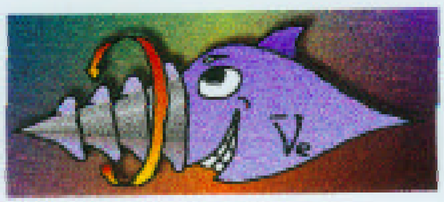
The Neutrino Mass

from Tritium β Decay

Ernst Wilhelm Otten

Email: ernst.otten@uni-mainz.de



- Introduction
- Tritium β decay experiments in Mainz
- The improved Mainz Experiment
- *Analysis and Discussion*
- Summary and Outlook

Present group members:

Jochem Bonn
Lutz Bornschein
Beate Degen
Christian Weinheimer
E. O.

Visitors:

from Troitzk:

Vladimir Lobaschew
Oleg Kazachenko
Juri Jeraskin
⋮

from Dubna/Prague:

Alois Kovalik

Collaborator in T_2-film physics:

Paul Leiderer (Konstanz)

Fresh Diploma Students as from 1999:

Lars Fickinger
Christine Kraus
Holger Ullrich

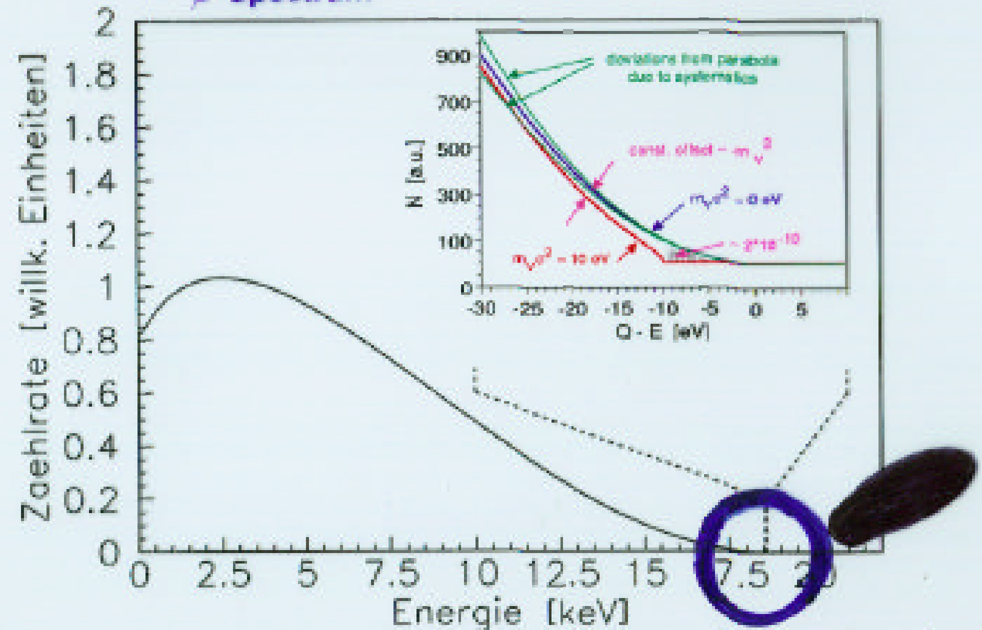
Direct measurement of m_{ν_e}

$^3H \longrightarrow {}^3He^+ + e^- + \bar{\nu}_e$:

superallowed transition

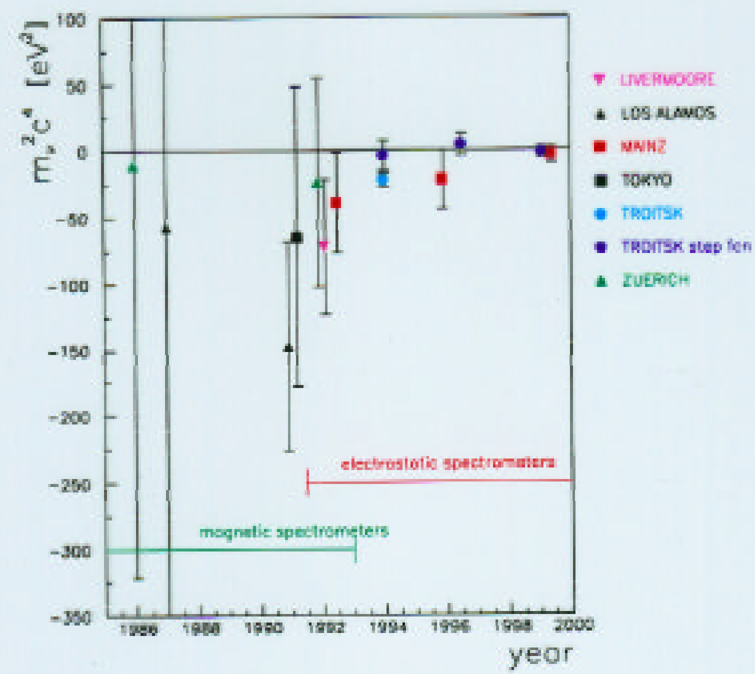
Q = 18.6 keV, $t_{1/2}$: 12.3 a

β-Spectrum



if more than one mass eigenstate contributes (not resolved): $\overline{m_\nu^2} := \sum_i |U_{ei}|^2 \cdot m_i^2$

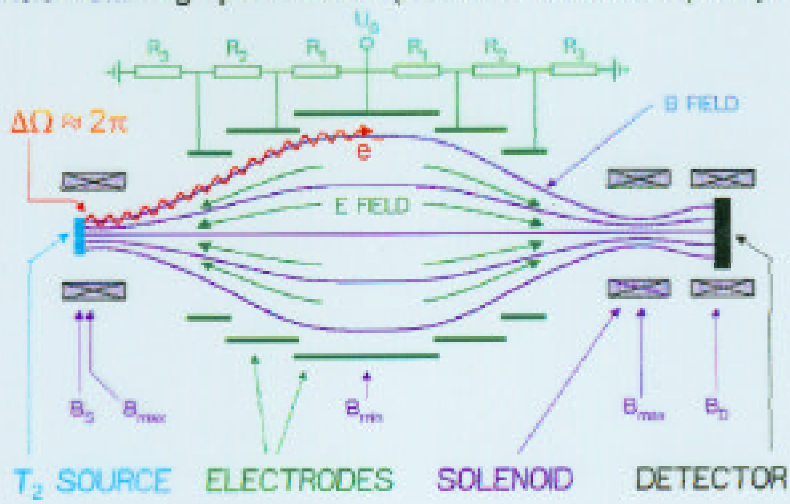
Tritium β decay: last decade



- 2 running experiments: Mainz, Troitsk
- Mainz 1991/1994 and Troitsk 1994::
  only data close to endpoint: $m_\nu^2 \approx 0$
  down to 500 eV below endpoint: $m_\nu^2 \approx -100 \mathrm{eV}^2$
  $\rightarrow$ undetected additional energy loss

Magnetic Adiabatic Collimation + Electrostatic filter

"Solenoid Retarding Spectrometer" (Nucl. Inst. Meth. B63 (1992) 345)



$\vec{F} = (\vec{\mu}\vec{\nabla})\vec{B} + q\vec{E}$ $\mu = \frac{E_\perp}{B} =$ constant

