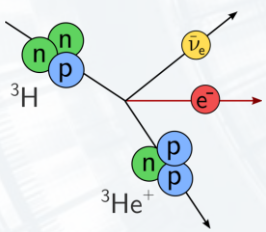
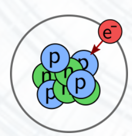
Direct Neutrino Mass Measurements

Using Weak Decays

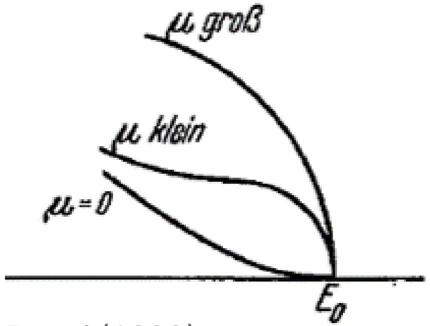




marco.kleesiek@kit.edu (Institute of Nuclear Physics)
PhyStat-ν 2016 in Kashiwa, Japan – May 30th

Outline

1. Motivation
2. Direct ν-mass measurement principle (β-decay)
3. History of direct ν-mass results
4. Introduction to the KATRIN experiment

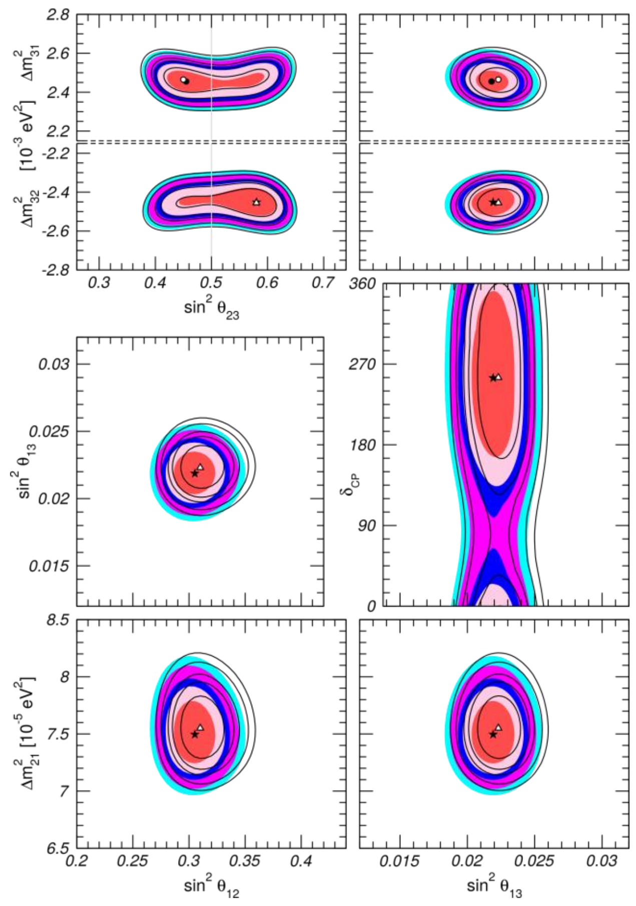


Fermi (1933)

Motivation

- Oscillation experiments have unambiguously established $m_\nu > 0$ eV
  - Nobel prize in 2015
- Non-zero neutrino masses are not easily explainable within the SM
  - Hint towards lepton number violation, new source of CP violation, sterile (right-handed) neutrinos, new energy scale, …
- m_ν of major interest for astrophysics and cosmology

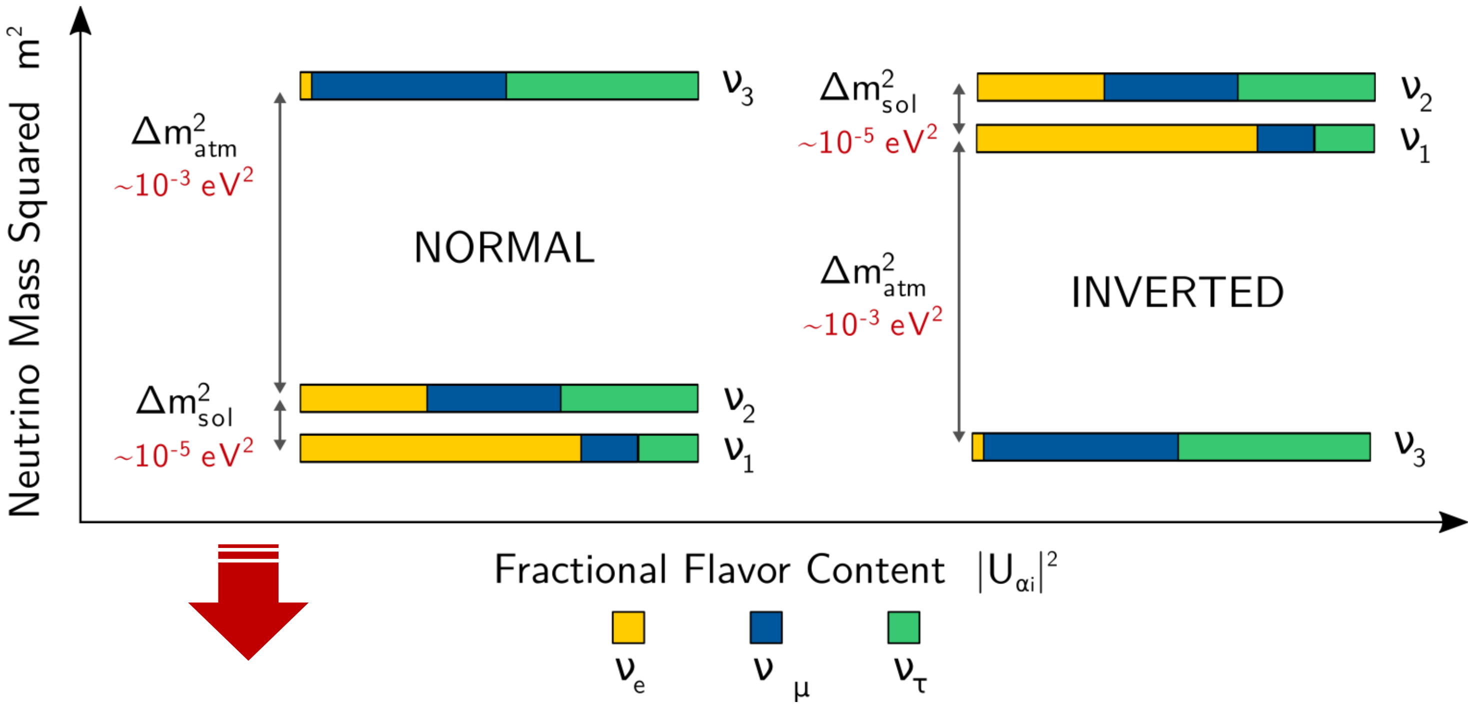
several talks on ν oscillation this workshop



Gonzalez-Garcia, Maltoni, Schwetz (2014)

Neutrino mass spectrum

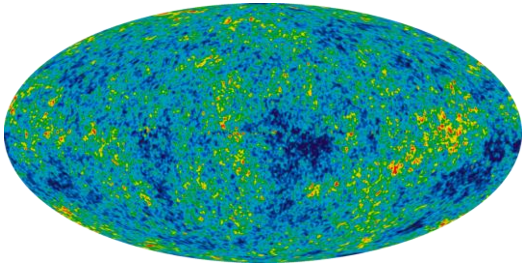
- Flavor states ≠ propagation (mass) states
- Oscillation results: tiny mass splittings + large mixing



Absolute ν mass scale?

Ways to the absolute neutrino mass scale

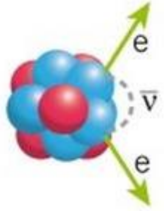
- Cosmology
  - CMB, LSS, BAO
  - model-dependent
  - $\sum_i m_i \lesssim 0.12 - 1.0\ \mathrm{eV}$

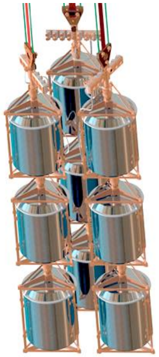


Francisco VILLAESCUSA-NAVARRO (Tuesday)

- Neutrinoless double beta decay (0νββ)
  - model-dependent (Majorana CP phases)
  - $m_{\beta\beta} = \left|\sum_i U_{ei}^2 m_i\right| < 0.2 - 0.4\ \mathrm{eV}$
  - GERDA, EXO/nEXO, SNO+, MAJORANA, CUORE, CANDLES, NEXT, KamLAND-Zen, …

Itaru SHIMIZU (Tuesday)

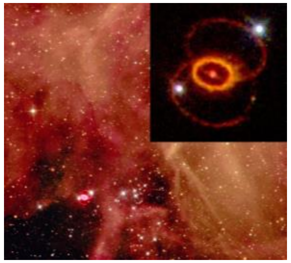




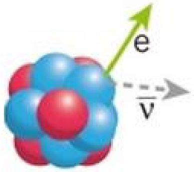
GERmanium Detector Array

Direct neutrino mass search

- SN1987a (time-of-flight analysis)
  - $m(\nu_e) < 5.7$ eV (95% C.L.)

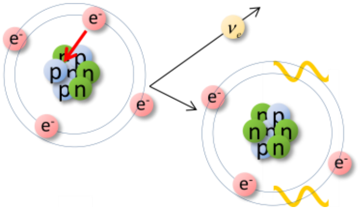


- Kinematics / spectroscopy of weak decays
  1. **β-decay of tritium (T_2)**
     - KATRIN, PROJECT 8
  2. electron capture of holmium (^{163}Ho)
     - ECHO, HOLMES

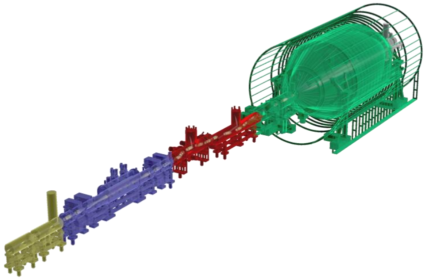


  - model-independent:

$$m^2(\nu_e) = \sum_i |U_{ei}^2| \, m_i^2$$



  - status: $m(\nu_e) < 2000$ meV (95% C.L.)
  - potential: $m(\nu_e) < 200$ meV (90% C.L.)

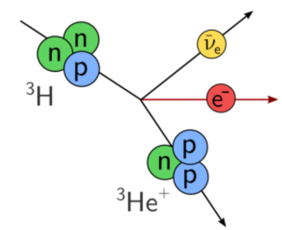


Measurement Principle

of tritium β-decay spectroscopy

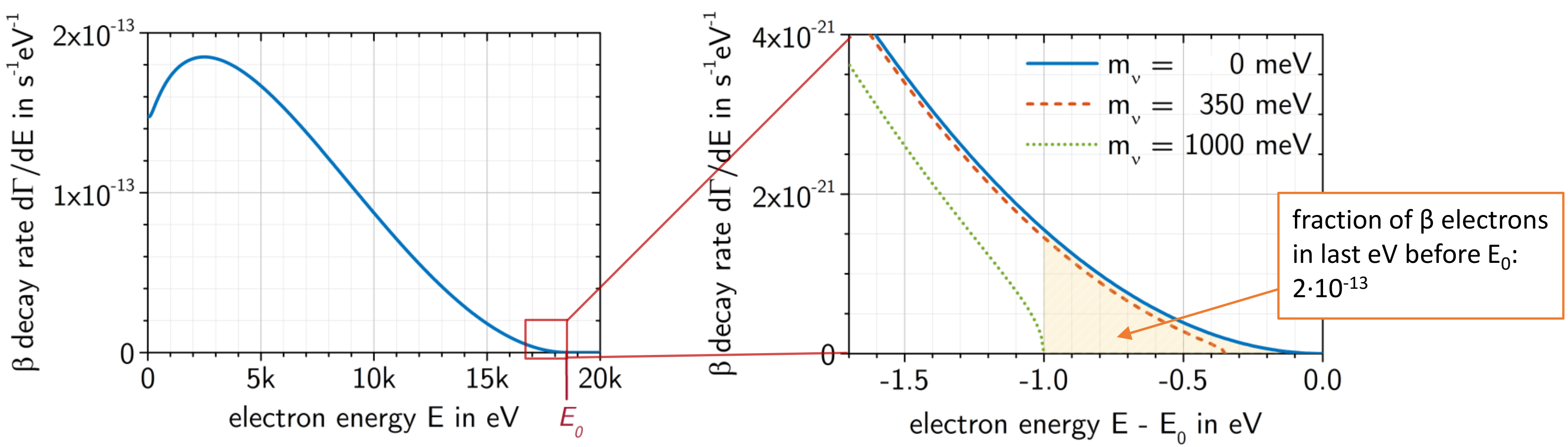
Shape of the β electron spectrum

- β-decay of tritium: ${}^{3}H \rightarrow {}^{3}He^{+} + \bar{\nu}_e + e^{-}$
- spectroscopy of the emitted electron kinetic energy



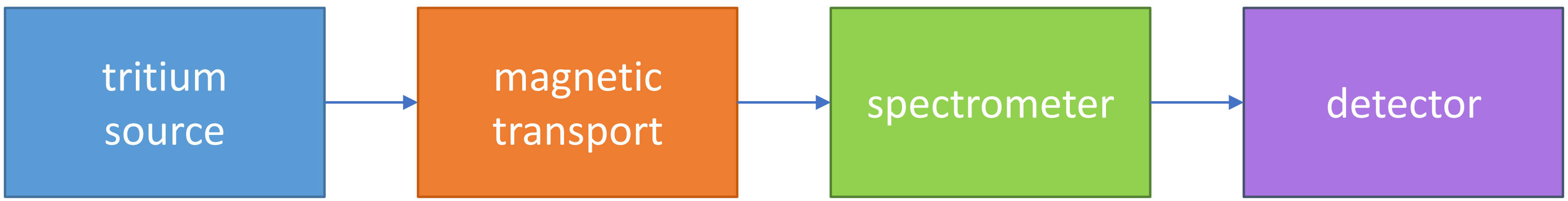
$$\frac{d\Gamma}{dE} \propto (E_0 - E) \cdot \sqrt{(E_0 - E)^2 - m_{\nu_e}^2} \cdot \theta(E_0 - E - m_{\nu_e}^2)$$

$$m^2(\nu_e) = \sum_i |U_{ei}|^2 m_i^2$$



Standard experimental tritium β-decay setup

- essentially since 1952 (only few exceptions)



