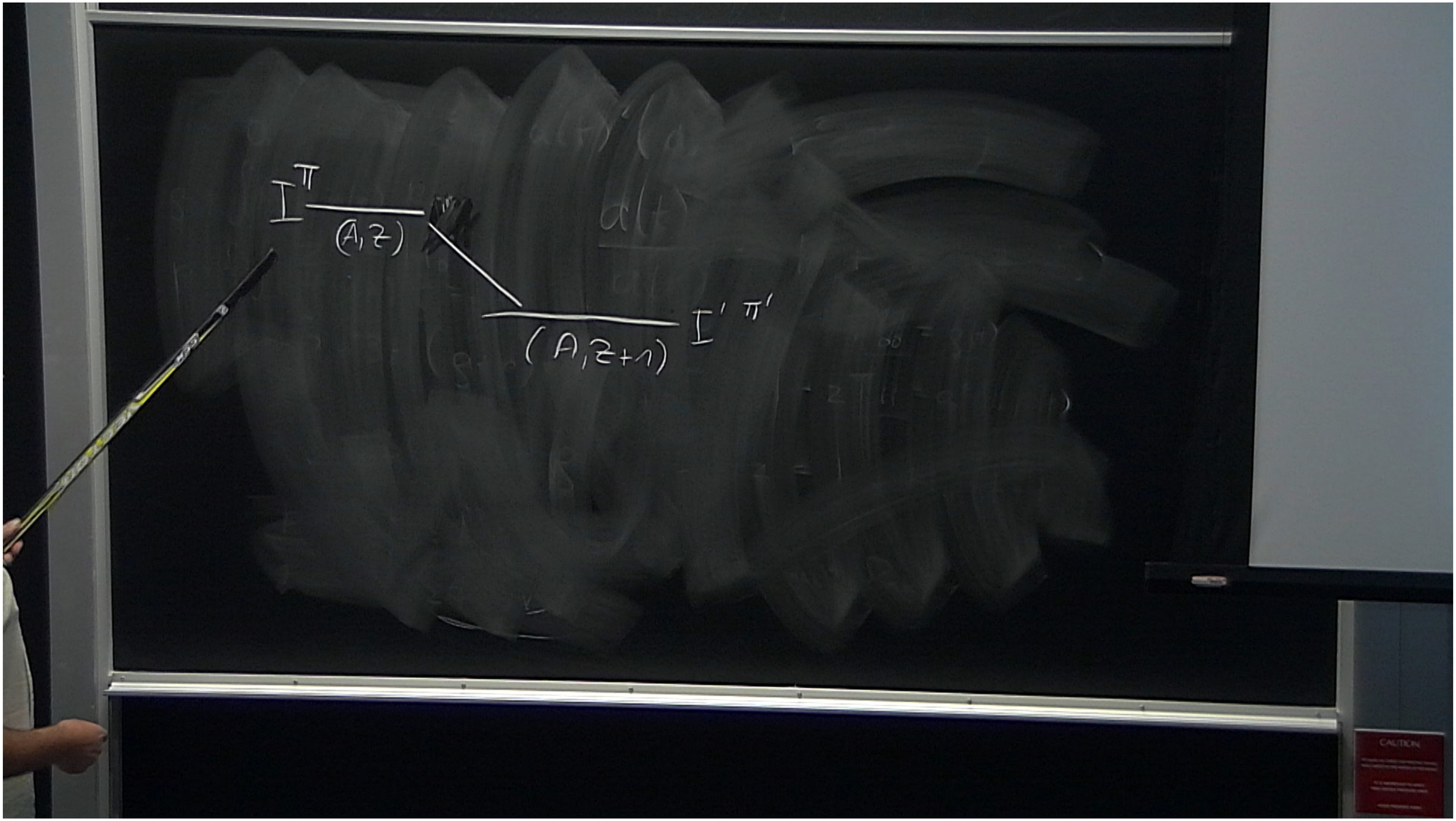
$$e^- + (Z,A) \rightarrow (Z-1,A) + \nu_e \qquad (\text{Electron capture})$$

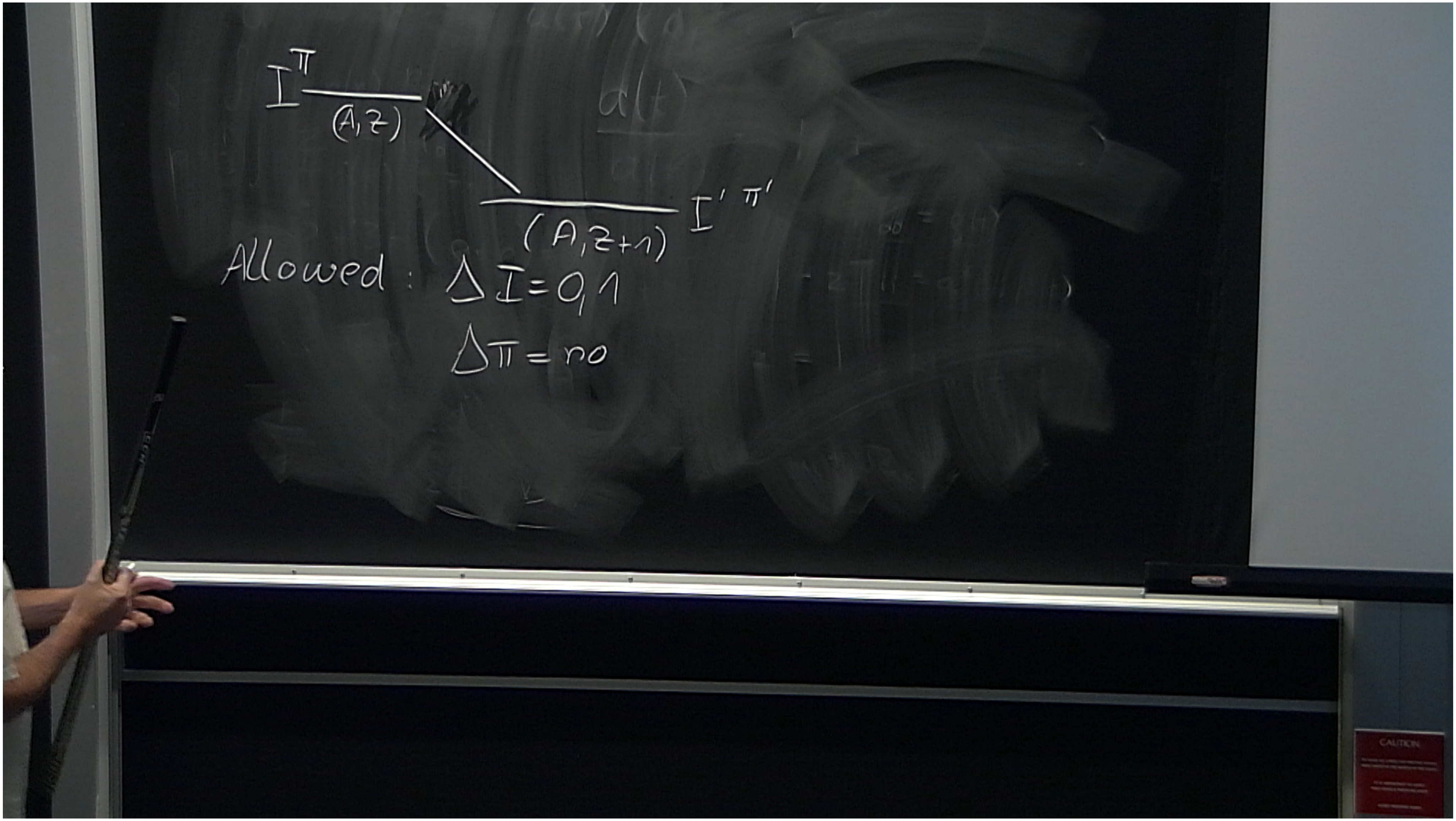


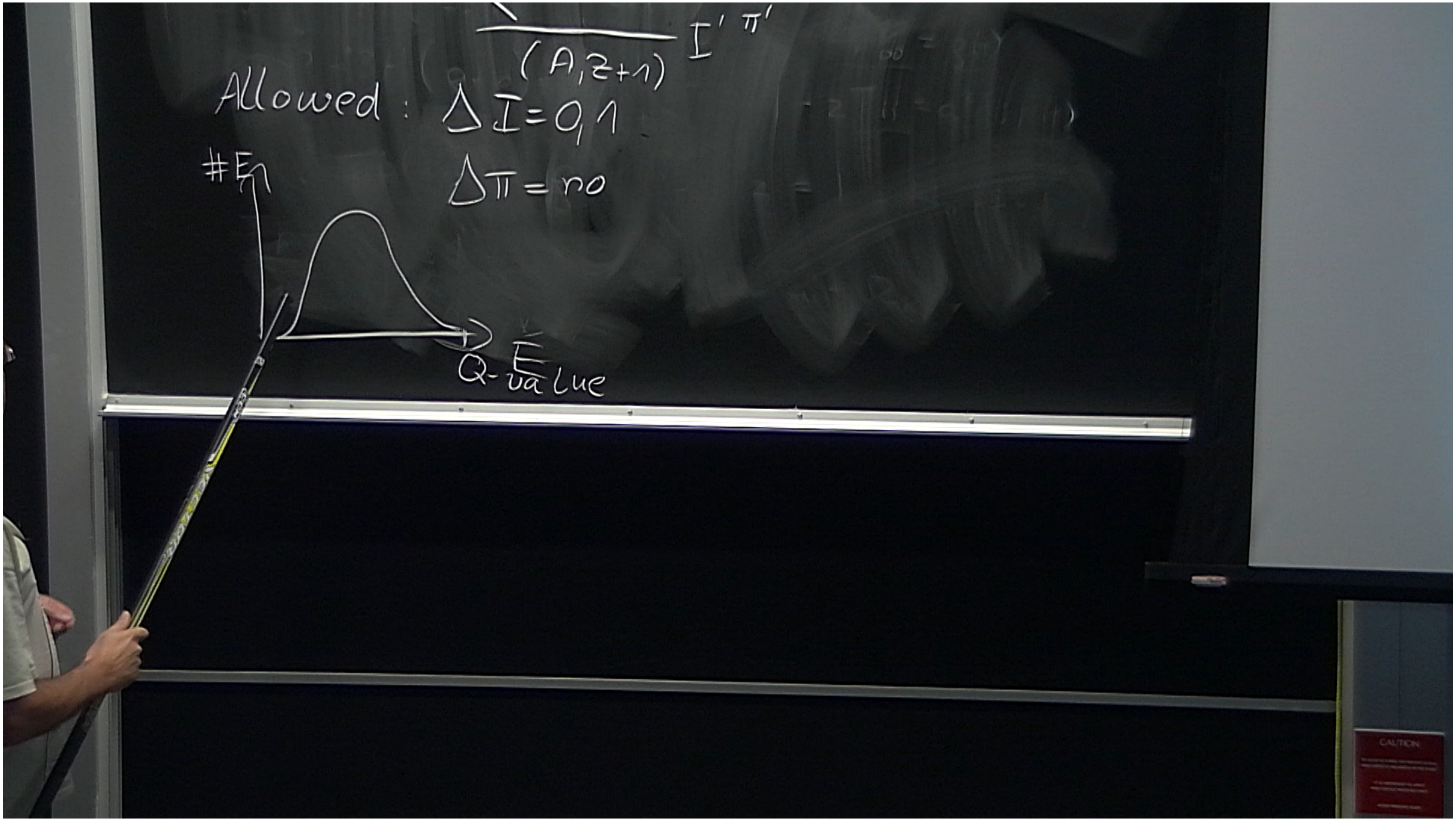


Allowed transitions (no angular momentum involved), energy spectrum can be reasonably well calculated




