Neutrino mass sensitivity with the Ptolemy demonstrator

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Neutrino mass

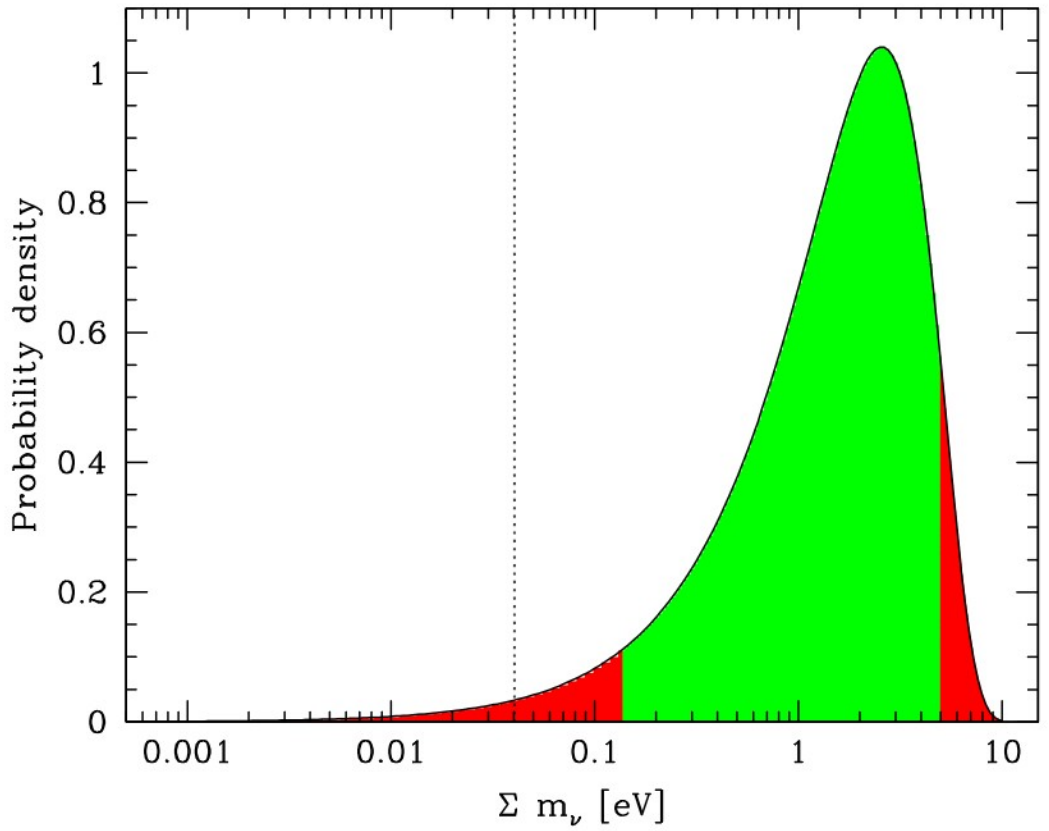
$$m_{\mathrm{eff}}^2 = \sum_i |U_{ei}|^2 m_i^2 \lesssim 800 \text{ meV}$$ **KATRIN**

$$\sum_i m_i \lesssim 100 \text{ meV}$$ **Cosmology**

$$m_{\beta\beta} = \left| \sum_i U_{ei}^2 m_i \right| \lesssim 100 - 300 \text{ eV}$$ **ββ0v (^{76}Ge, ^{130}Te, ^{136}Xe)**

(If Majorana)

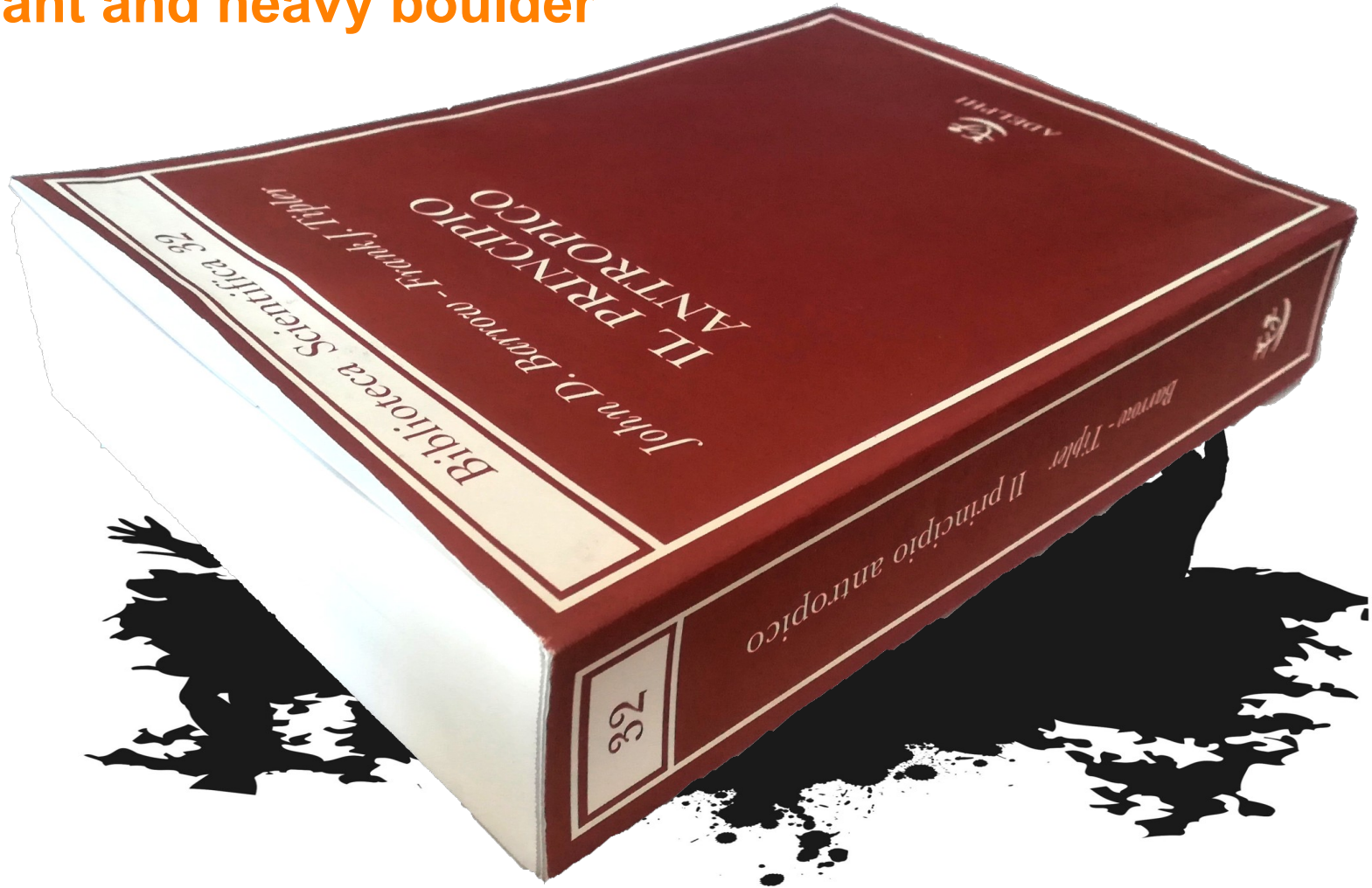
Anthropic predictions for neutrino masses



[Tegmark et al. (2005)]

Atropic Principle

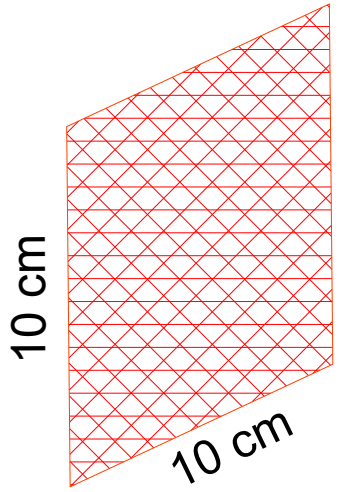
The Anthropic Principle is a giant and heavy boulder