β emitter (tritium source)

- **high luminosity**
- gaseous or solid
- good understanding of energy loss processes

electron collimation (magnetic transport)

- adiabatic / undisturbed transport of β electrons
- removal of residual T_2

energy filter (spectrometer)

- **high energy resolution**
- low background
- magnetic or (since 90s) electrostatic

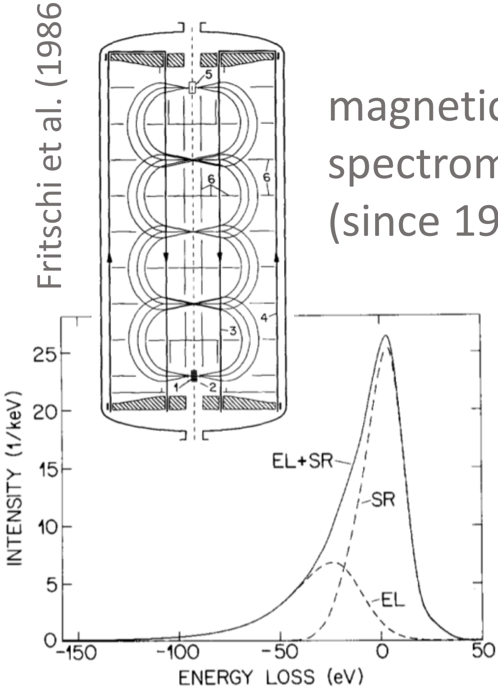
counter (detector)

- high efficiency
- low backscattering
- low background

Response of the experimental apparatus

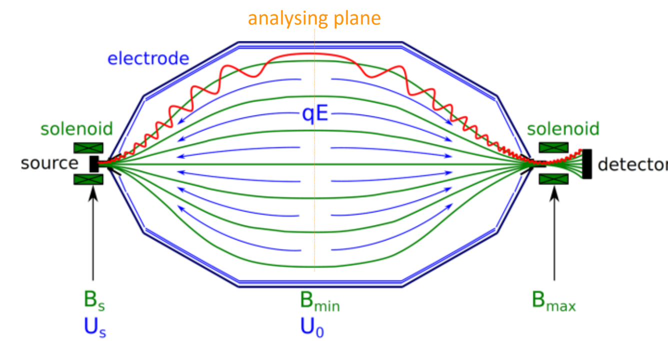
- Response function $R(E)$ describes the influence of the apparatus on the β-decay spectrum
  - Spectrometer energy resolution / transmission characteristics
  - Energy loss processes of β electrons

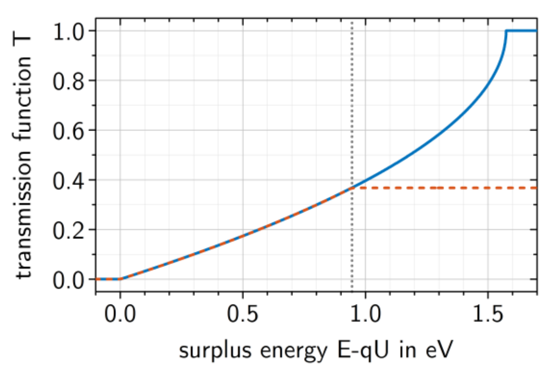
Fritschi et al. (1986)

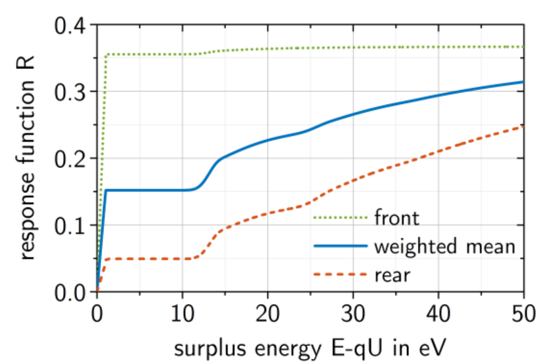


magnetic spectrometers (since 1952)

electrostatic spectrometers (since 1990)

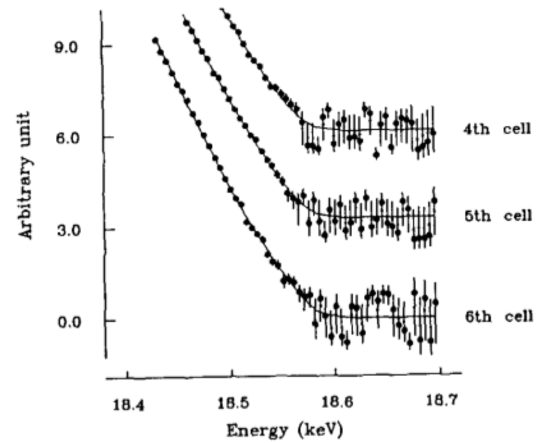






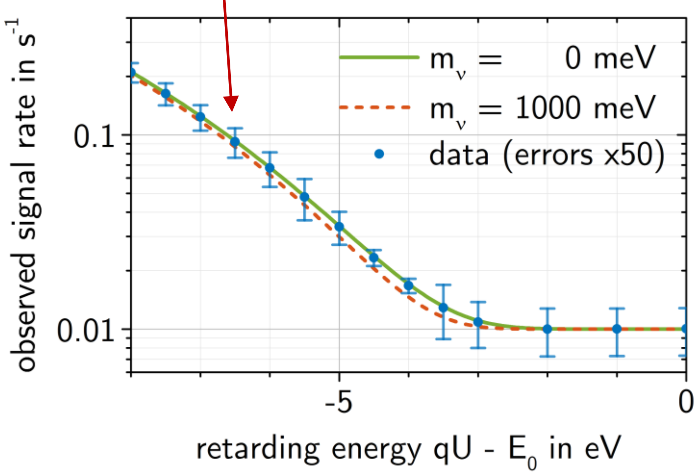
Observed signal

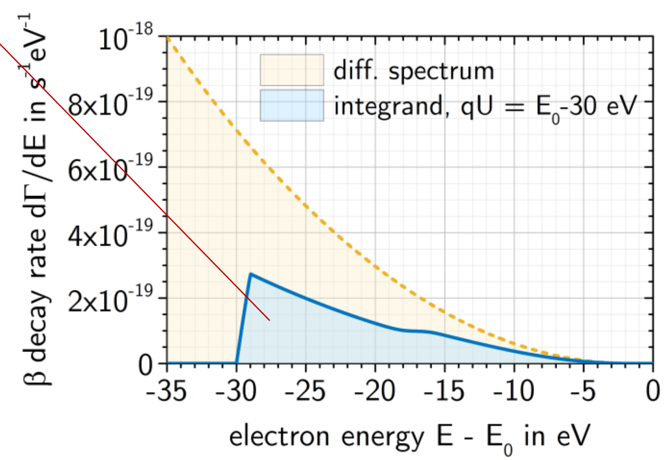
- For magnetic spectrometers (till early 90s)
  - $\dot{N}_{\mathrm{sig}}(E) \propto R(E) \otimes \frac{d\Gamma}{dE}\left(m_{\nu_e}^2, E_0\right)$



Kawakami et al. (1990), Tokyo

- For electrostatic spectrometers (Troitsk, Mainz, KATRIN)
  - $\dot{N}_{\mathrm{sig}}(U) \propto \int_{qU}^{\infty} R(U,E) \cdot \frac{d\Gamma}{dE}\left(m_{\nu_e}^2, E_0\right) dE$



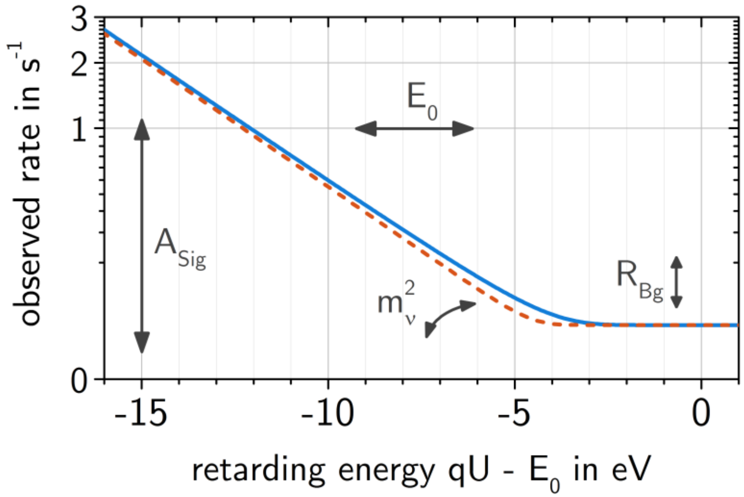


Standard 4 parameter model fit

- Number of observed events N_i at retarding step i with retarding voltage U_i (recent setups):

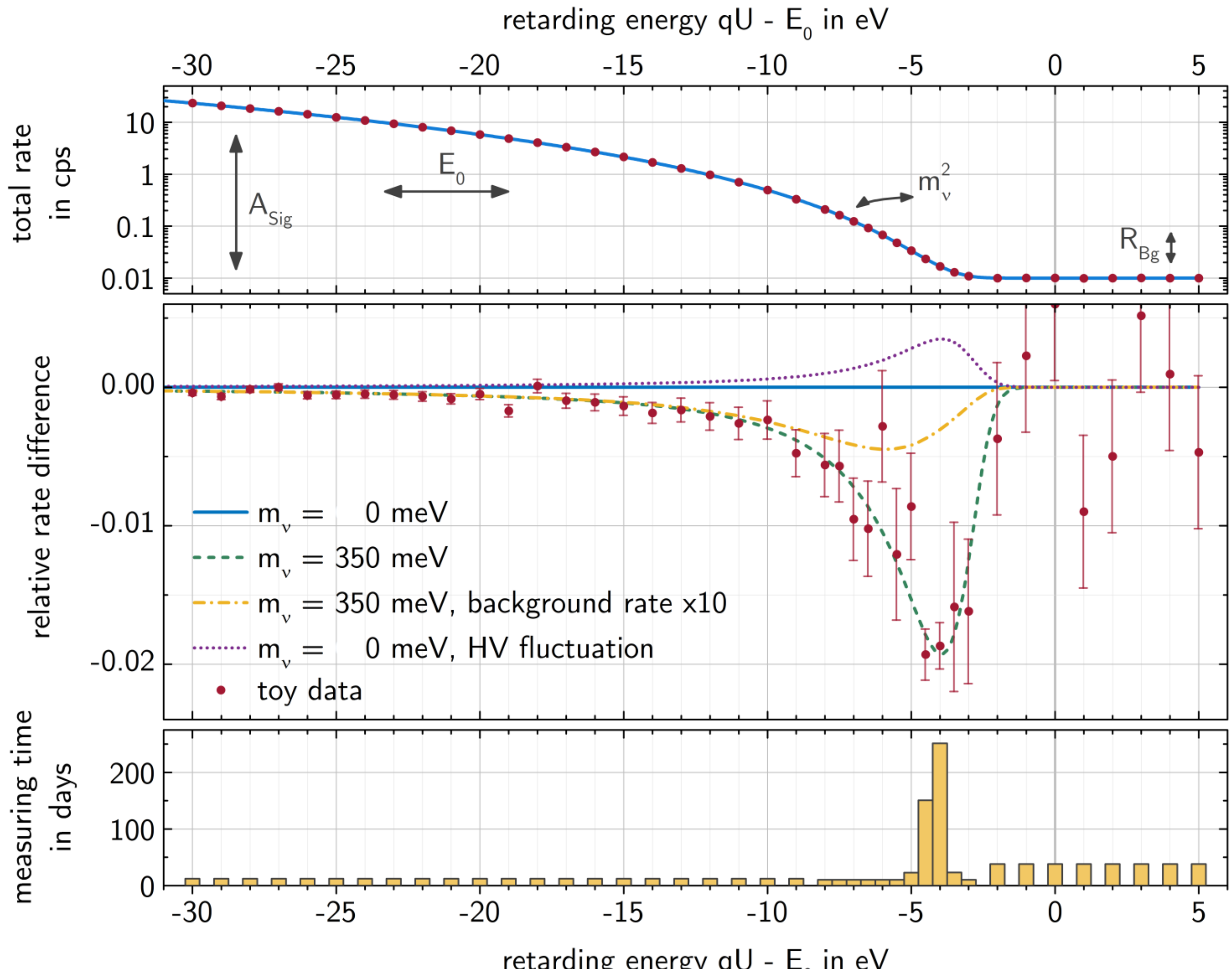
$$N_i \propto t_i \cdot \left[A_{\text{sig}} \cdot \int_{qU_i}^{\infty} R(U_i) \cdot \frac{d\Gamma}{dE}\left(m_{\nu_e}^2, E_0\right) dE + R_{\text{bg}} \right]$$

- Parameter of interest:
  - Squared neutrino mass $m_{\nu_e}^2$
- Nuisance parameters:
  - Tritium endpoint energy E_0
  - Signal amplitude A_{sig}
  - Mean background rate R_{bg}



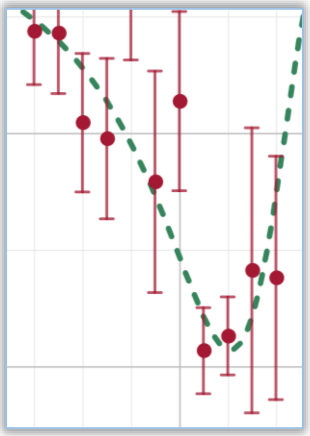
- $A_{\text{sig}}, E_0, R_{\text{bg}}$ are correlated with $m_{\nu_e}^2$ and apriori not known well enough

