Search for new light bosons with the KATRIN experiment

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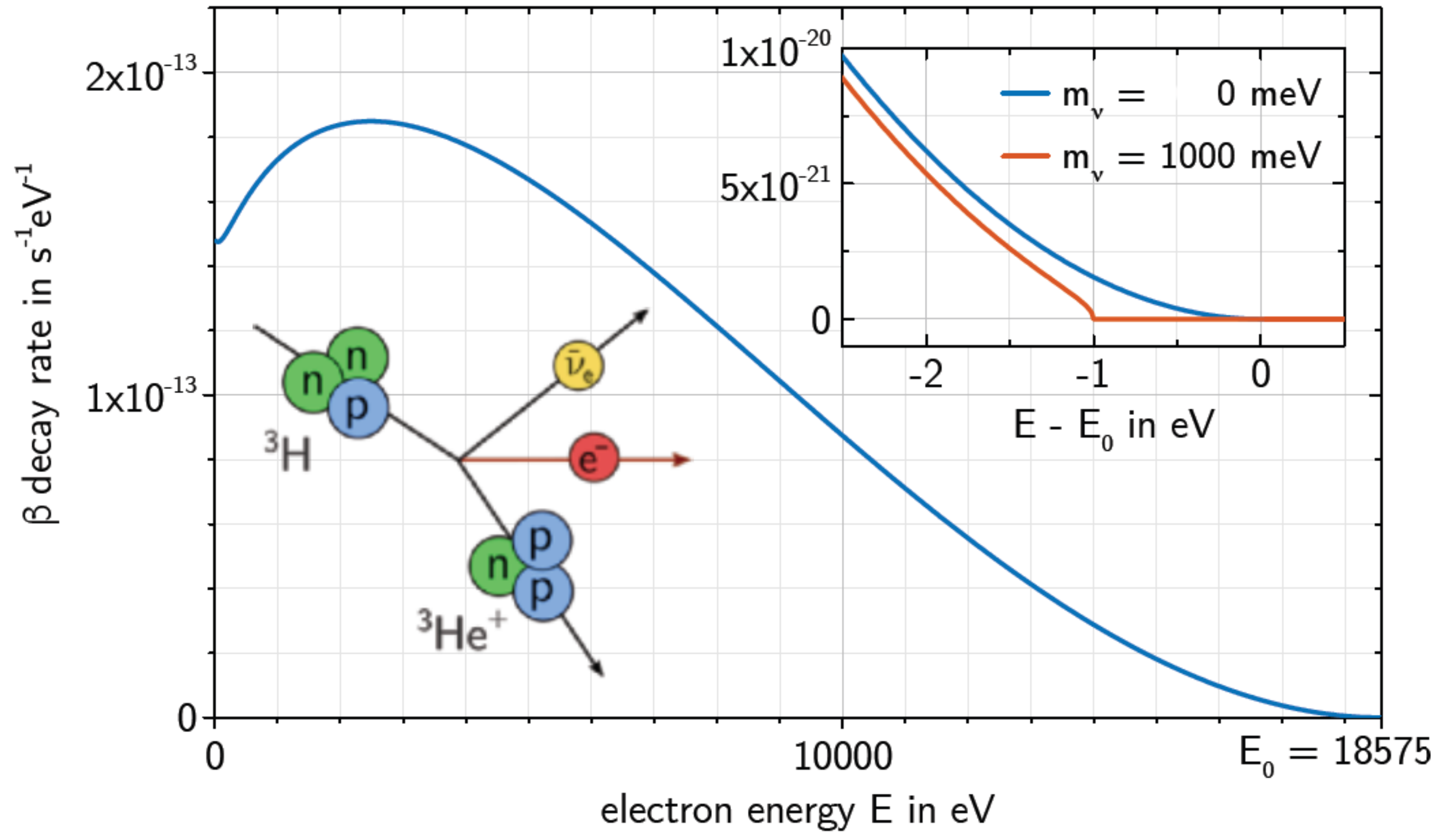
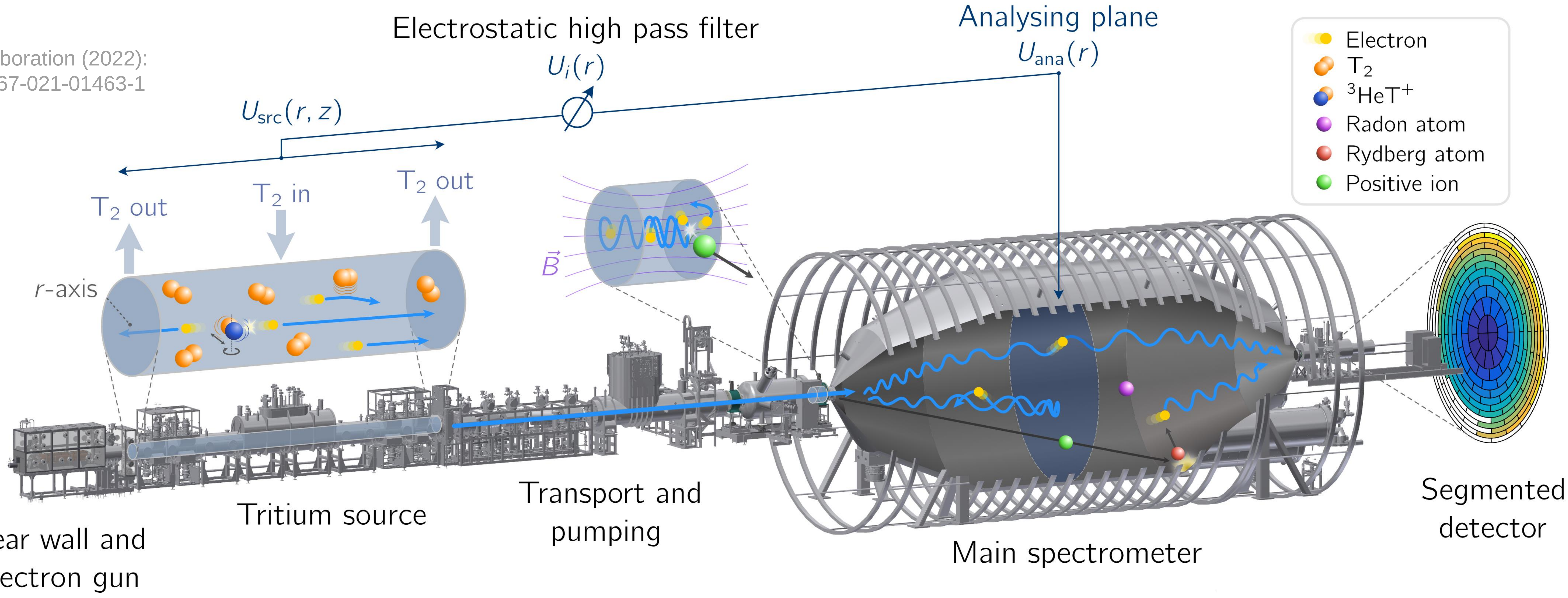
The KATRIN experiment

- Observable: effective electron antineutrino mass $\boldsymbol{m_\nu^2 = \sum_i |U_{ei}|^2 m_i^2}$
- Kinematic approach: electron energy spectrum of **tritium β-decay**

