Statistical wavelet analysis to detect keV-neutrinos with a KATRIN-like experiment

Marc Korzeczek at Karlsruhe Institute for Technology KIT, IKP

Outline

- Introduction
  - Why keV-sterile neutrinos?
  - How is KATRIN suited to measure keV-sterile neutrinos?
  - Can we probe the cosmological favored region?
- Wavelet analysis of the Tritium $\beta-$ decay spectrum
- Results

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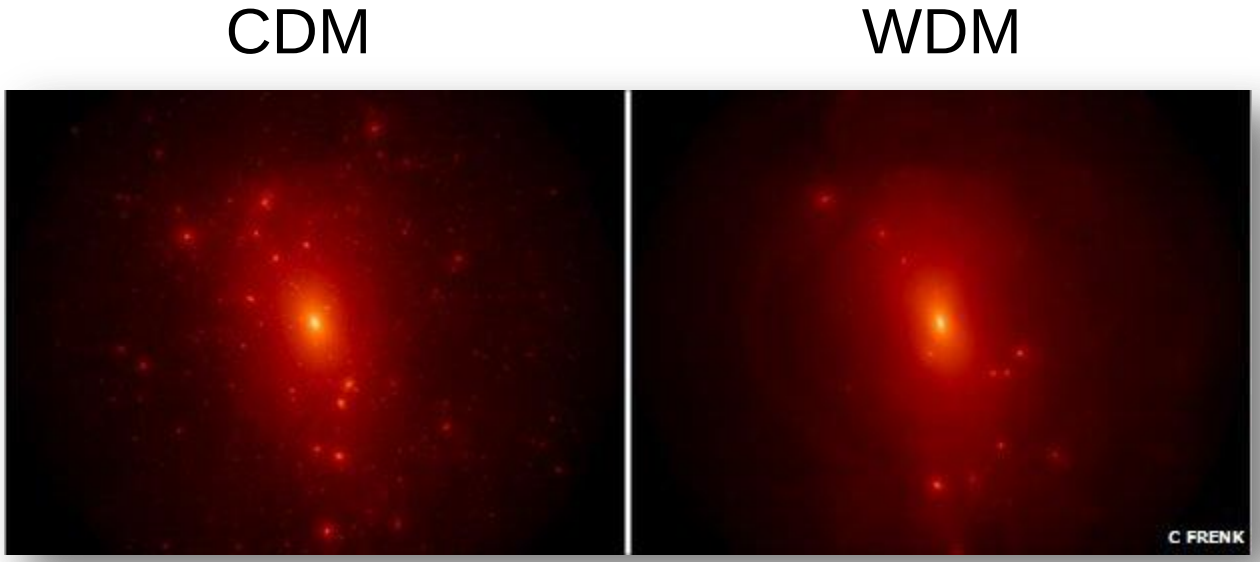
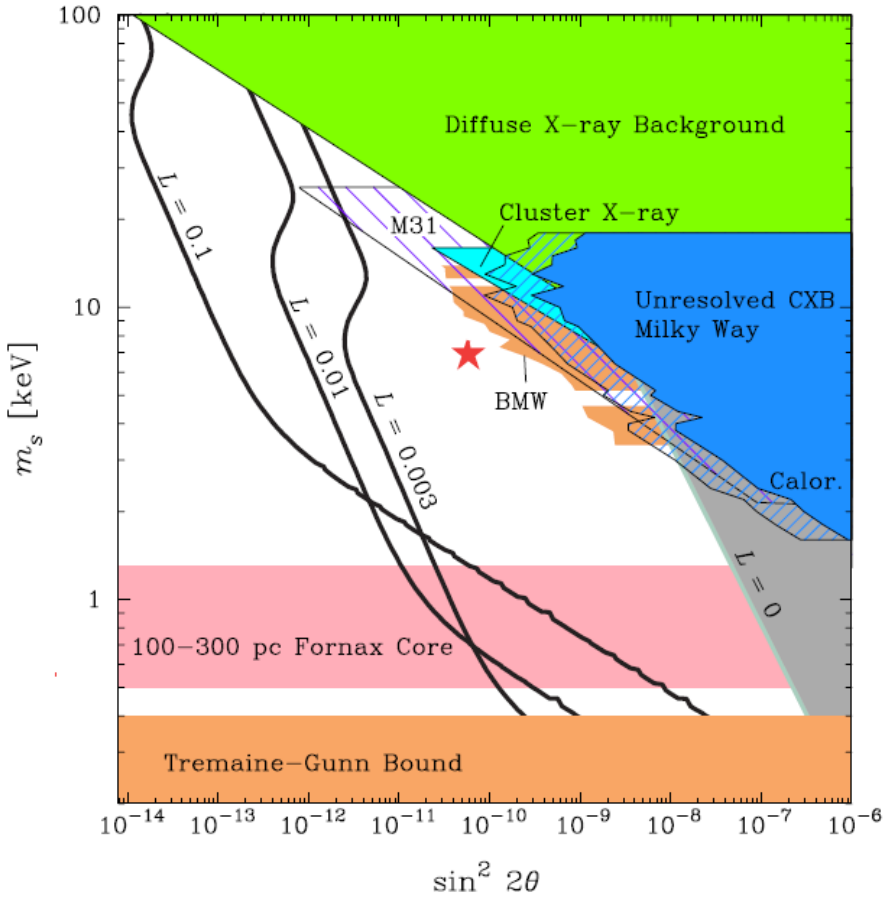
Why keV-sterile neutrinos?



- WDM mitigates problems of structure formation (number of dwarf galaxies)
- Candidate for WDM: sterile neutrinos with masses of a few keV

Talk: Vega/Sanchez

Why keV-sterile neutrinos?



Analysis of XMM Newton telescope data points at

$$m_S = 7.1\ \text{keV}$$

$$\sin^2\theta = 1.75 \times 10^{-11}$$

[Bulbul et al, arxiv:1402.2301v1 [asatro-ph.CO], 2014, 10th February]

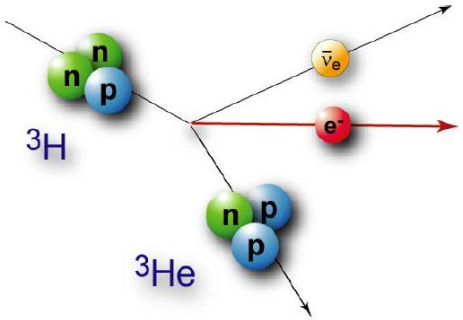
Talk: Bulbul

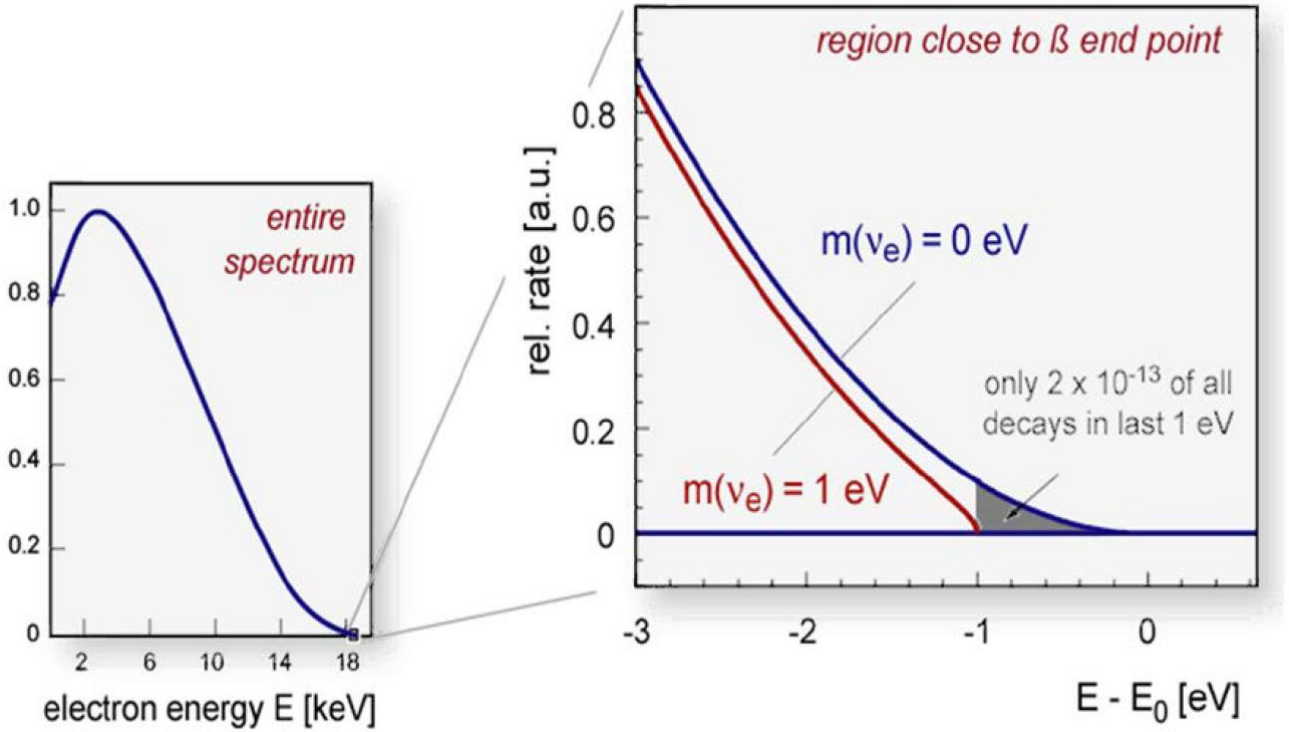
→To probe the favored region $\sin^2\theta < 3 \cdot 10^{-8}$ needed.

