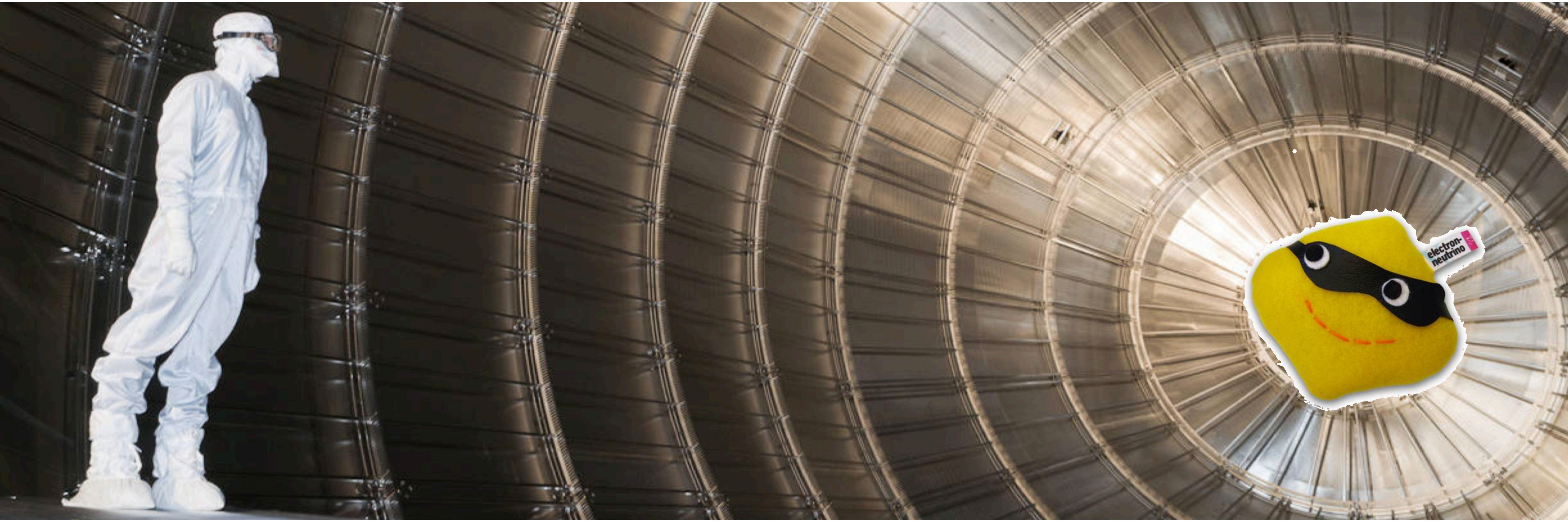
Bayesian Analysis of Neutrino Mass in Katrin

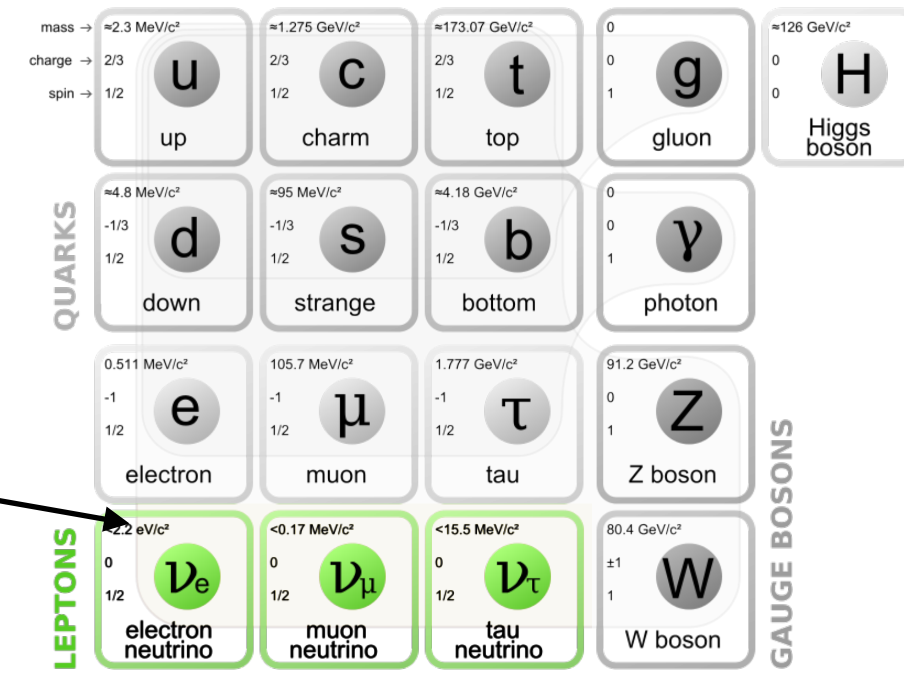
Björn Lehnert



SciDAC Discussion
online, Jan 26th 2022

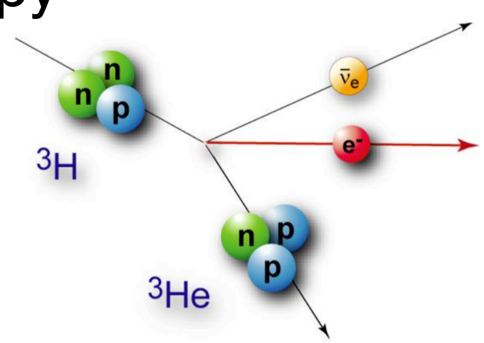
Measuring the Neutrino Mass

- Neutrinos are most abundant matter particles in Universe
- Relevant for particle physics and cosmology
- Mass is very small but still unknown



