MAX-PLANCK-INSTITUT
FÜR PHYSIK

Latest neutrino mass results from the KATRIN experiment

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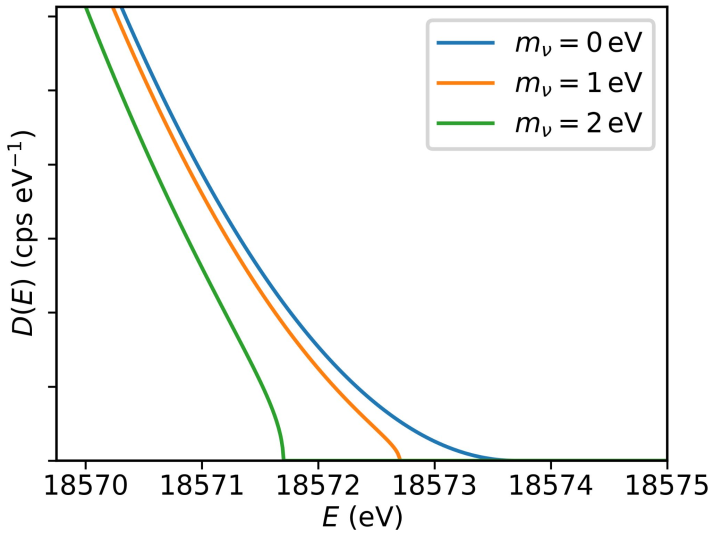
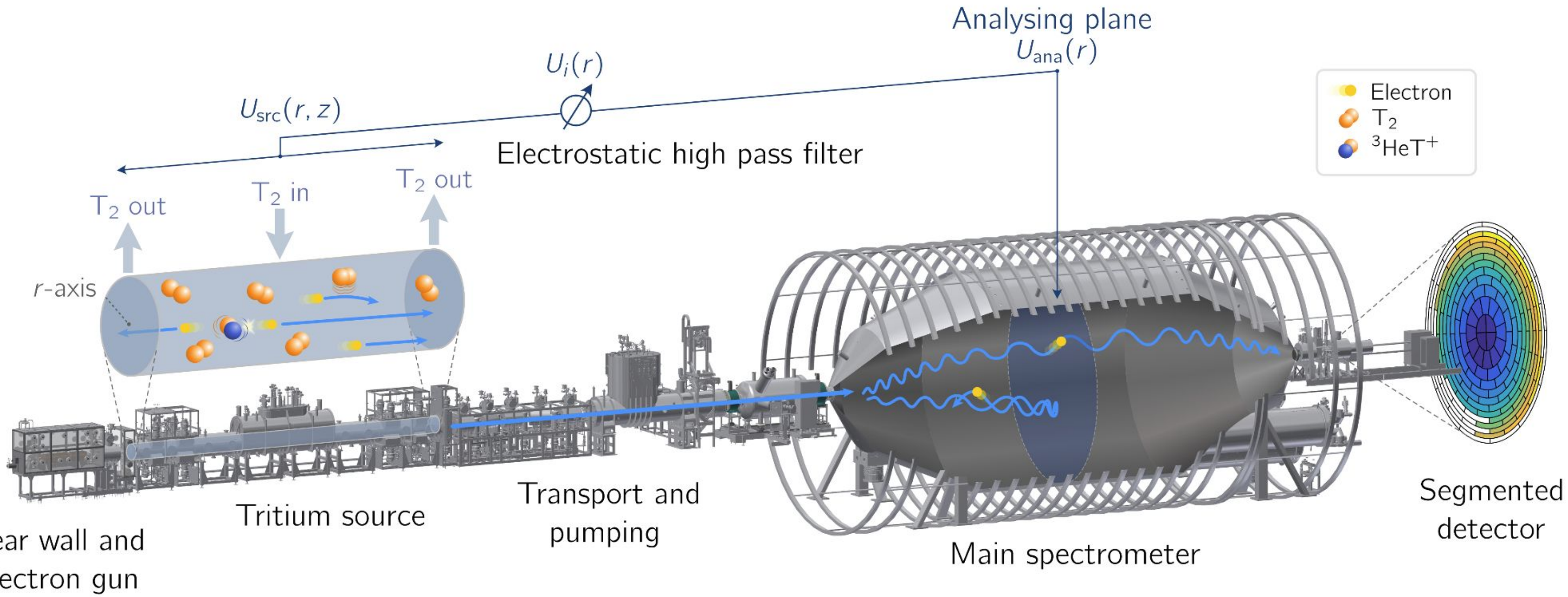
43rd International School of Nuclear Physics (Erice), 2022

Neutrino mass measurement from β-decay

- β-decay: $X \to Y + e^- + \bar{\nu}_e$
- Smoking gun: **spectral distortion** near endpoint E_0
- Challenges:
    - Small effect (eV-scale)
    - Low count rates (close to endpoint)
- Source: (Molecular) **Tritium**
    - **Super-allowed** β-decay
    - Low half-life (**12.3 years**)