How is KATRIN suited to measure keV-sterile neutrinos?

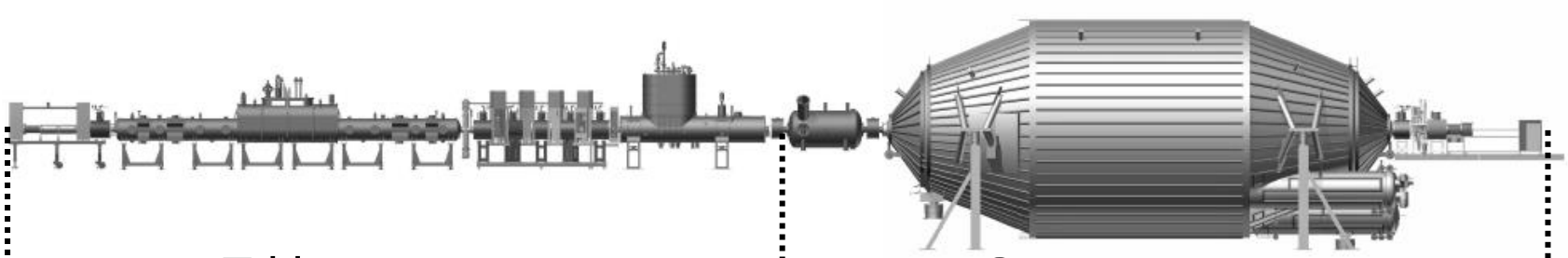
The KArlsruhe TRitium Neutrino experiment (KATRIN)

→ Measure the effective mass of the electron antineutrino





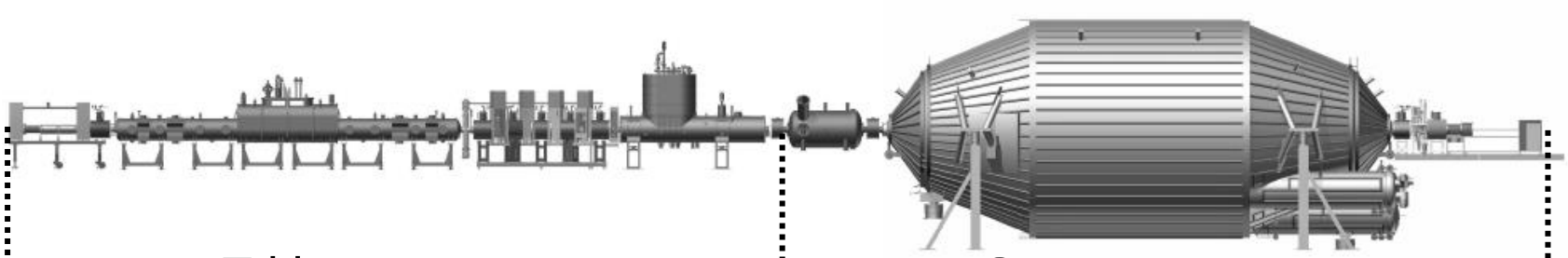
How is KATRIN suited to measure keV-sterile neutrinos?



Tritium source + pumping section

Spectrometer + detector

How is KATRIN suited to measure keV-sterile neutrinos?



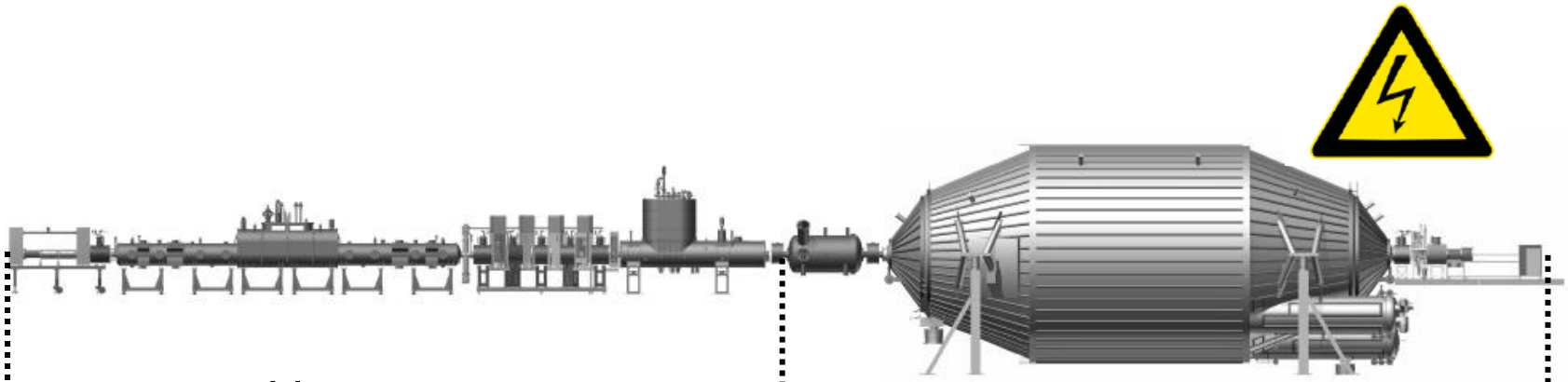
Tritium source + pumping section

Spectrometer + detector

+ source of high luminosity and stability → 10^{11} dps (decays per second)

- High count rates require new detector systems

How is KATRIN suited to measure keV-sterile neutrinos?

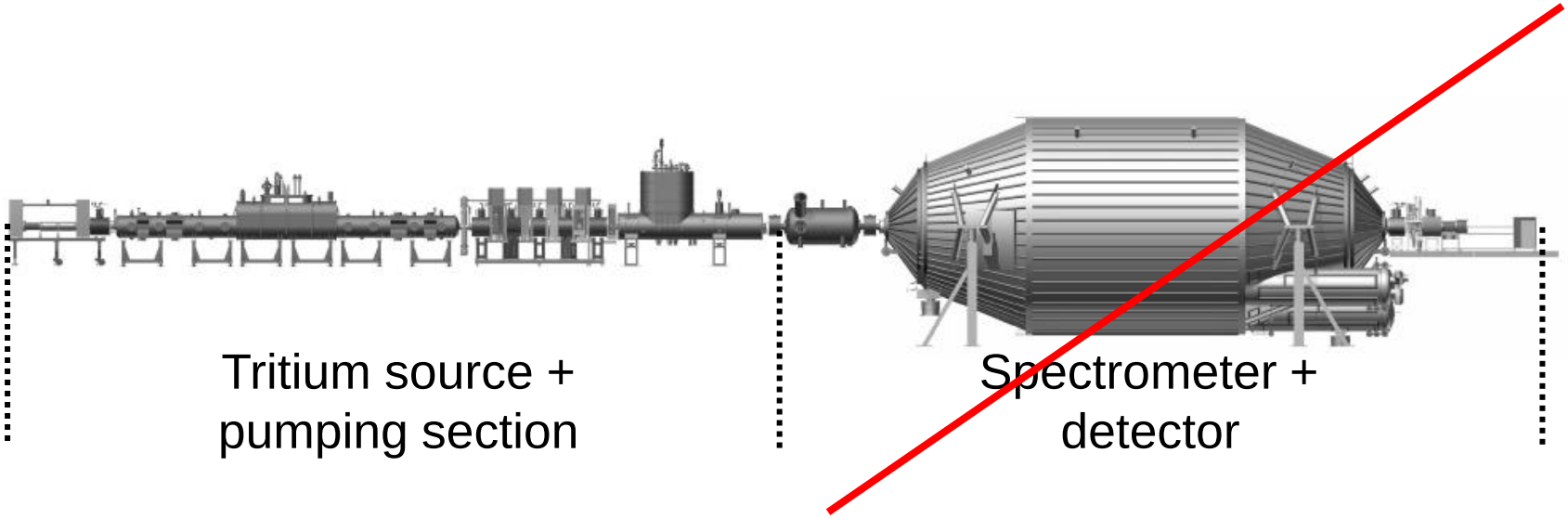


Tritium source + pumping section

Spectrometer + detector

1. Counting detector
   → Integral measurement

How is KATRIN suited to measure keV-sterile neutrinos?



