Measuring the energy loss function of e$^-$-T2 scattering inside the Tritium source of KATRIN

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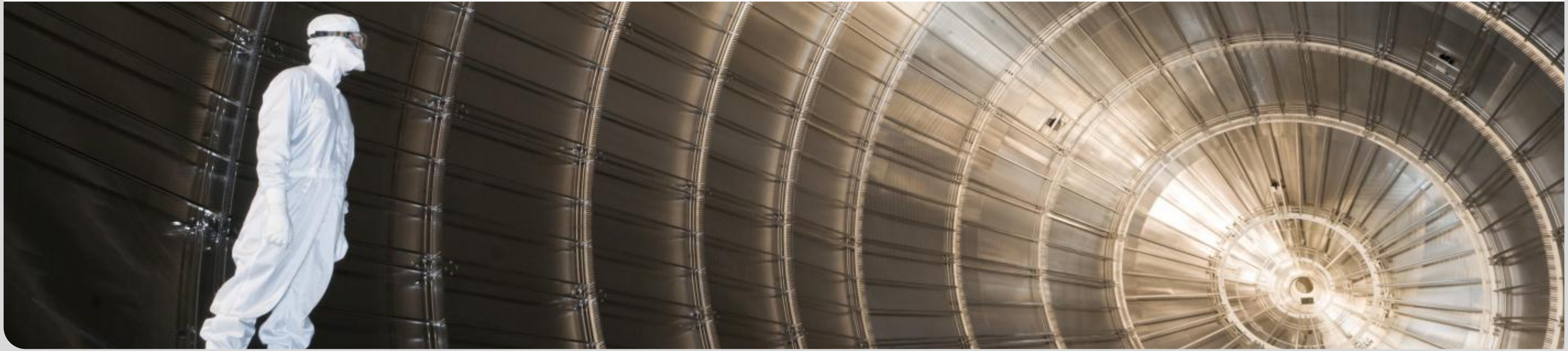
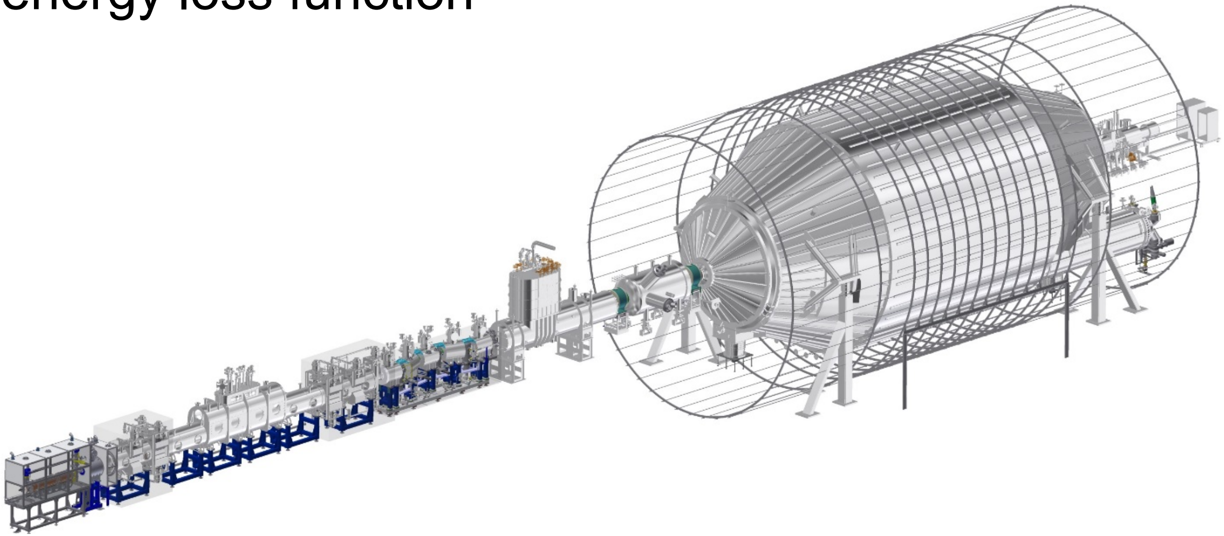
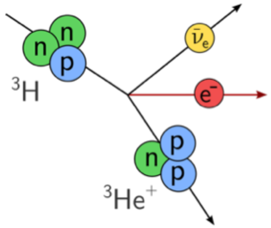


Outline

- The KATRIN neutrino mass experiment
- Existing energy loss models
- Measurement of the energy loss function
- Data analysis
- Outlook

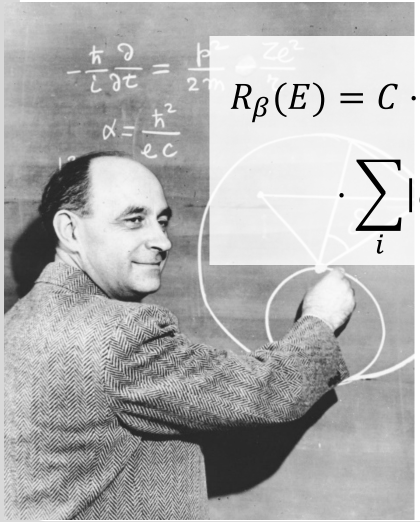


Principle of direct ν mass measurements



Measurement of beta decay spectrum of molecular Tritium

$$E_0 = 18.6\ \mathrm{keV}$$
$$t_{1/2} = 12.3\ yr$$

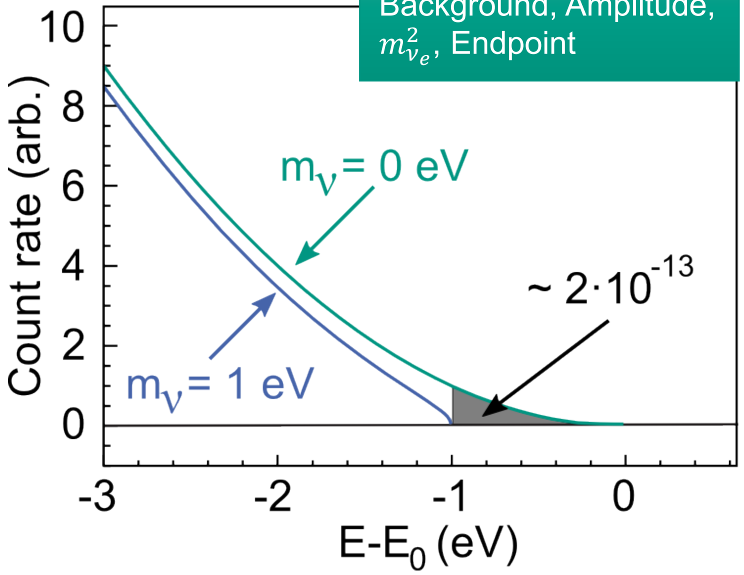


$$R_\beta(E) = C \cdot F(Z.E) \cdot p(E + m_e c^2) \cdot (E - E_0) \cdot \sum_i |U_{ei}|^2 \cdot \sqrt{(E_0 - E)^2 - m_i^2} \cdot \Theta(E_0 - E - m_i)$$