Reference source

$$N_{dec} = \frac{1}{2}\left(\frac{m_S \mathcal{N}_A}{A_{(^3H)}}(1 - e^{-t/\tau})\right) \simeq 1.1 \times 10^{16}$$

(50% Efficiency for total events)



(x 1 year)

ρ = 0.2 mg/m²
(full loading)

→ 2 µg

716 MBq
(19.3 mCi)

Formulas

$$S_{\sigma,m}(E) \simeq R(E) \sum_i |U_{ei}|^2 \sqrt{(E_0 - E)^2 - (m_{\nu_e}^{\text{eff}})^2)} \otimes \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{E^2}{2\sigma^2}}$$

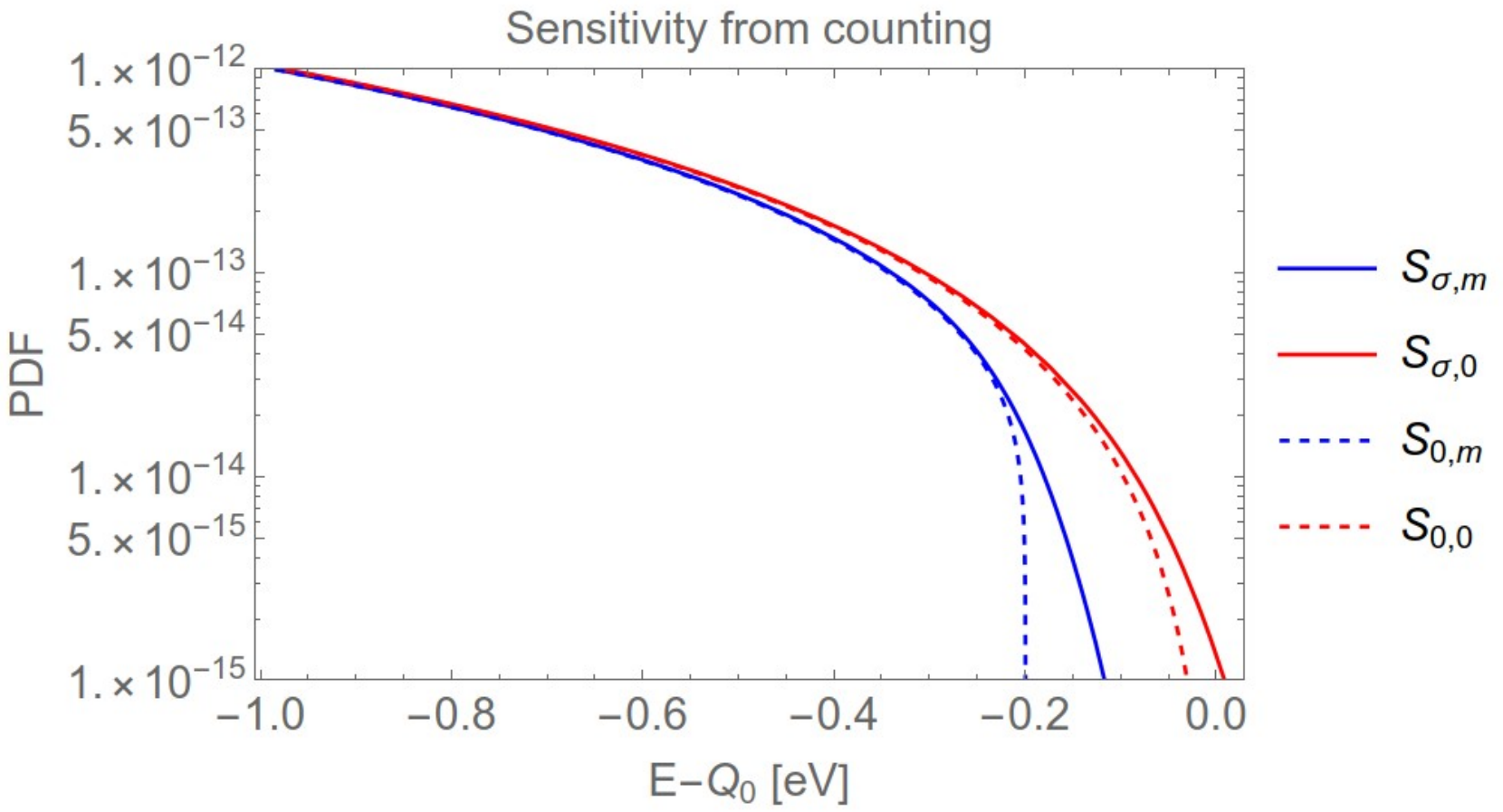
Theory

Resolution

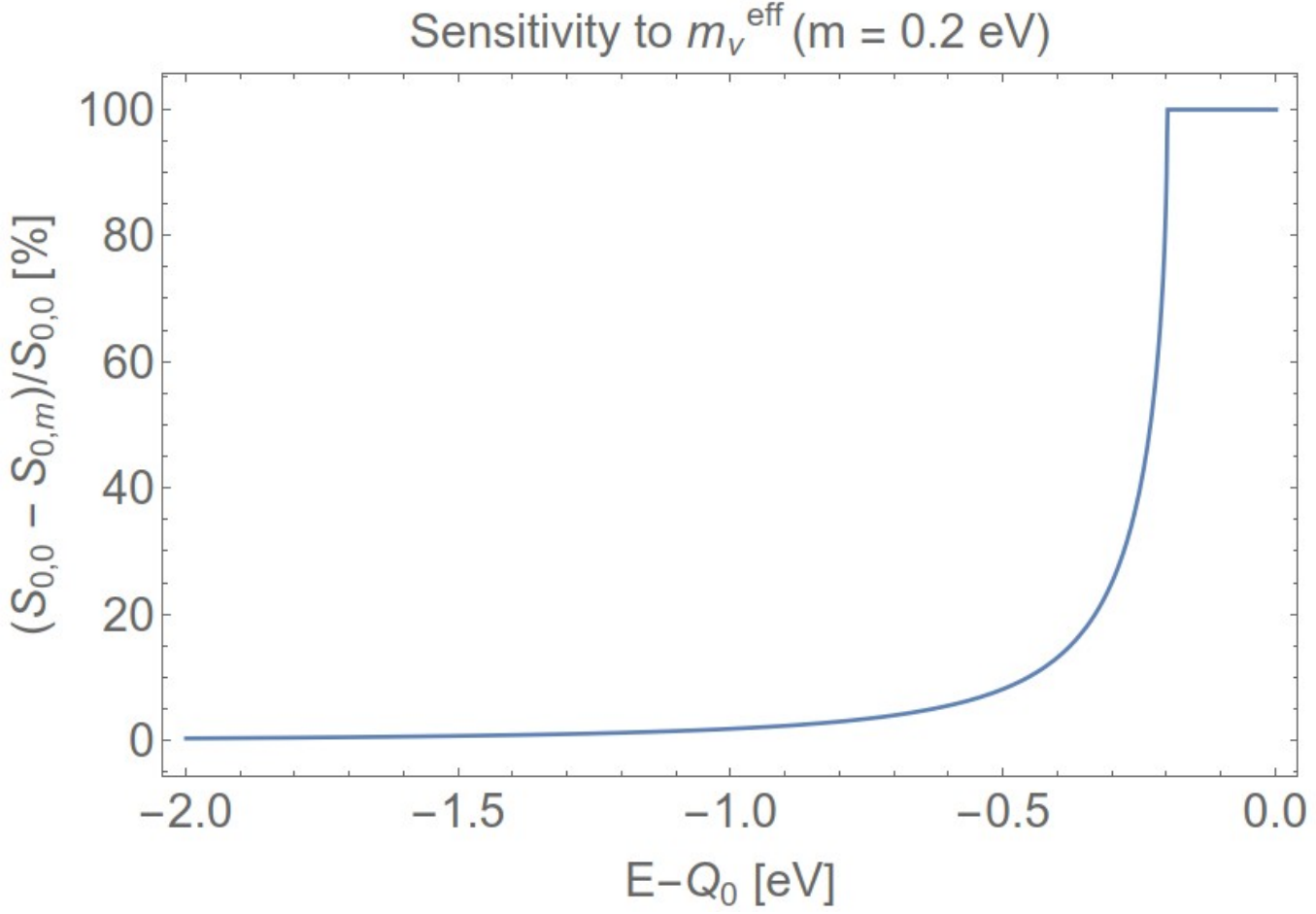
Cases:

$S_{0,0}$ = Therotical spectrum with massless neutrino
$S_{0,m}$ = Therotical spectrum with massive neutrino
$S_{\sigma,0}$ = Experimental spectrum with massless neutrino
$S_{\sigma,m}$ = Esperimantal spectrum with massive neutrino

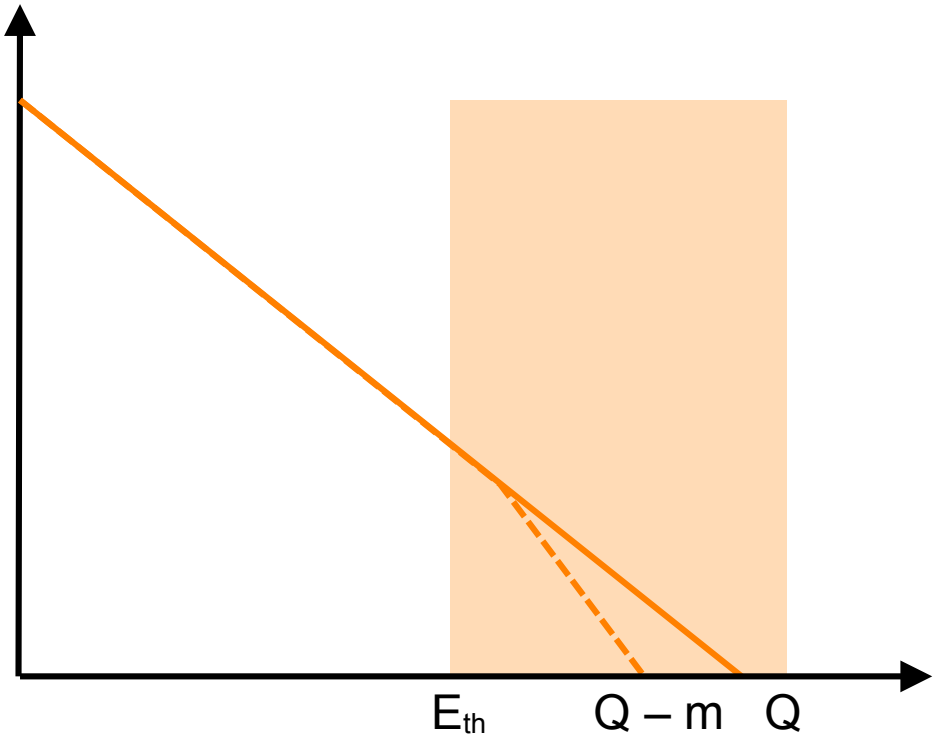
End-point


Sensitivity from counting
PDF
1. × 10^−12
5. × 10^−13
1. × 10^−13
5. × 10^−14
1. × 10^−14
5. × 10^−15
1. × 10^−15
−1.0
−0.8
−0.6
−0.4
−0.2
0.0
E−Q0 [eV]
Sσ,m
Sσ,0
S0,m
S0,0