I^π
(A,Z)
I' π'
(A,Z+1)


Iπ
(A,Z)
I' π'
(A,Z+1)
Allowed : ΔI = 0,1
ΔΠ = no


(A,Z+1) I' π'
Allowed: ΔI = 0,1
ΔΠ = no
#E
E
Q-value

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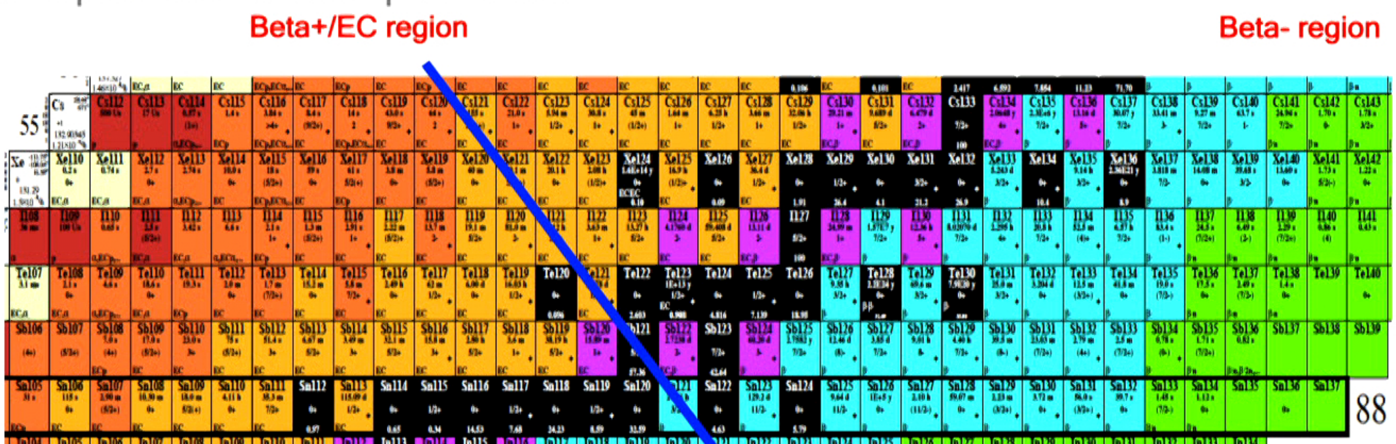
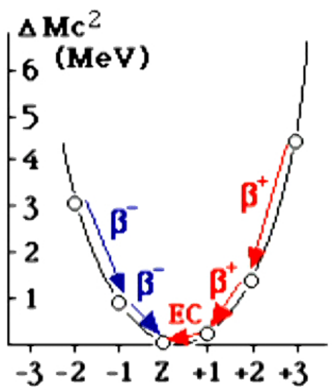
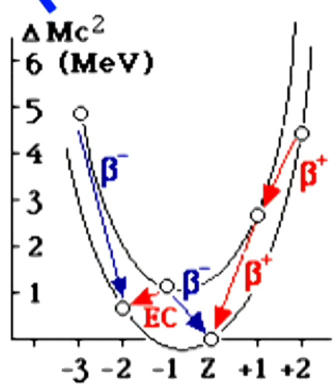
Isotopes and mass parabola





Odd A



Even A

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The mass of the neutrino - beta decay

$$(Z,A) \rightarrow (Z+1,A) + e^- + \bar{\nu}_e \qquad (\beta^-\text{-decay})$$

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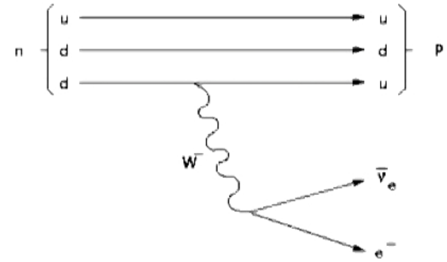
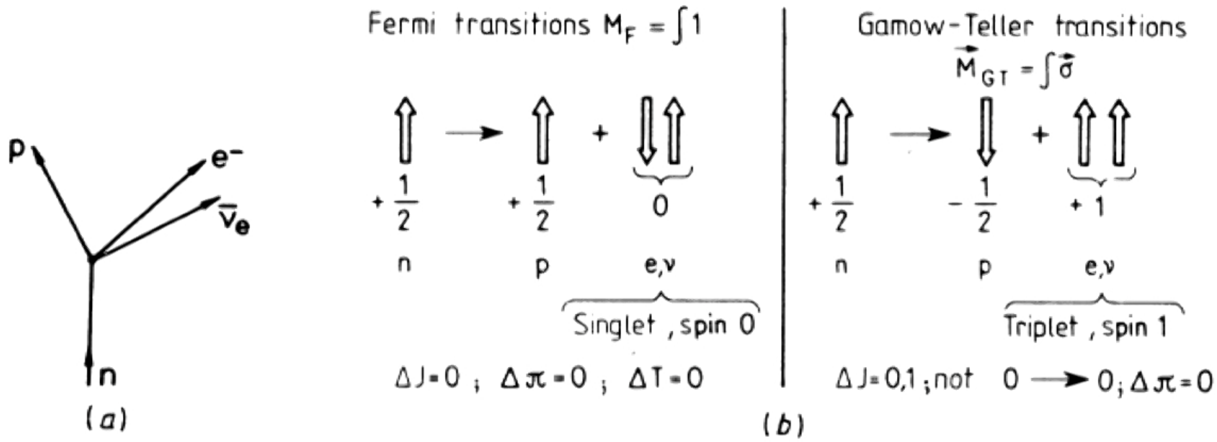
$$e^- + (Z,A) \rightarrow (Z-1,A) + \nu_e \qquad (\text{Electron capture})$$





Allowed transitions (no angular momentum involved), energy spectrum can be reasonably well calculated

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Beta decay and neutrino mass measurement

Basic idea: Study the endpoint region of the electron spectrum (Fermi 1934)

How can you determine a mass in the range of eV from a several GeV object?

Starting point: Fermi's golden rule (simplified derivation)

Transition rate of beta decay producing an electron with energy in intervall E to E+dE

$$\frac{\mathrm{d}^2 N}{\mathrm{d}t\,\mathrm{d}E} = \frac{2\pi}{\hbar} |\langle f | H_{if} | i \rangle|^2 \rho(E)$$

For allowed transitions this is independent of E (→ $|\langle f | H_{if} | i \rangle|^2$)

Neutrino mass comes in here (→ $\rho(E)$)

Endpoint energy: $E_0 = E_\nu + E_e$

Find isotope(s) with small endpoint

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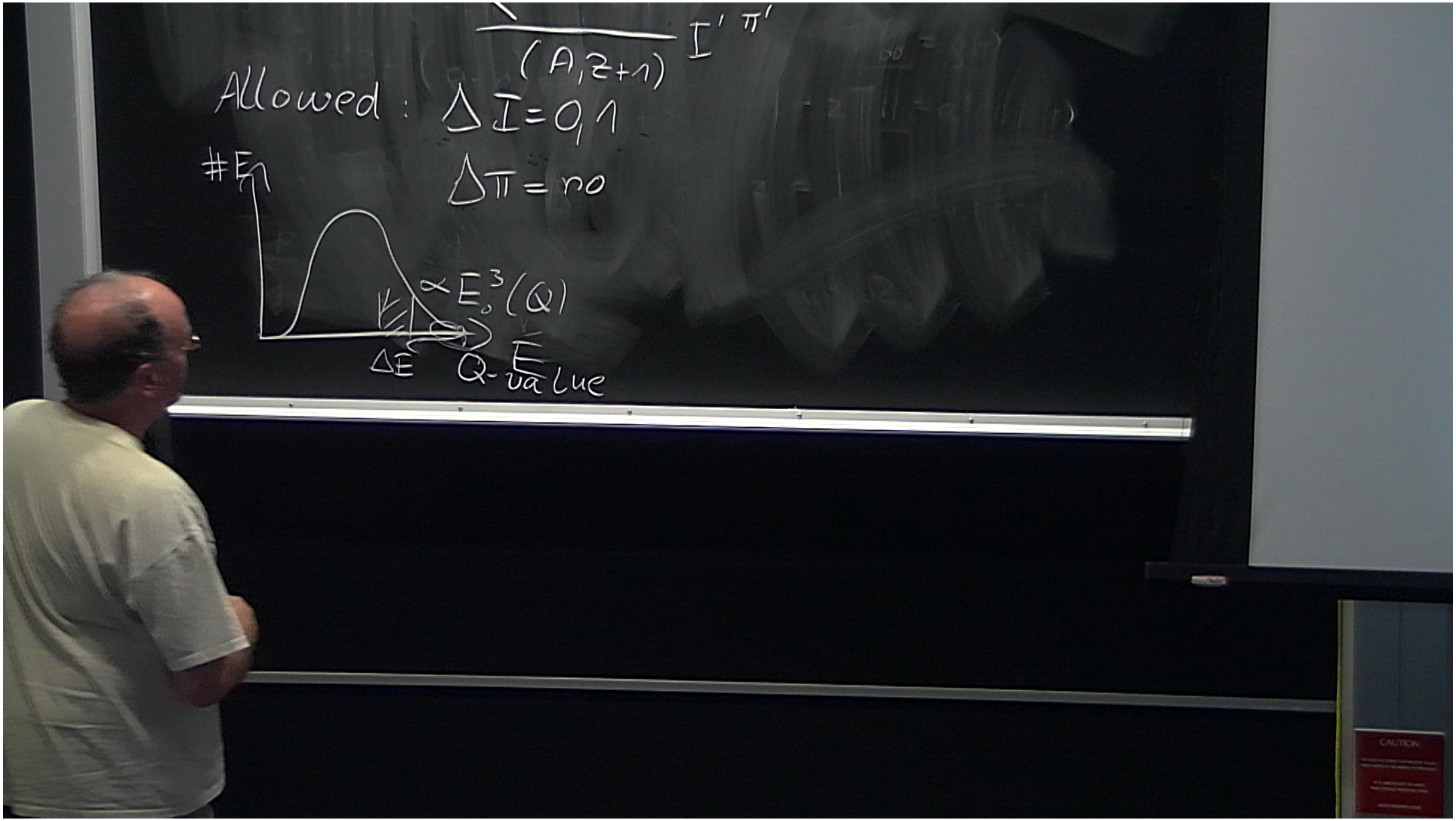