K. Valerius (2023)

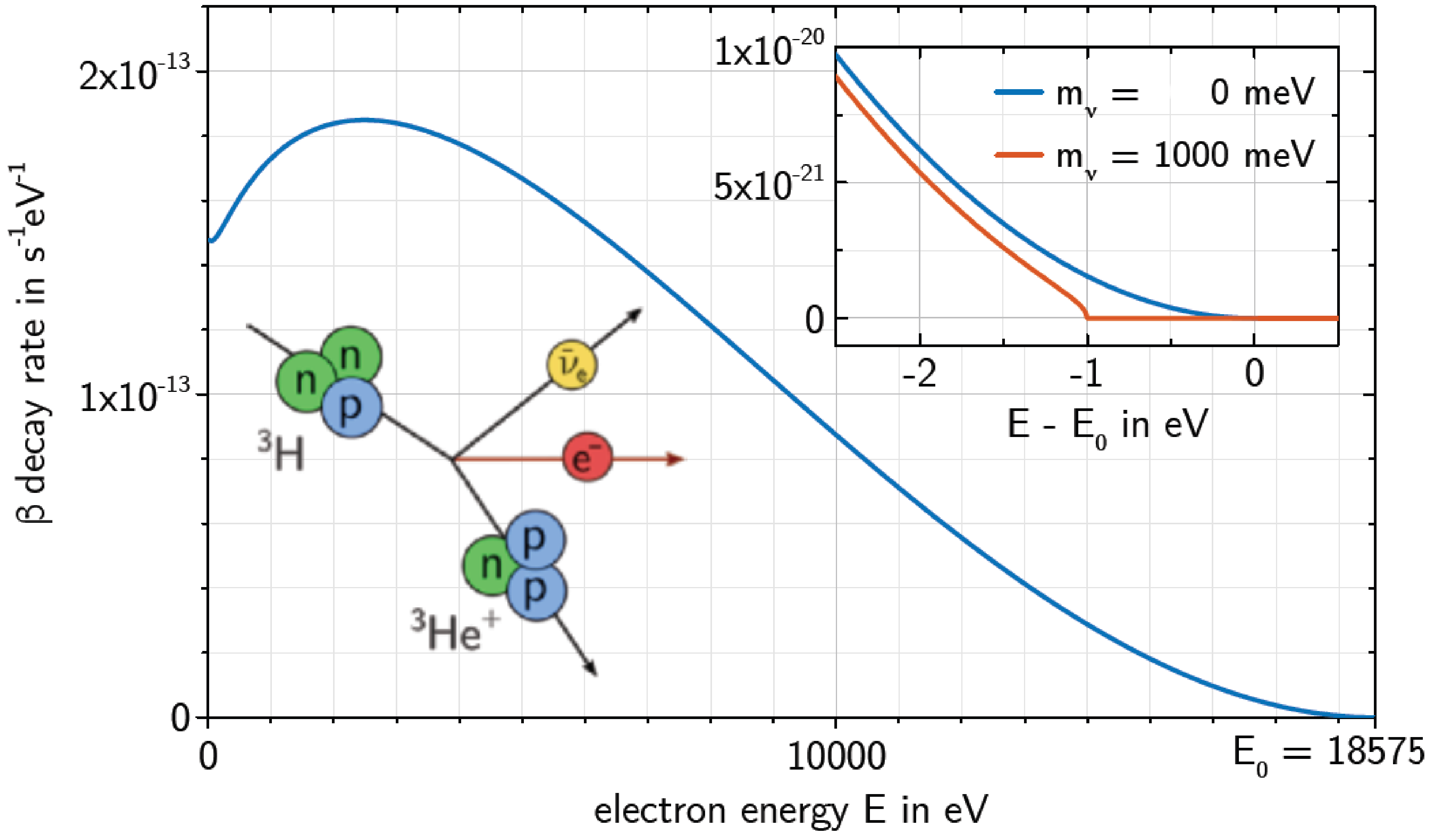


KATRIN Collaboration (2022):
10.1038/s41567-021-01463-1



Tritium β-decay in KATRIN

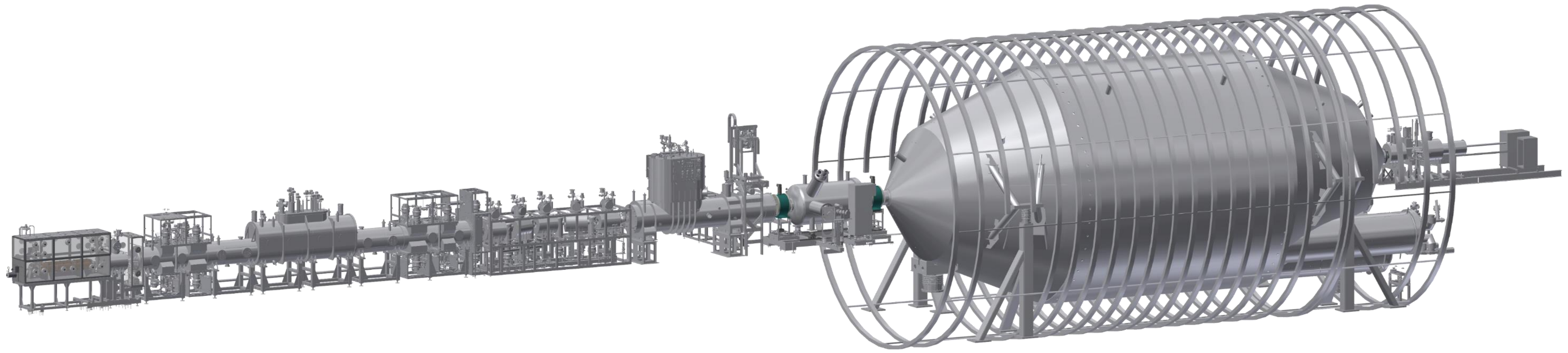
K. Valerius (2023)



- Super-allowed decay $\mathrm{T_2} \rightarrow {}^3\mathrm{HeT}^+ + e^- + \bar{\nu}_e$, endpoint: $E_0 \approx 18.6\,\mathrm{keV}$
- Fermi's interaction: $\mathcal{L}_\mathrm{F} = -\frac{G_\mathrm{F}}{\sqrt{2}}\, \bar{p}\gamma^\mu n\, \bar{e}\gamma_\mu \nu + \mathrm{h.c.}$
- → differential β-spectrum:

$$\frac{\mathrm{d}\Gamma_\beta}{\mathrm{d}E}(E, m_\nu^2) = C \cdot (E + m_e) \cdot p \cdot E_\nu \cdot \sqrt{(E_0 - E)^2 - m_\nu^2} \cdot F(Z+1, E)$$

- Measurement of integral rate: $R(qU) = A_\mathrm{Sig} \int_{qU}^{E_0} f(E - qU)\, \frac{\mathrm{d}\Gamma}{\mathrm{d}E}(E, m_\nu^2)\, \mathrm{d}E + R_\mathrm{Bg}$
- → fit in the endpoint region



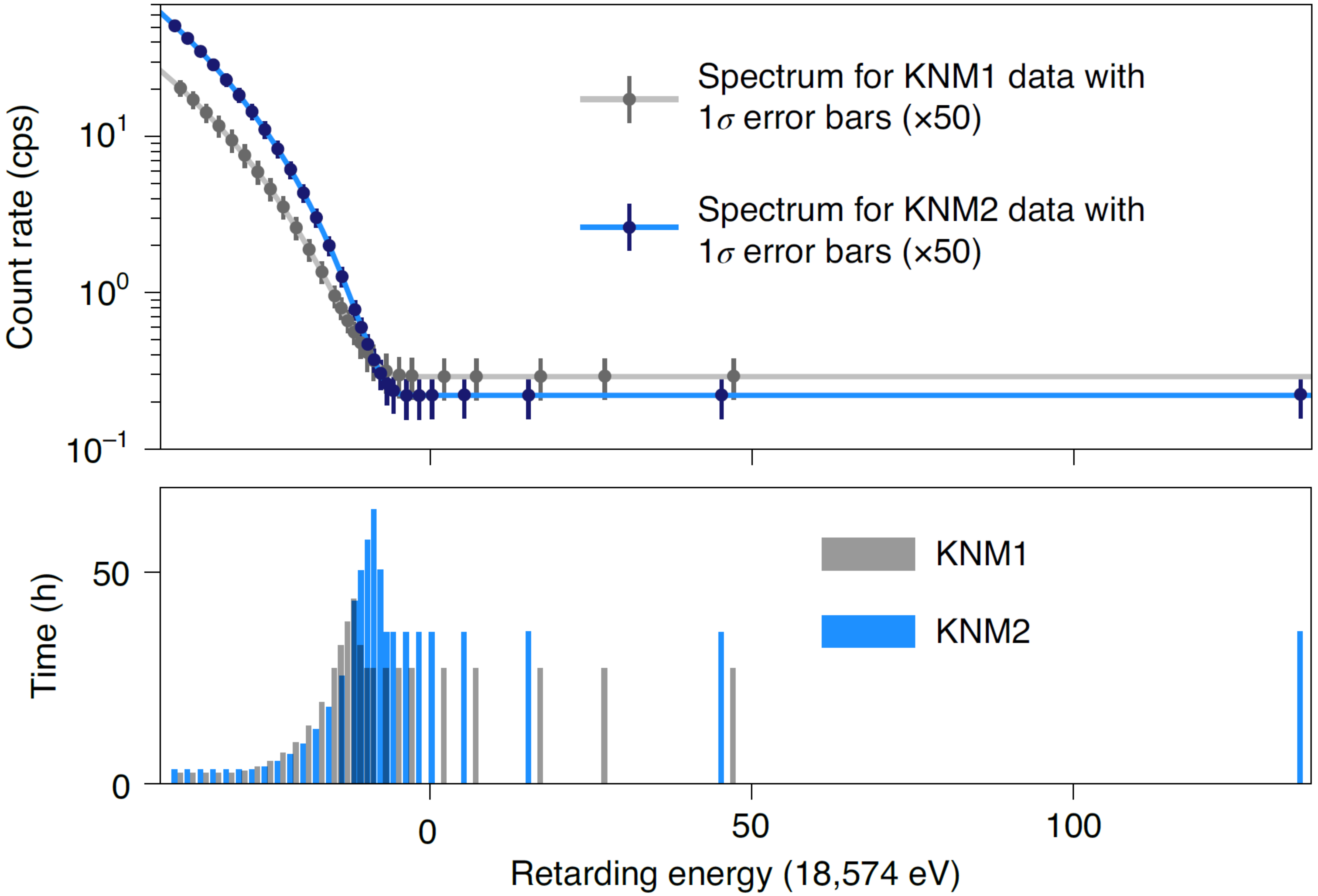
KATRIN Collaboration (2022): 10.1103/PhysRevD.105.072004

Spectrum fitting

- C++-based analysis framework *KaFit*
- Precise model evaluation, Gauss-Legendre integration
- $R(qU) = A_{\mathrm{Sig}} \int_{qU}^{E_0} f(E-qU)\, \frac{\mathrm{d}\Gamma}{\mathrm{d}E}\left(E, m_\nu^2\right) \mathrm{d}E + R_{\mathrm{Bg}}$
- Four fit parameters:
  - Neutrino mass m_ν^2
  - Endpoint E_0
  - Amplitude A_{Sig}
  - Background level R_{Bg}

KATRIN Collaboration (2022):
10.1038/s41567-021-01463-1

→ $m_\nu < 0.8$ eV (90% CL)