Sensitivity to neutrino mass



Counting analysis



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

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

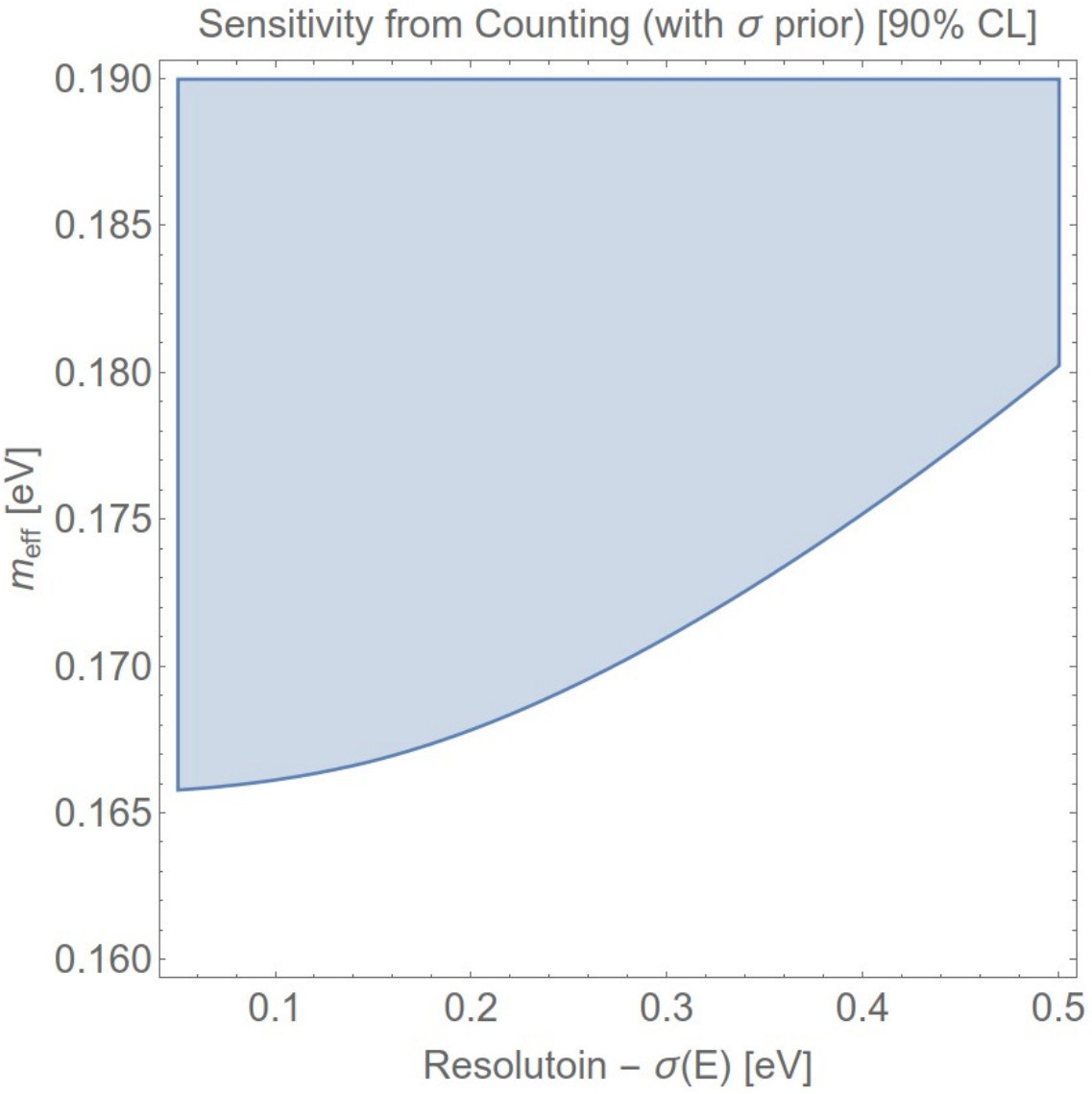
Sensitivity 90%CL :=

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

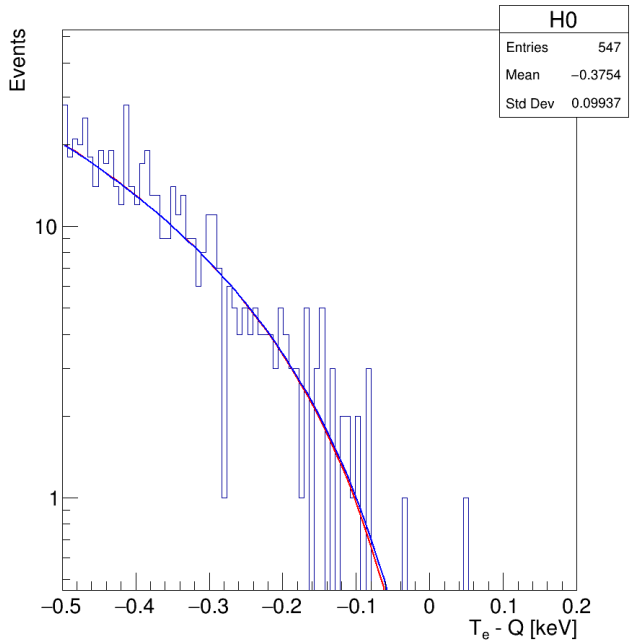
Sensitivity from counting analysis

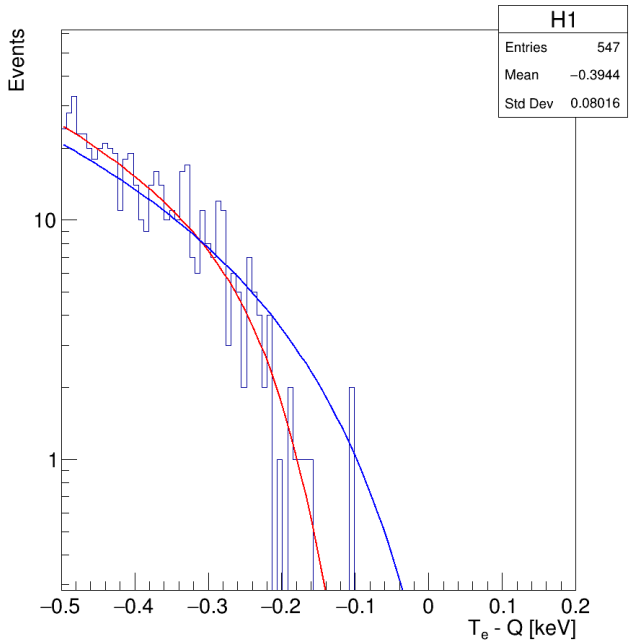
Narrow prior on resolution:

- Esperimental resolution
- Uncentainty principle smearing (Δ)



Profile likelihood approach



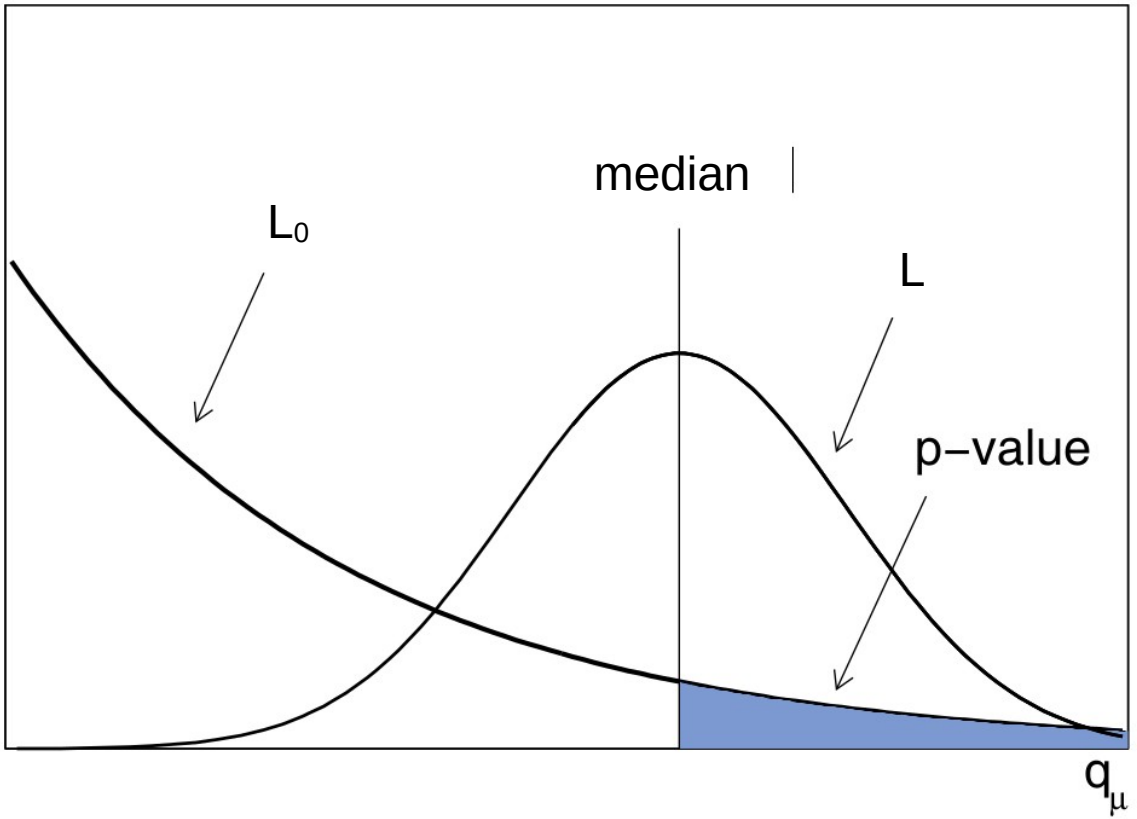


Sensitivity

P-value of the L medial over the L_0 distribution

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

Median sensitivity



[Cowan et al. (2013)]

TOOL: PtSens (GitHub)

Plot your spectrum:

./ptsens plot mass [eV] sigma [eV]

Random sample from toy MC and fit:

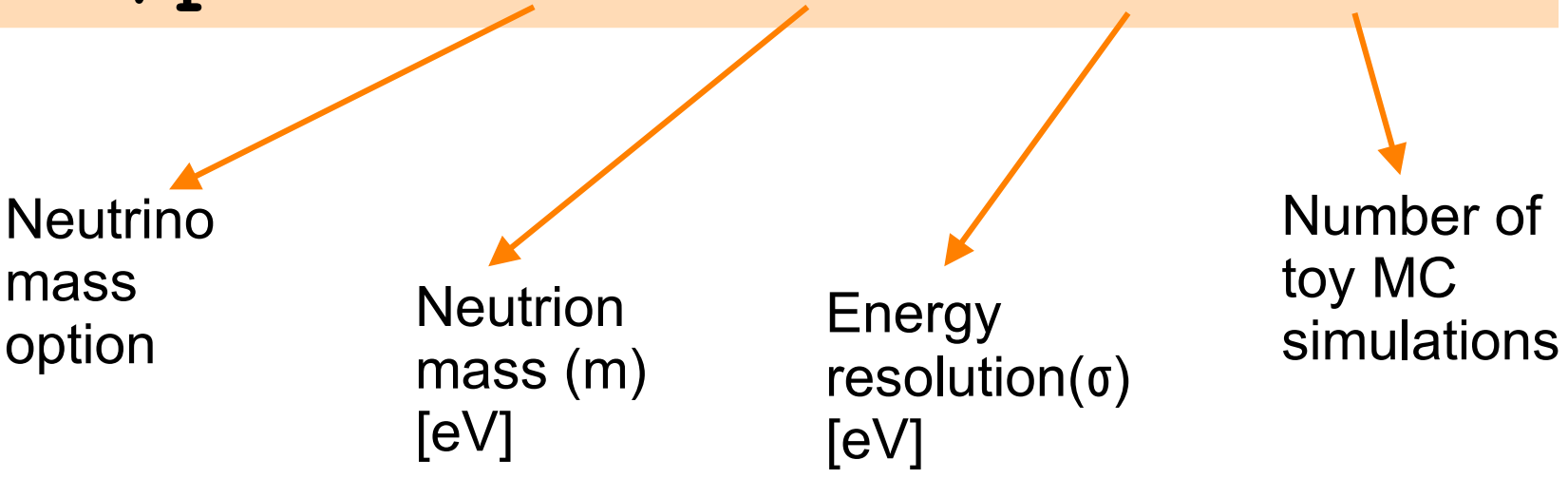
./ptsens mc mass [eV] sigma [eV]

Profile likelihood for discovery (sensitivity):