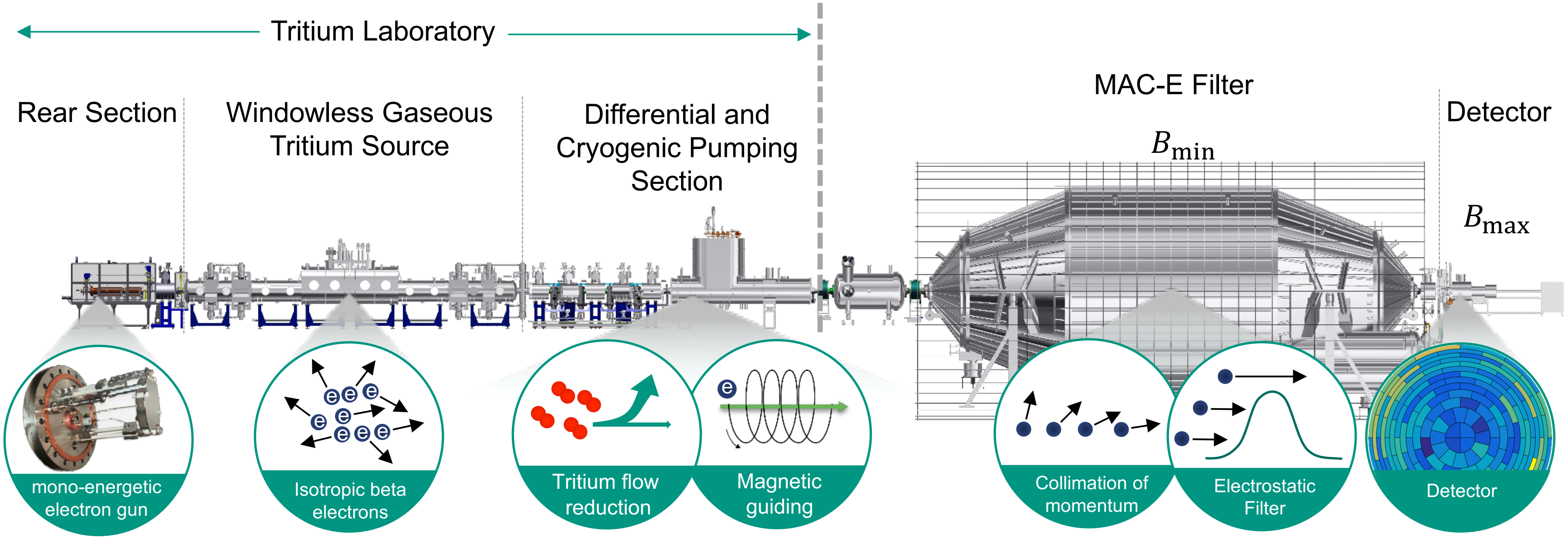
Observable

$$m_{\nu_e}^2 = \sum_i^3 |U_{ei}|^2 \cdot m_i^2$$

4 Parameters:
Background, Amplitude, $m_{\nu_e}^2$, Endpoint

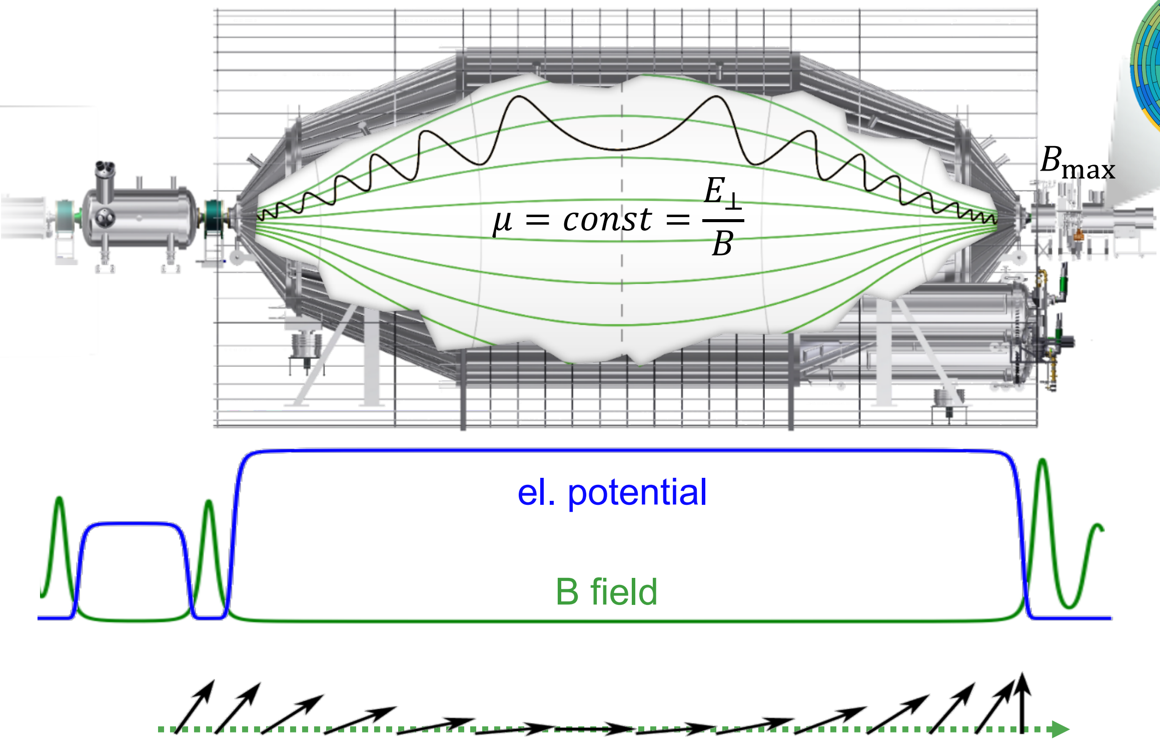


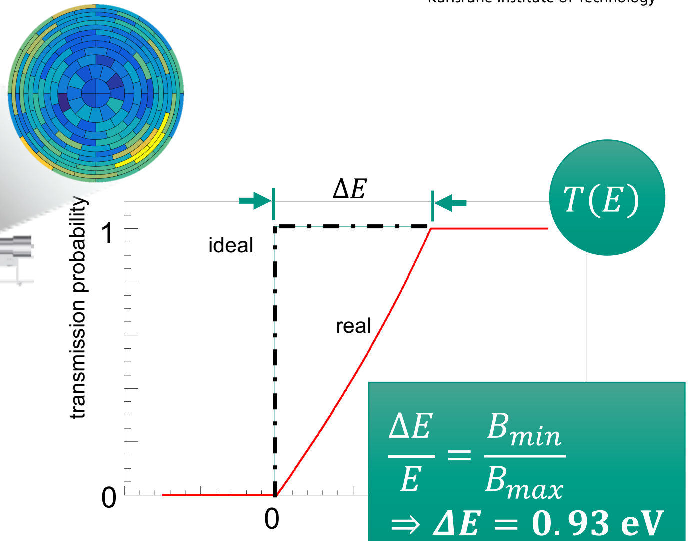
Experimental Setup



10^{11} β-decays per second

MAC-E Filter





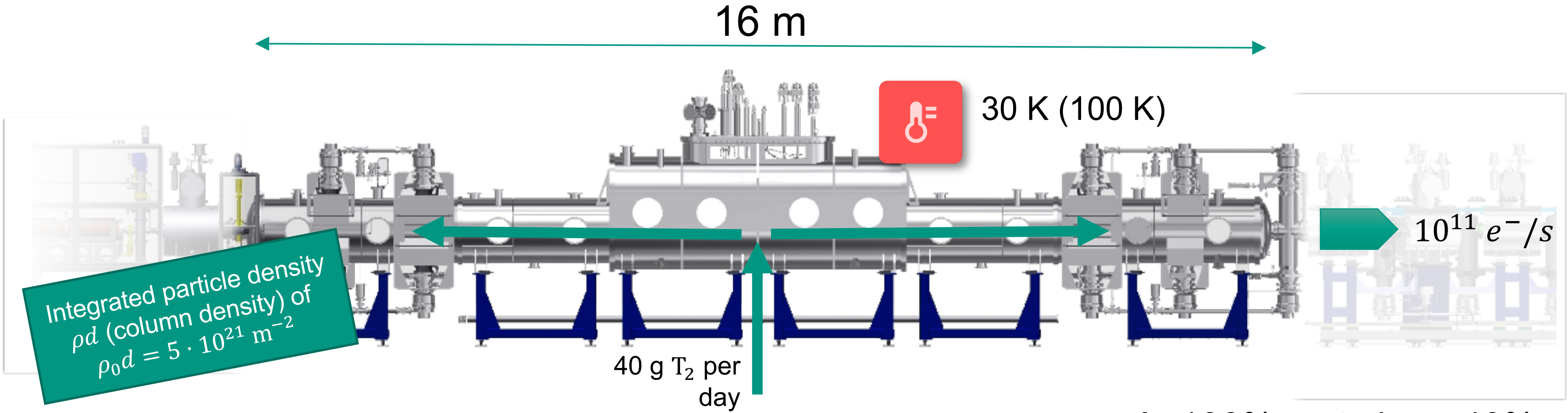
$$\frac{\Delta E}{E} = \frac{B_{min}}{B_{max}}$$

$$\Rightarrow \boldsymbol{\Delta E = 0.93\ \text{eV}}$$

Integrating high-pass filter

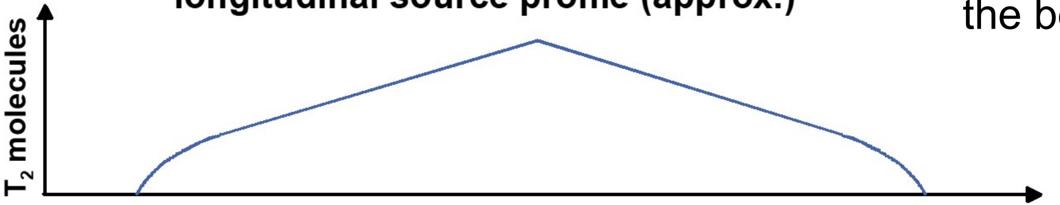
$$R(E) = \text{T}(E) \otimes R_\beta(E)$$

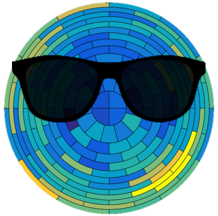
Gaseous Tritium Source



At 100% $\rho_0 d$ about 40% of the beta-electrons scatter

longitudinal source profile (approx.)





Response function modelling

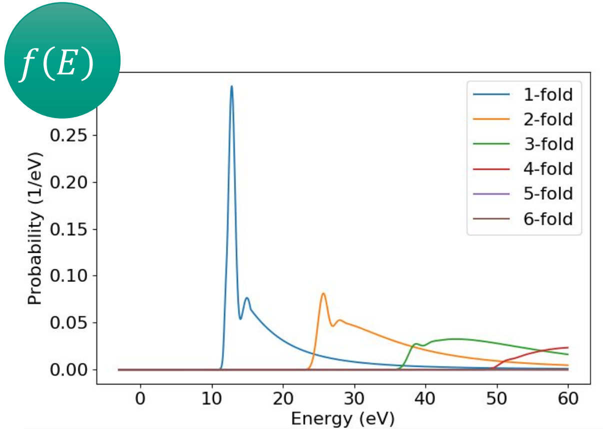
$$R(E) = \mathrm{T}(E) \otimes R_\beta(E)$$

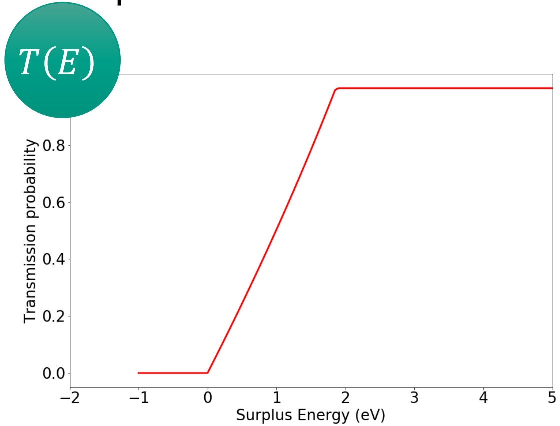
Include scattering

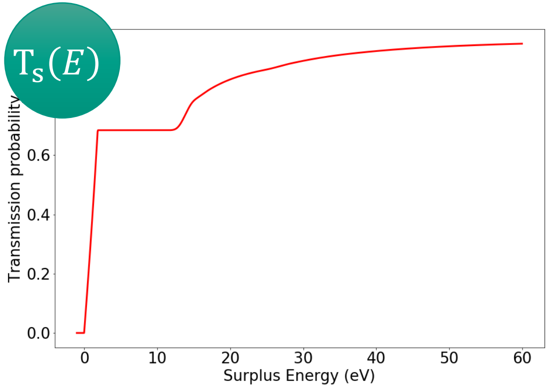
$$\mathrm{T_s}(E) = P_0 \cdot T(E) + P_1 \cdot f(E) \otimes T(E) + P_2 \cdot f(E) \otimes f(E) \otimes T(E) + \cdots$$