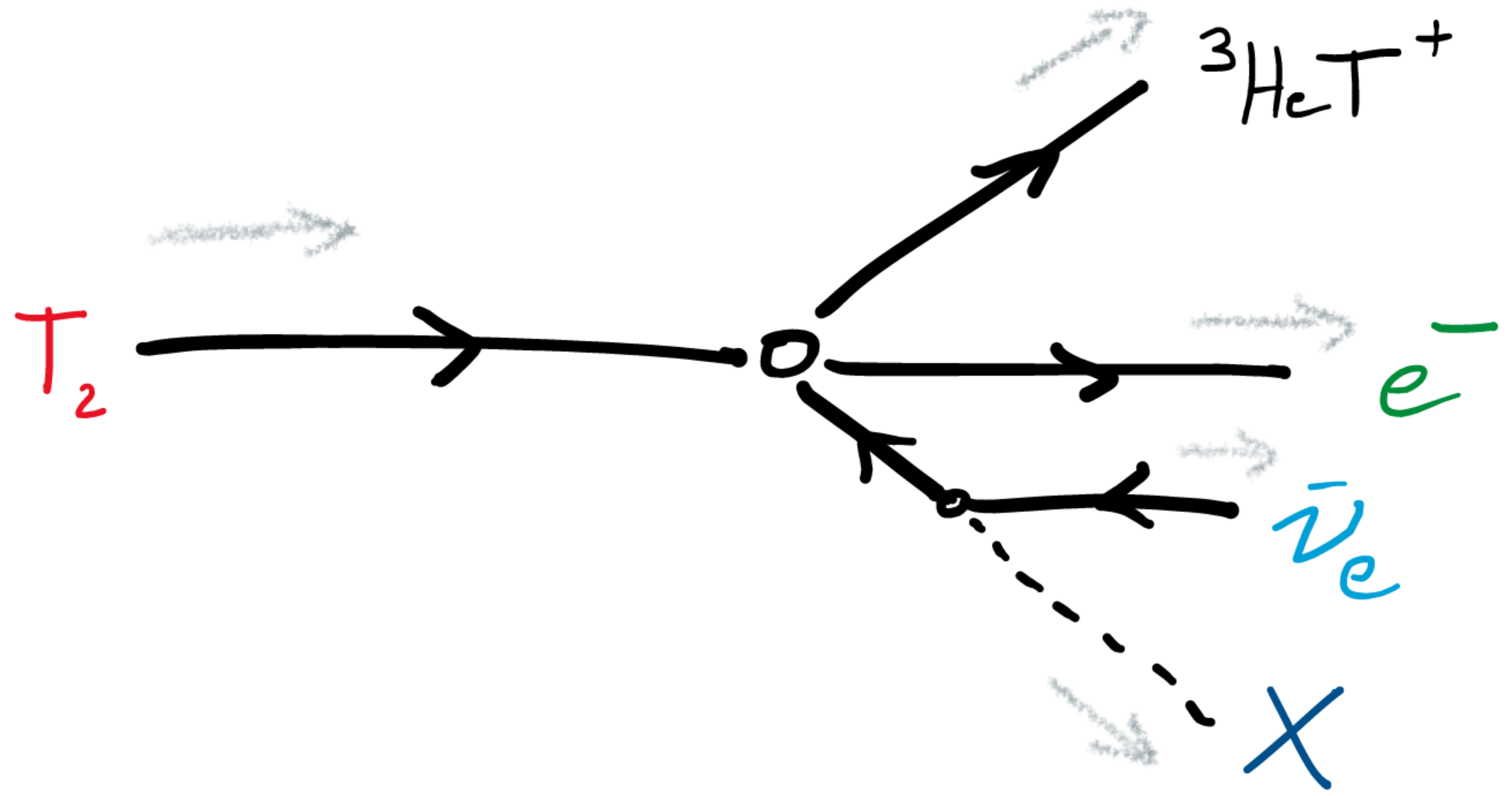


Beyond standard β-decay – light bosons

- Spectral shape distortion → KATRIN provides sensitivity

- Consider real emission of particle X in the final state: $\mathrm{T}_2 \rightarrow {}^3\mathrm{HeT}^+ + e^- + \bar{\nu}_e + X$
- Motivation: hypothetical new light bosons in BSM theories
  - Pseudoscalars J (like axions or majoron)
  - Vector bosons Z' (e.g. dark photons)
- Measurement range: $m_X \leq 40\ \mathrm{eV}$ → light bosons

β-decay with additional boson emission



Ref. Arcadi et al. JHEP01 (2019) 206:

- BSM models: boson couplings to leptons
  - Pseudoscalar J: $\mathrm{i}g_{\nu J}\bar{\nu}\gamma_5\nu J,\ \ \mathrm{i}g_{eJ}\bar{e}\gamma_5 eJ$
  - Vector boson Z': $g_{\nu Z'}\bar{\nu}\gamma^\mu P_\mathrm{L}\nu Z'_\mu,\ \ g_{eZ'}\bar{e}\gamma^\mu eZ'_\mu,\ \ g_{L_eZ'}j^\mu_{L_e}Z'_\mu$
- $\mathcal{L} = \mathcal{L}_\mathrm{F} + \mathcal{L}_X$ → additional decay channel $\Gamma = \Gamma_\beta + \Gamma_X \neq \Gamma_\beta$
- Boson branch: reduced kinematic enpoint at $E^X_\mathrm{max} = E_0 - (m_\nu + m_X) < E^\beta_\mathrm{max}$

Spectrum implementation

- Calculation presented by Arcadi et al.

- Excellent fit with relation

$$\frac{\mathrm{d}\Gamma_X}{\mathrm{d}E}(E, m_\nu, m_X, g_X)$$

$$= \frac{K(g_X, m_X)}{\hbar}\sqrt{\frac{E}{m_e}}\left(\frac{E_{\max}(m_\nu, m_X) - E}{E_{\max}(m_\nu, m_X) + m_e}\right)^{n(m_X)} F(Z+1, E)$$

- Mapping of m_X, g_X to values of *normalization* $K \propto g_X^2$ and *spectral index* n

- Values provided for entire mass range for any type
  → efficient model calculation in KaFit

Arcadi et al. JHEP01 (2019) 206

The M_{134}^2 and M_{34}^2 integrals are trivial, leading to the final expression for the differential decay rate

$$\frac{\mathrm{d}\Gamma}{\mathrm{d}E_e} = \int_{m_{\mathcal{J}}^2}^{\left(\sqrt{m_{\mathcal{A}}^2 - 2m_{\mathcal{A}}E_e + m_e^2} - m_{\mathcal{B}}\right)^2} I \,\mathrm{d}M_{12}^2 \tag{A.7}$$

with rather lengthy integrand

$$\begin{aligned} I = {} & \frac{G_F^2 g_{\nu\mathcal{J}}^2 |V_{ud}|^2 \sqrt{E_e^2 - m_e^2}\,(M_{12}^2 - m_{\mathcal{J}}^2)^2}{3072\pi^5 (M_{12}^2)^3 m_{\mathcal{A}} (m_{\mathcal{A}}^2 - 2E_e m_{\mathcal{A}} + m_e^2)^3}\left[g_V^2 m_{\mathcal{A}} W_V + 2g_V g_A W_{VA} + g_A^2 m_{\mathcal{A}} W_A\right] \\ & \times \sqrt{-2m_{\mathcal{B}}^2(-2E_e m_{\mathcal{A}} + M_{12}^2 + m_{\mathcal{A}}^2 + m_e^2) + (-2E_e m_{\mathcal{A}} - M_{12}^2 + m_{\mathcal{A}}^2 + m_e^2)^2 + m_{\mathcal{B}}^4}\,, \end{aligned} \tag{A.8}$$

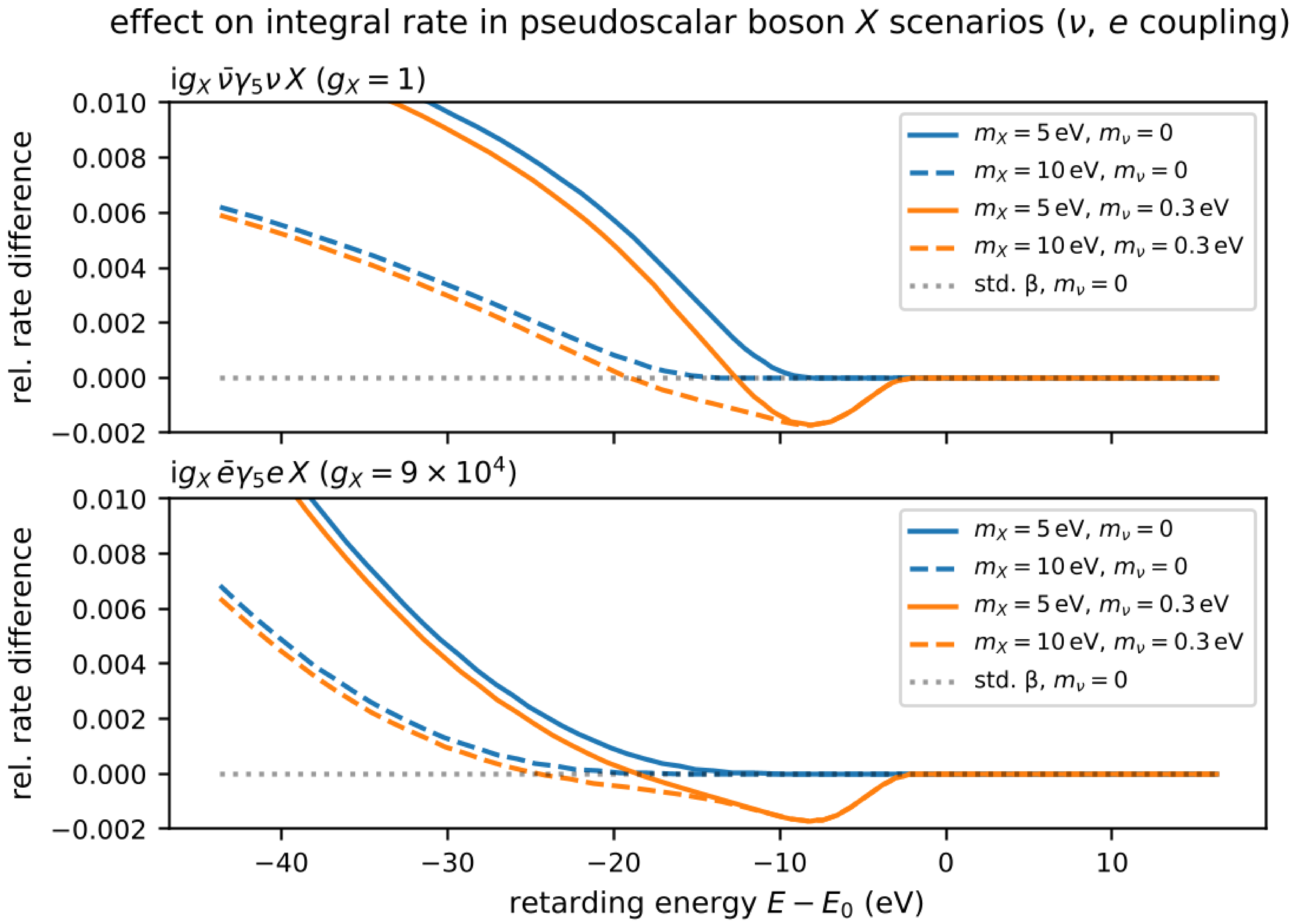
$$\begin{aligned} W_V = {} & -6m_{\mathcal{A}}^2 m_{\mathcal{B}}(-2E_e m_{\mathcal{A}} + m_{\mathcal{A}}^2 + m_e^2)(-2E_e m_{\mathcal{A}} + M_{12}^2 + m_{\mathcal{A}}^2 - m_{\mathcal{B}}^2 + m_e^2) \\ & + m_{\mathcal{A}}\Big[-2(-2E_e m_{\mathcal{A}} + m_{\mathcal{A}}^2 + m_e^2)^2\left(4(M_{12}^2 + m_{\mathcal{B}}^2) + m_e^2\right) + 4m_e^2(M_{12}^2 - m_{\mathcal{B}}^2)^2 \\ & + (-2E_e m_{\mathcal{A}} + m_{\mathcal{A}}^2 + m_e^2)\left((M_{12}^2 - m_{\mathcal{B}}^2)^2 - 2m_e^2(M_{12}^2 + m_{\mathcal{B}}^2)\right) + 7(-2E_e m_{\mathcal{A}} + m_{\mathcal{A}}^2 + m_e^2)^3\Big] \\ & + 6m_{\mathcal{B}}(-2E_e m_{\mathcal{A}} + m_{\mathcal{A}}^2 + m_e^2)(-2E_e m_{\mathcal{A}} + m_{\mathcal{A}}^2 + 2m_e^2)(-2E_e m_{\mathcal{A}} + M_{12}^2 + m_{\mathcal{A}}^2 - m_{\mathcal{B}}^2 + m_e^2) \\ & + (2E_e - m_{\mathcal{A}})\Big[(-2E_e m_{\mathcal{A}} + m_{\mathcal{A}}^2 + m_e^2)^2\left(m_e^2 - 7(M_{12}^2 + m_{\mathcal{B}}^2)\right) \\ & + (-2E_e m_{\mathcal{A}} + m_{\mathcal{A}}^2 + m_e^2)\left(m_e^2(M_{12}^2 + m_{\mathcal{B}}^2) - (M_{12}^2 - m_{\mathcal{B}}^2)^2\right) \\ & + 8(-2E_e m_{\mathcal{A}} + m_{\mathcal{A}}^2 + m_e^2)^3 - 2m_e^2(M_{12}^2 - m_{\mathcal{B}}^2)^2\Big] \\ & + m_{\mathcal{A}}^3\left((M_{12}^2 + m_{\mathcal{B}}^2)(-2E_e m_{\mathcal{A}} + m_{\mathcal{A}}^2 + m_e^2) + (-2E_e m_{\mathcal{A}} + m_{\mathcal{A}}^2 + m_e^2)^2 - 2(M_{12}^2 - m_{\mathcal{B}}^2)^2\right), \end{aligned} \tag{A.9}$$