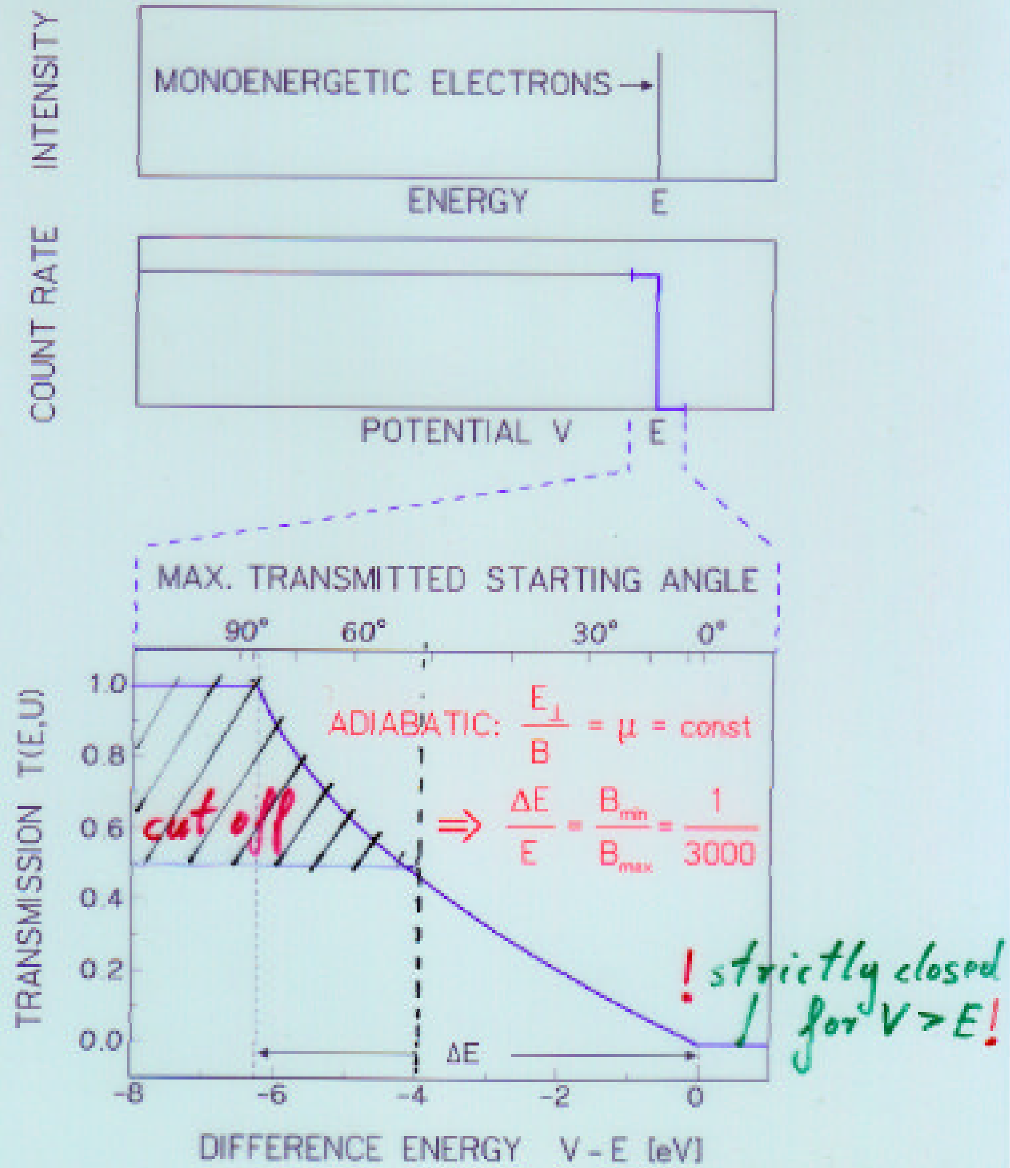
- magnetic guiding field

$\rightarrow \Delta\Omega \approx 2\pi$

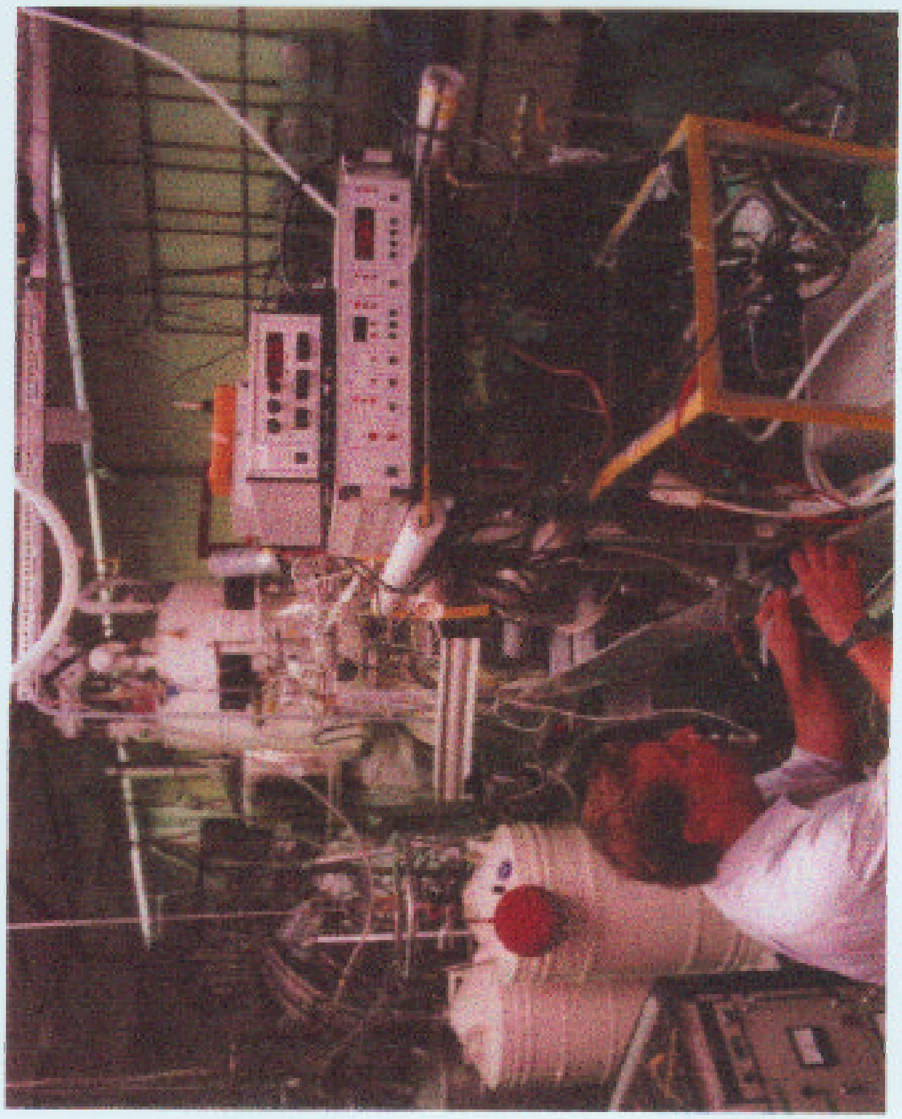
- adiabatic transf. $E_\perp \rightarrow E_\parallel$ + electrostatic retardation

