Exploring β-decay with light boson emission in the KATRIN experiment

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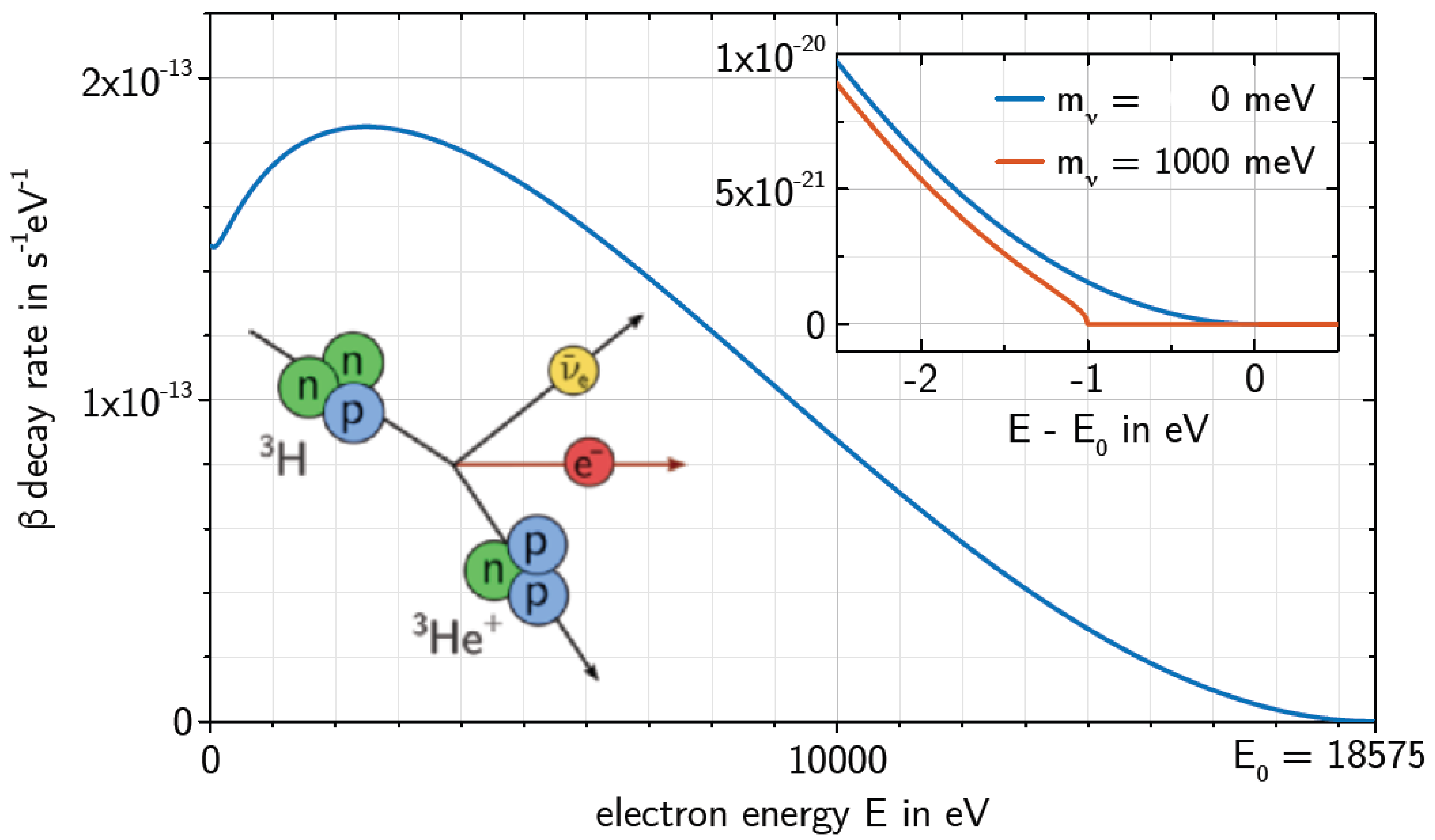
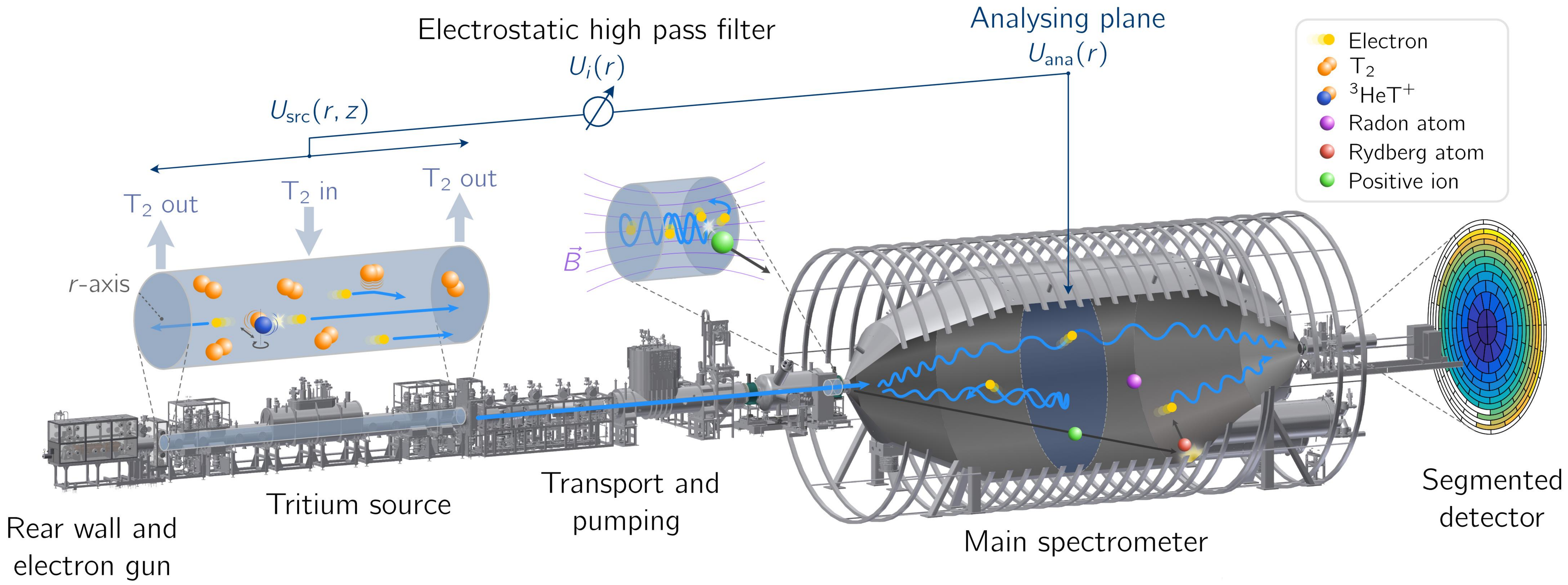
The KATRIN experiment