$$\begin{aligned} W_{VA} = {} & -2(M_{12}^2 - m_{\mathcal{B}}^2)^2(m_{\mathcal{A}}^2 - m_e^2)^2 - 5(-2E_e m_{\mathcal{A}} + m_{\mathcal{A}}^2 + m_e^2)^3(M_{12}^2 + m_{\mathcal{A}}^2 + m_{\mathcal{B}}^2 + m_e^2) \\ & + 4(-2E_e m_{\mathcal{A}} + m_{\mathcal{A}}^2 + m_e^2)^4 + (-2E_e m_{\mathcal{A}} + m_{\mathcal{A}}^2 + m_e^2)^2\left[(M_{12}^2)^2 + 2m_{\mathcal{A}}^2\left(2(M_{12}^2 + m_{\mathcal{B}}^2) - m_e^2\right)\right. \\ & \left. - 2M_{12}^2 m_{\mathcal{B}}^2 + 4M_{12}^2 m_e^2 + m_{\mathcal{A}}^4 + m_{\mathcal{B}}^4 + 4m_{\mathcal{B}}^2 m_e^2 + m_e^4\right] + (-2E_e m_{\mathcal{A}} + m_{\mathcal{A}}^2 + m_e^2)\Big[m_{\mathcal{A}}^4(M_{12}^2 + m_{\mathcal{B}}^2) \\ & + m_{\mathcal{A}}^2\left((M_{12}^2 - m_{\mathcal{B}}^2)^2 - 2m_e^2(M_{12}^2 + m_{\mathcal{B}}^2)\right) + m_e^4(M_{12}^2 + m_{\mathcal{B}}^2) + m_e^2(M_{12}^2 - m_{\mathcal{B}}^2)^2\Big], \end{aligned} \tag{A.10}$$

$W_A = W_V$ with $m_{\mathcal{B}} \to -m_{\mathcal{B}}$.

The remaining integral over M_{12}^2 can be performed numerically to obtain $\mathrm{d}\Gamma/\mathrm{d}E_e$.

β-decay with additional boson emission



Analysis procedure

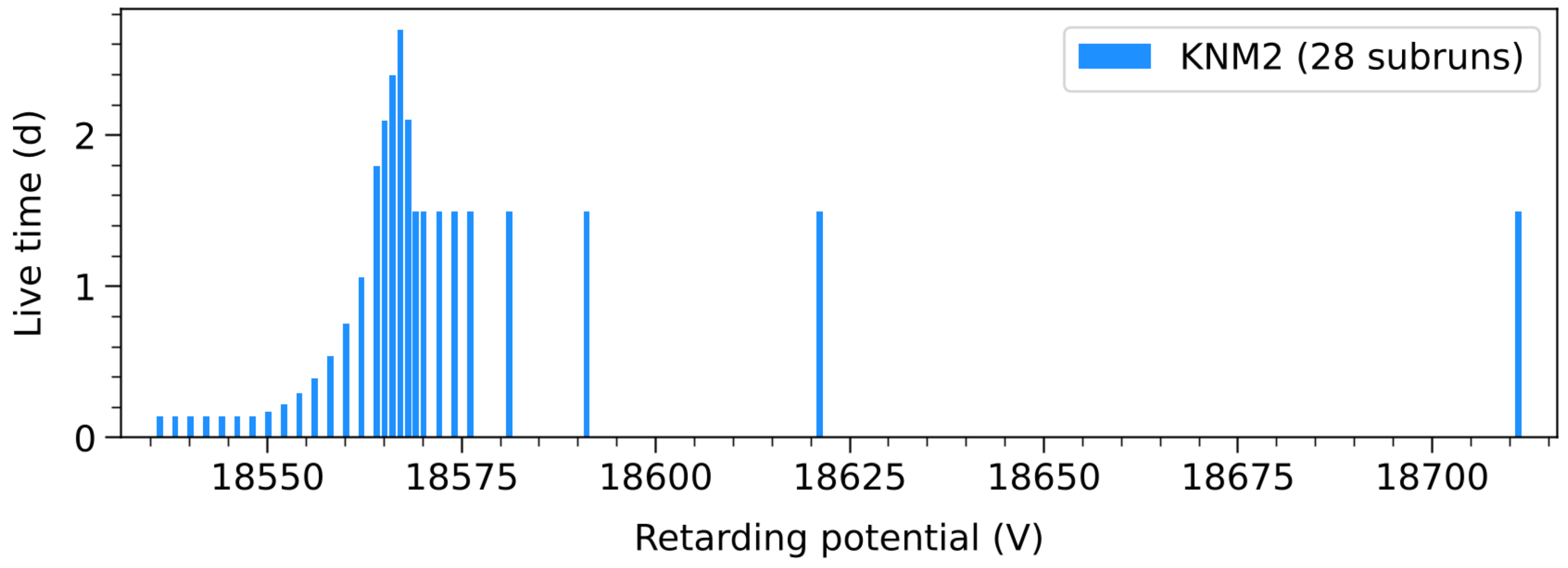
Dataset

- Based on the second KATRIN measurement campaign (KNM2):
  - 4×10^6 collected electrons
  - ROI: $[E_0 - 40\ \mathrm{eV},\ E_0 + 130\ \mathrm{eV}]$
- MC Asimov twin dataset:
  - $m_\nu^2 = 0,\ g_X = 0$ (no signatures)
  - Experimental settings adapted

Analysis (grid scan)

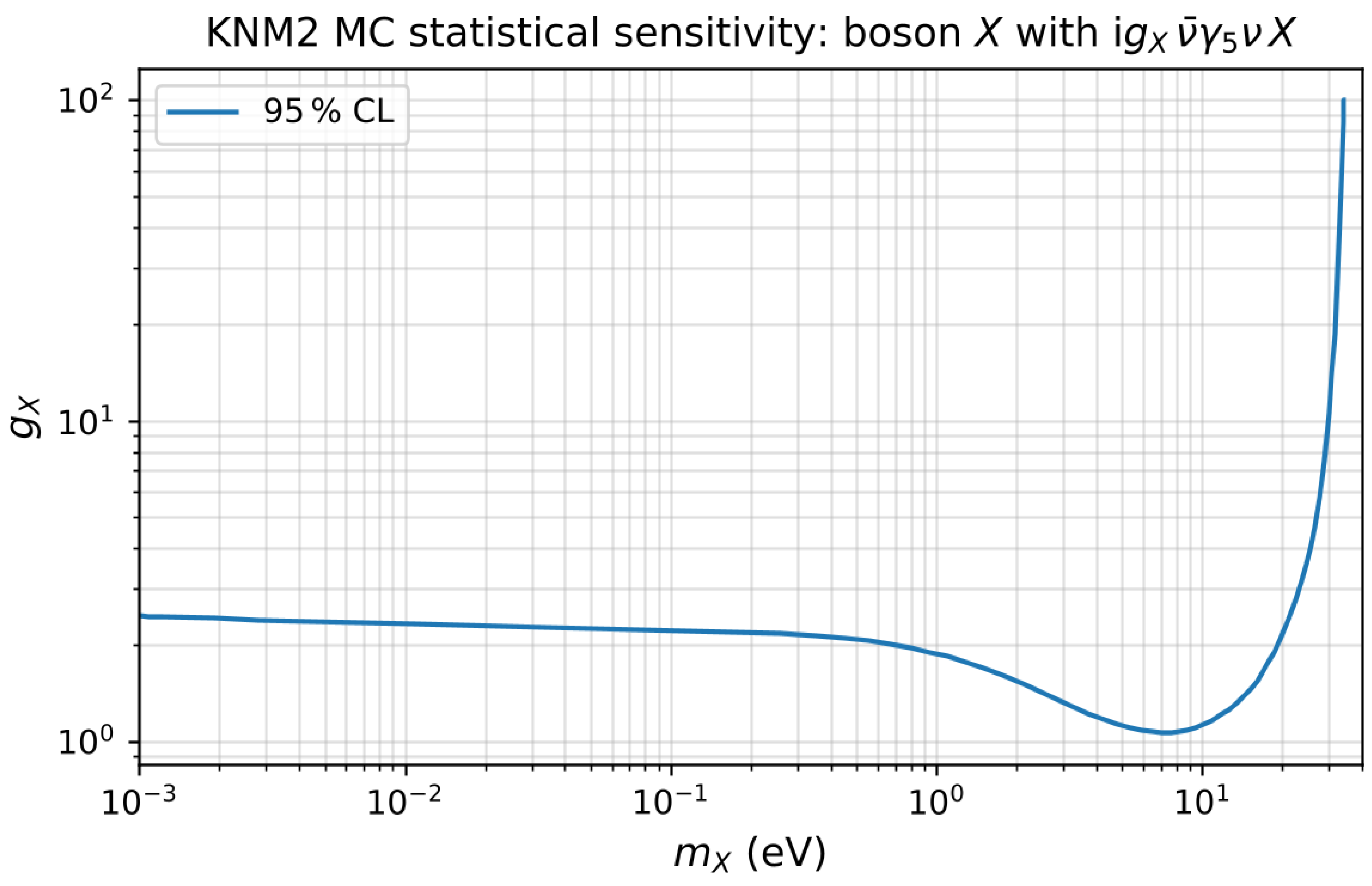
- 30×30 fixed grid points in m_X-g_X-plane
  → 900 fits
- Fixed $m_\nu^2 = 0$
- Free $E_0,\ A_{\mathrm{Sig}},\ R_{\mathrm{Bg}}$
- 95% CL contour at $\chi^2_{\mathrm{crit}} = \chi^2_{\mathrm{BF}} + \Delta\chi^2$ with $\Delta\chi^2 = 5.99$ for 2 DOF