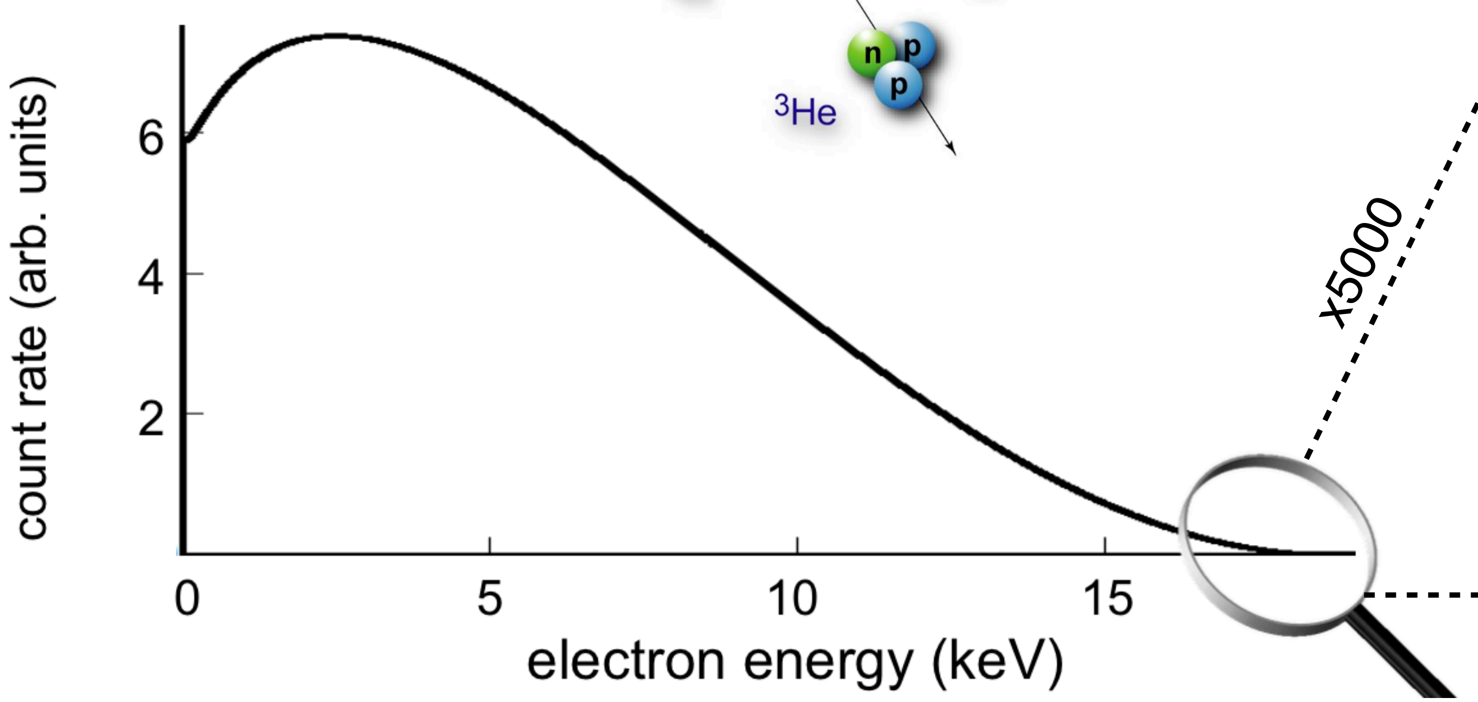
Observable: $m_\beta^2 = \sum_i m_i^2 \, |U_{ei}|^2$

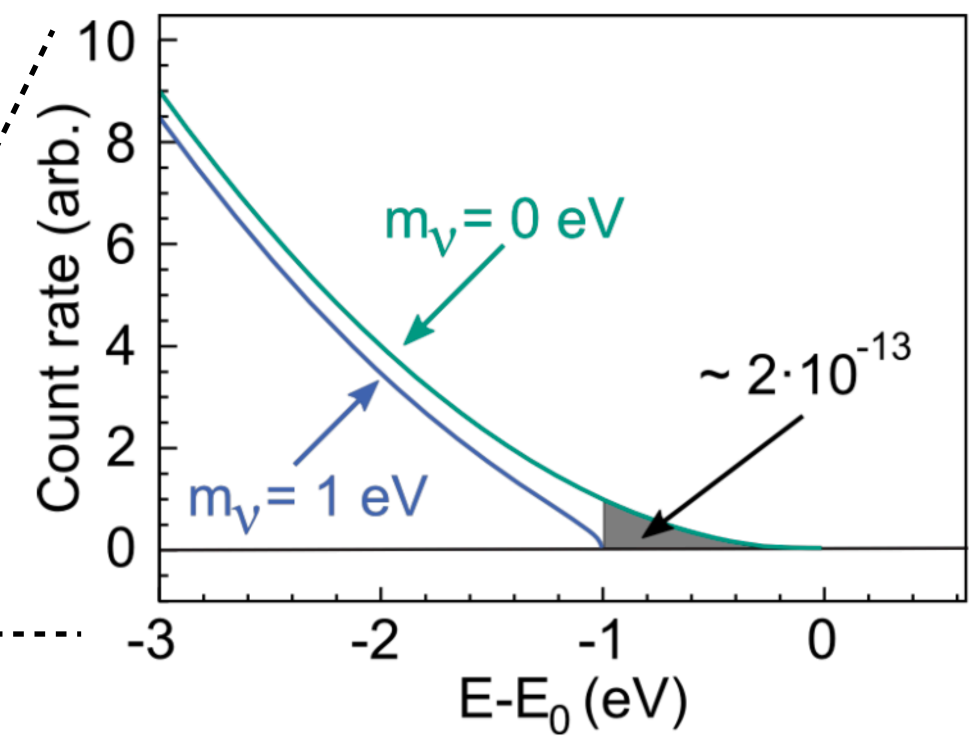
Precision spectroscopy of tritium β-decays



Experimental signature:

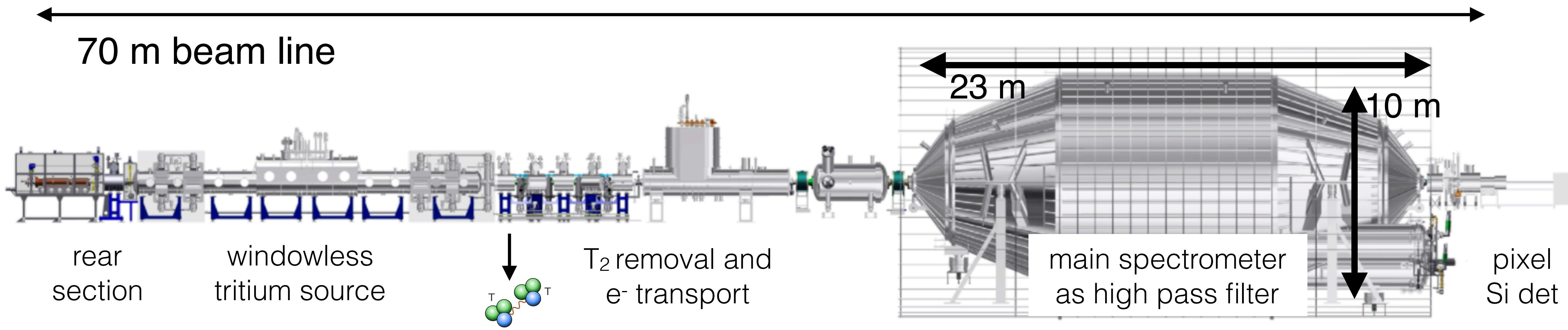
- Spectral distortion at endpoint

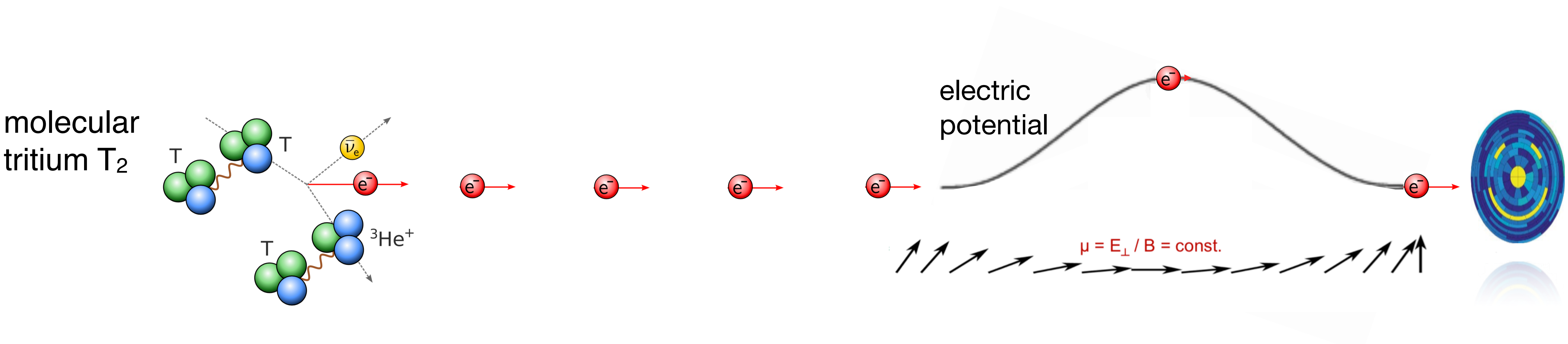




How we do the measurement?

Beamline with source, spectrometer, pixellated detector

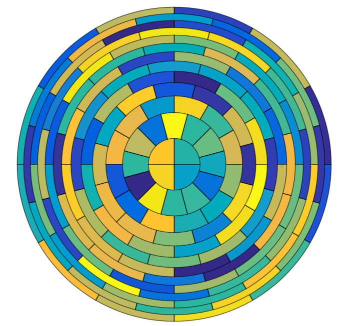




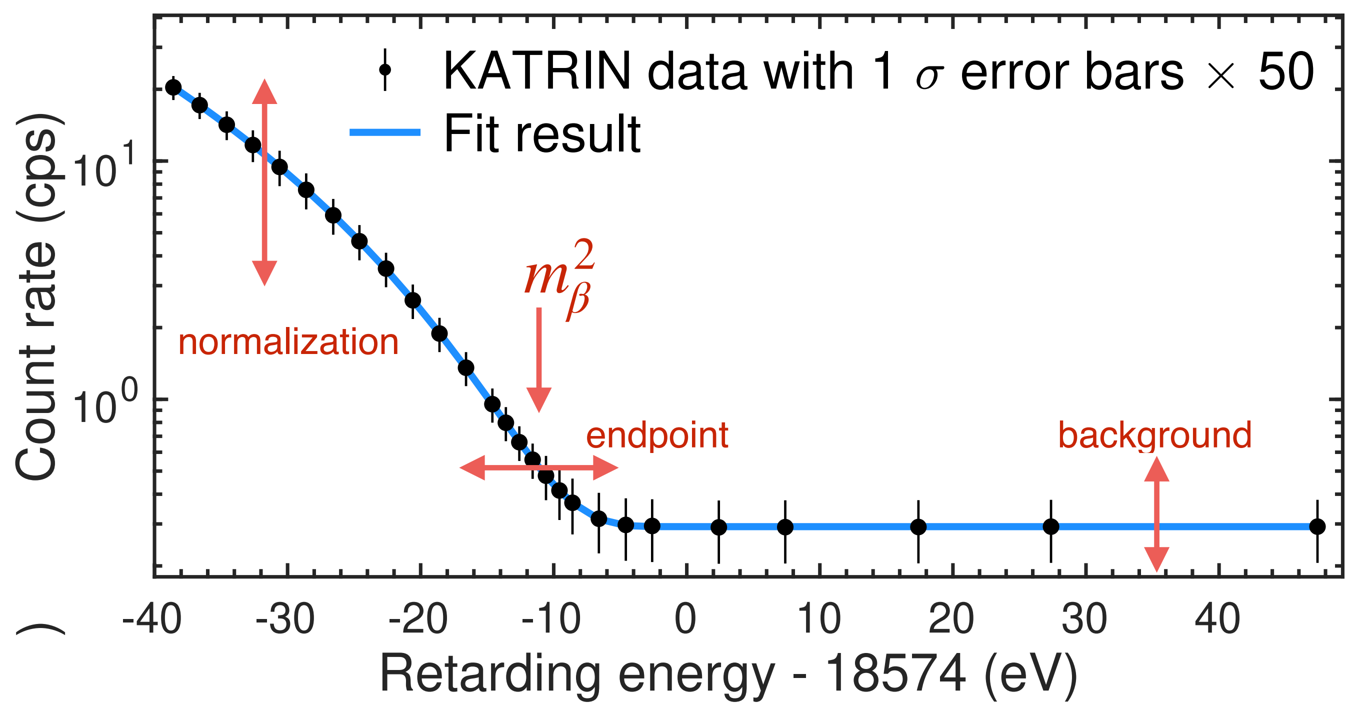
Fit Model

Minimal fit: 4 parameter
- normalization (A), endpoint (E_0), constant background (R_{bg}), neutrino mass (m_β^2)

Complete fit: ≈ 25 parameters
- Many systematic variations
- Correlations between datasets

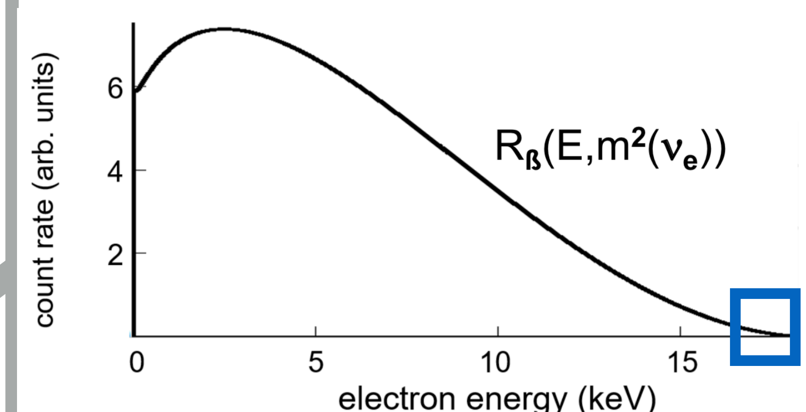


detector pixelation
(14 patches)