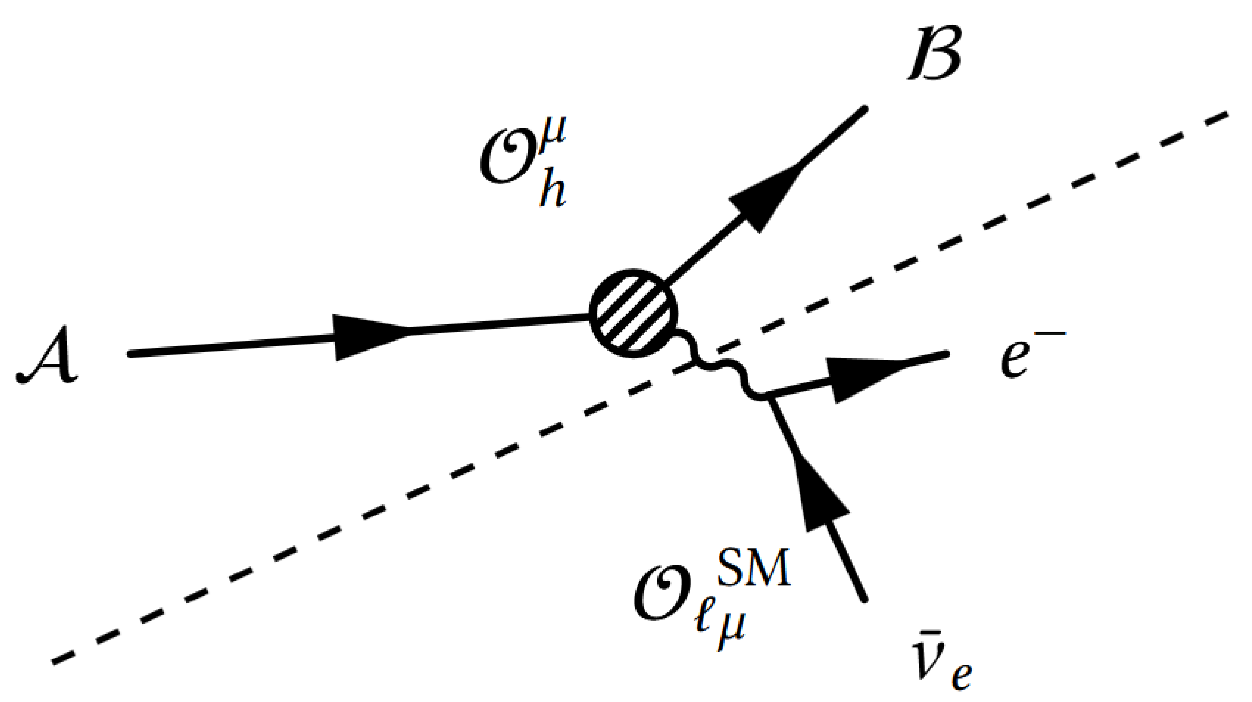
- Observable: effective electron antineutrino mass $\boldsymbol{m_\nu^2 = \sum_i |U_{ei}|^2 m_i^2}$
- Kinematic approach: electron energy spectrum of **tritium β-decay**