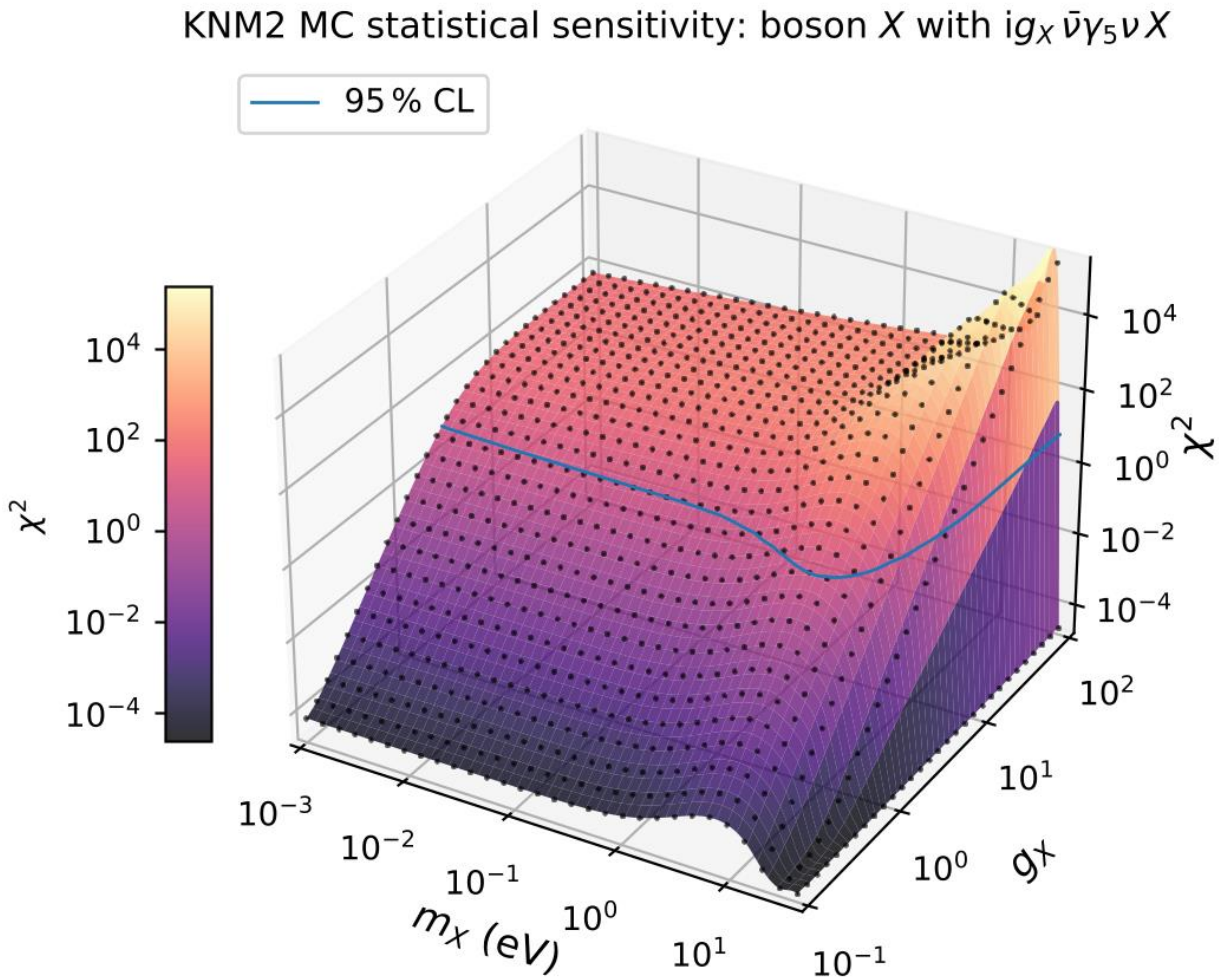
S. Hickford (2023)



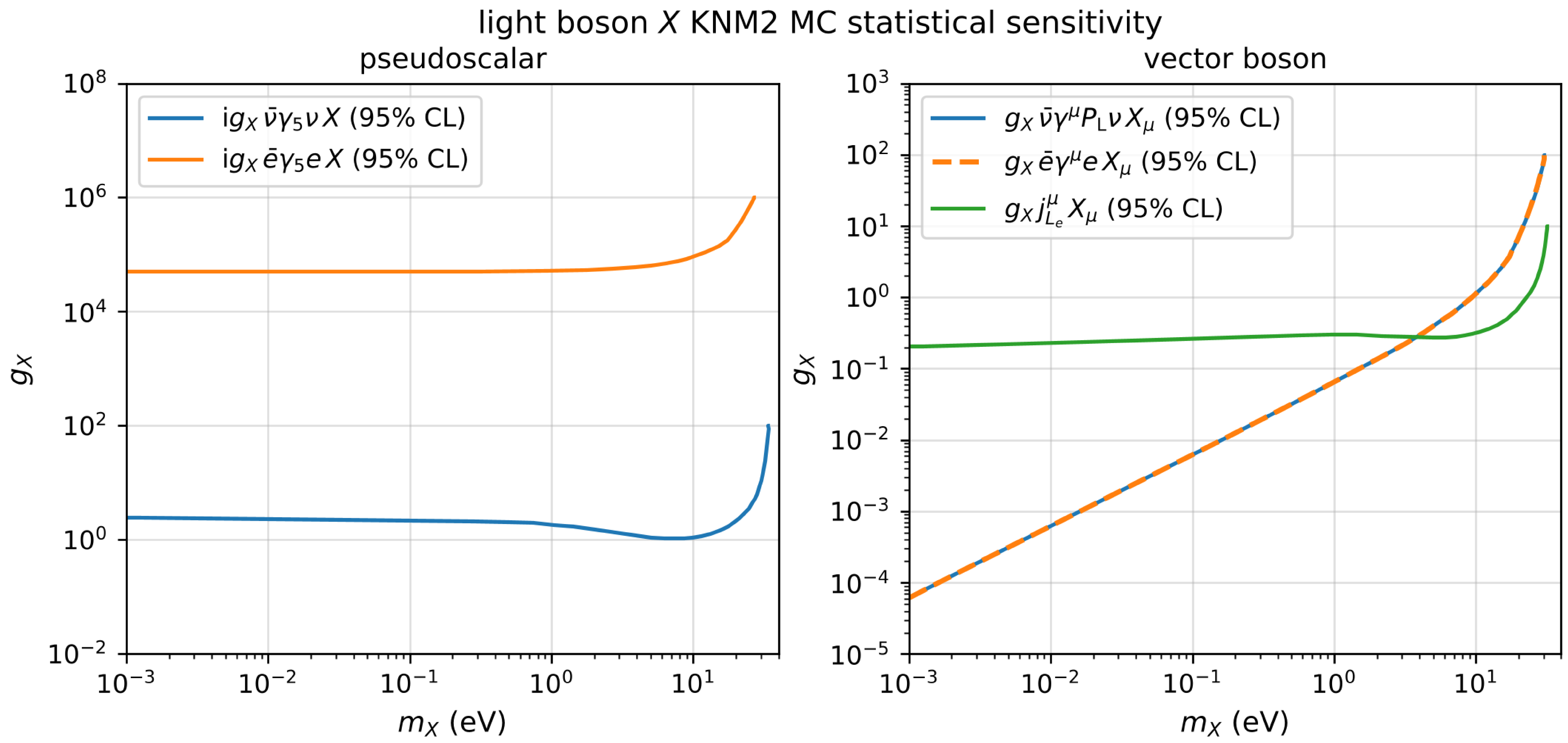
Sensitivity estimation

- Example: pseudoscalar emission from neutrino
- Best fit at $\chi^2_{\mathrm{BF}}/\mathrm{DOF} = 2.46 \times 10^{-5}/2$
- 3d interpolation for 95% CL contour

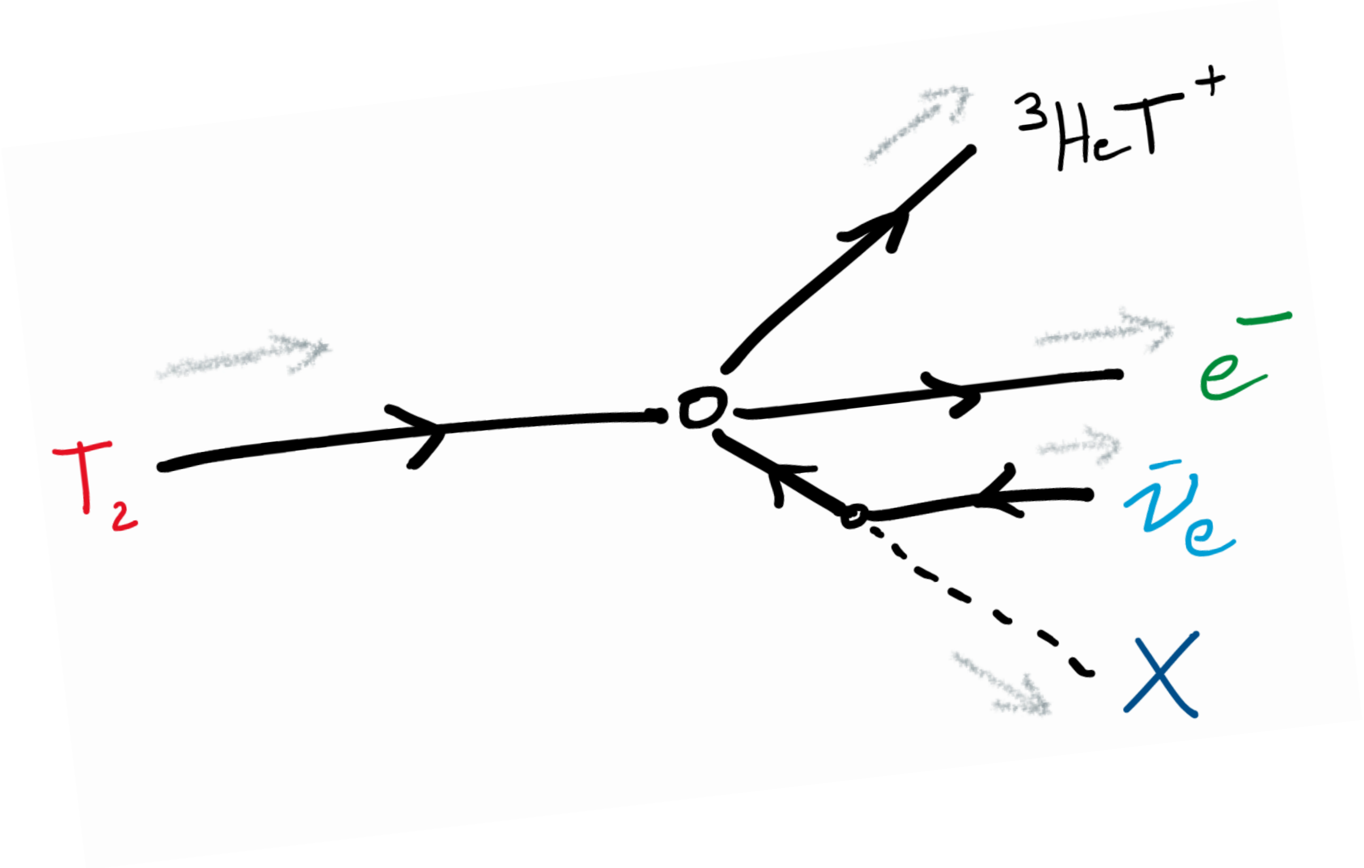




Light boson statistical sensitivities



Summary and outlook



- Statistical sensitivity for light BSM boson couplings is obtained
- KATRIN serves as a complementary laboratory probe in this field

