KATRIN
Karlsruhe Tritium Neutrino Experiment

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Sterile Neutrino Detection by TOF with KATRIN

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Overview

- Neutrino Mass and KATRIN
- Measuring m_{ν_e} by TOF
- WDM Detection by TOF

Neutrino Mass and KATRIN

Neutrino mass basics

- Flavour eigenstates superpositions of mass eigenstates:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{\text{PMNS}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \tag{1}$$

- Oscillation probability (for 2 generations):

$$P(\nu_\alpha \to \nu_\beta) = \sin^2(2\theta)\ \sin^2\left(\frac{\Delta m^2\ L}{4E}\right) \tag{2}$$

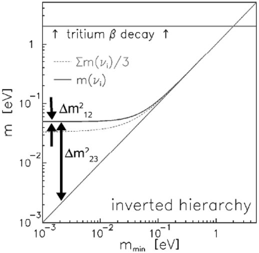
- Known: mixing angles, mass **differences**, sign of Δm^2_{12}

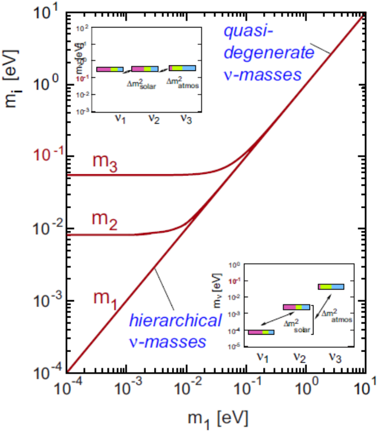
Δm^2_{12}	$\lvert\Delta m^2_{23}\rvert$	$\sin^2 2\theta_{12}$	$\sin^2 2\theta_{23}$	$\sin^2 2\theta_{13}$
$8.0^{+0.4}_{-0.3} \cdot 10^{-5}\,\mathrm{eV}^2$	$[1.9, 3.0] \cdot 10^{-3}\,\mathrm{eV}^2$	$0.86^{+0.03}_{-0.04}$	$[0.92, 1]$	0.092 ± 0.017

- Unknown: sign of Δm^2_{23}, **absolute values** of neutrino mass states!

Why need to know $m(\nu_i)$?

- Cosmology: contribution to energy density Ω_ν
- Mass generation models: Which one? Degenerate or hierarchical mass states?
- Links to new physics: e.g. Higgs triplet (Seesaw type II), scale of 'sterile' mass states





Electron neutrino mass, Mainz and KATRIN

Definition: 'electron neutrino mass in Tritium beta decay'

$$m_{\nu_e} = \sqrt{\sum_i U_{ei}^2 m_i^2}. \tag{3}$$

- Upper limit (Mainz experiment):

  $$m_{\nu_e} < 2.3 \text{ eV} \quad (95 \text{ \% C.L.})$$

- KATRIN: successor of Mainz, improves sensitivity limit by factor 10:

  $$L_{m_{\nu_e}} = 0.2 \text{ eV} \quad (90 \text{ \% C.L.})$$

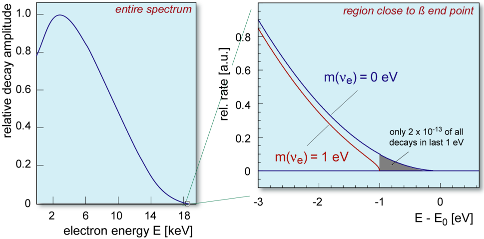
- Sounds tiny, but huge improvements:
  - Diameter of main spectrometer: 10 m
  - Tritium source activity: $1.1 \cdot 10^{11}$ Bq
  - Background: $<$ 10 mHz