1. Counting detector
   → Integral measurement
2. Energy resolving detector
   → Differential measurement

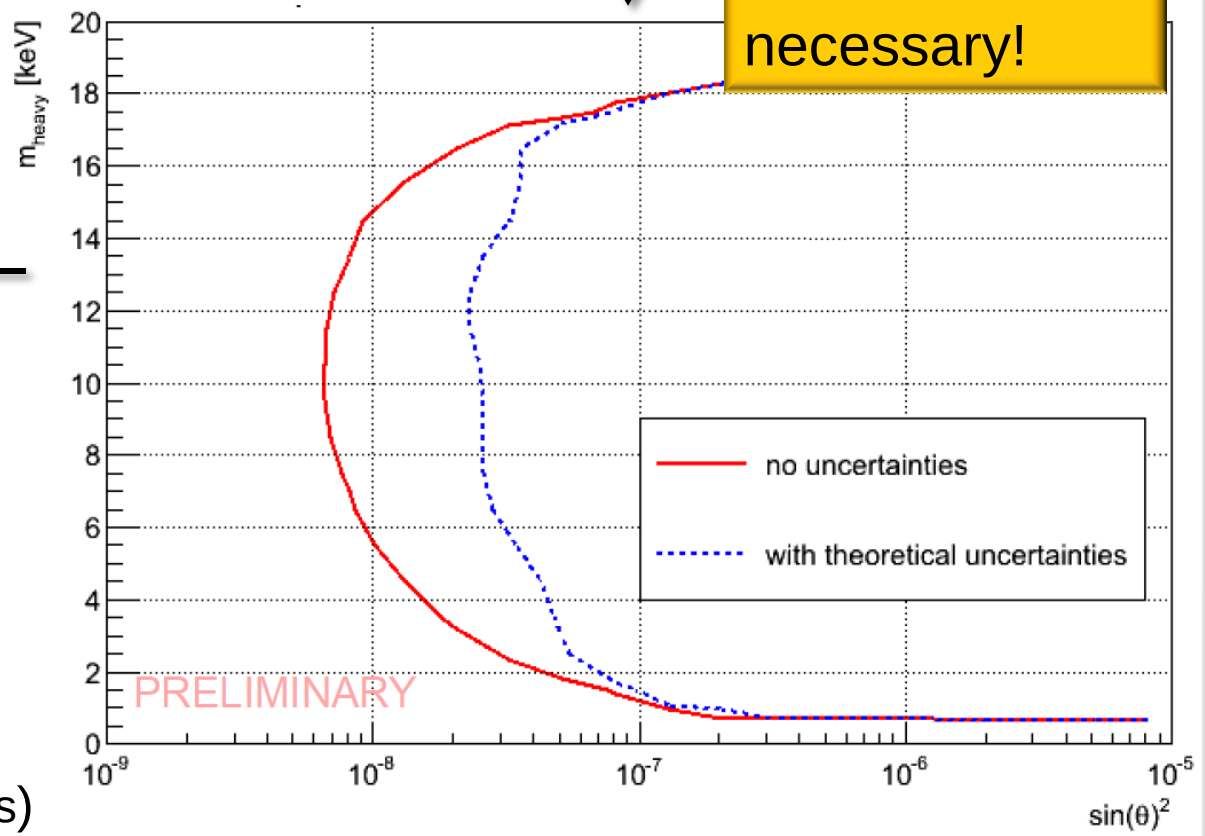
Can we probe the cosmological favored region?

1. Spectral Fit Approach

2. Wavelet Approach

Perfect under-standing of all corrections necessary!

Better:
Use a model independent approach



- 11 free parameter fit
- KATRIN source strength
- 3 years measurement time

(By Susanne Mertens)

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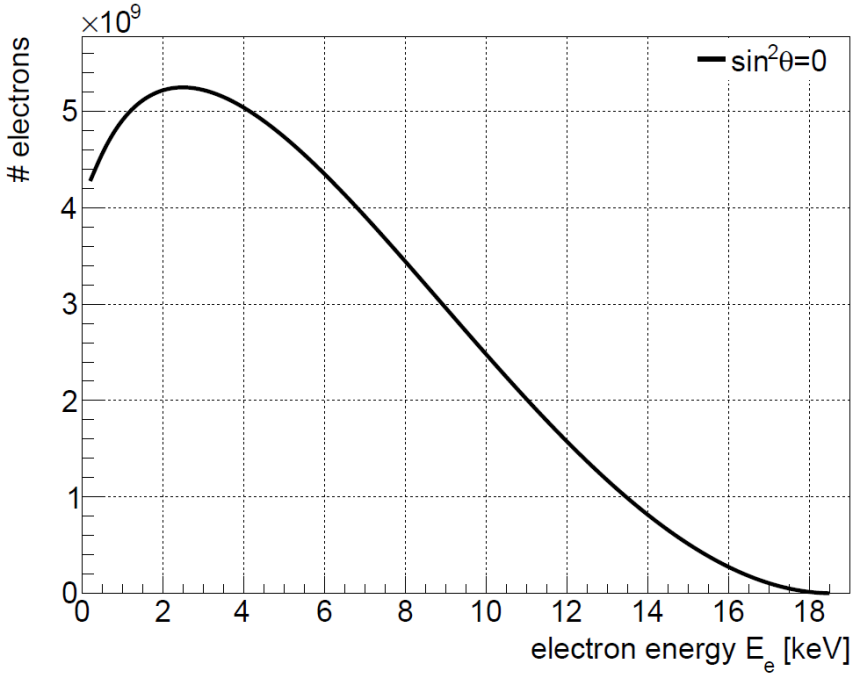
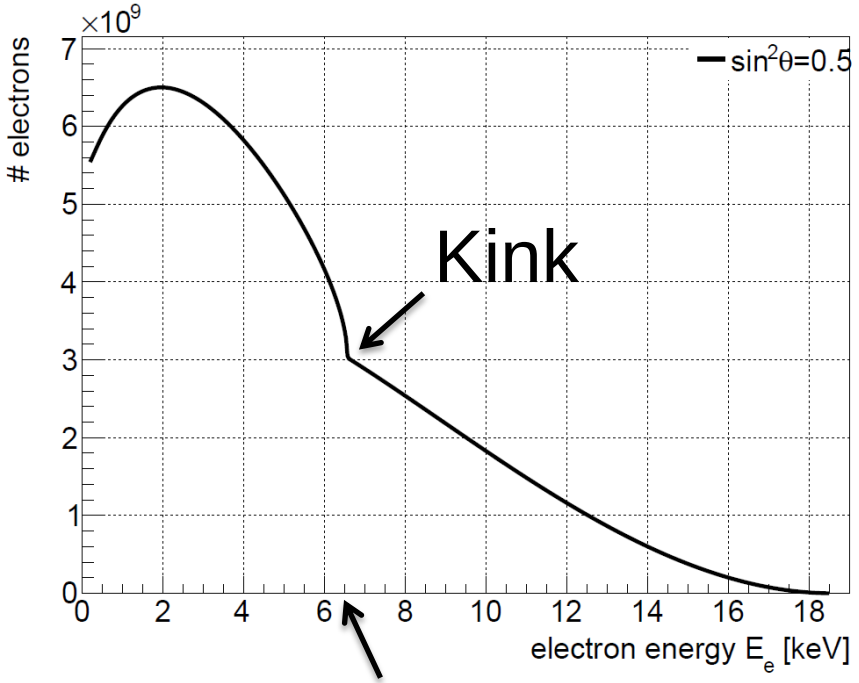
Analysis of the Tritium $\beta-$ decay spectrum





no keV-neutrino

$\rightarrow sin^2\theta = 0$

with keV-neutrino

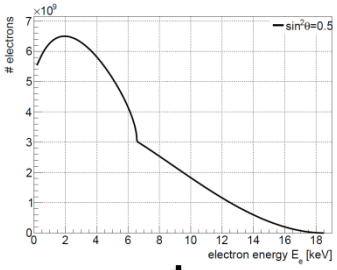
$sin^2\theta = 0.5$ & $m_s = 12$ keV

$\rightarrow E_e \approx 6.5$ keV

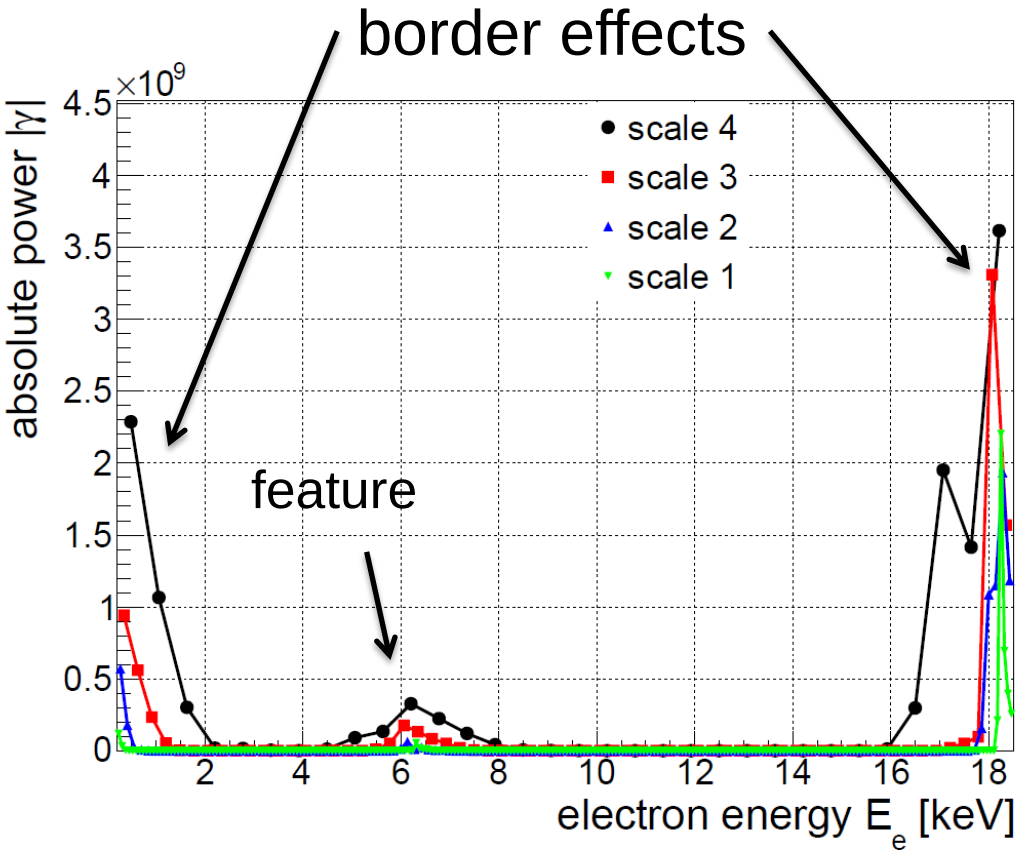
Remember:

$$\frac{d\Gamma}{dE_e} = \sin^2\theta \left(\frac{d\Gamma}{dE_e}\right)_{m_s} + \cos^2\theta \left(\frac{d\Gamma}{dE_e}\right)_{m_\nu}$$