- The systematic uncertainties will also be included as next step
- Application to measured data after testing thoroughly on MC and fixing of procedure

Acknowledgements

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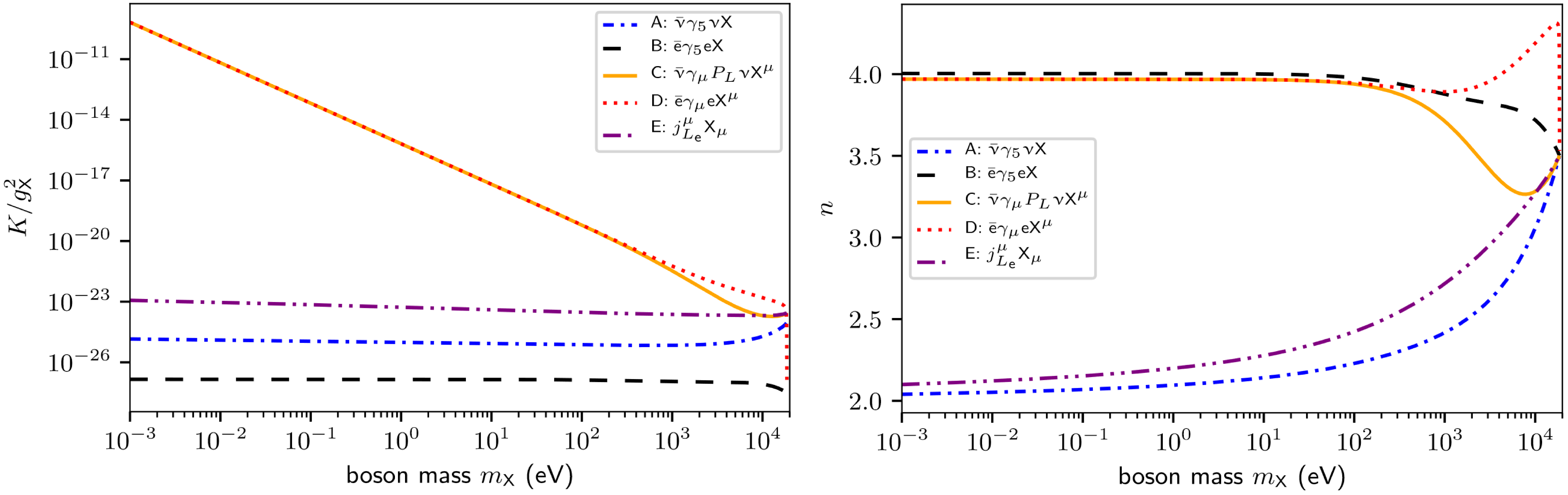
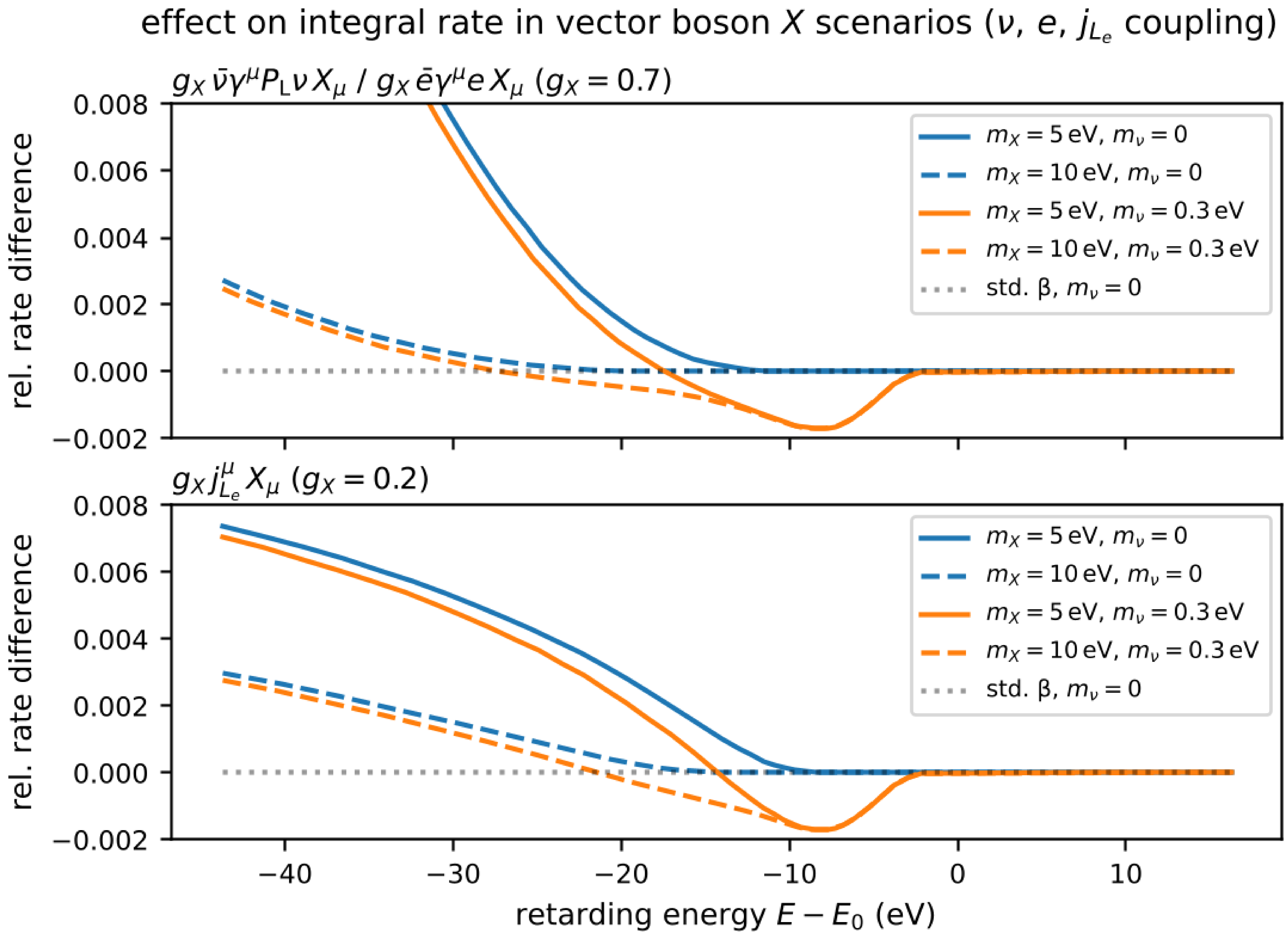
Backup