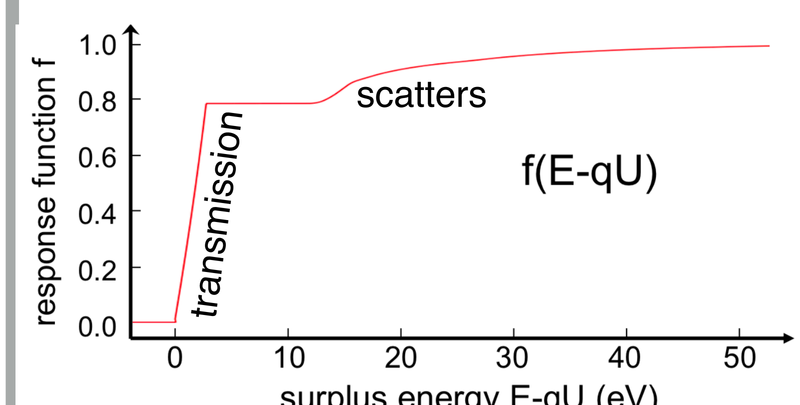


Model ingredients and systematics

Beta spectrum:
- Multiple spectra from T_2, DT, HT
- Various final states



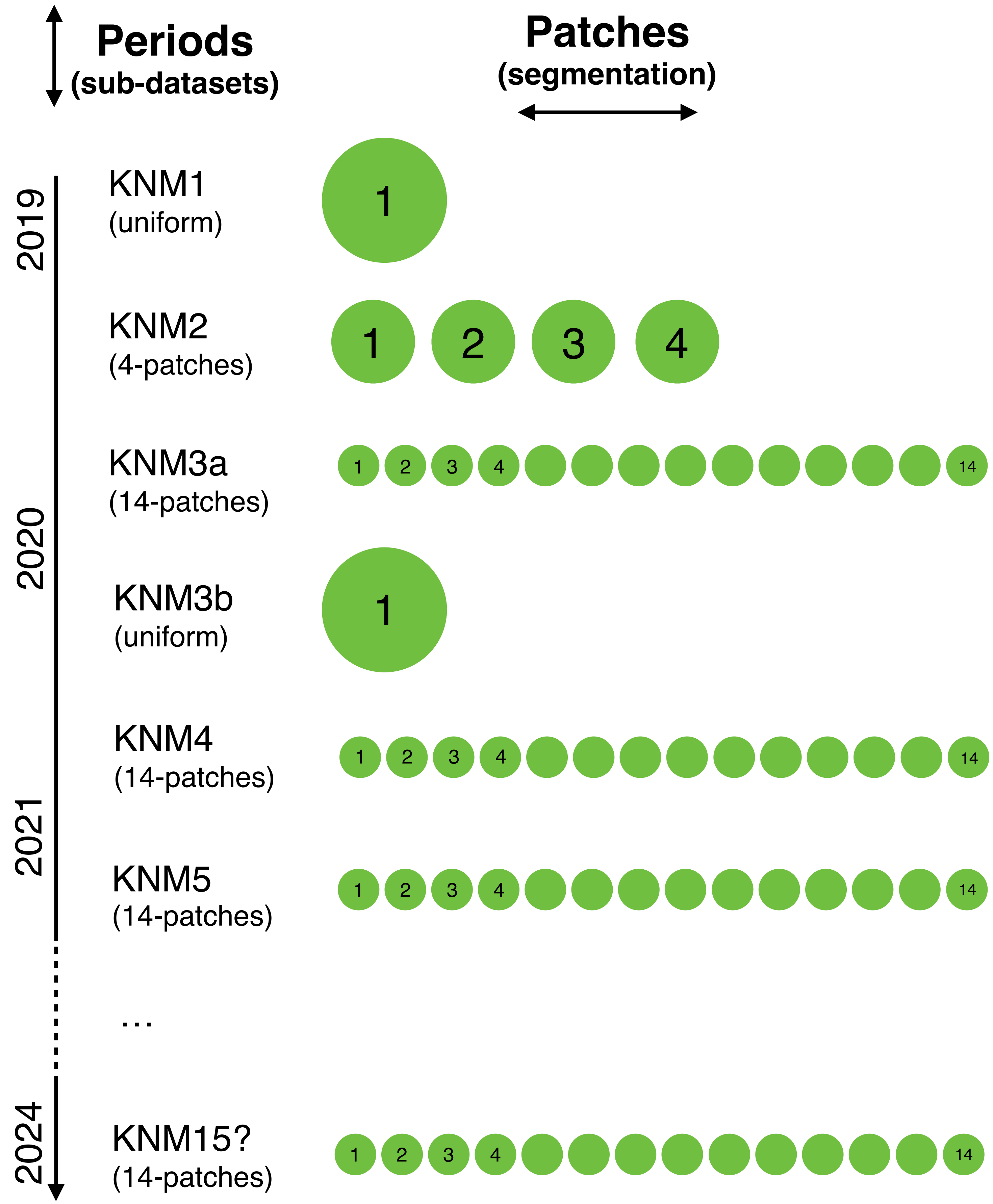
Response function:
- Transmission: B-fields
- Source density: Probability of scatter
- Electron energy loss: If scatter occurs



Constant background
- Time varying component
- Potential slope

Performance for response calculation (single thread):
- ≈ 20 ms per MCMC step (minimal fit)
- ≈ 10 s per MCMC step (complete fit)