Analysis of the Tritium $\beta-$ decay spectrum

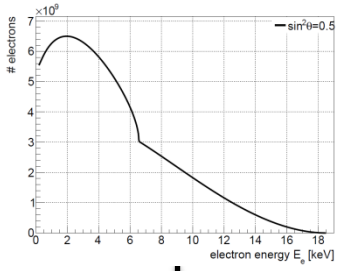


DWT
(Discrete Wavelet Transform)



Power Spectrum

Analysis of the Tritium $\beta-$ decay spectrum



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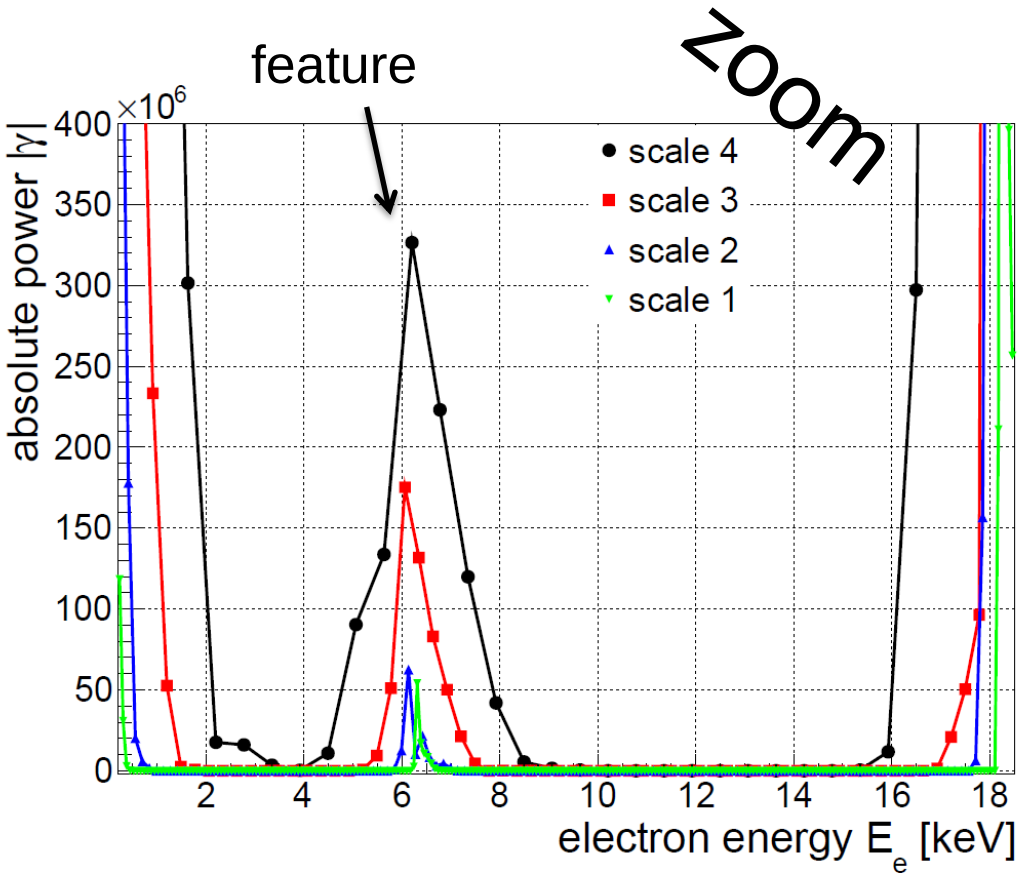
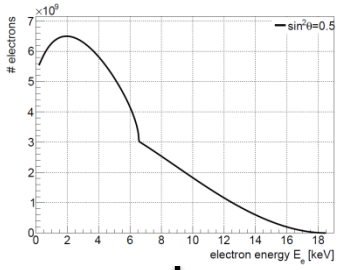
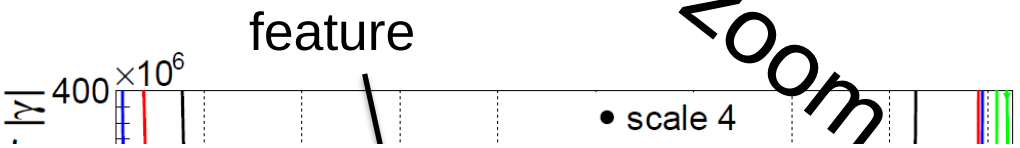
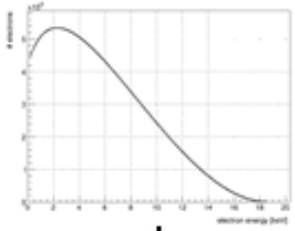


Power Spectrum - zoom

Analysis of the Tritium $\beta-$ decay spectrum







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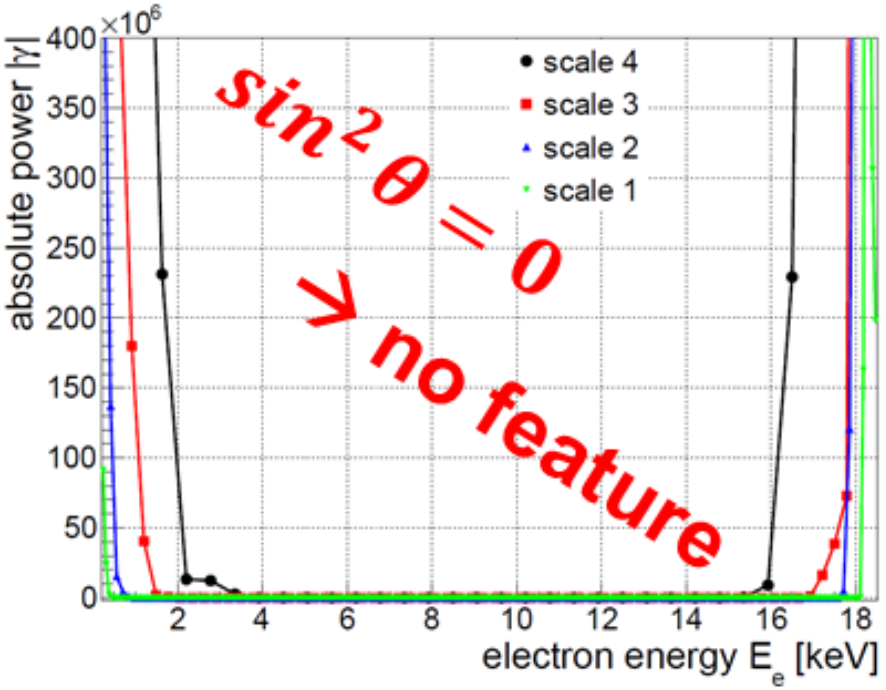

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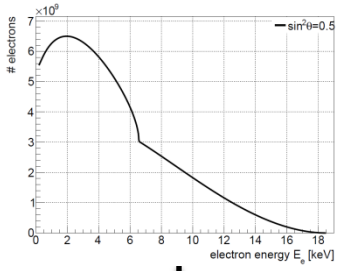

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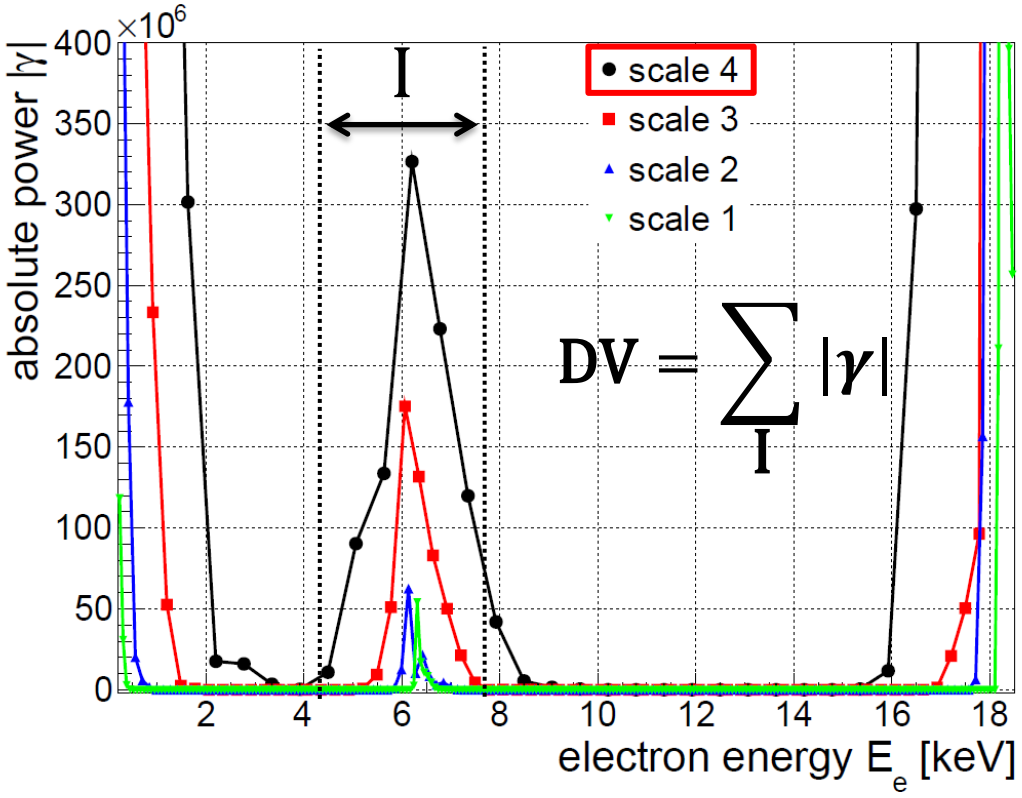
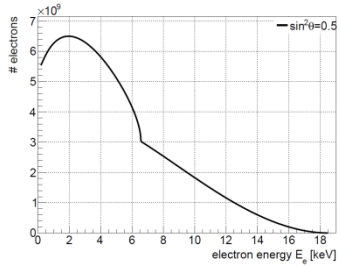