Hypothetical neutrino mass signal (KATRIN)



Data analysis – probabilistic model

- Having several data points $N_{\mathrm{obs},i}$
  - number of counted / observed electrons
  - random variable with Poissonian distribution (radioactive decays)
  - with statistical error $\sigma = \sqrt{N_{mod,i}}$
  - no binning required



- and a model prediction for the mean value $N_{\mathrm{mod},i}(m_\nu^2, A_{\mathrm{sig}}, E_0, R_{\mathrm{bg}})$

- formulate likelihood

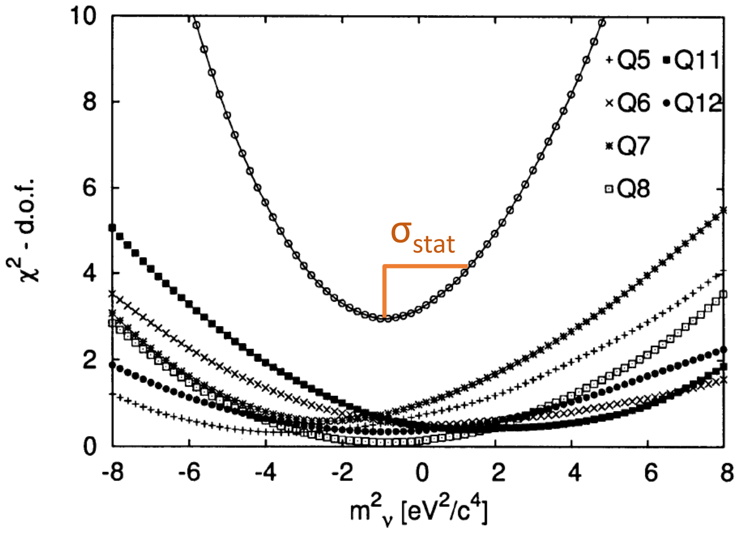
$$L = \prod_i p\left(N_{\mathrm{obs},i} \middle| N_{\mathrm{mod},i}\right)$$

- and χ^2 statistic for $p \approx$ Gaussian distr. with $\sigma = \sqrt{N}$

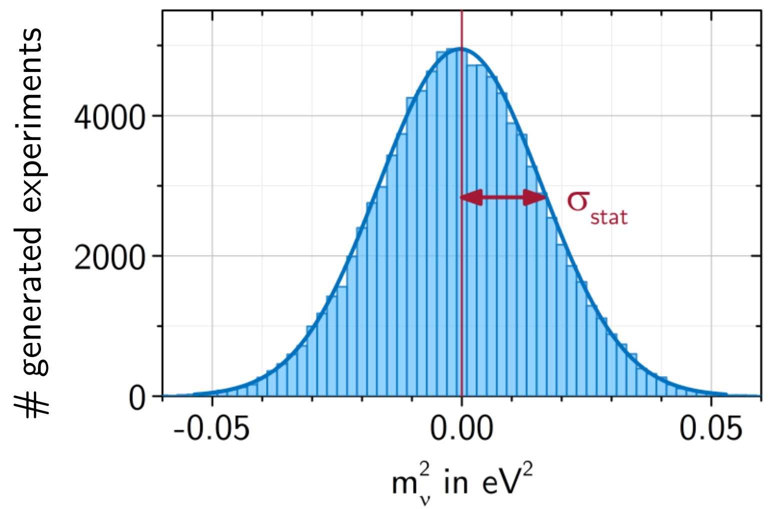
$$-2 \log L = \chi^2 = \sum_i \left(\frac{N_{\mathrm{obs},i} - N_{\mathrm{mod},i}}{\sigma}\right)^2$$

Data analysis – parameter inference

- Method of least squares (most common):
  - χ^2 minimization → $\hat{m}_\nu^2$ best-fit estimate
  - determine statistical error $\sigma_{\text{stat}}(m_\nu^2)$ from profile likelihood / $\Delta\chi^2$ shape ($\Delta\chi^2$ = 1 rule, considering nuisance parameters)
  - or ensemble tests



Kraus et al. (2005) Mainz χ^2 curves



KATRIN ensemble tests for $m_\nu^2 = 0\ \text{eV}^2$

Data analysis – systematic errors

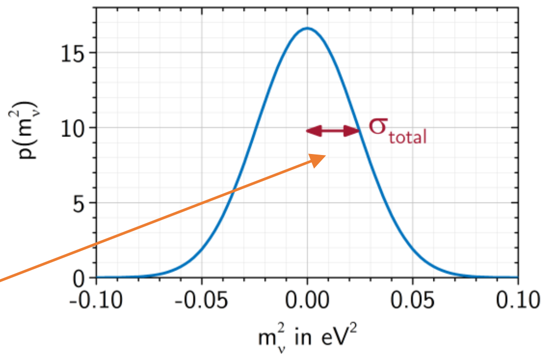
- Common practice for systematic errors:
  - Evaluate shift of the estimate $\Delta\widehat{m}_\nu^2$ for each systematic effect / variable + covariances using Monte Carlos
  - Add systematic errors in quadrature, incl. correlation terms:

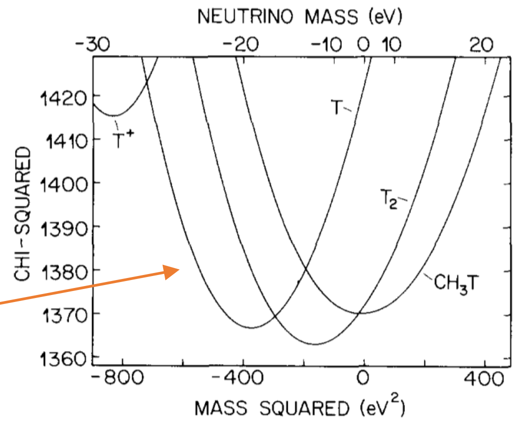
$$\sigma_{\text{syst}}(m_\nu^2) = \sqrt{\Delta_1^2 + \Delta_2^2 + \rho(\Delta_1\Delta_2) + \cdots}$$

  - Combine statistical and systematic error in quadrature:

$$\sigma(m_\nu^2) = \sqrt{\sigma_{\text{stat}}^2 + \sigma_{\text{syst}}^2}$$

- Publish distinct results if a systematic is 'not parameterizable'
  - E.g. different final state calculations

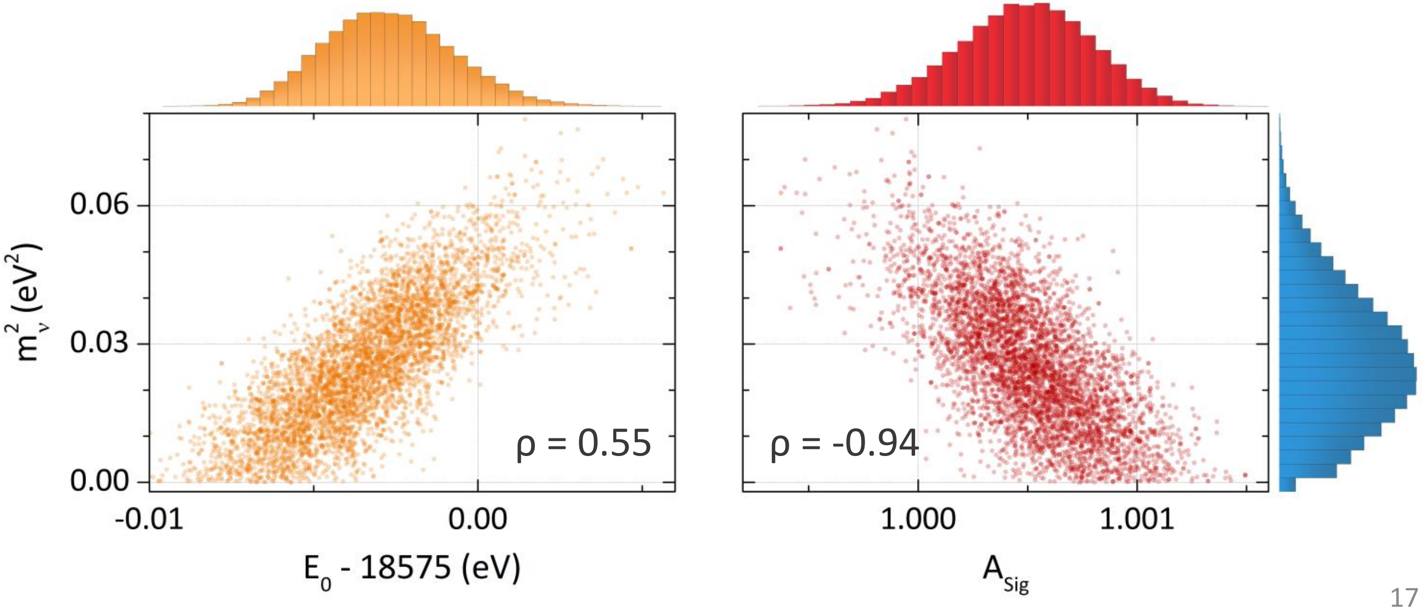




Fritschi et al. (1986) Zürich

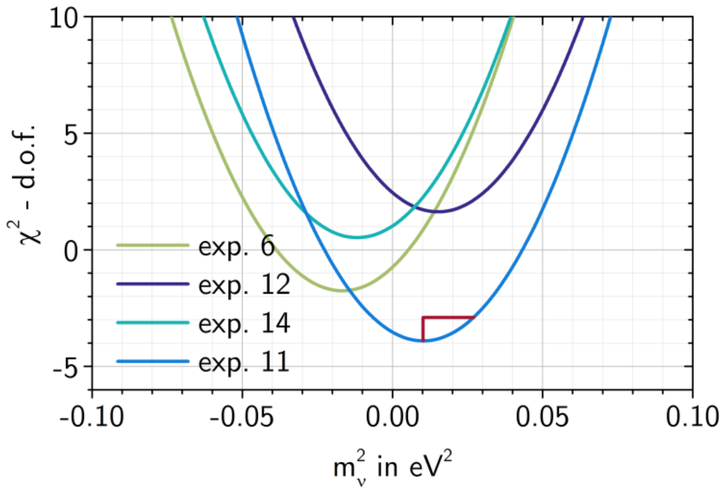
Data analysis – Bayesian approach

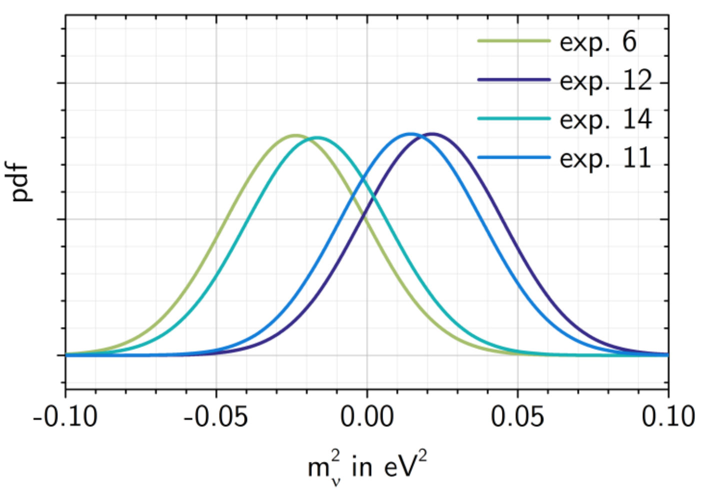
- rarely used in direct ν-mass analyses
- perform Markov Chain Monte Carlos to sample posterior probility density distributions from the likelihood based on Bayes‘ Theorem
- no distinction between nuisance and systematic parameters necessary
  - likelihood constraints for each systematic (e.g. Gaussian prior)
- priors must be agreed on (especially m_ν or m_ν^2 resp.)



Why measure the *squared* neutrino mass?

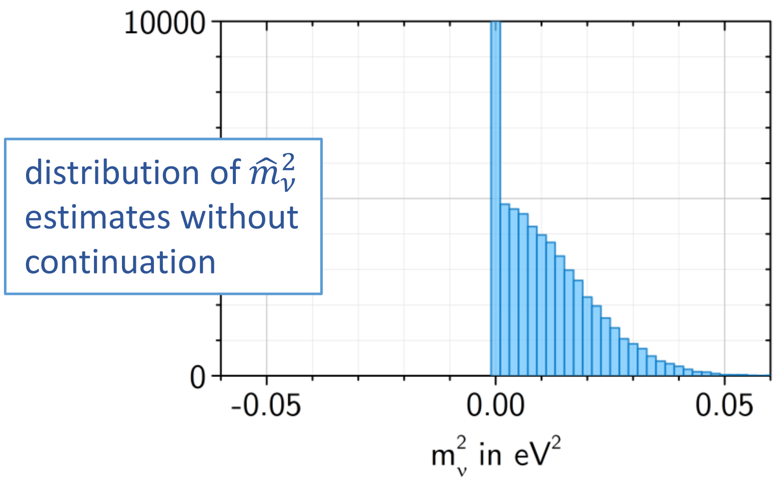
- $\frac{d\Gamma}{dE} \propto \sqrt{(E_0 - E)^2 - m_\nu^2}$, for $m_\nu^2 \ll E$: $\chi^2 \propto (m_\nu^2)^2$
- χ^2 is parabolic in m_ν^2
- m_ν^2 estimates are Gaussian distributed – very convenient error treatment
- Errors for m_ν strongly depend on absolute value of m_ν
  $\rightarrow$ for m_ν^2 they don't.