KATRIN working principle

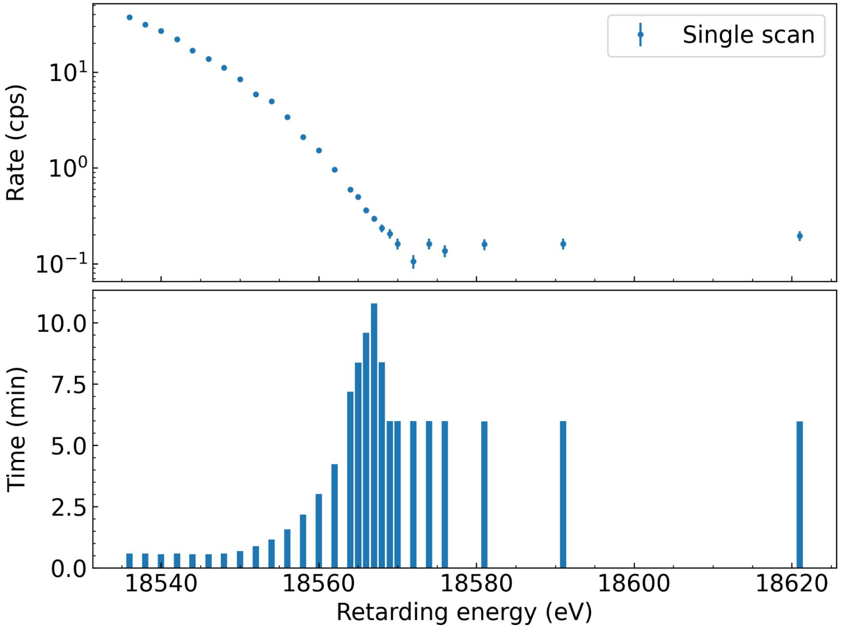


Sketch by Leonard Köllenberger

Measurement strategy

- **MAC-E filter**: Only electrons with $E_{||} > qU_{ret}$ make it to the detector
- Scan spectrum at ~40 scan steps
  - ➢ Set retarding voltage
  - ➢ Count events at the detector
  - ➢ **Integral spectrum**

➔ **Repeat** scanning procedure O(100) times



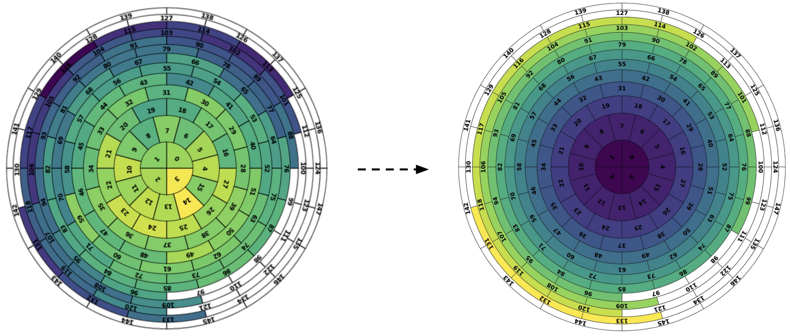
Analysis strategy

Analysis strategy – data combination

Pixel combination

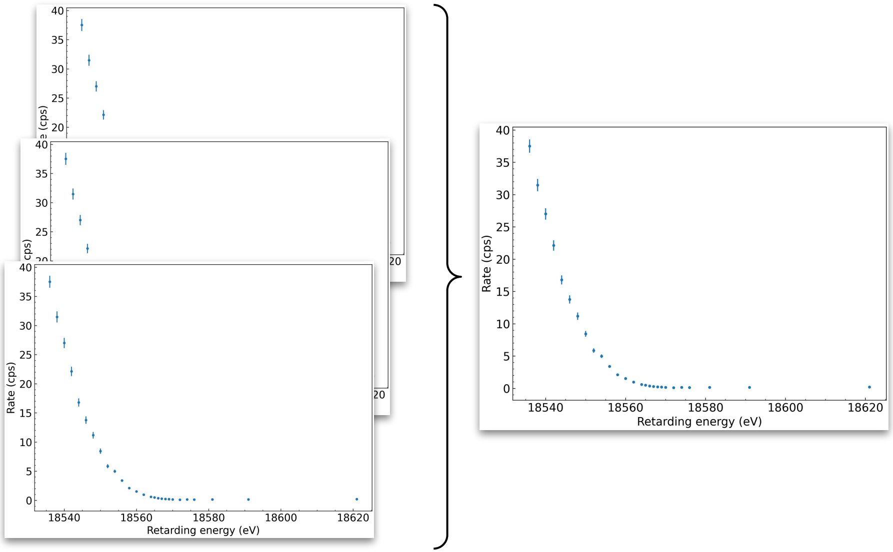
➔ **Combine** into one pixel / rings

➔ **Sum** counts, use **average response**



Scan combination

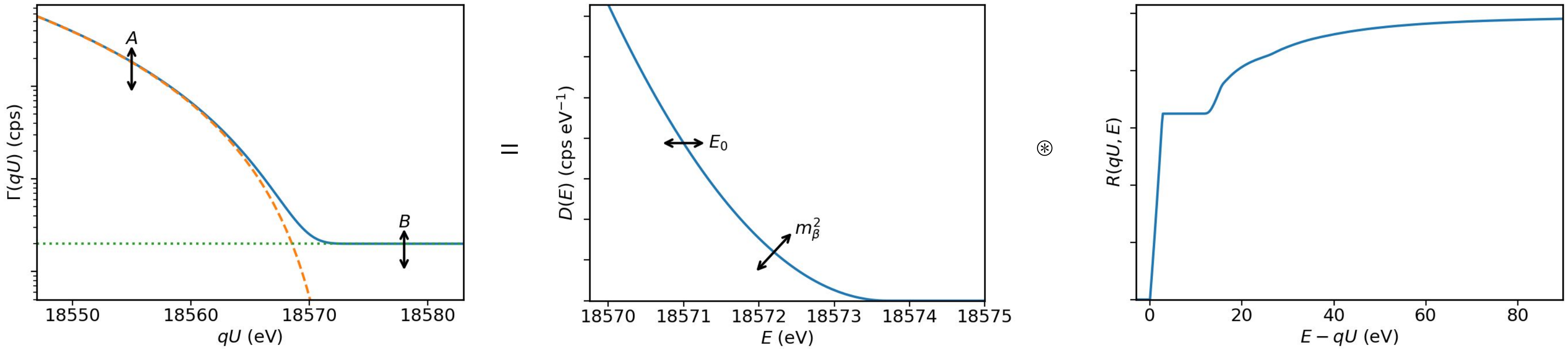
➔ **Sum** counts, use **average ret. energy**



Analysis strategy – Model

- maximum likelihood fit of **model**

$$\Gamma(qU) \propto A \int_{qU}^{E_0} D(E; m_\beta^2, E_0)\, R(qU, E)\, \mathrm{d}E + B$$