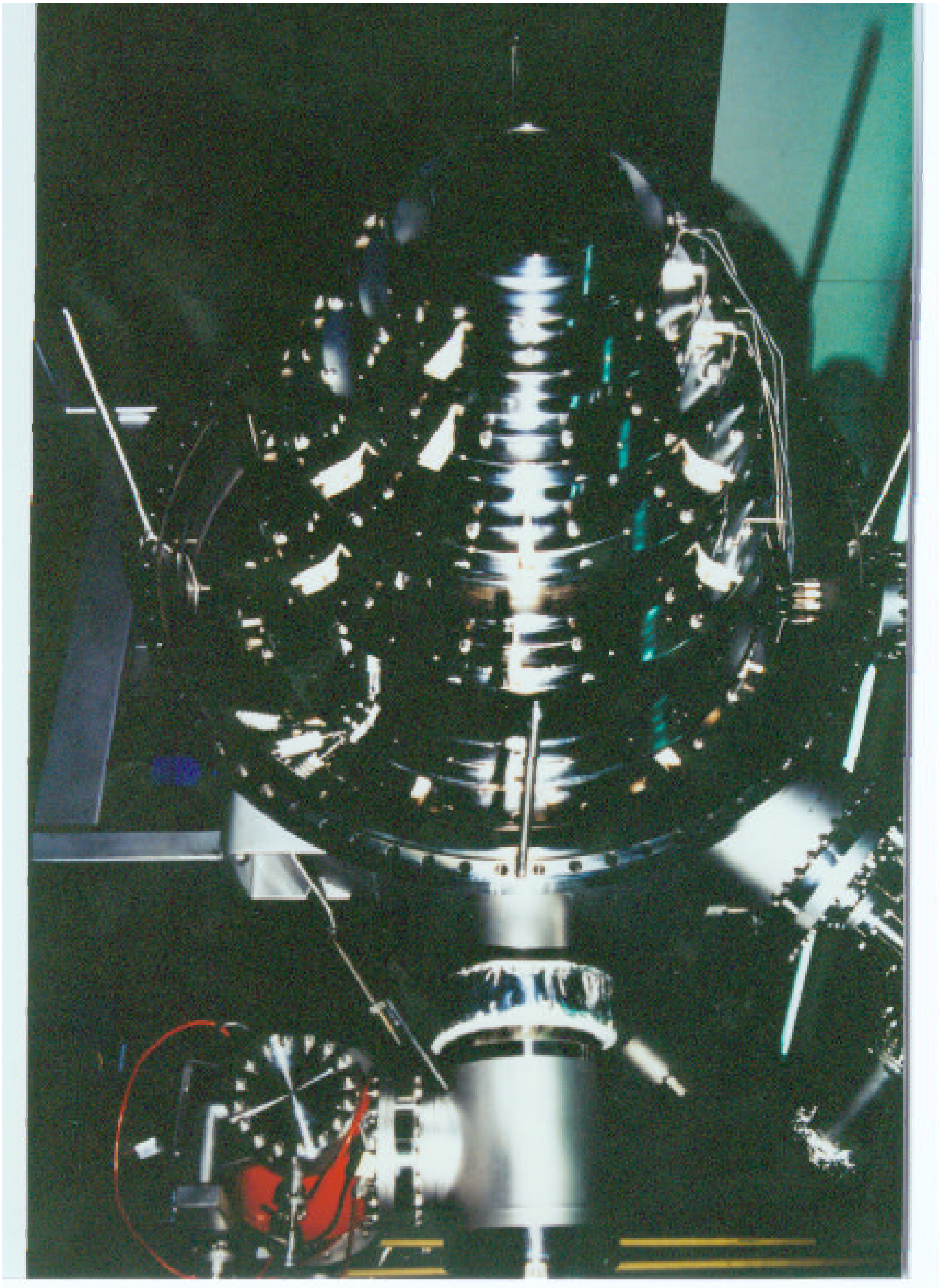
$\rightarrow \Delta E \approx 4 - 6 eV$

- performs point to point image
- keeps off background originating outside flux tube

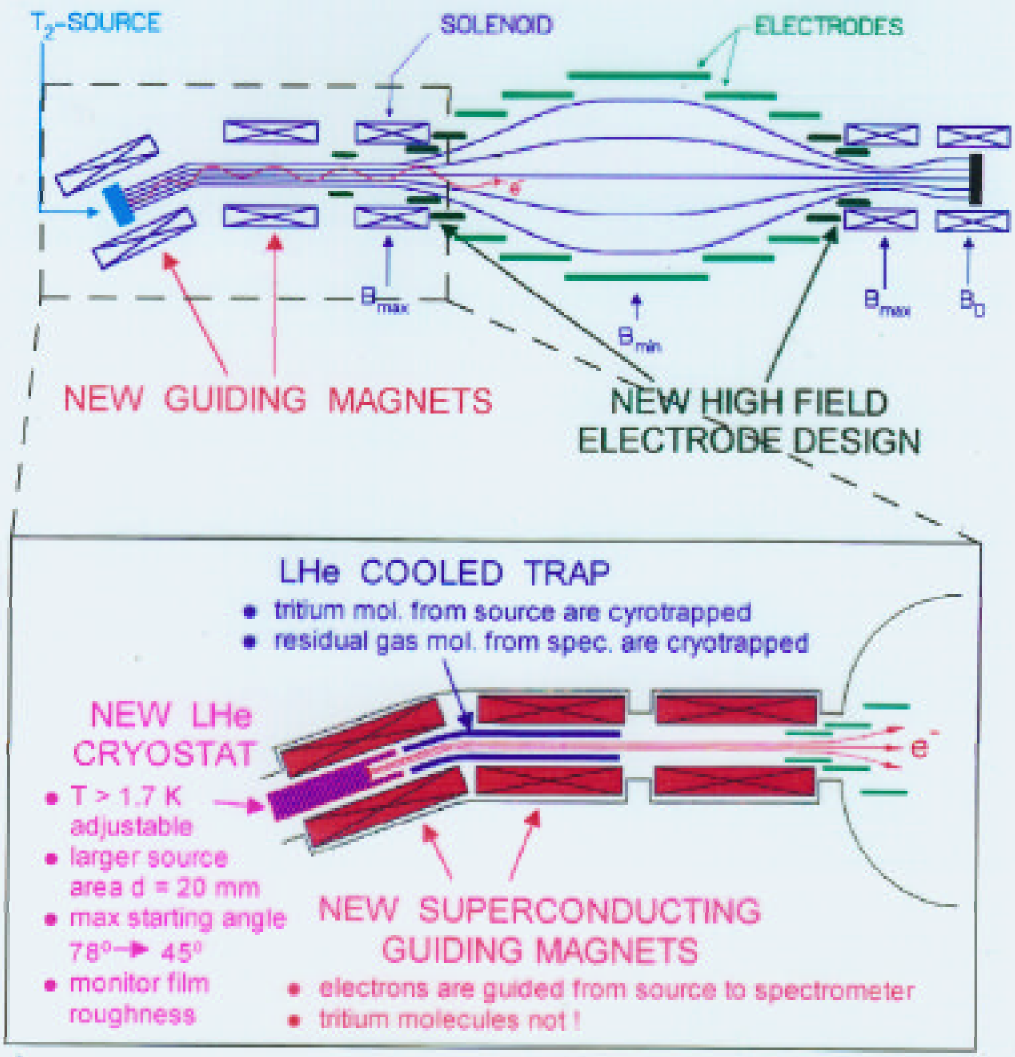


ISOTROPIC SOURCE: $$T(E, V) = \frac{1 - \sqrt{1 - \frac{(E - V) \cdot B_S}{E \cdot B_{min}}}}{1 - \sqrt{1 - \frac{B_S}{B_{max}}}}$$