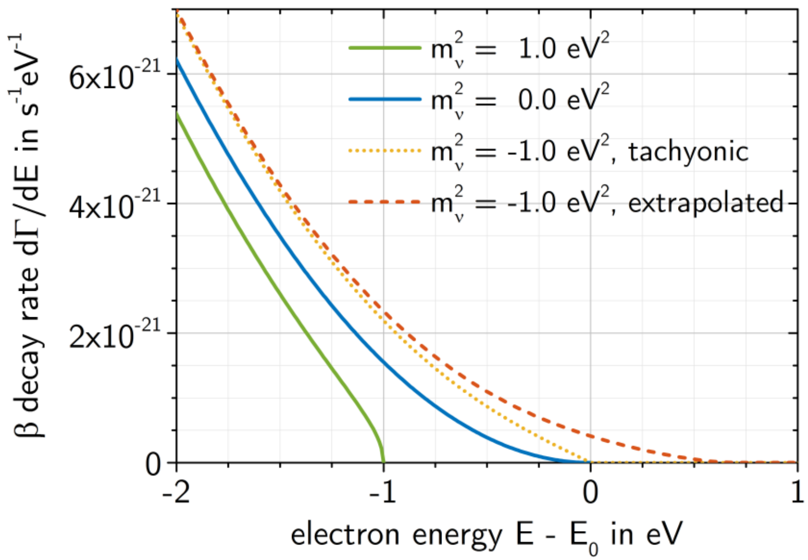


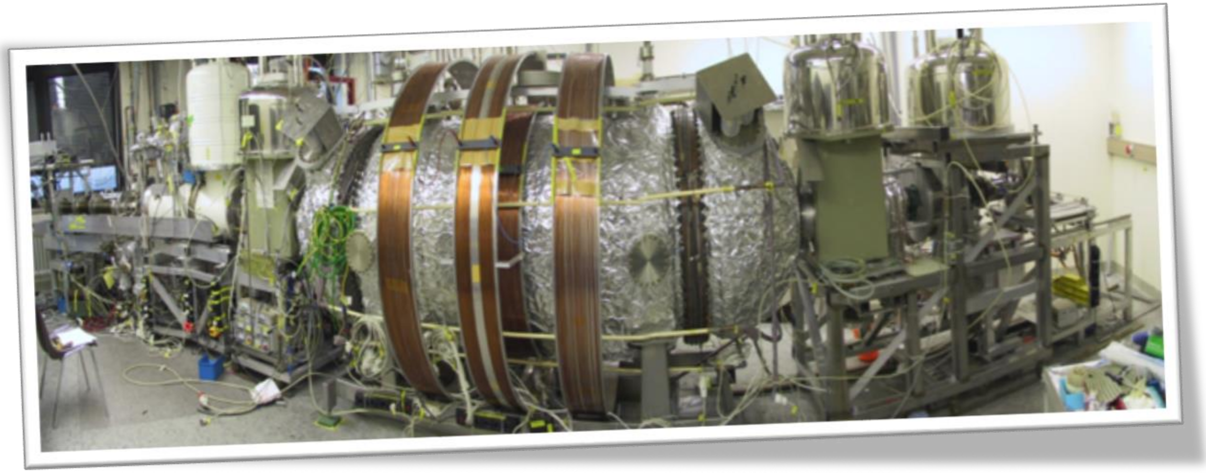


Continuation for non-physical $\hat{m}_\nu^2 < 0$

- Required to reflect statistical fluctuations of observed data
  - χ^2 statistic / goodness-of-fit
  - Frequentist confidence interval construction
- Demands arbitrary non-physical continuation of the model
  - Symmetrical continuous likelihood / χ^2 around minimum
- Not required in bayesian methods
  - Choose prior with $m_\nu^2 \geq 0$.







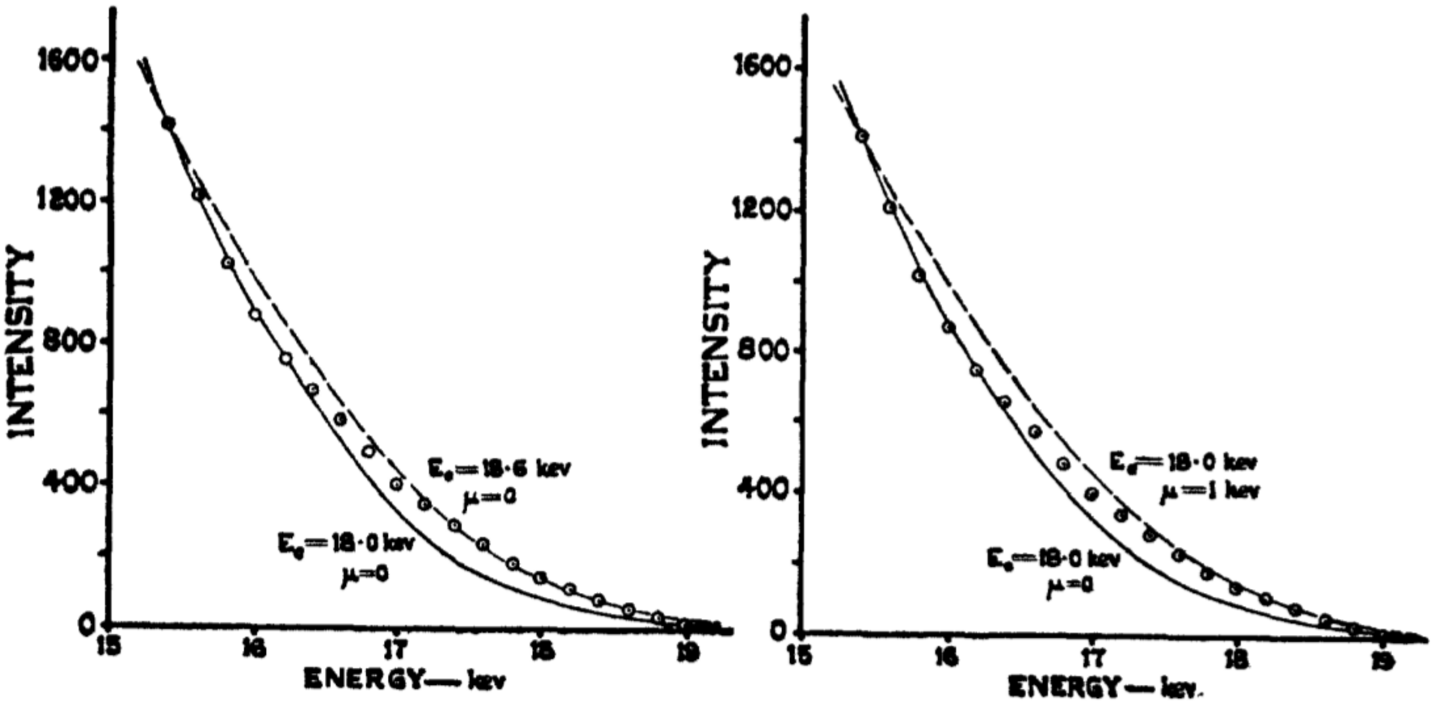
Mainz ν-mass experiment (MAC-E filter)

Results of Previous β-Decay Experiments

and the statistical method involved

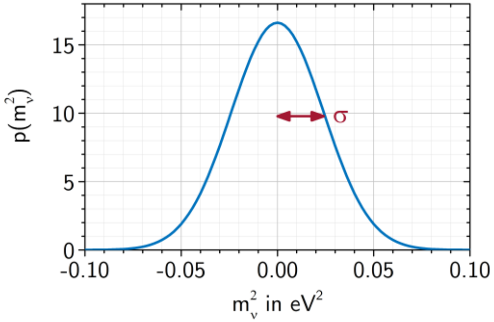
First tritium β-decay ν-mass limit

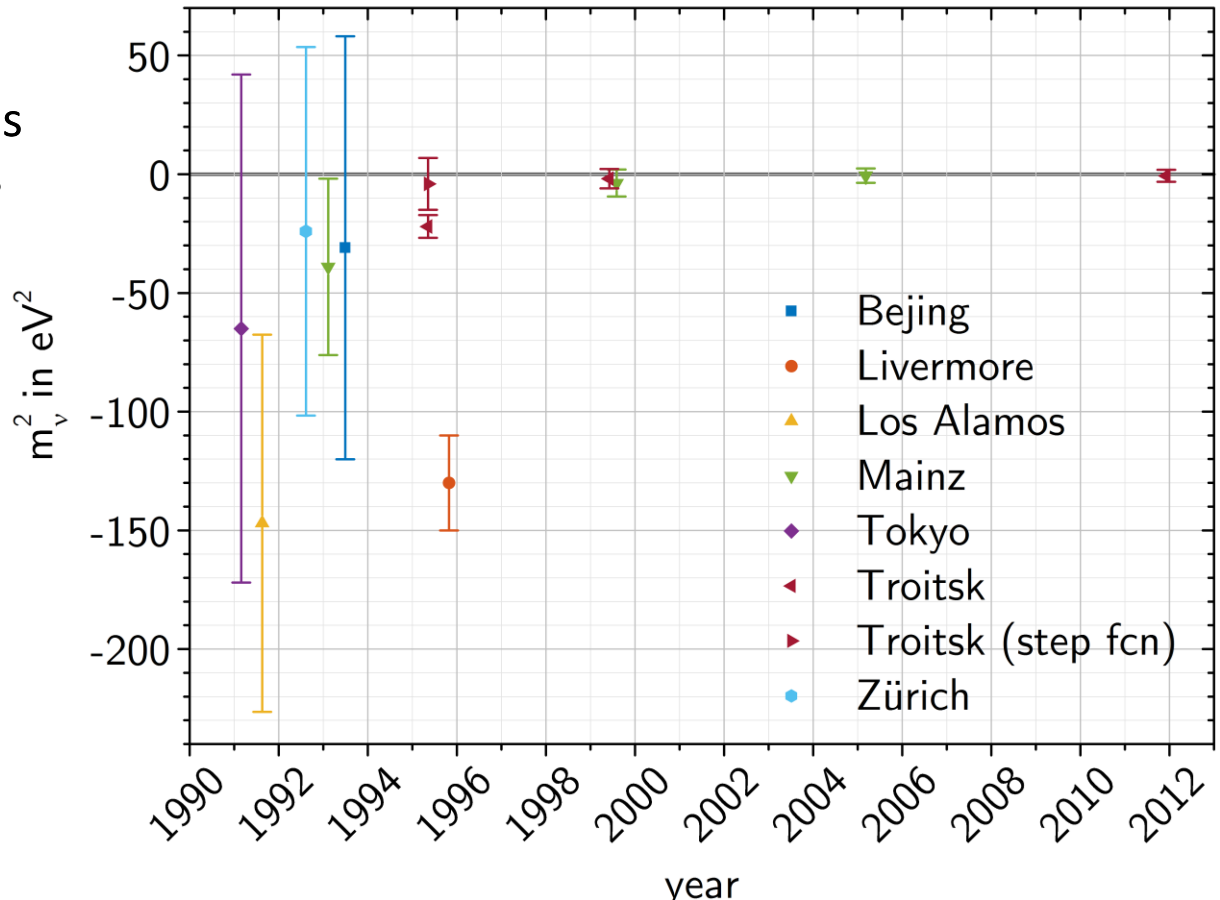
- Curran et al., Phys. Rev. 76 (1949)
- pulse height distribution measured with proportional counter
- $0\ \mathrm{keV} < m(\nu_e) < 1\ \mathrm{keV}$



Direct ν-mass measurements since 1990

- about a dozen direct ν-mass experiments since 1949
- early estimates clearly tend towards non-physical values

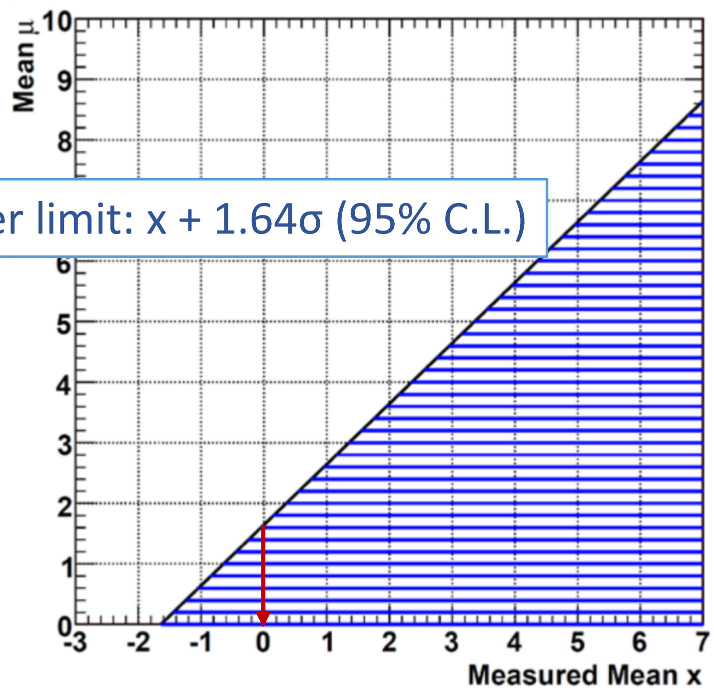




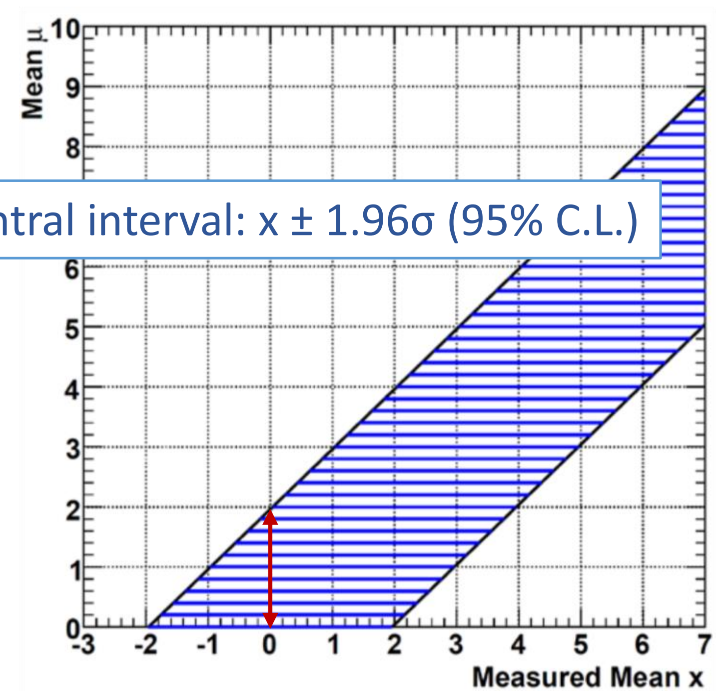
Interpretation of non-physical m_ν^2 estimates

A. k. a. the *neutrino problem* or *bounded Gaussian mean* problem:

- Many experiments with m_ν^2 best-fit in a non-physical region
- Resulting in small or empty classical confidence intervals



upper limit: x + 1.64σ (95% C.L.)

