Search for keV Neutrinos with KATRIN

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HELMHOLTZ ASSOCIATION
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KIT
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BERKELEY LAB
Lawrence Berkeley National Laboratory

Overview

- What is the imprint of a keV Neutrino on the beta spectrum?
- What is the theoretical sensitivity of a future KATRIN-like experiment?
- Why are the advantages and limitations of KATRIN?
- What experimental systematic effects can be expected?

Overview

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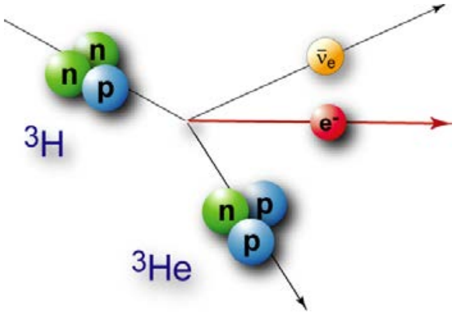
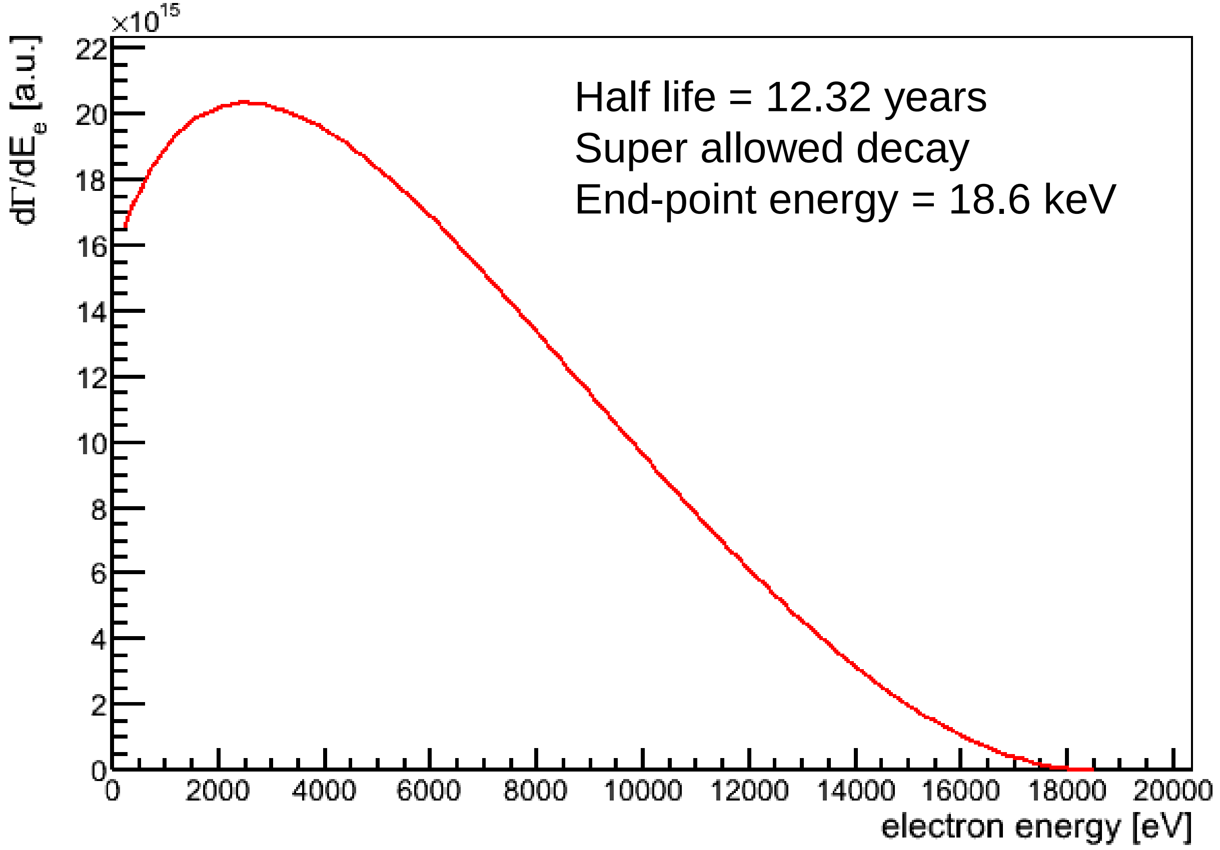
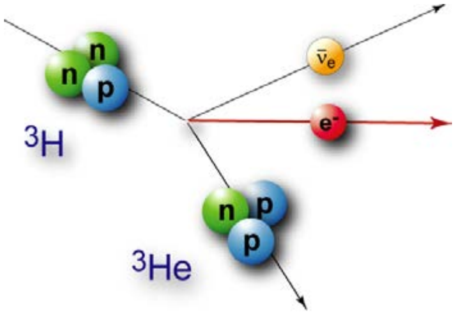
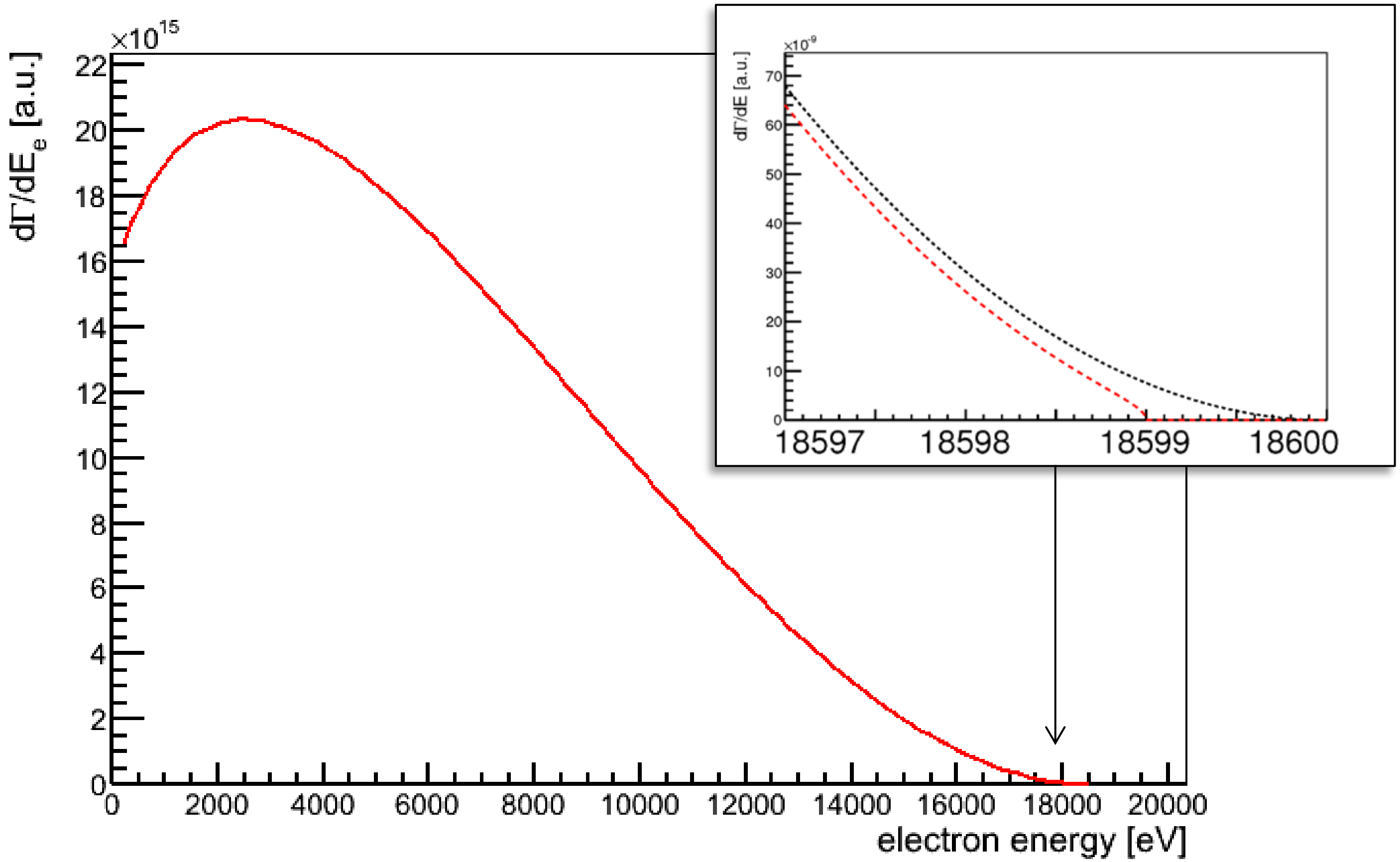
The Tritium beta spectrum



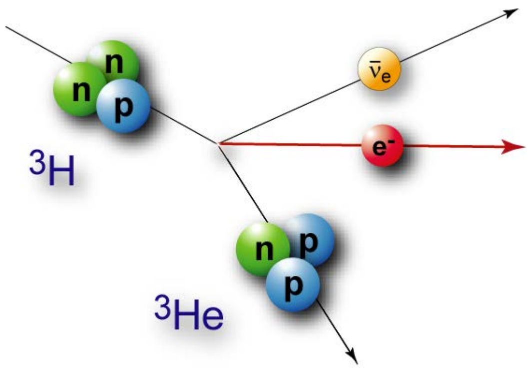


The Tritium beta spectrum



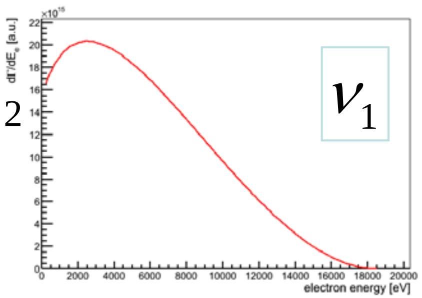


The Tritium beta spectrum

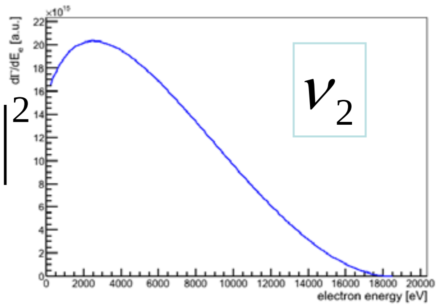


$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

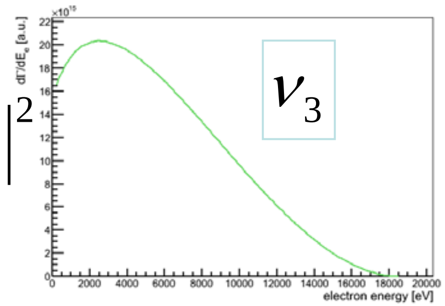
$|U_{e1}|^2$



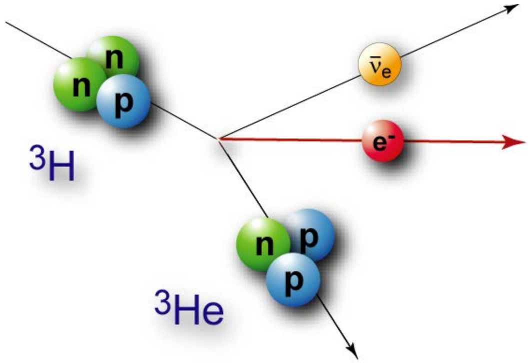
$+ \ |U_{e2}|^2$



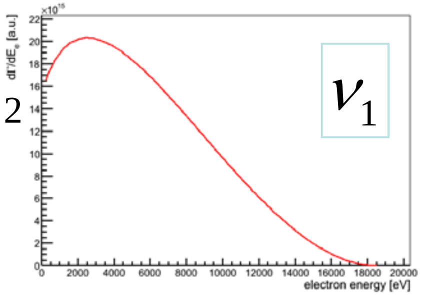
$+ \ |U_{e3}|^2$

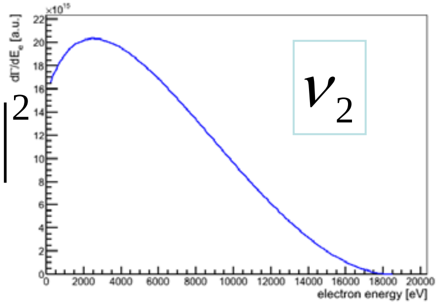


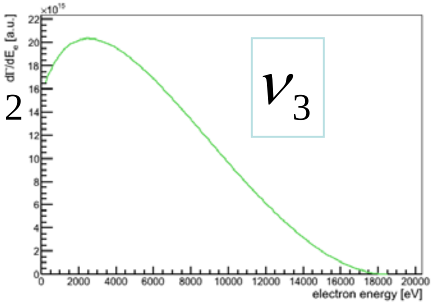
The Tritium beta spectrum



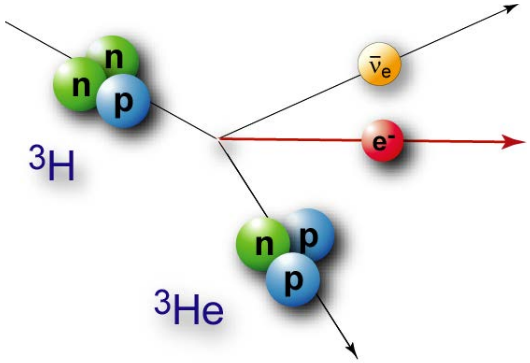
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & 0 \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & 0 \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & 0 \\ 0 & 0 & 0 & U_s \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \boxed{\nu_s} \end{pmatrix}$$