./ptsens pf mass [eV] sigma [eV] nToys

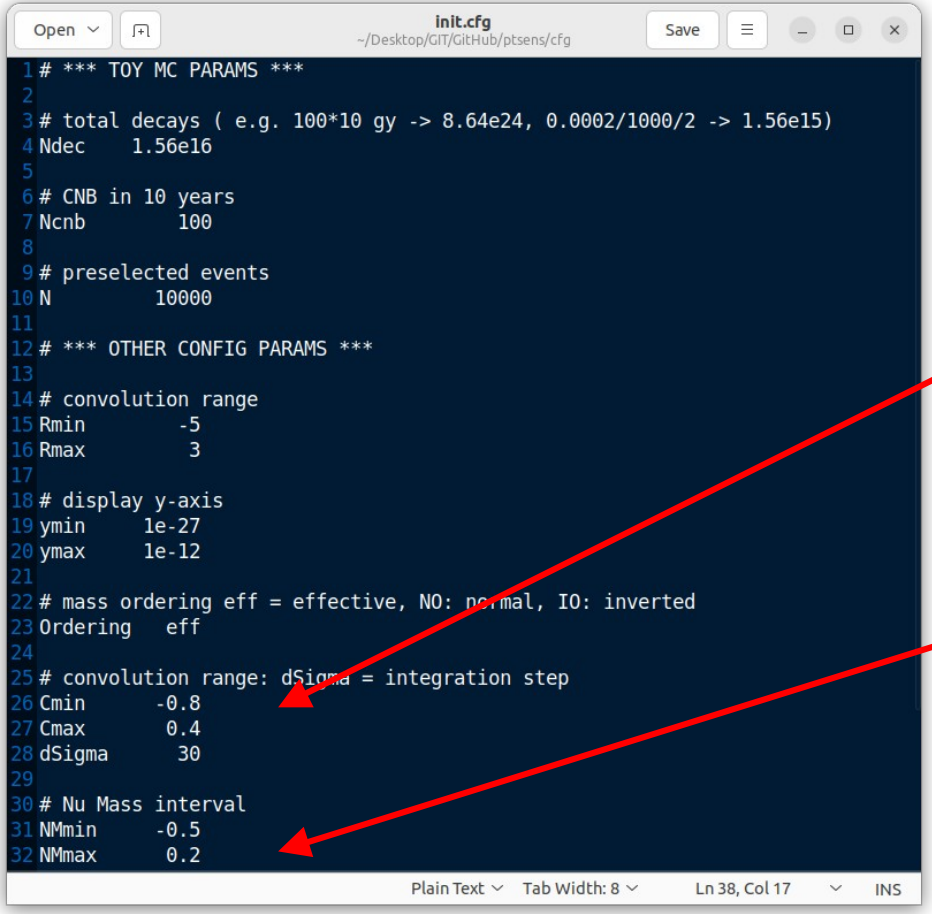
A new option

```
./ptsens nm 0.200 0.050 1000
```



Output: **`ptolemy.root`**

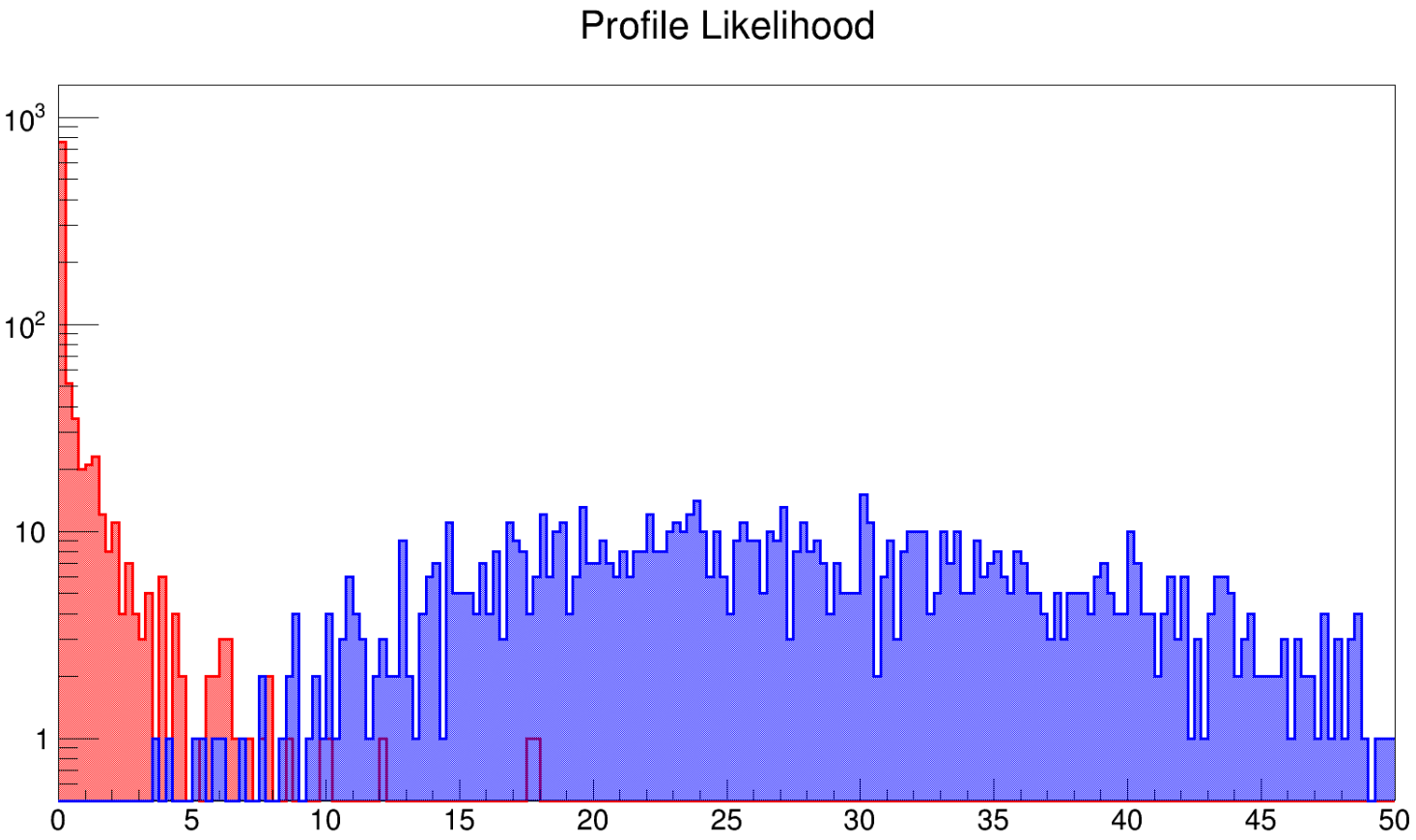
New cfg file (part 1/2)



New option #1
Explicit convolution range

New option #2
Nu mass energy interval [eV]