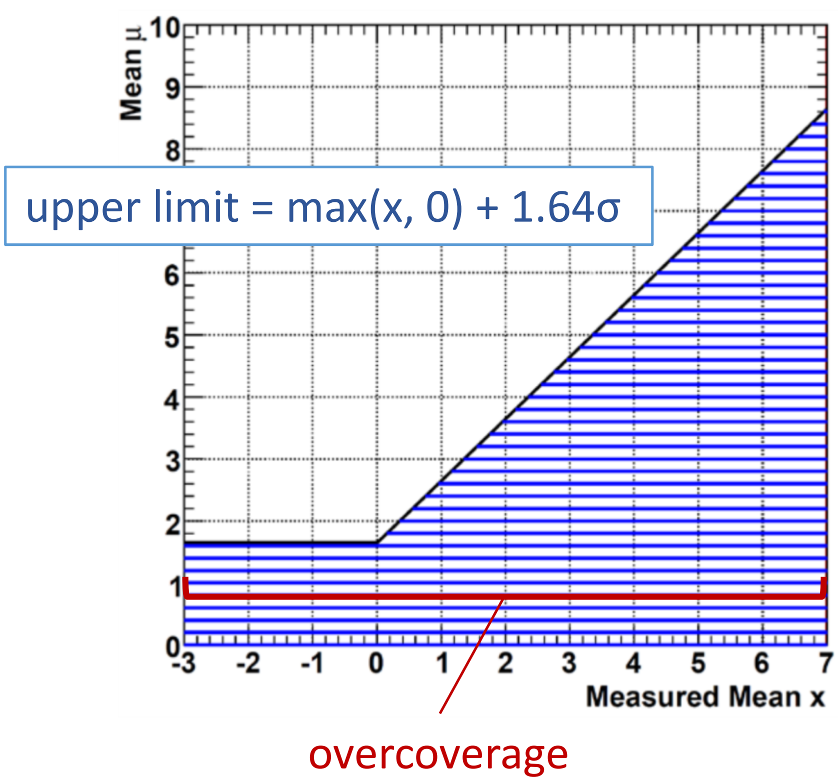


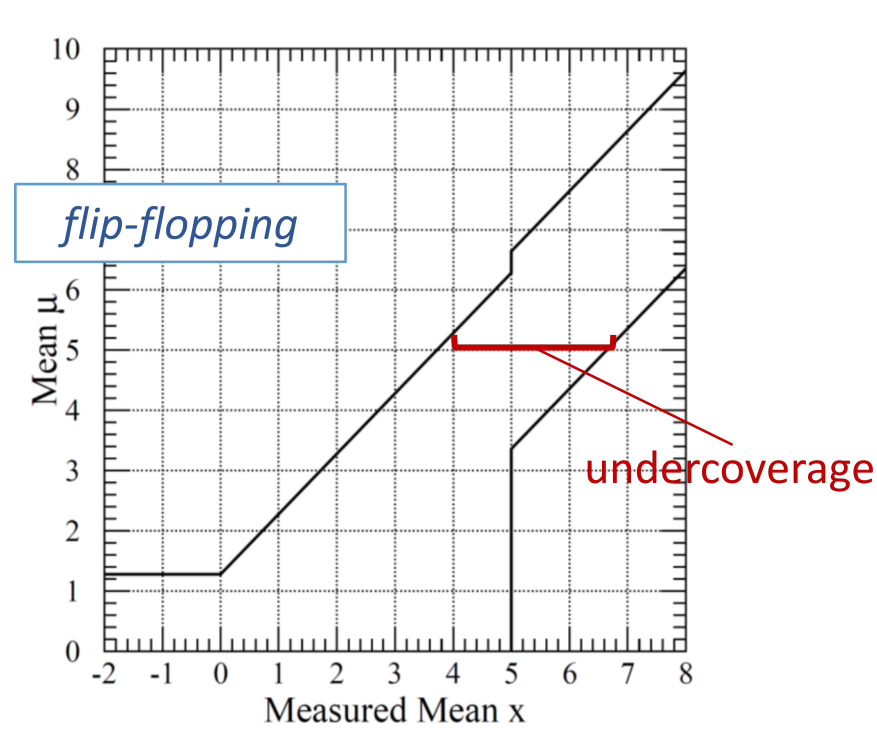
central interval: x ± 1.96σ (95% C.L.)

Bob Cousins, Virtual Talk (2012)

Interpretation of non-physical m_ν^2 estimates

- Some workarounds do not produce correct Frequentist coverage

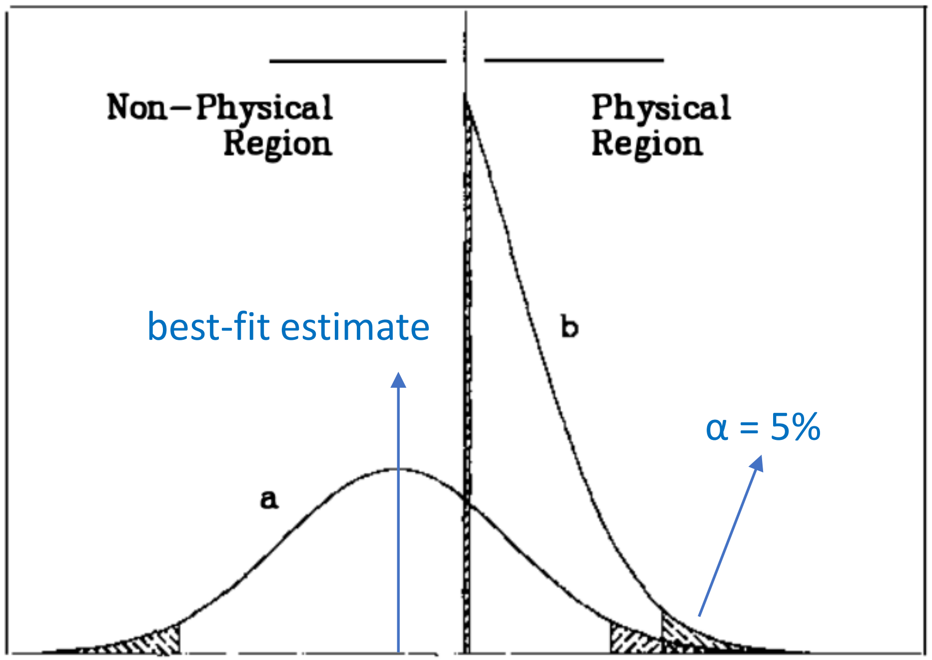




Bob Cousins, Virtual Talk (2012)

Interpretation of non-physical m_ν^2 estimates

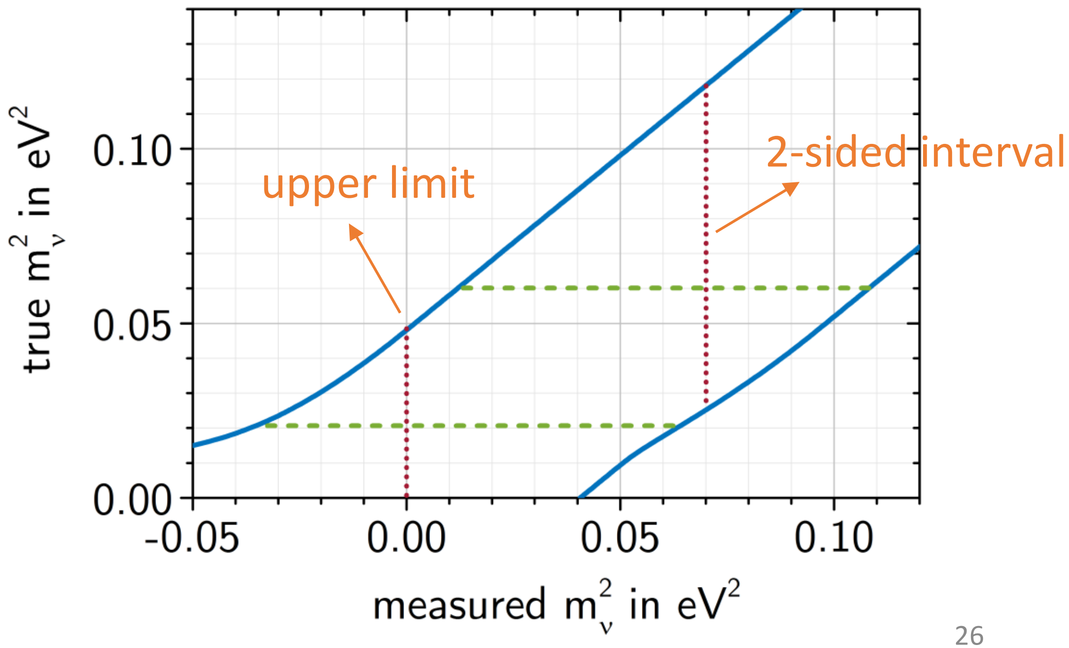
- In 1979 the particle data group (PDG) recommended a *Bayesian approach* with flat prior in $m_\nu^2 \geq 0$ (curve b):



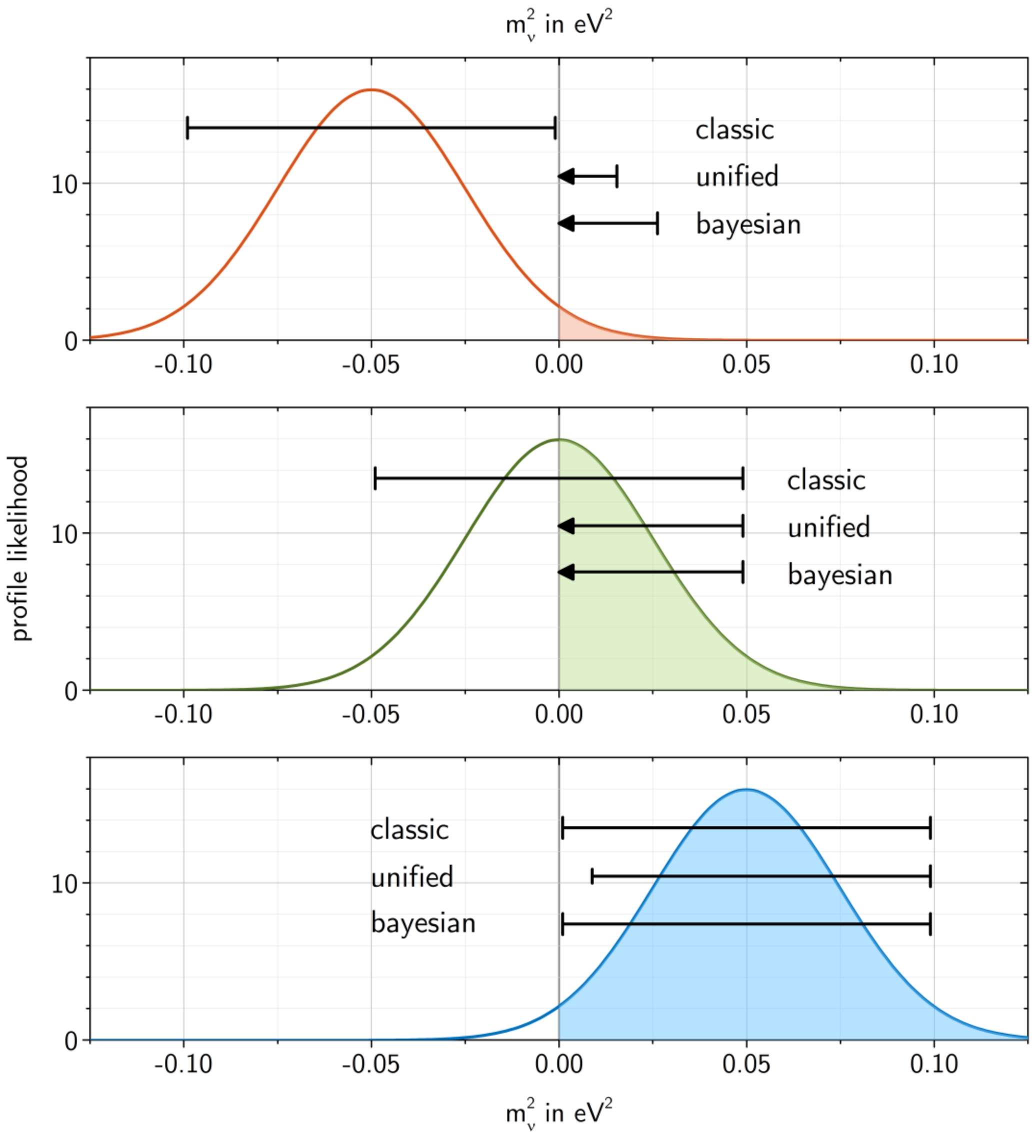
Robertson & Knapp (1988)

Interpretation of non-physical m_ν^2 estimates

- In 1997 Feldman & Cousins present their unified approach
  - Neyman confidence belt construction with ordering principle
  - Non-null Frequentist confidence intervals beyond physical boundaries
  - Correct global coverage
- Recommended by particle data group (PDG) since 1998