$|U_{e1}|^2$ 

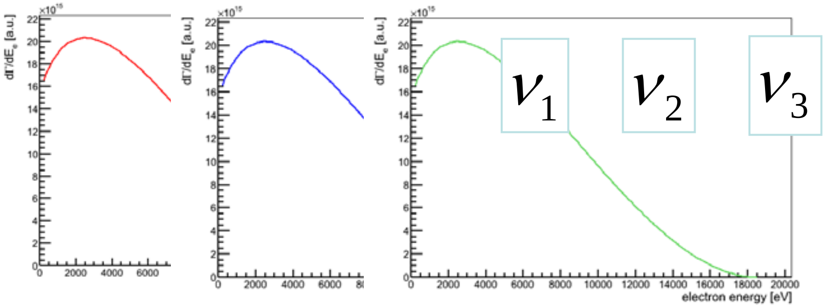
$+$ $|U_{e2}|^2$ 

$+$ $|U_{e3}|^2$ 

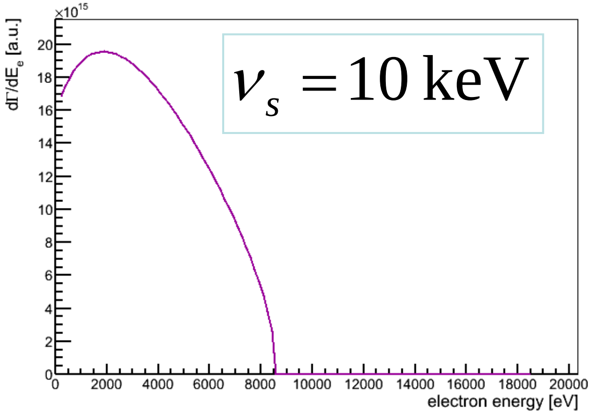
Imprint of a keV Neutrino on the beta spectrum



$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & \boxed{U_{es}} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & 0 \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & 0 \\ 0 & 0 & 0 & U_s \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \boxed{\nu_s} \end{pmatrix}$$



$+ \; |U_{es}|^2$



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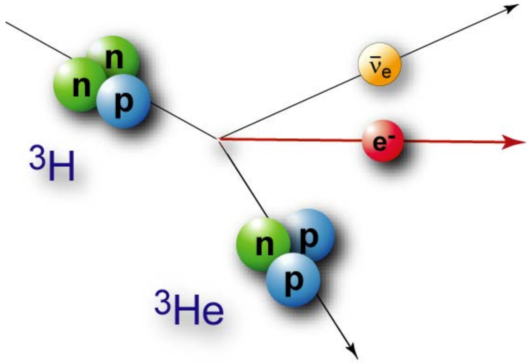
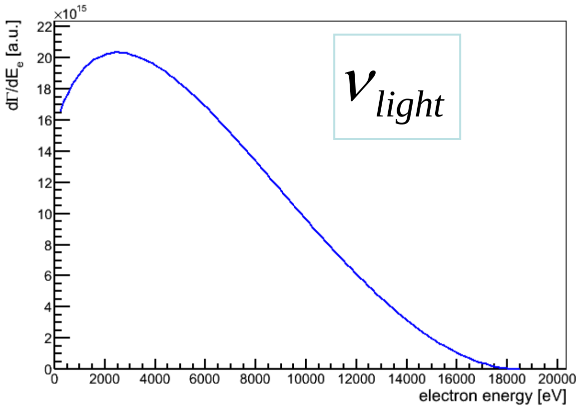
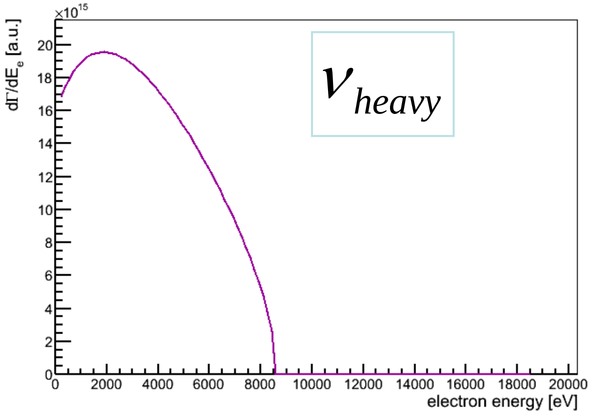


$$\begin{pmatrix} \nu_e \\ \nu_s \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_{light} \\ \nu_{heavy} \end{pmatrix}$$