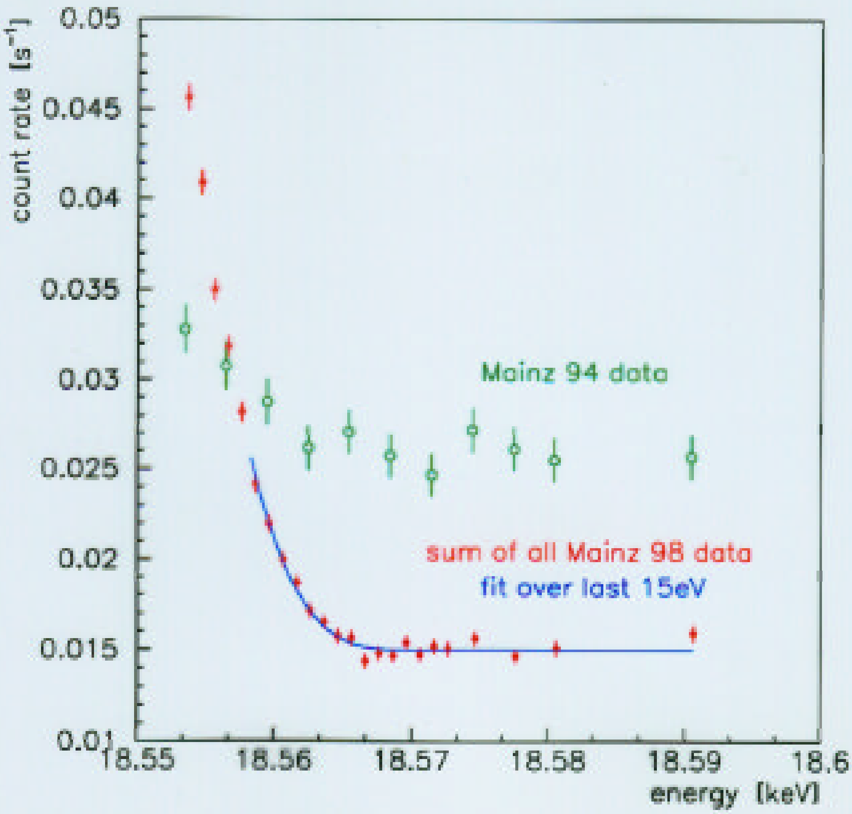


IMPROVEMENTS OF THE EXPERIMENTAL SETUP



Summing up all 1998 data

Q3+Q4+Q5



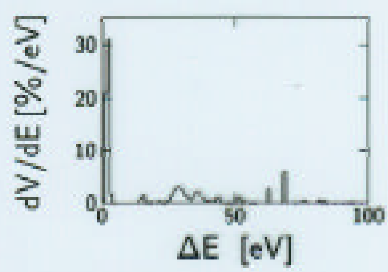
The Fitfunction

$$\dot{N}(E) = \text{amp} \sum_i P_i \, \epsilon_i^2 \sqrt{1 - \frac{m_\nu^2 c^4}{\epsilon_i^2}} \otimes f_{response} + BG$$

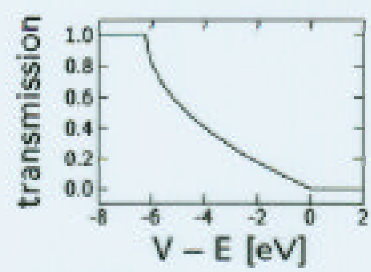
$f_{resp} \approx$ Charging $\otimes$ TF $\otimes$ EL $\otimes$ BS

with $\epsilon_i = E_0 - V_i - E$: final states

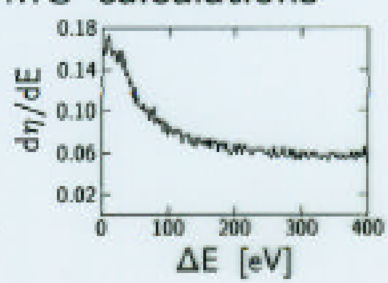
final states:
sudden approx.
(Kolos, Fackler)



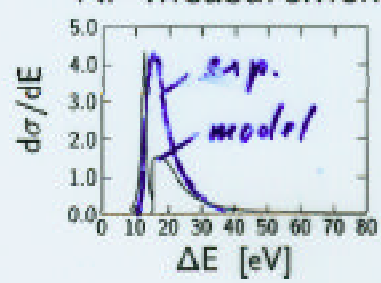
TF:
transmission fcn
(analytically known)



BS: backscatter:
MC–calculations



EL: energy–loss:
^{83m}Kr–measurements



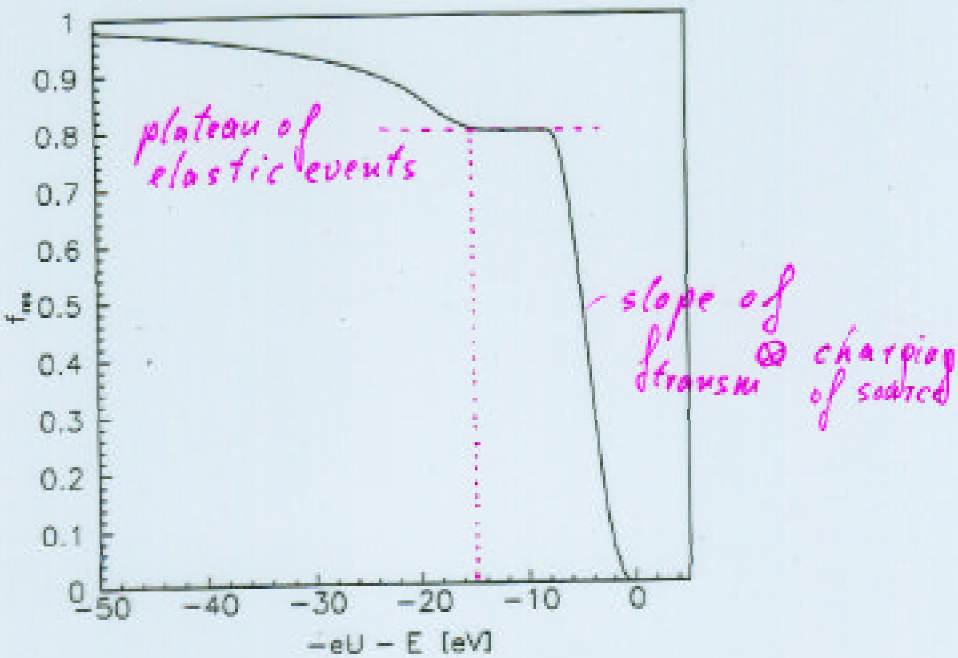


Figure 2. Normalised response function of the spectrometer f_{res} for a monoenergetic electron source of energy E in dependence on the retarding energy -eU. The energy loss f_{eloss} and the charging effect f_{charge} are calculated for a source thickness of 490 Å as used for measurements Q3-Q5.