How KATRIN works - Tritium β^- decay

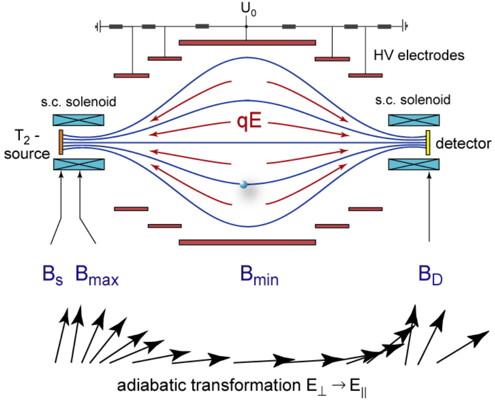
- $^3\mathrm{H} \longrightarrow {}^3\mathrm{He} + e^- + \bar{\nu}_e$
- Endpoint region of the **differential** beta electron spectrum:

$$\frac{dR}{dE} \propto (E_0 - E)\sqrt{(E_0 - E)^2 - m_{\nu_e}^2} \tag{4}$$

- Massive neutrino 'steals' energy and phase space of the electron
- Measure endpoint region of the spectrum $\rightarrow$ fit endpoint E_0 and squared mass $m_{\nu_e}^2$



How KATRIN works - MAC-E-Filter

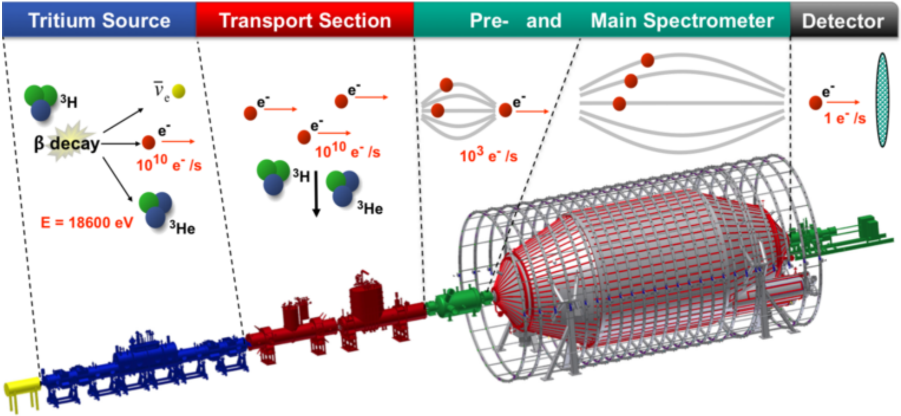


- Electrostatic filter: blocks all electrons with $E_{kin} < qU_{ret}$
- Measure count rate for different retarding potentials qU_{ret} $\rightarrow$ obtain **integrated** beta spectrum $\rightarrow m^2_{\nu_e}$
- Magnetic adiabatic collimation: transforms transverse electron momentum into longitudinal

$$\mu = \frac{p_\perp^2}{B} = \text{const.} \qquad (5)$$

- Principle of MAC: source in high B-field, analysis plane in low B-field

Set-up of KATRIN



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.

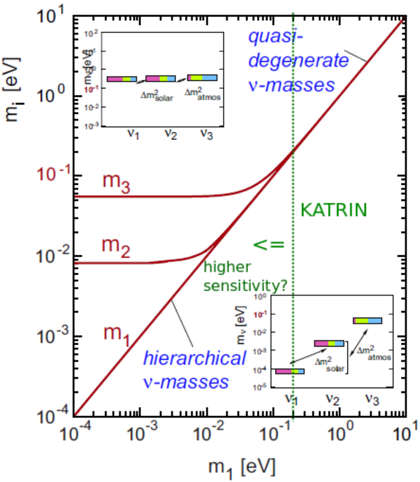
The electron energy is analyzed by applying an electrostatic retarding potential. Electrons are only transmitted if their kinetic energy is sufficiently high.

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.

Measuring m_{ν_e} by TOF

Beyond KATRIN?

- KATRIN sensitivity $L_{m_{\nu_e}}$ at transition region between hierarchical and quasi-degenerate masses
- Recently: Results from Planck + BAO $\sum m_i < 0.23$ eV
- Can not build bigger KATRIN $\rightarrow$ need something different



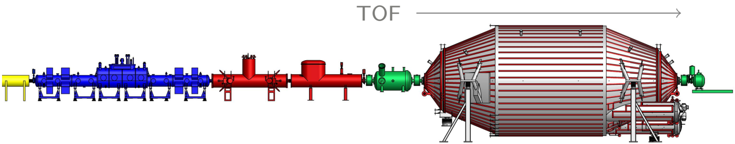
MAC-E-TOF mode - principle

Possible way to go: measure m_{ν_e} by TOF spectroscopy.