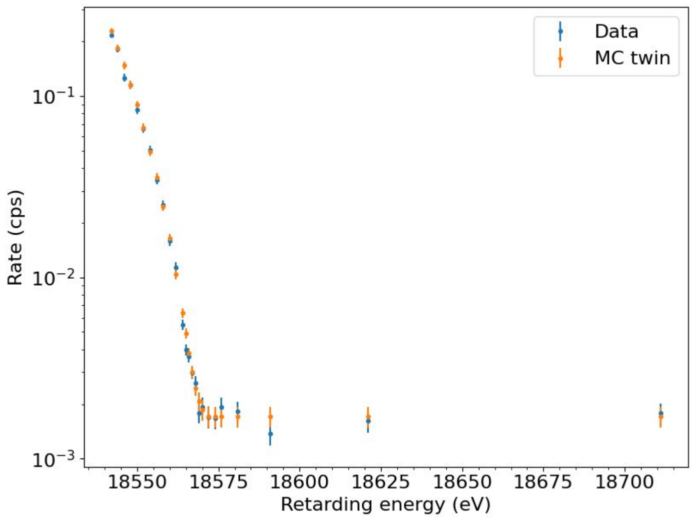
with free **amplitude** *A*, **squared neutrino mass** m_ν^2, **endpoint** E_0 and **background** *B*

- **theoretical** (Fermi theory, molecular excitations) and **experimental** inputs (calibration measurements)

Analysis strategy – Blinding

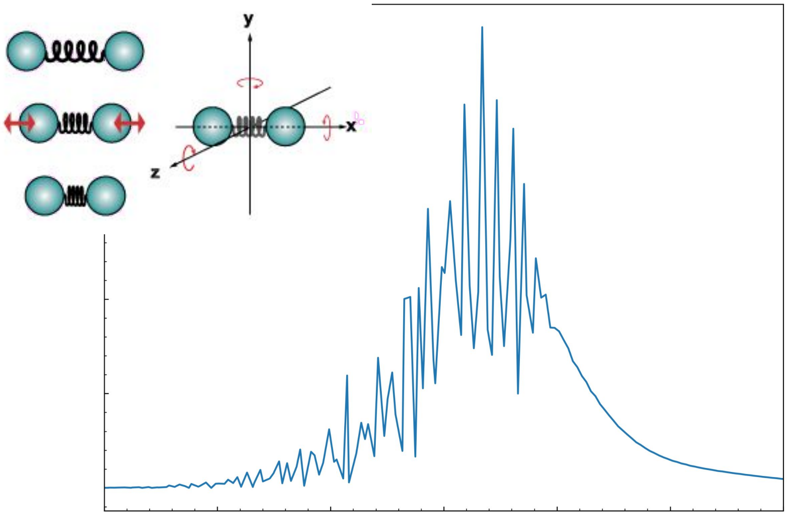
Monte Carlo (MC) twin data

- MC copy of each scan ($m_{\nu}^2 = 0\ eV^2$)



Model blinding

- Modified molecular final state distribution

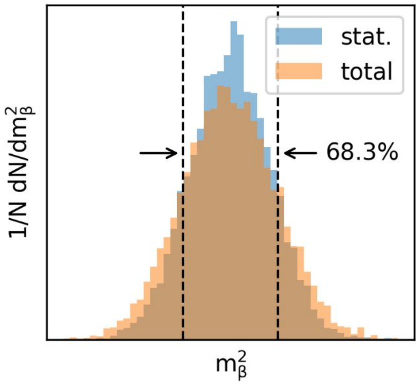


Treatment of systematics

Monte Carlo propagation

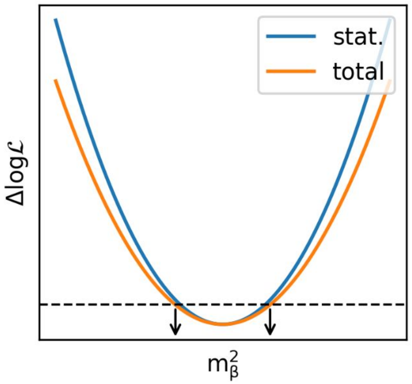
- Fit data multiple times, varying systematic(s) parameter in model