(A,Z+1) I' π'
Allowed : ΔI = 0,1
ΔΠ = no
#E
∝ E₀³(Q)
ΔE
E
Q-value

Phase space

Otten, Weinheimer, Rep. Prog. Phys. 71 (2008)

Number of states in a momentum range p+dp

$$\mathrm{d}n = \frac{4\pi V p^2\,\mathrm{d}p}{h^3} = \frac{4\pi V pE\,\mathrm{d}E}{h^3}$$

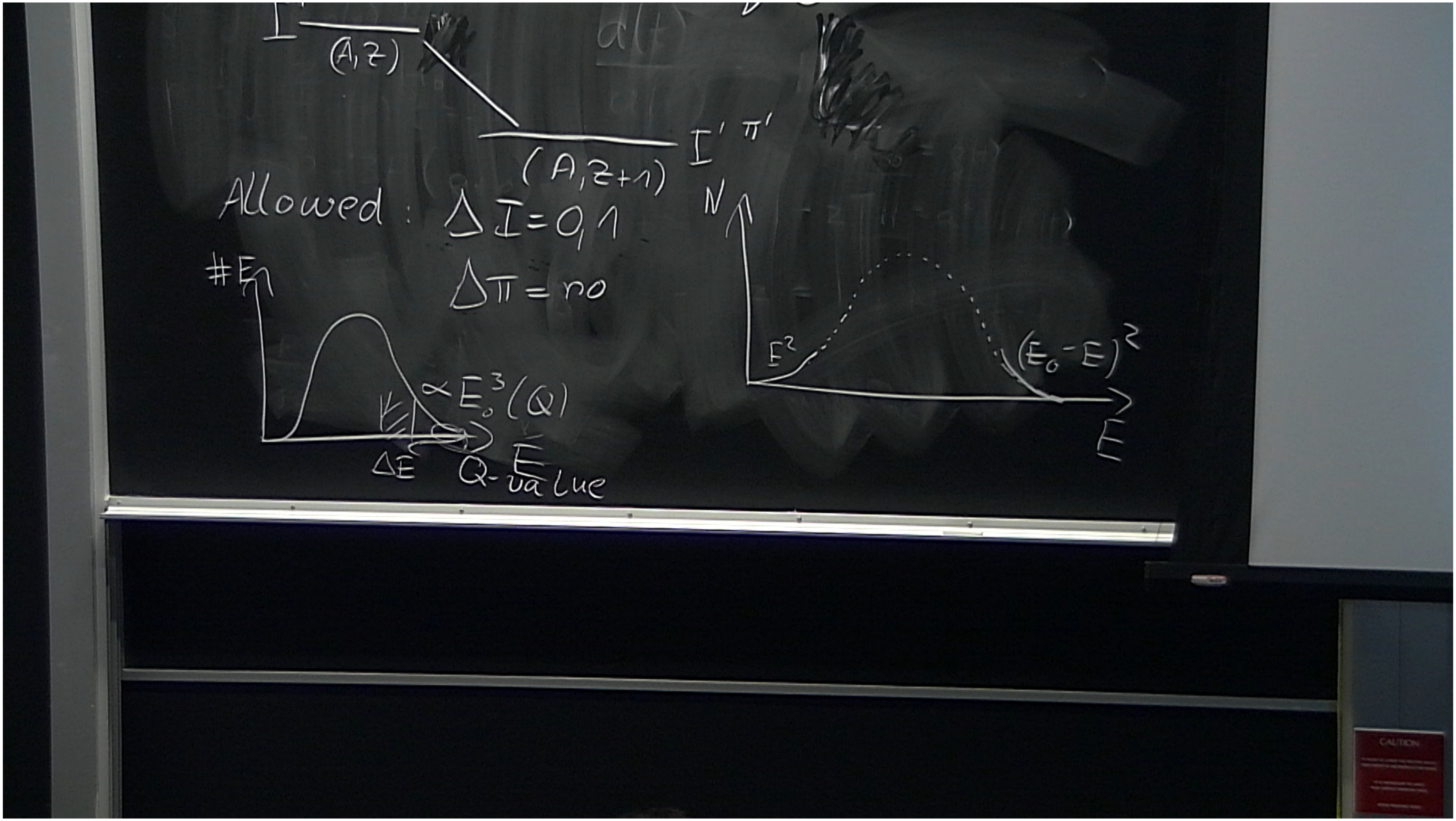
$$\frac{\mathrm{d}n}{\mathrm{d}E} = \frac{4\pi V pE}{h^3} = \frac{V pE}{2\pi^2\hbar^3}$$

Neutrino and electron momenta are not correlated

$$\rho(E) = \frac{V^2 p_e E_e p_\nu E_\nu}{4\pi^4\hbar^6}$$

Equation from previous slide (omitting subscript e)

$$\rho(E) = \frac{V^2 p_e E\sqrt{(E_0 - E)^2 - m^2(\nu_e)}(E_0 - E)}{4\pi^4\hbar^6}$$



(A,Z)
(A,Z+1)
I' π'
Allowed : ΔI = 0,1
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∝ E₀³(Q)
ΔE
Q-value
E
N
E²
(E₀-E)²
E

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Phase space

Otten, Weinheimer, Rep. Prog. Phys. 71 (2008)

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A few things to add

- Modification due to shell electrons: Fermi-function $$F(Z+1,E) = \frac{|\phi_e(0)_{\mathrm{Coul}}|^2}{|\phi_e(0)|^2}$$

Nonrelativistic approximation (Primakoff-Rosen)

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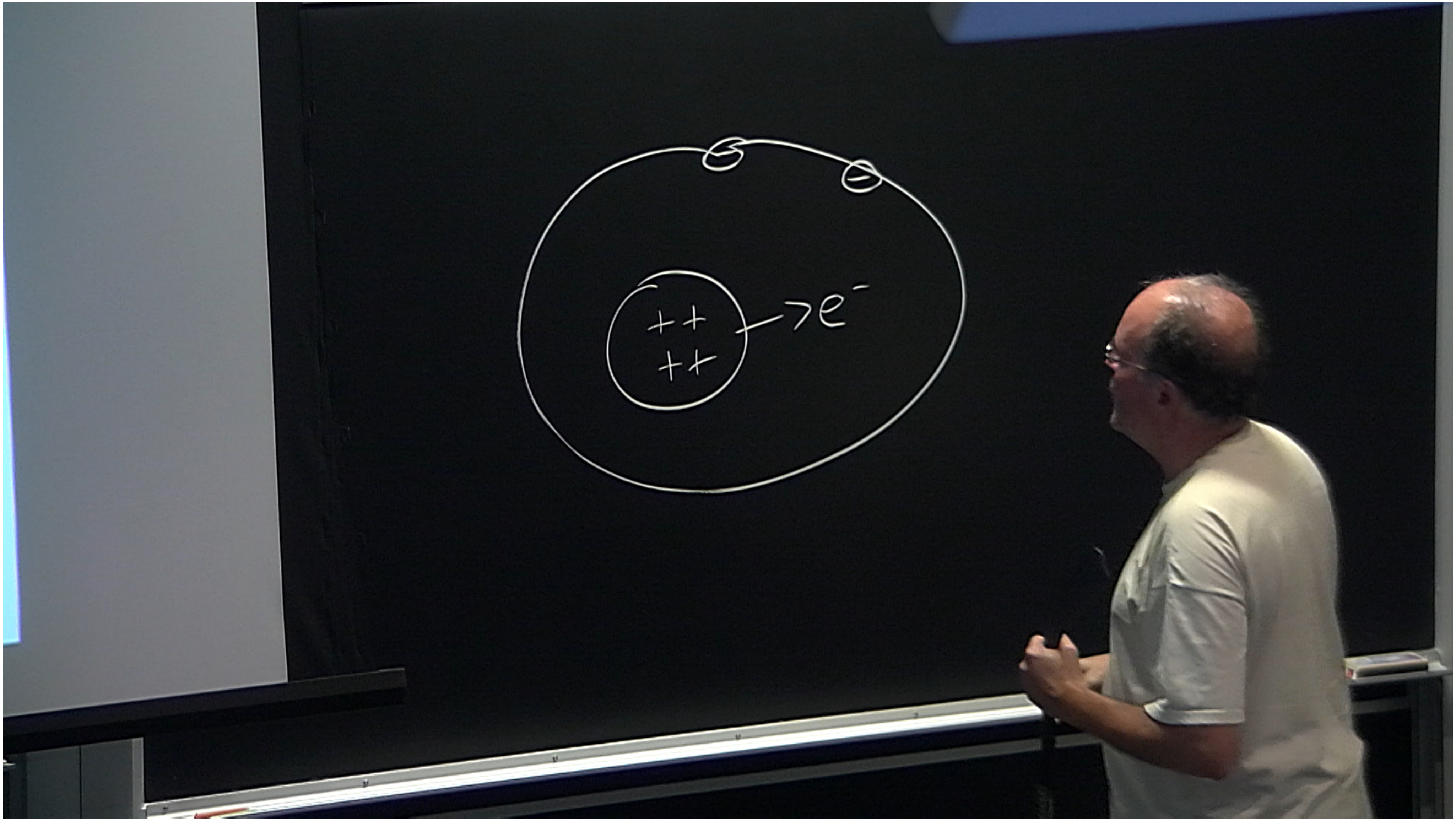
++
++
→e⁻