Systematic uncertainties

- **Inelastic Scattering** — film thickness, λ_{free}, shape of energy loss function (49 %)

- **Final states** — (effects due to solid state) (37 %)
  - spectator excitation
  - changes of excited states energy levels

- **T_2 film charging up** — new (14 %)

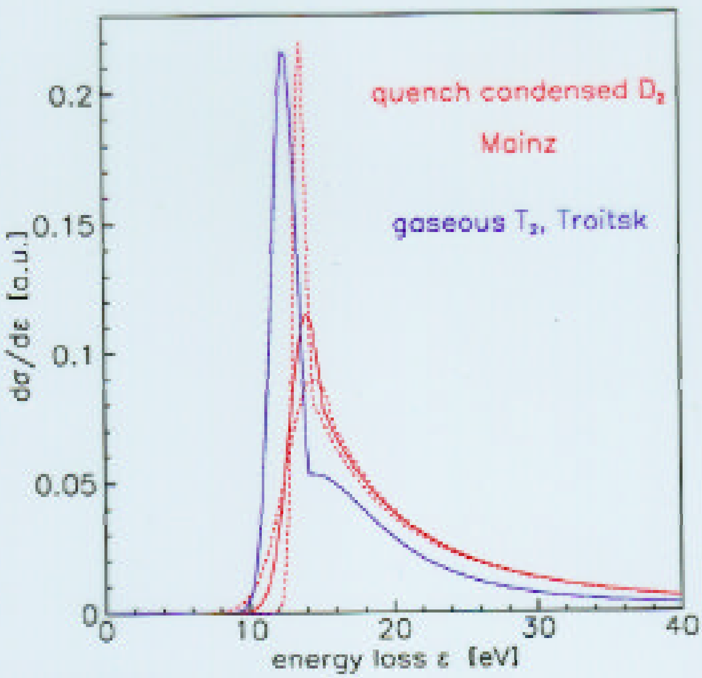
- **T_2 film roughness** — (avoided) (-)

- **Backscattering** — (small) < 1%)

- **Detector efficiency** — (small) (-)

(contribution to systematic uncertainty for Q5, last 70 eV ⟷)

Energy loss function



Determination with conversion e^- through D_2 films:

- → shape for quench condensed film is significantly different to shape for gas!

  Influence of Pauli blocking for excited molecular states!

- → $\sigma_{tot} = 3.00 \pm 0.16 \cdot 10^{-18}$ cm^2:

  14% smaller than expected

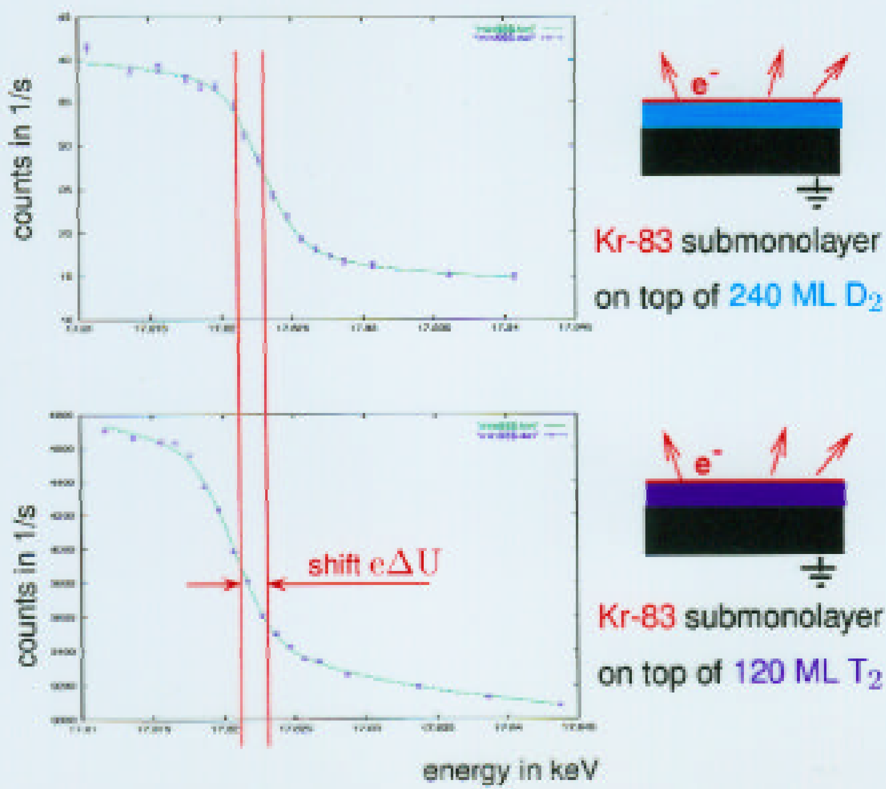
  Influence of Pauli blocking for excited molecular states!

Charging up of T_2 film

Shift of endpoint energy (run 1997)

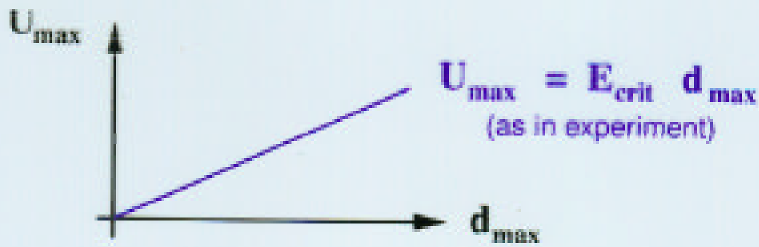
Charging up of the T_2 film (40 mCi)

⇒ Measurements with K conversion electrons of Kr-83



Does microscopic picture fit?

1) Expectation from picture:



2) Measured critical field E_{crit}:

$E_{crit} = 6\ V / 288$ Monolagen

$\rightarrow\ W_{pass} = e \cdot E_{crit} \cdot d_{ML} \approx 250\ K$

(right order of magnitude !)

⊕ charging up effect probably understood

⊖ deterioration of energy resolution

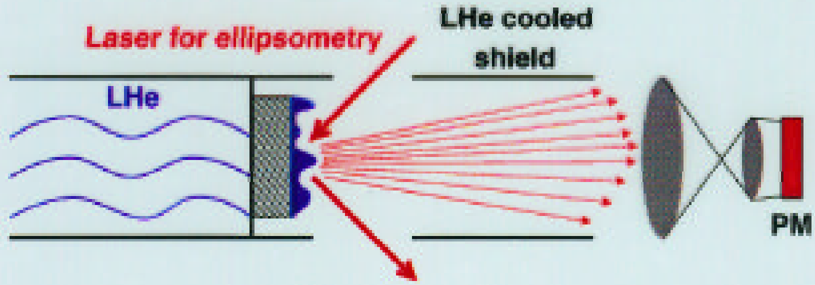
(10% – 90% : 3.5 eV → 6.0 eV)