Datasets and Systematics



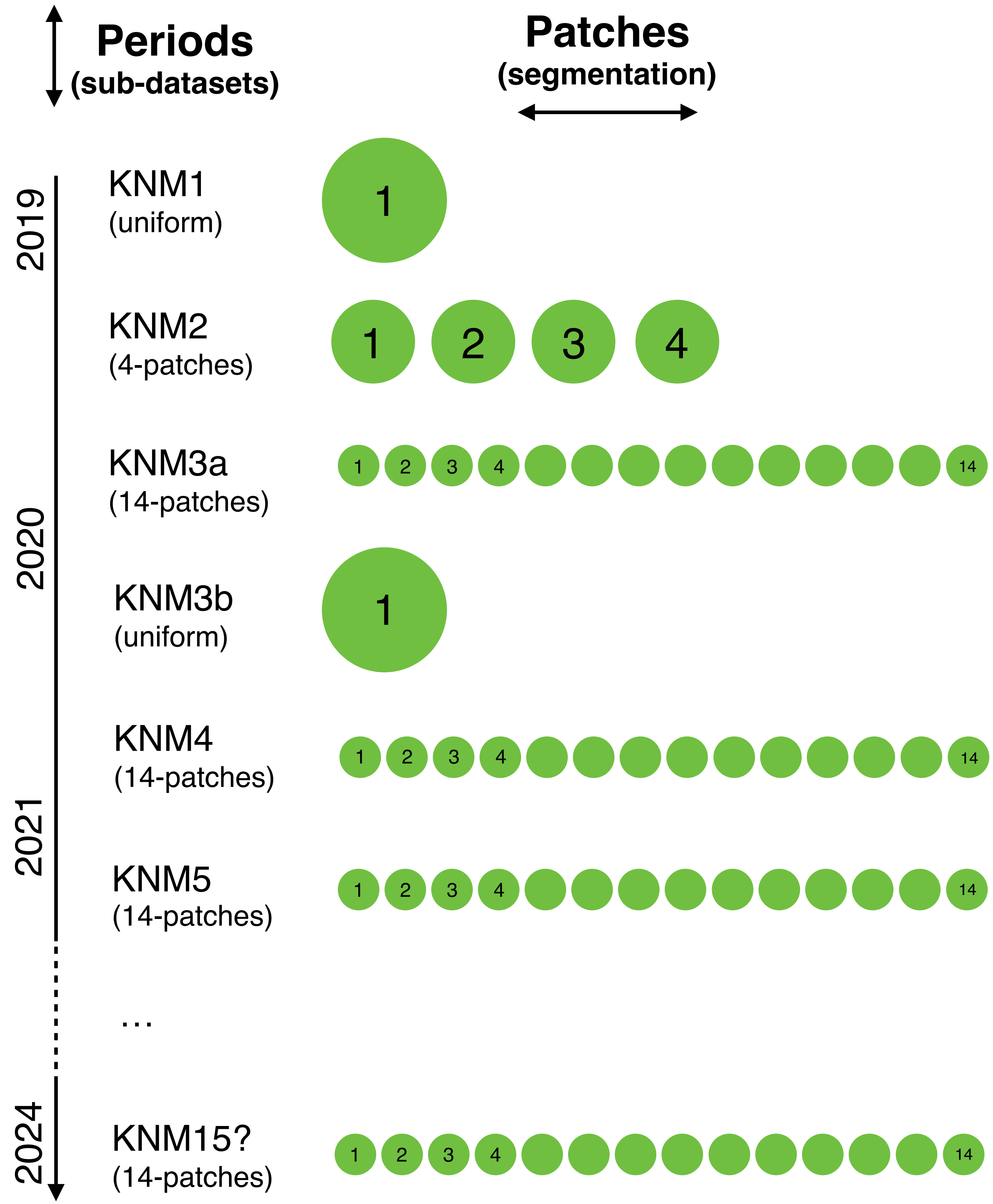
Number of basic parameters:

- ≈ 600 in final dataset (1+ 3 x 14 x 15)

Number of systematic parameters:

- ≈ 300 in final dataset
- Some correlated between periods
- Some correlated between patches

Datasets and Systematics



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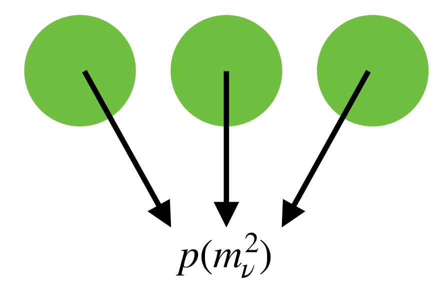
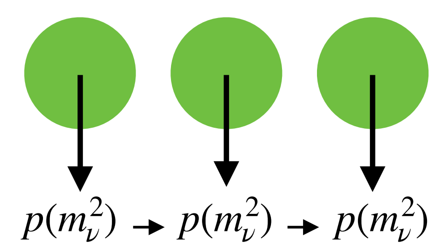
Approaches for handling large number of parameters:

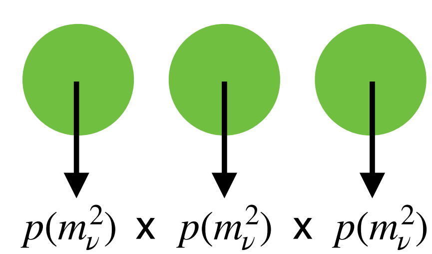
Multi-patch fit



Posterior chain

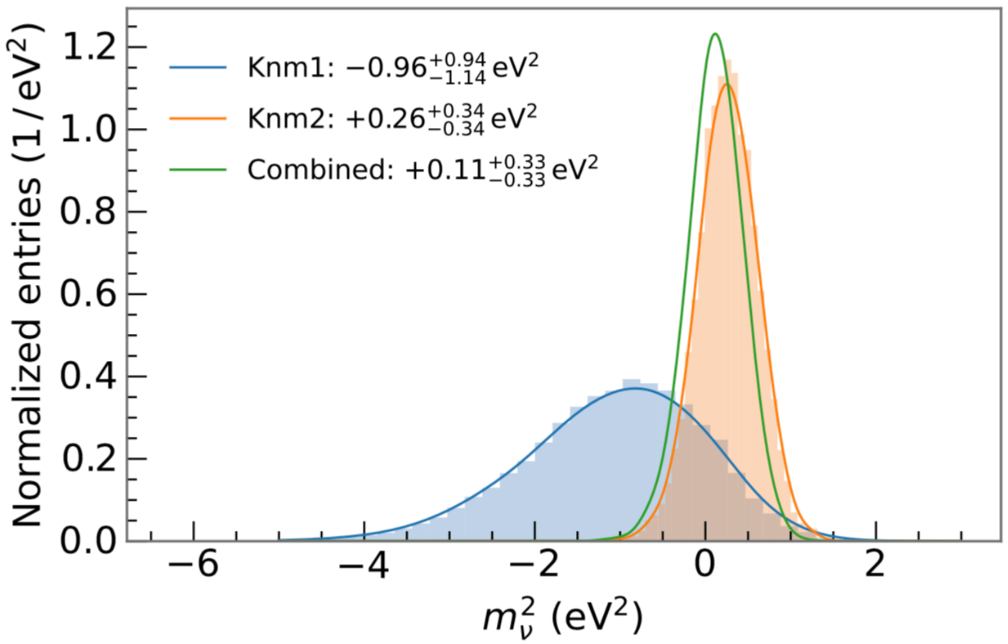


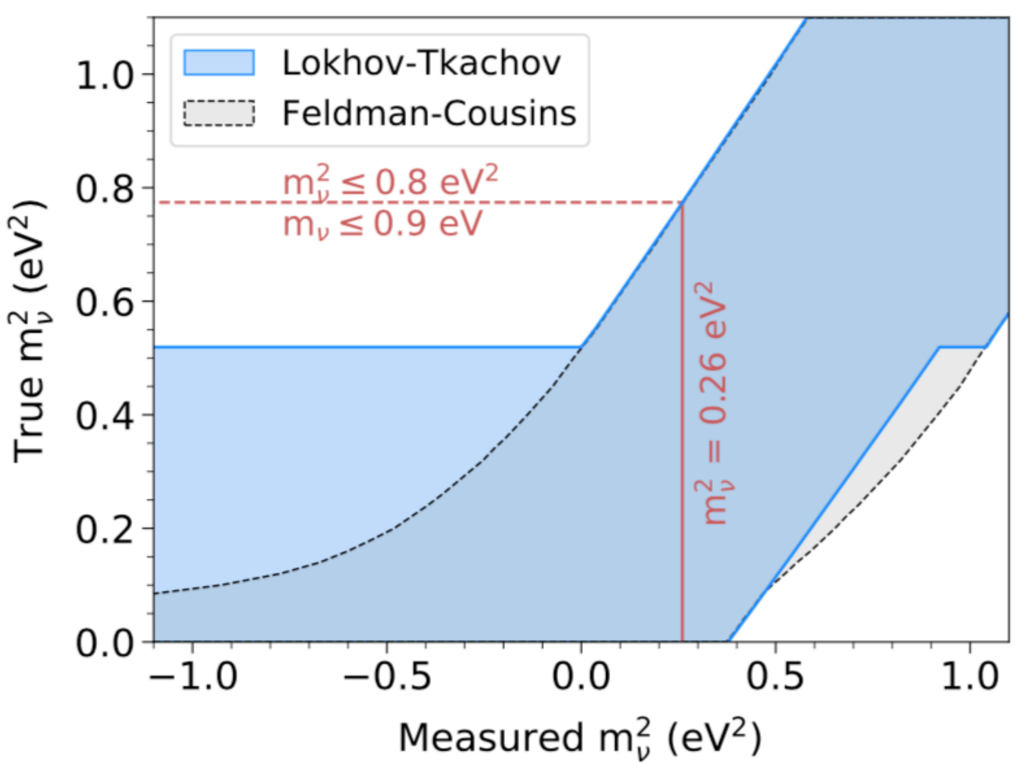
Posterior product



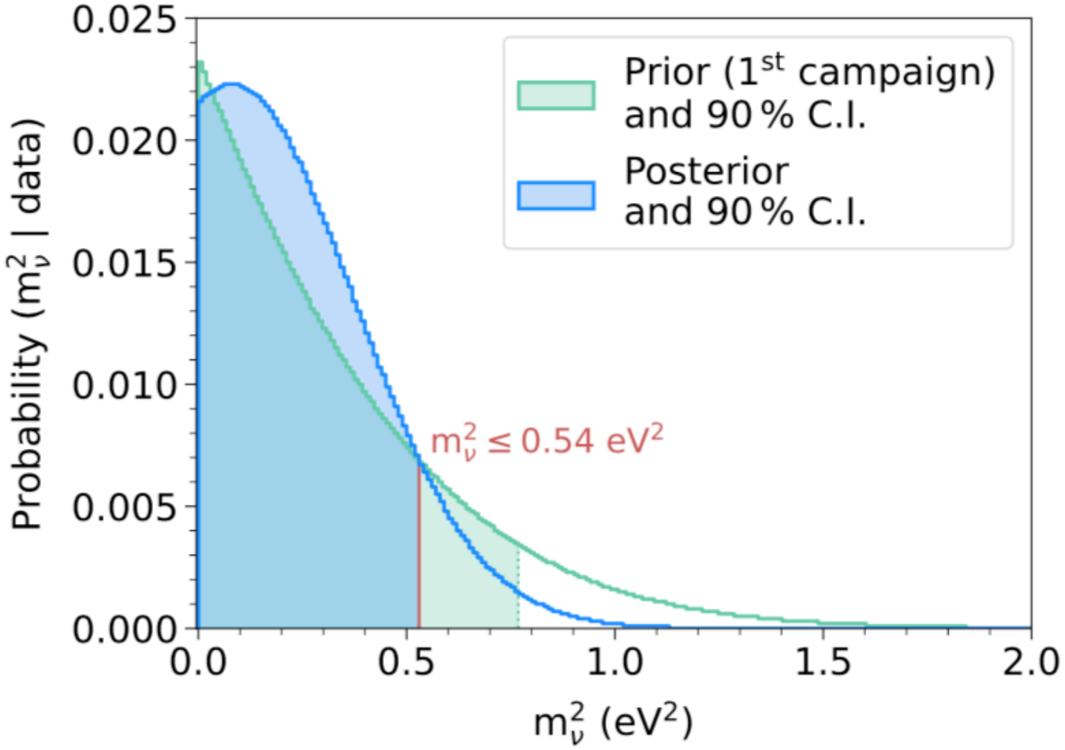
Latest Results

Traditionally Frequentist analyses in KATRIN-style experiments:





Bayesian analysis:



Advantages for Bayesian analysis:

- Straight forward limit setting only allowing physical parameter space (other analysis extend fit into unphysical region)
- Including prior information from other neutrino experiment
- Easier interface in global fits: use posterior distribution directly
- Other studies: Least informative priors etc.

Procedures and Challenges

https://bat.mpp.mpg.de

currently used → in development

BAT
BAYESIAN ANALYSIS TOOLKIT

- c++
- Metropolis

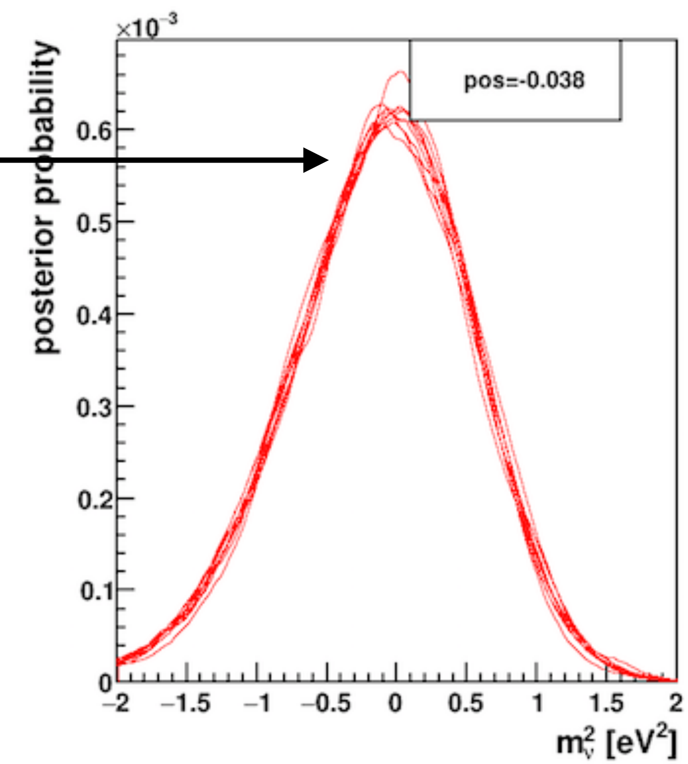
BAT.jl
Bayesian Analysis Toolkit

- Julia
- Metropolis-Hastings
- More clever convergence

Challenges:

- Large number of parameters
- Expensive response function calculation
- Precision requirements
  - Numerical noise in posterior
  - Quantifying impact of small systematics
- Repeat analysis many times
  - Code comparisons
  - Unblinding steps
  - Different priors
- Acceptance of Bayesian statistics in community

- Metropolis-Hasting
- Neutral network interpolation of response parameter space for fast evaluation