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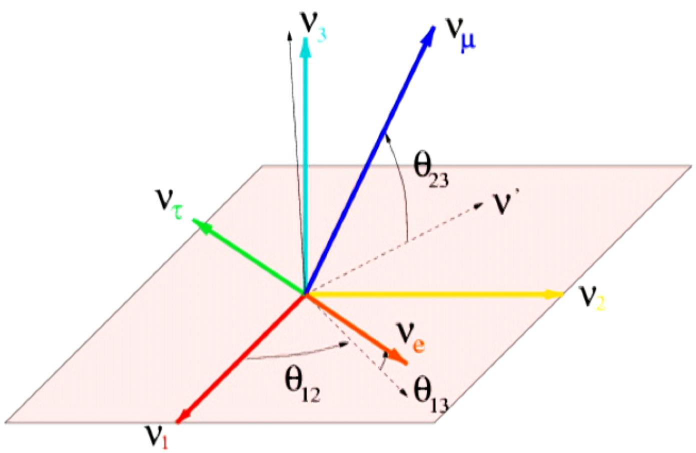
Neutrino mixing

Known in the quark - sector for more than 40 years (Fermi constant)



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2 Flavour Scenario

$$U = \begin{pmatrix} \cos\Theta & \sin\Theta \\ -\sin\Theta & \cos\Theta \end{pmatrix}$$

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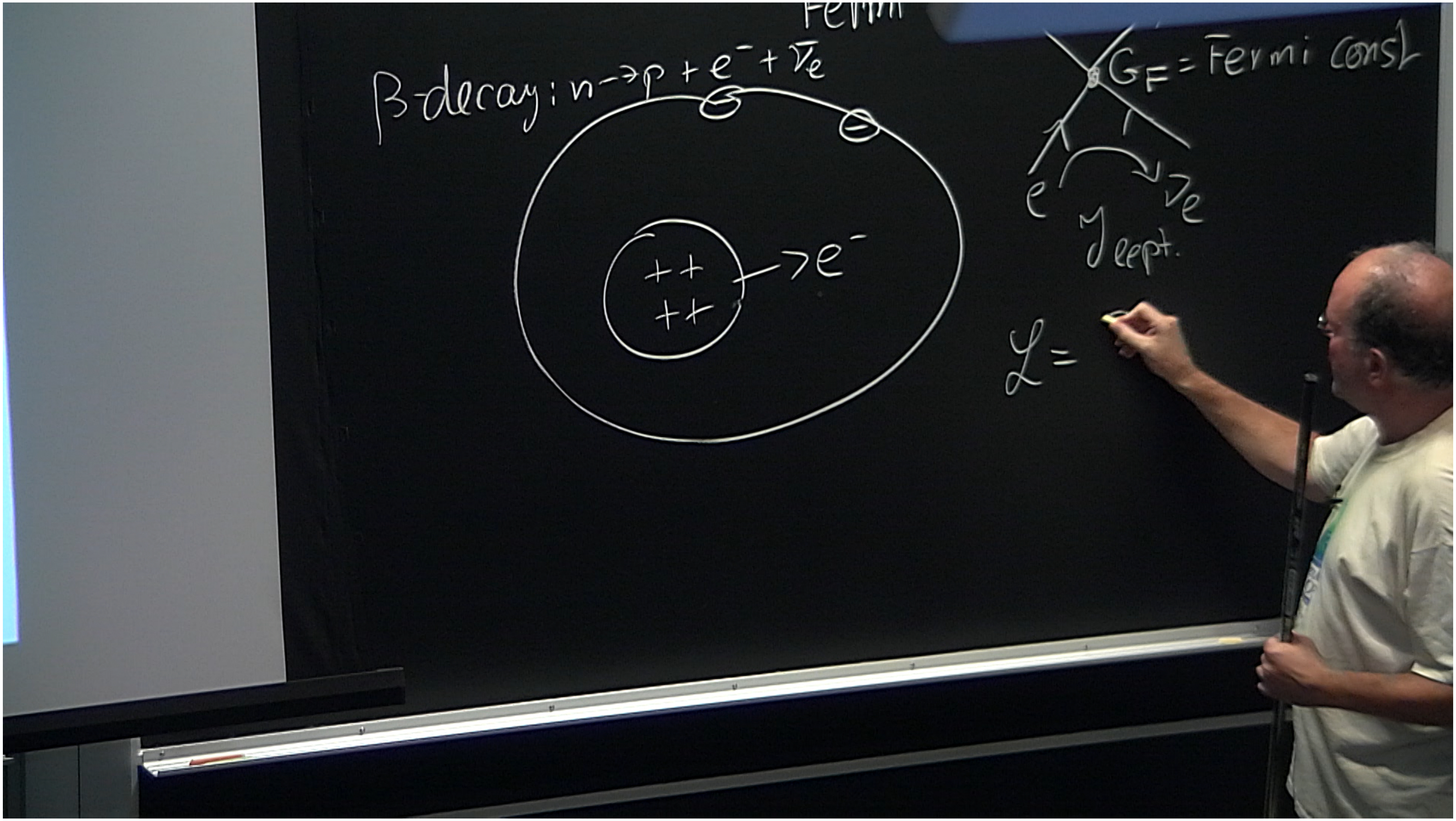
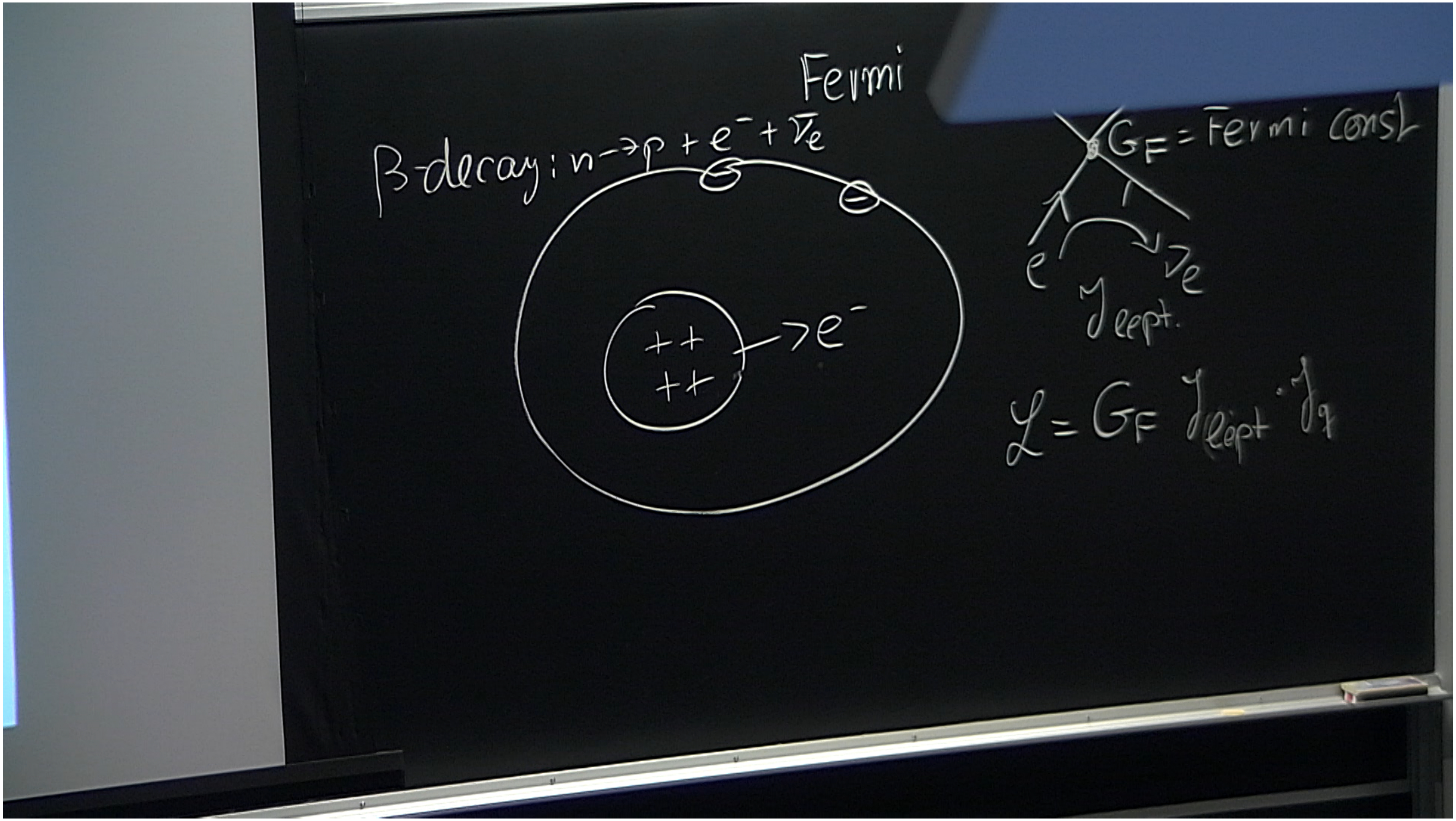