Comparison of confidence / credible intervals



95% C.L. intervals

μ = -2σ

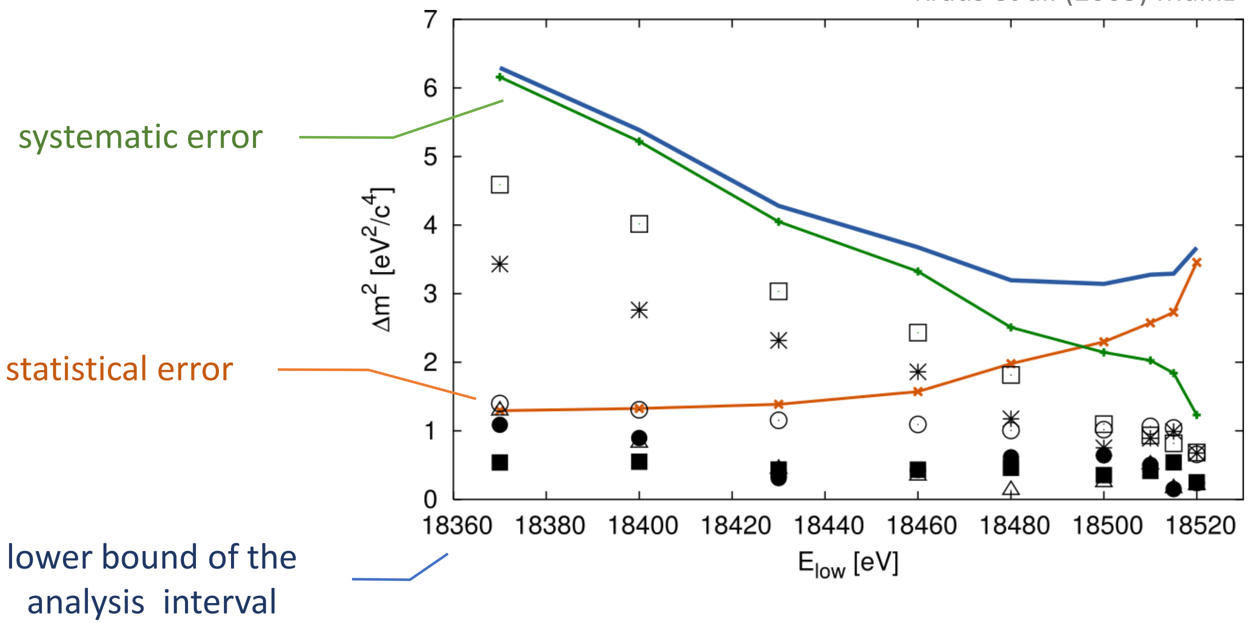
μ = 0

μ = +2σ

Critical systematic effects

- Underestimated / missed energy loss processes usually lead to smaller (or negative) m_ν^2
- Usually, these systematic errors increase for smaller energies (further away from E_0)

Kraus et al. (2005) Mainz



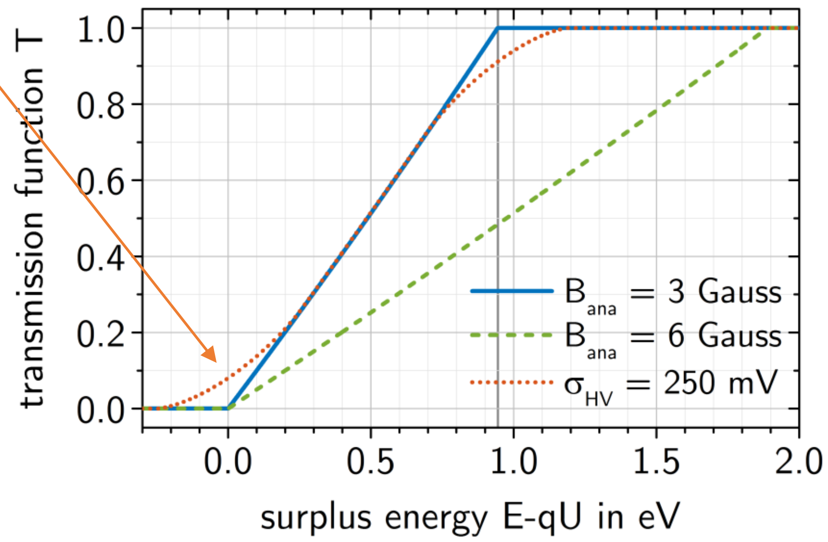
Critical systematic effects

- Any missed experimental broadening of the energy spectrum with Gaussian width σ leads to

$$\Delta m_\nu^2 \approx -2\sigma^2$$

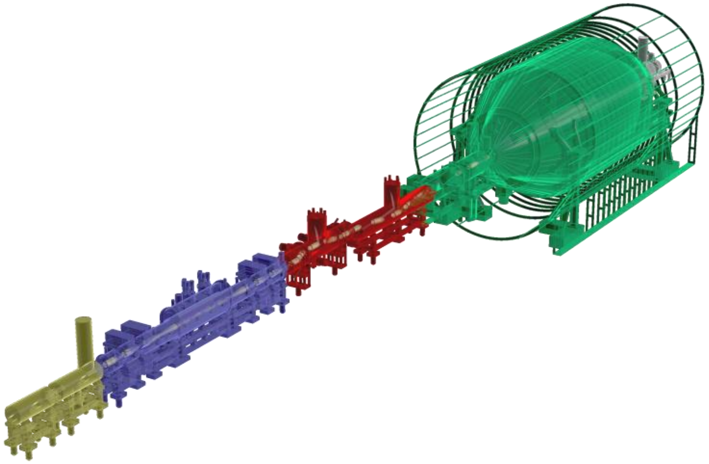
  - Thermal Doppler broadening (source)
  - High voltage fluctuations (spectrometer)

- Often without any effect on the χ^2 statistic (goodness-of-fit) of a measurement!



The **K**arlsruhe **TRI**tium **N**eutrino Experiment

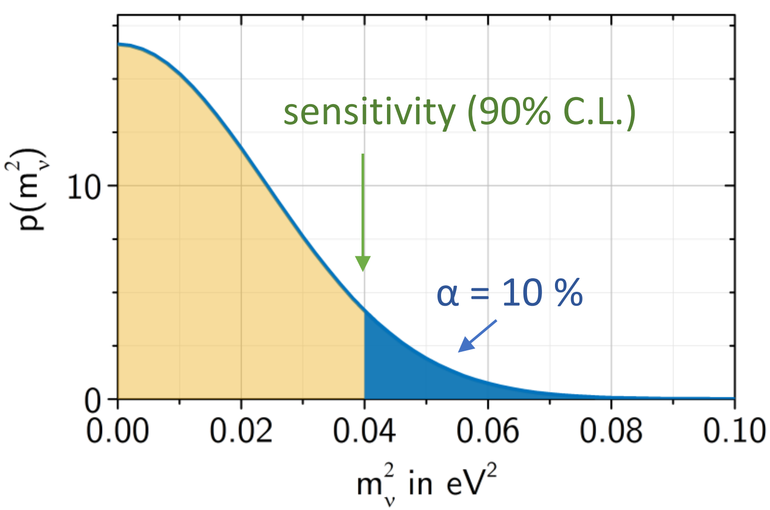
A ~~next~~ current generation effort of probing the ν mass scale



KATRIN‘s primary physics objective

- Improve sensitivity on $m(\nu_e)$ by one order of magnitude to 200 meV (90% C.L.)

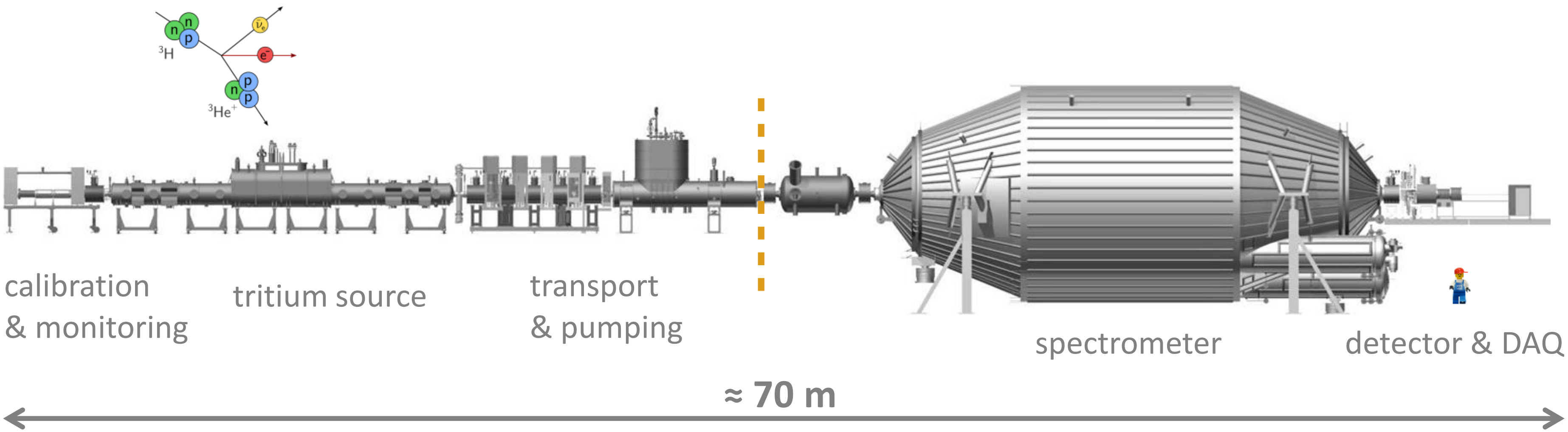
- Statistical and systematic errors on $m^2(\nu_e)$ must be improved by two orders of magnitude to $\sigma_{\text{stat}}(m_\nu^2) \approx \sigma_{\text{syst}}(m_\nu^2) \approx 0.017\ \text{eV}^2$



KATRIN setup

TLK Tritium Laboratory Karlsruhe

KIT Karlsruhe Institute of Technology



Source & transport section

- Windowless gaseous tritium source
- Intensity (10^{11} s^{-1})
- Stability (10^{-3} h^{-1})
- Isotopic purity (> 95%)
- Tritium retention factor (> 10^{14})
- Adiabatic transport of electrons

Spectrometer & detector section

- Spectrometer UHV ($p < 10^{-11}$ mbar)
- Energy resolution (<1 eV at 18.6 keV)
- High voltage stability (ppm/month)
- Low background rate (10 mcps)
- High detection efficiency (mcps to kcps)

Design aspects

^{3}H β-decay

- Short $T_{1/2}$ of 12.3 y
  → high-intensity source
- Low endpoint of 18.6 keV
  → good rel. signal strength
- Gas, closed loop
  → high isotopic purity
- Computation of final states, radiative & recoil corrections

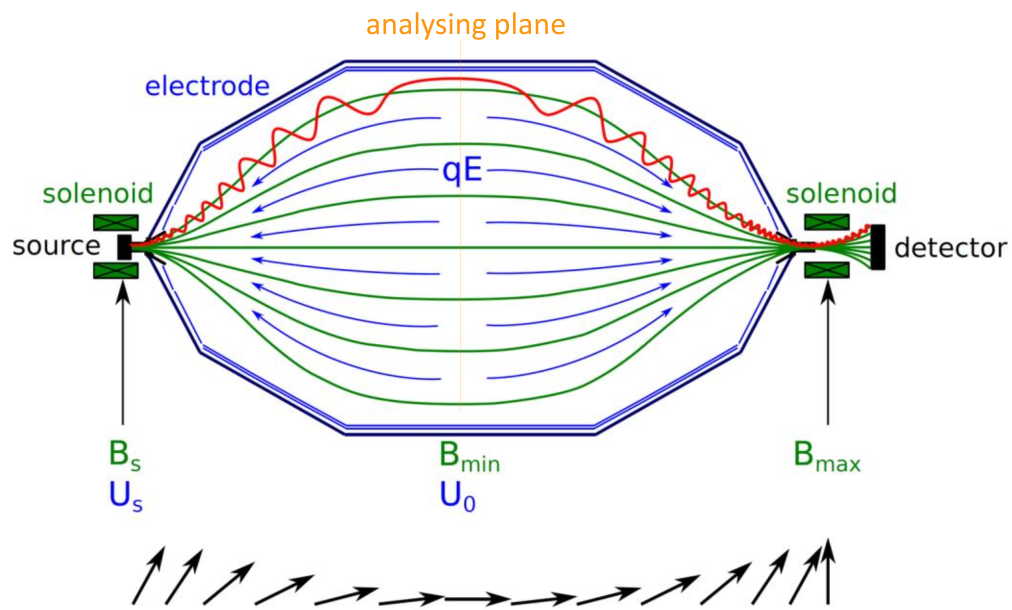
- Isotropic emission, strong B_s
- Energy filtering, weak B_{min}
- Resolution:

$$\frac{\Delta E}{E} = \frac{B_{\mathrm{min}}}{B_{\mathrm{max}}} = \frac{1}{20000}$$

(at KATRIN)

MAC-E filter technique

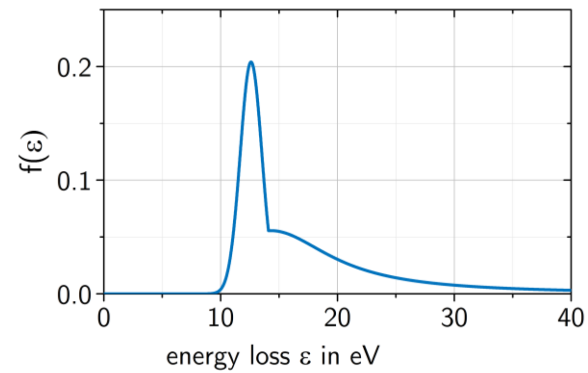
Magnetic Adiabatic Collimation with Electrostatic filter
Picard et al., NIM B63 (1992) 345