➔ **Distribution of m_ν^2**, width quantifies uncertainty

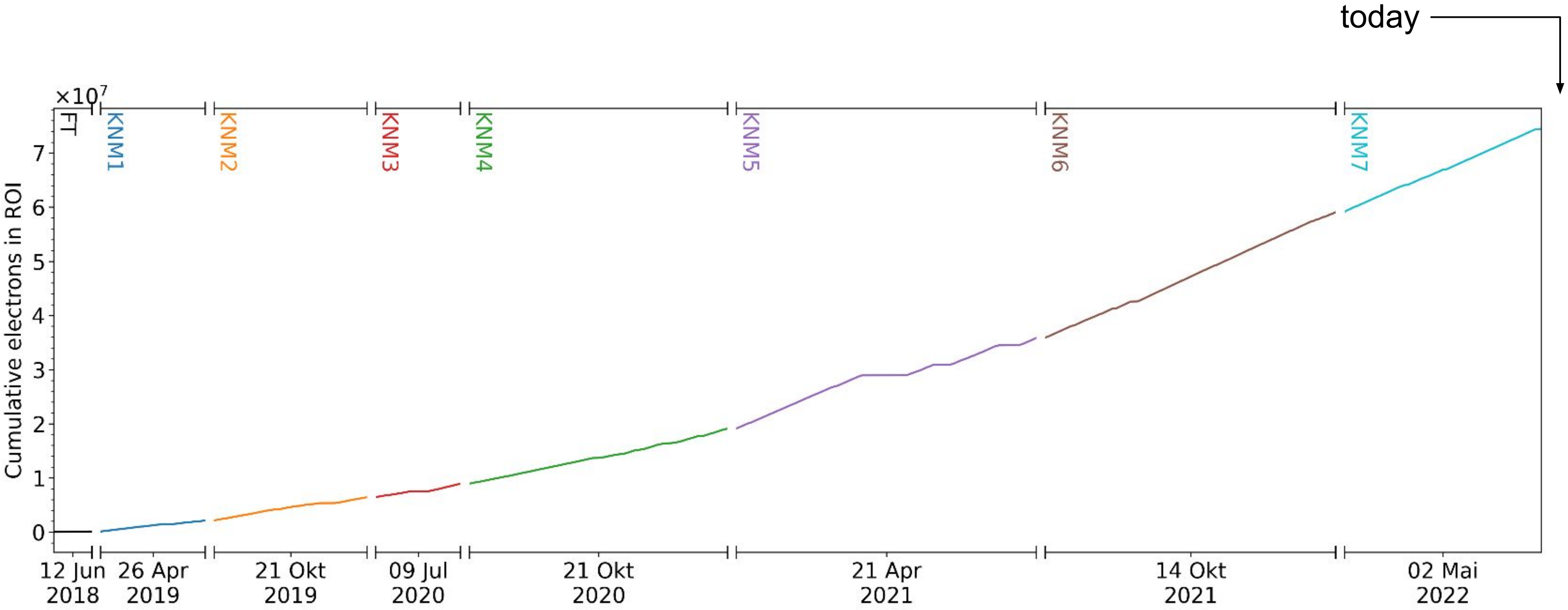


Nuisance parameter

- Fit data once, systematic(s) parameter free in the fit but constrained via pull-term
- **Broadening of likelihood** quantifies uncertainty



Current status



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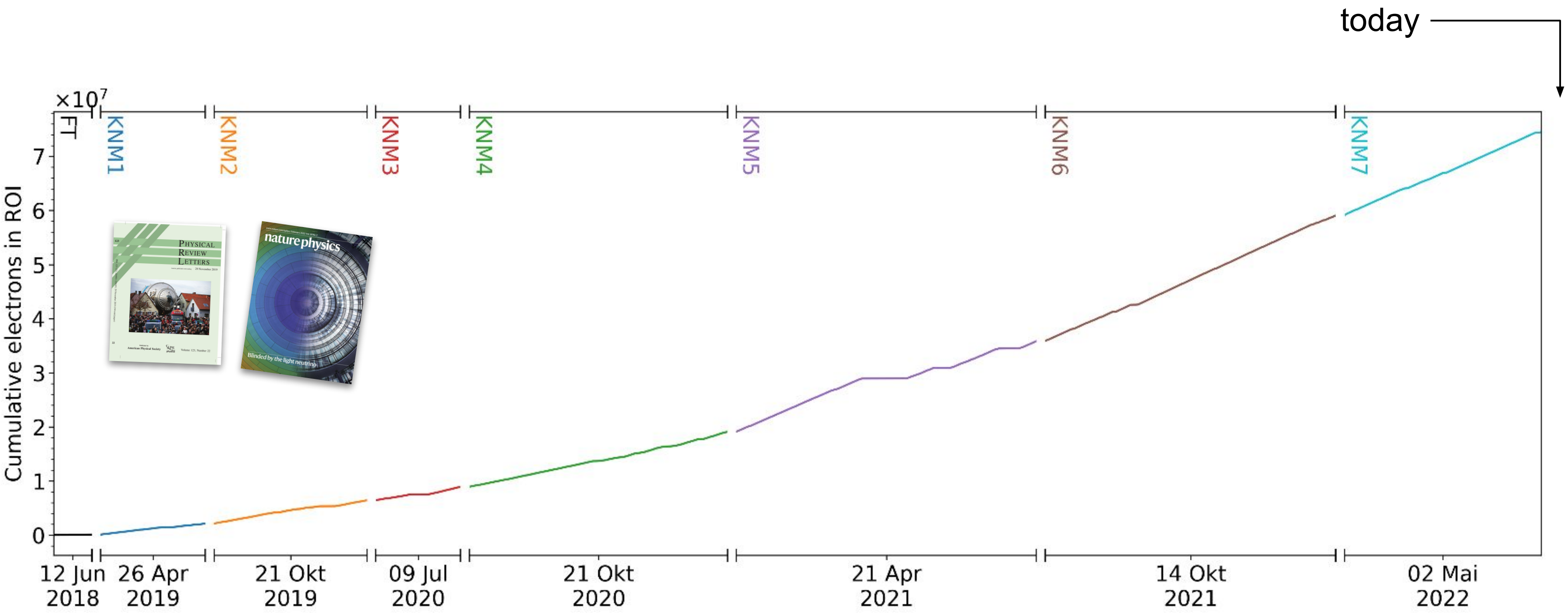
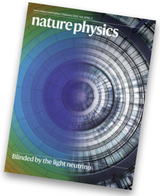




2^{nd} neutrino mass measurement campaign (KNM2)

- Best fit compatible with zero (**p-value: 0.8**):