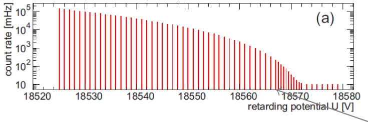
- TOF is a function of velocity parallel to magnetic field $v_{\parallel}$
  $\rightarrow$ function of energy E and angle θ w.r.t magnetic field

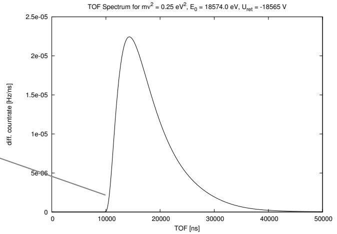
$$\tau(E,\theta) = \int dz\ \frac{1}{v_{\parallel}} = \int_{z_{\text{start}}}^{z_{\text{stop}}} dz\ \frac{E - qU_{\text{ret}} + m_e c^2}{\sqrt{p_{\parallel}^2(z,E,\theta)\ c^4}}. \qquad (6)$$

- TOF spectrum $\frac{dN}{dt}$ depends on m_{ν_e} via energy distribution, given by beta spectrum (4)



TOF mode vs. standard mode





standard mode

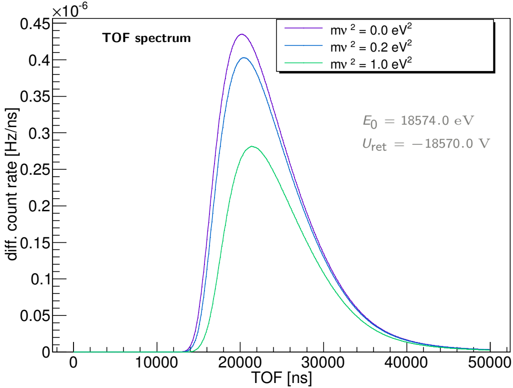
integrated spectrum: only number of events per retarding potential measured

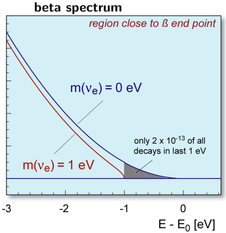
TOF spectroscopy

differential spectrum: TOF measured for each event, number of potential steps can be reduced

→ **More information by TOF measurement**

TOF spectra - the calculated model



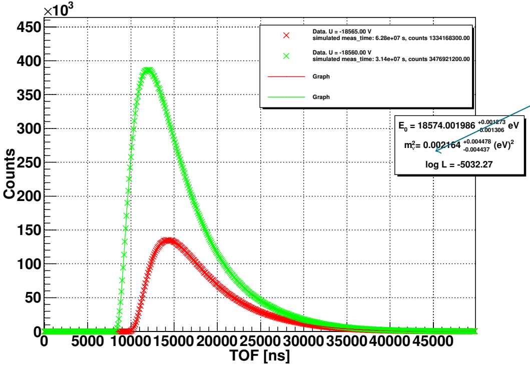


Observations

- Minimal TOF $\widehat{=}$ maximal kinetic energy
- No maximal TOF $\rightarrow$ energies close to the potential barrier give slow velocities
- m_{ν_e} affects the minimal TOF, the count-rate and the slope of the peak

MC Data and Fit

- Optimal case: no background, infinite time resolution (3 yrs measurement)



mean $\sigma_{\text{stat}}(m^2_{\nu_e})$
TOF mode:
0.0043 eV^2

$\sigma_{\text{stat}}(m^2_{\nu_e})$
standard mode:
$\mathcal{O}(0.02\ \text{eV}^2)$

- Only two potential steps used! (KATRIN: $\sim$ 40)
- $\rightarrow$ Improvement of $\sigma_{\text{stat}}(m^2_{\nu_e})$ by up to factor 4-5
- Measure with higher retarding energies only $\rightarrow$ also reduction of systematics expected!
- Improvement of total sensitivity $L_{m_{\nu_e}}$ depends on systematics, rough estimate: up to factor 2.