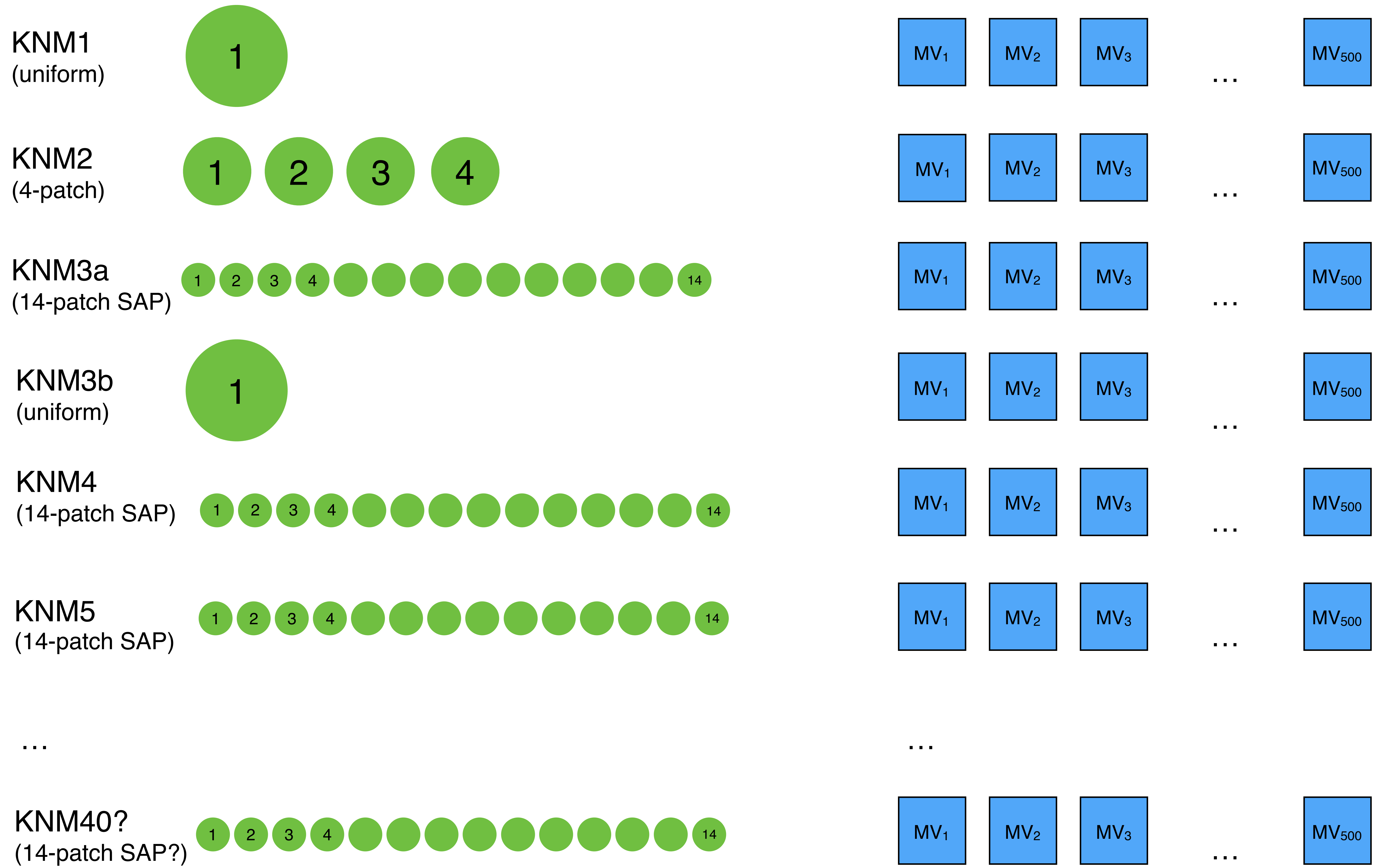


Backup

Datasets and Systematics

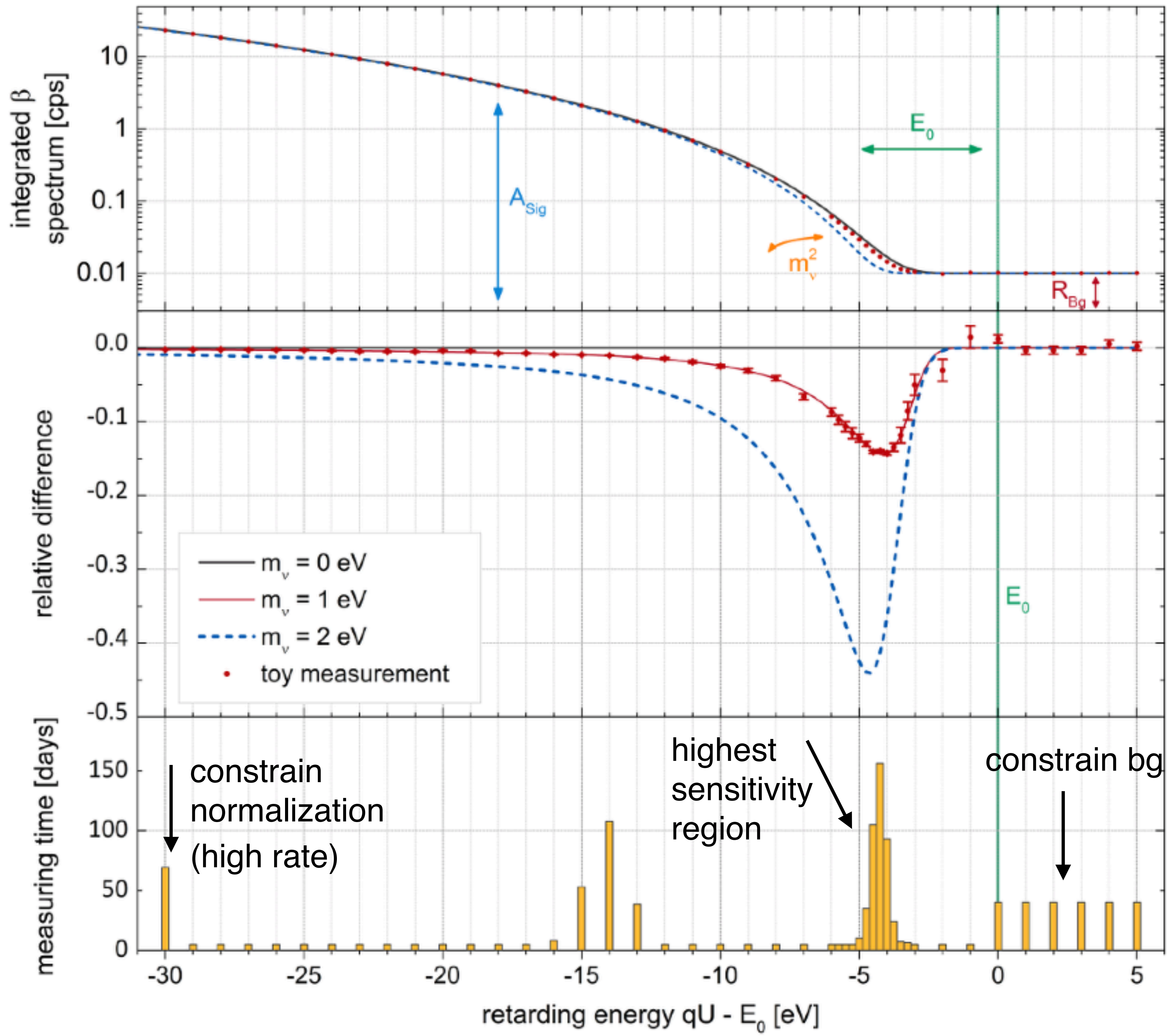
Datasets

Systematics model variation (MV)