Standard Model β-decay of tritium

$$\mathcal{A} \to \mathcal{B} + e^- + \bar{\nu}_e$$

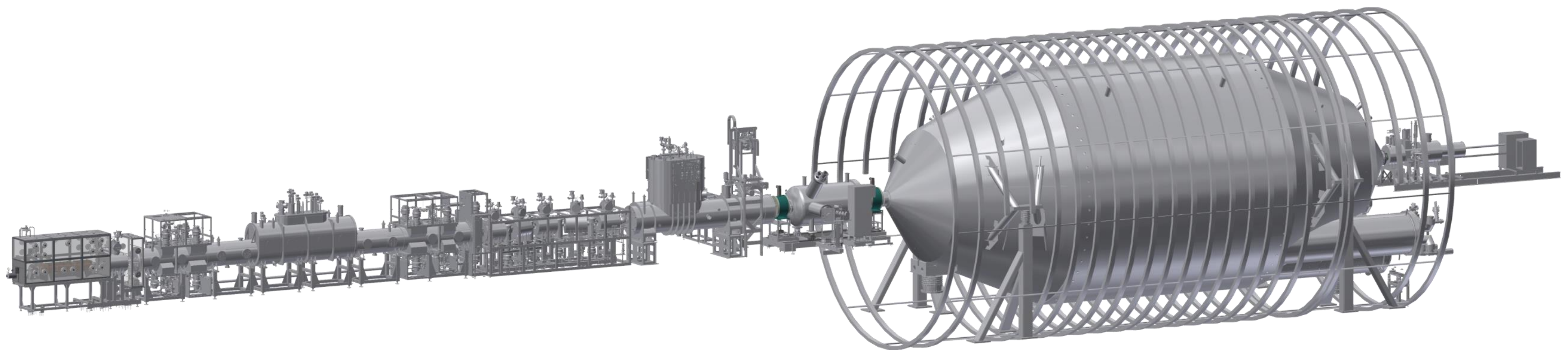


- Fermi's golden rule (decay rate): $\mathrm{d}\Gamma = \frac{(2\pi)^4}{2m_\mathcal{A}} \overline{|\mathcal{M}|^2}\, \mathrm{d}\Phi$

$$\mathcal{M} = -\frac{G_\mathrm{F}}{\sqrt{2}} (\bar{\mathcal{B}} \mathcal{O}_h^\mu \mathcal{A})(\bar{e} \mathcal{O}_{\ell_\mu} \nu)$$

- Differential spectrum $\frac{\mathrm{d}\Gamma_\beta}{\mathrm{d}E}(E, \boldsymbol{m_\nu^2}) = C \cdot (E + m_e) \cdot p_e \cdot E_\nu \cdot \sqrt{(E_0 - E)^2 - \boldsymbol{m_\nu^2}} \cdot \mathrm{Corr}(E)$