  $m_\nu^2 = (0.26 \pm 0.34)\ \mathrm{eV}^2$

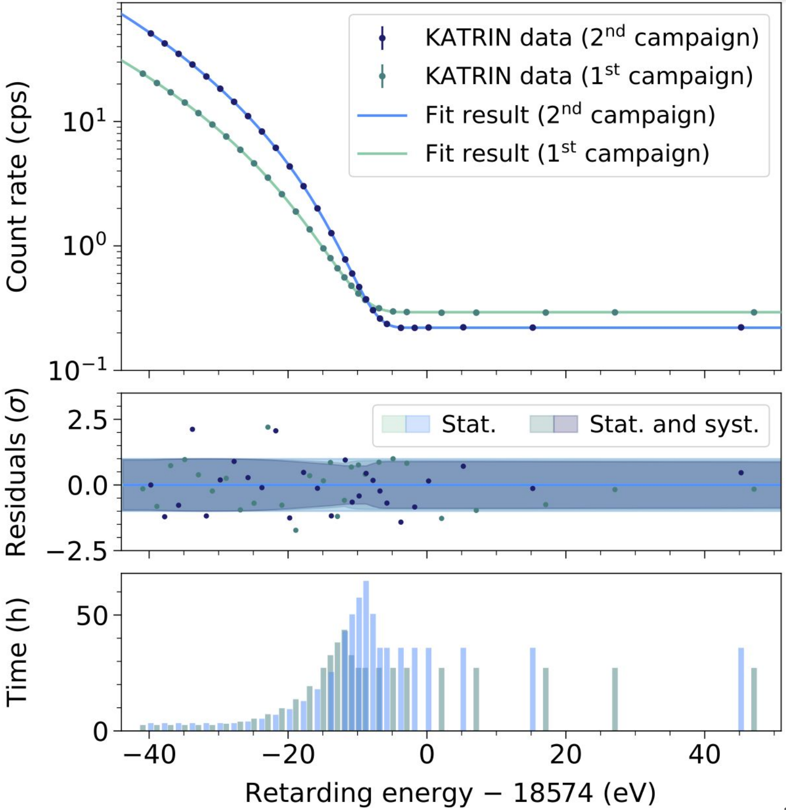
  [Aker et al., Nat. Phys. 18, 160–166 (2022)]

- Derived upper-limit using Lokhov-Tkachov confidence belt:

  $m_\nu < 0.9$ eV at 90% CL

- Combined with KNM1:

  $m_\nu < 0.8$ eV at 90% CL



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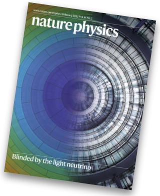

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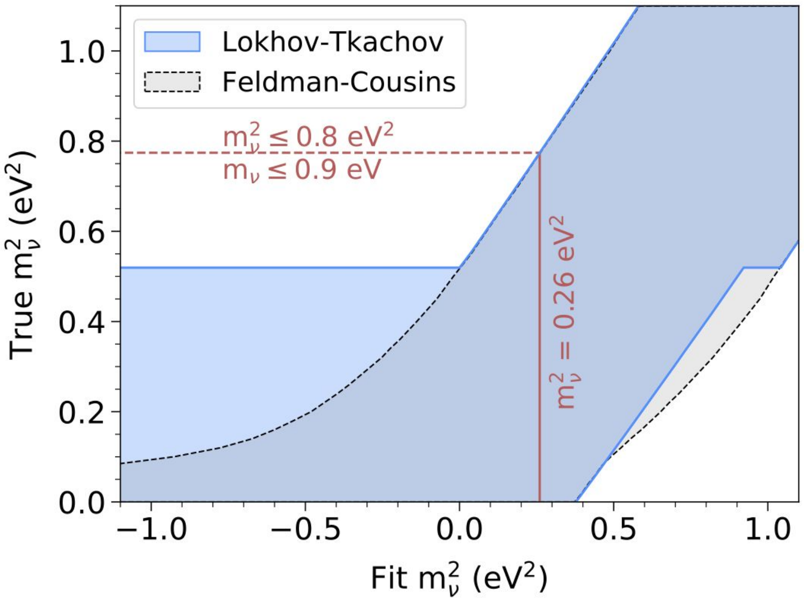
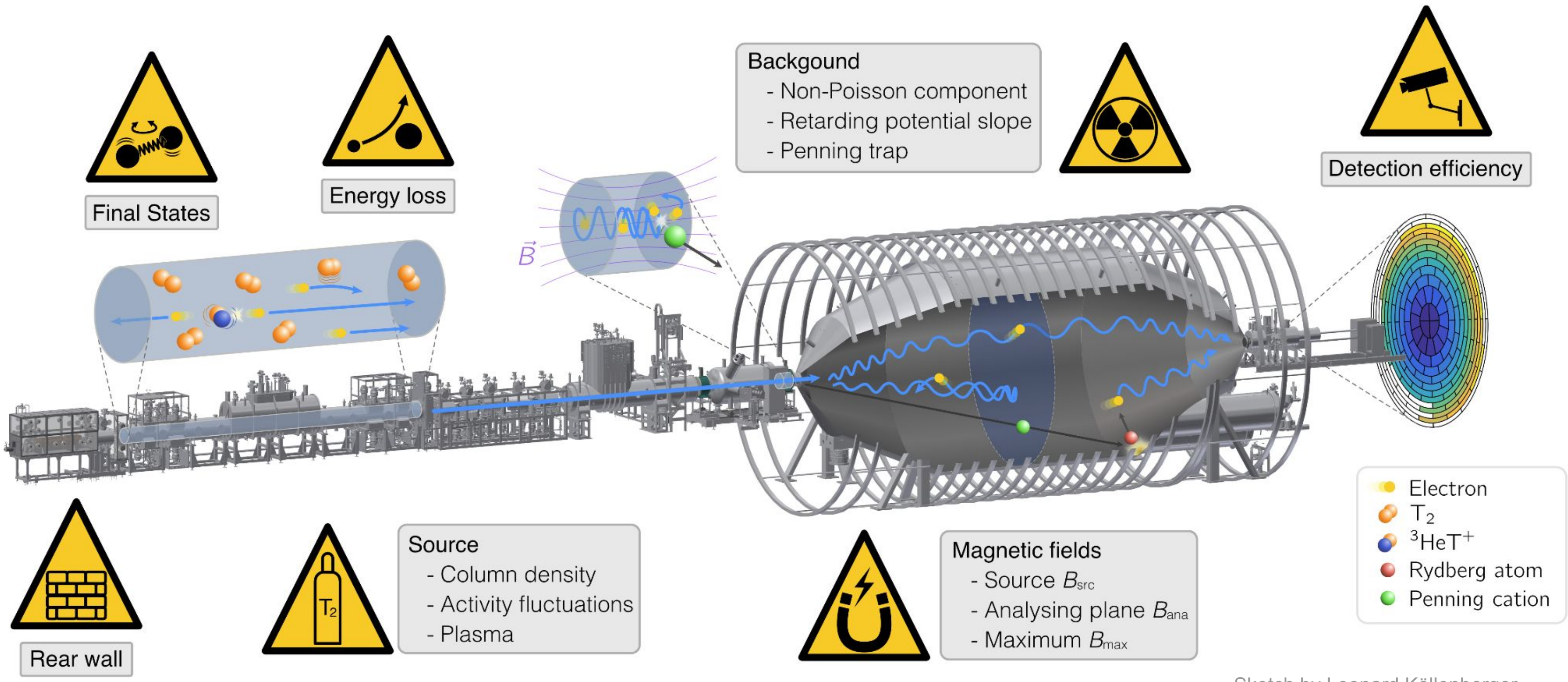