Fermi
β-decay: n → p + e⁻ + ν̄e
GF = Fermi const
e
νe
Jlept.
→ e⁻
ℒ =


Fermi
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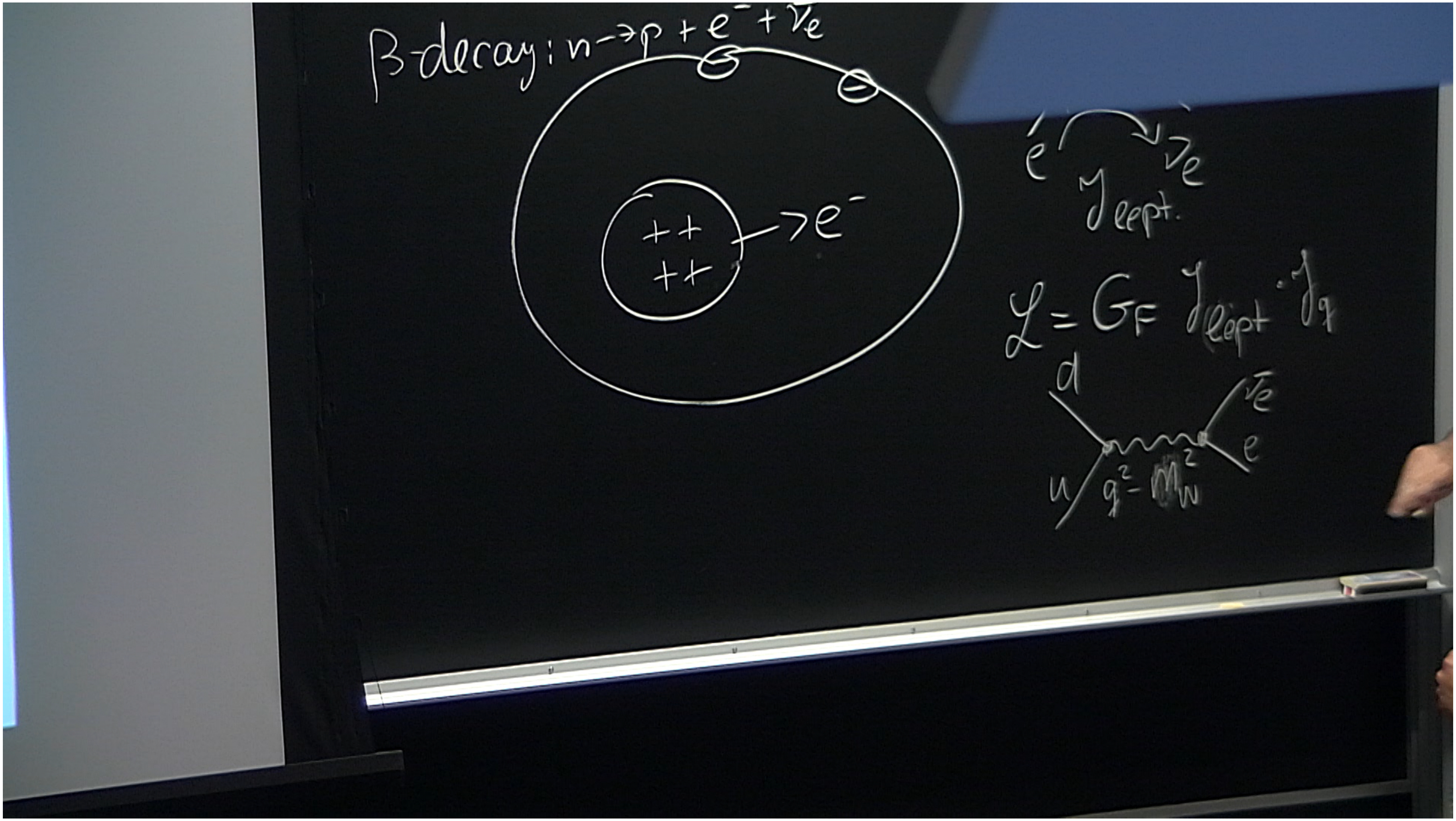
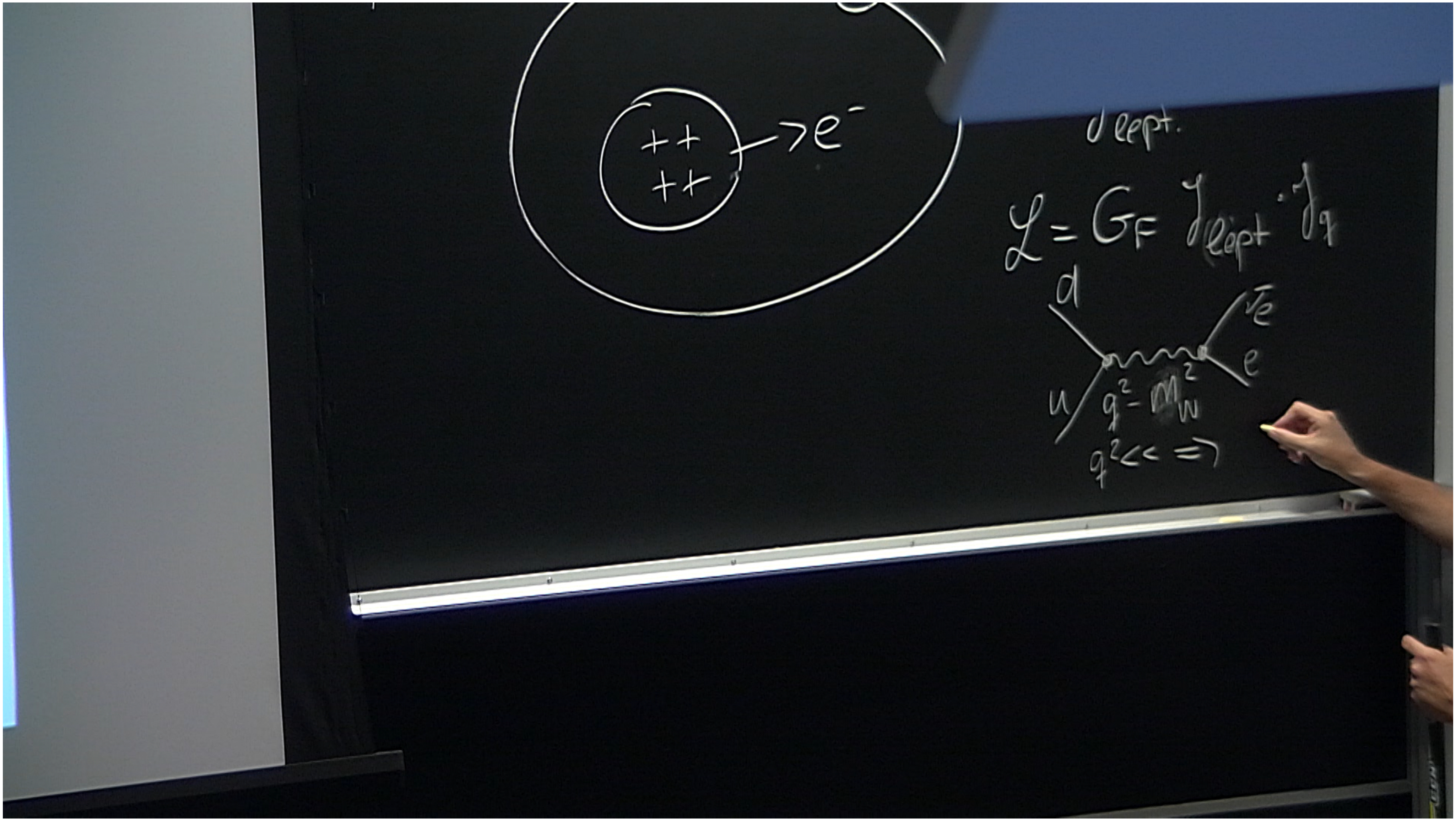
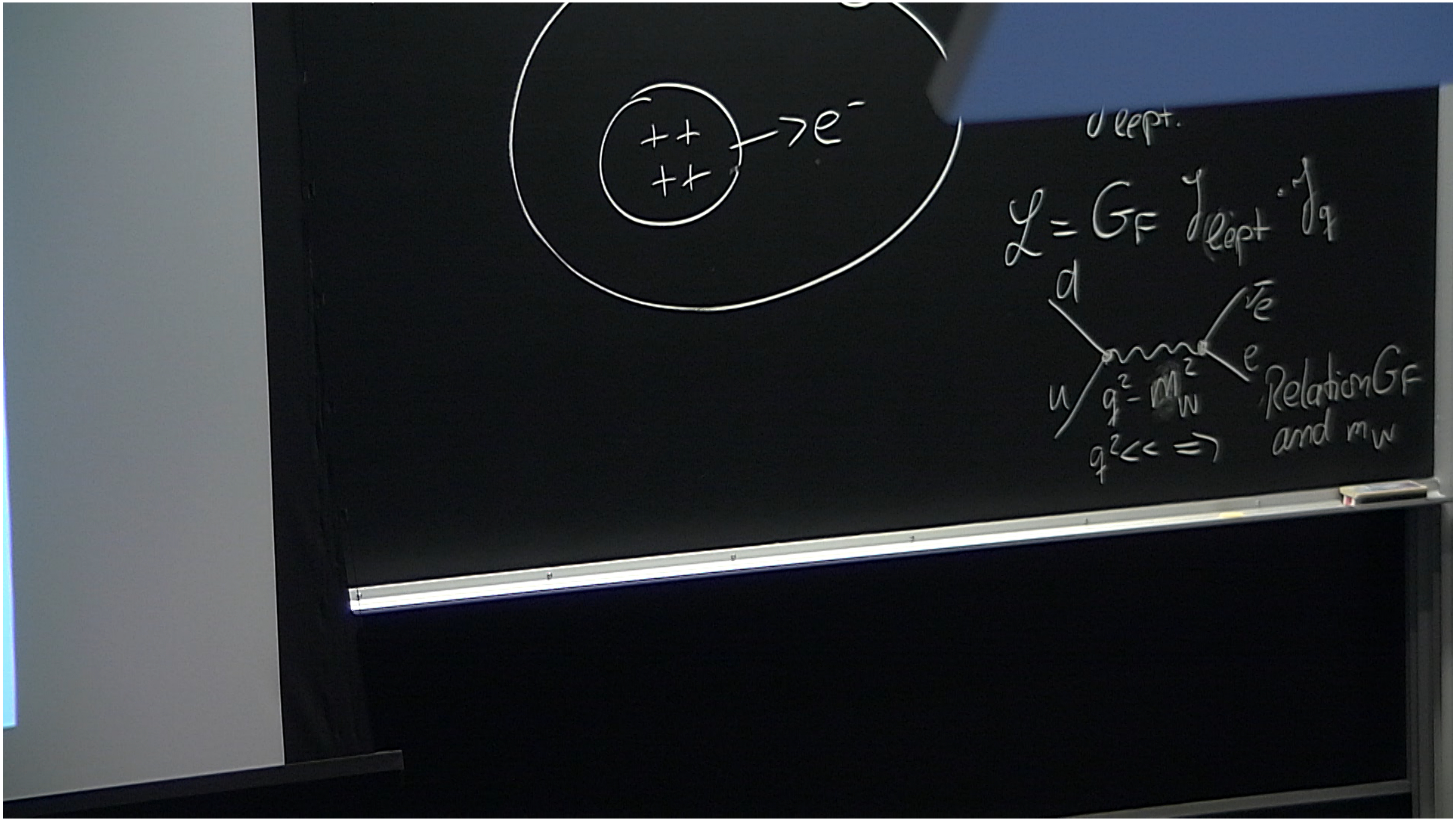
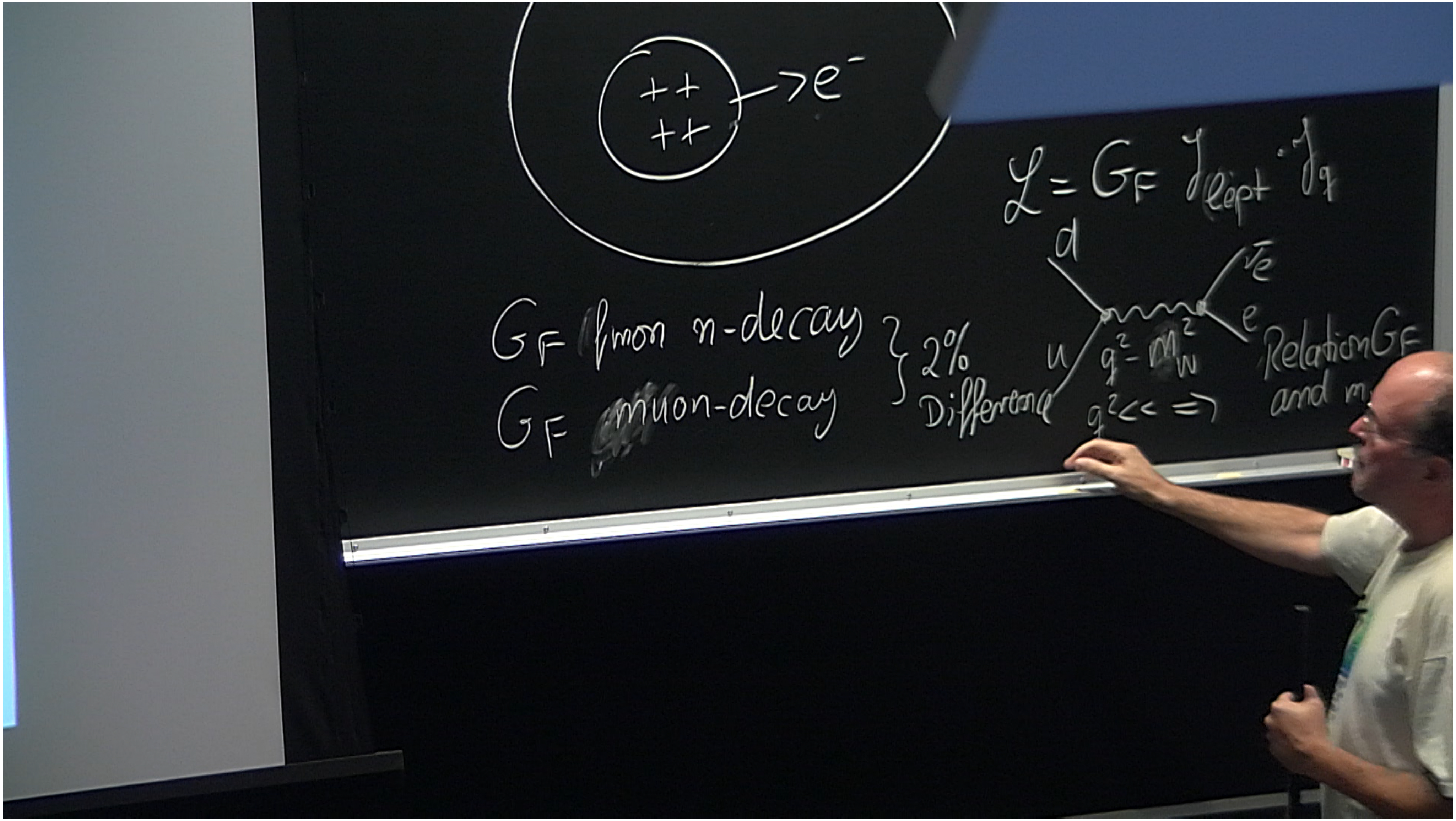
GF = Fermi const
e
νe
J lept.
L = GF J lept · J q