With

$$P_n = \frac{(\rho d\sigma)^n}{n!} \exp(-\rho d\sigma)$$







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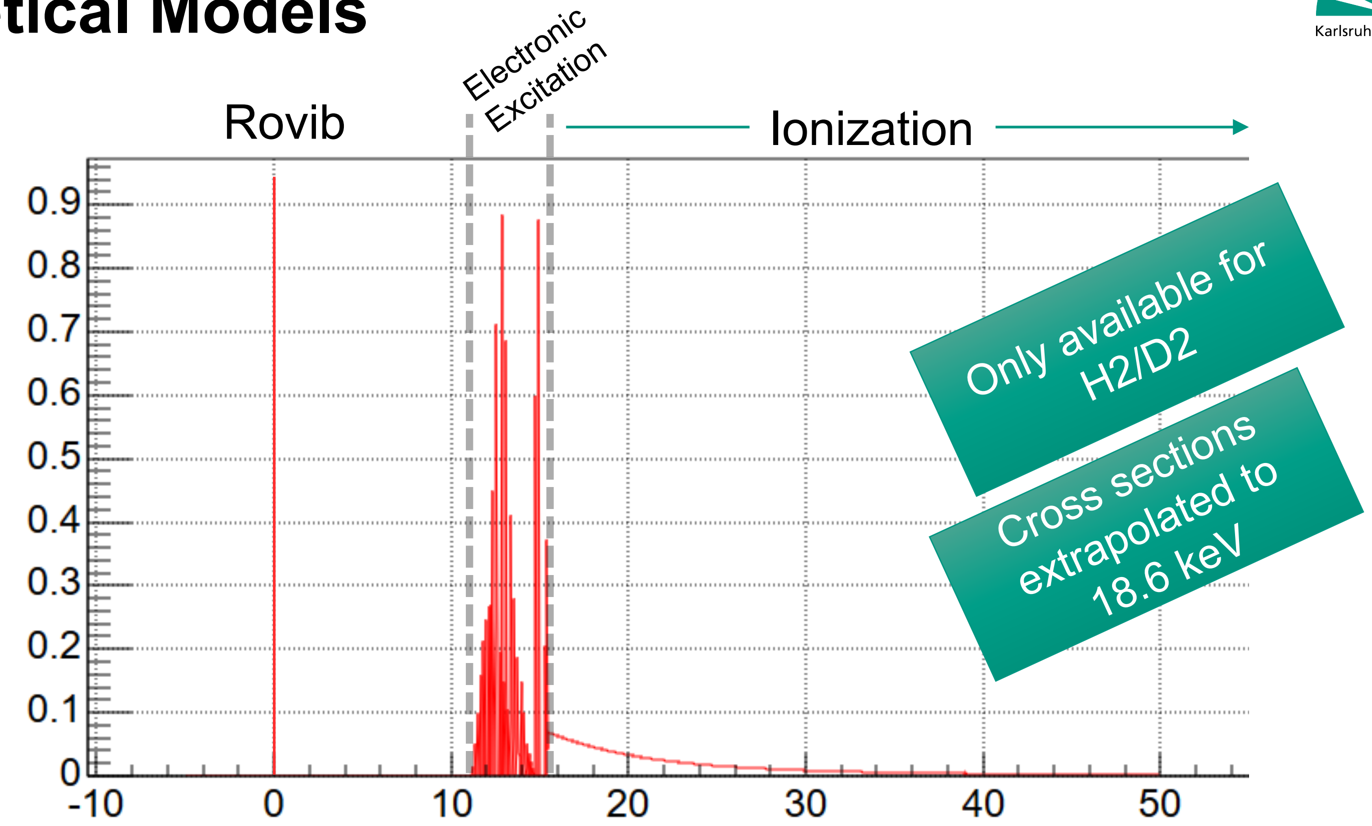
Theoretical and empirical