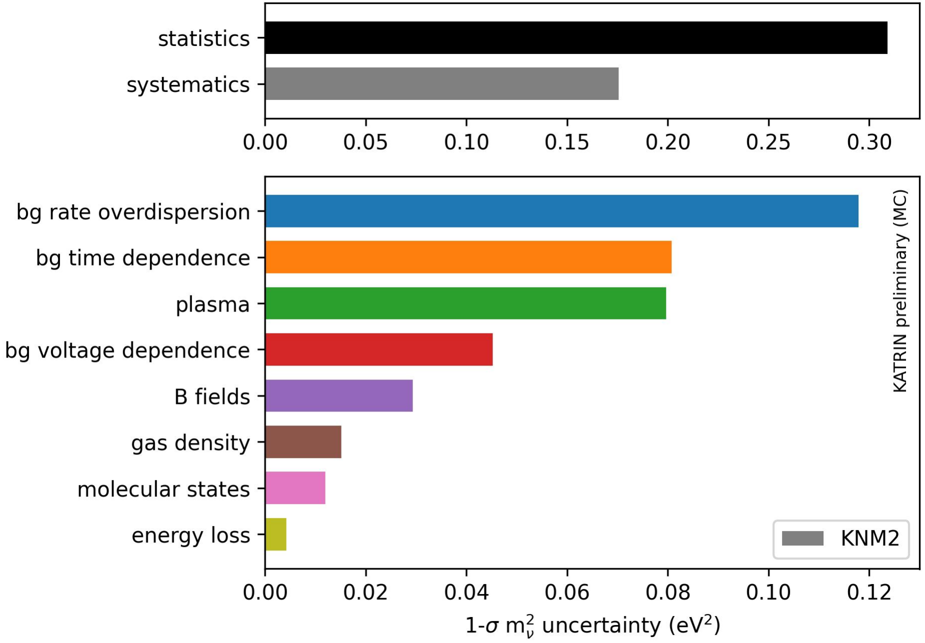
Systematic uncertainties



Sketch by Leonard Köllenberger

2^{nd} neutrino mass measurement campaign (KNM2)

- **Statistically dominated**, systematics non-negligible
- **Background related** systematics dominate
- Significant contribution from **Plasma** uncertainty



Improvements since KNM2

- **Statistically dominated**, systematics non-negligible

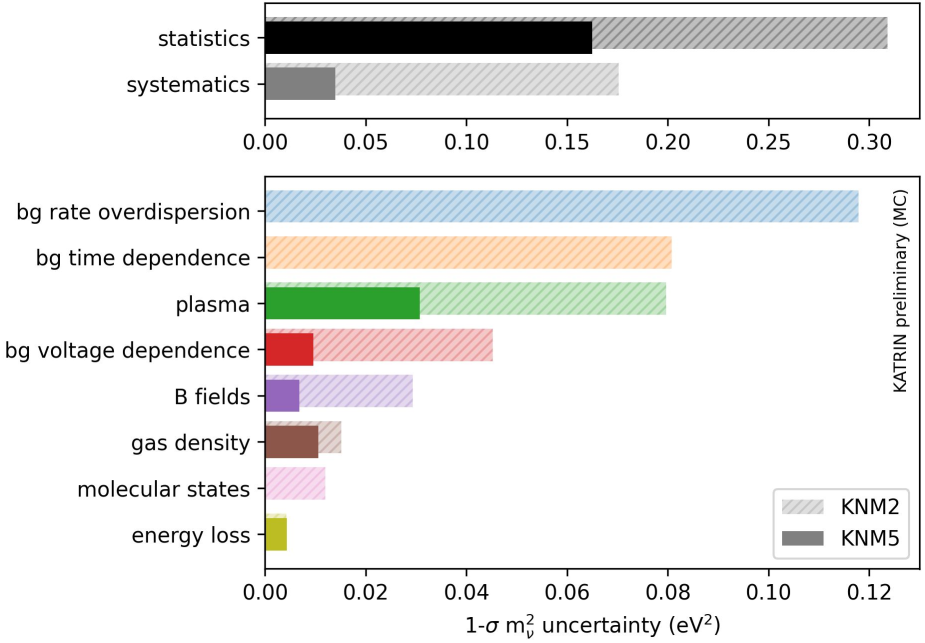
➔ Systematics largely **improved**

- **Background related** systematics dominate

➔ Successfully **mitigated** (Penning trap removed, new measurement mode: SAP)

