Review on sensitivity to neutrino mass

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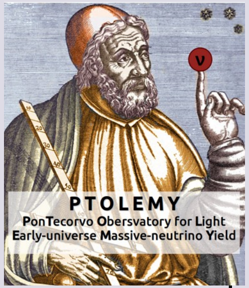


Part I

What we know about neutrino mass

Neutrino mass

1. $m_\beta^2 = \Sigma_i |U_{ei}|^2 m_i^2$ [beta decay]
2. $m_{\beta\beta} = |\Sigma_i U_{ei}^2 m_i|$ [double beta decay]
3. $\Sigma = \Sigma_i m_i$ [cosmology]

Depending on

- Mass ordering
- Oscillation parameters
- Cosmological model

NuFIT 5.2 (2022)

Reference formulae

$$m_{\nu_e}^{\text{eff}} = \sqrt{\sum_i m_i^2 |U_{ei}|^2} = \begin{cases} \sqrt{m_0^2 + \Delta m_{21}^2 (1 - c_{13}^2 c_{12}^2) + \Delta m_{32}^2 s_{13}^2} & \text{in NO} \\ \sqrt{m_0^2 + \Delta m_{21}^2 c_{13}^2 c_{12}^2 - \Delta m_{32}^2 c_{13}^2} & \text{in IO}\,, \end{cases}$$

$$m_{ee} = \left| \sum_i m_i U_{ei}^2 \right|$$

$$= \begin{cases} \left| m_0 c_{12}^2 c_{13}^2 + \sqrt{\Delta m_{21}^2 + m_0^2}\, s_{12}^2 c_{13}^2 e^{2i(\eta_2 - \eta_1)} + \sqrt{\Delta m_{32}^2 + \Delta m_{21}^2 + m_0^2}\, s_{13}^2 e^{-2i(\delta_{\text{CP}} + \eta_1)} \right| & \text{in NO} \\ \left| m_0 s_{13}^2 + \sqrt{m_0^2 - \Delta m_{32}^2}\, s_{12}^2 c_{13}^2 e^{2i(\eta_2 + \delta_{\text{CP}})} + \sqrt{m_0^2 - \Delta m_{32}^2 - \Delta m_{21}^2}\, c_{12}^2 c_{13}^2 e^{2i(\eta_1 + \delta_{\text{CP}})} \right| & \text{in IO} \end{cases}$$

without SK atmospheric data

	Normal Ordering bfp	3σ range	Inverted Ordering ($\Delta\chi^2 = 2.3$) bfp	3σ range
$\sin^2\theta_{12}$	[illegible]			$0.270 \to 0.341$
$\theta_{12}/^\circ$	[illegible]			$31.31 \to 35.74$
$\sin^2\theta_{23}$	$0.572^{+0.018}_{-0.023}$	$0.406 \to 0.620$	$0.578^{+0.016}_{-0.021}$	$0.412 \to 0.623$

with SK atmospheric data

	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 6.4$)	
$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.41^{+0.21}_{-0.20}$	$6.82 \to 8.03$	$7.41^{+0.21}_{-0.20}$	$6.82 \to 8.03$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.507^{+0.026}_{-0.027}$	$+2.427 \to +2.590$	$-2.486^{+0.025}_{-0.028}$	$-2.570 \to -2.406$

About ordering

~~N.O.~~

I.O.

Y.E.S.

Yearningly
Expected
Spectrum

[F. Vissani, Neutrino 2018]

Beta decay ent-point

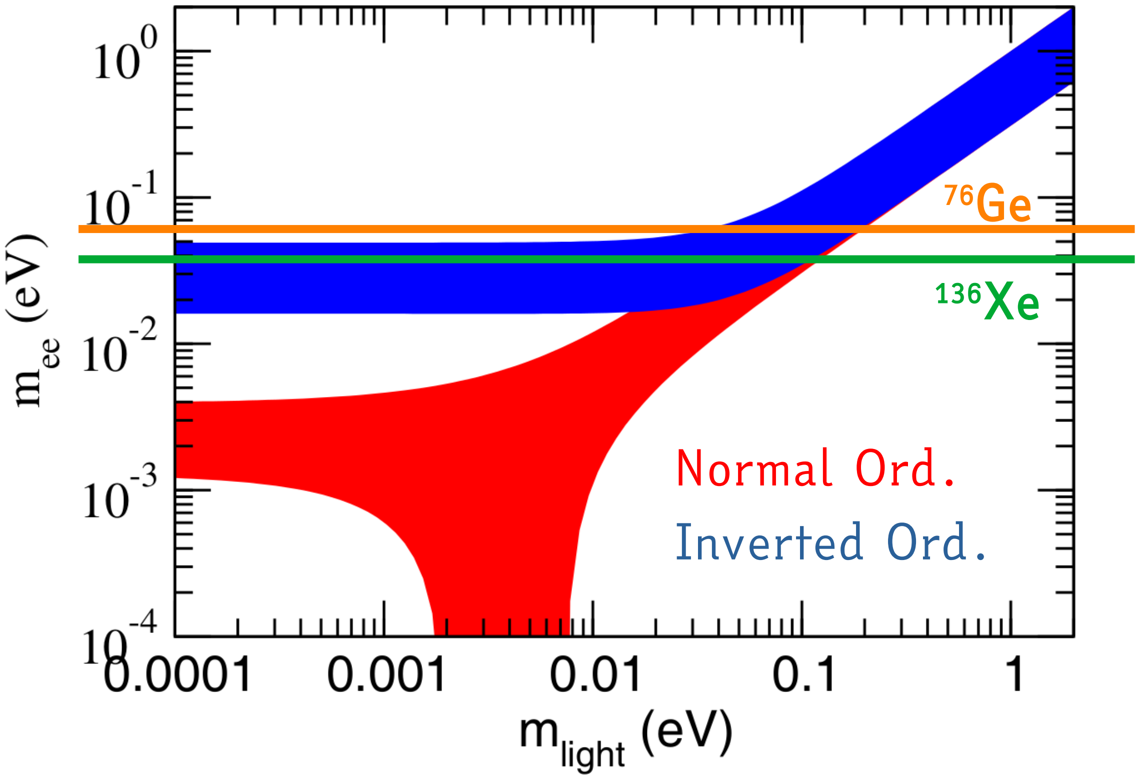
KATRIN (Tritium)

$m_\beta < 0.45$ meV (90% CL)
(Lokhov-Tkachov)

$m_\beta < 0.31$ meV (90% CL)
(Feldman-Cousins)