To measure the kink we define a so called Distinctive Value (DV)

Analysis of the Tritium $\beta-$ decay spectrum



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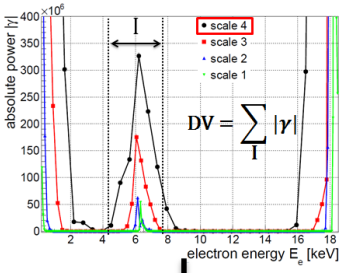
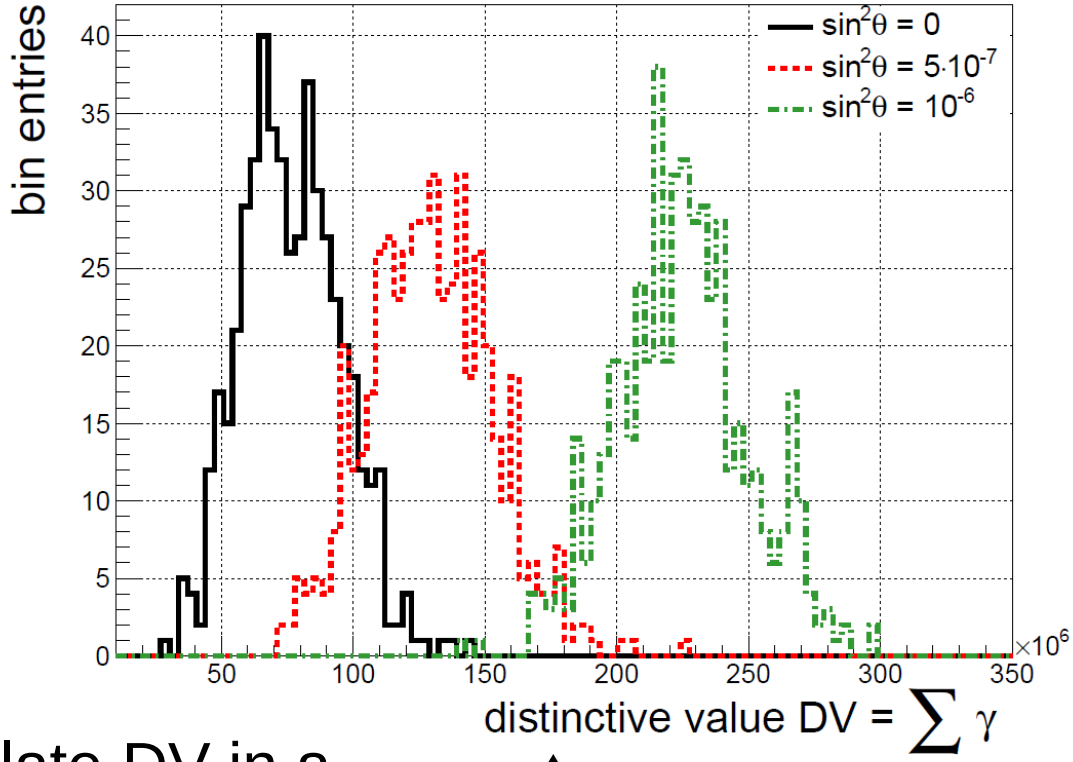
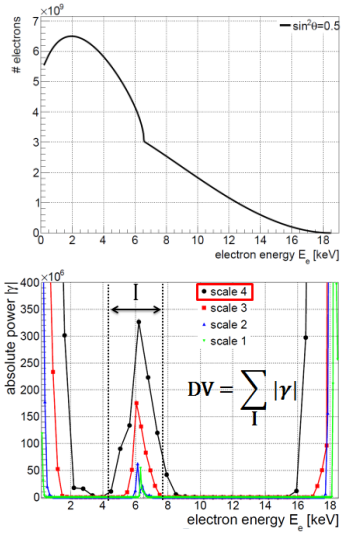




Calculate DV in a Monte Carlo simulation

Analysis of the Tritium $\beta-$ decay spectrum



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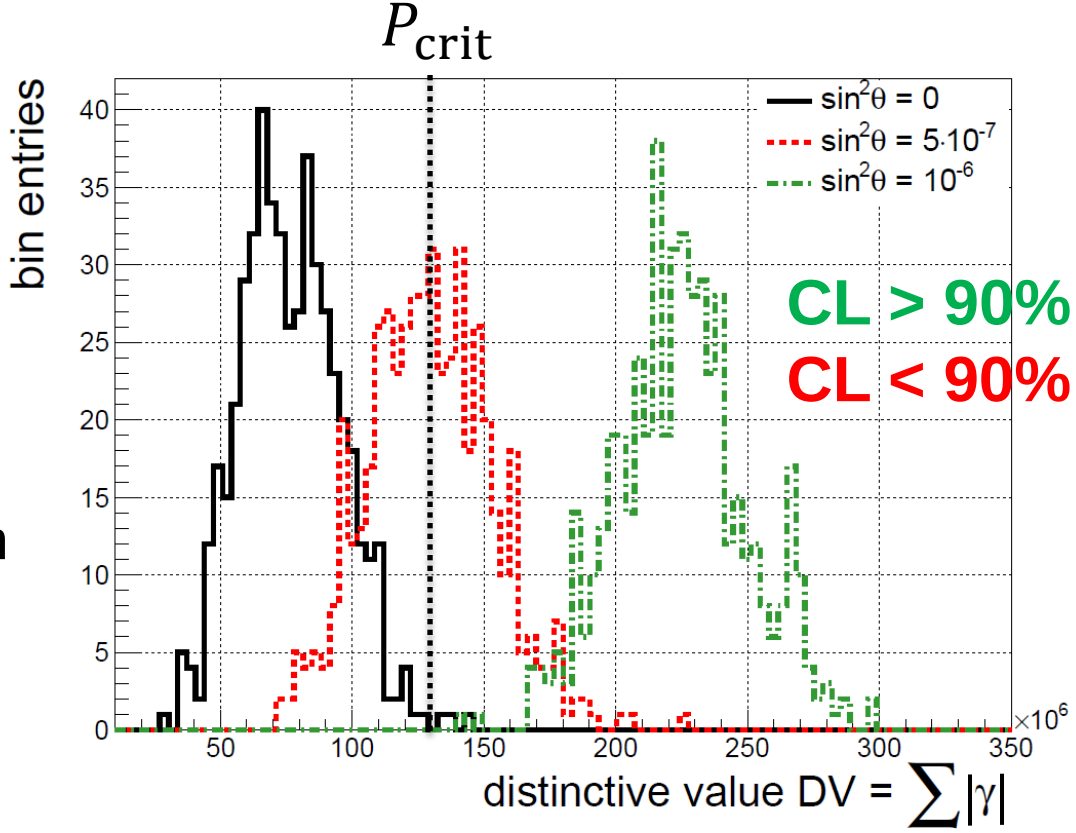
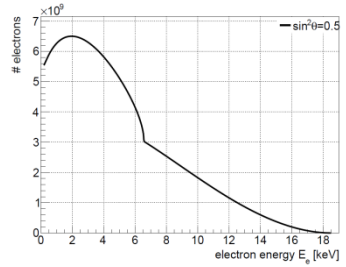


Compare DV-distribution from $\sin^2\theta = 0$ to one with $\sin^2\theta \neq 0$.