- Significant contribution from **Plasma** uncertainty

➔ Reduced using high-statistics **^{83m}Kr calibration** source



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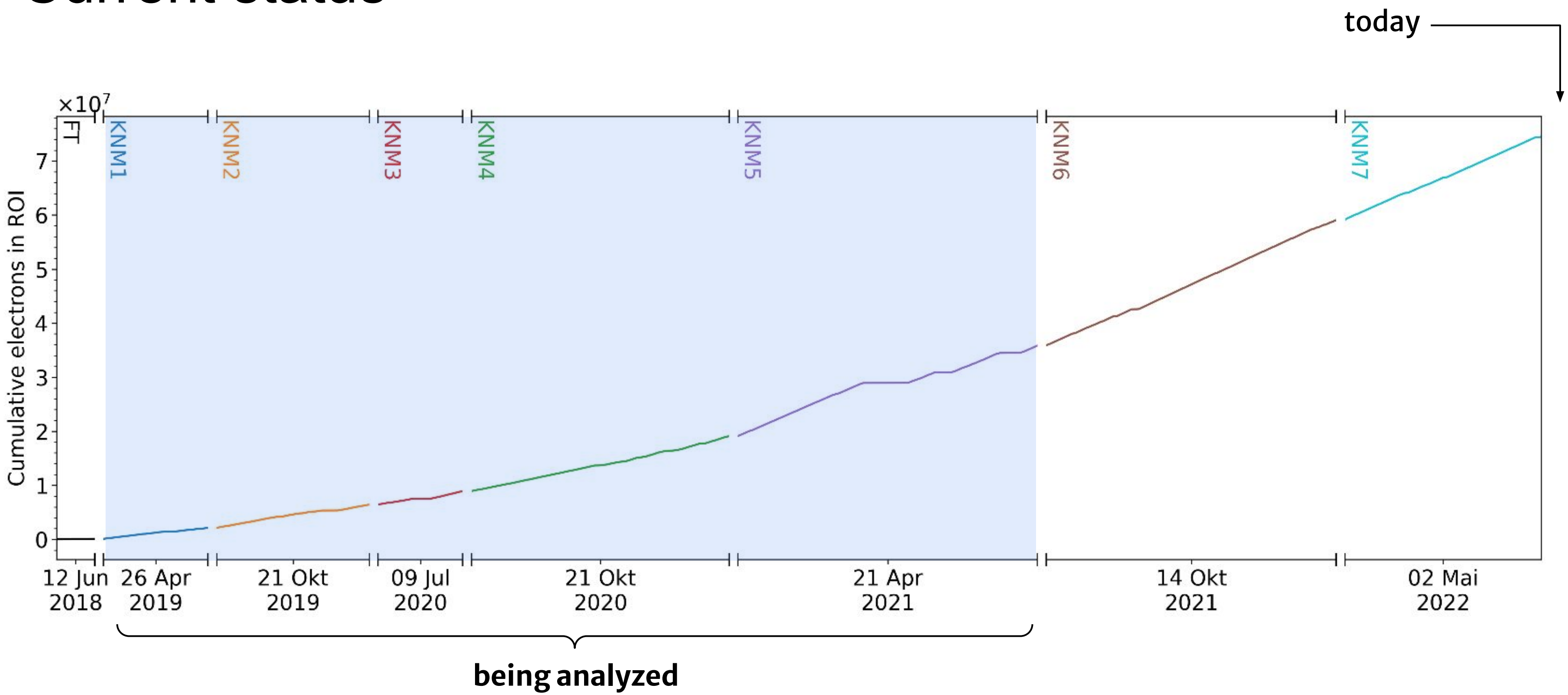


Data combination

Data combination – The challenge

- Multiple datasets in different settings (magnetic fields, …)

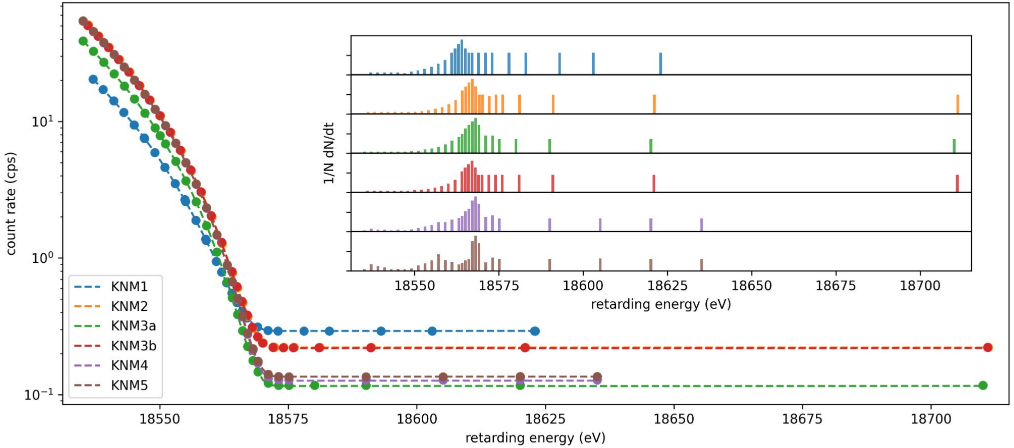
➔ Each dataset needs its own model

- Simultaneous fit with **common m_ν^2** (correlated systematic uncertainties)

➔ Large number of **fit parameters: > 200**

➔ In total **1259 data points**

➔ **Computationally challenging** (nested integrals, root searches)



Data combination – The solution

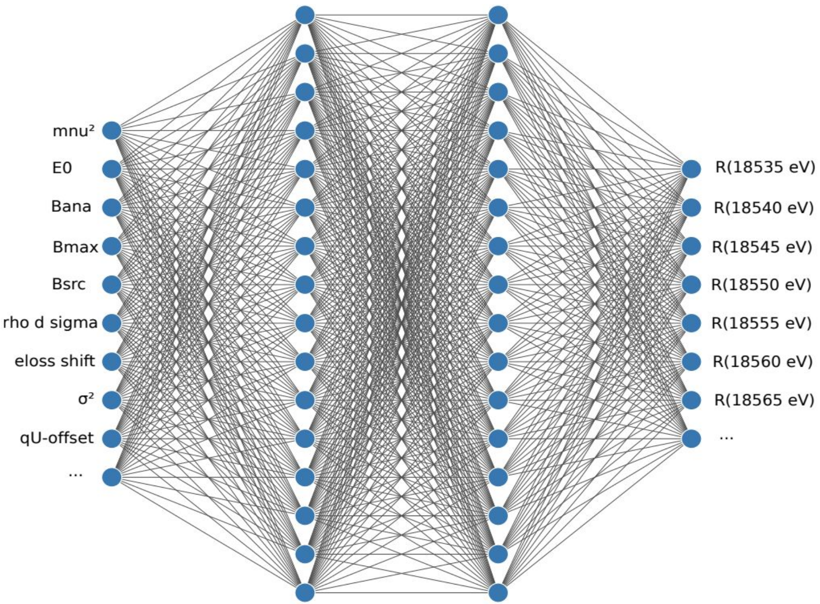
- Use a neural net for fast and precise model evaluations -> **“smart interpolator”**