Measurement Concept

Illustration only



Integrated spectrum

- Run: complete scan of all HV points
- 4 fit parameters to describe spectrum
- Background is flat

Residuals

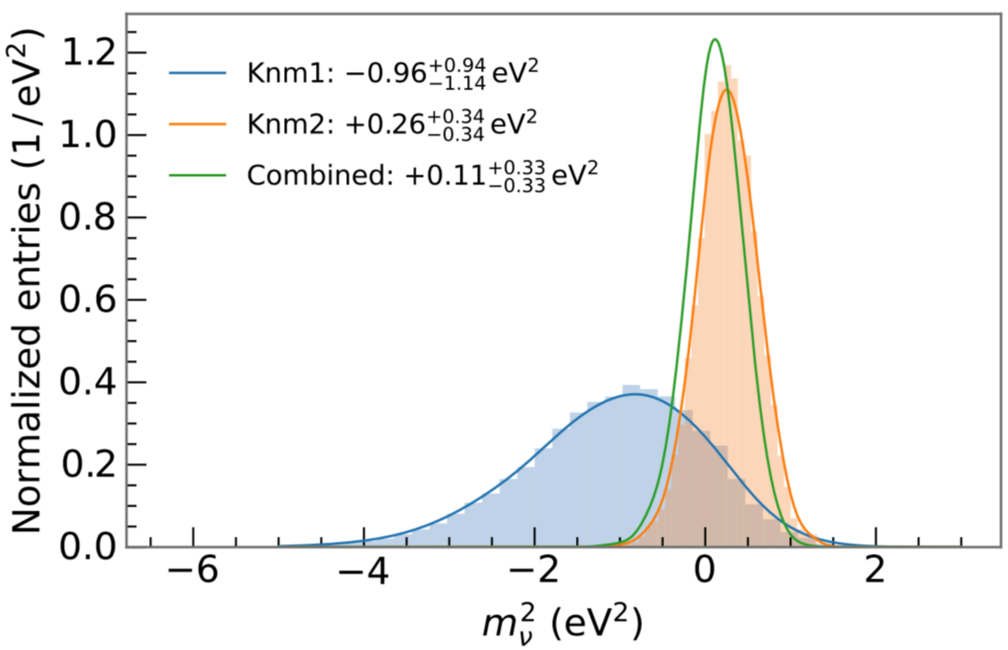
- Most sensitive region around endpoint
- With higher background the sensitive region moves lower in energy
- Statistical fluctuations can result in “negative m²”

Measuring time distribution

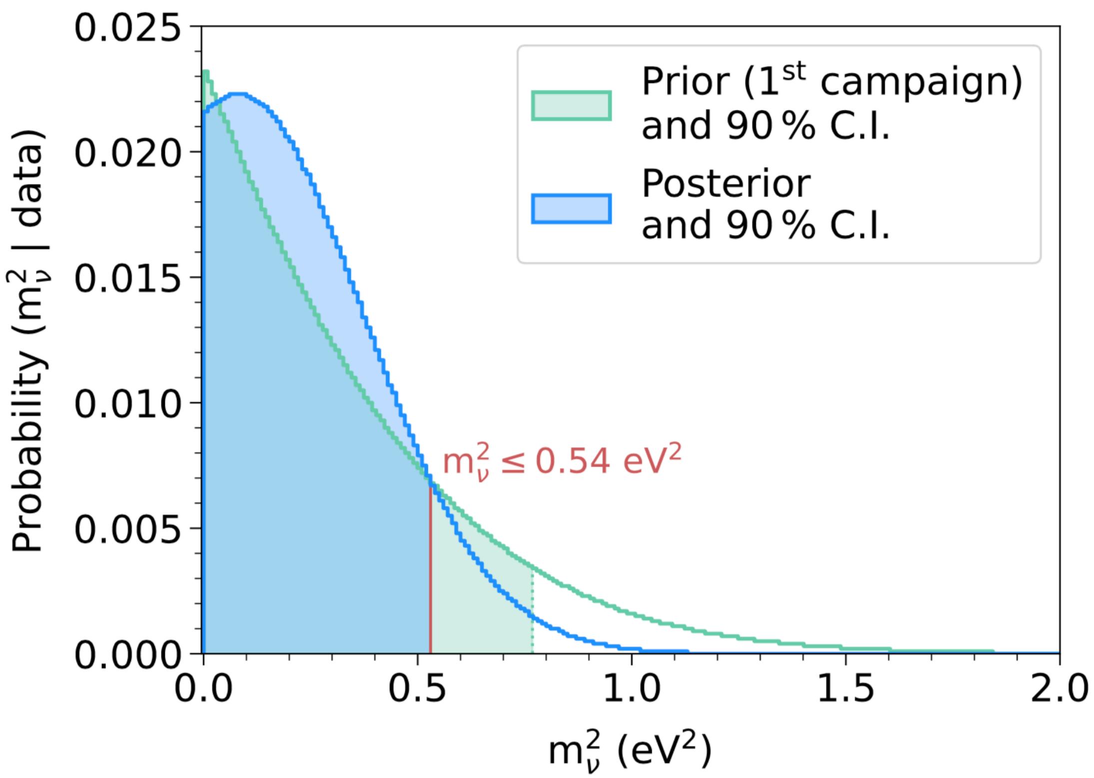
- Choose HV points and statistics in each point
- Optimize for sensitivity e.g. constrain background, normalization

Results Combined KNM1 + KNM2

Frequentist likelihoods (multiplication or combined fit)



Bayesian posteriors (KNM1 posterior as KNM2 prior):



Best fit: $m_\beta^2 = 0.1 \pm 0.3\ \mathrm{eV}^2$

Limits LT and FC: $m_\beta < 0.8\ \mathrm{eV}$ (90% CL)

Limits Bayesian: $m_\beta < 0.73\ \mathrm{eV}$ (90% CI)

2 months KATRIN data better than Mainz, Troitsk

- Statistics x6, systematics x12
- First sub-eV neutrino mass sensitivity in lab
- Multiple independent blind analyses