$Q_\beta = 18575.0 \pm 0.3$ meV

Neutrino-less double beta decay



KamLAND-Zen

$T_{1/2} > 3.8 \times 10^{26}$ y

$m_{\beta\beta} < 28\text{-}122$ meV

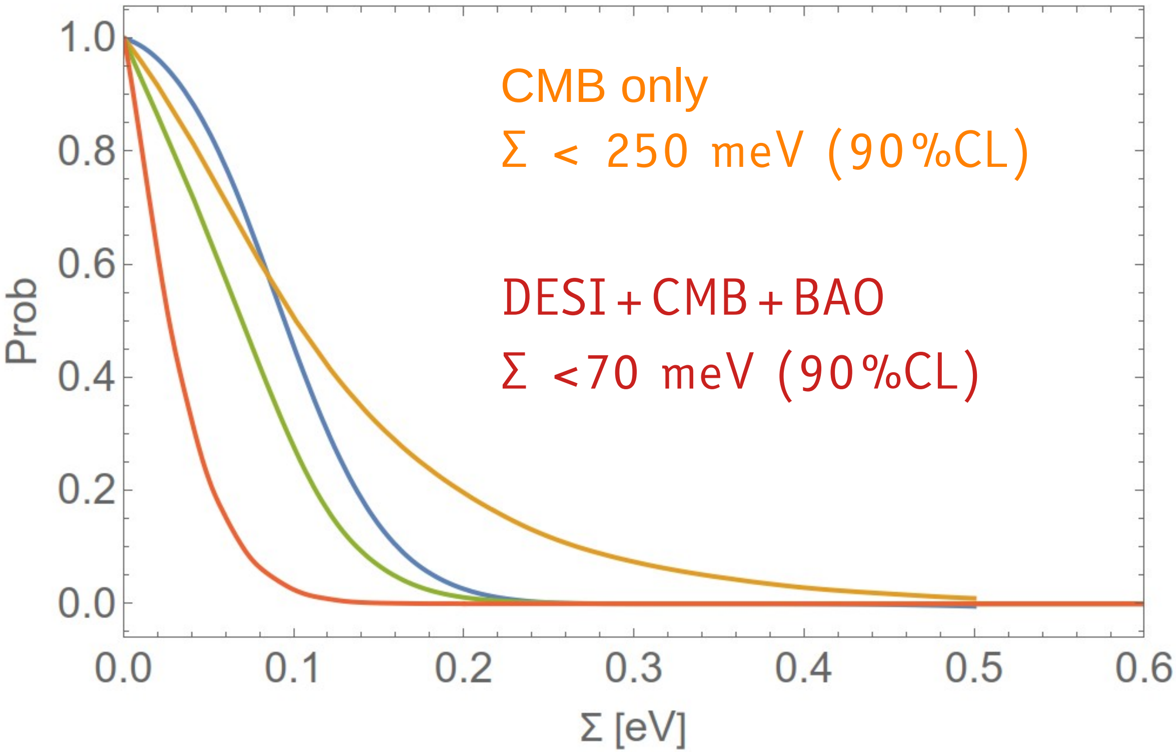
LEGEND-200

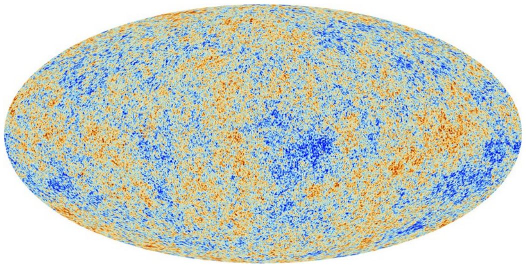
$T_{1/2} > 1.9 \times 10^{26}$ y

$m_{\beta\beta} < 79\text{-}180$ meV

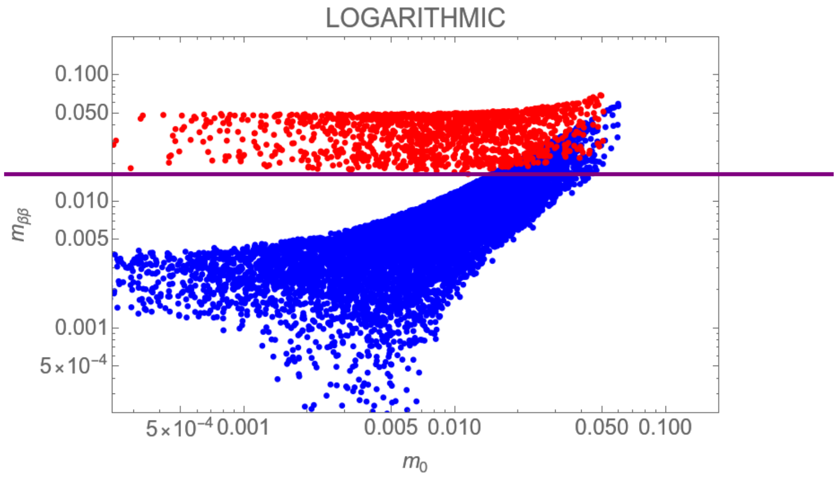
Cosmology

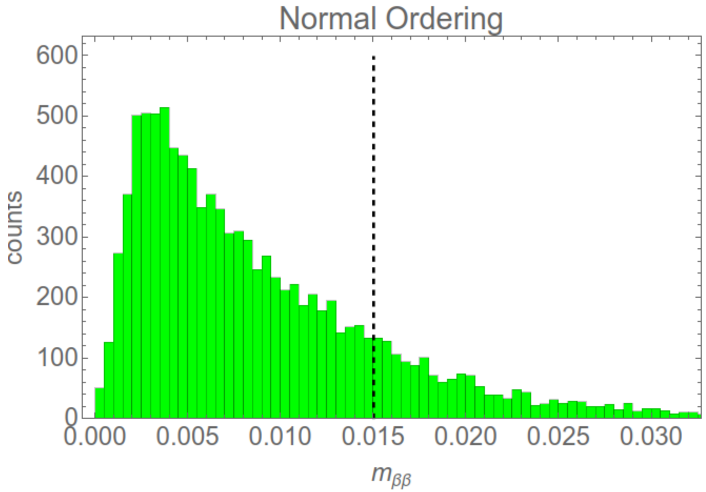
Neutrinos affects the growth of the cosmic clustering → CMB, LSS





$m_{\beta\beta}$ Bootstrap



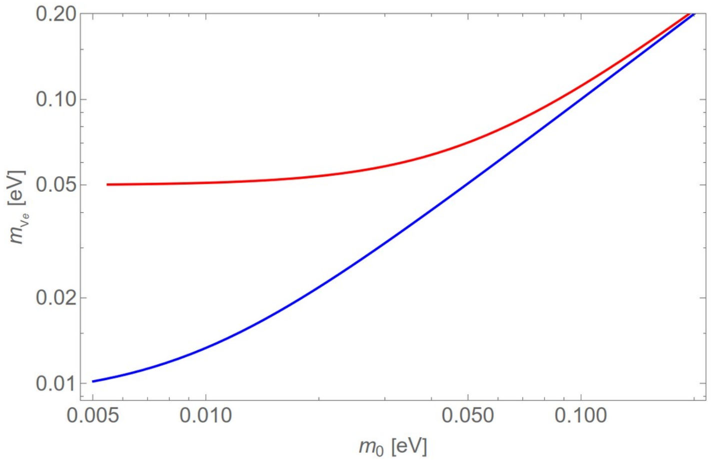


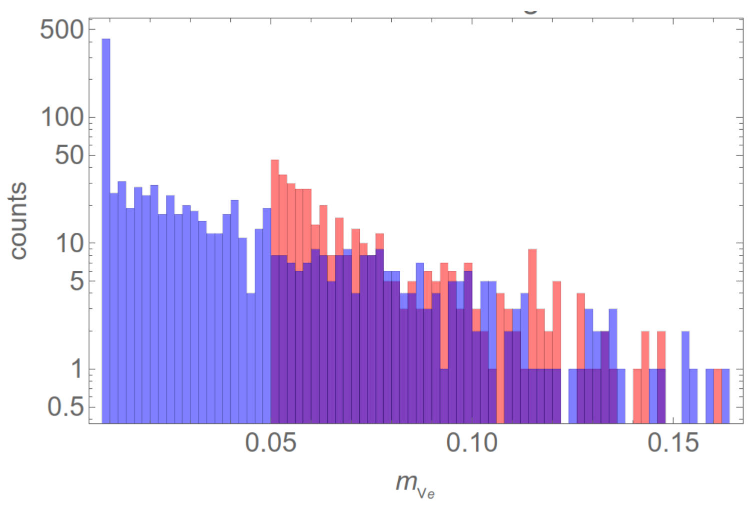
Next generation $0\nu\beta\beta$
(KamLAND-Zen, LEGEND-1000, CUPID)
$m_{\beta\beta} \sim$ 15 meV

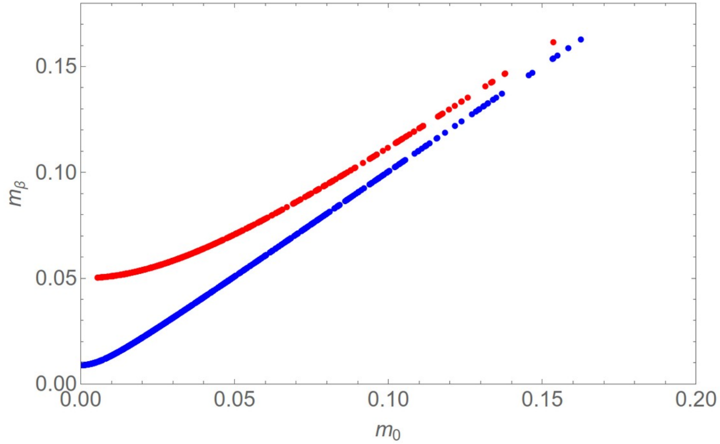
$(m_0, m_{\beta\beta}) = f$(oscillation, Majorana, Cosmology)

Chance for discovery:
Planck + ACT: **66%**
Planck + BAO: **41%**
Planck + BAO + ACT + RDS: **36%**
Planck + BAO + DESI: **16%**

m_β Bootstrap







Most conservative choice (CMB only)

$<m_\beta>$ = 31 meV (NO)

$<m_\beta>$ = 72 meV (IO)

(challenging)

Dirac vs Majoarana

Race for Majorana Neutrino

$T_{1/2} > 10^{28}$ y

LEGEND-1000

(1t of ^{76}Ge, 500 M$, >10 y)

nEXO

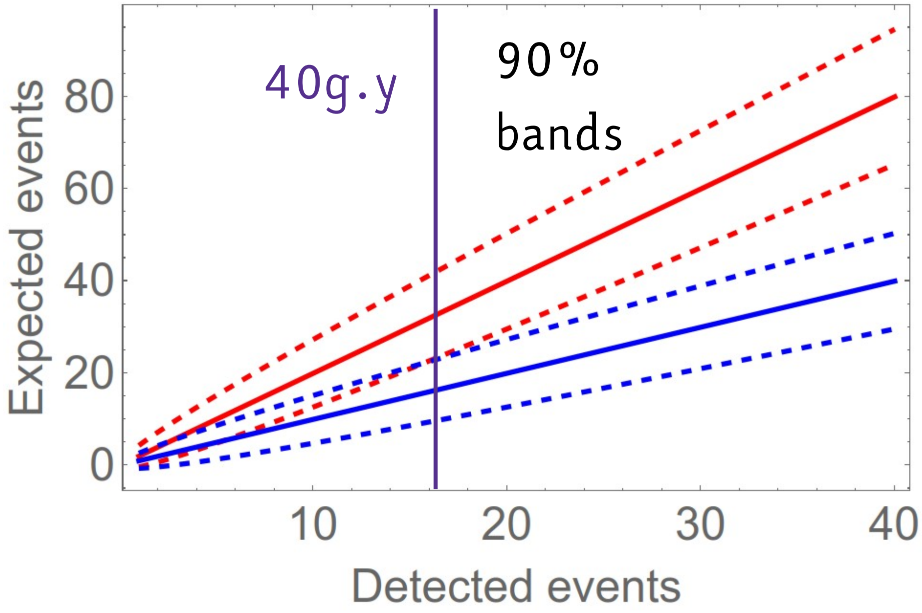
(5t of ^{136}Ge, 500 M$, >10 y)

CUPID

(1t of ^{100}Mo, 100 M$, >10 y)