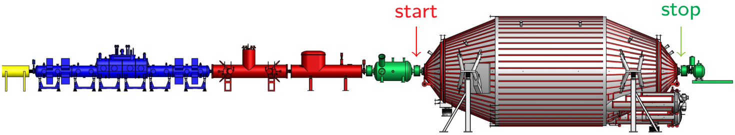
Measurement of TOF

We need a measurement of the 'start' and the 'stop' time

- 'stop': KATRIN detector with < 50 ns time precision ☺
- 'start': complicated ☹

Hypothetical method - electron tagging

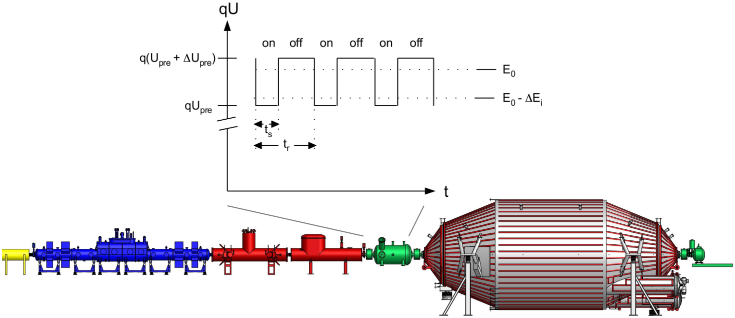
- On-thy-fly detections of electrons at starting point with minimal interference
- Advantage: can distinguish background from real counts by previous 'start' signal
- Unrealistic in near future.



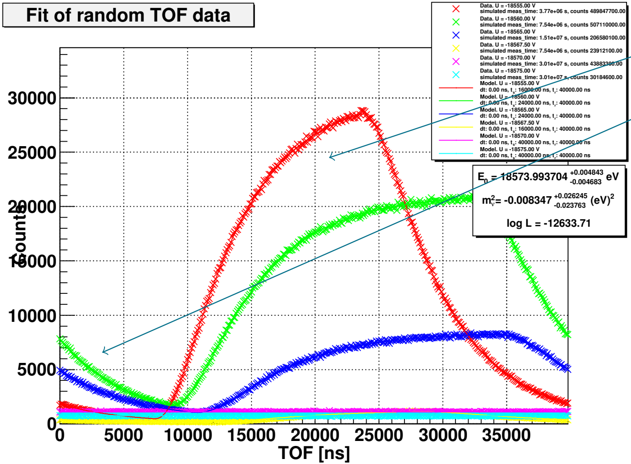
More realistic method: 'gated filtering'

(cf. Bonn et al., Nucl. Instr. Meth. A 421 (1999))

- Periodically block the beam at the 'start' position
- Performed by pulsing pre-spectrometer potential
- Electrons can only pass during 'on'-cycle → 'start' time known with some uncertainty
- Choice of duty cycle → trade-off between time resolution and signal rate



Gated filter simulation



- Peak broadening due to step function
- Residuals from earlier periods at the beginning of the spectrum
- 6 potential steps used, timing parameters optimized

Results

- $\sigma_{\text{stat}}(m^2_{\nu_e}) \approx 0.025\ \text{eV}^2$
- compare standard mode: $\sigma_{\text{stat}}(m^2_{\nu_e}) \approx 0.018\ \text{eV}^2$
- Sensitivity improvement by reduction of systematics possible?

WDM detection by TOF with KATRIN

Hints towards WDM

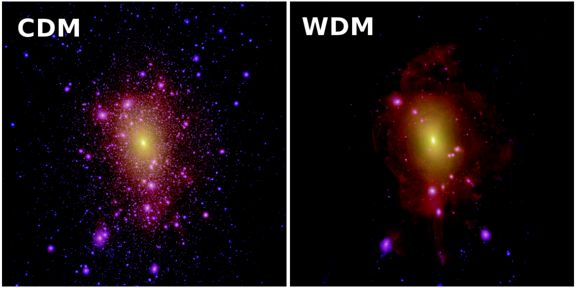


Figure: Simulation, Lovell et al. (2012), CIAS Meudon Workshop 2012

To much sub-structure with CDM:

- Dwarf galaxy problem: much less dwarf galaxies observed than predicted
- Cuspy halo problem: sharply increasing DM density in halos predicted ('cusps'), in contrast with observations ('cores')
- Much more: galaxy surface density, emptiness of the voids, velocity dispersions ...