- take effect into account in analysis

estimate for uncertainty: ≈ 50 % of total effect

Detection of Roughening Transition

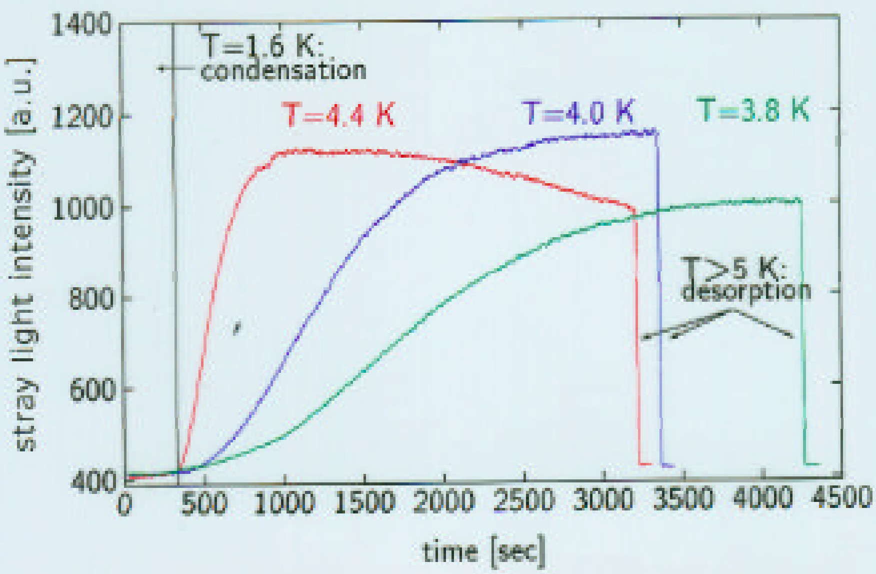
Observation of stray light



Temperature Dependence of Roughening Transition

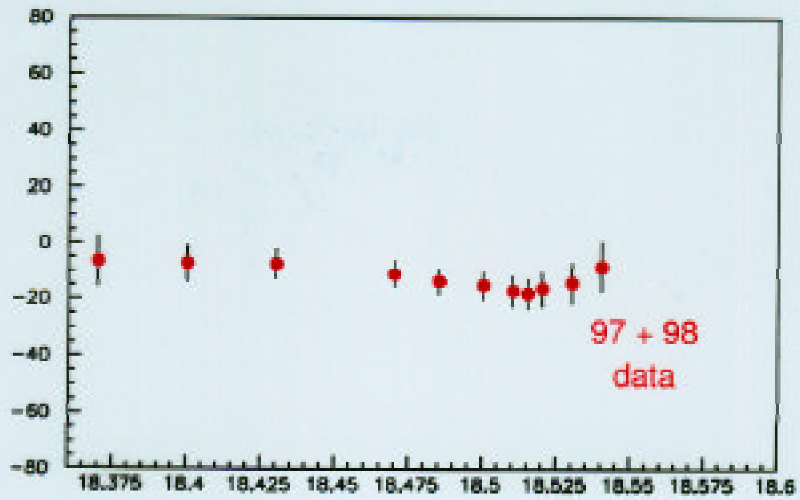
condensation | roughening transition | desorption

1.6 K | 3.8-4.4 K | > 5 K

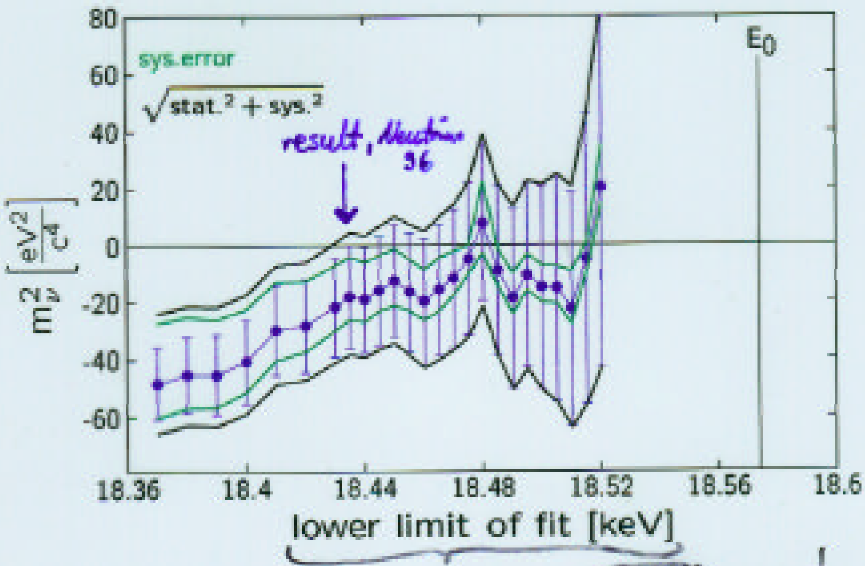


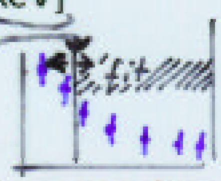
Extrapolated time constants for T_2
(ok, if T_2 decays do not matter)

T	4.2 K	2.8 K	1.6 K
τ	hours	days	years


80
60
40
20
0
-20
-40
-60
-80
18.375
18.4
18.425
18.45
18.475
18.5
18.525
18.55
18.575
18.6
97 + 98
data

Result 1994





→ fit abuses fit parameter m_ν^2

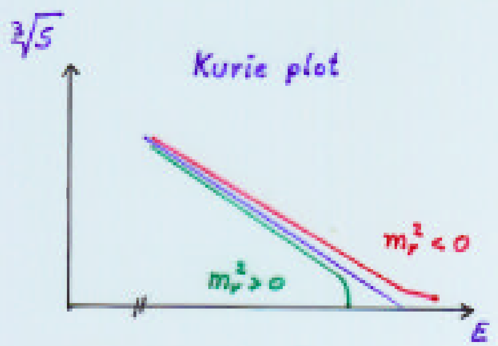
to compensate systematic discrepancies

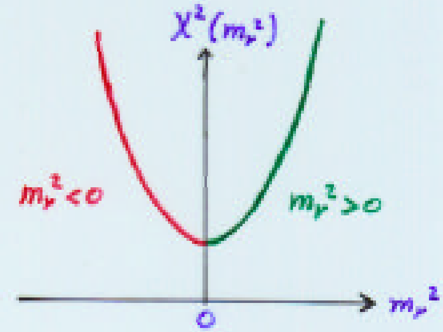
between data and fit function

→ trend explainable by missing energy loss

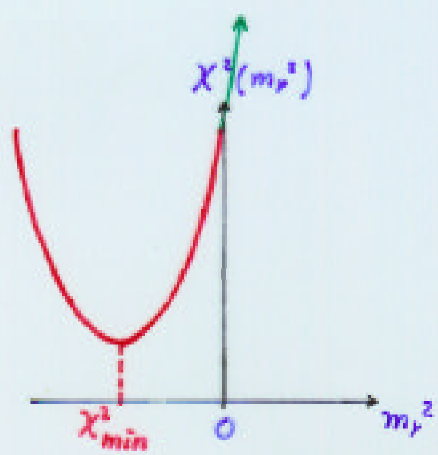
How to treat negative m_ν^2- values in the fit function ?