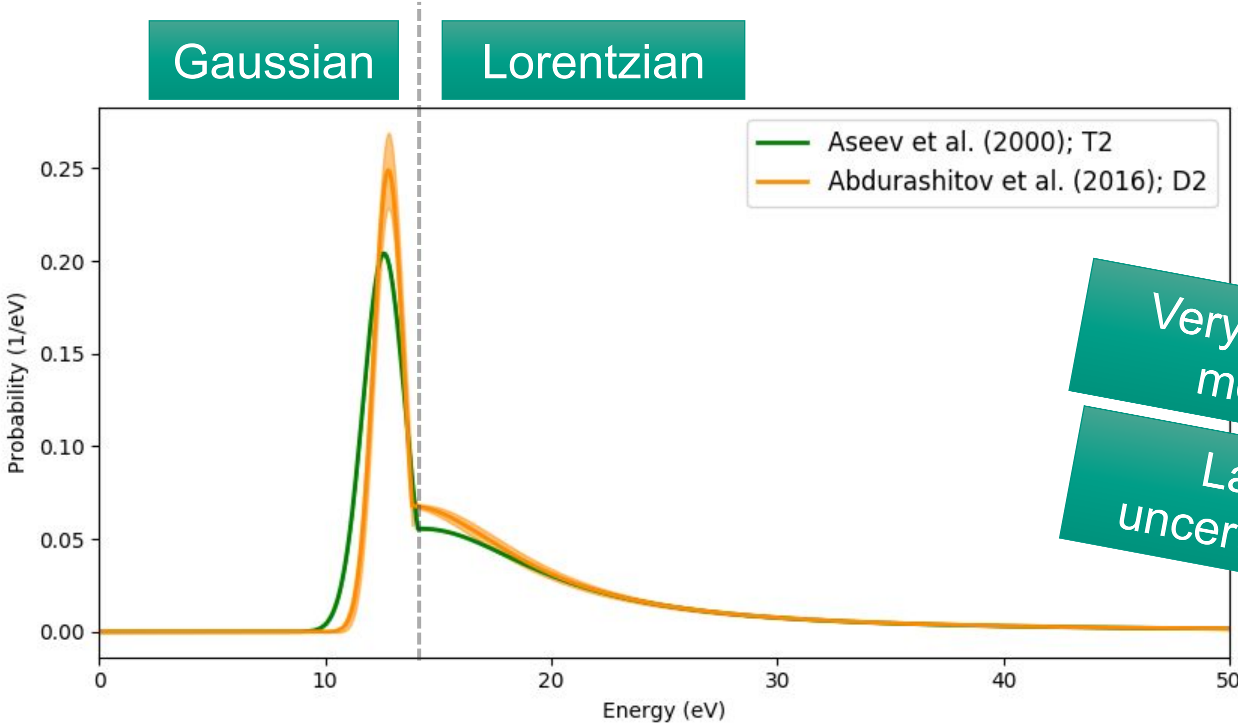
ENERGY LOSS MODELS

Theoretical Models



See N. Trost 2019, DOI: 10.5445/IR/1000090450

Experimental Models



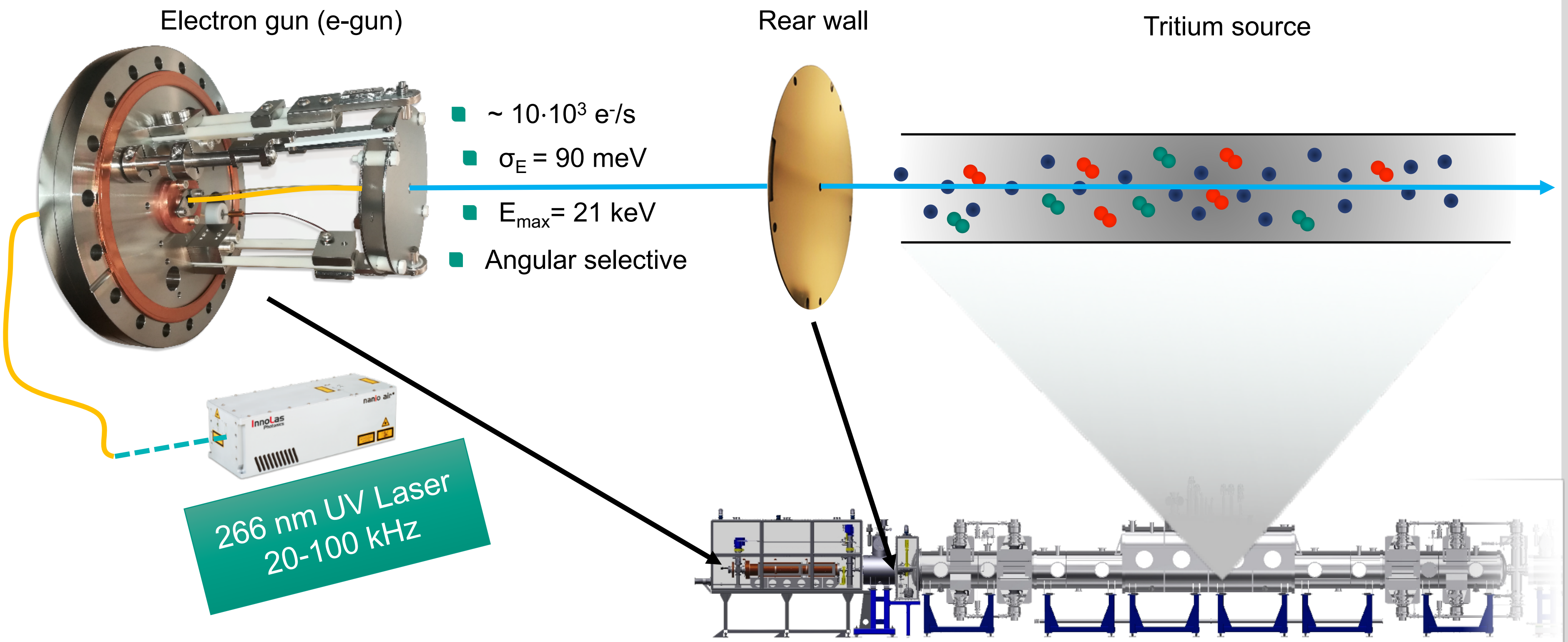
Very simple model

Large uncertainties

Energy loss function

MEASUREMENT AT KATRIN

Rear Section



- ~ $10 \cdot 10^3$ e^-/s
- σ_E = 90 meV
- E_{max}= 21 keV
- Angular selective

Integral Measurements

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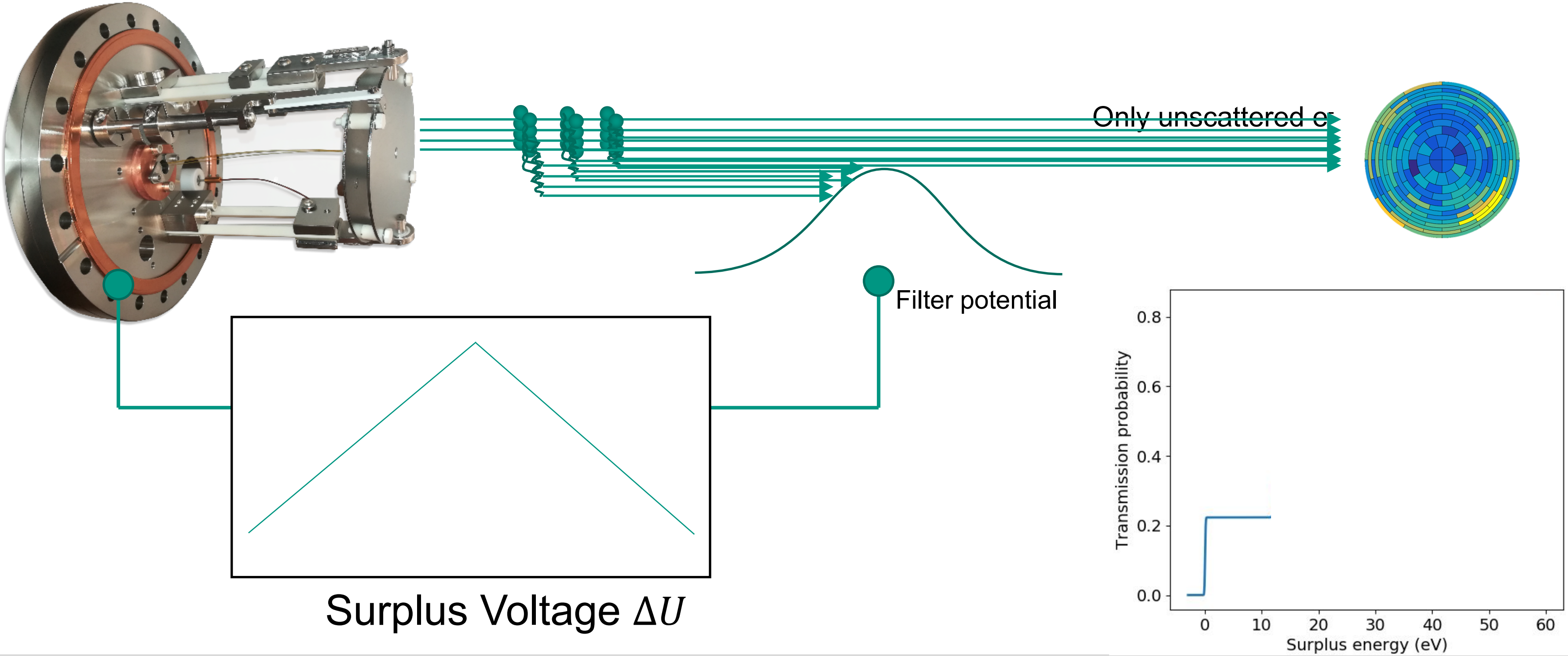
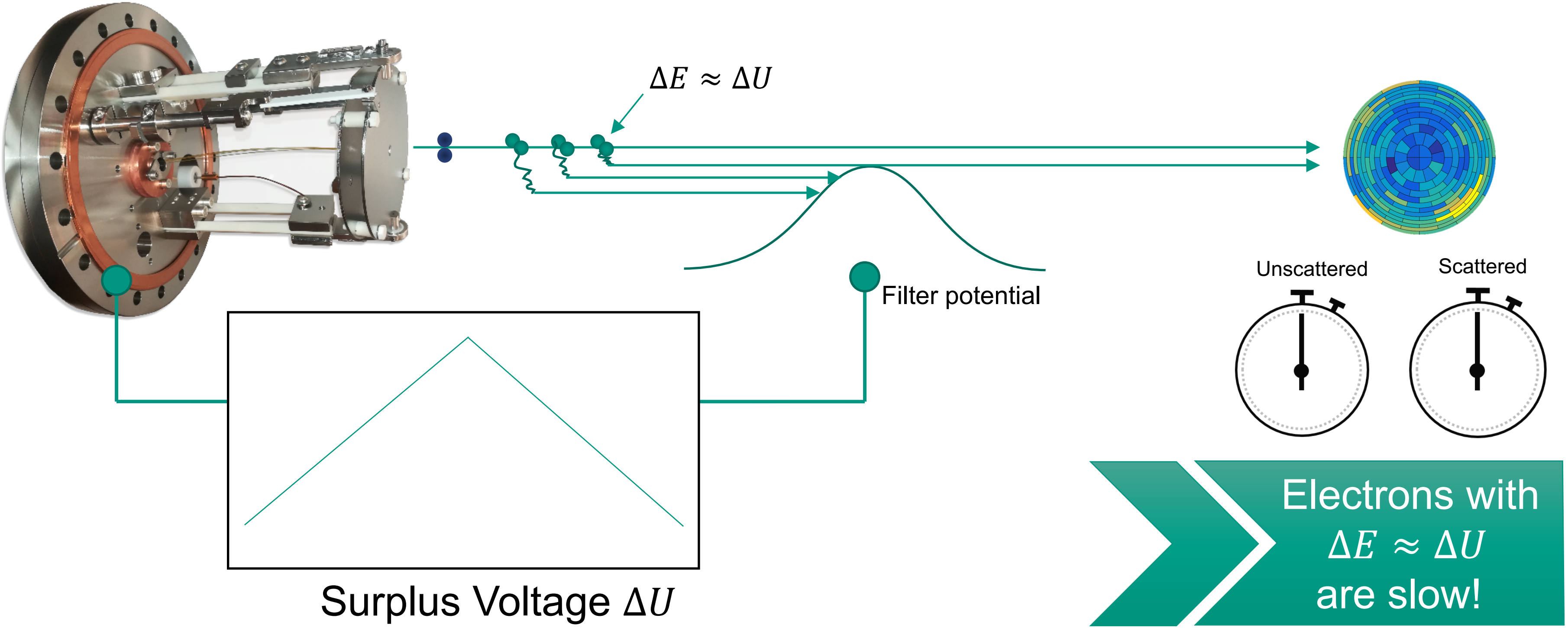
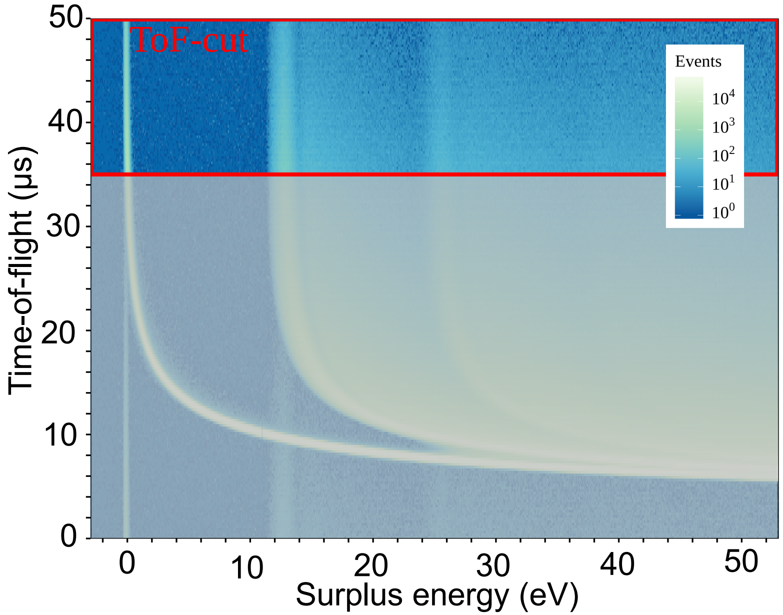


Differential Measurements



Electrons with $\Delta E \approx \Delta U$ are slow!