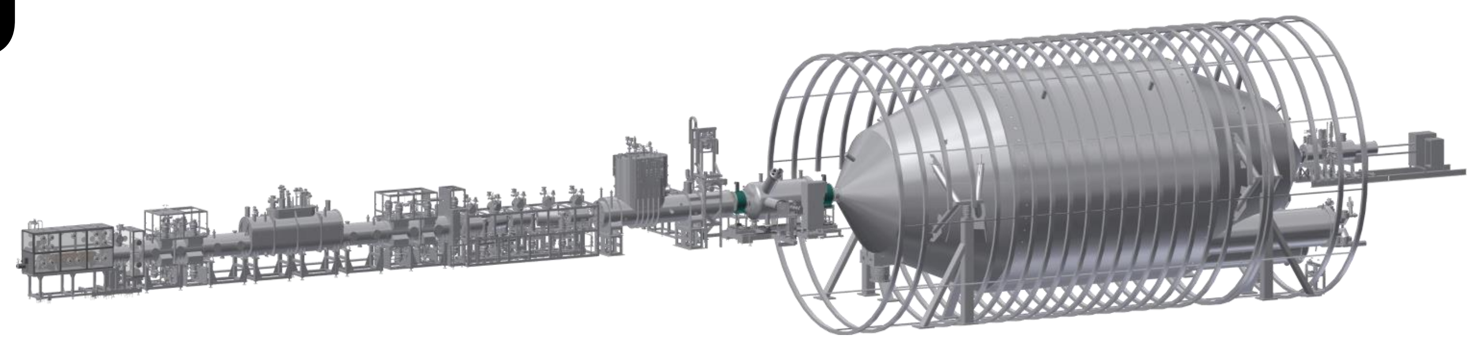
- Energy scale: tritium *Q*-value ~ $\boldsymbol{E_0}$ **≈ 18.6 keV** (kinematic limit)