Expected rate

- Dirac 0.4 events/g/y
- Majorana 0.8 events/g/y

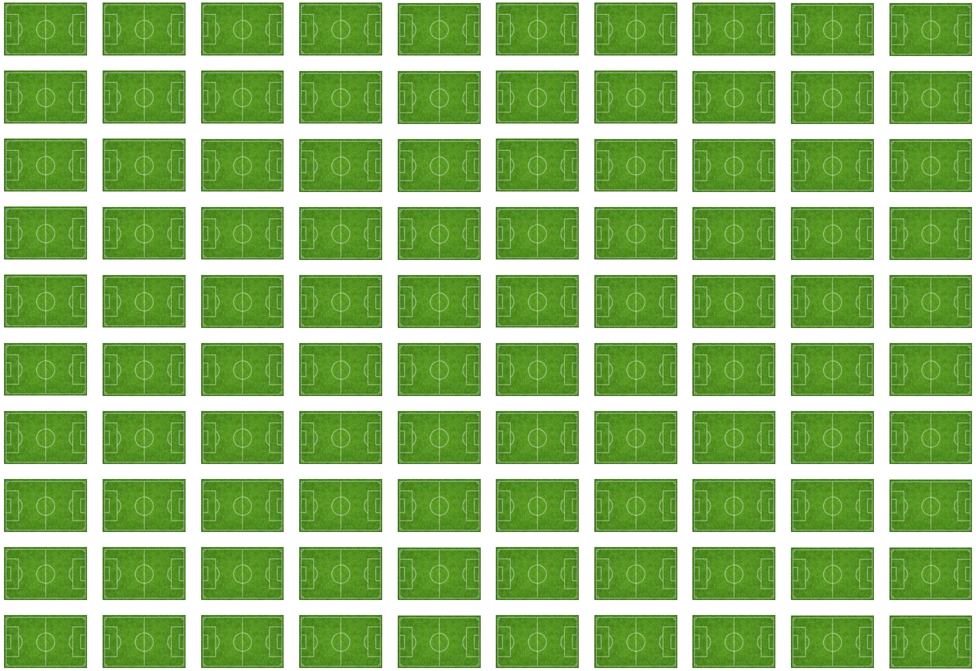


Problem to face

1 g

5000 m^2

We urgently need source compactification!!!



100 g

500000 m^2

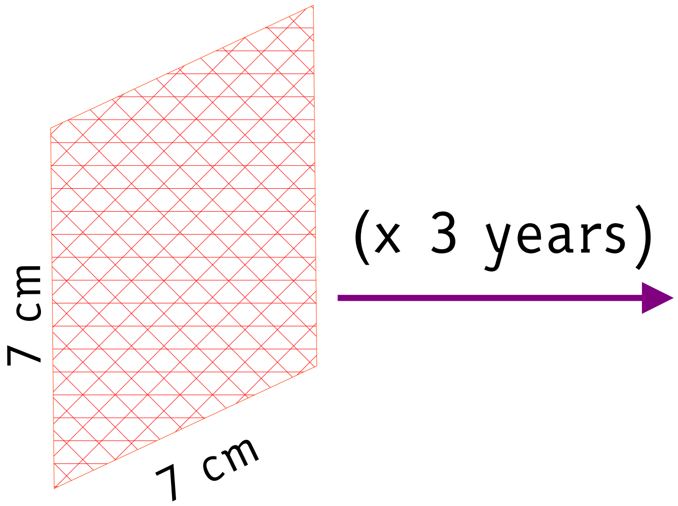
Part II

Experimental sensitivity to neutrino mass

Reference source

$$N_{dec} = \frac{1}{2}\left(\frac{m_S N_A}{A_{(^3H)}}(1 - e^{-t/\tau})\right) \simeq 10^{16}$$

(50% Efficiency for total events) in 3 y

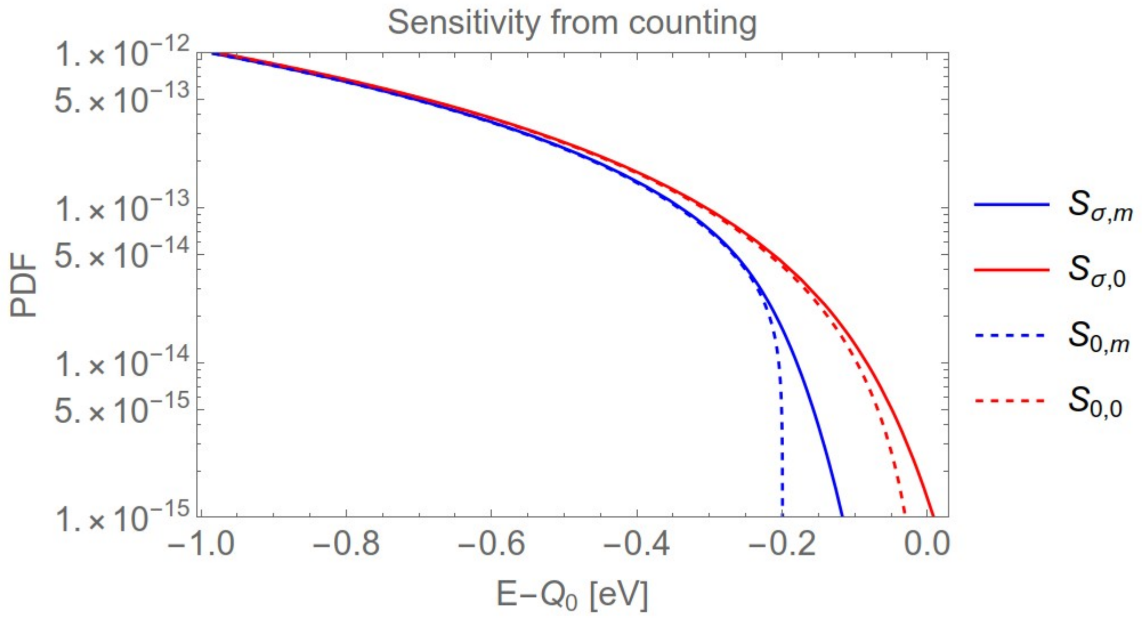


ρ = 0.2 mg/m²
(full loading)