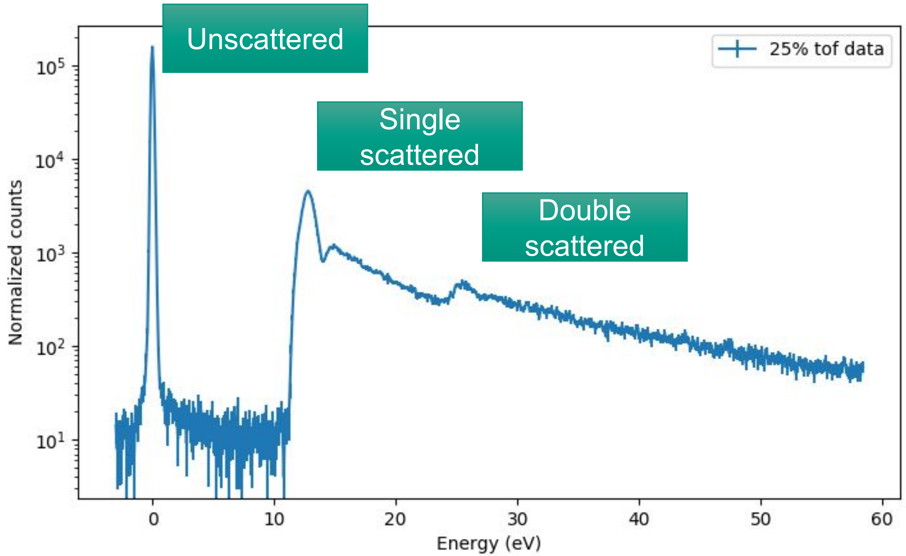
Energy loss function measurements



- Long time-of-flight in MAC-E filter for $\Delta E \approx \Delta U$

- Only slow electrons (i.e. $\Delta E \approx \Delta U$) are selected

➔ Narrowband filter

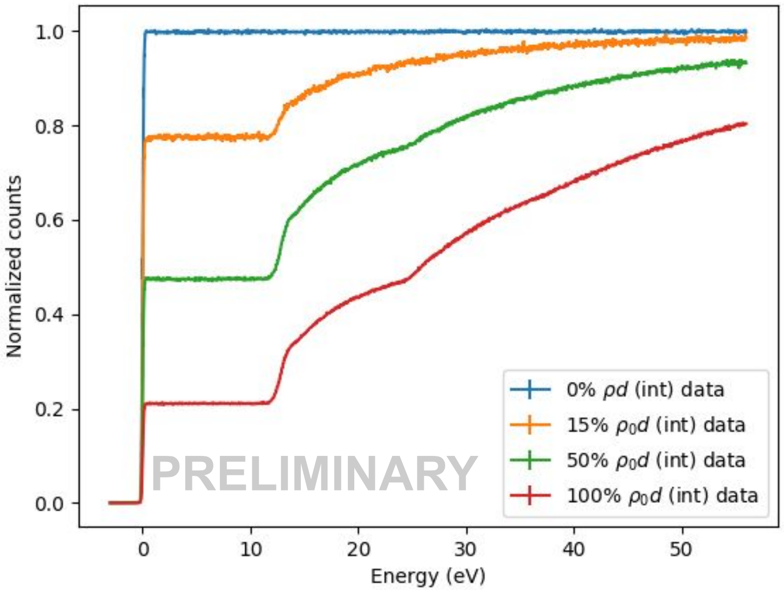


Measurement results and

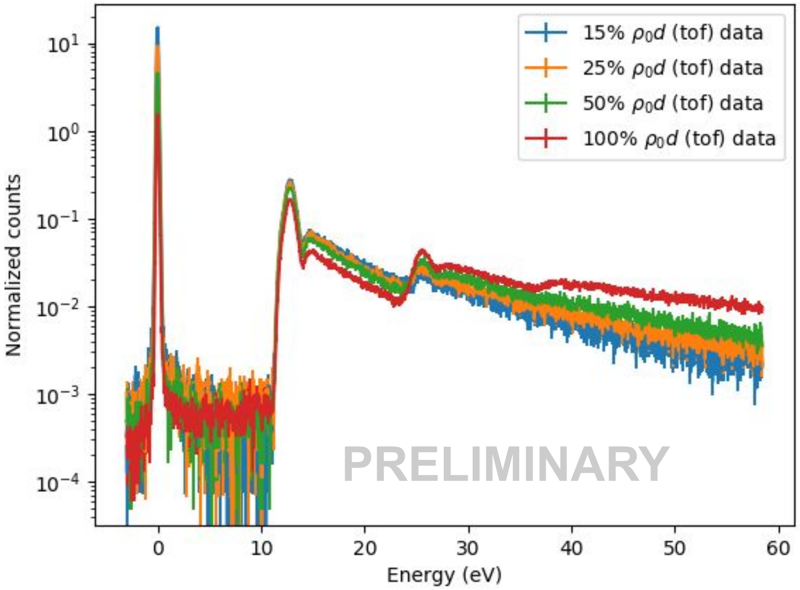
DATA ANALYSIS

Measurement Data

- Quality-selected runs: 119h of net measurement time
- Integral



- Differential



Semi-empirical energy loss model

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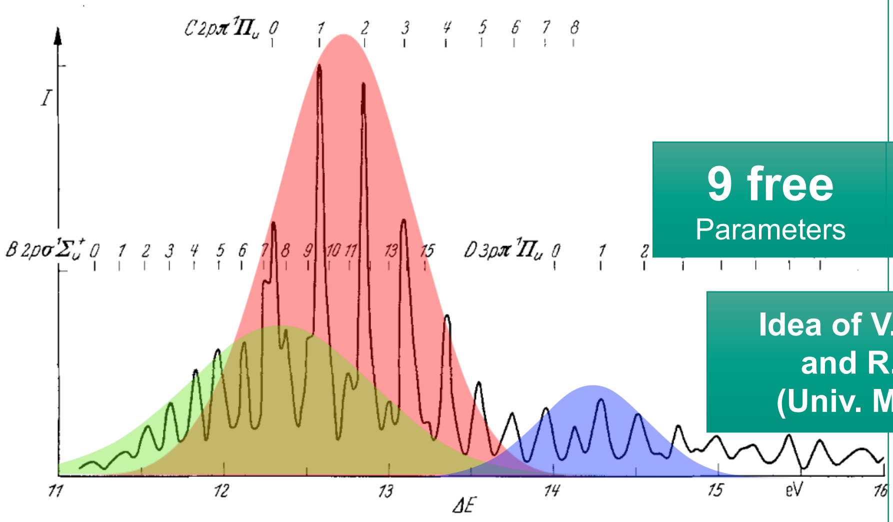
Excitation



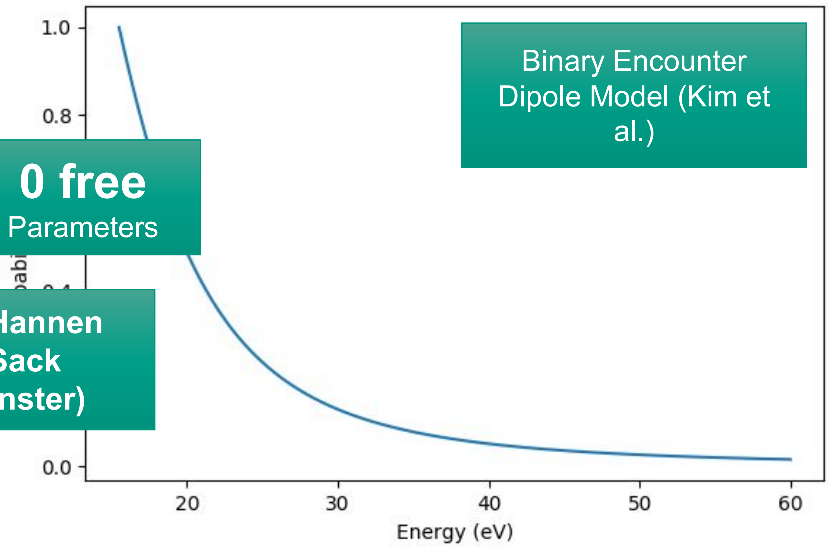
J. Geiger: Streuung von 25 keV-Elektronen an Gasen (1964)
DOI: 10.1007/BF01380873

9 free Parameters

0 free Parameters

Idea of V. Hannen and R. Sack (Univ. Münster)

Ionization

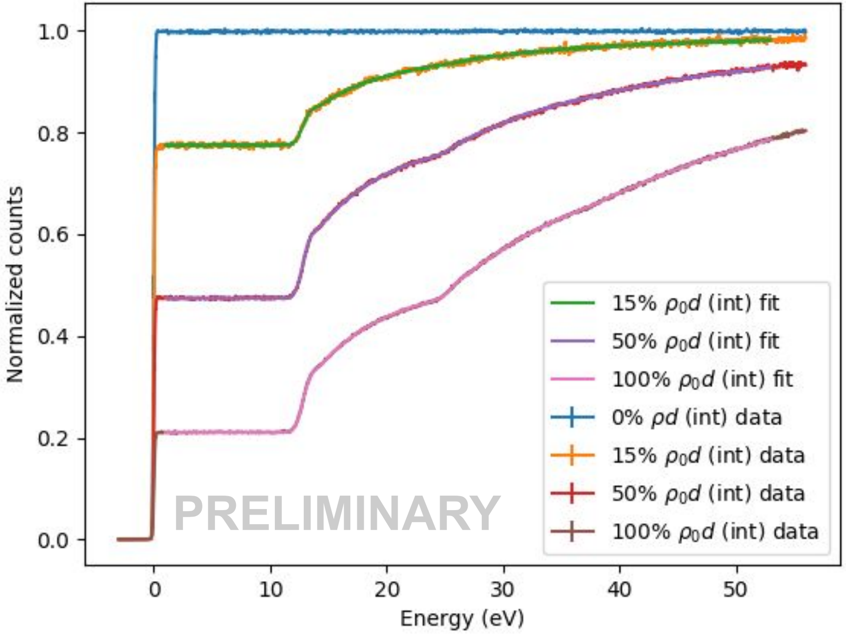


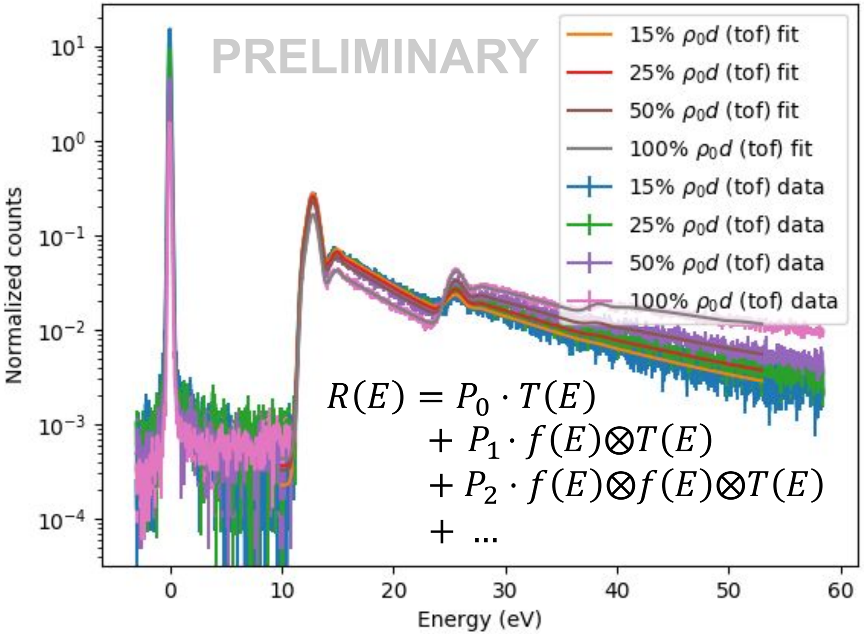
Binary Encounter Dipole Model (Kim et al.)