WDM particle

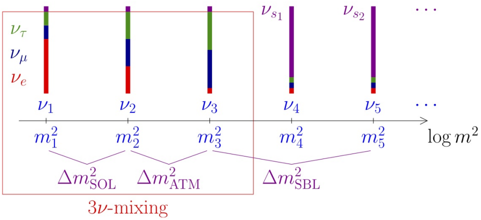


Figure: http://neutel11.wordpress.com/2011/03/17/sterile-neutrino-fits-by-carlo-giunti/

Particle candidate: sterile neutrino ν_s with mass $\mathcal{O}$(keV)

- Right-handed gauge singulet - interacts only via gravitation
- Additional mass eigenstate, e.g. m_4 - mixes extremely weak with active ν states
- Remark: light sterile ν (eV range) can possibly explain reactor neutrino anomaly
- Important decay channel: $\nu_s \to \nu + \gamma$ (X-ray scale)
- Current X-ray constraints by Chandra (Dodelson-Widrow):

$$\sin^2\theta \lesssim 10^{-7} \qquad m_4 < 2.2 \text{ keV}$$

Sterile neutrino detection in β decay

- Superposition of classic and 'heavy neutrino' β spectrum:

$$\frac{dN_{\text{tot}}}{dE} = \sin^2\theta \frac{dN}{dE}(m_4) + \cos^2\theta \frac{dN}{dE}(m_{\nu_e}) \quad (7)$$

$\rightarrow$ 'kinks' in β spectrum at $E_0 - m_4$

- Note: in reality kink is smeared by electronic final states and inelastic scattering!

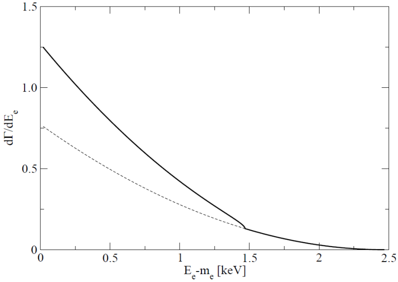
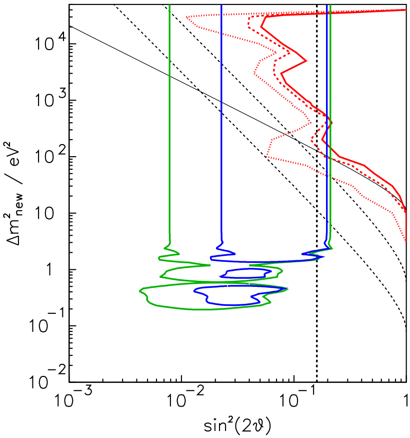


Figure: Differential decay rate of $^{187}\mathrm{Re}$ for $m_4 =$ 1 keV. *De Vega et al.* (2011, arXiv: 1109.3452)

Sensitivity on light sterile neutrinos

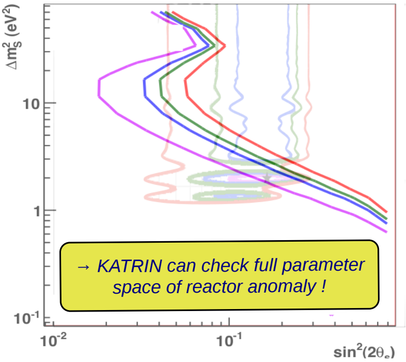
MAINZ



exclusion limits from Mainz data

Ch. Kraus et al., Eur. Phys. J. C (2013) 73:2323

KATRIN

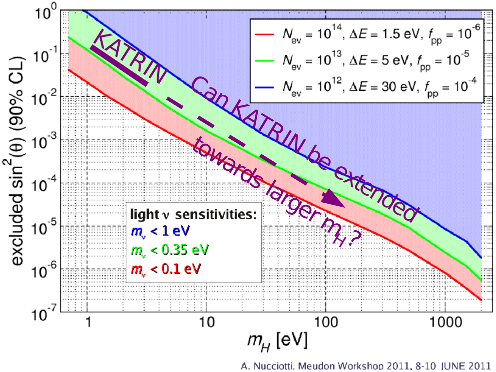


KATRIN simulations

J. A. Formaggio, J. Barret, PLB 706 (2011) 68
A. Sejersen Riis, S. Hannestad, JCAP02 (2011) 011
A. Esmaili, O.L.G. Peres, arXiv:1203.2632

Extension towards larger sterile ν masses?