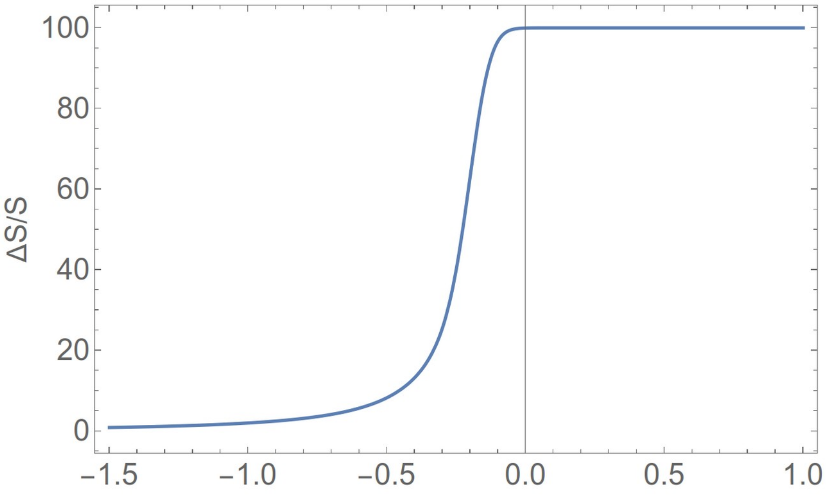
→ **1 μg**

716 MBq
(19.3 mCi)

Origin of sensitivity

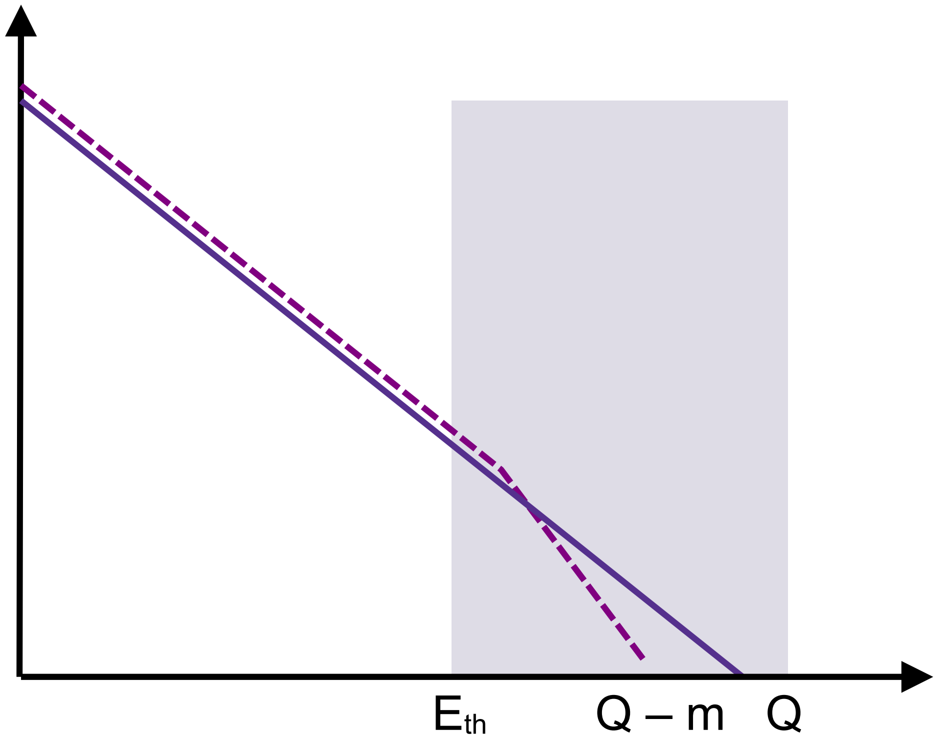


Spectrum distortion



Region of interest

Counting analysis



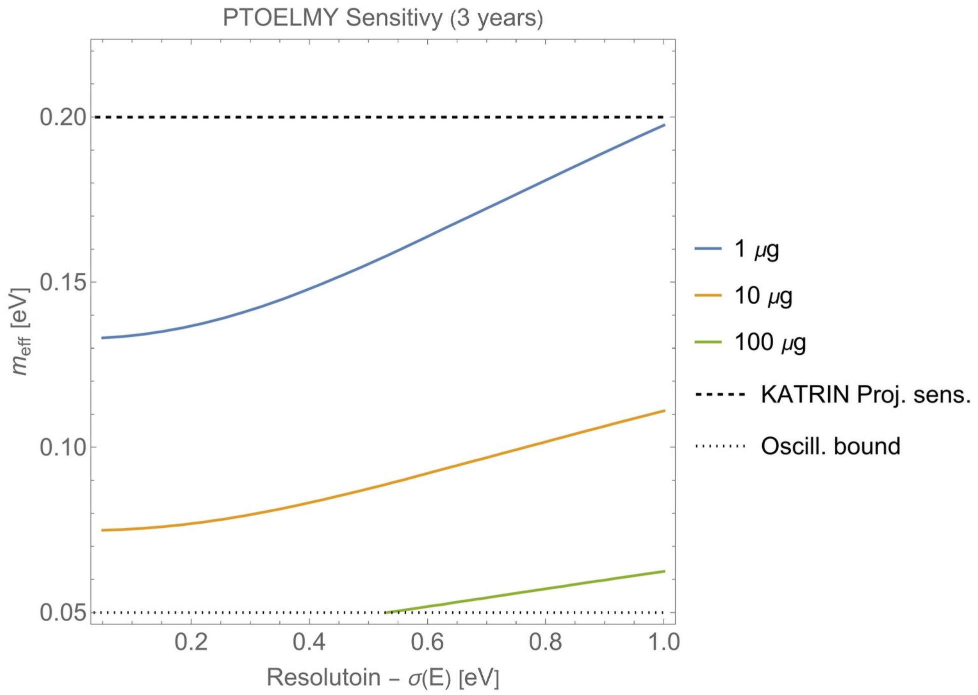
$$N_{\sigma,m} = \int_{E_{th}} S_{\sigma,m}(E)dE$$

$$N_{\sigma,0} = \int_{E_{th}} S_{\sigma,0}(E)dE$$

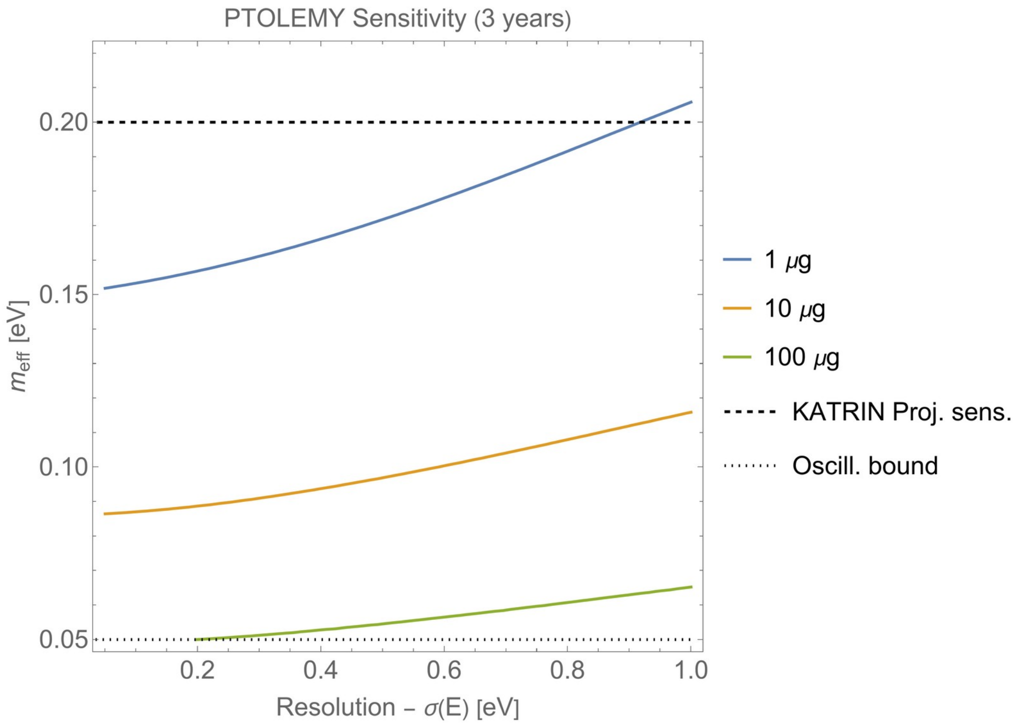
Sensitivity 90%CL :=

$$\frac{N_{\sigma,0} - N_{\sigma,m}}{\sqrt{N_{\sigma,0} + N_{\sigma,m}}} = 1.64$$

Sensitivity from counting

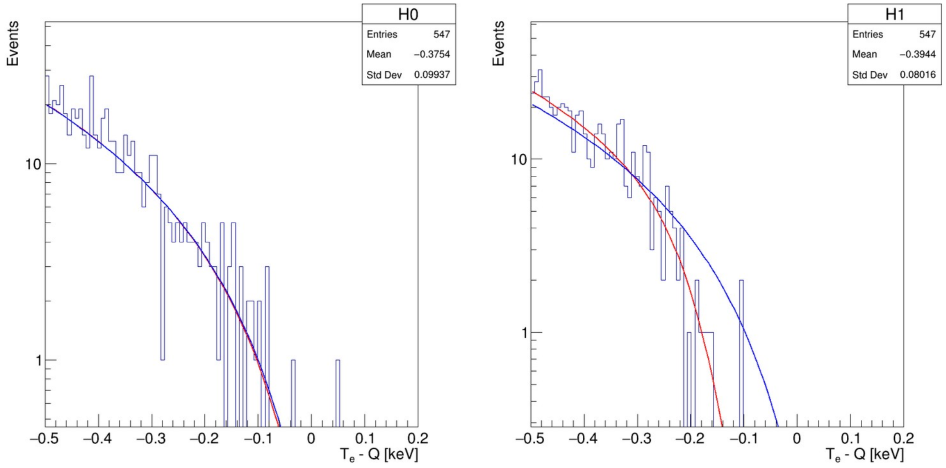


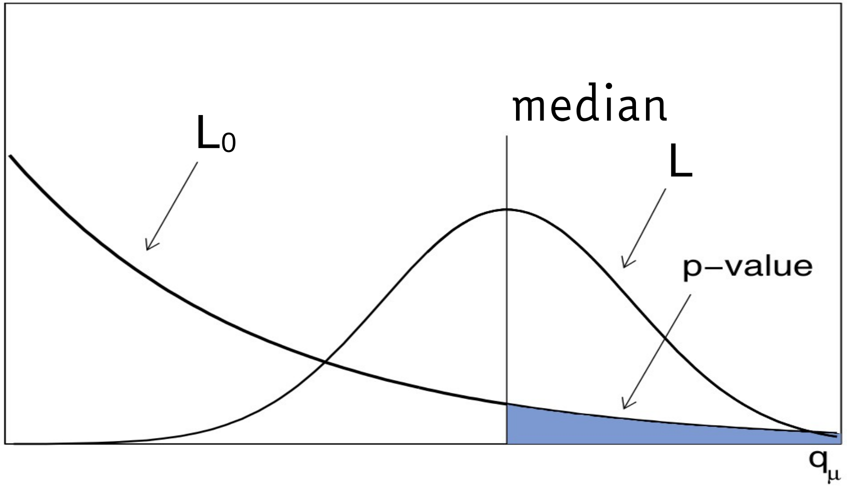
Simple counting



Effect of Q_0 (KATRIN)