Y.Kim et al. : Binary-encounter-dipole model for electron-impact ionization (1994) DOI:10.1103/PhysRevA.50.3954

Fit results

Combined χ^2 fit 30 free parameters

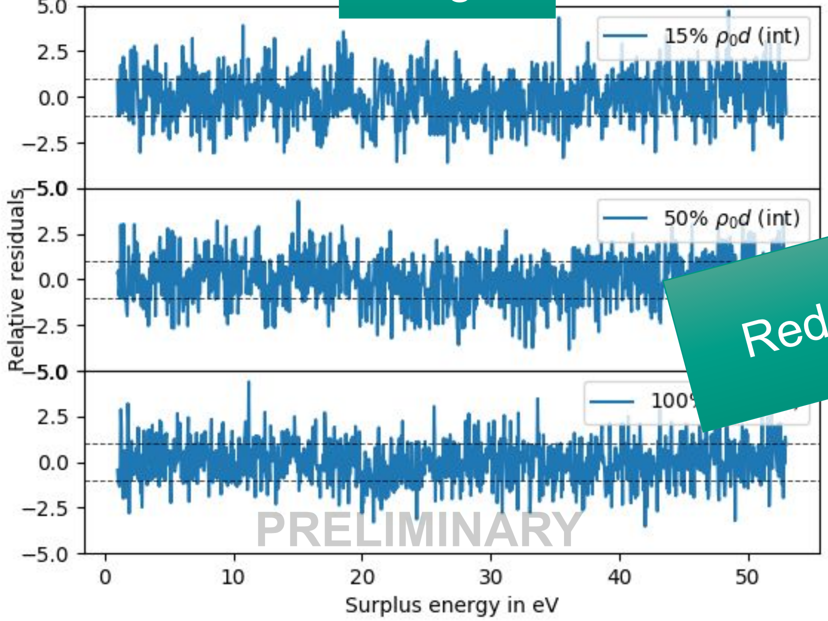




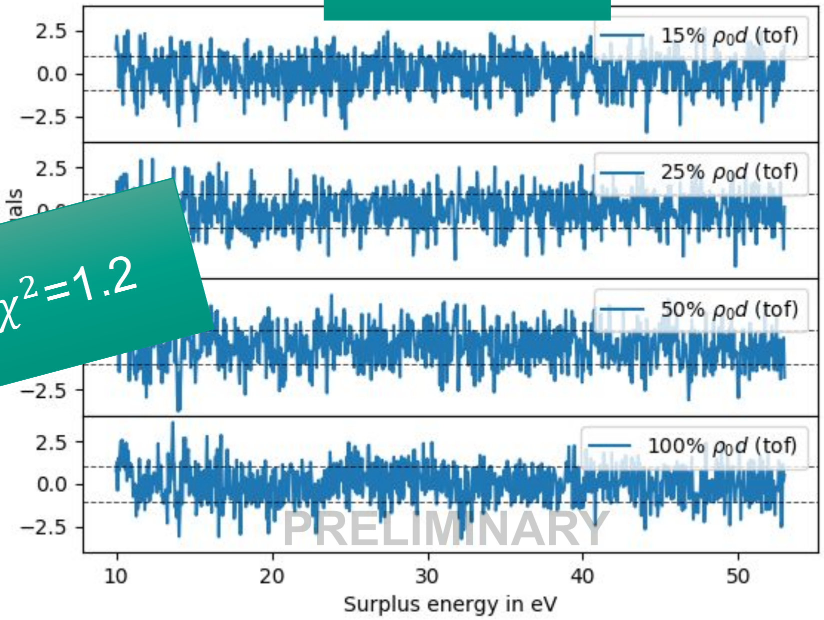
$$R(E) = P_0 \cdot T(E) + P_1 \cdot f(E) \otimes T(E) + P_2 \cdot f(E) \otimes f(E) \otimes T(E) + \ldots$$

Fit results

Integral

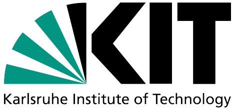


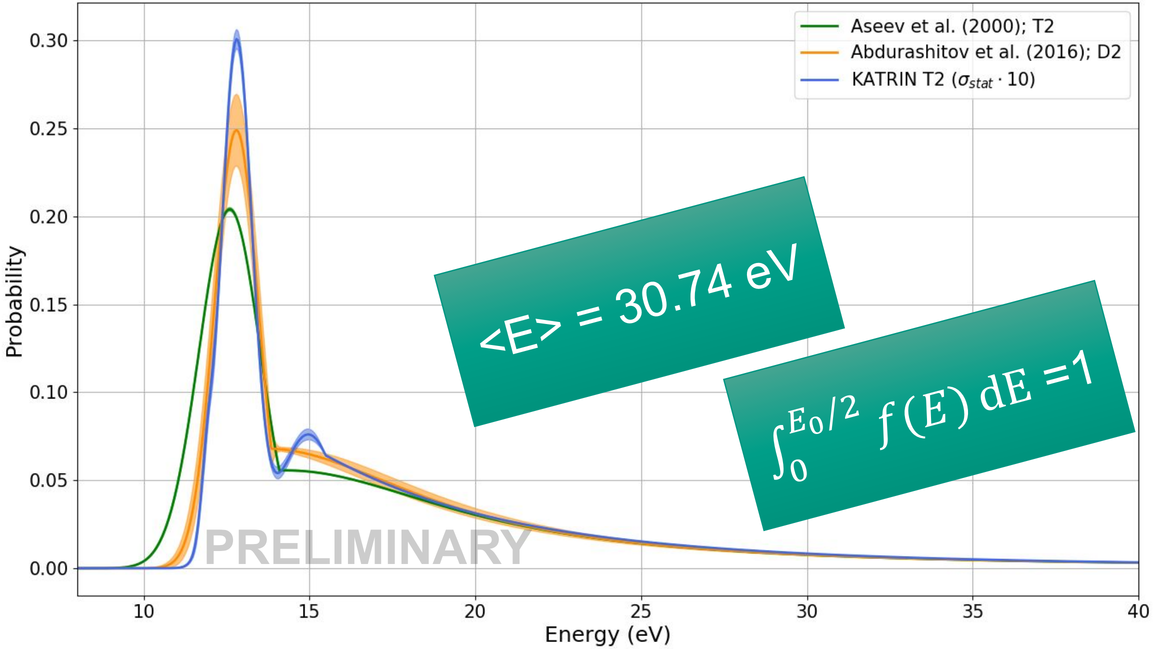
Differential



Red. χ^2=1.2

Final result





- Plot only showing 1σ statistical uncertainty
- Full Monte Carlo error propagation and KATRIN sensitivity studies ongoing
- Publication in preparation

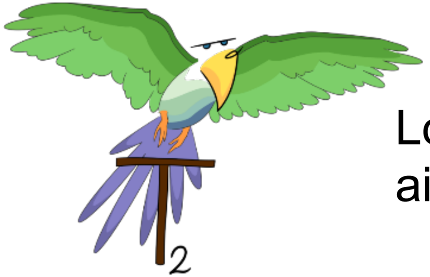
Summary and outlook

- Energy loss measurement of 18.6 keV electrons for T_2 using precision electron gun
  - Integral
  - Differential

✓ Improved semi-empirical energy loss model for T_2

✓ Measured energy loss function used for KATRIN first ν mass result

Improved Upper Limit on the Neutrino Mass from a Direct Kinematic Method by KATRIN (2019) DOI: 10.1103/PhysRevLett.123.221802

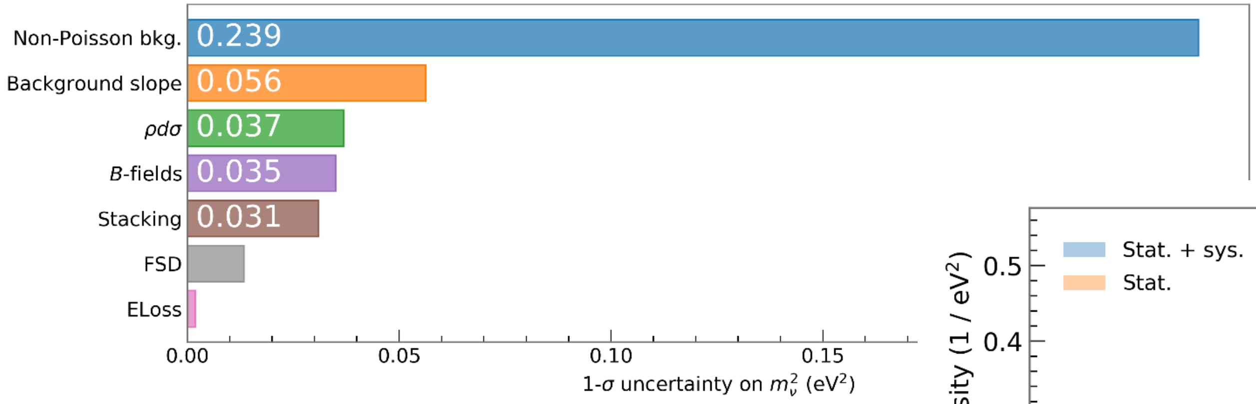


Long-term measurements (starting this year) aim for sensitivity of 200 meV

THANK YOU!