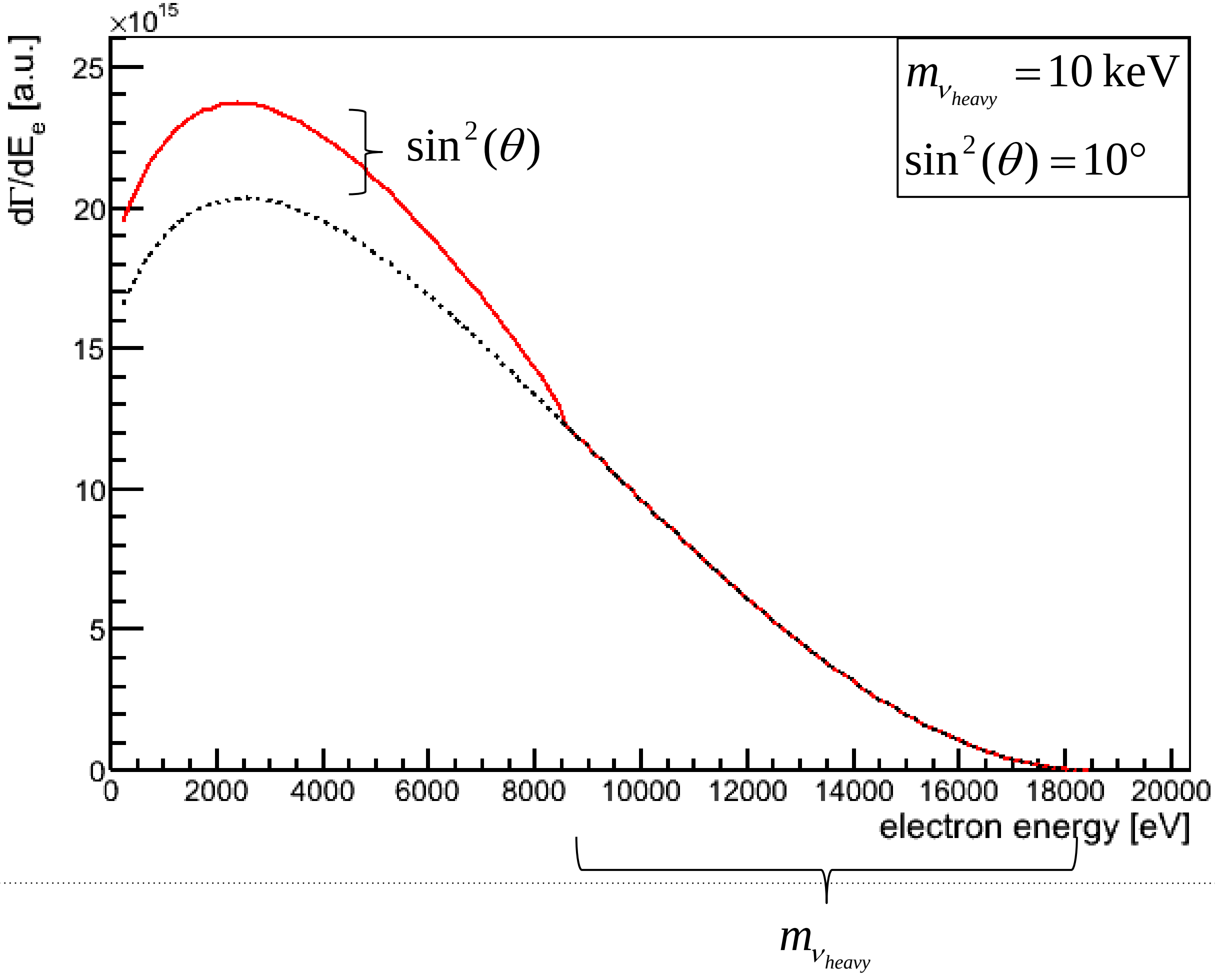
$\cos^2(\theta)$



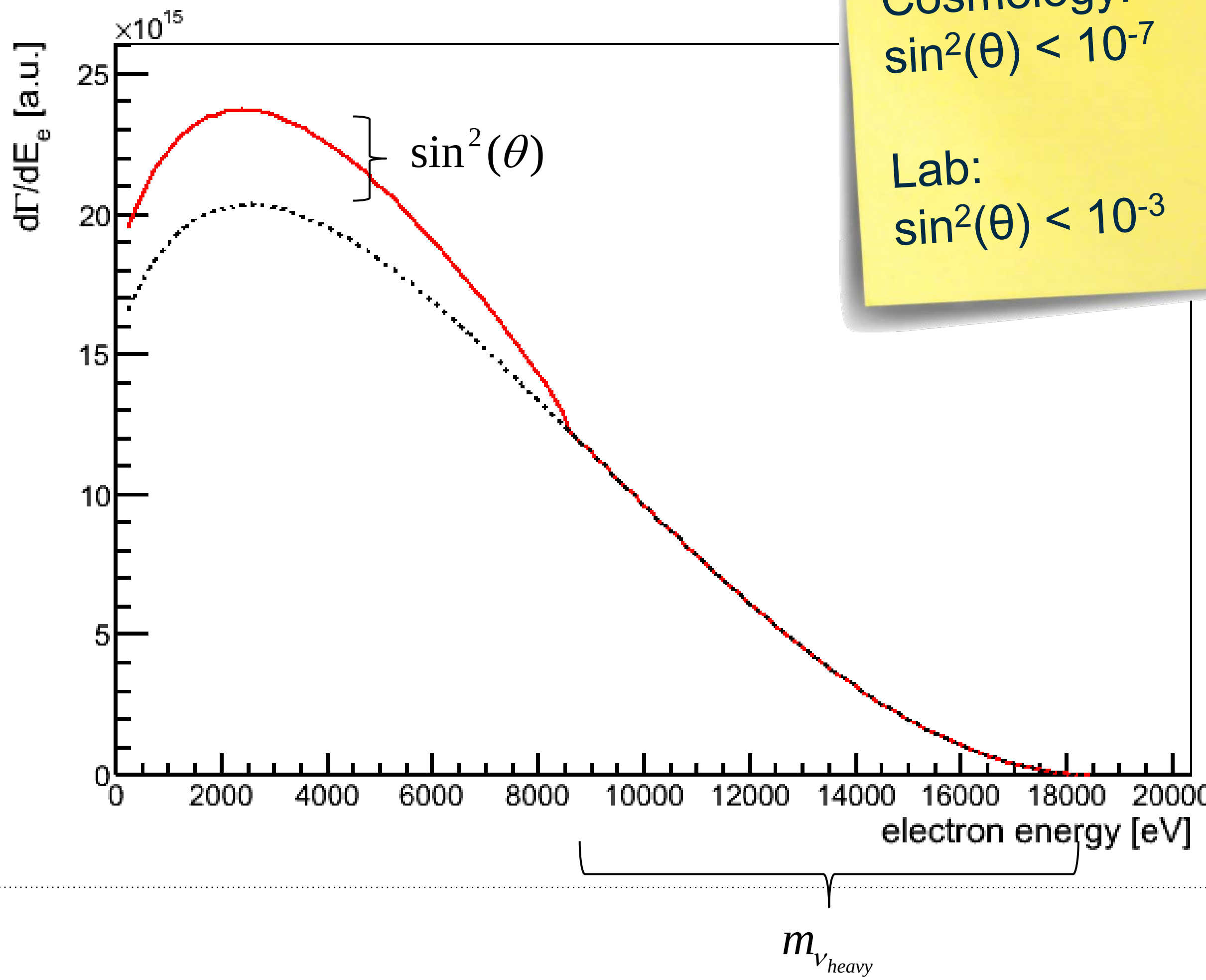
$+ \sin^2(\theta)$



Imprint of a keV Neutrino on the beta spectrum



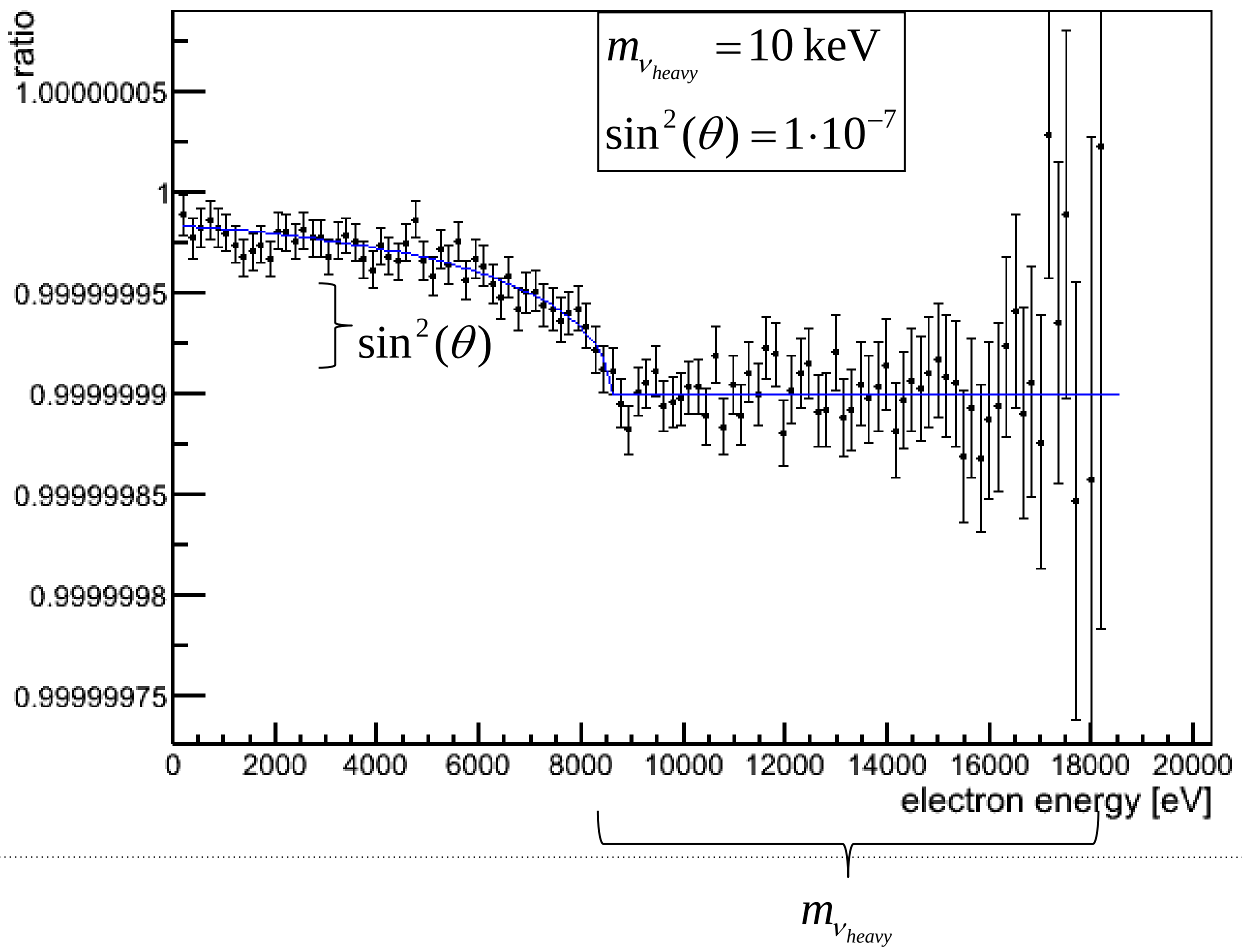
Imprint of a keV Neutrino on the beta spectrum



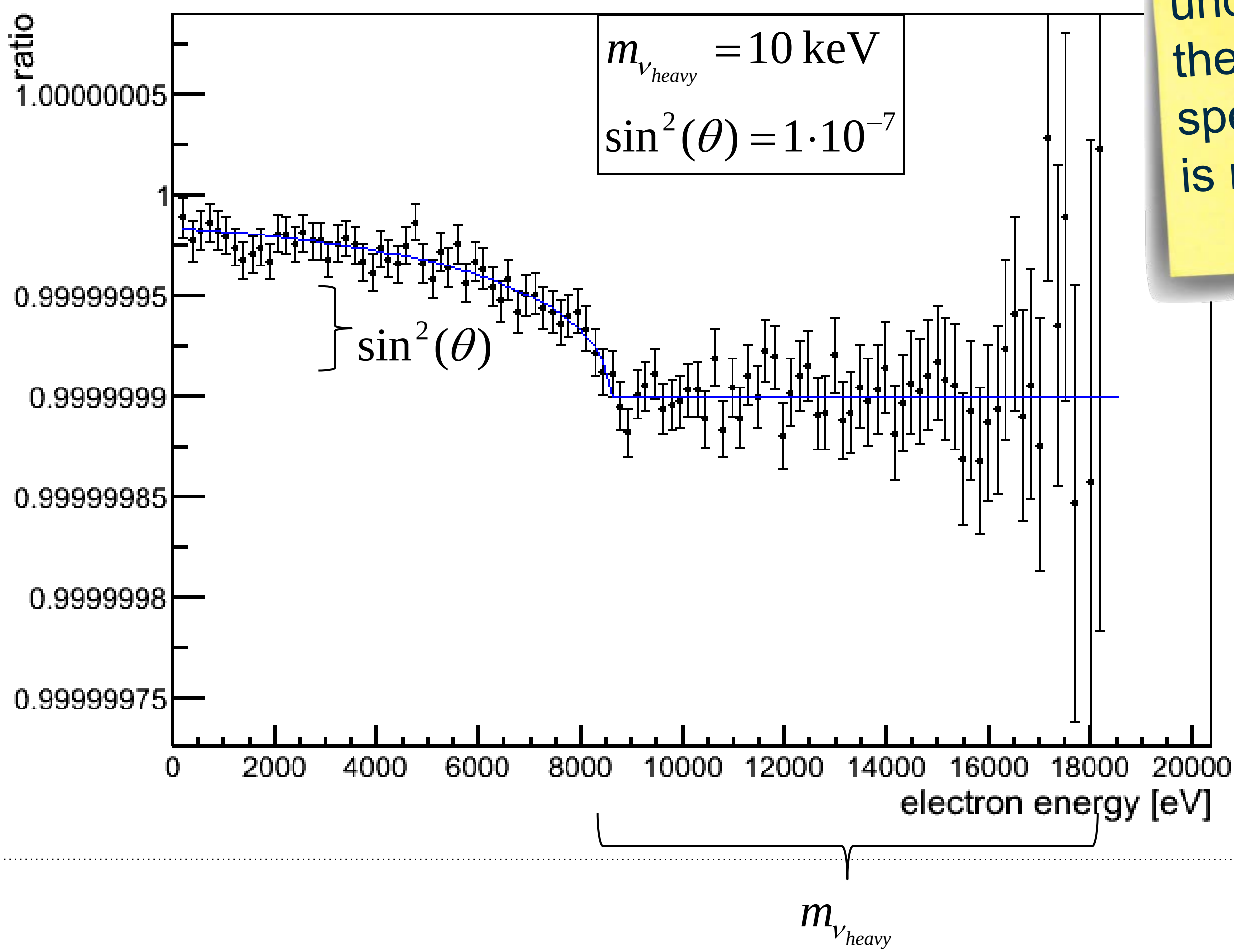
Cosmology:
$\sin^2(\theta) < 10^{-7}$

Lab:
$\sin^2(\theta) < 10^{-3}$

Imprint of a keV Neutrino on the beta spectrum



Imprint of a keV Neutrino on the beta spectrum



Extremely precise undertanding of the theoretical spectrum is necessary

Overview

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Beta spectrum for a single mass

$$\frac{d\Gamma}{dE_e}(m_{\nu_i}) = C \cdot p_e E_e \cdot \sqrt{(E_e - E_0)^2 - m_{\nu_i}{}^2} \cdot (E_e - E_0) \cdot F(E_e, Z) \cdot S(E_e, Z)$$

Normalization constant

Phase space factor

Relativistic Fermi function

Electron screening function

Theoretical corrections

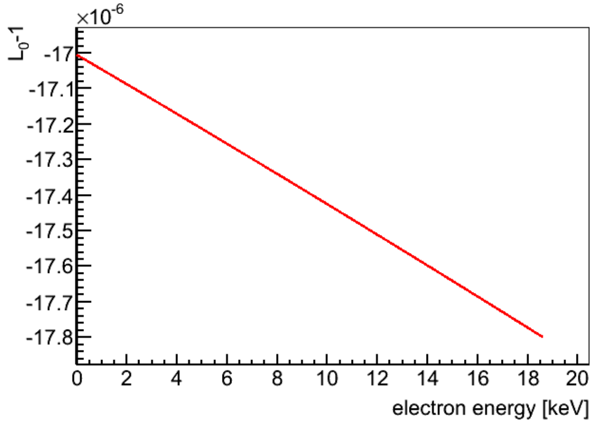
$$\frac{d\Gamma}{dE_e}(m_{\nu_i}) = C \cdot p_e E_e \cdot \sqrt{(E_e - E_0)^2 - m_{\nu_i}{}^2} \cdot (E_e - E_0) \cdot F(E_e, Z) \cdot S(E_e, Z)$$

- Beta electron to orbital electron exchange (E)
- He recoil corrections: 3 body decay, weak magnetism, V-A correction (R)
- Recoiling Coulomb field (Q)
- Finite extension of the nucleus: Coulomb field and weak interaction (L0, C)
- Radiative corrections (G)

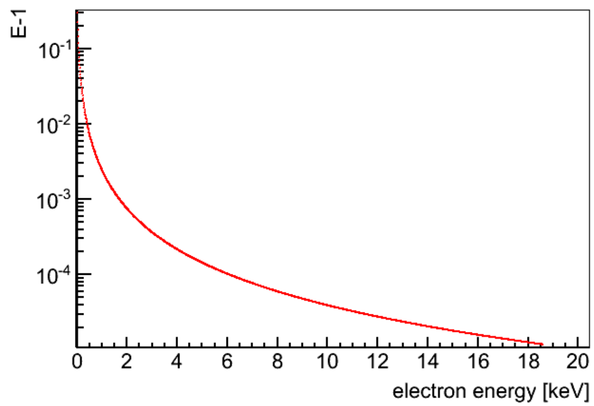
D. H. Wilkinson, Nuclear Physics A 526 (1991)
Wayne W. Repko and Chonge-en Wu, Phys. Rev. C, 28, 6, (1983)
Wayne W. Repko and Chonge-en Wu, Phys. Rev. C, 27, 4 (1983)
J. J. Simpson Pys. Rev D23 (1981)
L. R. B. Elton, Nucl. Phys. 5, 173 (1958)
John A. Jaros, SLAC-PUB-5958, 1992
P. Huber, arXiv:1106.0687v4

Theoretical corrections

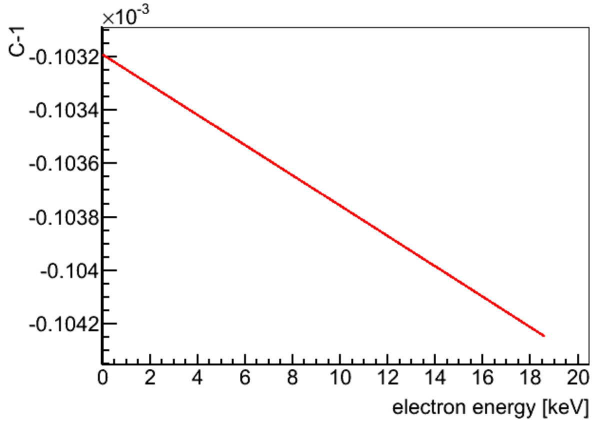
Finite extension of nuleus



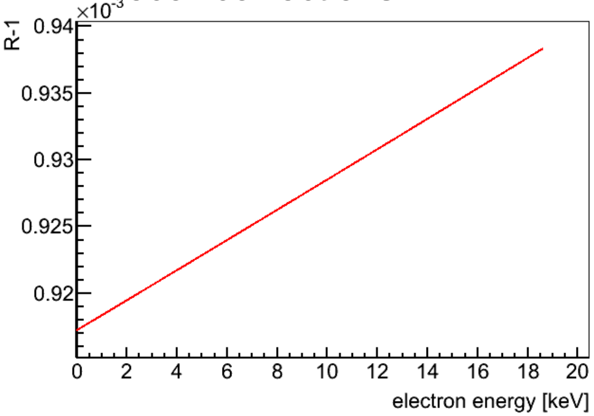
Orbital exchange



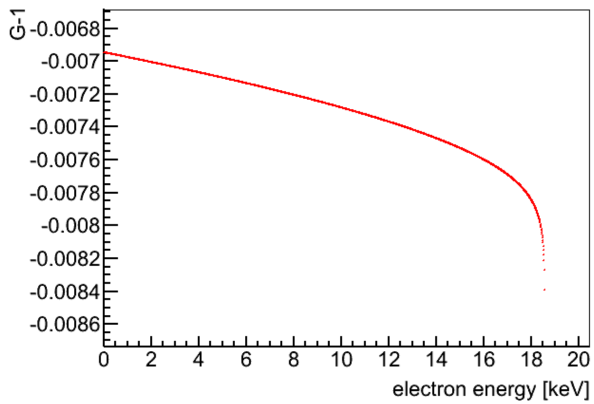
Weak interaction finite size



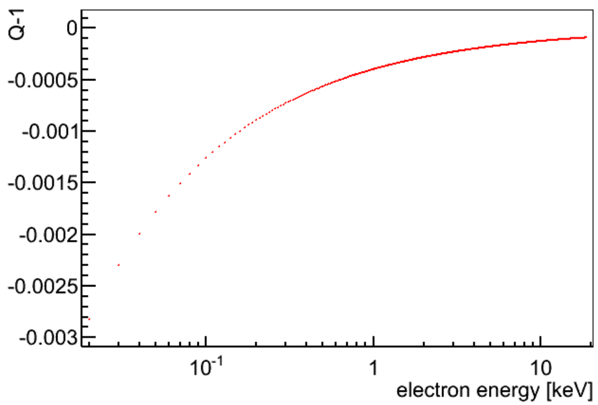
Recoil corrections



Radiative corrections



Recoiling Coulomb field



Theoretical corrections

$$\left(\frac{d\Gamma}{dE_e}\right)^{corr} = \frac{d\Gamma}{dE_e} \cdot \left[\prod_{\Psi = \mathrm{L}_0, \mathrm{S}, \mathrm{E}, \mathrm{Q}, \mathrm{R}, \mathrm{G}} \Psi(E_e, Z) \right]$$

$$\uparrow$$

$$\Psi = 1 + \alpha \cdot f(E_e, E_0)$$

Theoretical corrections

$$\left(\frac{d\Gamma}{dE_e}\right)^{corr} = \frac{d\Gamma}{dE_e}\cdot\left[\prod_{\Psi=\mathrm{L}_0,\,\mathrm{S},\,\mathrm{E},\,\mathrm{Q},\,\mathrm{R},\,\mathrm{G}} \Psi(E_e, Z)\right]\cdot SF(E_e)$$