Profile likelihood



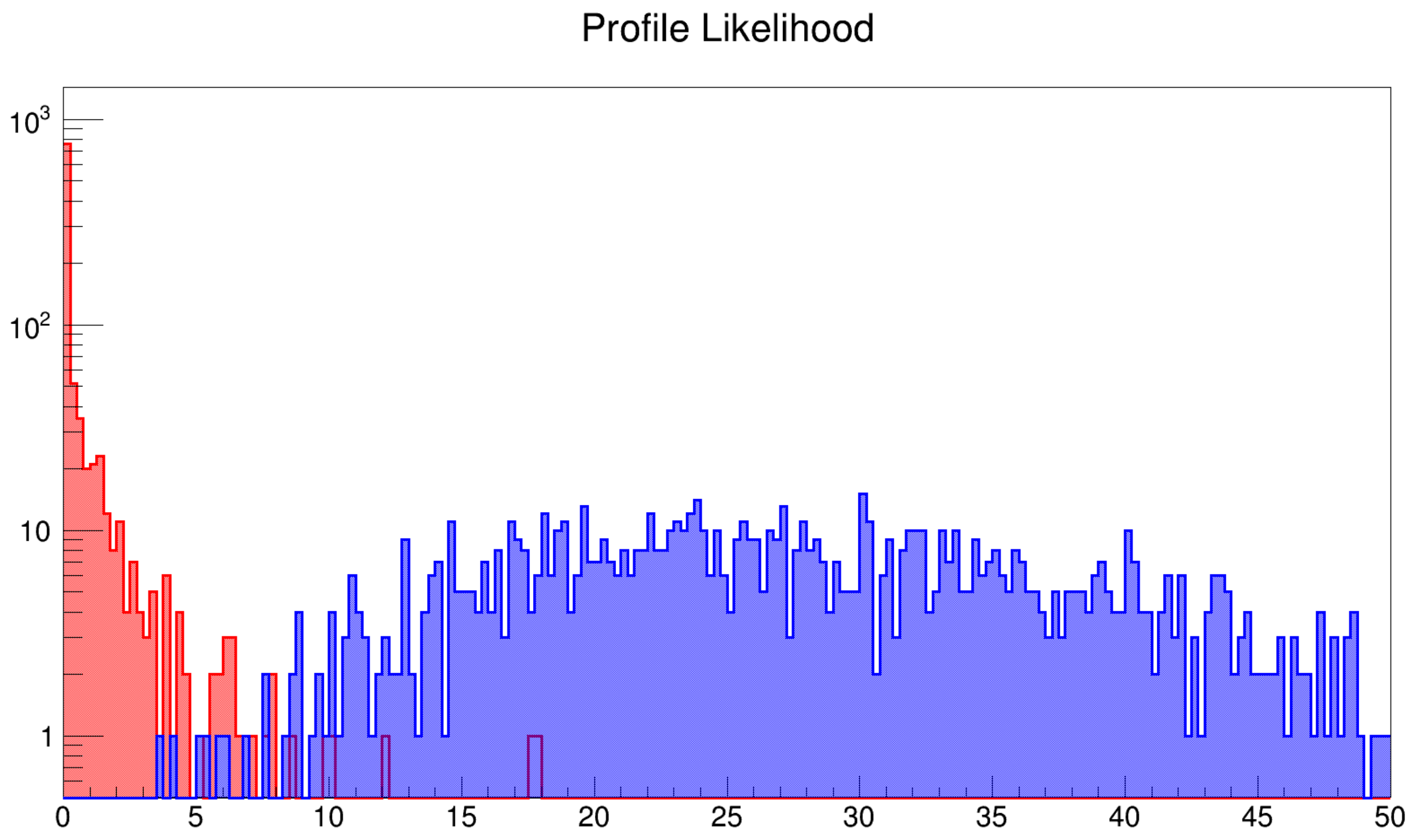


$$\mathcal{L}_0 = -2\log\frac{\mathcal{L}(S_{\sigma,0}|\mathrm{data}_0)}{\mathcal{L}(S_{\sigma,m}|\mathrm{data}_0)}$$

$$\mathcal{L} = -2\log\frac{\mathcal{L}(S_{\sigma,0}|\mathrm{data_m})}{\mathcal{L}(S_{\sigma,m}|\mathrm{data_m})}$$

[Cowan et al. (2013)]