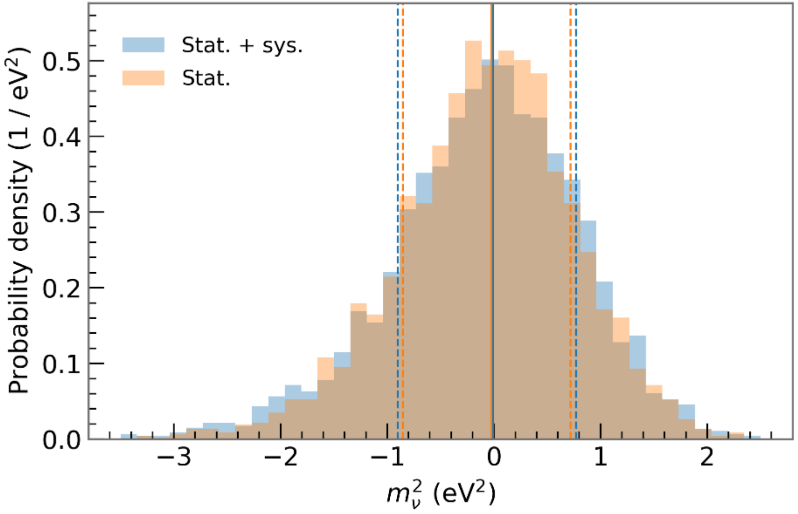
BACKUP

Systematics budget



σ_{stat} = 0.97 eV²

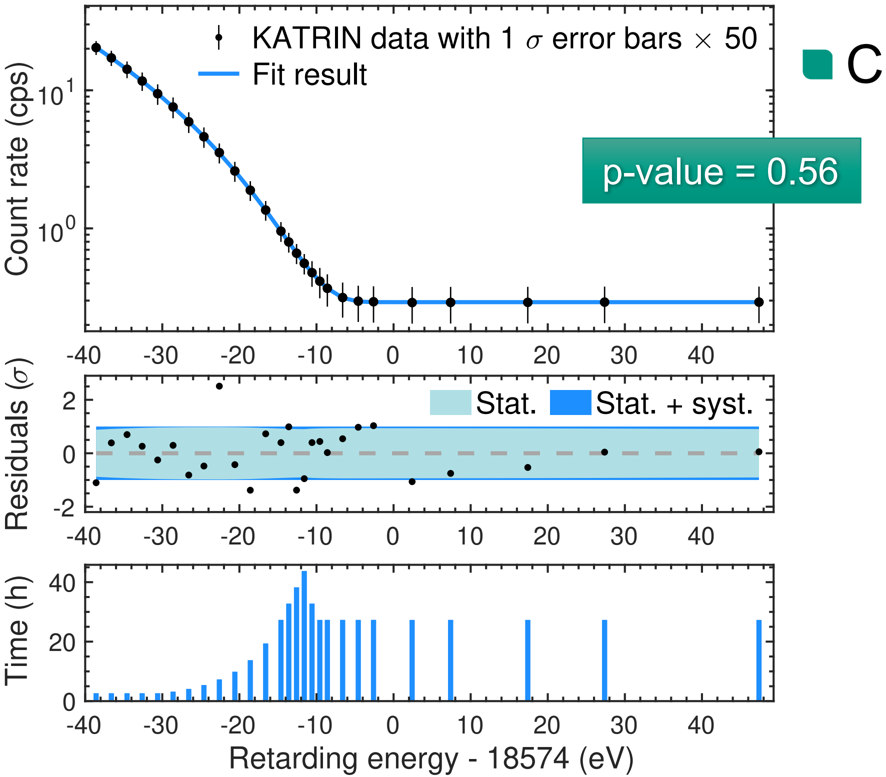
σ_{syst} = 0.32 eV²



Results of MC error propagation

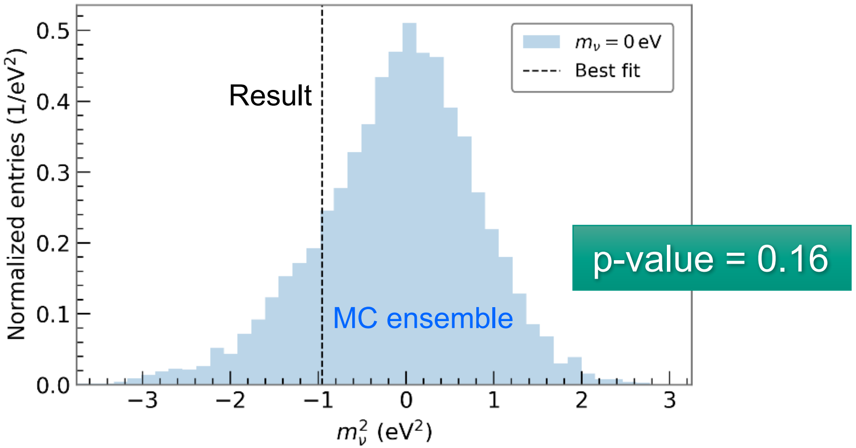
Similar for Covariance Matrix approach

Fit result m_ν^2



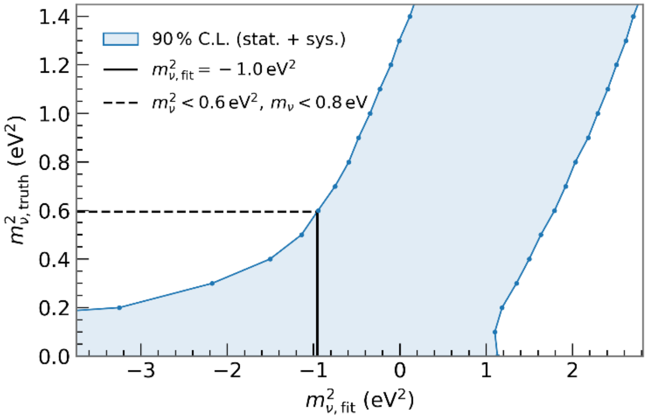
- Combined fit result (90 eV range):

$$m_\nu^2 = (-1.0\ ^{+0.9}_{-1.1})\ \mathrm{eV}^2$$



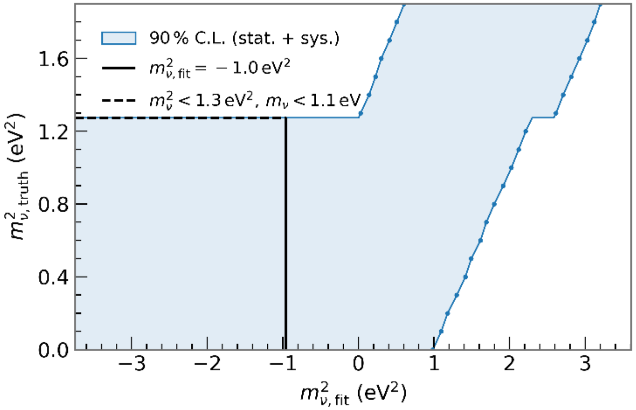
Neutrino mass limit

Feldman-Cousins



$m_\nu < 0.8$ eV (90% C.L.)

Tkachov-Lokhov



$m_\nu < 1.1$ eV (90% C.L.)

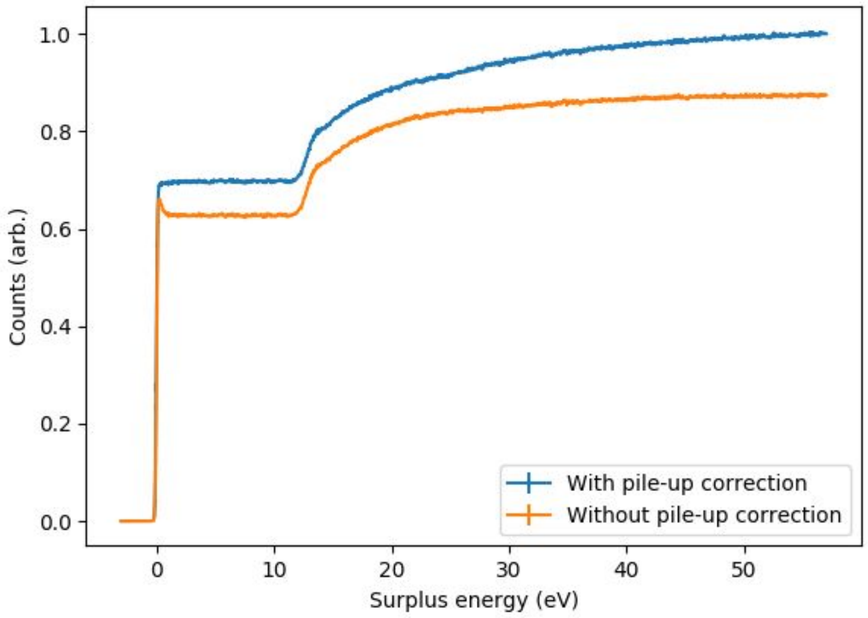
A. V. Lokhov, F. V. Tkachov (2015): Confidence intervals with a priori parameter bounds, 10.1134/S1063779615030089