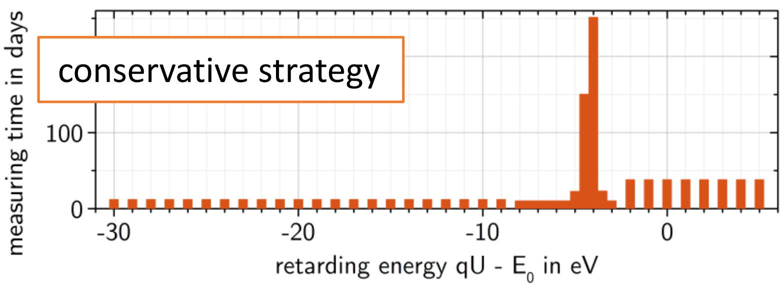


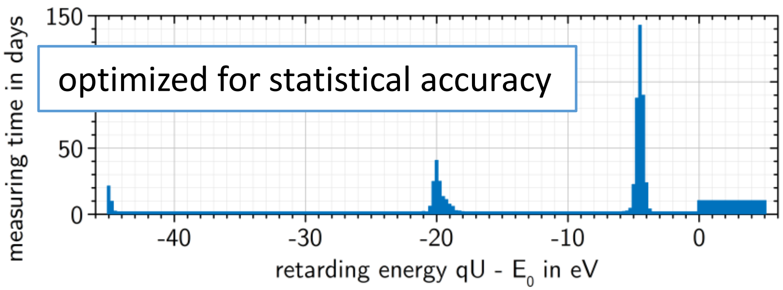
$$\mu = \frac{E_{\perp}}{B} = const.$$

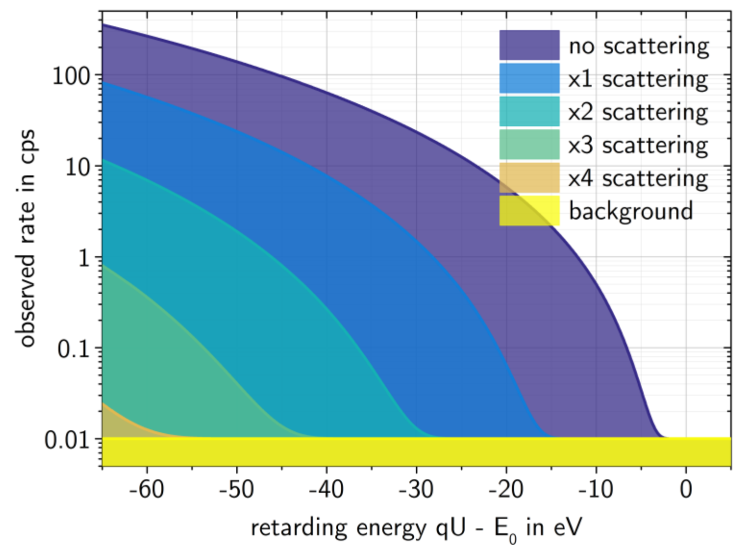
KATRIN measuring strategy

- Choice of measuring time distribution determines balance between statistical and systematic errors
- Absolute observed rates, thus statistical errors, are smaller at lower spectrum energies
- Systematic uncertainties (energy loss) are larger at lower spectrum energies

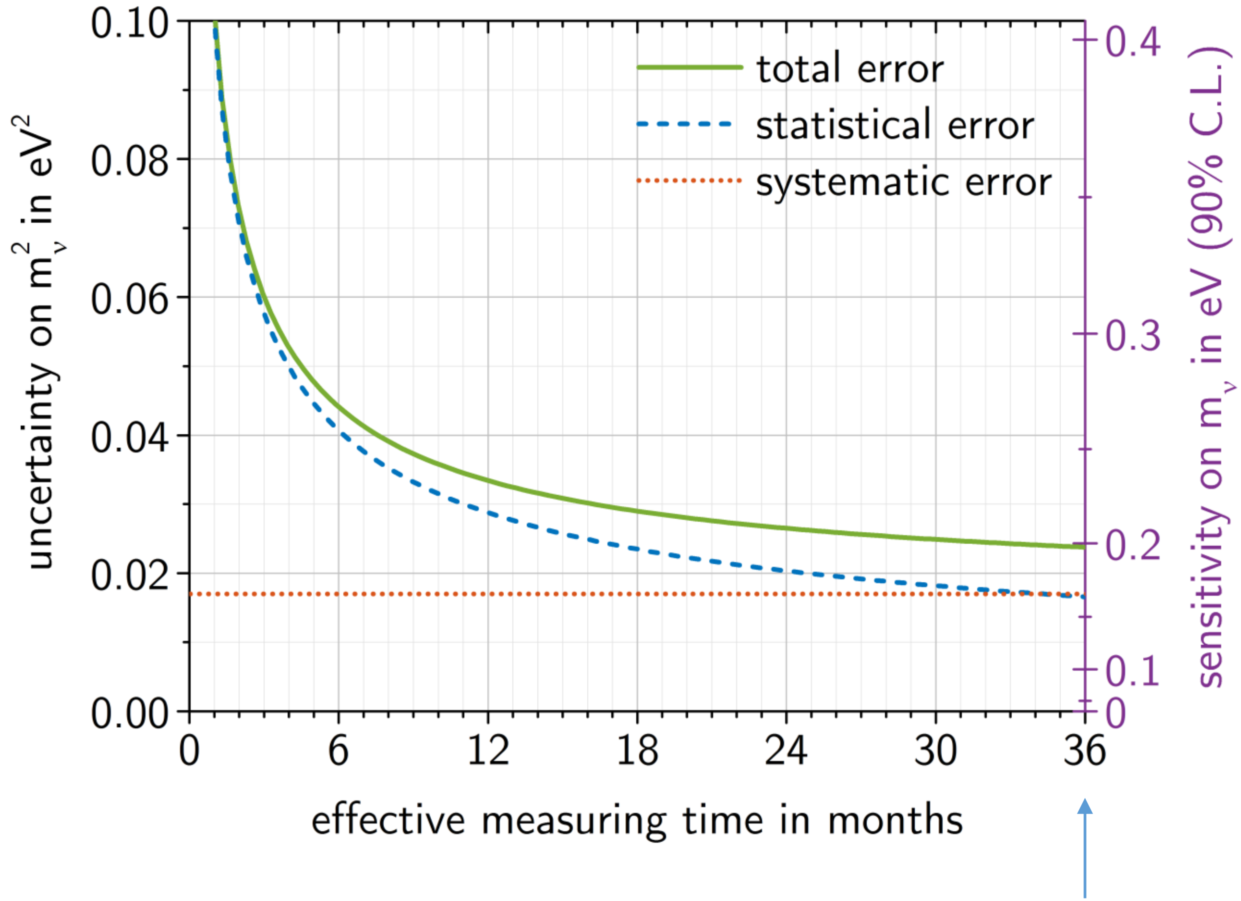








KATRIN sensitivity



corresponds to 5 calender years of data-taking

ν-mass … and more!

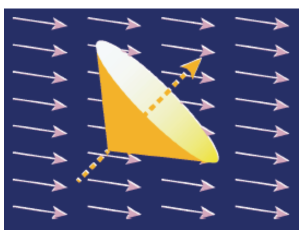
Explore physics potential

- close to the spectral endpoint E_0:

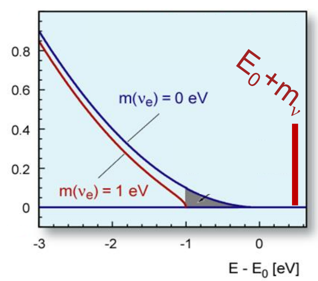
standard operation mode for KATRIN

RH currents
Bonn et al. (2011)

Violation of Lorentz symmetry
e.g. Diaz, Kostelecky & Lehnert (2013)

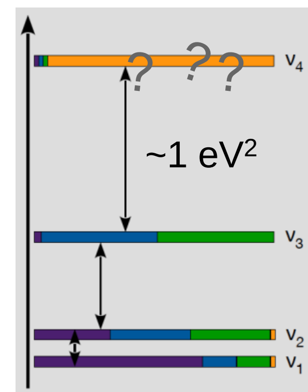


Constraining local
CνB overdensities
e.g. Kaboth & Formaggio (2010)



capture of relic ν on β-instable nuclei

Search for eV-scale sterile ν

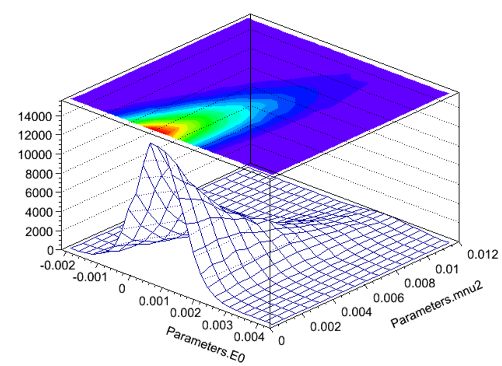


- and further away from E_0:
  Search for keV-mass scale sterile ν as WDM candidates
  S. Mertens et al. (2015)

non-standard operation, requires novel concepts

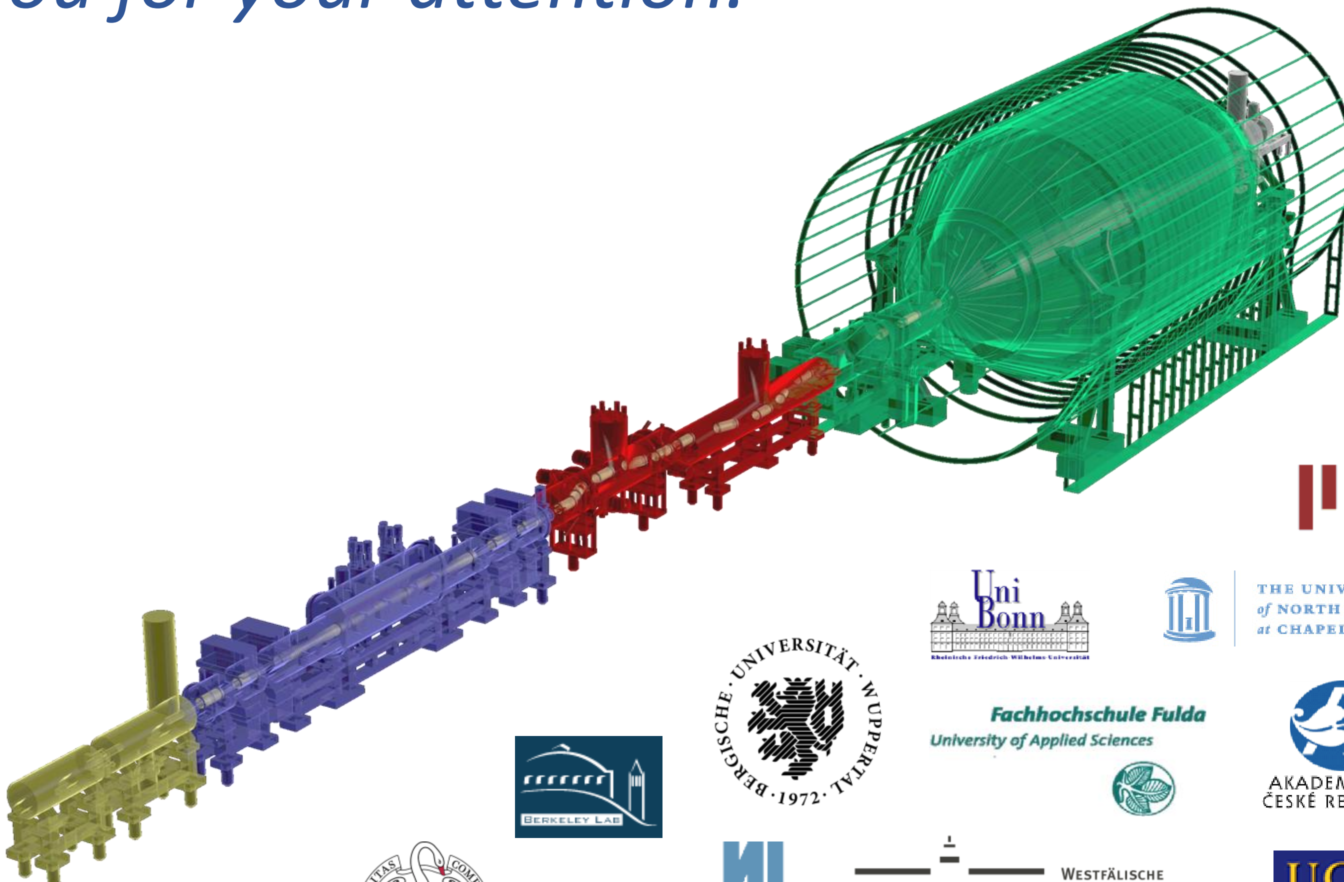
Status

- All hardware components are on site
  - Beam line integration and commissioning ongoing
- Analysis strategy and software in final dev. stage
  - Comprehensive probabilistic model
  - Gas dynamics simulations of the tritium source
  - Response function modelling incl. energy loss processes
  - 3D particle tracking suite
  - Blinding strategies evaluated
  - Frequentist (unified approach) & Bayesian (Markov Chain MCs) methods implemented



- First tritium runs in 2017

Thank you for your attention.