Profile likelihood with spectral fit: 1 μg

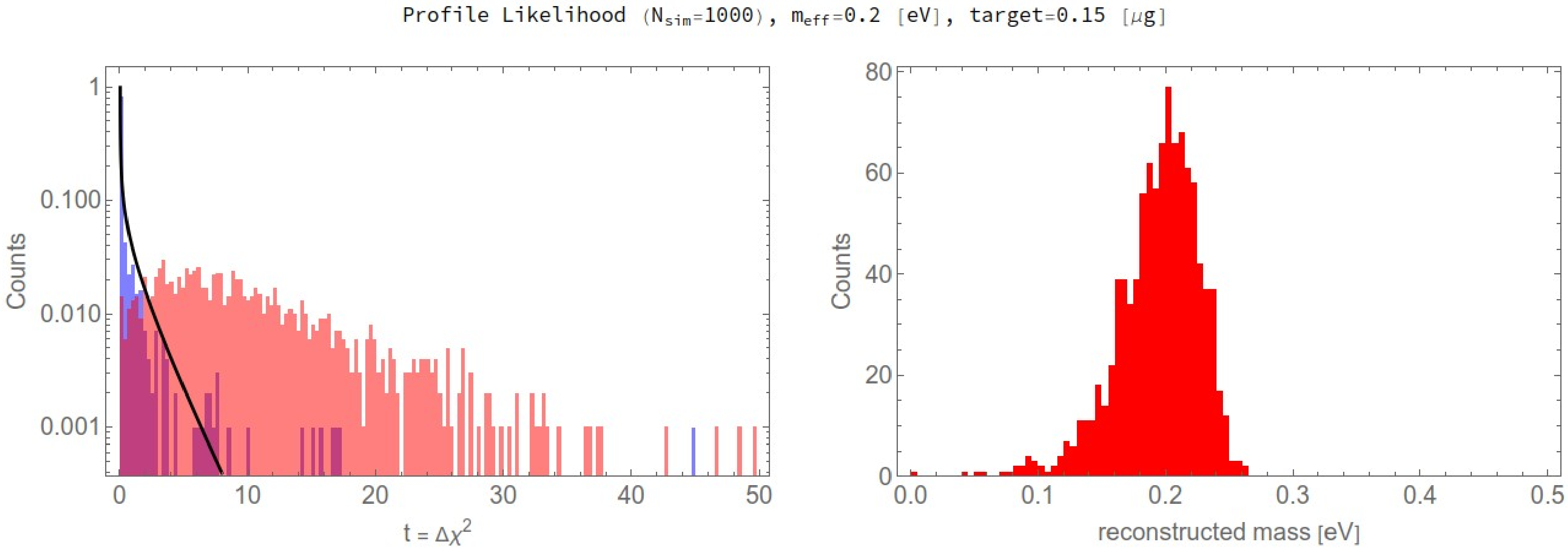


Example

m = 200 meV,

σ = 50 meV

Limit case: 150 ng

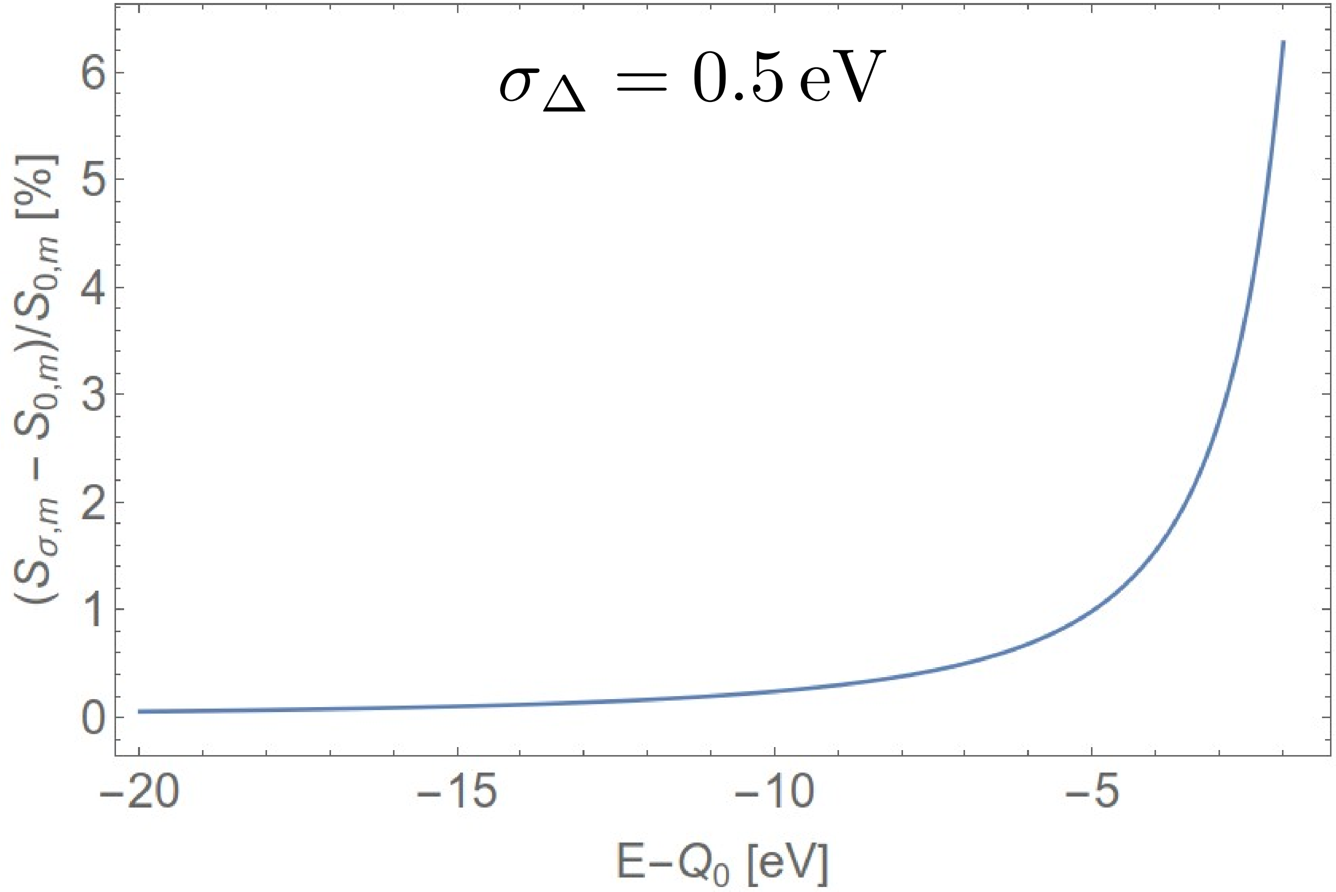


Source = 150 ng

M = 200 meV

σ = 50 meV

Sensitivity to (unknown) smearing



Strategy

Region I: [-20, -3] eV

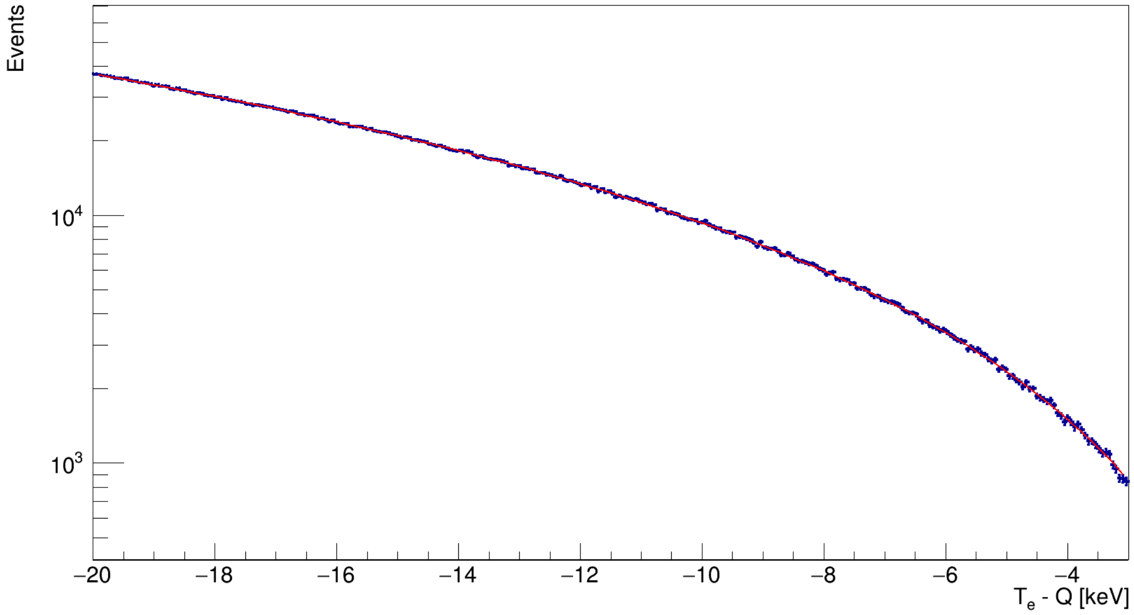
Extraction of σ_Δ
With 1/10 of the total exposure
(1.56 e15 events)

Region II: [-3, 1] eV

Fit on the spectrum
With penalty on σ_Δ

$$\sigma_\Delta(\mathrm{R-I}) = \sqrt{\sigma^2_\Delta(\mathrm{R-II}) - \sigma^2_{\mathrm{exp}}(\mathrm{prior})}$$

Example



Simulated:

σ_Δ = 500 meV

m_ν = 200 meV

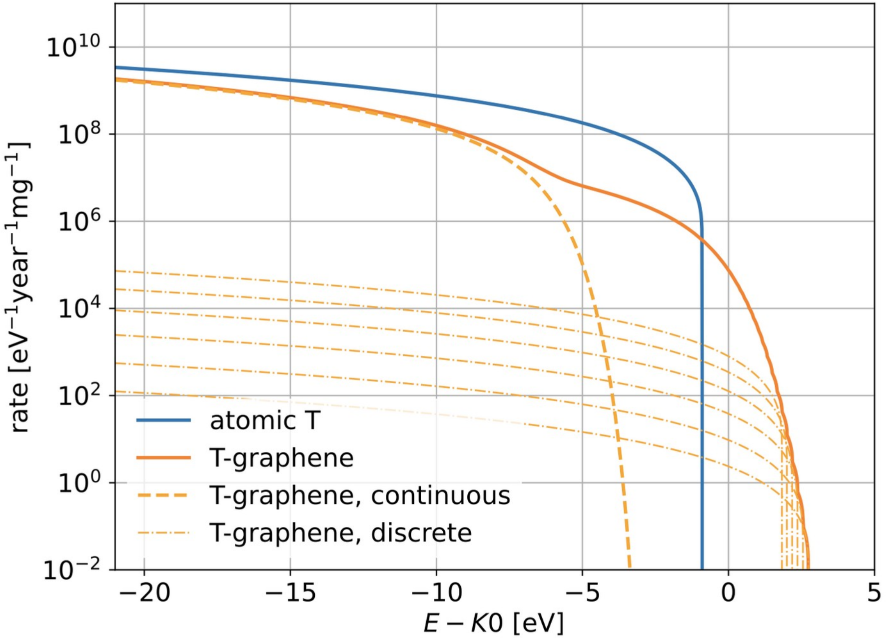
Returned from the fit in (-20, -3):

σ_Δ = 0.49 +/- 0.06 eV (12%)

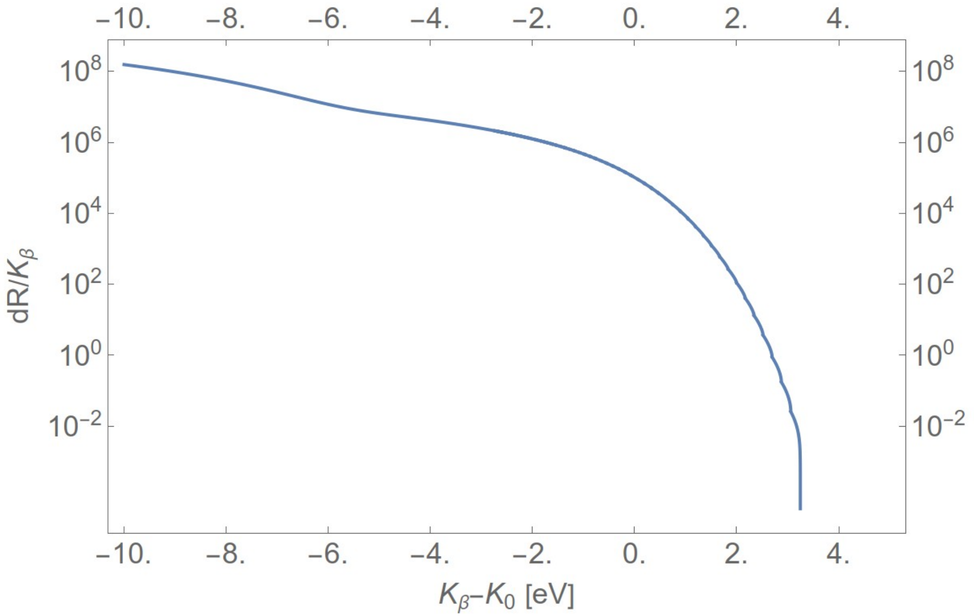
Mass with prior from fit in (-3, 2):

m_ν = 0.196 +/- 0.026 eV (13%)