Pile-up Correction

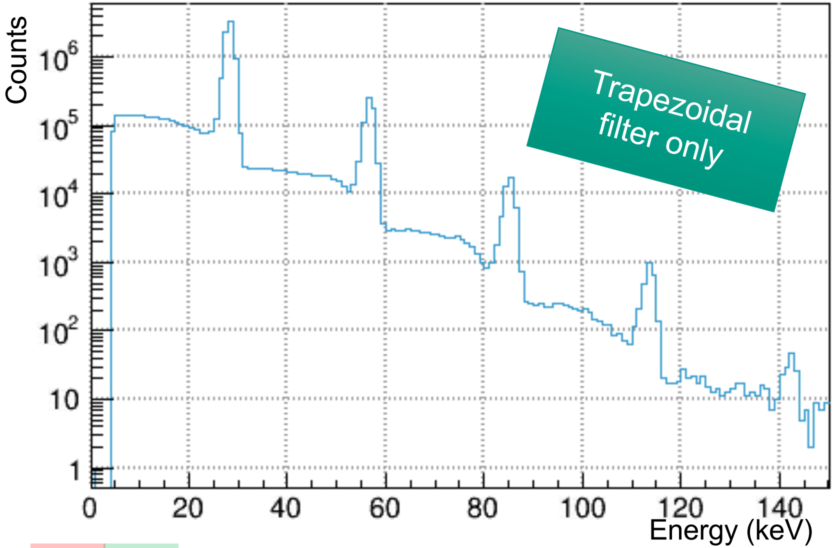
- Detector designed for single electron detection
- Laser with pulse lengths of <18ns FWHM

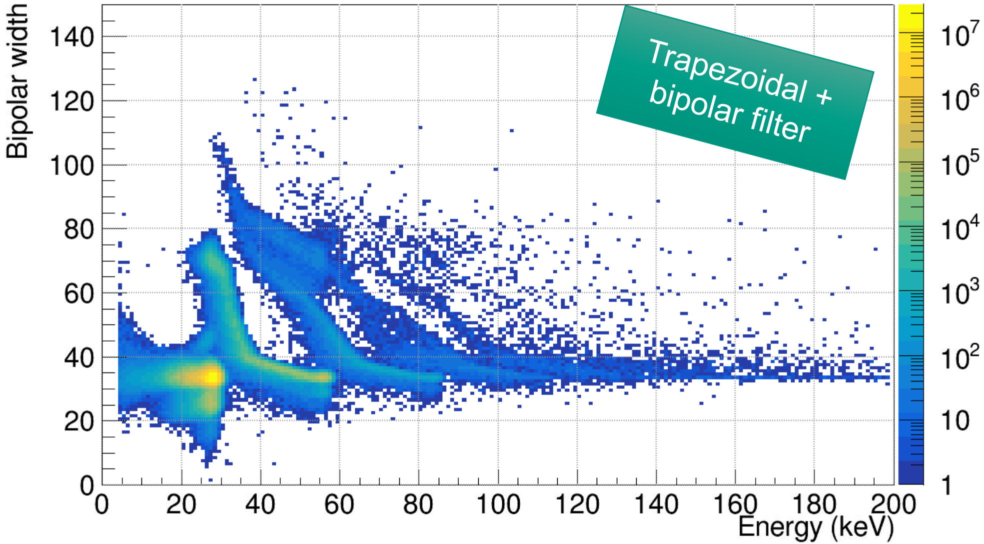
- Retarding potential influencing the time-of-flight

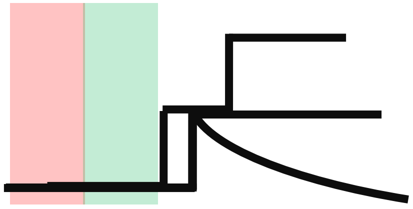
➔ Non-Poissonian pile-up

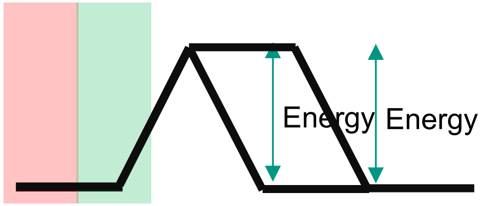


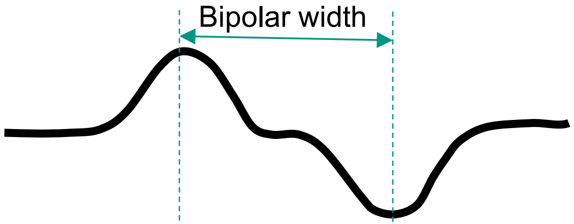
Pile-up Correction





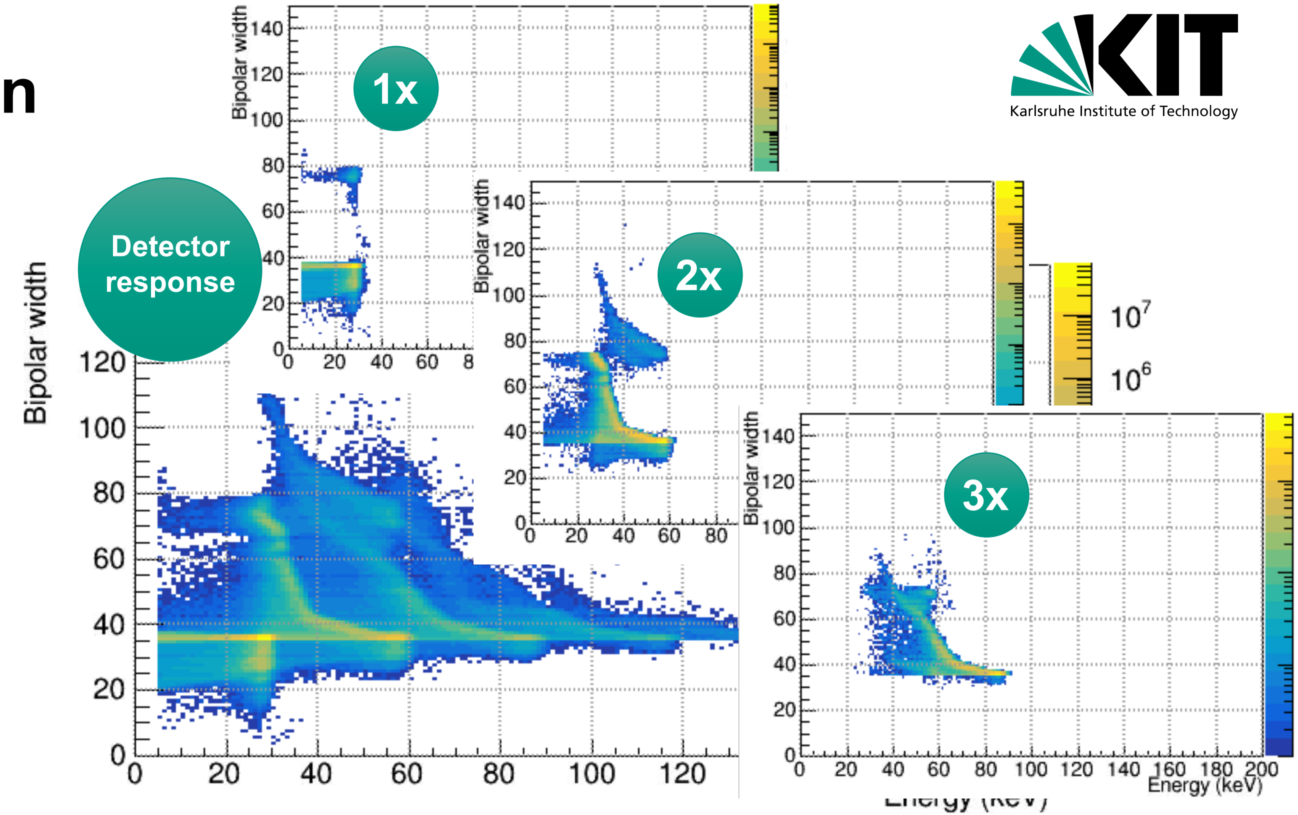




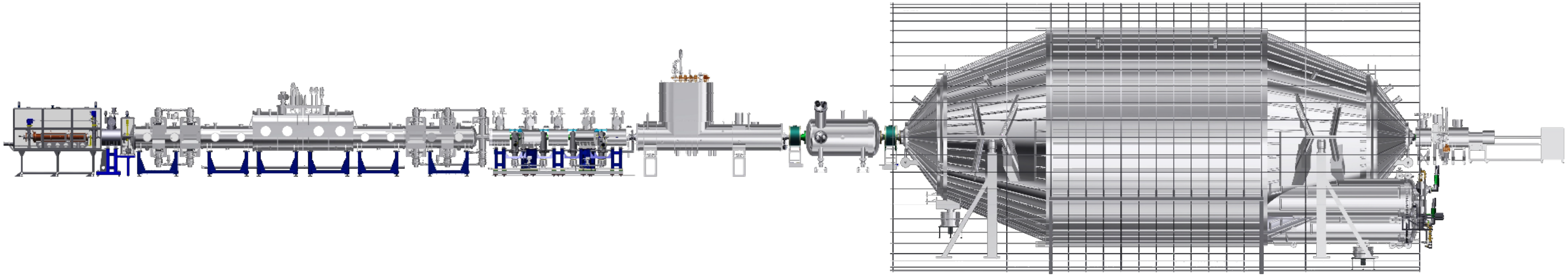


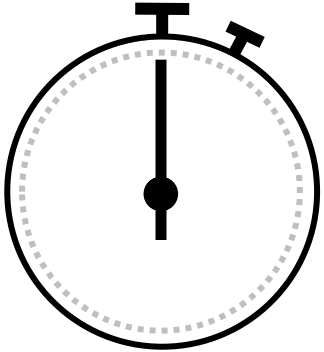
Pile-up Correction

- Angular resolution
- Flight time simul.
- Energy distribution
- Full DAQ simulation
- Deadlayer effects
- ...
- Detector response



Experimental Setup





Mean Stopping power

- Stopping power: 18.58keV: 30.96 MeV cm^2/g
  https://physics.nist.gov/PhysRefData/Star/Text/ESTAR.html
- And M_H2=3.3E-24g (wolfram Alpha)
- ➔dE/(rho*dx)=1.0217E-16 eV cm^2
- Liu: 3,49E-18 cm^2
- Aseev et. al. : 3,40E-18 cm^2
- Glück: 3.668E-18cm^2
  https://ikp-katrin-wiki.ikp.kit.edu/katrin/images/3/36/SigmainelTheorH2D2T2.pdf
- Stopping Power <E>=dE/sigma=30.04 eV (for Aseev)