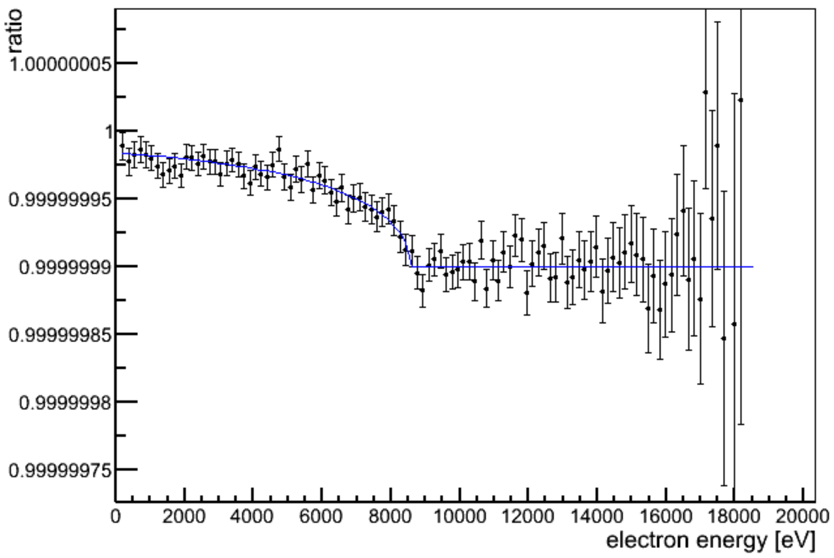
$$\uparrow \qquad\qquad \uparrow$$

$$\Psi = 1 + \alpha\cdot f(E_e, E_0) \qquad SF = \text{polynomial shape factor}\,(\beta, \gamma, \delta)$$

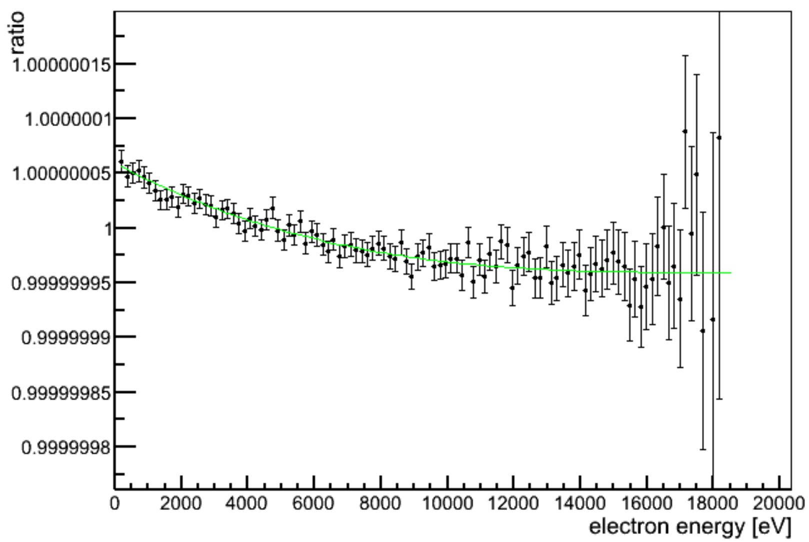
free parameters

Effect of theoretical uncertainty

Signal of keV neutrino



Effect of an unknown polynomial correction



$$X^2 = \sum_i \frac{\left(N_i^{data} - N_i^{\mathrm{mod}el}\right)^2}{\sigma_i^2} + \sum_j \frac{\left(\alpha_j^{real} - \alpha_j^{fit}\right)^2}{\sigma_j^2}$$

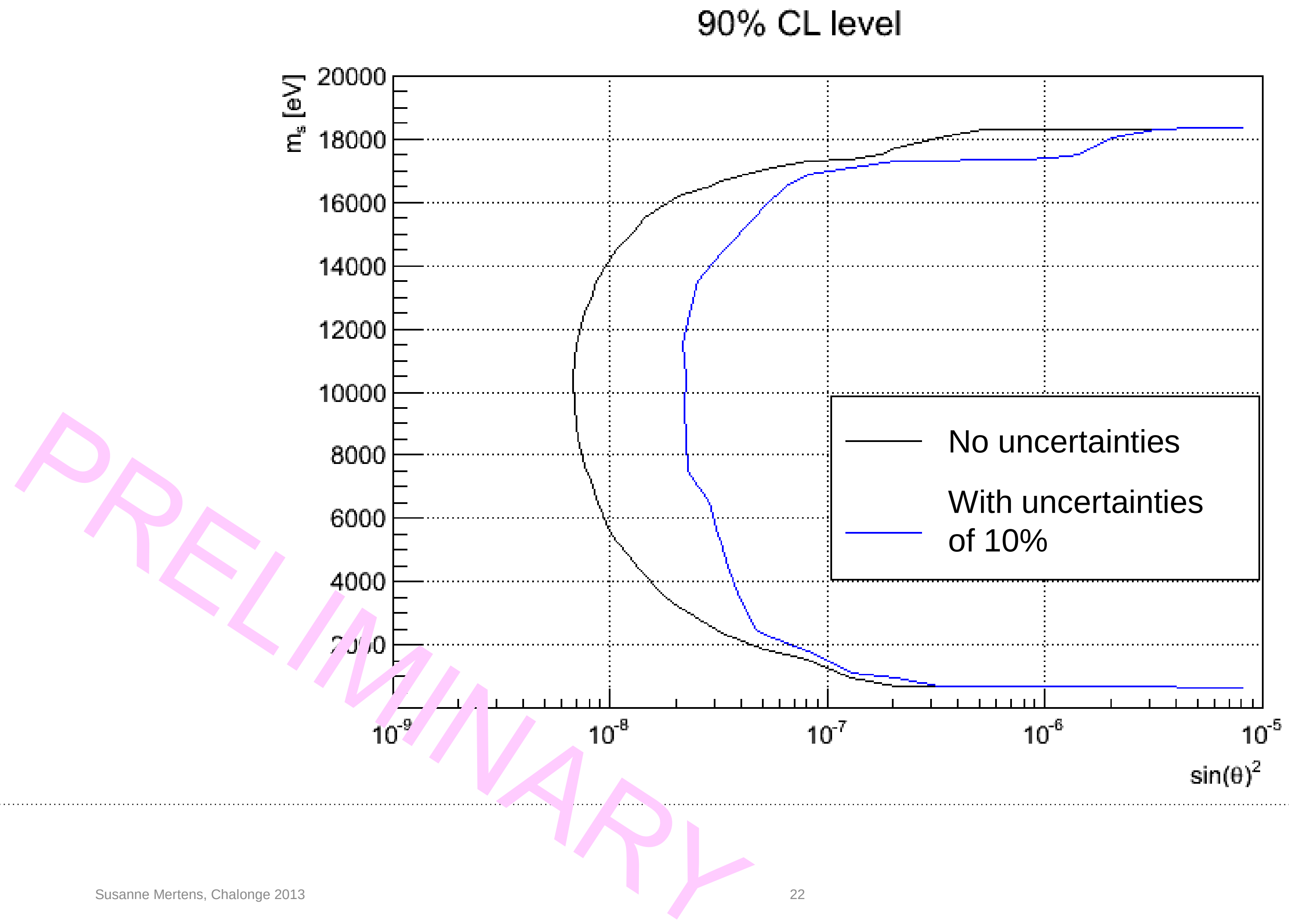
Setup for this study

- Assume KATRIN source strength of 10^{11} e/s
- 3 years measurement time

$\rightarrow 10^{18}$ decays

- Perfect detector

Is it worth considering this experiment?



Final state distribution

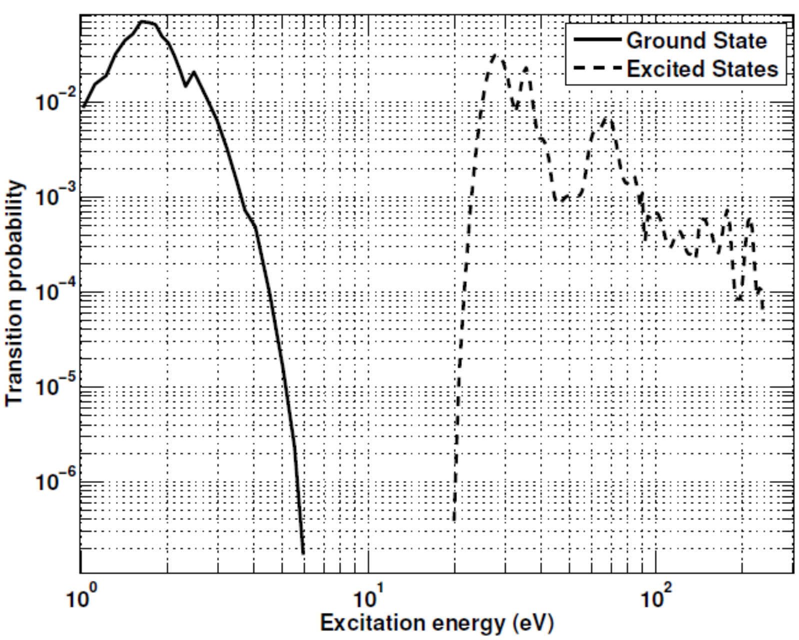
$$\left(\frac{d\Gamma}{dE_e}\right)^{corr} \propto \sum_i P_i \frac{d\Gamma}{dE_e}\left(E_0 - E_i^f\right)$$

$$P^{ground} = 0.6 - \varepsilon$$

$$P^{excited} = 0.4 + \varepsilon$$

free parameter

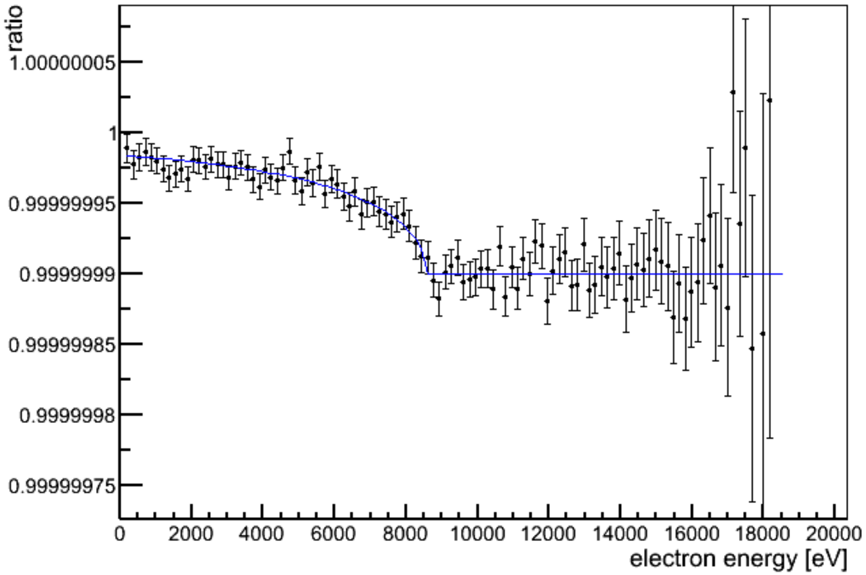
Excitation spectrum of the daughter (^{3}HeT)$^+$ in β–decay of molecular T_2



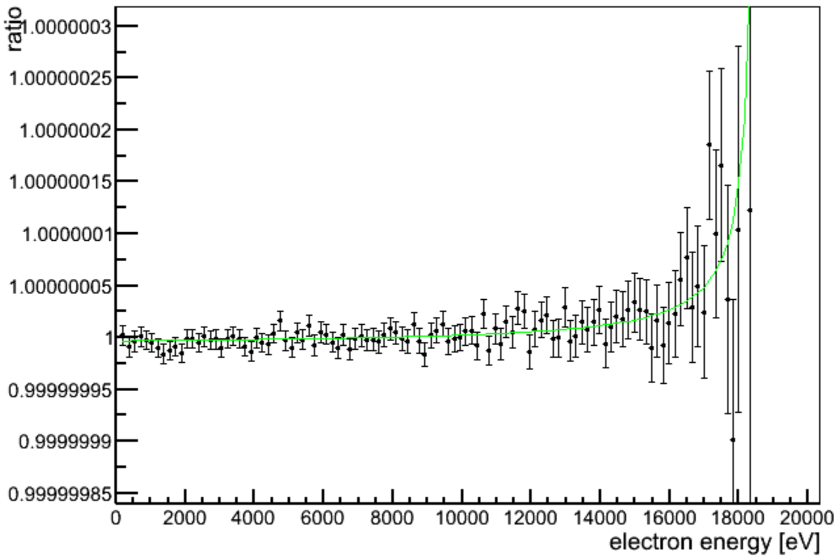
N. Doss and J. Tennyson, J. Phys. B, At. Mol. Opt. Phys. 41 (2008)
N. Doss, J. Tennyson, A. Saez, S. Jonsell, Phys. Rev. C 73, 025502 (2006)
A. Saez, S. jonsell, P. Froelich, Phys. Rev. Lett. 84, 242–245 (2000)

Can the FSD distribution fake a signal?