→ **Right sided hypothesis testing to the value P_{crit} !**

Analysis of the Tritium $\beta-$ decay spectrum



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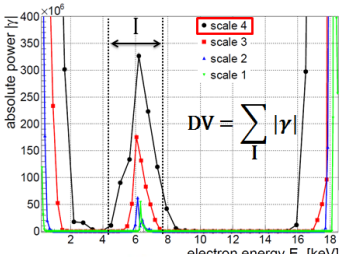
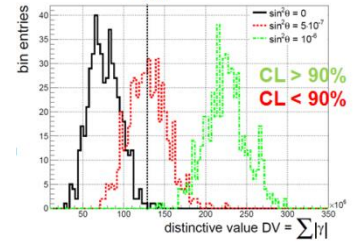
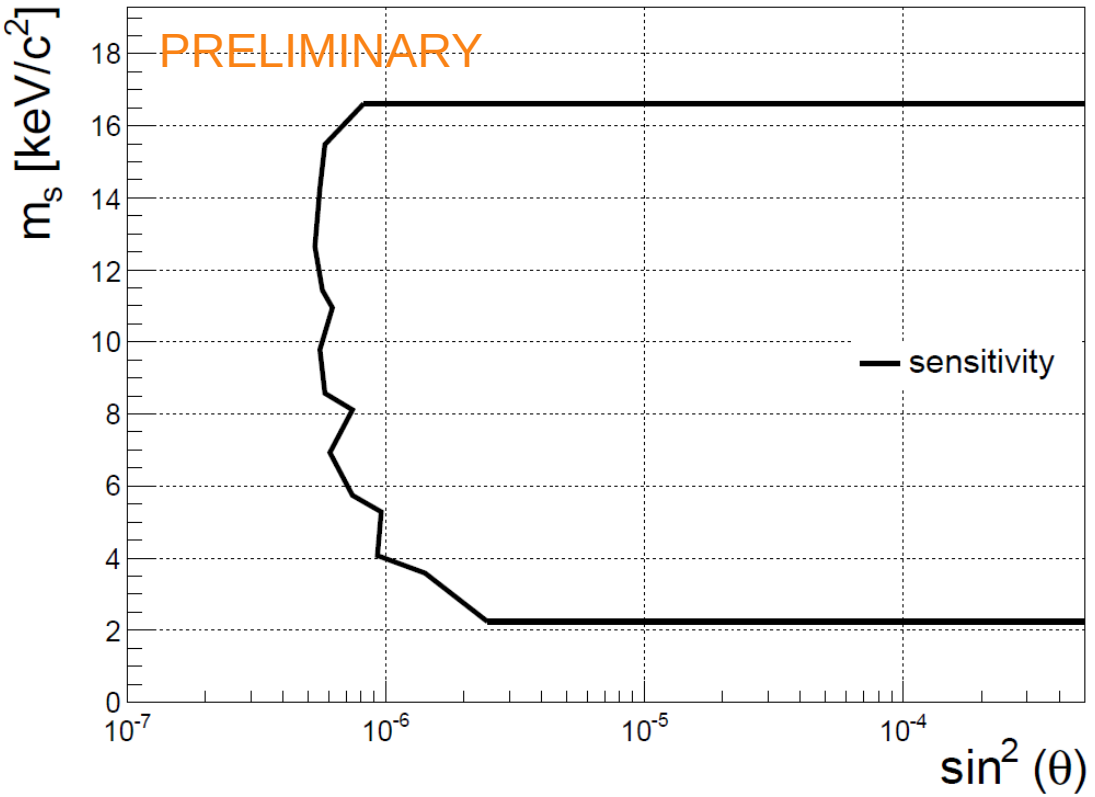


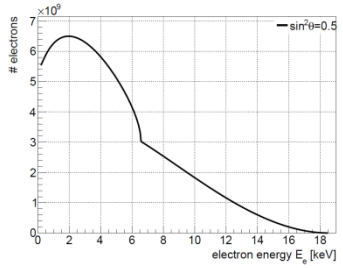
MC+
CL90





Apply steps above for different keV-neutrino masses m_s

Analysis of the Tritium $\beta-$ decay spectrum



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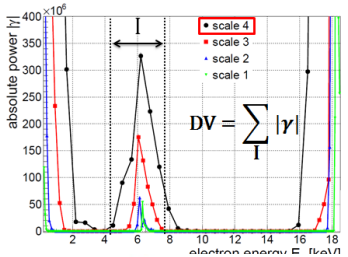

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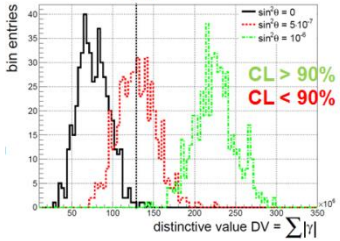

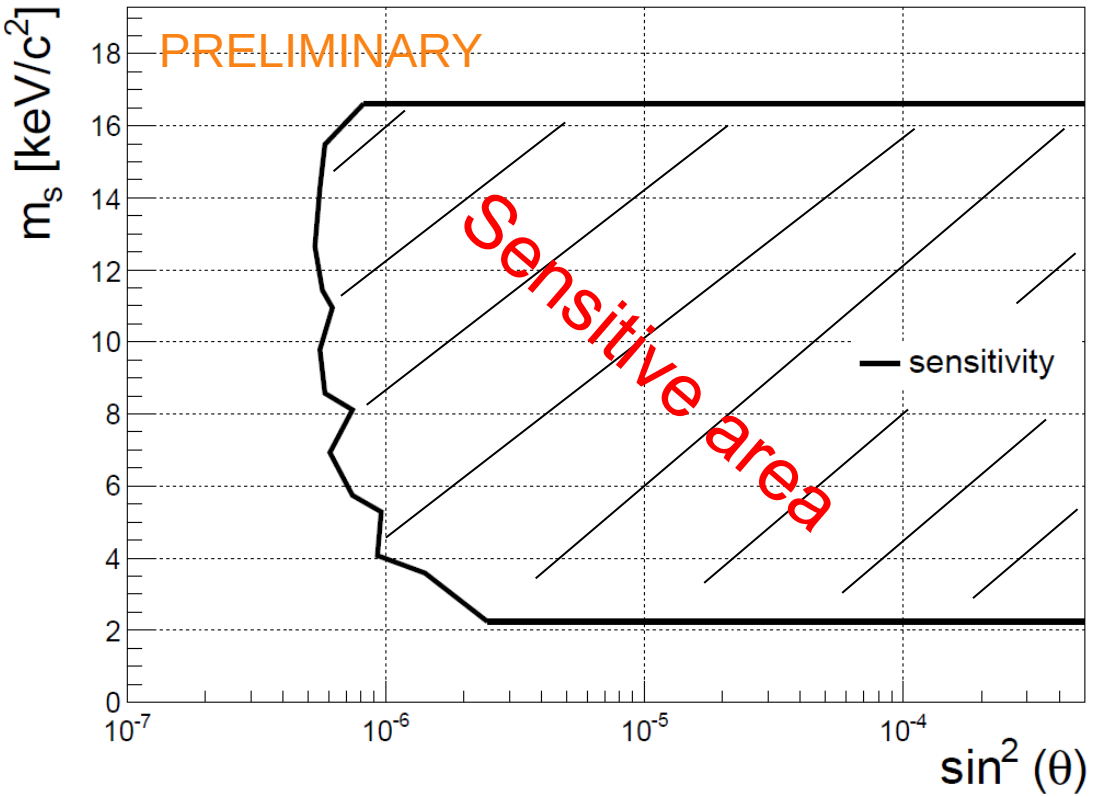

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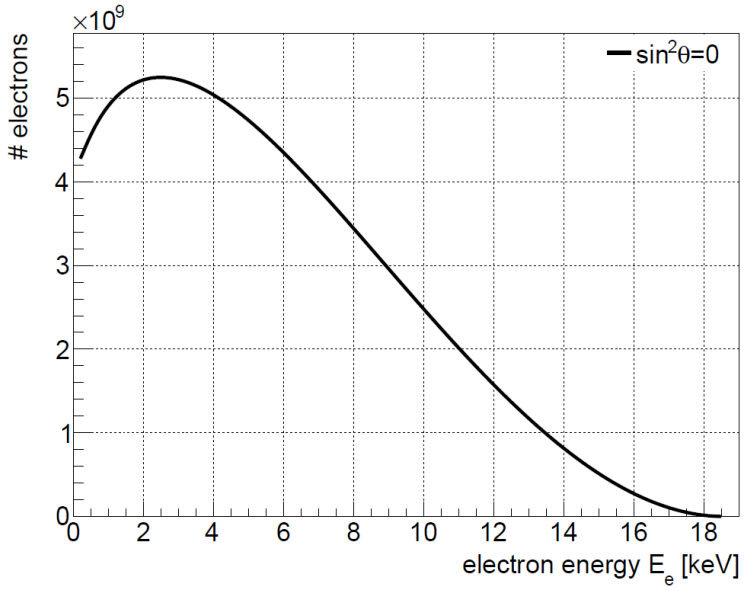
Results – Statistical sensitivity

How is the sensitivity effected by:

- The detector type
- The time of measurement

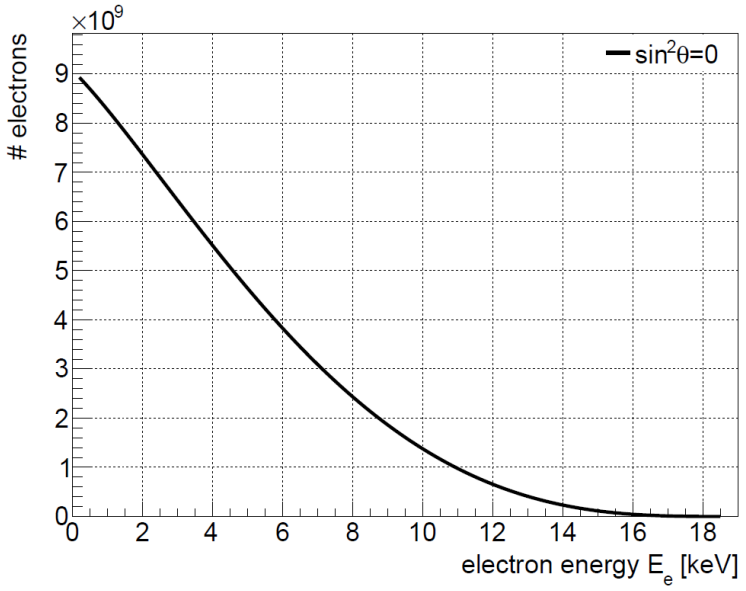
Results – Statistical sensitivity

Differential detector



$$\sin^2\theta = 0$$

Integral detector



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Results – Statistical sensitivity