MARE II



A. Nucciotti, Meudon Workshop, June 2011

as cited in C. Weinheimer, Paris Cosmology Colloquium, July 2012

WDM detection and systematics

- Systematics grow with distance from endpoint
  - compare data of Mainz neutrino experiment (2005)

  → Region of WDM 'kink' is dominated by systematics!
- Especially: inelastically scattering of electrons, electronic final states
- need smart ways to handle systematics
  - E.g. atomic sum rules
  - lower WGTS column density/maximal starting angle → reduce electron scattering
  - kink detection technique - S. Mertens
  - differential spectrum

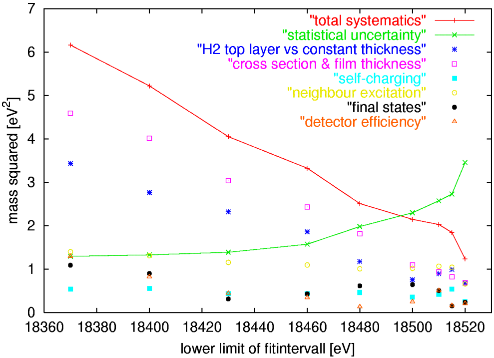


Figure: Systematic (red) and statistical uncertainty (green) at the Mainz experiment C. Kraus et al., Eur. Phys. J. C (2005) 40;447

WDM detection by TOF

TOF spectrum is a differential spectrum

Advantages:

- Integral spectrum only precise close to E_0
- count-rates of $\mathcal{O}$(kHz) at 'kink' region
  $\rightarrow$ use gated filter with small duty cycles, giving sharp timing! (no problem since not statistically limited)
- Reduction of systematics due to differential method

  Can distinguish spectral parts with higher energy and no sterile ν information!

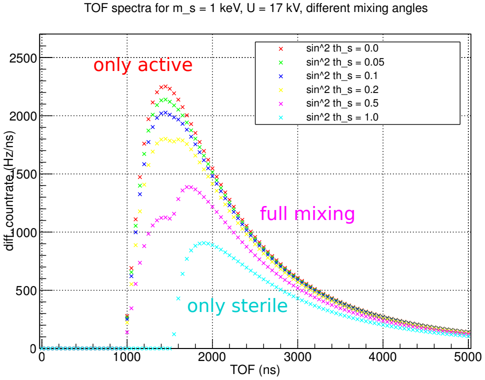
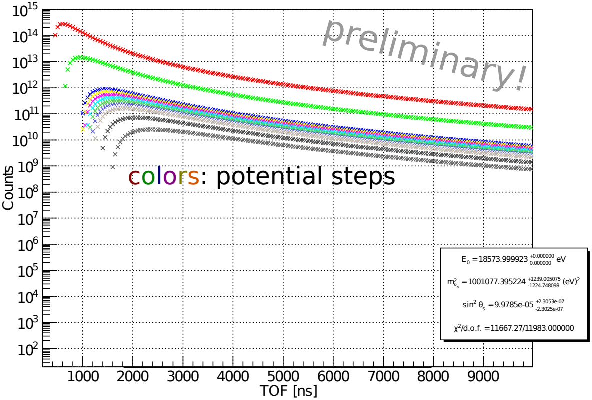


Figure: TOF spectra for $m_4 = 1keV$ and different mixing angles

First check - toy model fit



No final states, no electron scattering, no background, no gated filter simulation, arbitrary parameters...

Results:

$\sigma(\sin^2\theta) \sim 10^{-7}$

→ compatible with S. Mertens' results

Assumed:
$m(\nu_s) = 1$ keV, $\sin^2\theta = 10^{-6}$

Remark:
Measure at energys close to kink to see it in TOF spectrum
→ larger number of potential steps needed

Towards the KATRIN WDM sensitivity determination

1. Detailed understanding of systematics
   - Theoretical
   - Experimental
     - e.g. energy loss spectrum, column density and high rate detector behaviour by measurements with angular selective e-gun
   - Phenomenological
     - e.g. final states distribution by sum rules, extrapolation
   - via MC simulations (KASSIOPEIA, KRONOS)
   - ...