Sensitivity to (known) smearing

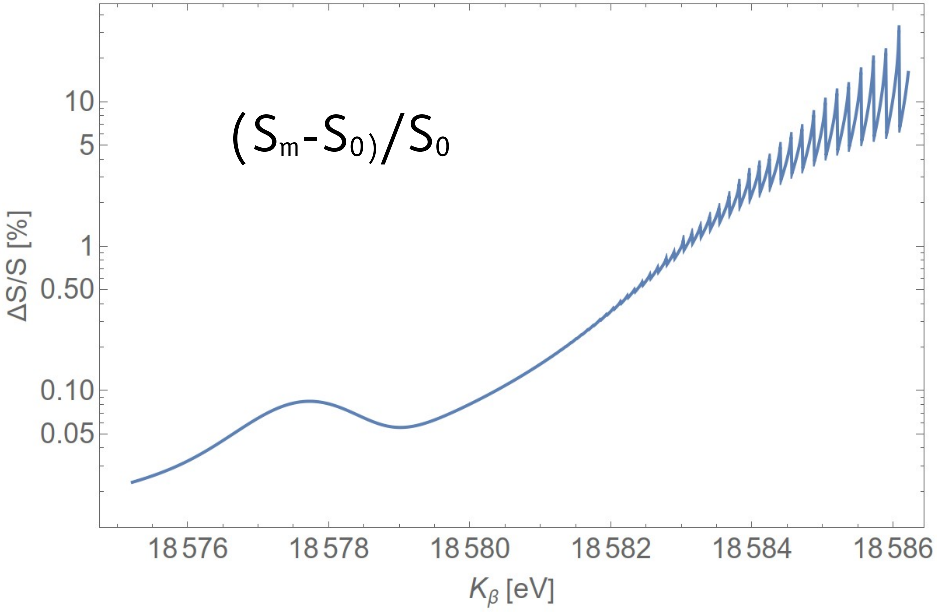


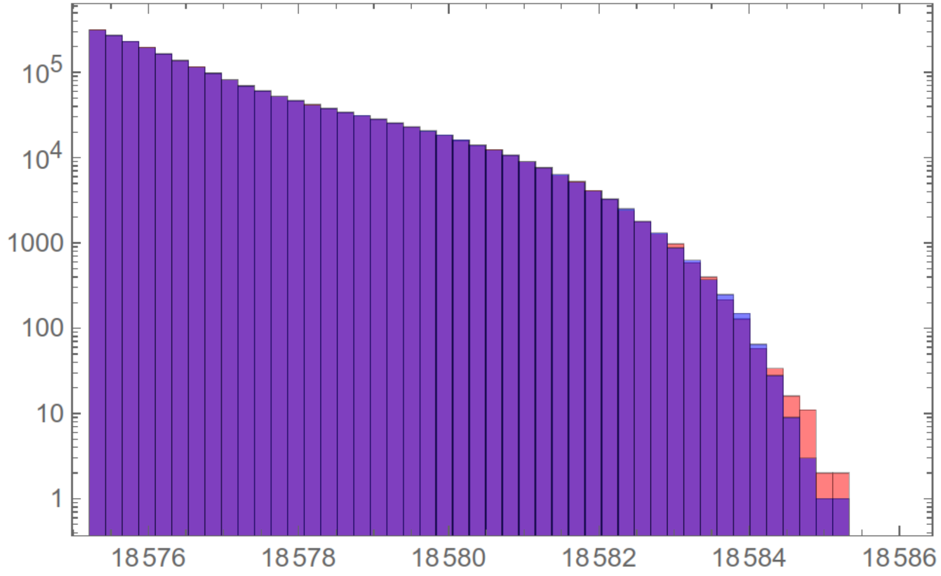
Quantum levels



Total spectrum

Region of interest





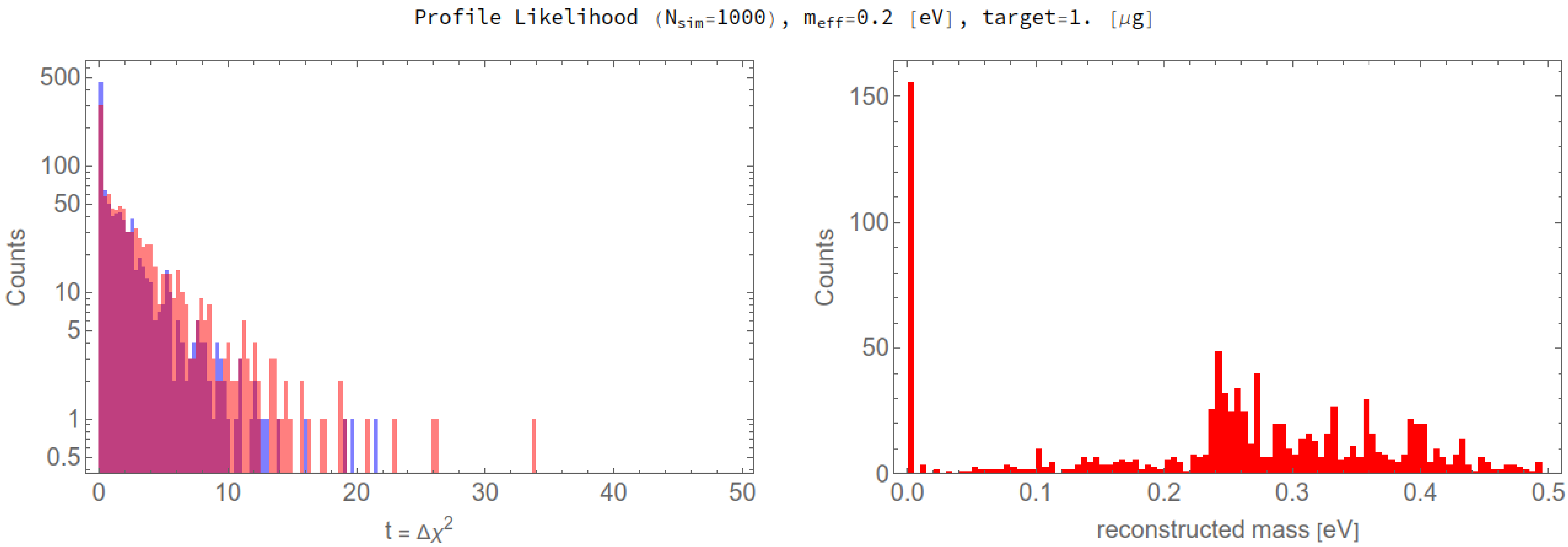
S_m (200 meV)

S_0 (0 meV)