Signal of keV neutrino

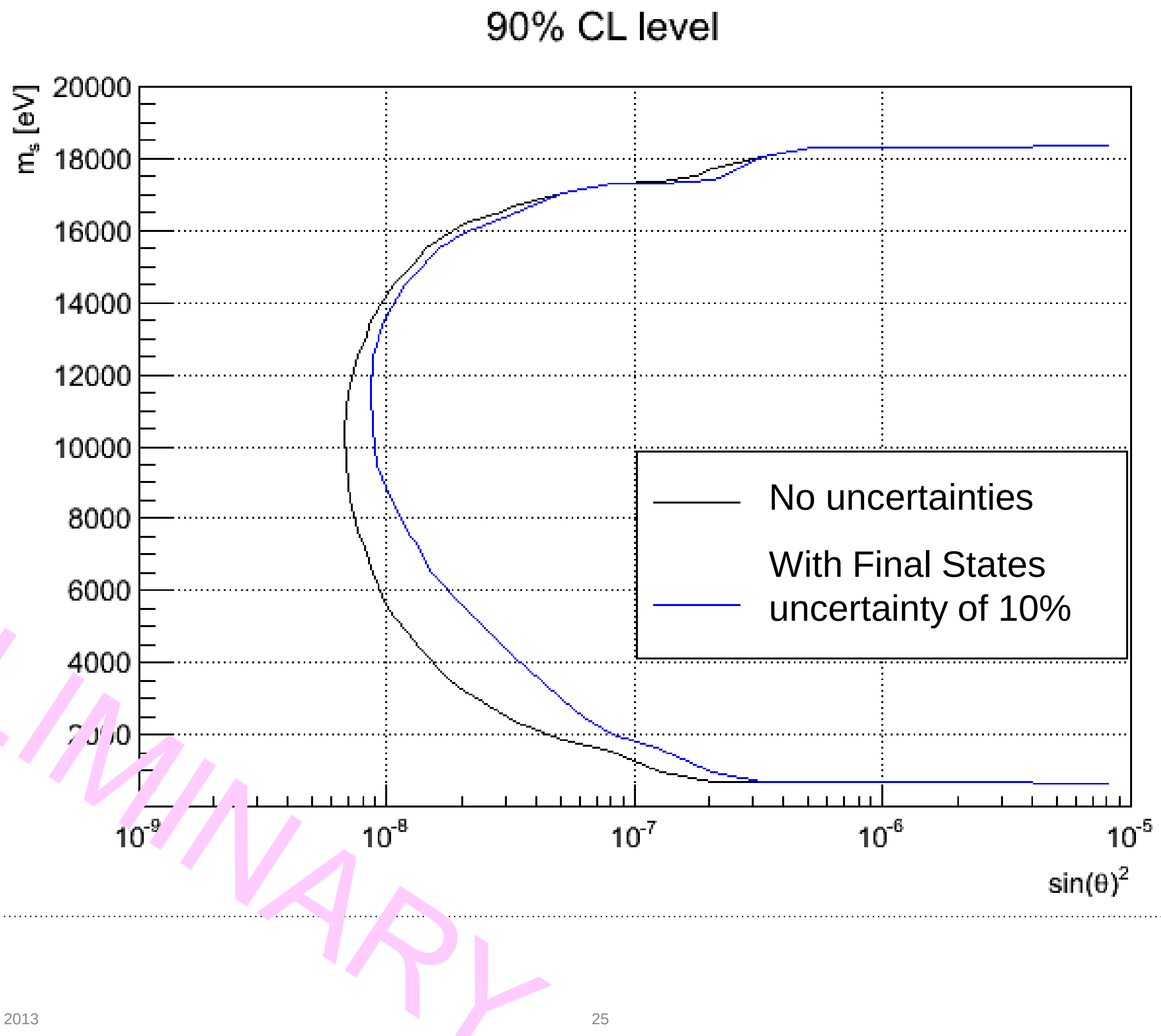


Effect of a wrong ground state probability



$$X^2 = \sum_i \frac{\left(N_i^{data} - N_i^{\mathrm{mod}el}\right)^2}{\sigma_i^2} + \sum_j \frac{\left(\alpha_j^{real} - \alpha_j^{fit}\right)^2}{\sigma_j^2}$$

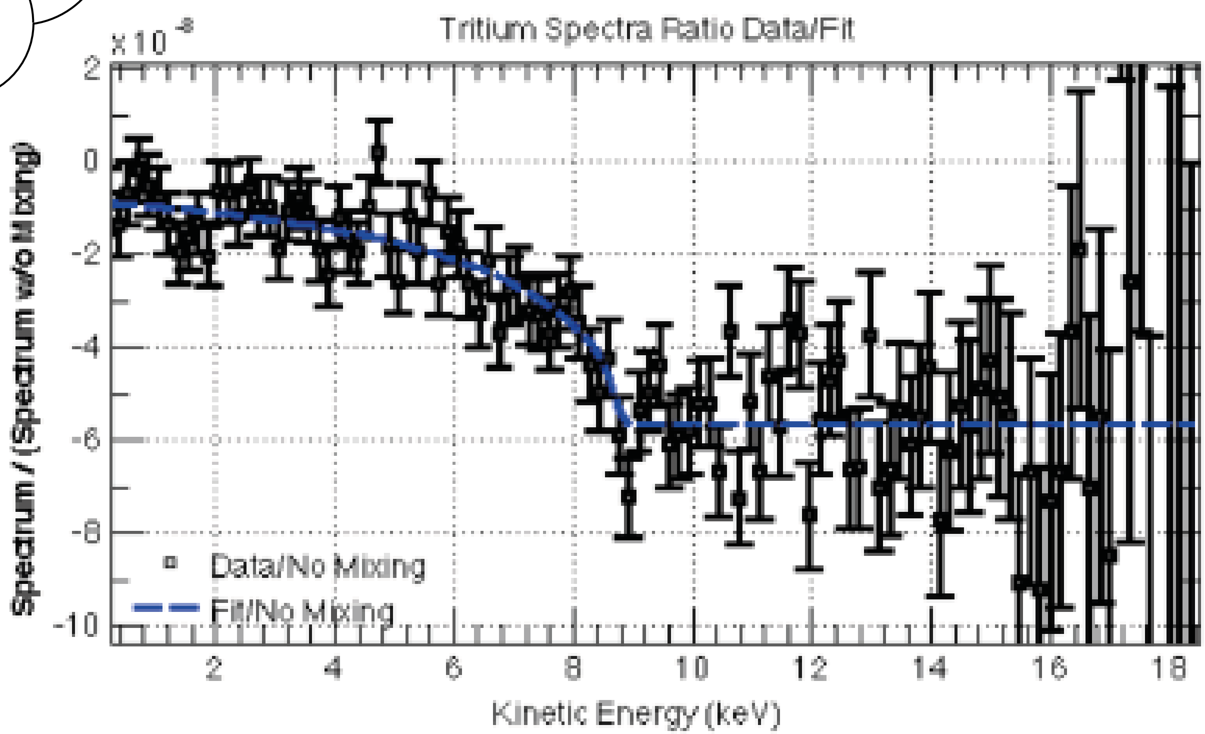
Is it worth considering this experiment?



Blind Test with Thierry

$$m_{\nu_{heavy}} = 10\,\mathrm{keV}$$

$$\sin^2(\theta) = 5\cdot 10^{-8}$$



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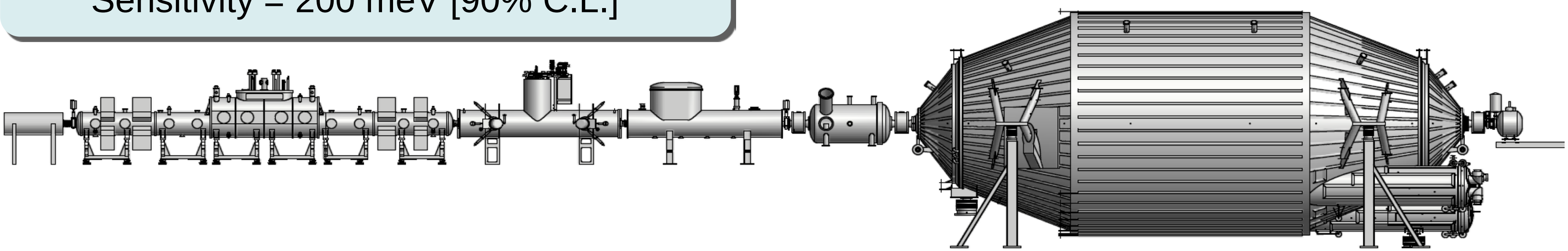
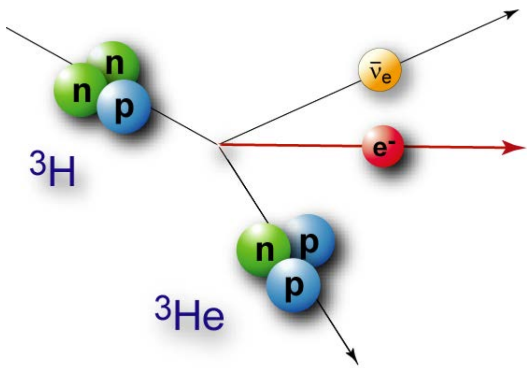
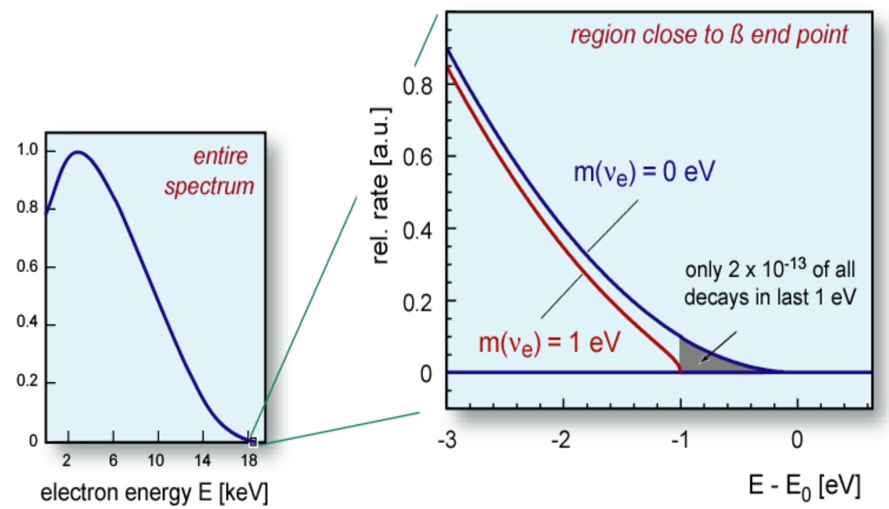
The KATRIN experiment

Goal: Direct neutrino mass measurement
Sensitivity = 200 meV [90% C.L.]



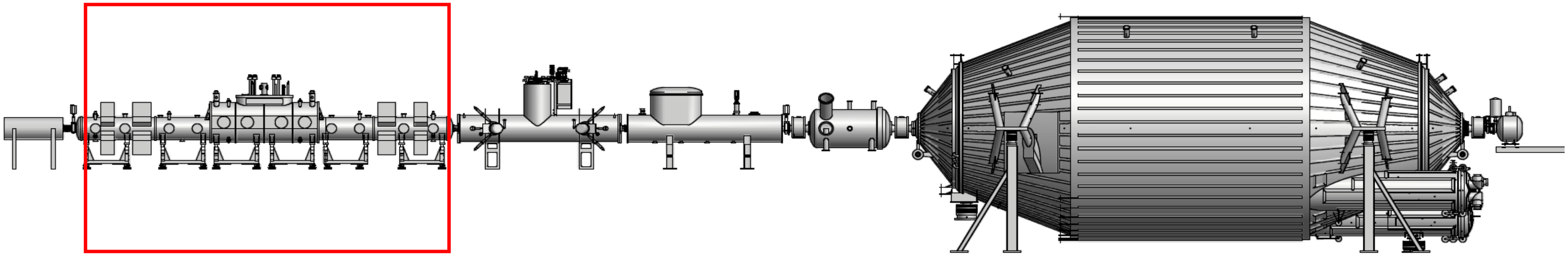


$$^3H \rightarrow {}^3He + e^- + \bar{\nu}_e$$



The KATRIN experiment

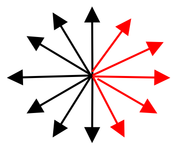
Windowless gaseous tritium source



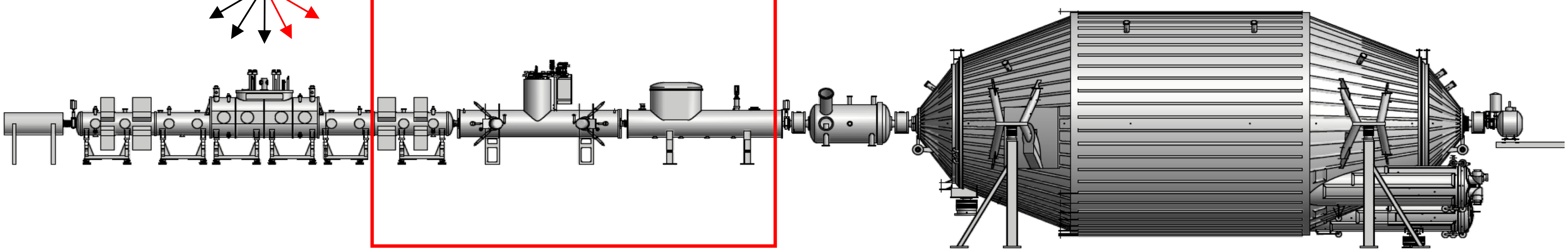
Yearly throughput of
10 kg (≡ ITER)