Towards the KATRIN WDM sensitivity determination

Optimization of many parameters

- Measurement region
- Potential steps and measurement times
- Gated filter duty cycles
- Column density
- Maximum starting angle
- Minimum TOF
- ...

Many of the parameters (e.g. region of interest) depend where we want to look at...

$\rightarrow$ **communication with WDM and neutrino community**

Conclusion

Conclusion

- KATRIN most sensitive experiment in near future to measure m_{ν_e} (others in planning: MARE, ECHo, Project-8)
- TOF mode in principle able to improve statistical sensitivity, depends on implementation

to be submitted soon for publication

- KATRIN able to resolve full reactor anomaly parameter space, but at higher sterile ν masses dominated by systematics
- TOF for keV sterile neutrino search measures beta spectrum differentially, it will allow to reduce systematics
- Implementation no problem since rates are high $\rightarrow$ gated filter with low duty cycle and sharp timing

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Backup slides

How much better is the TOF mode?

Sensitivity = statistical uncertainty + systematic uncertainty

Simulation

a) Write a method to calculate TOF spectrum for all possible $(E_0, m^2_{\nu_e}, U_{\mathrm{ret}})$

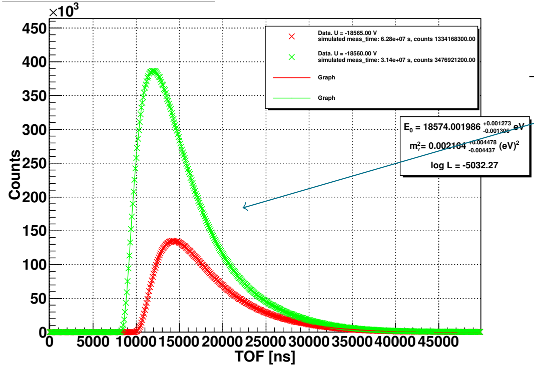
b) Assume an arbitrary E_0 and $m^2_{\nu_e}$ and create Monte Carlo data using a)

c) Fit the data with the theoretical spectrum

$\rightarrow$ $\sigma_{\mathrm{stat}}(m^2_{\nu_e})$

Best case simulation results

- No background, infinite time resolution



lowest qU_{ret} [eV]	$\sigma_{stat}(m^2_{\nu_e})$ TOF mode [eV^2]	$\sigma_{stat}(m^2_{\nu_e})$ standard mode [eV^2]
18560	0.0043	-
18555	0.0040	0.020
18550	0.0038	0.019
18545	-	0.018

Results

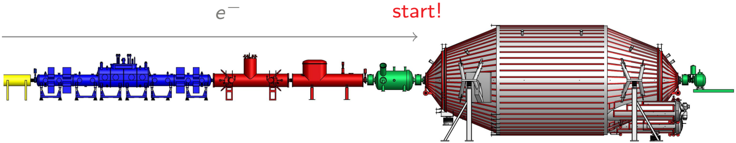
- With TOF only few (1-5) retarding energies needed! (KATRIN: $\sim$ 50)
- $\rightarrow$ Improvement by up to factor 4-5
- Need only higher retarding energies $\rightarrow$ also reduction of systematics expected!

Hypothetical method: 'electron tagging'

Parameters to characterize the performance of 'tagging'

- Time resolution σ_t
- Tagging efficiency ϵ_{tag}
- Tagging rate r_{tag} (= rate of incoming electrons + 'false' signals)

Note: limited ϵ_{tag} causes additional background. Untagged electrons might still reach detector and give false TOF!
$\rightarrow$ need low ϵ_{tag} and r_{tag} for background minimization.