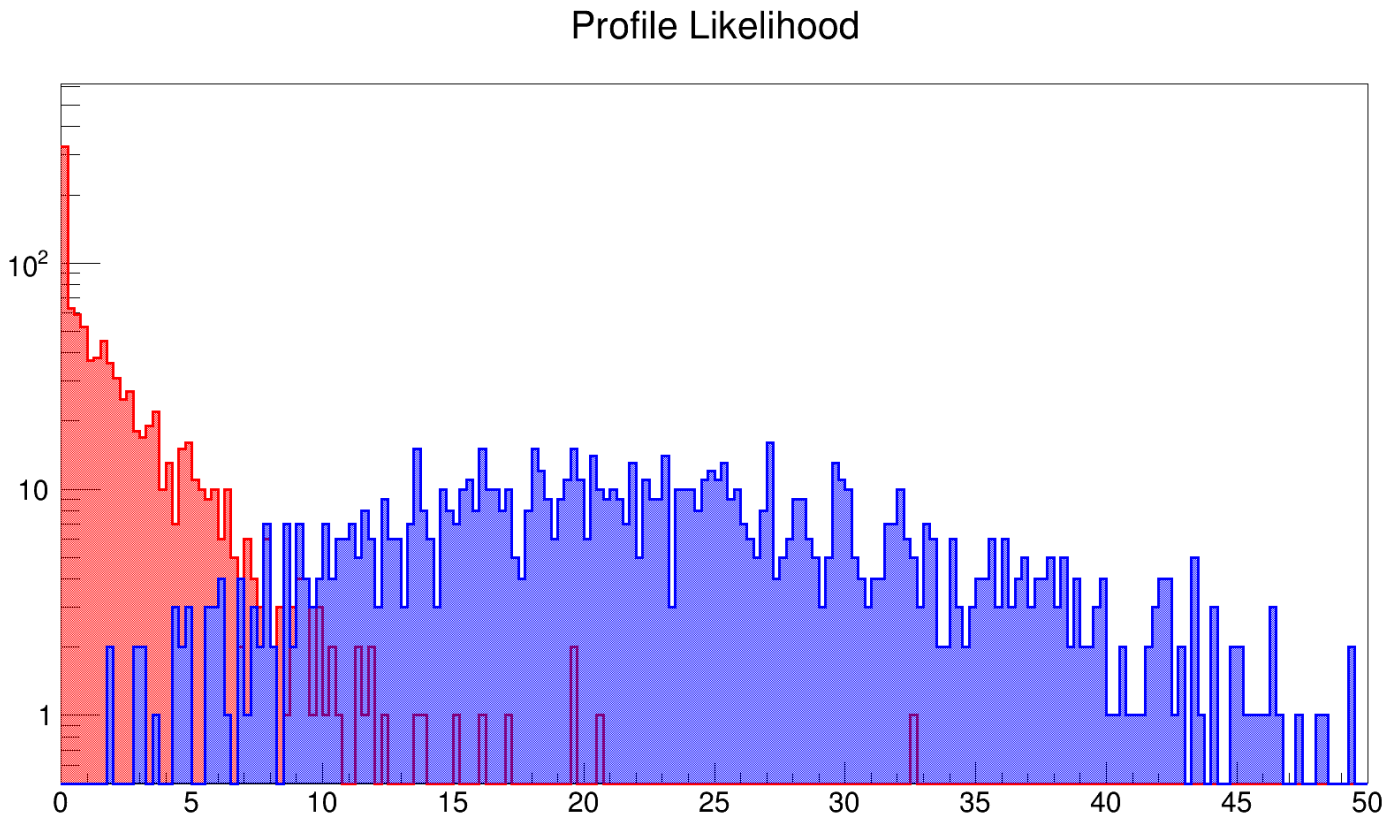
Example no. 1 (m=200 meV, σ=50 meV)



No events > medial

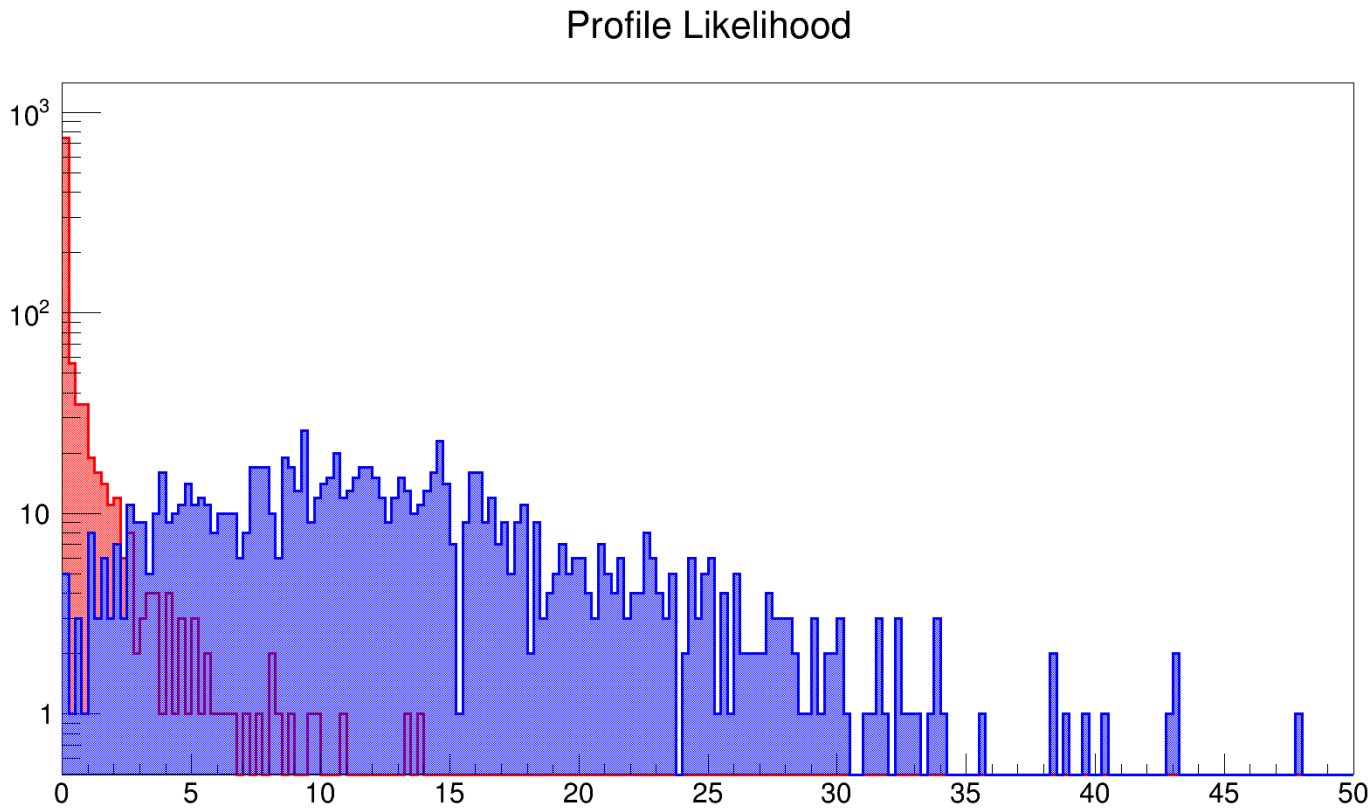
→ Better than 3 σ

Example no. 2 (m=200 meV, σ=500 meV)