Boson branch: spectral parameters

Arcadi et al. JHEP01 (2019) 206

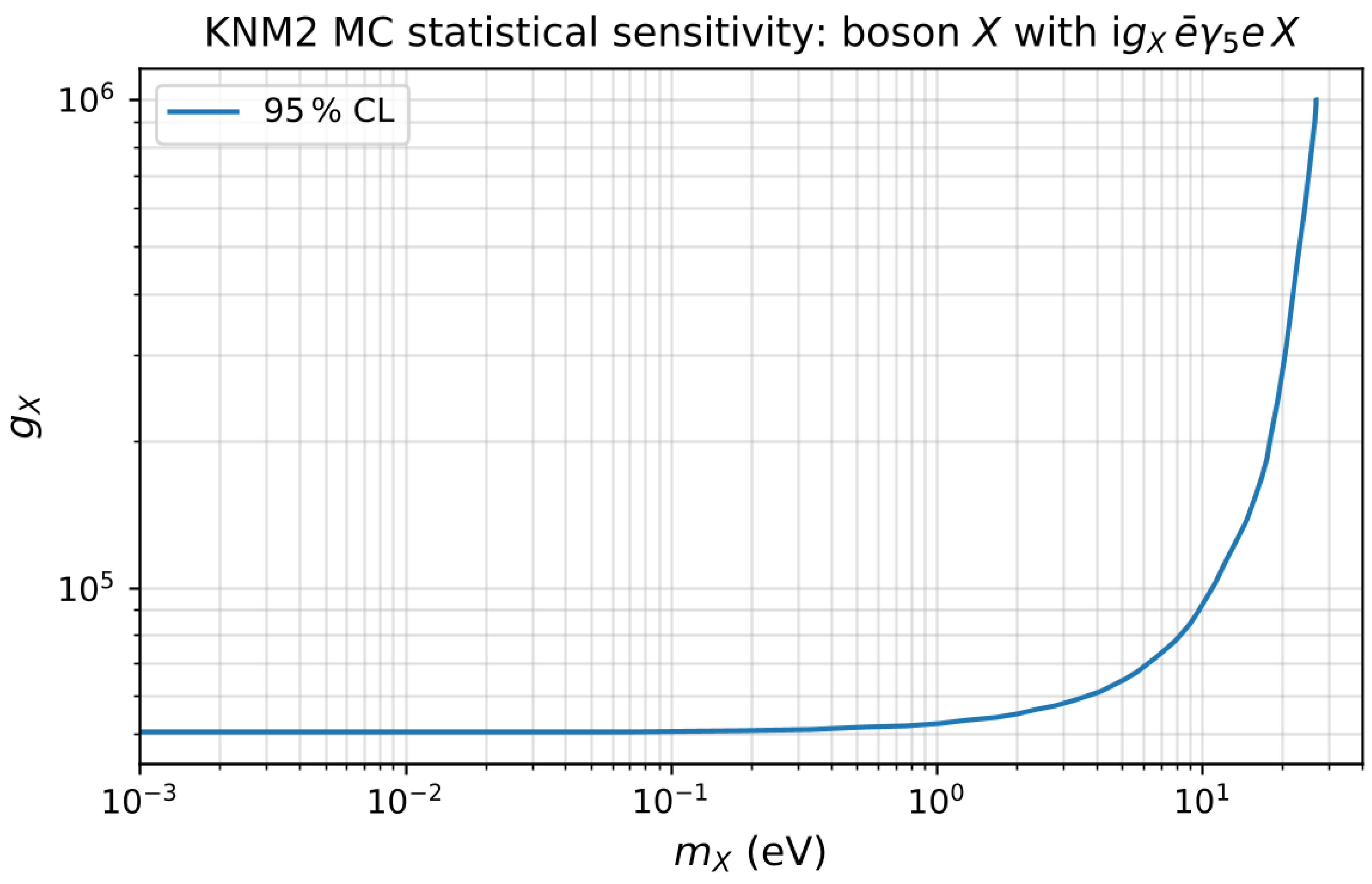


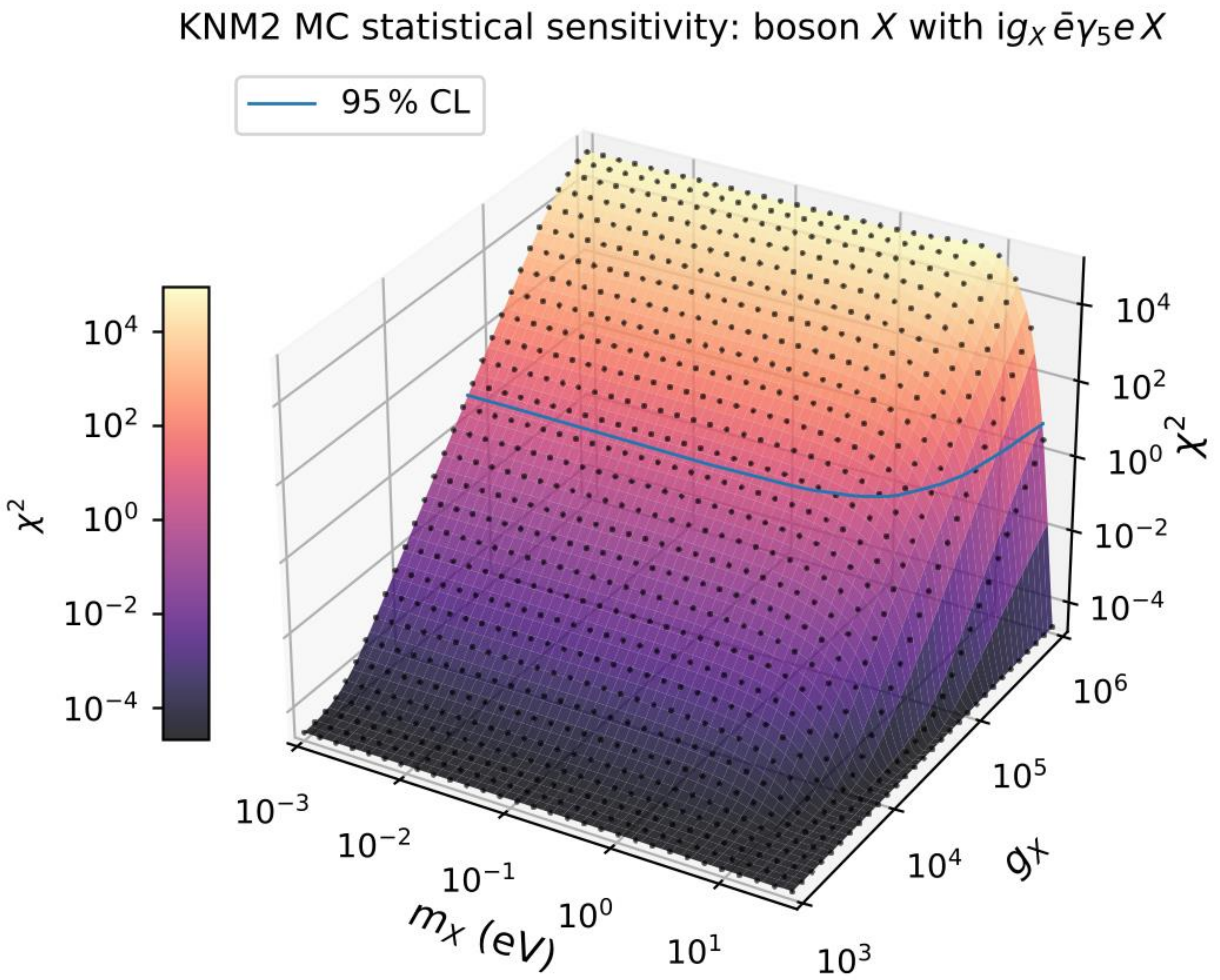
β-decay with additional boson emission



Sensitivity estimation

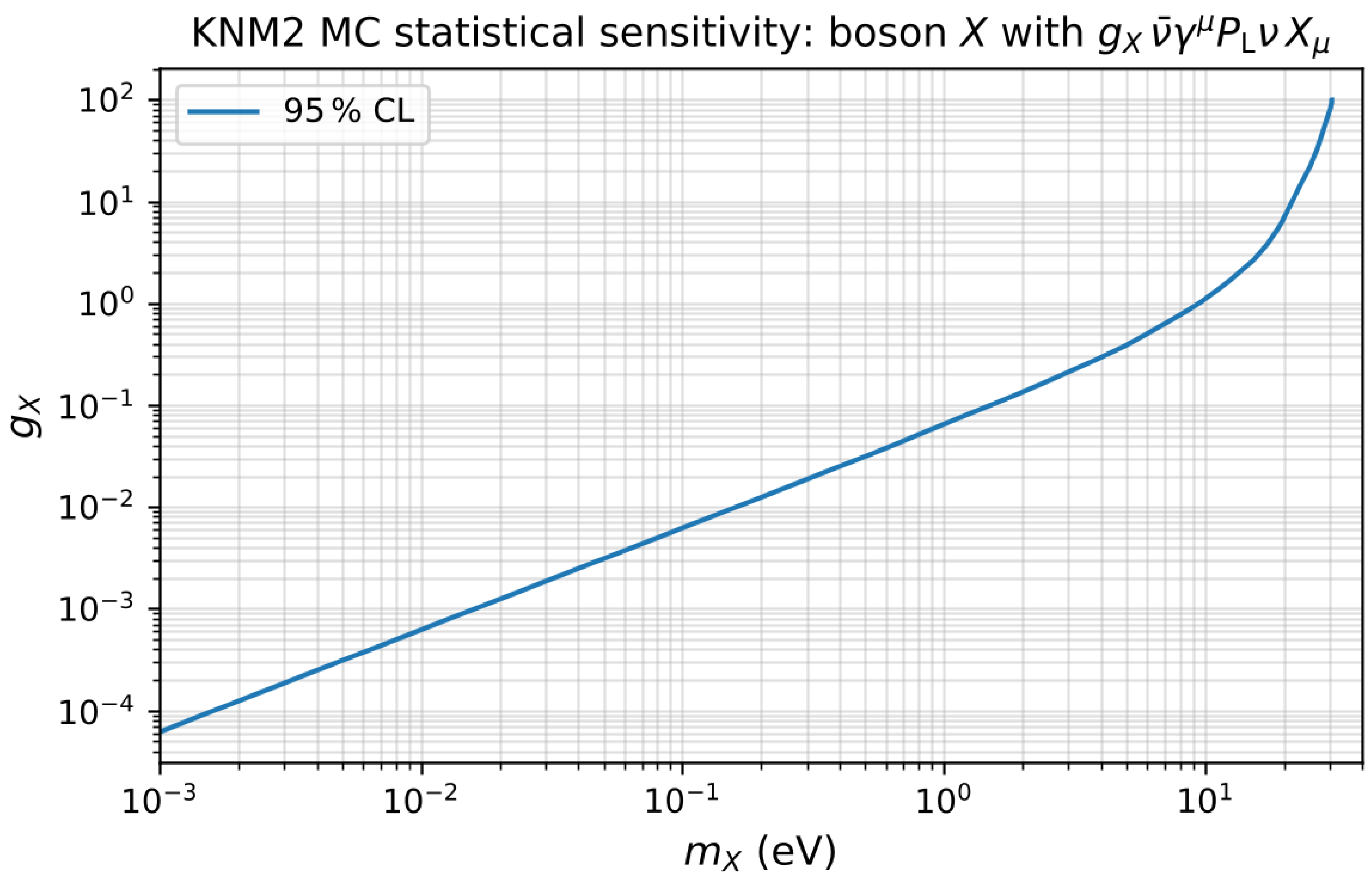
- Pseudoscalar emission from electron
- Best fit at $\chi^2_{\mathrm{BF}}/\mathrm{DOF} = 2.45 \times 10^{-5}/2$