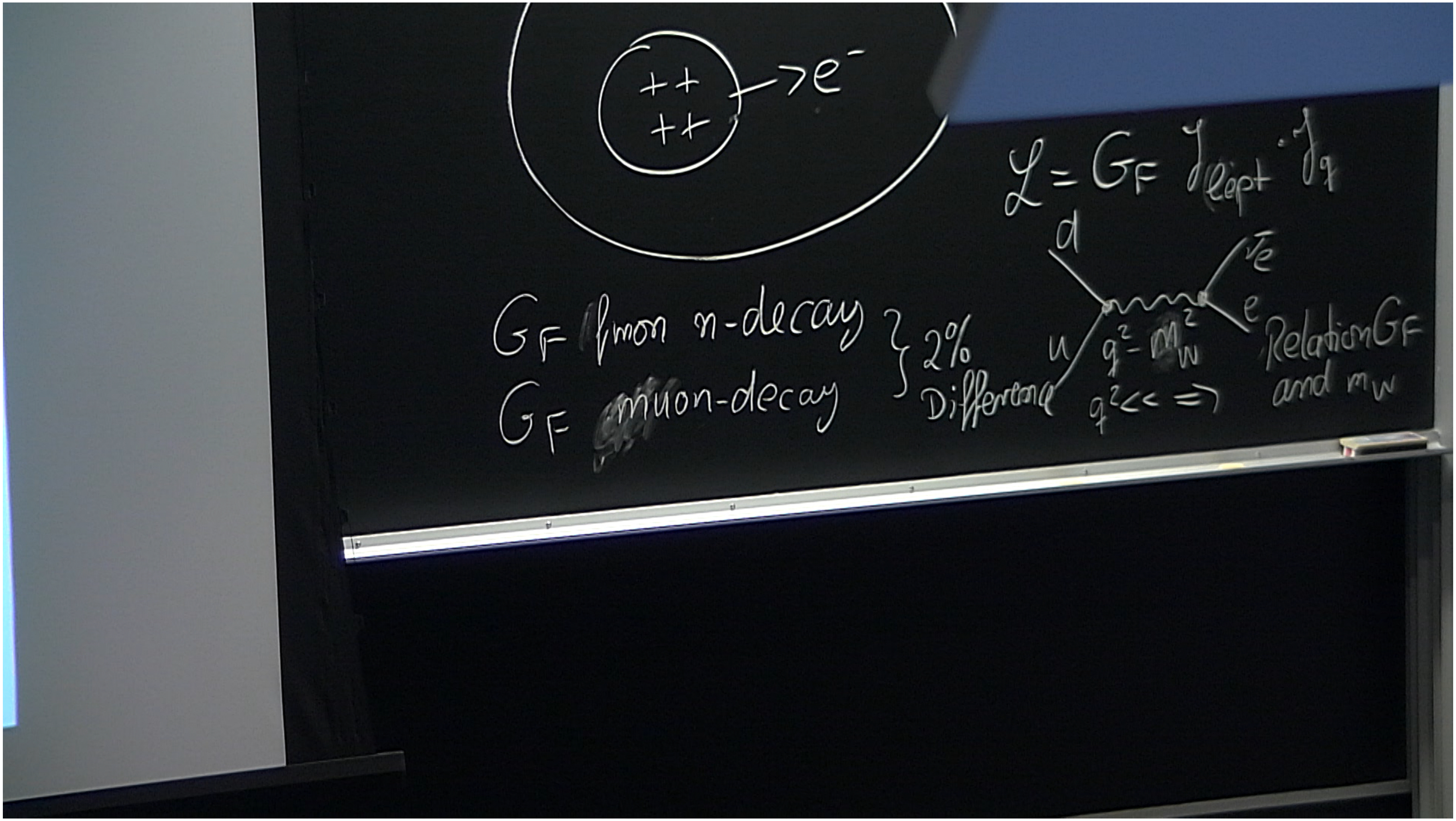

β-decay: n → p + e⁻ + ν̄e
→ e⁻
e⁻ ν̄e
J lept.
L = G_F J lept · J q
d
u
ν̄e
e
q² - M_W²



++
++
→e⁻
$J_{lept.}$
$\mathcal{L} = G_F\, J_{lept} \cdot J_q$
d
u
$\bar{\nu}_e$
e
$q^2 - M_W^2$
$q^2 \ll \Rightarrow$


++
++
→ e⁻
lept.
L = G_F J_lept · J_q
d
ν̄_e
e
u
q² - M_W²
q² << ⇒
Relation G_F
and m_W


++
++
e⁻
L = G_F J_lept · J_q
d
ν̄e
e
u
q² - M²_W
q² << ⇒
G_F from n-decay
G_F muon-decay
2%
Difference
Relation G_F
and m


++
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Difference

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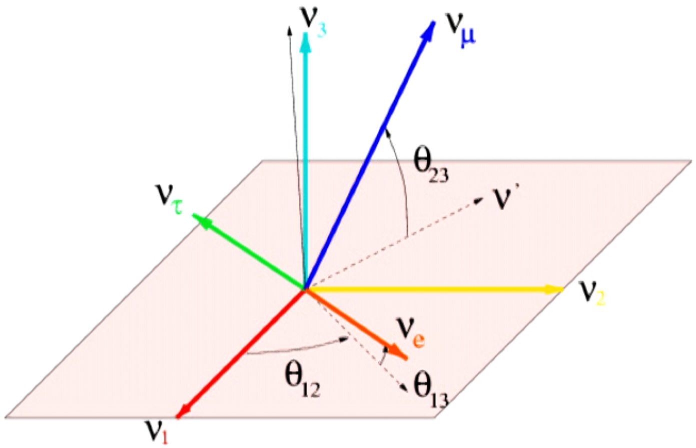

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Paramatrisation of CKM- and PMNS matrix

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}s_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

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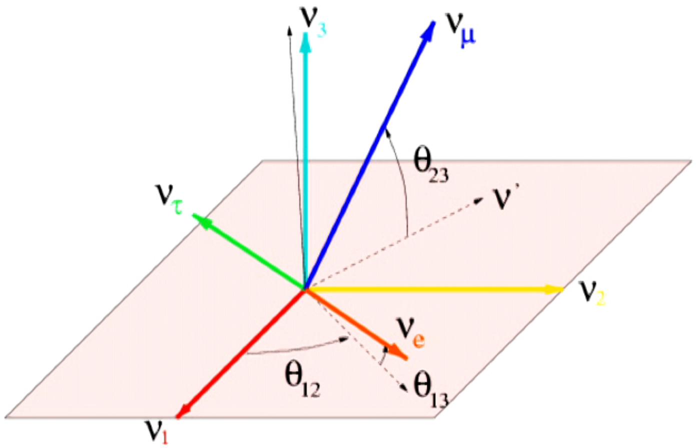

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Kinematic searches

Relativity $m^2 = E^2 - p^2$

Uncertainty $\Delta m_\nu^2 \approx \Delta E_\nu^2 + \Delta p_\nu^2 \approx 2E_\nu \Delta E_\nu + 2p_\nu \Delta p_\nu$

- the statistics of electrons with an energy close to the endpoint region is small (a small Q-value for the isotope under study is advantageous);
- good energy resolution;
- energy loss within the source;
- atomic and nuclear final state effects, excited state transitions; and
- a theoretical description of the involved wavefunctions.