Gated filter parameter optimization

Balancing of t_r and t_s

- High duty cycles: High count-rate but weak time resolution
- Small duty cycles: Low count-rate but good time resolution
- Simulation shows: strong parameter dependence only for extreme values.
- New measurement time optimization necessary since sensitivity now significantly lower

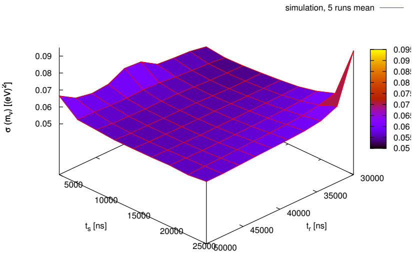


Figure: Sensitivity as a function of t_r and t_s (for 18560 V lowest U_{ret})

Measurement time optimization

- Idea 1: more standard mode like distribution.
- Idea 2: optimize duty cycle individually for each retarding potential

Constraints for measurement methods in general

For your custom TOF-Measurement method: see how good it will be
(in case it can be characterized by a simple Gaussian time resolution and an efficiency)

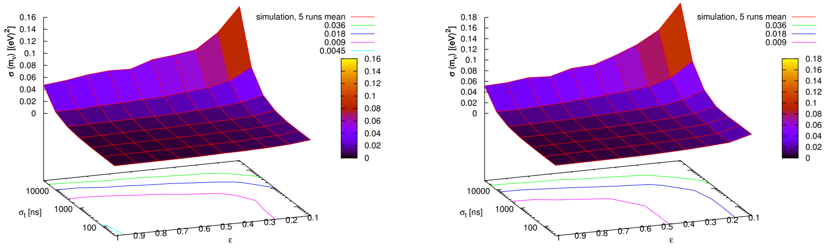
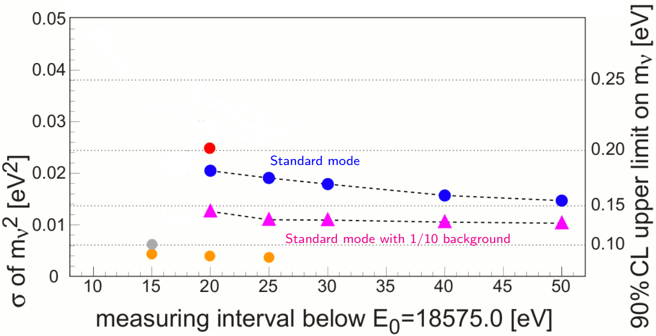


Figure: Sensitivity as function of time resolution and efficiency. Lowest retarding potential 15 eV below endpoint (measurement time optimum). Left: no background. Right: 0.01 mHz background. Blue line: sensitivity of standard mode.

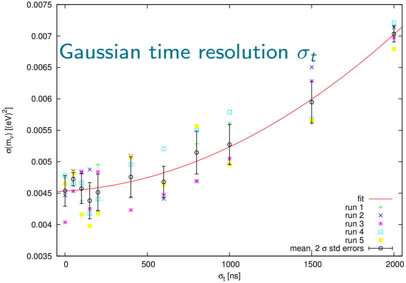
Statistical uncertainty - TOF vs. standard mode

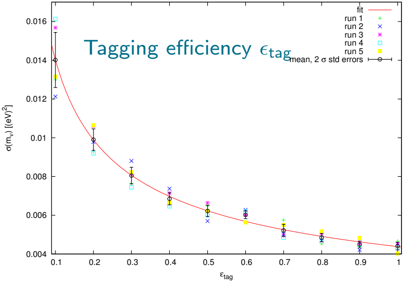


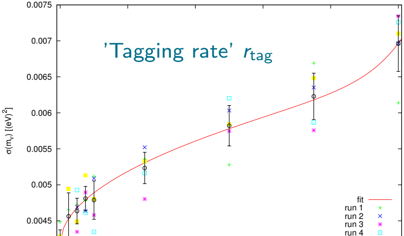
- TOF with no background and infinite time resolution: potential improvement of $\sigma_{\text{stat}}(m^2_{\nu_e})$ by factor 4-5
- TOF with electron tagging (example): high sensitivity but unrealistic.
- TOF with gated filter: realistic but not better than standard mode

Plus: reduction of systematics expected (higher retarding potentials)

Simulation of 'electron tagging'







Sensitivity as function of tagger performance

- Timing not so critical
- Beware of too high incoming electron rates

Example (from simulation)

'Realistic' parameters (σ_t=150 ns, r_{tag}=1 kHz, ϵ_{tag}=0.8)

$\sigma(m^2_\nu) \simeq 0.006\ \mathrm{eV}^2$