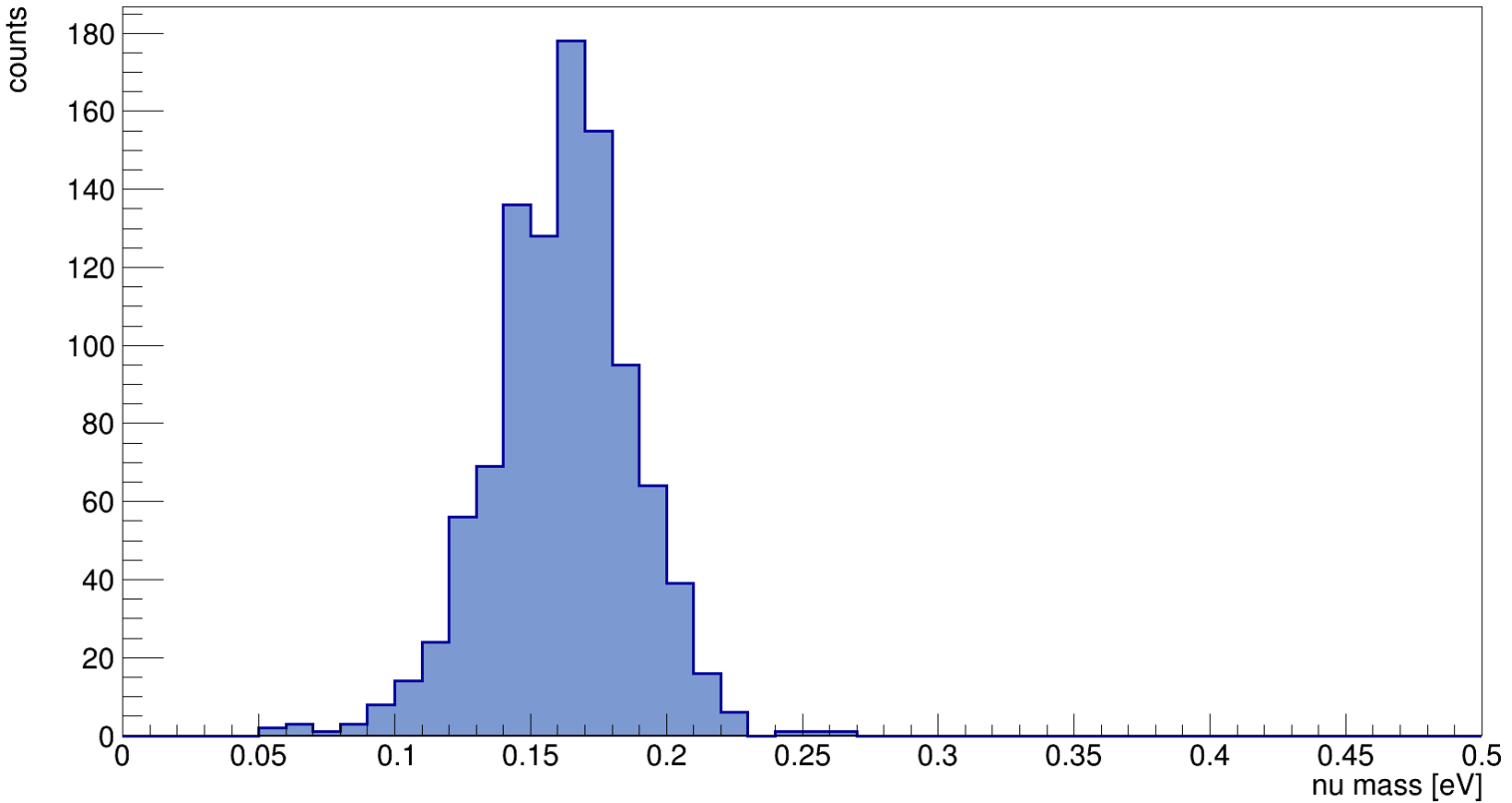
Close to
3 σ anyway

Example no. 3 (m=150 meV, σ=50 meV)



Still sensitive

Reconstructed m in Ex. 3



Comparison KATRIN

Table 1 | Comparison of key numbers for the KNM campaigns

	KNM1	KNM2
Number of scans	274	361
Total scan time	521.7 h	743.7 h
Background rate	290 mcps	220 mcps
T_2 column density	1.11×10^{17} cm^{-2}	4.23×10^{17} cm^{-2}
Source activity	2.5×10^{10} Bq	9.5×10^{10} Bq
Total number of β-electrons	1.48×10^{6}	3.68×10^{6}
β-electron-to-background ratio	3.7	9.9

KNM1 refers to the first KATRIN campaign results[17] and KNM2 refers to this work. The total number of β-electrons is counted in the last 40 eV interval of the integral spectrum, which is used for the spectral fit. The β-electron-to-background ratio is given by the ratio of this number and the background counts in the same energy range, that is, $E_0 - 40$ eV to E_0.