Best candidate: $^3\mathrm{H} \rightarrow {}^3\mathrm{He}^+ + \mathrm{e}^- + \bar{\nu}_\mathrm{e}$

Using molecular tritium, daughter will be $^3\mathrm{H}\,^3\mathrm{He}^+$ ion

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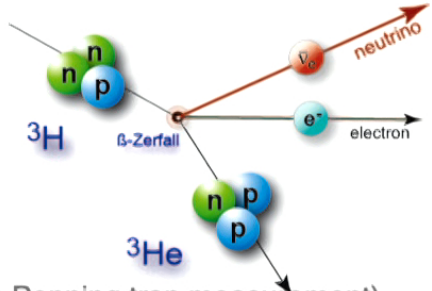
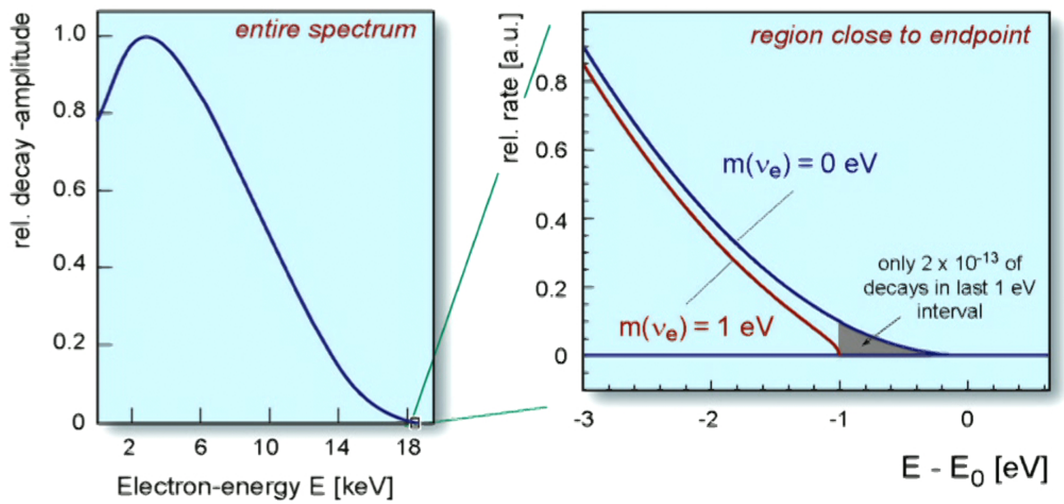
Tritium beta decay



Half-life :12.3 years

Matrix element [2] : 5.55

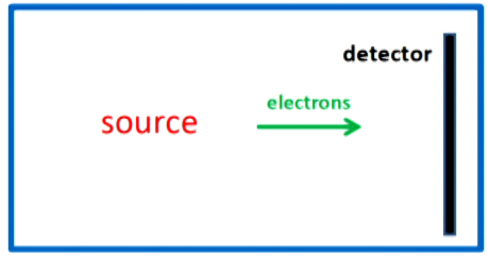
Endpoint energy: about 18590 eV (needs Penning trap measurement)



Kai Zuber

First measurements

How to measure?



The β-Spectrum of H^3

G. C. Hanna and B. Pontecorvo
Chalk River Laboratory, National Research Council of Canada, Chalk River, Ontario, Canada

January 28, 1949

Бруно Понтекорво

Bruno Pontecorvo

$m_\nu < 1$ keV/c^2

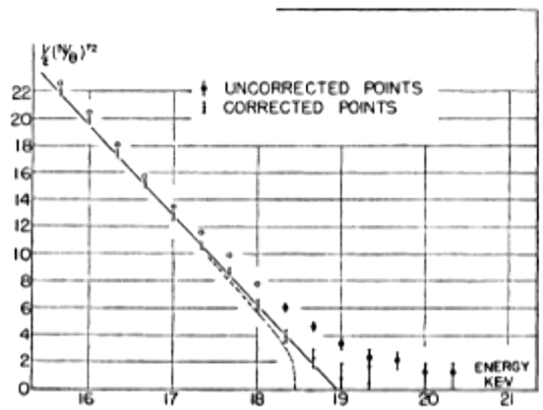
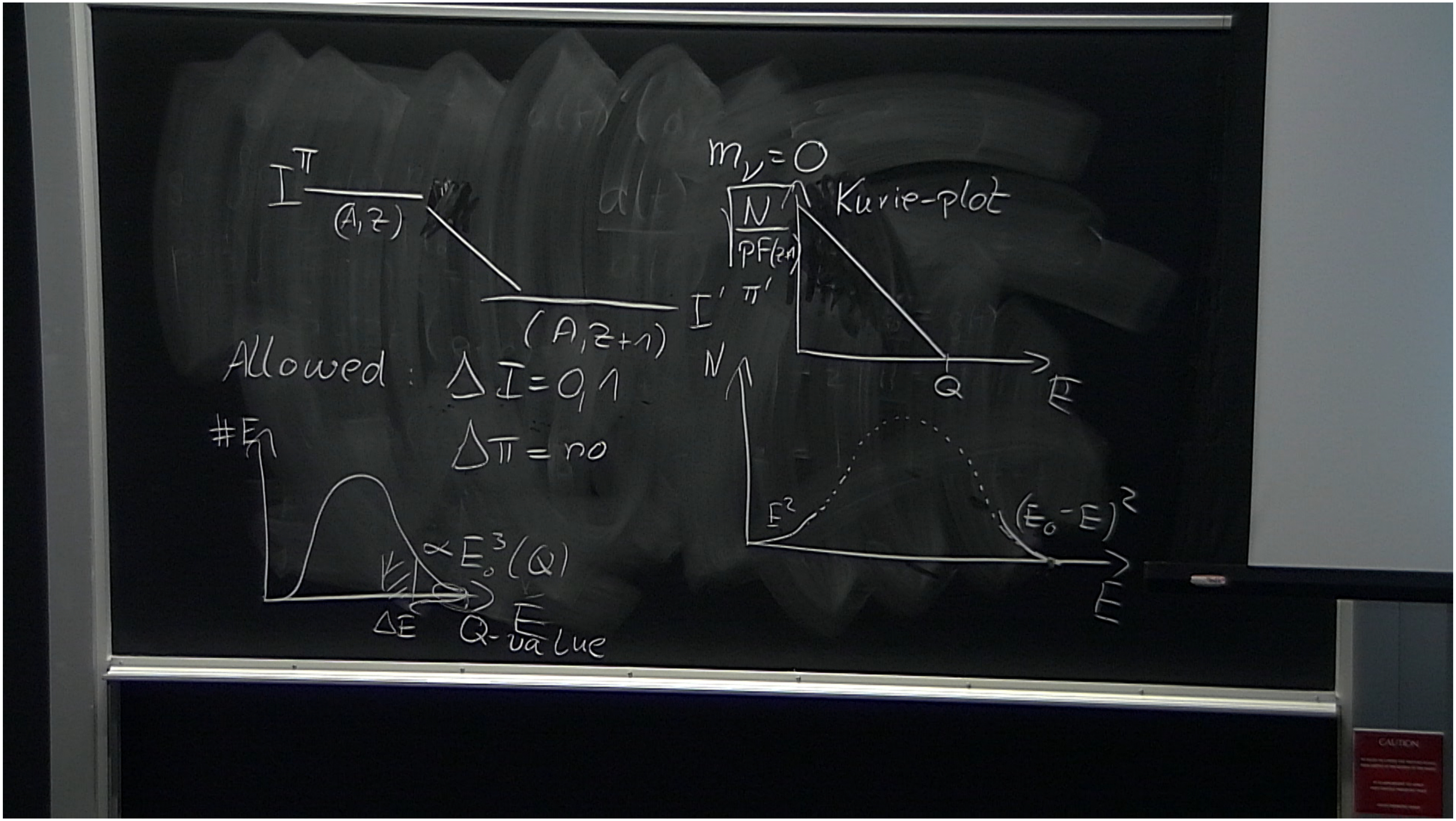


FIG. 2. "Kurie" plot of the end of the H^3 spectrum. The theoretical curve (shown dotted) corresponding to a finite neutrino mass of 500 ev (or 1 kev —see text) has been included for comparison.

Hanna G.C. and Pontecorvo B., Phys. Rev. 75 (1949) 983



I^{π}
(A, Z)
$I'\ \pi'$
(A, Z+1)
Allowed: $\Delta I = 0, 1$
$\Delta\pi = $ no
#E
$\propto E_0^3(Q)$
ΔE
E
Q-value
$m_\nu = 0$
$\sqrt{\frac{N}{pF(Z+1)}}$
Kurie-plot
Q
E
N
E^2
$(E_0 - E)^2$
E

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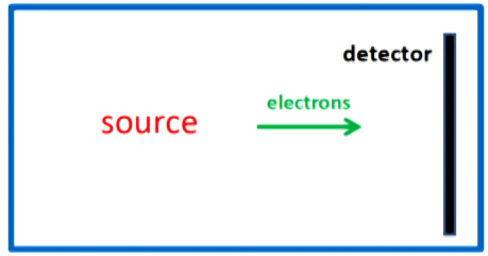

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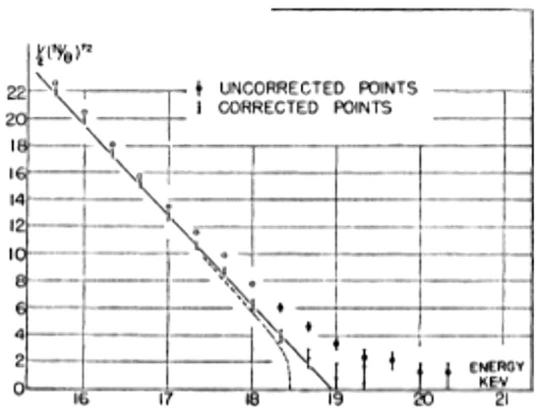

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16.07.2018 Kai Zuber

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Electrostatic spectrometer

PHYSICAL REVIEW VOLUME 92, NUMBER 6 DECEMBER 15, 1953

Upper Limits on the Neutrino Mass from the Tritium Beta Spectrum*

DONALD R. HAMILTON, W. PARKER ALFORD,† AND LEONARD GROSS‡
Palmer Physical Laboratory, Princeton University, Princeton, New Jersey
(Received August 25, 1953)

The shape of the tritium beta spectrum near the end point has been investigated in a spherical electrostatic integral spectrograph with particular reference to the possible effects of a nonzero neutrino mass. It is shown that the source thickness of 100 micrograms/cm² may be satisfactorily taken into account in the last kilovolt of the spectrum, upon which the results are based. An upper limit to the neutrino mass of 500, 250, and 150 electron volts is found for the Dirac, Majorana, and Fermi forms, respectively, of the beta interaction.