ß- intensity of
10^{11} electrons/s

The KATRIN experiment



Transport section



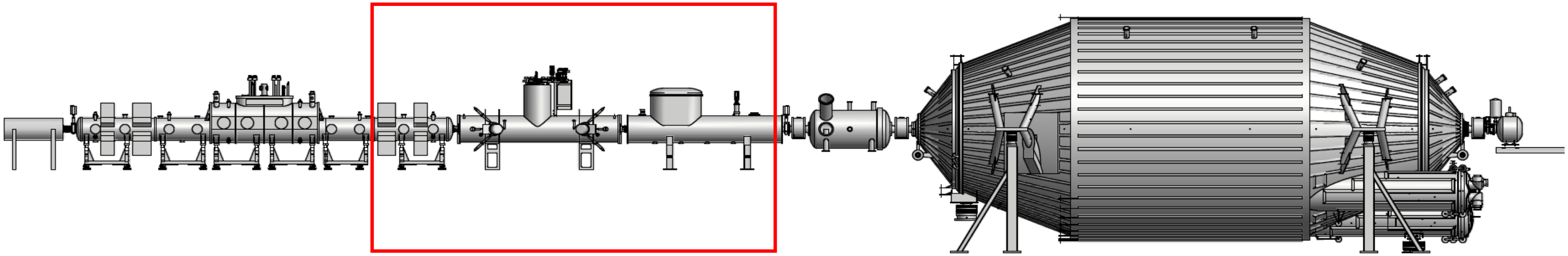
Adiabatic guidance of beta electrons

Transport section:
12 solenoids at 5.7 T

Total KATRIN system:
37 solenoids

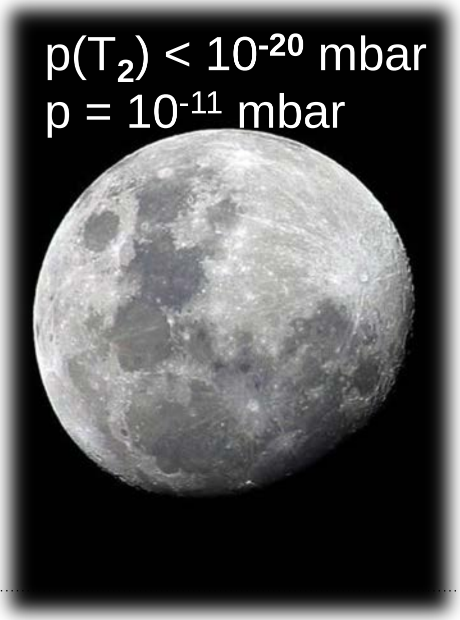
The KATRIN experiment

Transport section



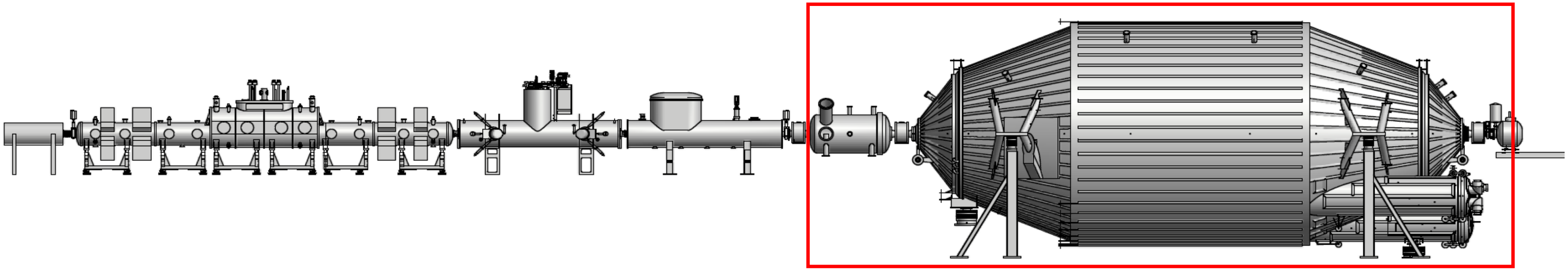
R>10^7 **R>10^7**

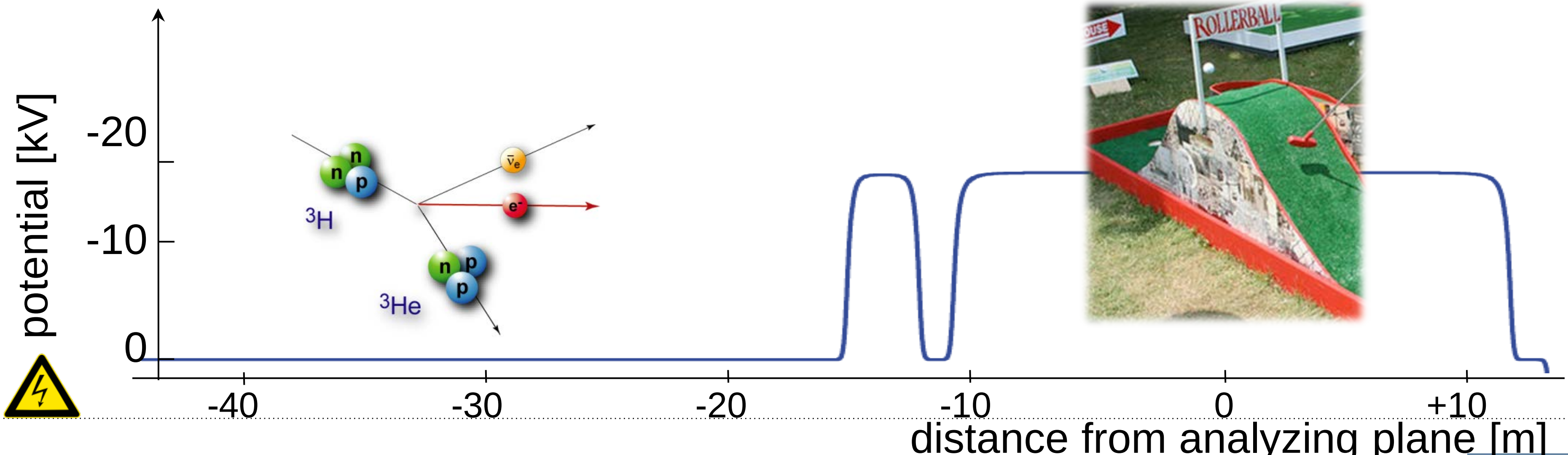
Reduction of tritium flow by 14 orders of magnitude