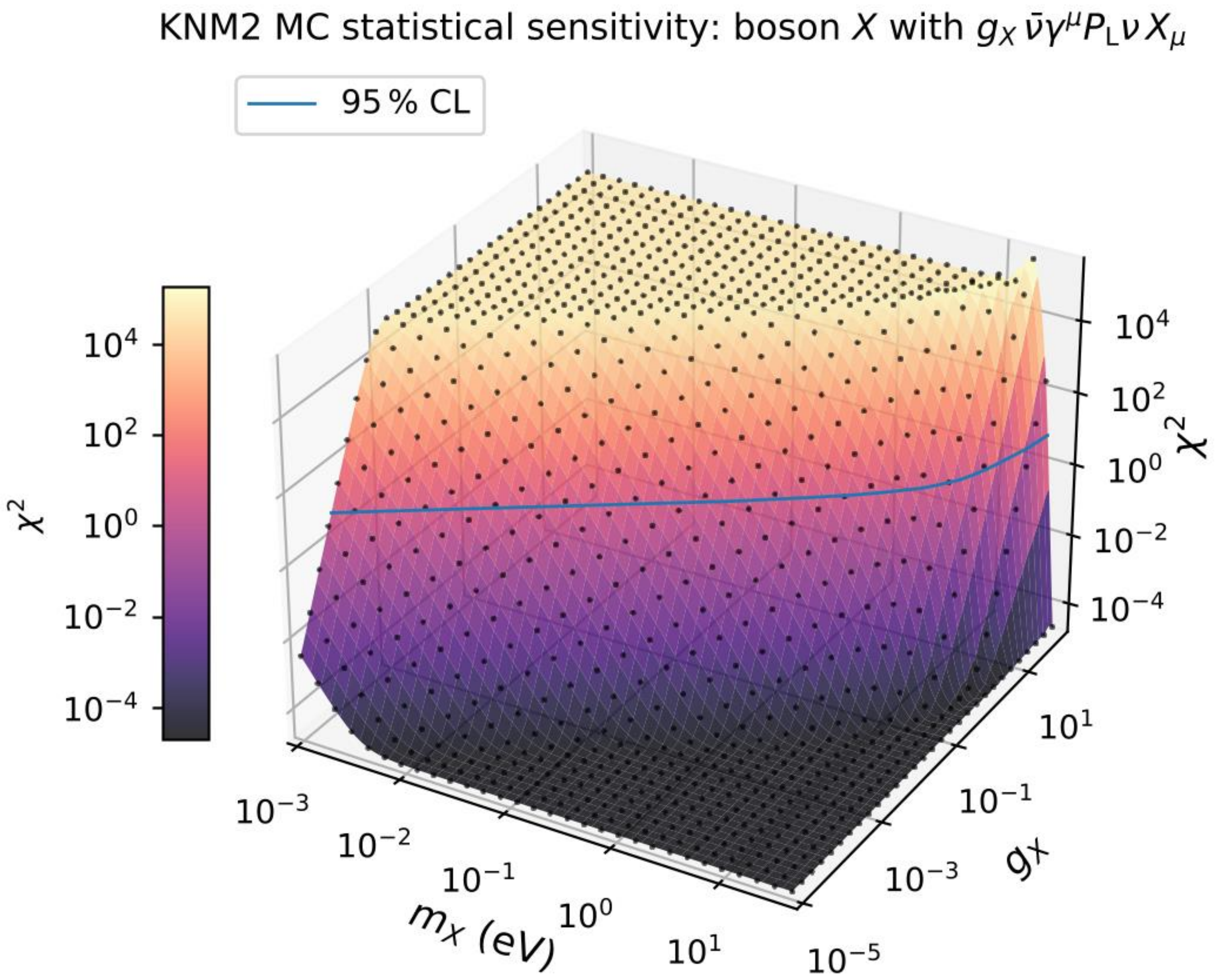




Sensitivity estimation

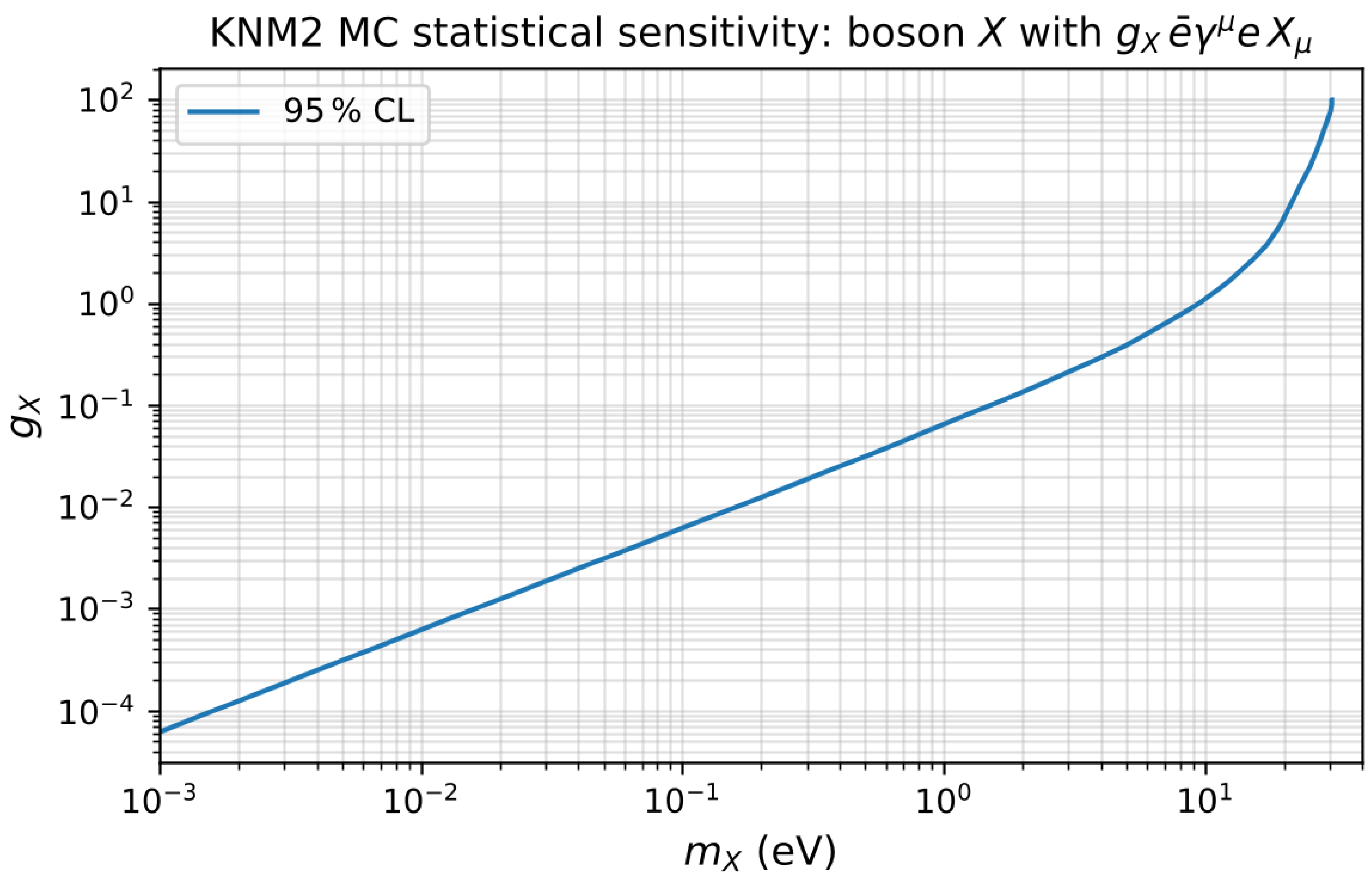
- Vector boson emission from neutrino
- Best fit at $\chi^2_{\mathrm{BF}}/\mathrm{DOF} = 2.46 \times 10^{-5}/2$

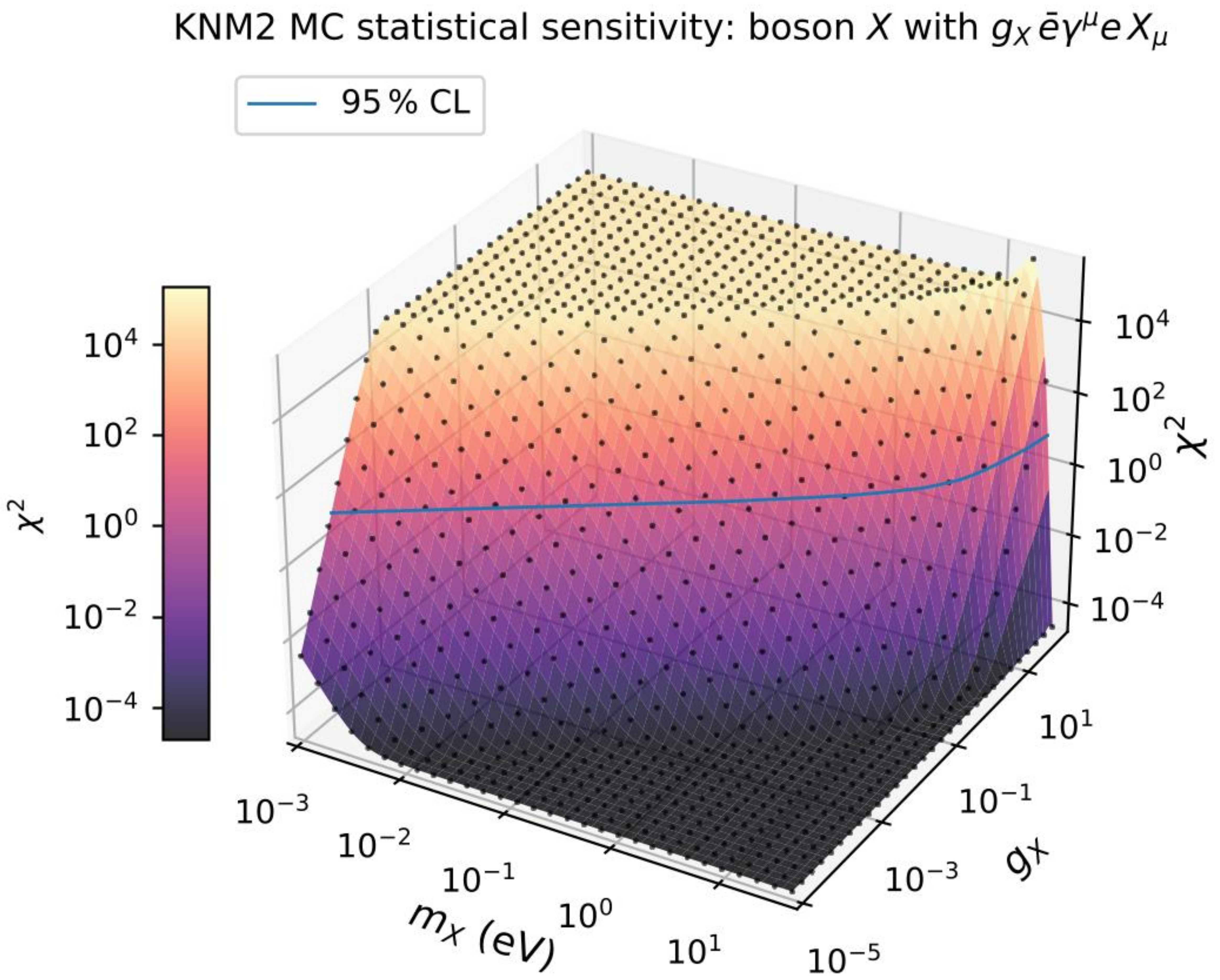




Sensitivity estimation

- Vector boson emission from electron
- Best fit at $\chi^2_{\mathrm{BF}}/\mathrm{DOF} = 2.46 \times 10^{-5}/2$





Sensitivity estimation

- Vector boson emission from neutrino and electron
- Best fit at $\chi^2_{\mathrm{BF}}/\mathrm{DOF} = 2.46 \times 10^{-5}/2$