KATRIN
Karlsruhe Tritium Neutrino Experiment

KIT
Karlsruhe Institute of Technology

Universitas Complutensis Matritensis

universität mainz

Berkeley Lab

Bergische Universität Wuppertal · 1972

Uni Bonn

Fachhochschule Fulda
University of Applied Sciences

Westfälische Wilhelms-Universität Münster

The University of North Carolina at Chapel Hill

Akademie věd České republiky

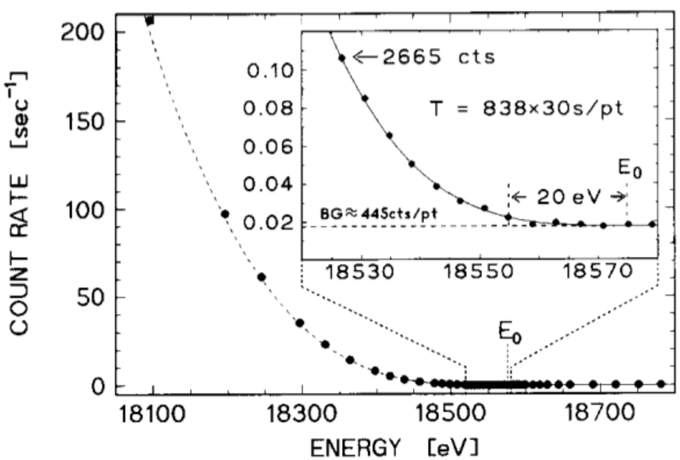
UCSB

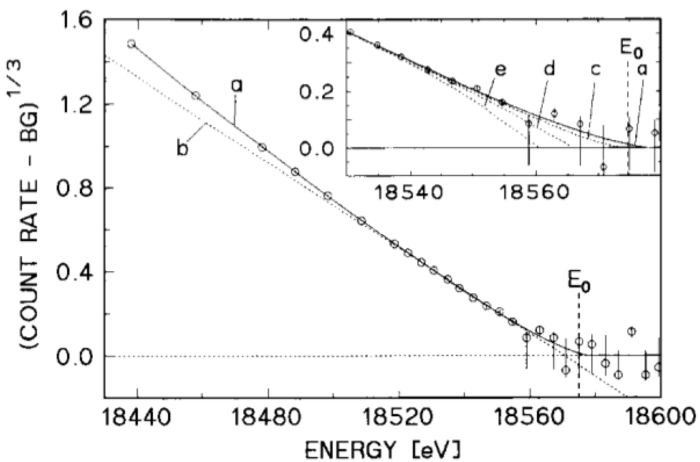
University of Washington

Backup slides

Mainz experiment results

- First analysis in 1992: $m^2(\nu_e) = -39 \pm 34_{stat} \pm 15_{syst}$ eV^2



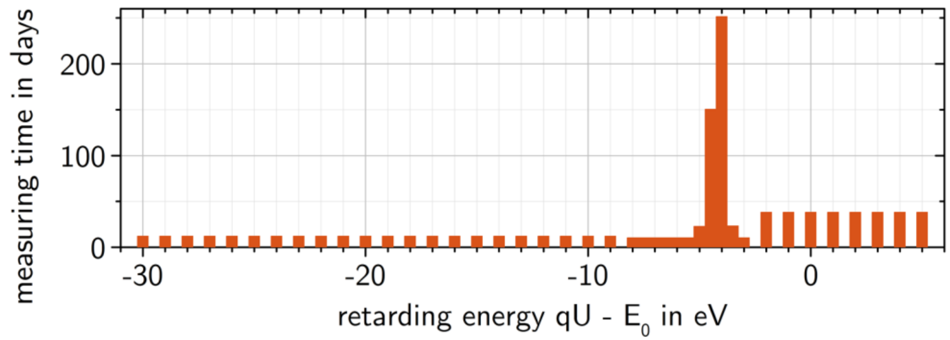


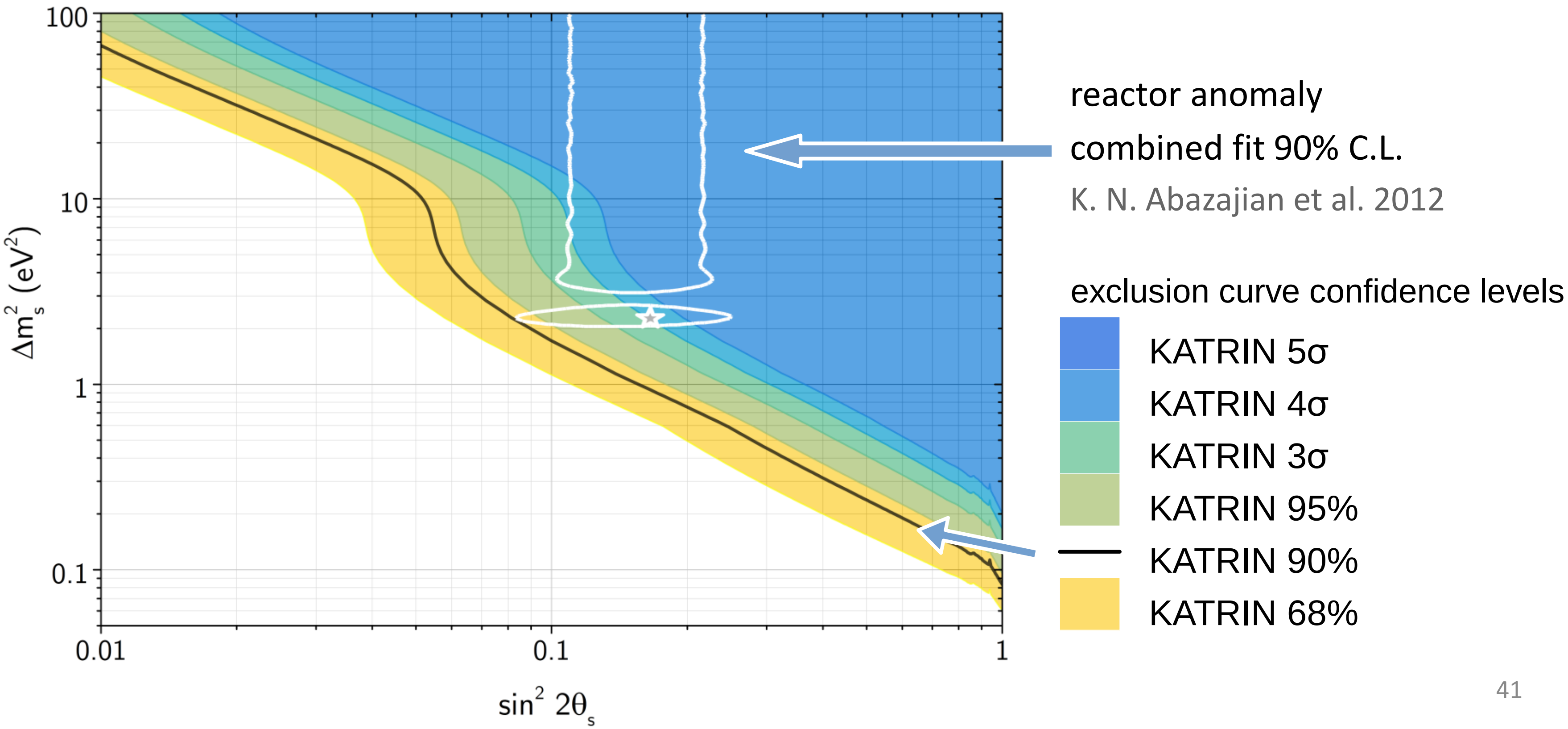
- A source-related systematic mistake was discovered later on
  - film of molecular tritium T_2 quench-condensed onto substrate
  - temperature-activated roughening, **missed increase of inelastic scattering**
- Final analysis in 2005: $m^2(\nu_e) = -0.6 \pm 2.2_{stat} \pm 2.1_{syst}$ eV^2
  - $m(\nu_e) < 2.3$ eV (90% C.L.)

sterile m_ν sensitivity

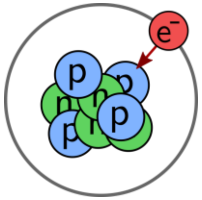
- standard measuring time distr.
  optimized for active ν search

- 5 cal. years of data taking
- active ν mass is fixed at 0 eV

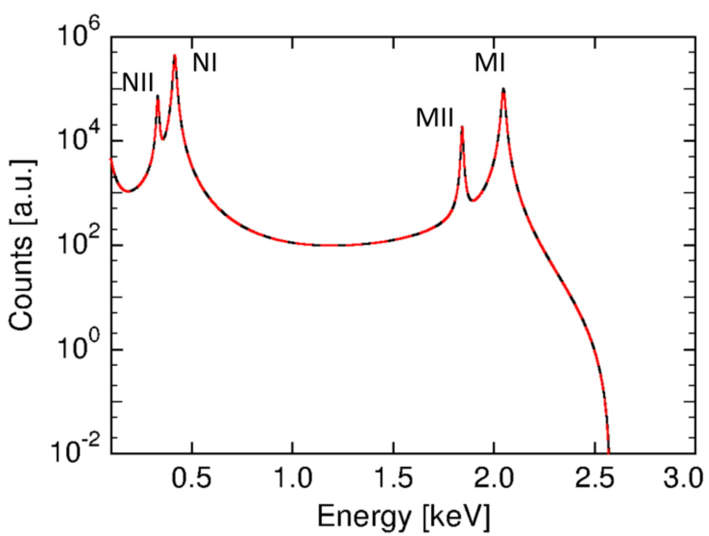


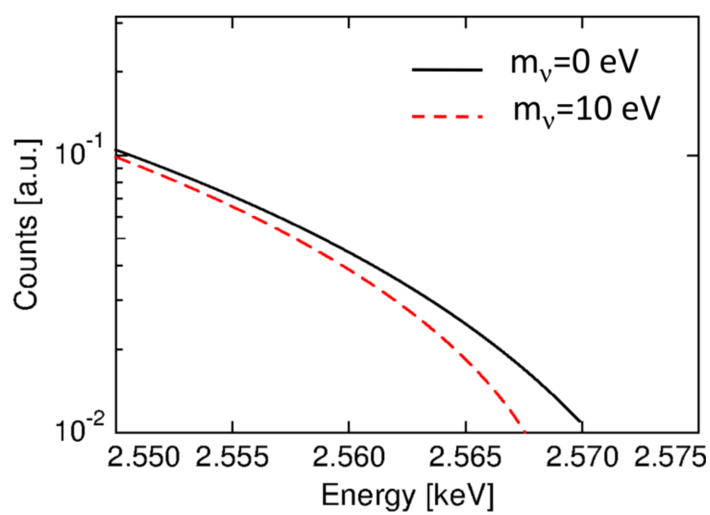


Principle of electron capture (EC) spectroscopy



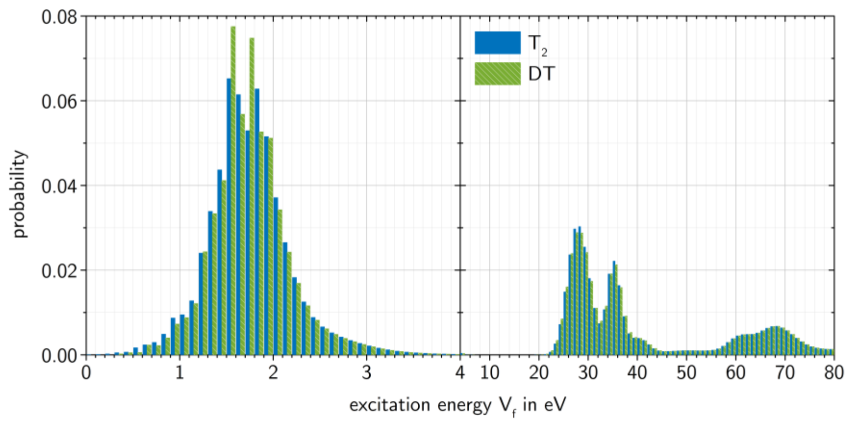
- Electron capture on Holmium ^{163}Ho:
  - $e^{-} + {}^{163}_{67}Ho \rightarrow {}^{163}_{66}Dy^{*} + \nu_e$
- Deexcitation energy of daughter atom in form of electrons and x-rays recorded in microcalorimeters
- Shape distortion close to the Q-value depends on $m^2_{\nu_e}$





Theoretical corrections

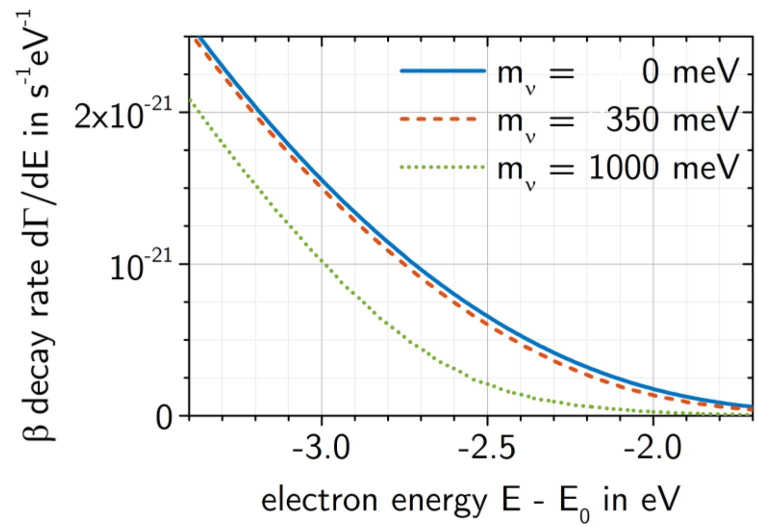
- Radiative corrections & recoil effects are well understood
- Final states of the excited daughter isotopes $^{3}\mathrm{HeT}^{+}$, $^{3}\mathrm{HeD}^{+}$, $^{3}\mathrm{HeH}^{+}$ lead to a broadening of the spectrum



Excited final state distribution of T_2 / DT

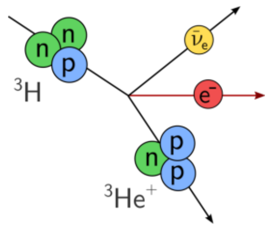
- 0.1 eV binning
- T = 30 K

β spectrum incl. final states and corrections



Why tritium?

$$\frac{d\Gamma}{dE} \propto |M|^2 \cdot F(Z,E) \cdot p(E+m) \cdot (E_0 - E) \cdot \sqrt{(E_0 - E)^2 - m_{\nu_e}^2}$$



- Superallowed transition:
  - Matrix element M is not energy dependent
- Low endpoint energy:
  - fraction of decays at the endpoint is comparatively high $\left(\sim \frac{1}{E_0^3}\right)$
- Short half life:
  - specific activity is high
  - low amount of source material / less inelastic scattering
- Hydrogen isotope:
  - simple atomic shell
  - final states precisely calculable