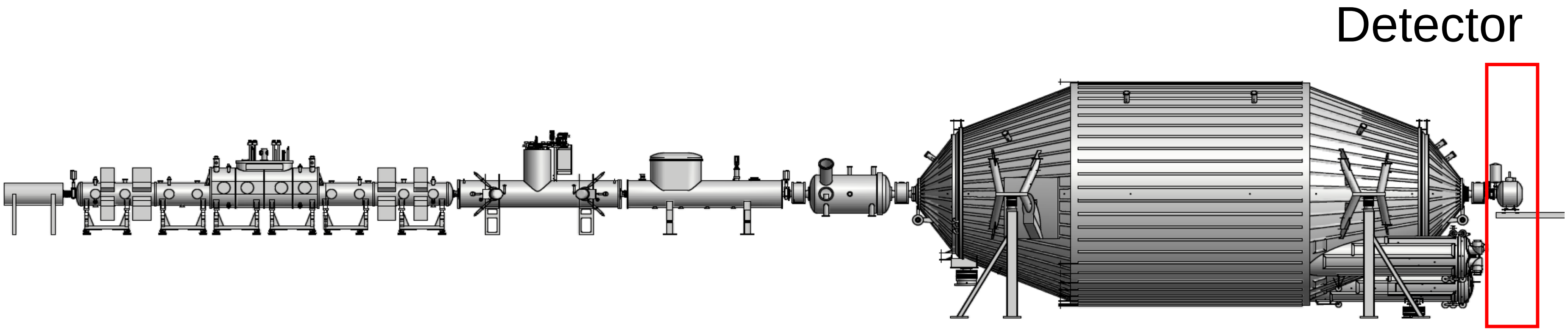
The KATRIN experiment

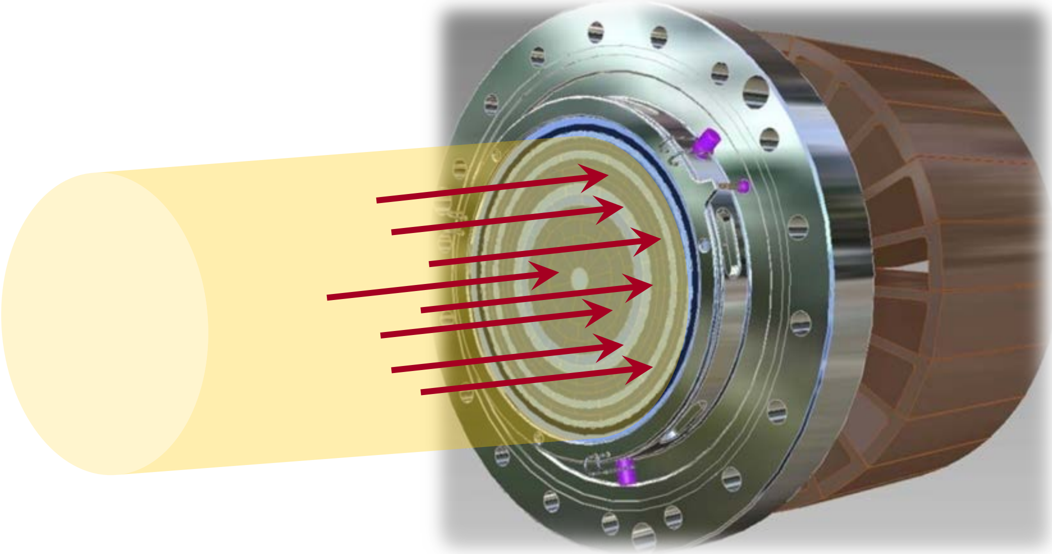
Pre- and main spectrometer

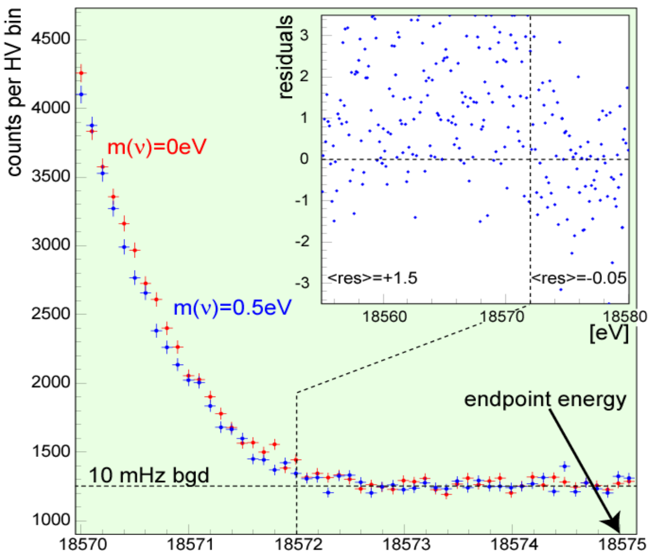




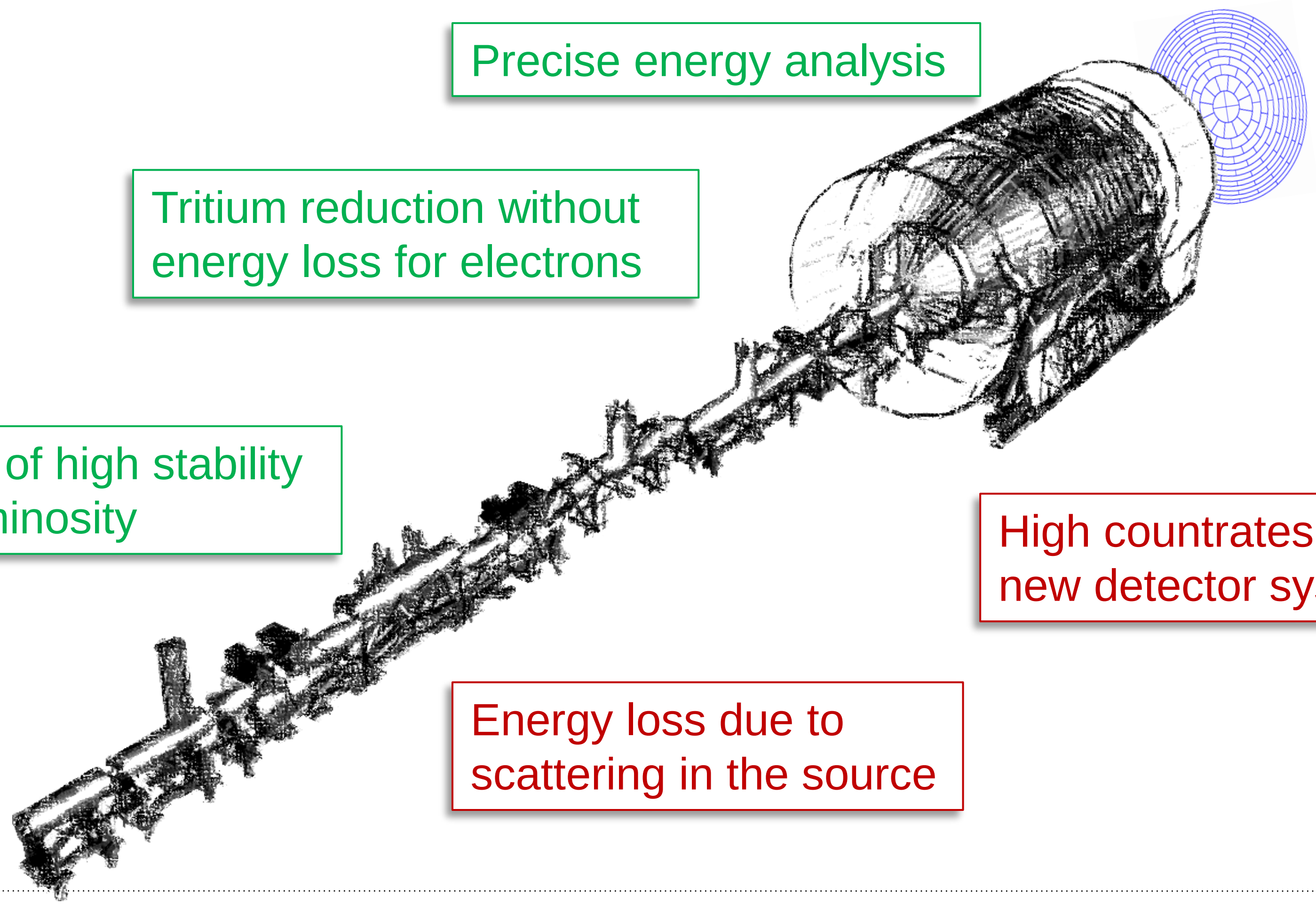
The KATRIN experiment







Pros and Cons of KATRIN



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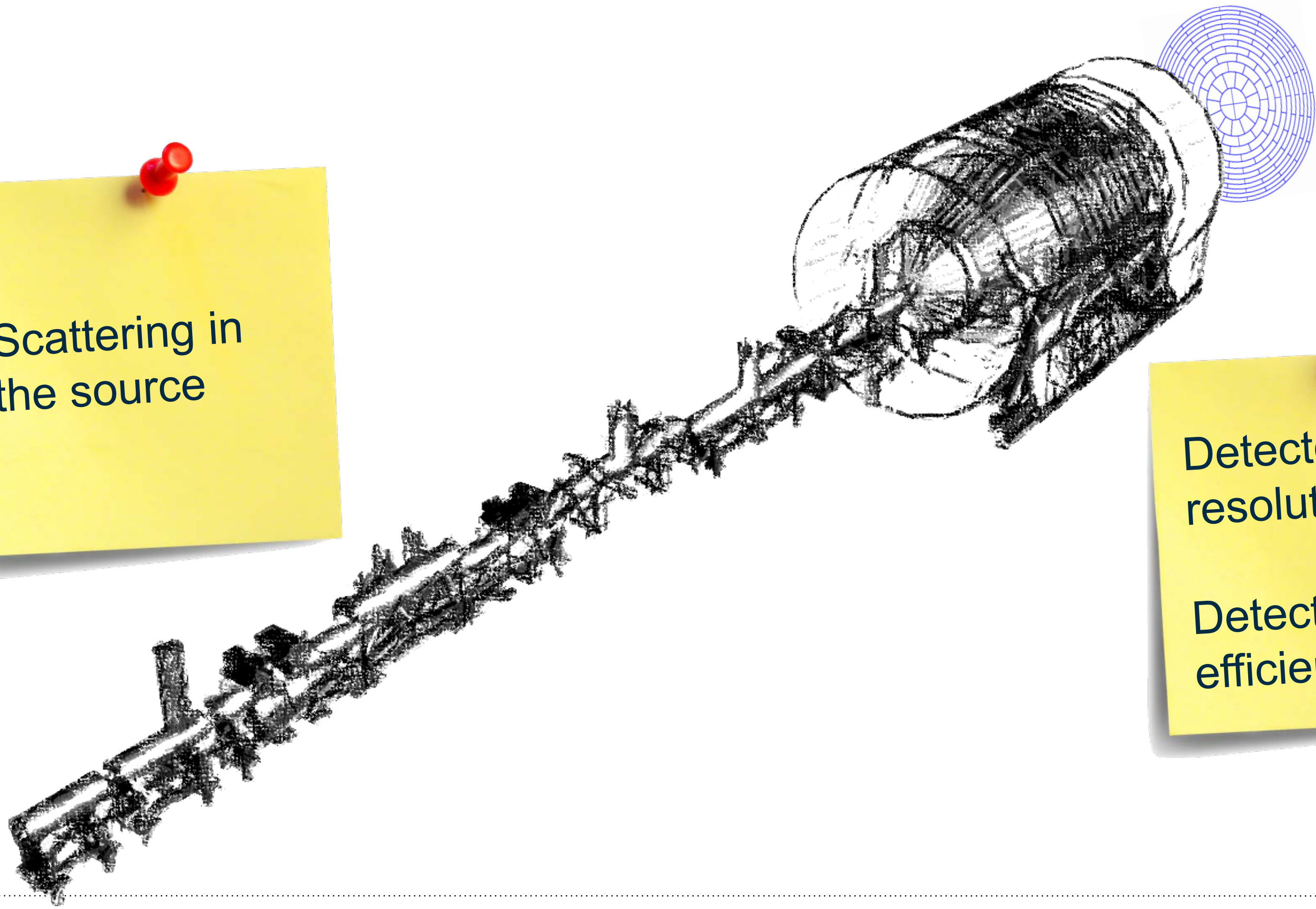
Experimental systematic effects