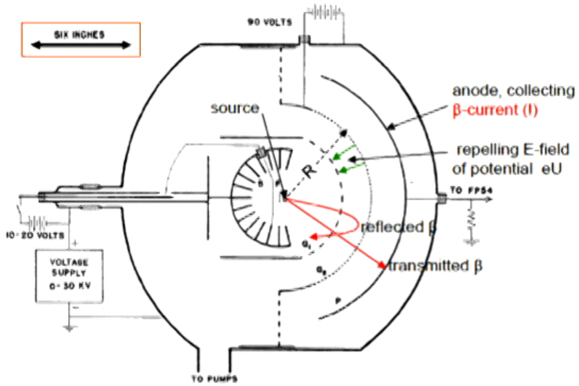

FIG. 1. Schematic diagram of electrostatic beta-spectrograph showing collector P, grids G_1 and G_2, source S, decharging filament F, and electron backstop B.

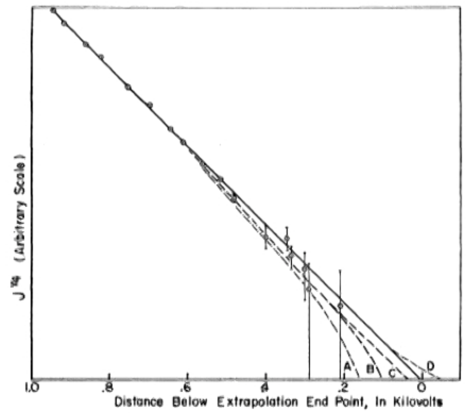

FIG. 3. Fourth root of tritium current plotted against kilovolts ow end point. Dotted curves represent curves predicted on the sis of measured resolution and for various neutrino masses and

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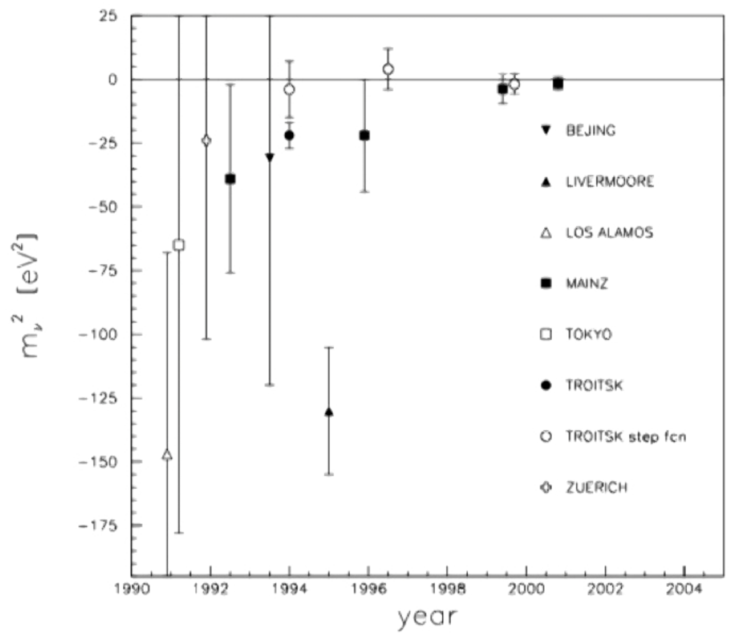
More experiments

- **1972** Bergkvist m<55 eV
- **1980** Lubimov **m= 35 eV!!!**
- **1980-1990** Livermore, Los Alamos, Zurich,...
- **1990-2005** Troitzk, Mainz m <2.35 eV



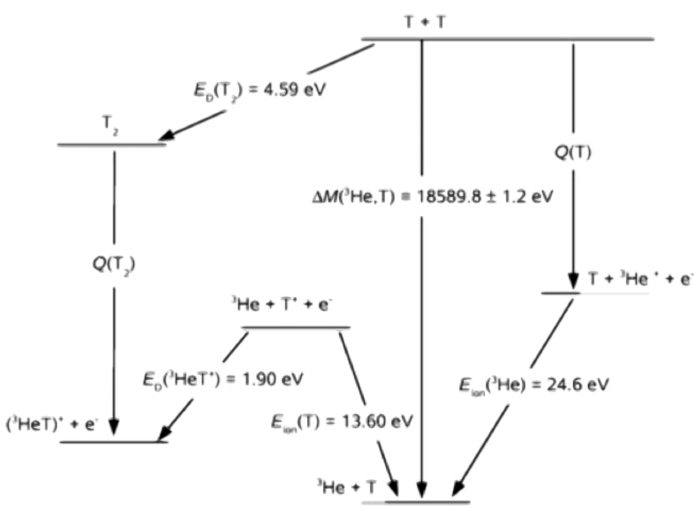
Before about 1995: Always negative m^2 far away from zero , some systematic effects were not understood

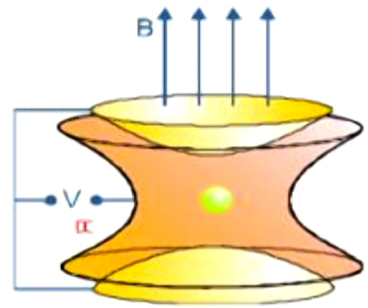
DRESDEN concept

Tritium beta decay

$$(A, Z) \rightarrow (A, Z+1)^{+} + e^{-} + \bar{\nu}_e + Q$$

$$Q = E + E_{\text{tot}\,\nu} + E_{\text{rec}} + V_j = E_0 + E_{\text{rec}} = \Delta M - \Delta E_B$$





$$f_c = \frac{1}{2\pi} \cdot \frac{q}{m} \cdot B$$

Q-value = 18592.01(7) eV E.G.Myers et al., PRL 114,013003 (2015)

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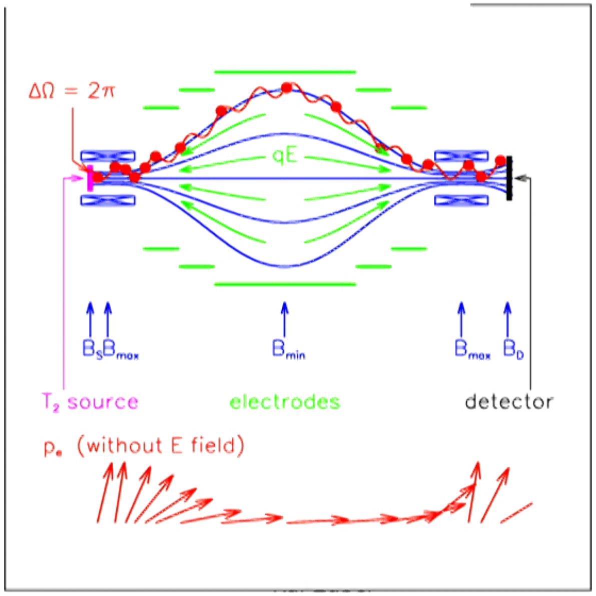
MAC-E Filter spectrometer (Mainz, Troitzk, KATRIN)

Magnetic Adiabatic Collimation combined with an Electrostatic filter

$$T_T = -\mu \cdot \mathbf{B} \qquad \text{with } \mu = \frac{e}{2m_e}\mathbf{L}$$

L = constant of motion



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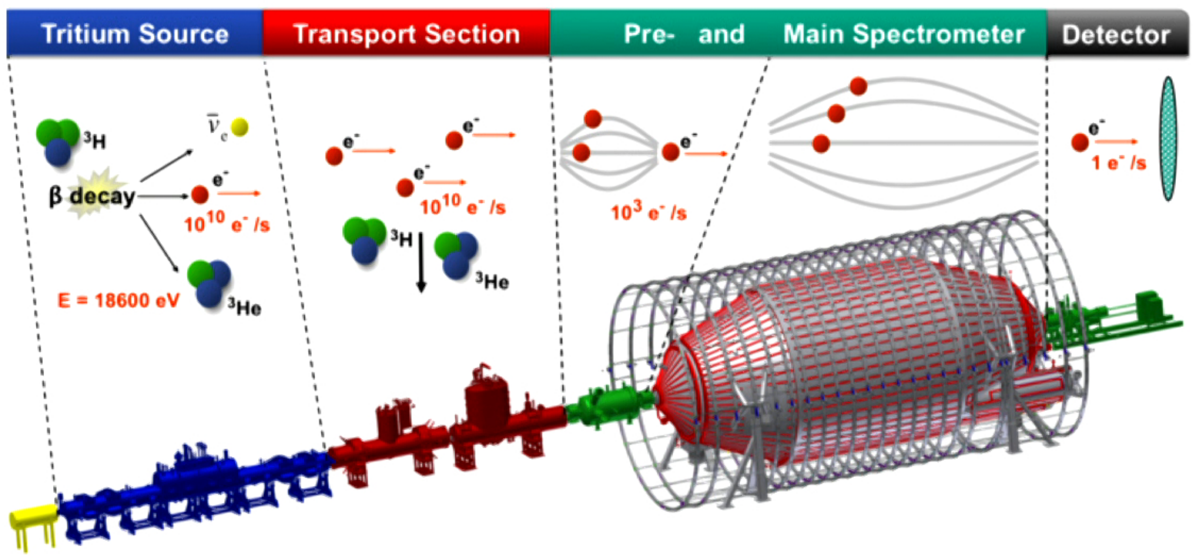
KATRIN

The next generation (ultimate spectrometer?): Aimed sensitivity of 0.2 eV



Tritium decays, releasing an electron and an anti-electron-neutrino. While the neutrino escapes undetected, the electron starts its journey to the detector.

Electrons are guided towards the spectrometer by magnetic fields. Tritium has to be pumped out to provide tritium free spectrometers.

The electron energy is analyzed by applying an electrostatic retarding potential. Electrons are only transmitted if their kinetic energy is sufficiently high.

At the end of their journey, the electrons are counted at the detector. Their rate varies with the spectrometer potential and hence gives an integrated β-spectrum.

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The next step

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Take the long way home ....

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KATRIN from inside