➔ Train net on model samples

➔ Predict spectrum depending on parameter inputs

➔ Speed improvement (x 1000), high accuracy

➔ **Key:** Sampling is **heavily parallelizable**



[Karl et al., EPJ C 82 (2022) 5, 439]

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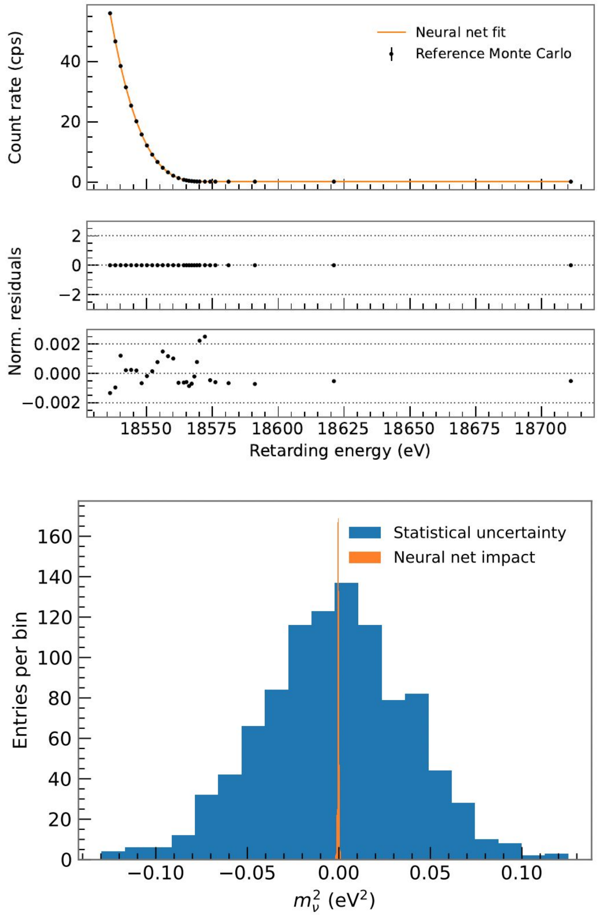

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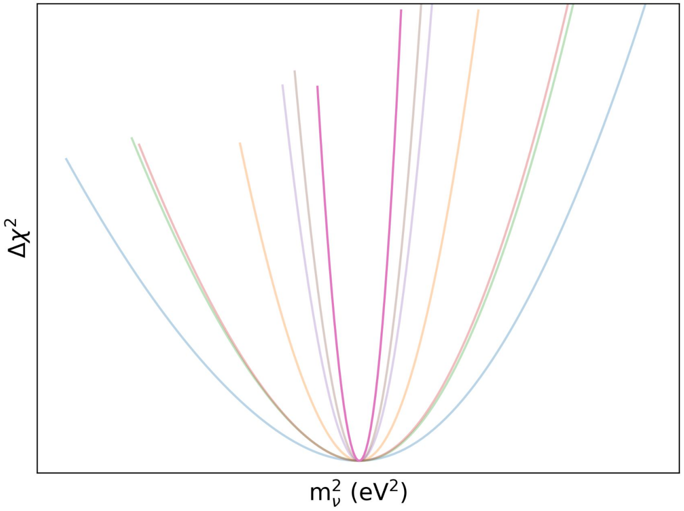
Data combination – Details on KNM1-5

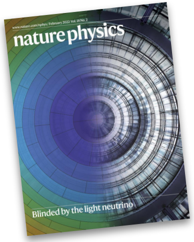
- Successfully applied **neural net** on KNM1-5
- **Fit time** (stat / total): 20 / **70 s** (profile scan 13 / 100 min) **compared to ~20 h**
- Projected sensitivity**:**

  m_ν < 0.5 eV (90% CL)

- Future campaigns can be added easily



Conclusion



- First **direct sub-eV** neutrino mass limit

  $m_\nu < 0.8$ eV at 90% CL

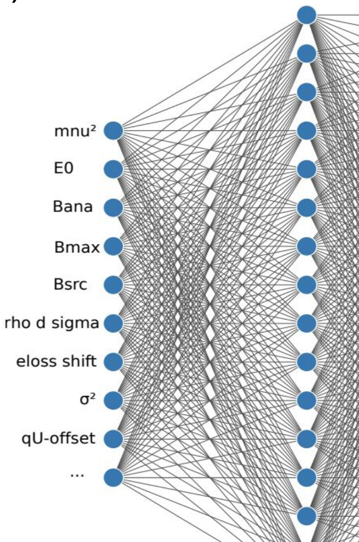
- Significant improvement of **systematic uncertainties**
- **Future proof** analysis framework successfully applied to KNM1-5 (Monte Carlo data)
- Sensitivity projection:

  $\mathbf{m_\nu < 0.5}$ **eV** (90% CL)

➔ **Unblinding** will happen soon

- 8^{th} data taking campaign (KNM8) about to start

➔ **Stay tuned!**



KATRIN collaboration

HELMHOLTZ ASSOCIATION
Alliance for Astroparticle Physics

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DFG
Deutsche Forschungsgemeinschaft

SFB 1258 Neutrinos Dark Matter Messengers

ORIGINS Excellence Cluster

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