Scattering in the source

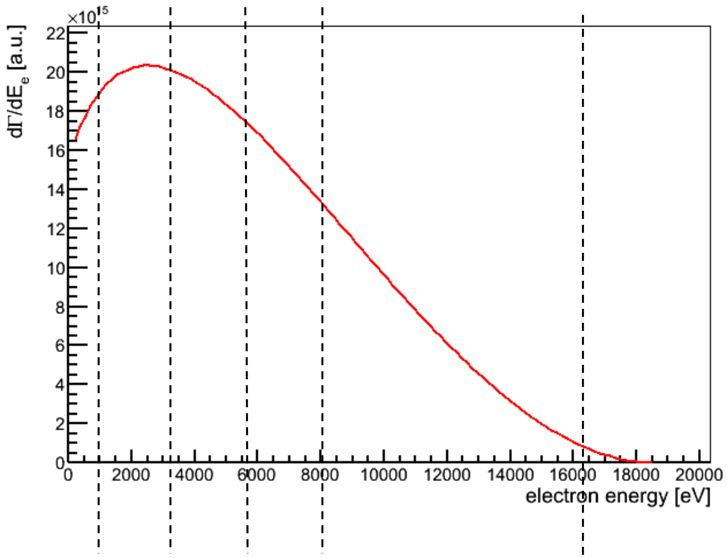


Detector resolution

Detection efficiency

Statistical sensitivity for integral and differential measurement

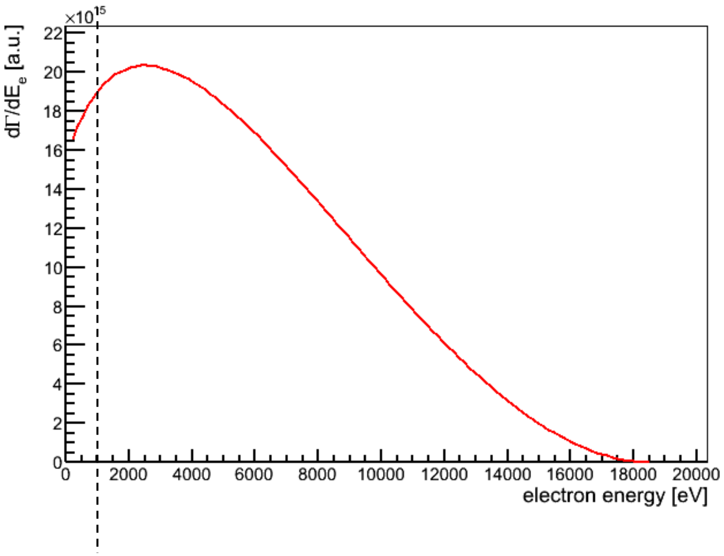
Integral



U_1 U_2 U_3 U_4 … U_{100}

… detector counts electrons

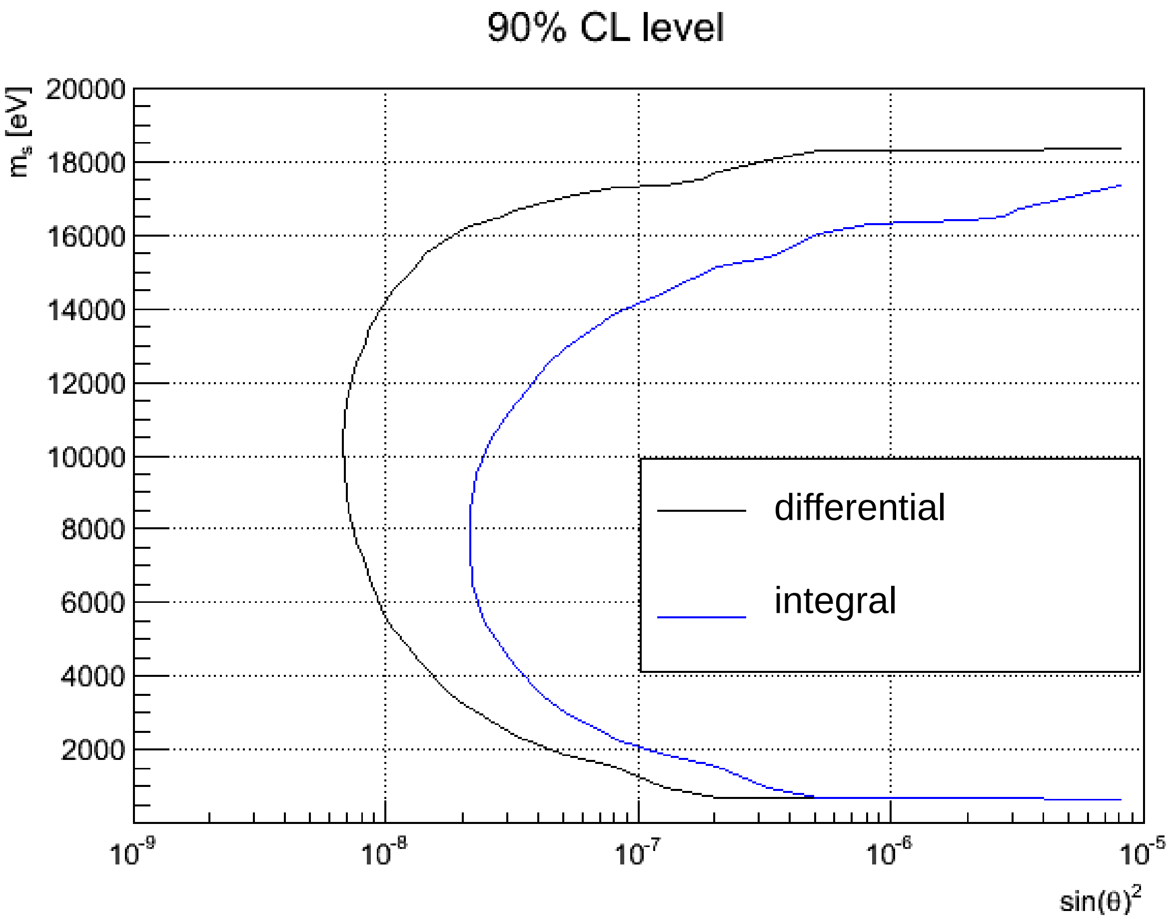
Differential



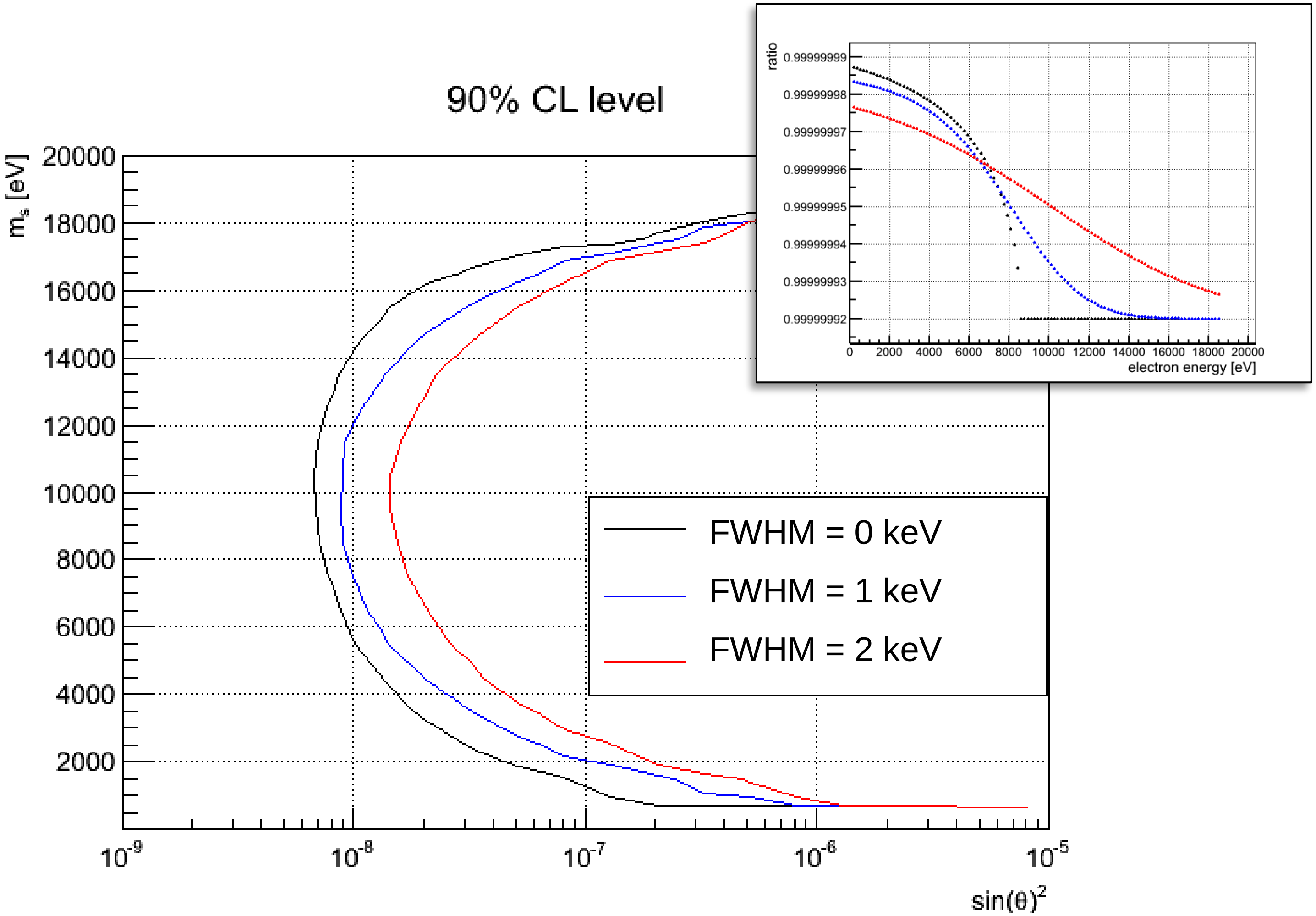
U_1

… detector measures energy

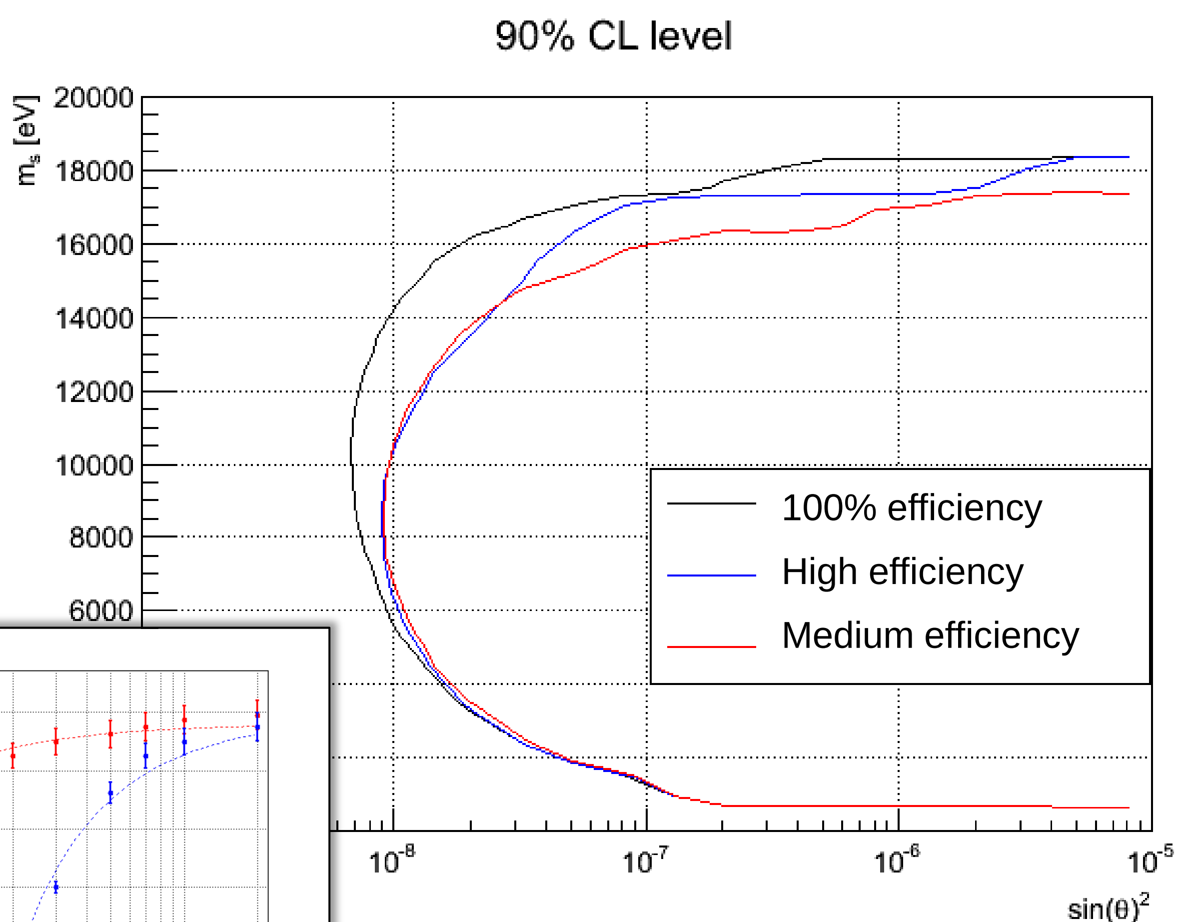
Statistical sensitivity for integral and differential measurement

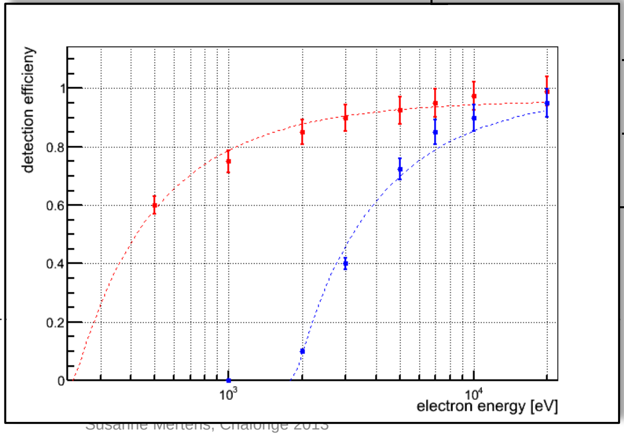


Detector Resolution



Detection Efficiency





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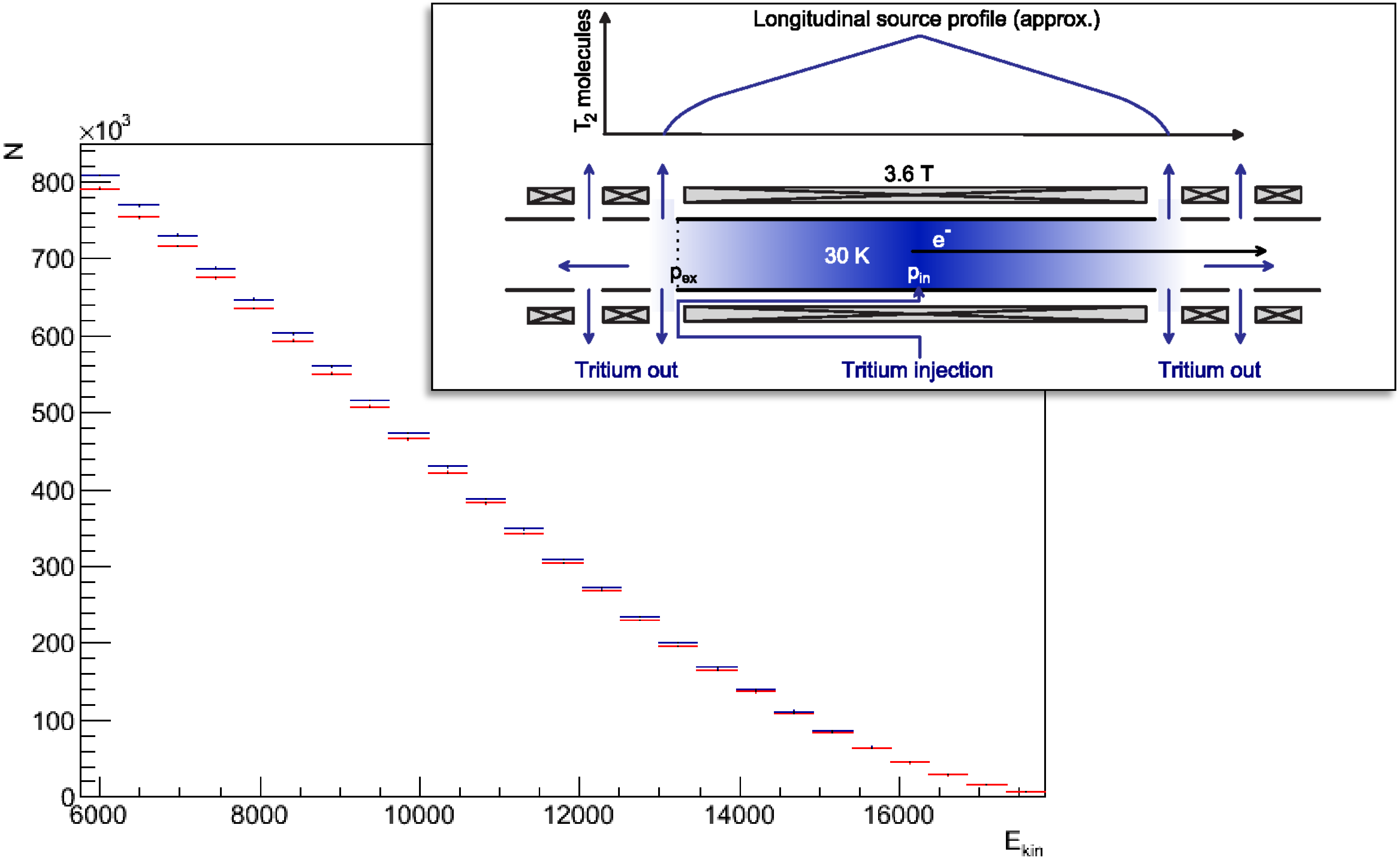
Energy loss in the tritium source



Summary and Outlook

- Statistical sensitivity of down to $\sin^2(\theta)=10^{-8}$
- „State-of-the-Arts“ theoretical corrections do not mimic a „kink“ with $\sin^2(\theta)>10^{-7}$
- KATRIN provides a source of high luminosity and stability but suitable detector system needs to be developed
- An extensive study of experimental systematic effects needs to be performed to access the real sensitivity
- A model-independent „kink“-search approach might mitigate systematic effects.

Thanks for your attention

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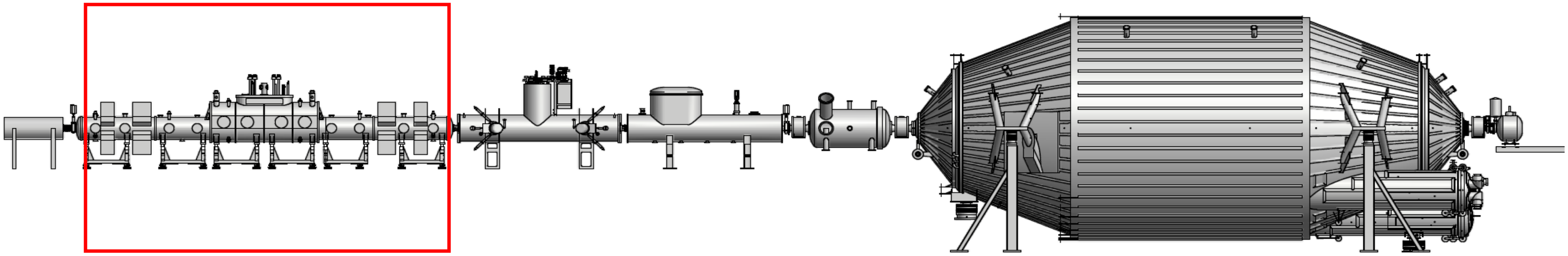
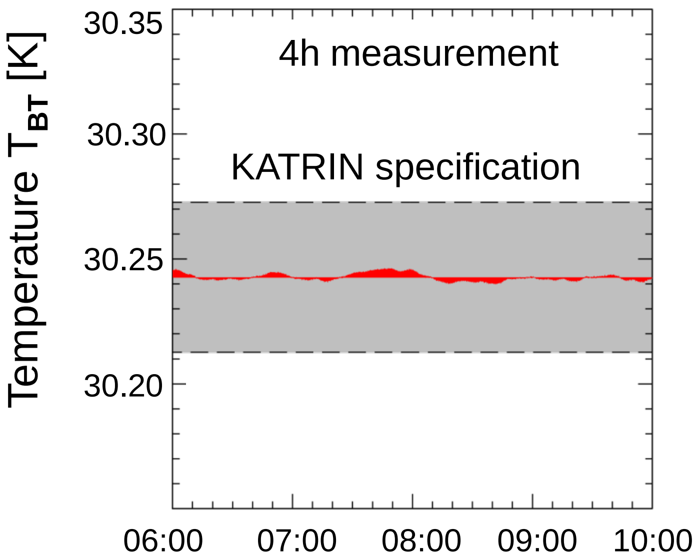
The KATRIN experiment

Windowless gaseous tritium source





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