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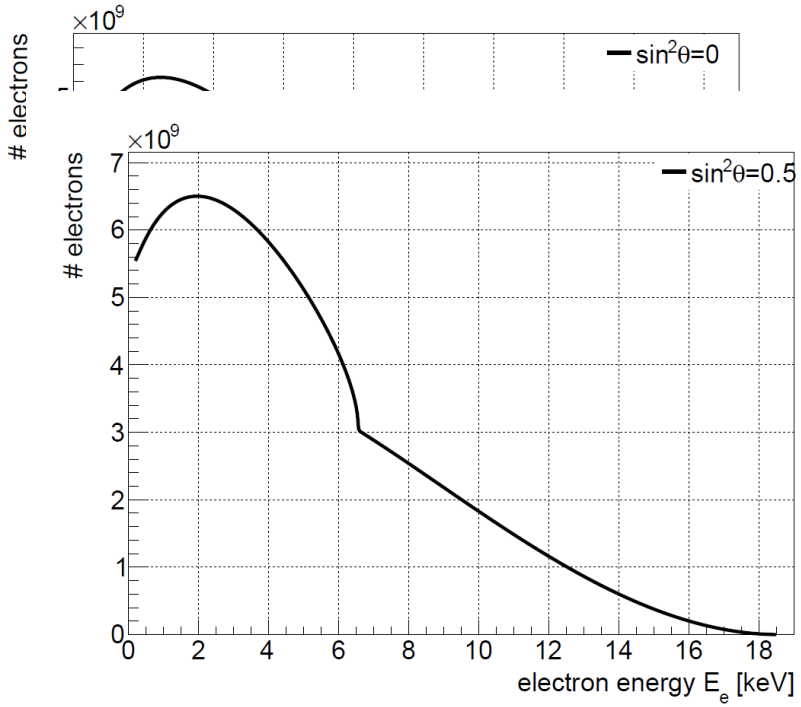
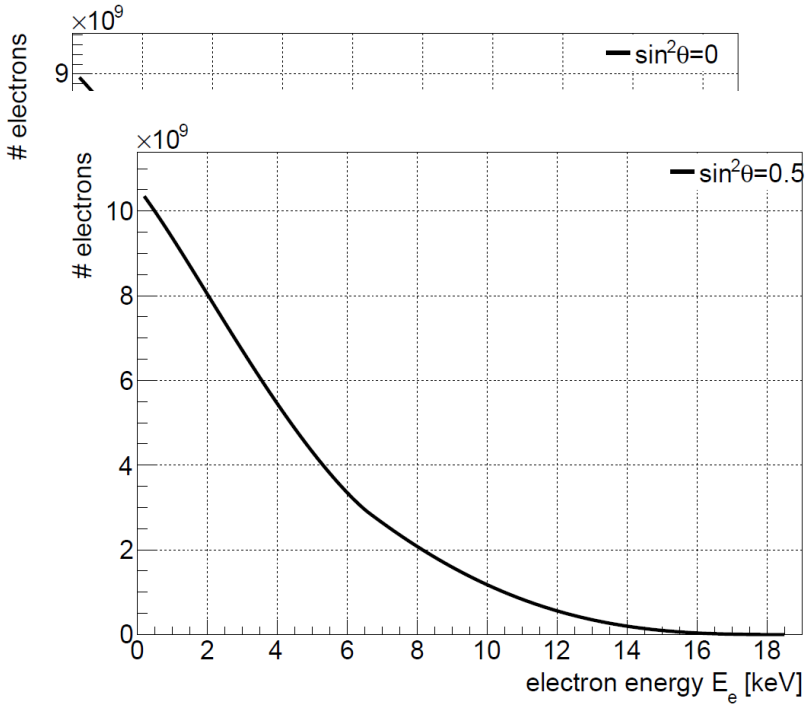