Find a suitable analytical continuation of β-spectrum beyond E_0 which produces a parabolic $\chi^2(m_\nu^2)$ - curve around $m_\nu^2 = 0$ to accomodate statistical fluctuations of excess count rate

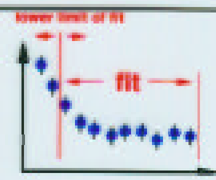


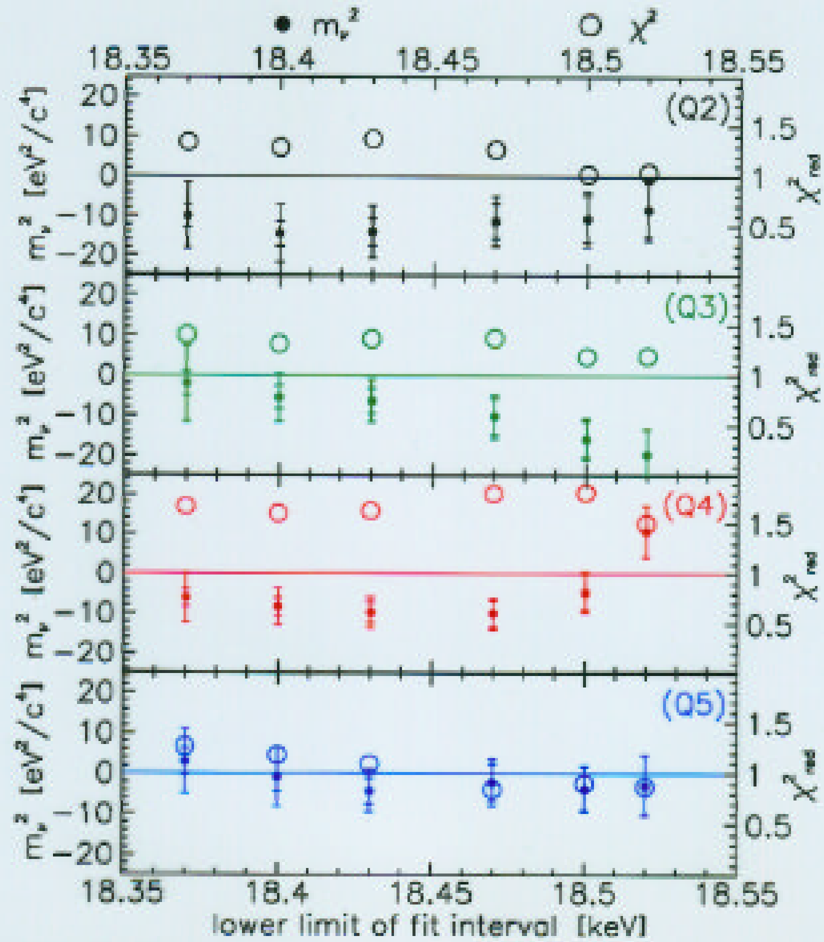


However:
systematic distortion of spectrum, e.g. by under-estimated fraction of inelastic processes produce significant but unphysical negative m_ν^2-values



m_{ν}^2(fit) versus fit interval





Mainz upper limits on neutrino mass 2

2.) If one believes in step as correct solution:

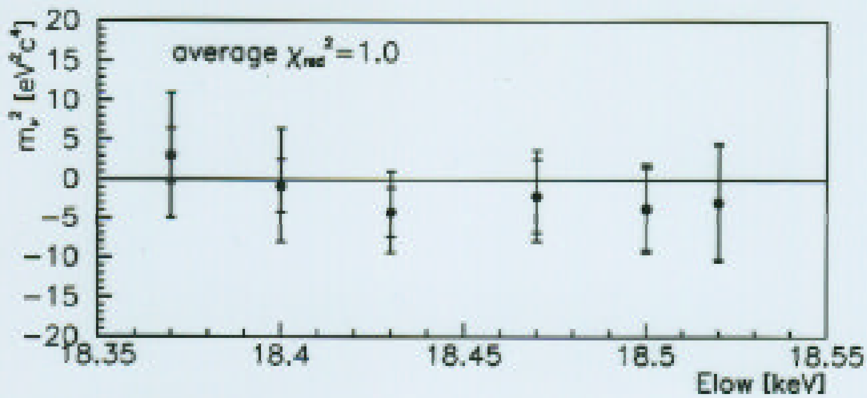
→ fit step and subtract it (only possible for Q4):

last 70 eV (Q4, 1998 run II):

$$m_\nu^2 c^4 = -1.8 \pm 5.1 \pm 2.0 \mathrm{eV}^2$$

$\rightarrow m_\nu c^2 \leq 3.0$ eV (95%C.L., unified approach)

3.) Considering Q5, 1998 run III alone:



→ Standardanalysis:

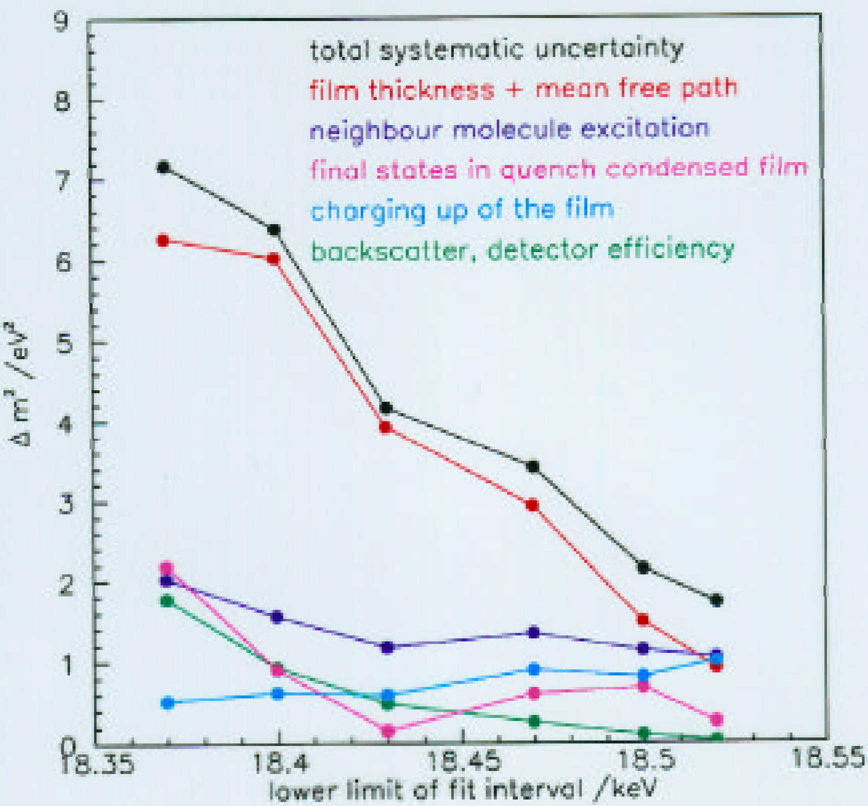
last 70 eV (Q5, 1998 run III):

$$m_\nu^2 c^4 = -3.7 \pm 5.3 \pm 2.1 \mathrm{eV}^2$$

$\rightarrow m_\nu c^2 \leq 2.8$ eV (95%C.L., unified approach)