$[E_0 - 40,\ E_0]$ eV

~10^{14} events

Current limit < 800 meV

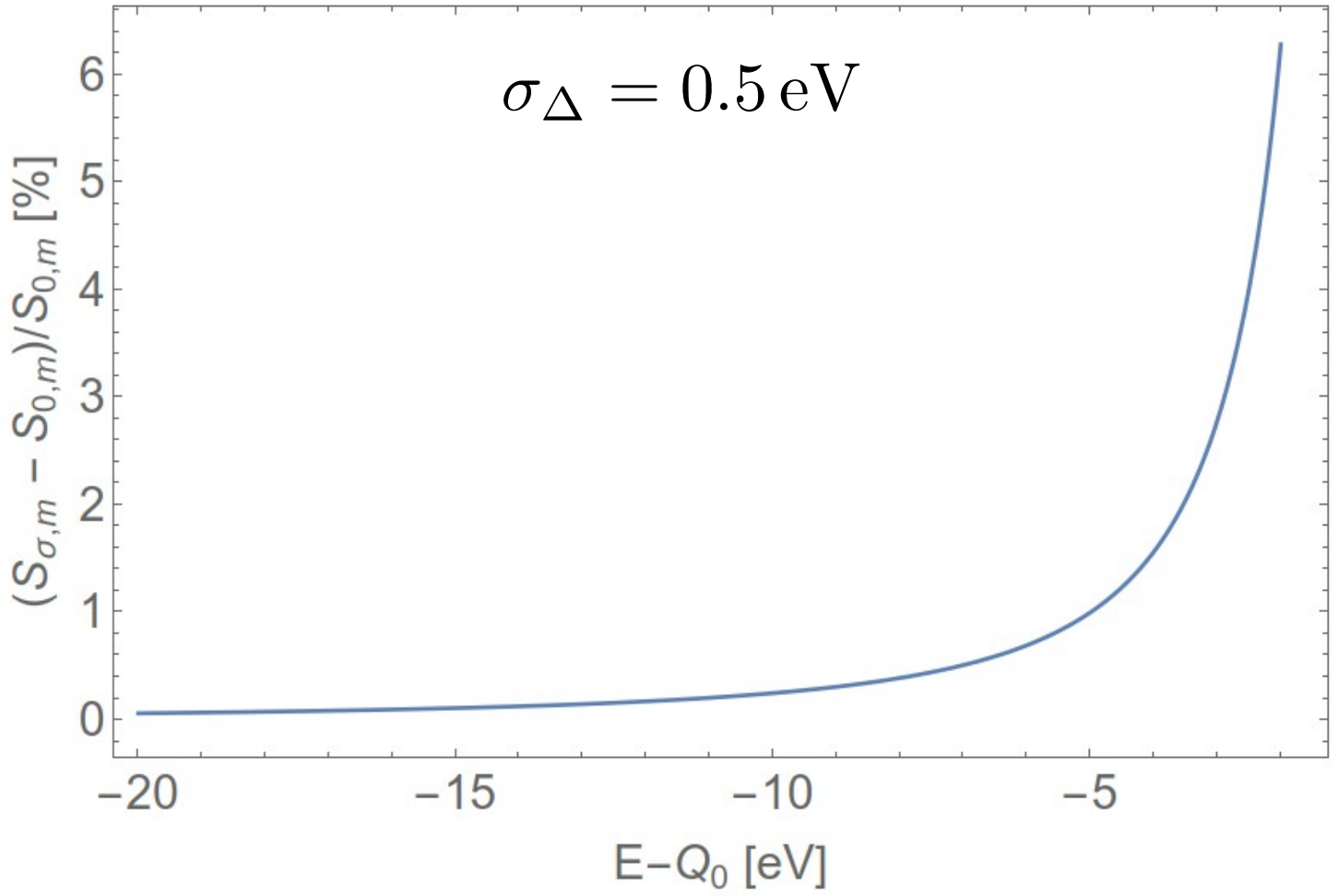
Sensitivity 700 meV
Resolution 930 meV

Δ: A way out

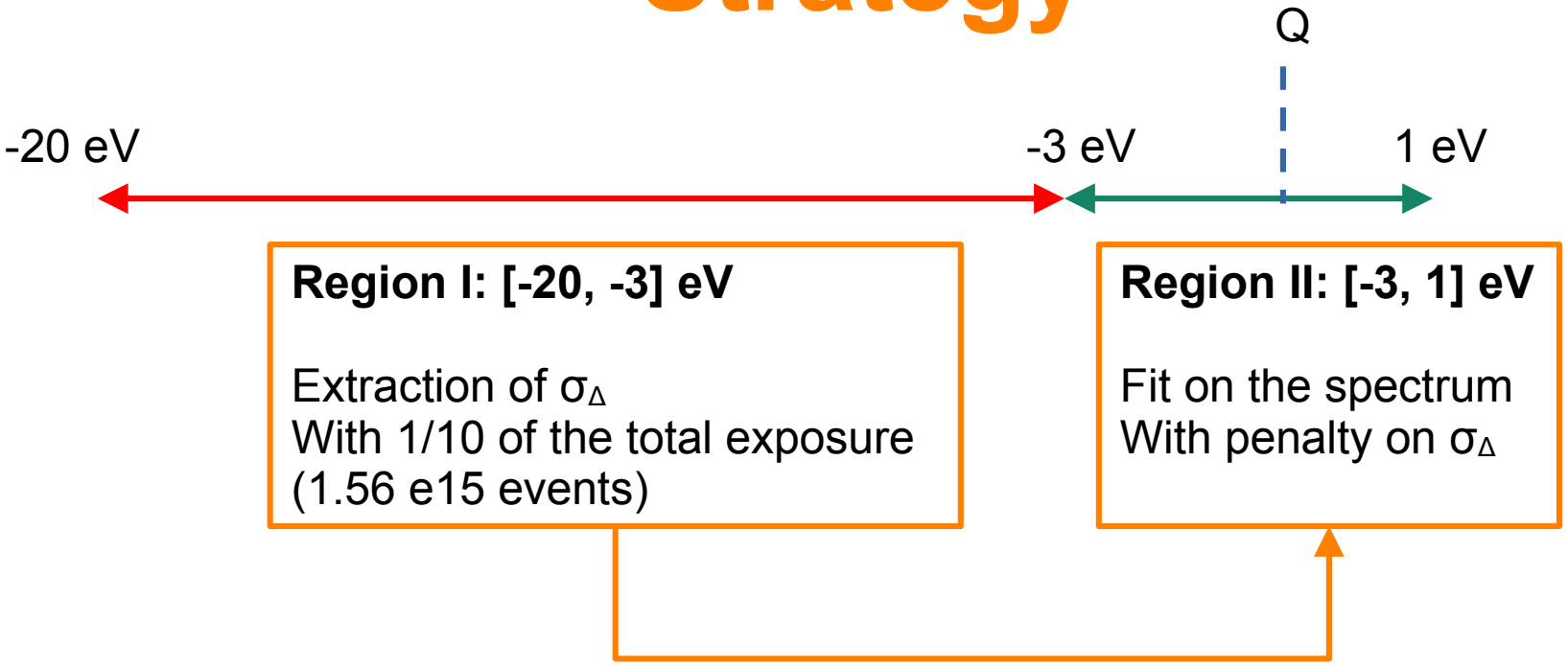
“If you want to prove that pigs fly, show at a least one pig flying and not hundreds of pigs a little jumping”

(Unknown philosopher)

Sensitivity to (unknown) Δ smearing

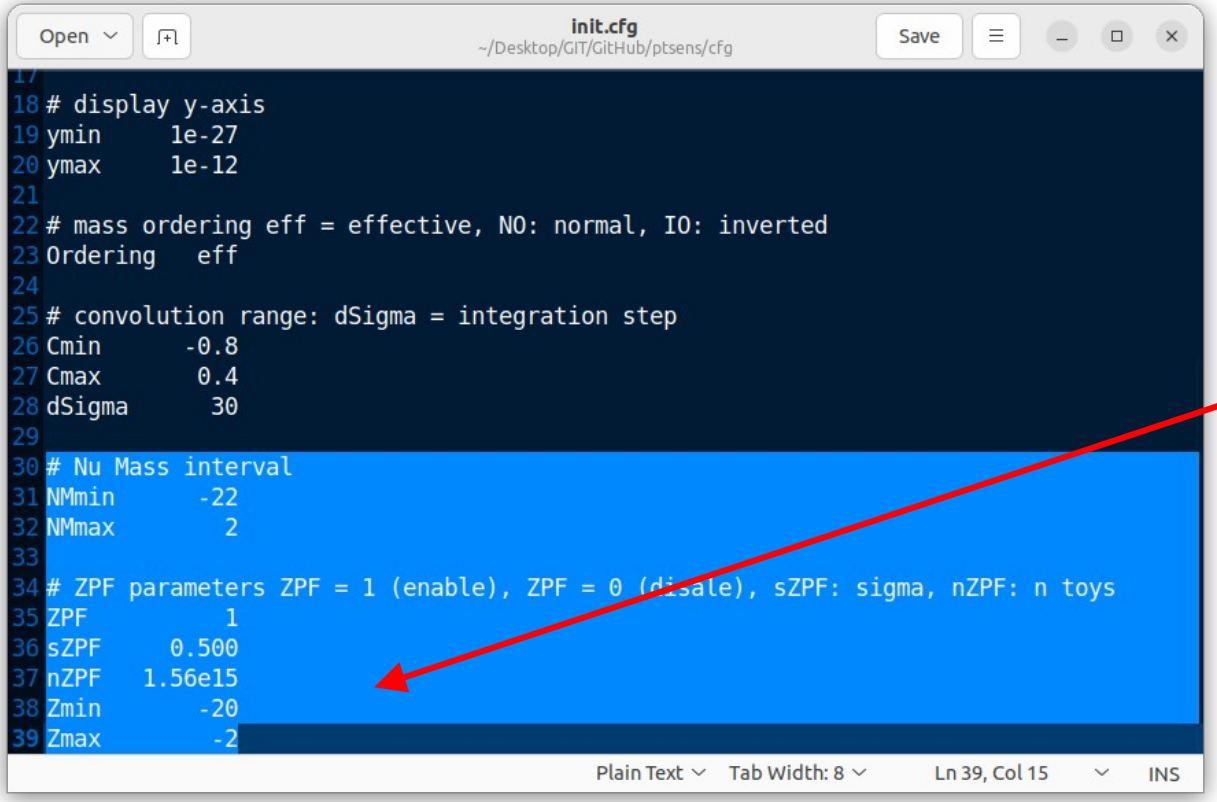


Strategy



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

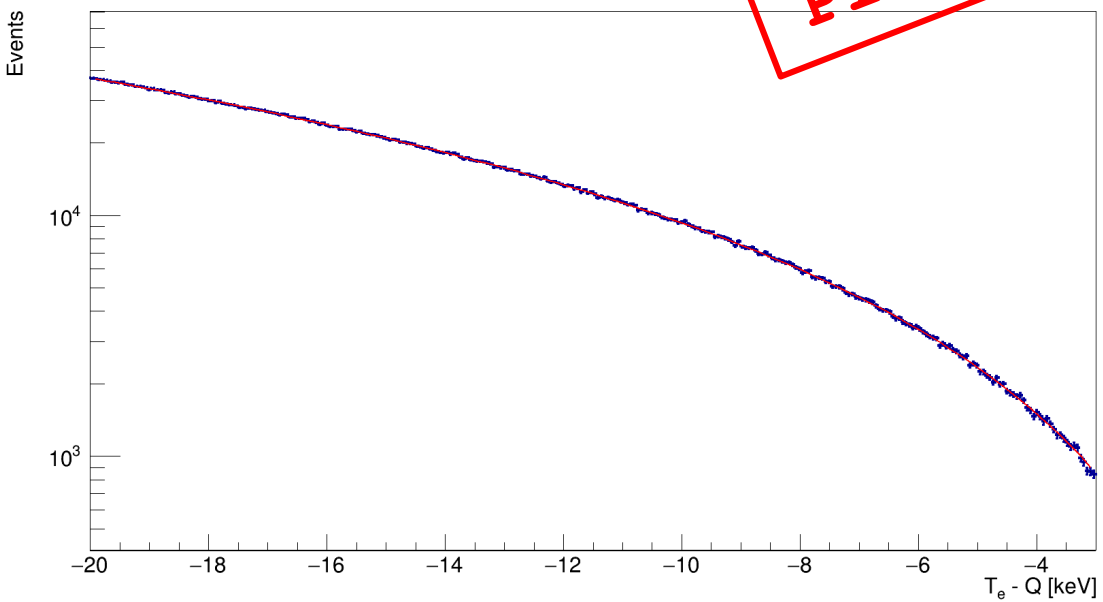
New cfg file (part 2/2)



New option #3
Δ strategy constraint
List of parameters

Example

Preliminary



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%)

Take-home message

Neutrino mass measurement is an extrimely important phyisical goal, and it is at our reach with the PTOLEMY demonstrator

Thank you very much
for your attention!