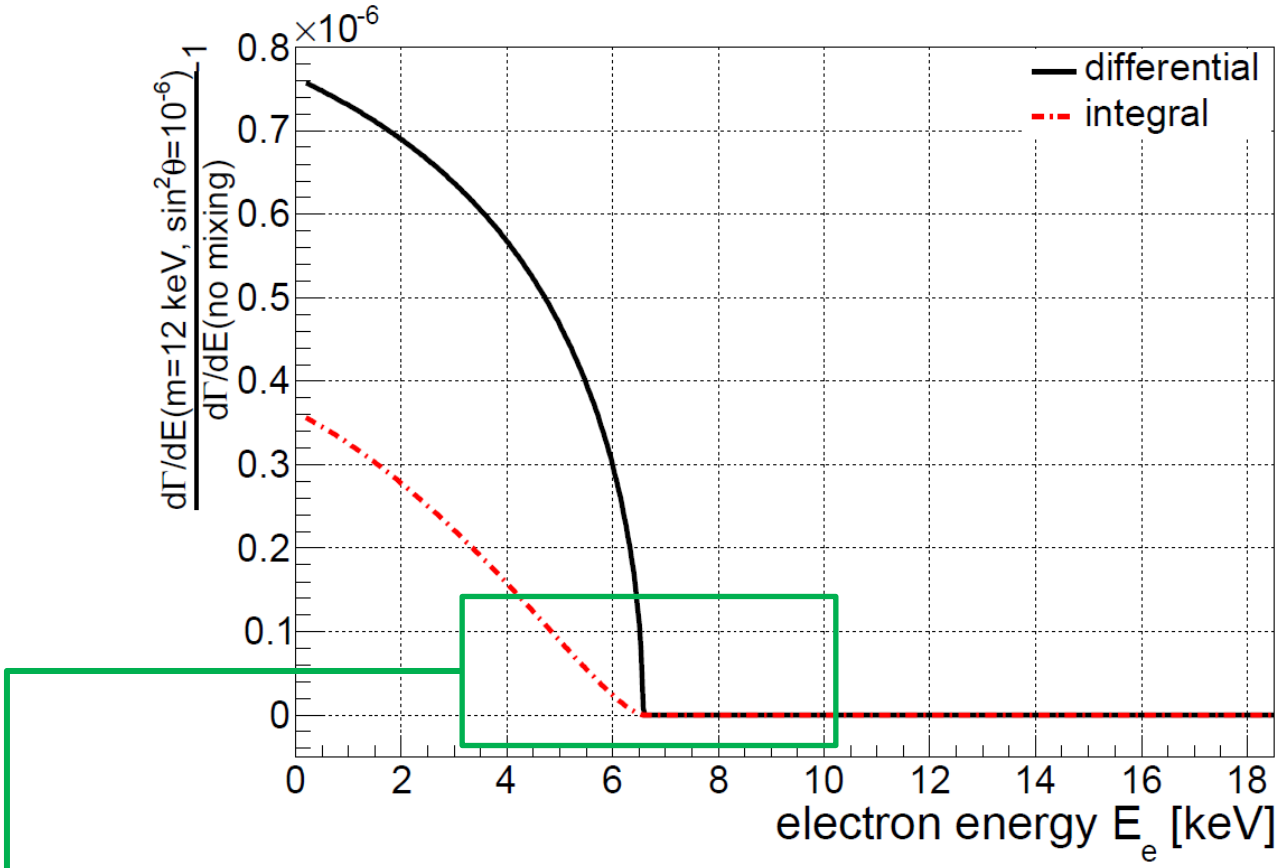
$$\sin^2\theta = 0.5$$

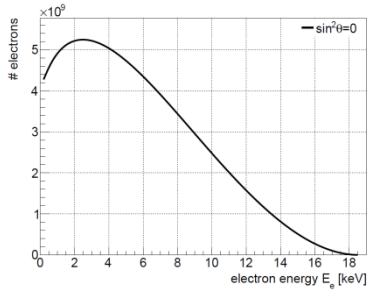
Integral detector



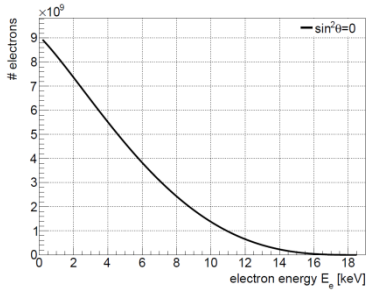
$$\sin^2\theta = 0.5$$

Results – Statistical sensitivity





differential

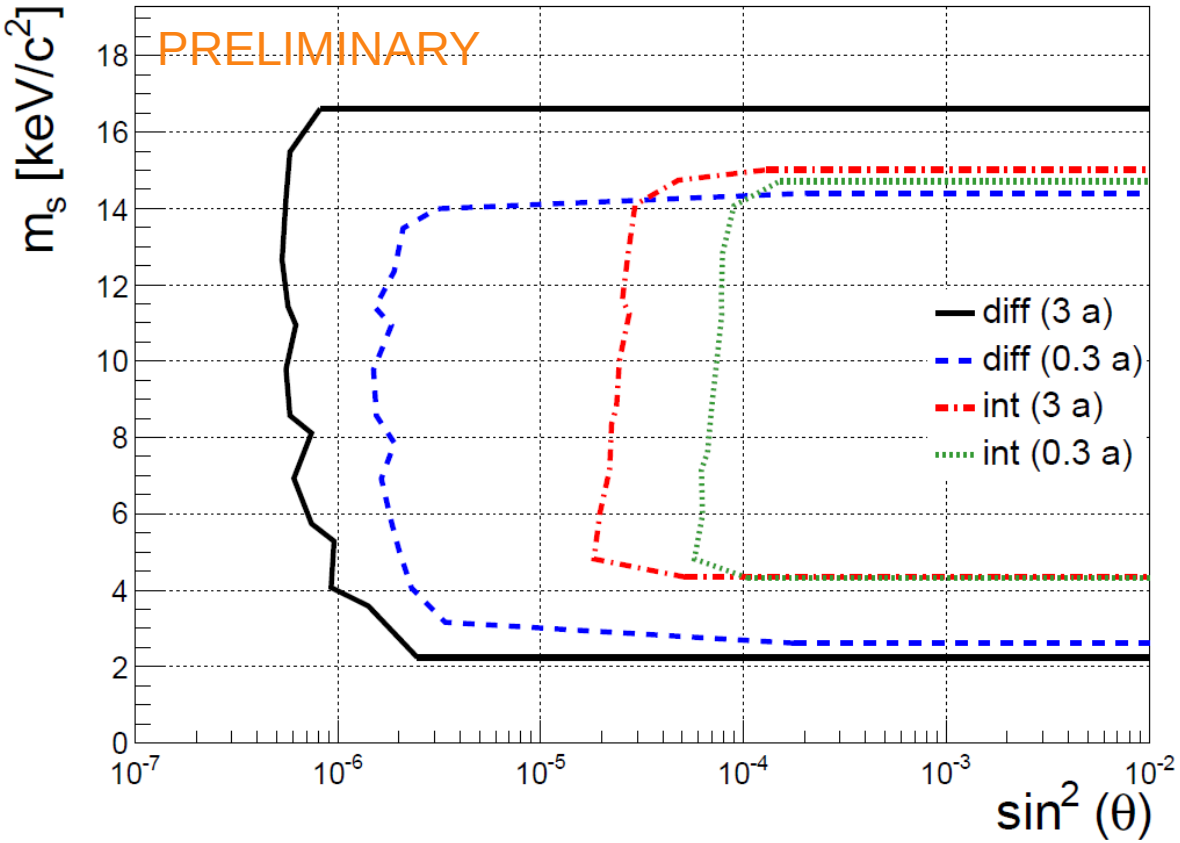


integral

The deviation differences are picked up by the DWT, thus directly correspond to the sensitivity

- $\sin^2\theta = 10^{-6}$
- No corrections

Results – Statistical sensitivity



→ Focus on differential measurement for following analysis

Results - Impact of systematical uncertainties

Detector resolution:

Simulate the detector resolution by convoluting the electron spectrum with a Gaussian curve ($\bar{x} = E$, $\sigma = \mathrm{FWHM}$).

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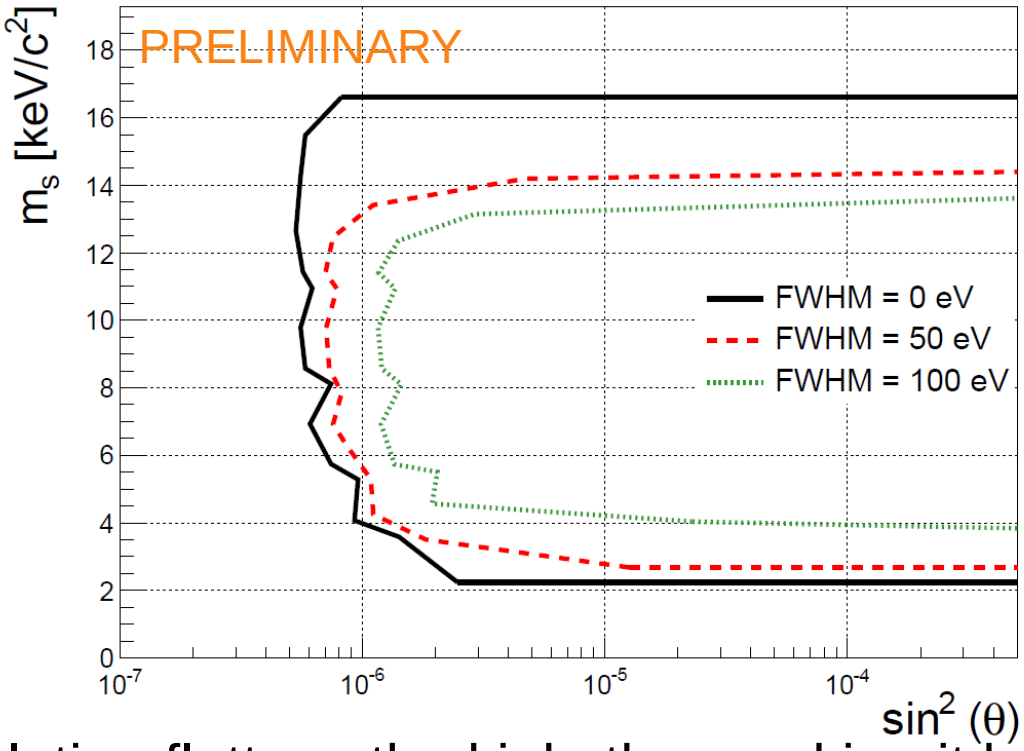


→ The resolution flattens the kink, thus making it harder to detect.

Results - Impact of systematical uncertainties

- Polynomial correction

  There are many corrections, that are to be applied to the electron spectrum.

Correction type	Magnitude
Electron screening	10^{-3}
Beta-eletron to orbital-electron exchange	10^{-3}
Radiative corrections	10^{-3}
nuclear recoil, weak magnetism	10^{-3}
e^- in moving field	10^{-4}
weak interaction finite size	10^{-4}
Extension of nucleus charge	10^{-5}
Final states	10^{-3}

Idea:

Consider a polynomial $p(E)$ which exceeds all other corrections!

Results - Impact of systematical uncertainties

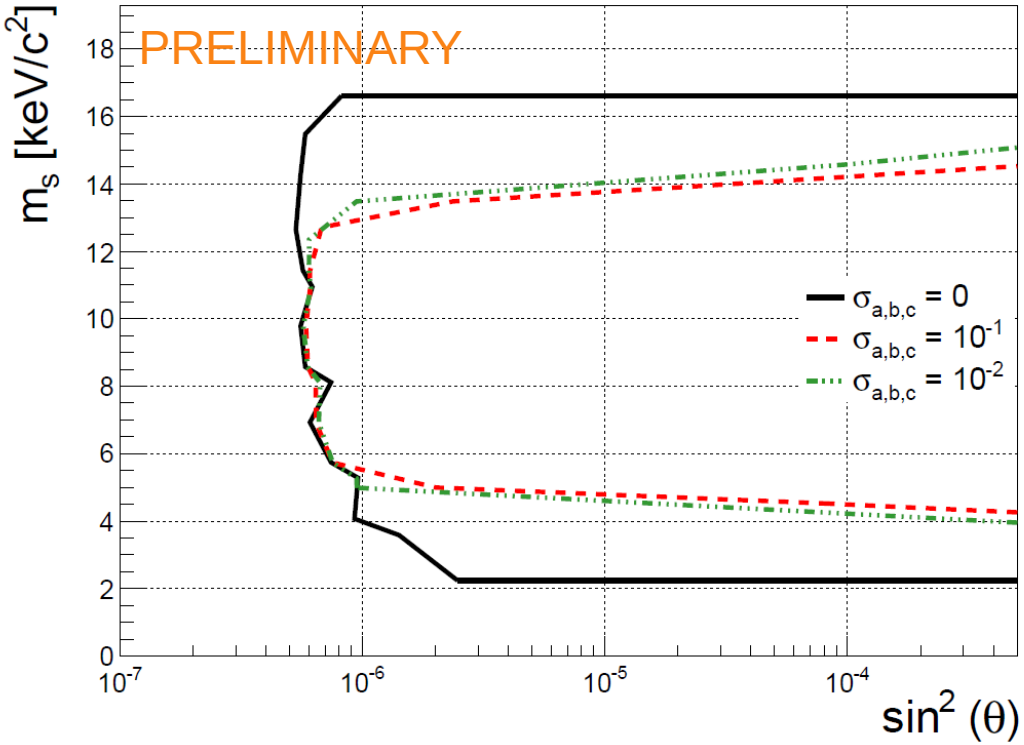
- Polynomial correction

$$p(E) = 1 + a \cdot \frac{E - E_0}{E_0} + b \cdot \left(\frac{E - E_0}{E_0} \right)^2 + c \cdot \left(\frac{E - E_0}{E_0} \right)^3$$

E is the electron energy, E_0 the spectrum endpoint and a, b, c are picked from a Gaussian distribution around $\mathbf{mean} = \mathbf{0}$ and $\boldsymbol{\sigma} = \mathbf{10^{-1}, 10^{-2}}$.

Results - Impact of systematical uncertainties

- Polynomial correction



Polynomial correction does not effect the sensitivity but changes the covered mass range.

Conclusion

- WDM is a viable scenario fitting all astro/cosmo data and keV neutrinos are suitable candidate for WDM
- Experiment with KATRIN source strength and a new detector system provides great statistical sensitivity of $\boldsymbol{\sin^2\theta > 10^{-8}}$ (**Spectral fit approach**), probing the cosmological favored region
- **Wavelet approach:**
  - Basically independent of shape of the tritium spectrum
  - A statistical sensitivity of $\boldsymbol{sin^2\theta > 6 \cdot 10^{-7}}$ is achievable
  - Good energy resolution ($\mathrm{FWHM} \approx 100\ \mathrm{eV}$) needed

Credits

Many thanks to Susanne Mertens,

Guido Drexlin and Alan Poon!