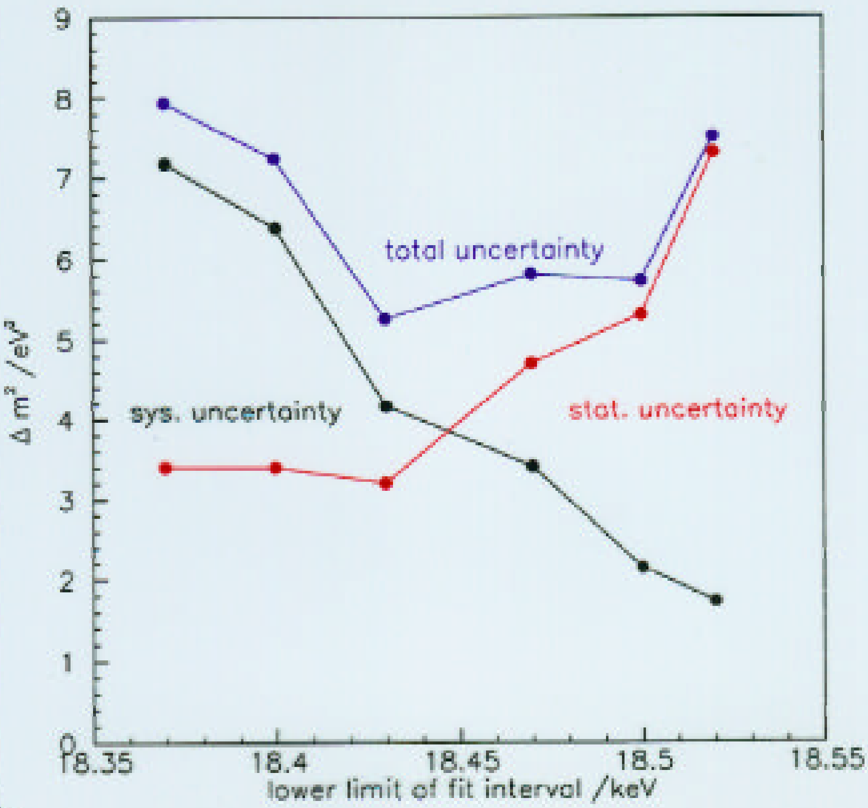
Systematic uncertainties

1998 run III: Q5



Statistical and systematic uncertainties

1998 run III: Q5

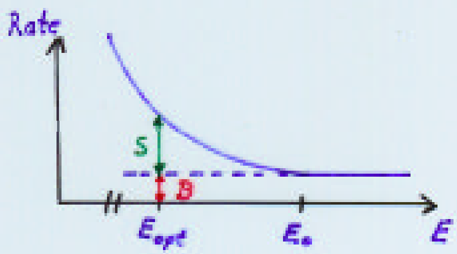


Statistical Error δm_ν^2

given: S = Signal rate
B = Background rate

$$\delta m_\nu^2(E) = \frac{2}{3c^4}(E_0 - E)^2 \frac{\sqrt{(S+B)/t}}{S}$$

Optimal point in the spectrum



$S(E_{opt}) = 2B$

There the dependence on

- source strength R
- background rate B
- measuring time t

is given as

$$\delta m_\nu^2 \propto R^{-\frac{2}{3}} \cdot B^{\frac{1}{6}} \cdot t^{-\frac{1}{2}}$$

Correlation of errors

- of $(\text{mass})^2$: δm_ν^2 and
- Endpoint E_0: δE_0

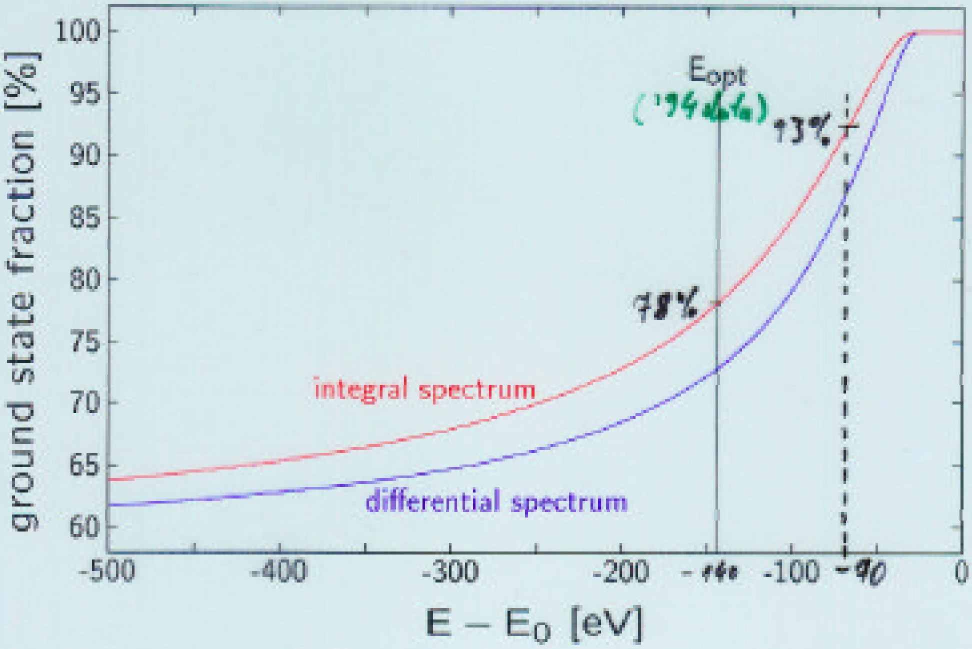
as function of point of measurement E

$$\delta m_\nu^2(E) = \frac{2}{c^4}(E_0 - E)\delta E_0$$

Example (1): Introduce an external value of E_0 from some other measurement into the fit which is too large , then the fit finds: $m_\nu^2 > 0$ (Ljubimov effect)

Example (2): E_0 is determined from fitting the experimental spectrum, but found too low , because the fraction of inelastic events has been underestimated than the fit yields: $m^2 < 0$ (Mainz effect and others)

Fraction of Ground State Transitions in T_2 β–Decay

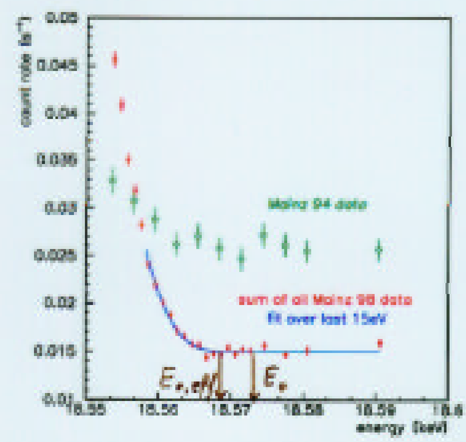


Mainz upper limits on neutrino mass 1

1.) Decorrelate m_ν^2 from systematics:

Sum of all 1998 data (Q3+Q4+Q5) (taken under same conditions)

- Take last 15 eV of β spectrum
  - $\rightarrow$ free of systematics (atomic phyiscs thresholds)
  - $\rightarrow$ no influence from "Troitsk-like" anomaly as observed in Q4
- Add two data points at 18470 eV and 18500 eV to decorrelate m_ν^2 from endpoint E_0 and amplitude
  - $\rightarrow$ minor influence of systematics
  - $\rightarrow$ minor influence from "Troitsk-like" anomalies



$$m_\nu^2 c^4 = -0.1 \pm 3.8 \pm 1.8 \text{eV}^2 \qquad (\chi^2/d.o.f. \approx 1)$$

$\rightarrow m_\nu c^2 \leq 2.9$ eV (95%C.L., unified approach)

Summary

- Present MAC-E-filters have reached mass limit m_ν well below 3eV
- Old puzzle of "negative" m_ν^2 has been solved: tricky excess of energy losses!
- Residual anomalies show up on a much finer scale, so close to the end point that they can hardly be caused by misinterpreting energy losses. They seem to vary in time
- Mainz is shortcircuiting this difficulty by choosing for the evaluation
  either "clean runs"
  or a data interval ≤ 15eV below E_0
- Present instruments in Troitzk and Mainz will eventually reach the mass limit of 2eV will probably be able to decide whether residual anomaly is a physics or an instrumental effect
- We need stronger instruments to break the astrophysically relevant 1eV limit and to resolve residual anomalies in the spectrum or search for new ones