Random sampling

10 μg sample

Profile likelihood

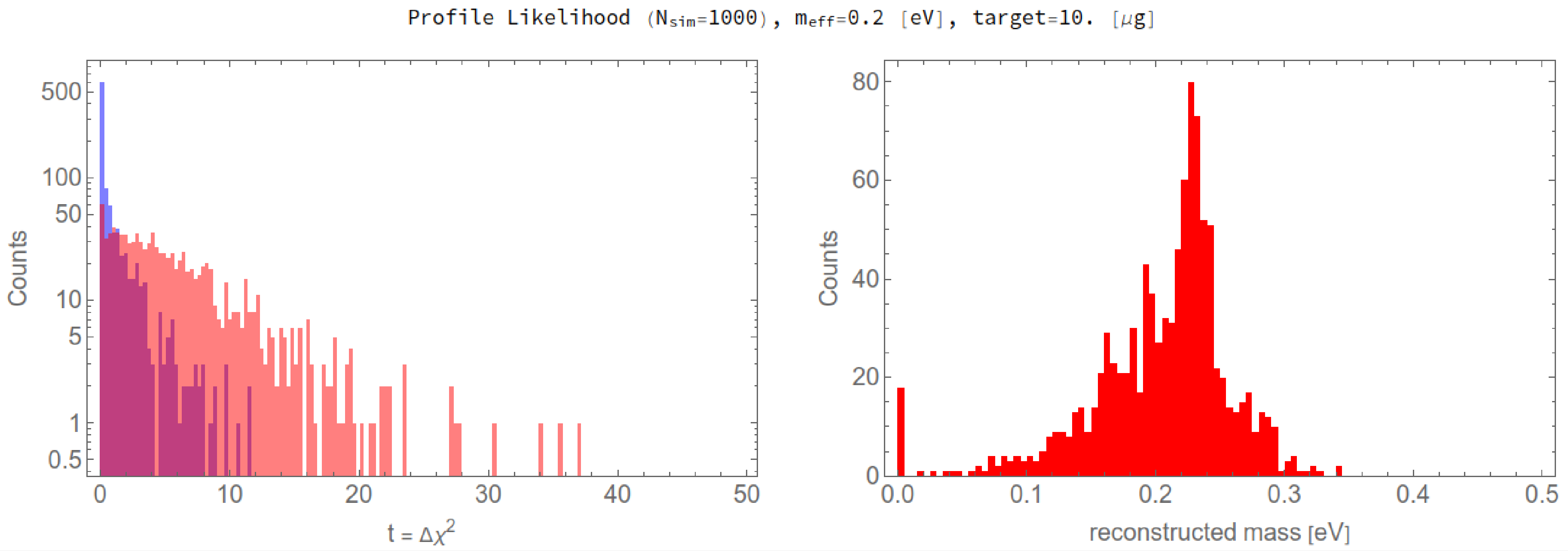


Source = 1 μg

m = 200 meV

σ = 50 meV

Profile likelihood

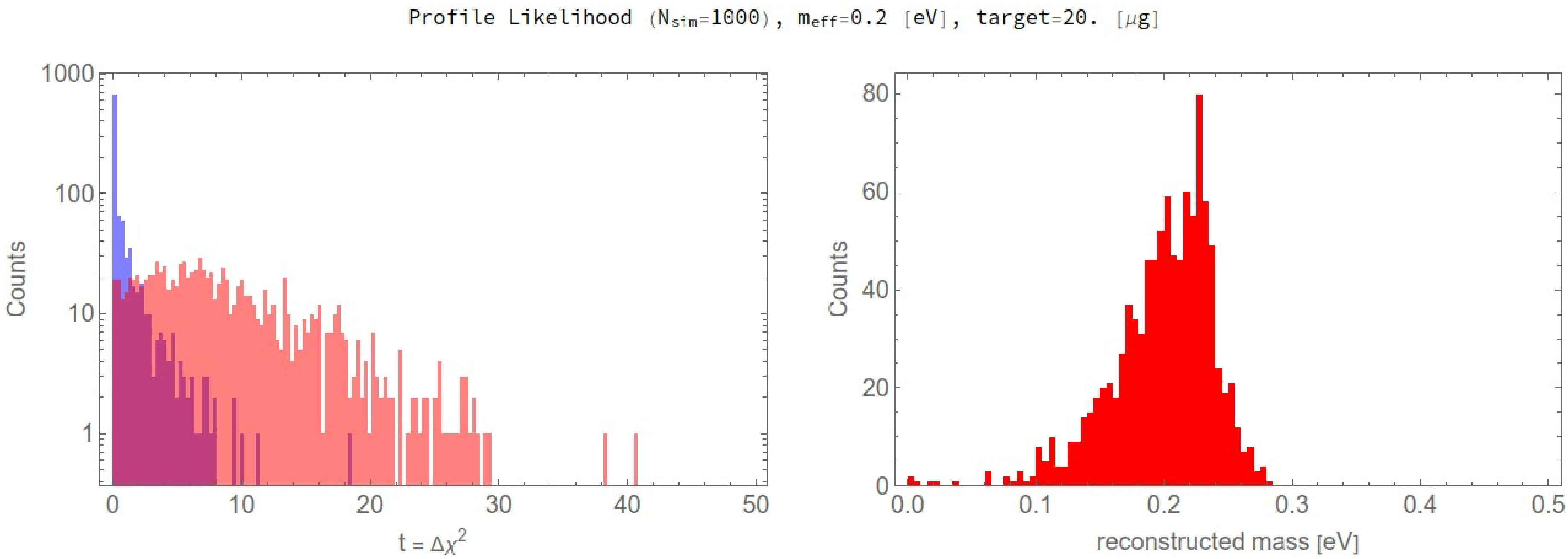


Source = 10 μg

m = 200 meV

σ = 50 meV

Profile likelihood

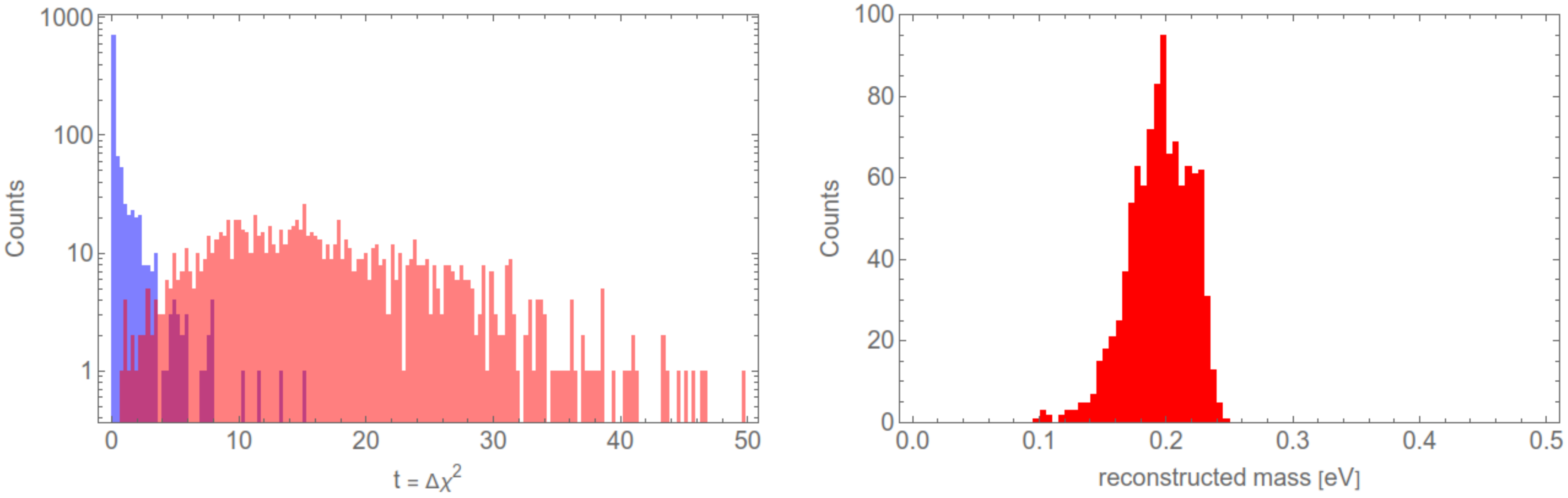


Source = 20 μg

m = 200 meV

σ = 50 meV

Profile likelihood

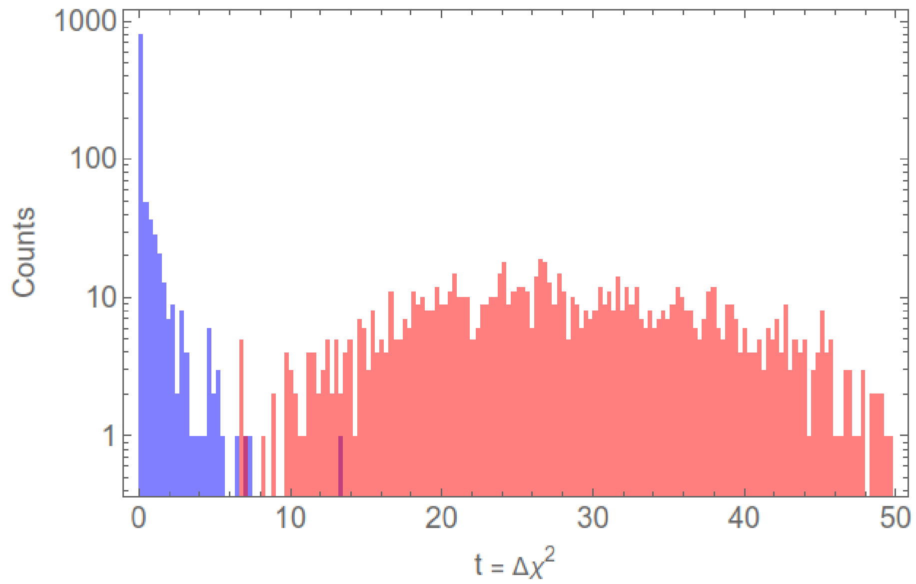


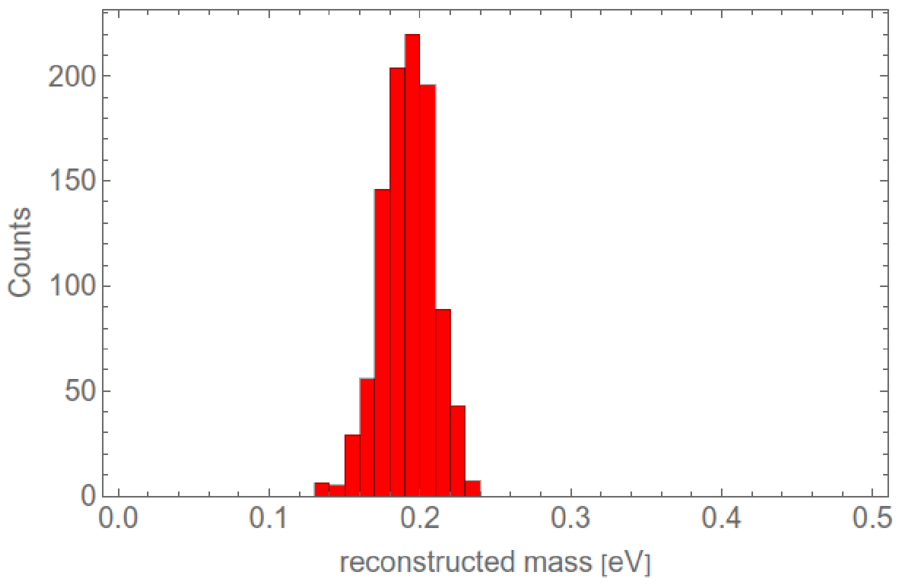
Source = 50 µg

m = 200 meV

σ = 50 meV

Profile likelihood





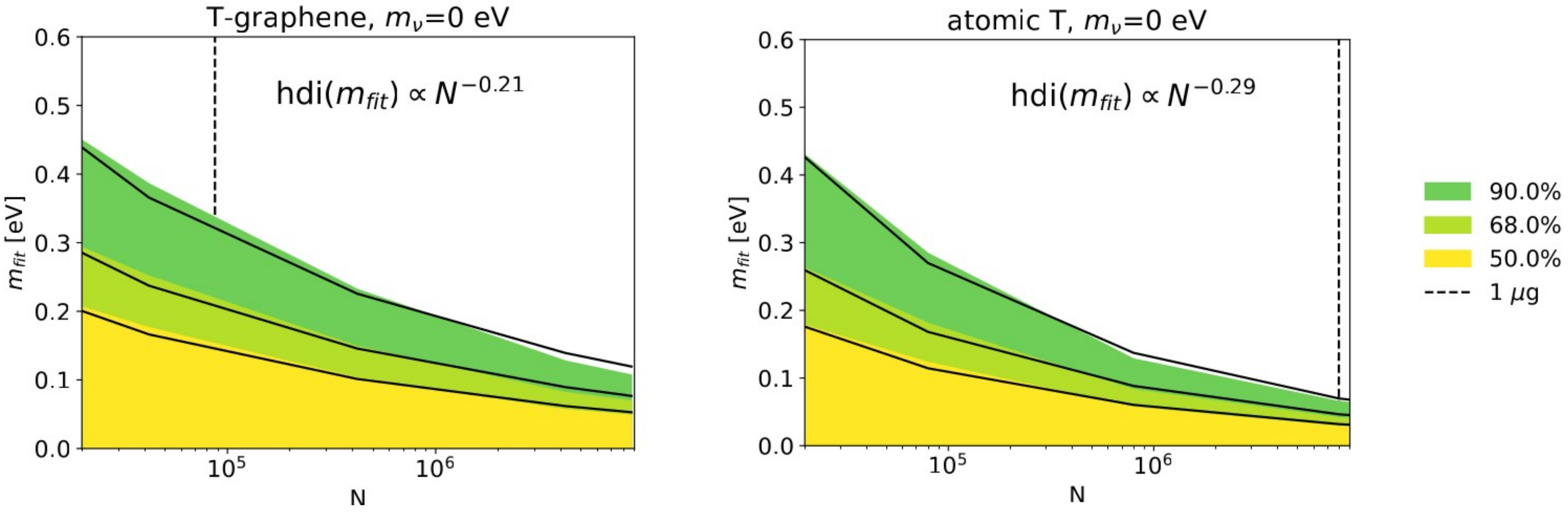
Source = 100 μg

m = 200 meV

σ = 50 meV

From P. Campana (Bayesian)

- The dependence of the upper limits on m_ν from the number of collected events N has been fitted with a power law.
- In each case, the results are consistent between different choices of CL.



Conclusions

- Ptolemy could be **competitive with KATRIN** in the neutrino mass exploration with a very small target (1μg)
- (Tough) **expectations for m_β** are not really promising
- Gaussian unknown or complex know **smearing** could be reasonably handled

Thank you very much!