→ Measurement of **integrated spectrum** beyond set retarding potential U_{ret}

Inferring the neutrino mass – spectrum fitting

$\mathcal{A} \rightarrow \mathcal{B} + e^{-} + \bar{\nu}_e$

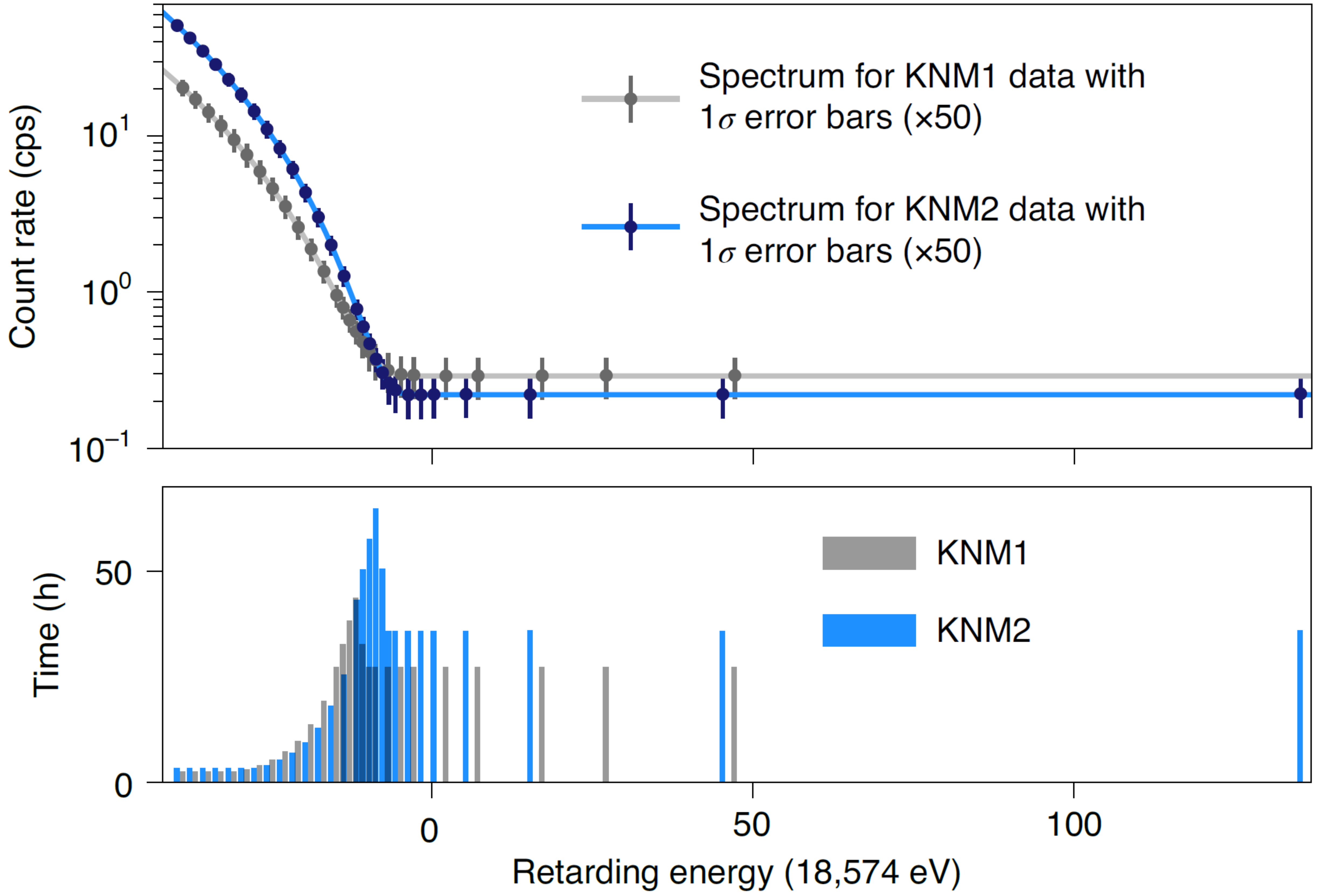


- **C++**-based analysis framework *KaFit*
- Precise model evaluation, Gauss-Legendre integration
- $R(qU_{ret}) = A_{\text{Sig}} \int_{qU}^{E_0} f(E - qU_{ret}) \frac{\mathrm{d}\Gamma_\beta}{\mathrm{d}E}(E, m_\nu^2)\, \mathrm{d}E + R_{\text{Bg}}$
- Four free fit parameters:
  - Neutrino mass m_ν^2
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

→ $m_\nu < 0.45$ eV (90% CL)

KATRIN Collaboration (2024): 2406.13516

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



Beyond the SM: emission of new light boson

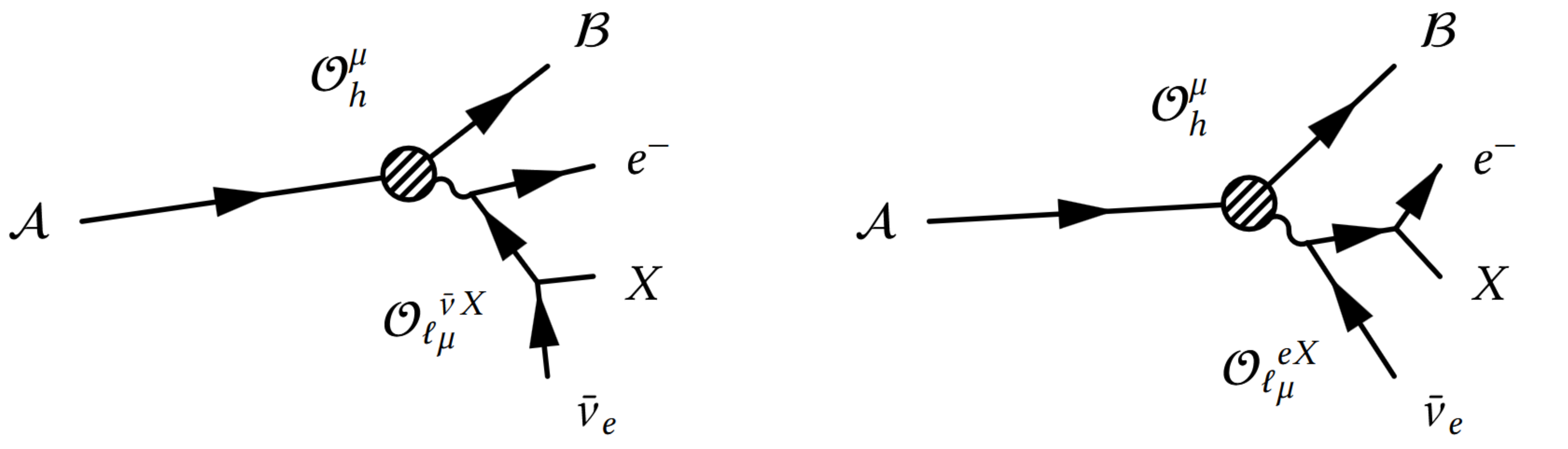
$$\mathcal{A} \to \mathcal{B} + e^- + \bar{\nu}_e + X$$

- Beyond SM (BSM) theories: new particles (light boson *X*), interacting with the final state leptons

$$\mathrm{i}g\bar{\nu}_e\gamma_5\nu_e X,\ \mathrm{i}g\bar{e}\gamma_5 eX, \quad \text{or} \quad g\bar{\nu}_e\gamma^\mu P_\mathrm{L}\nu_e X_\mu,\ g\bar{e}\gamma^\mu eX_\mu,\ gj^\mu_{L_e}X_\mu$$

ref. *Arcadi et al.:*

JHEP01(2019)206



(a) boson X coupling to the neutrino $\bar{\nu}$ (b) boson X coupling to the electron e^-

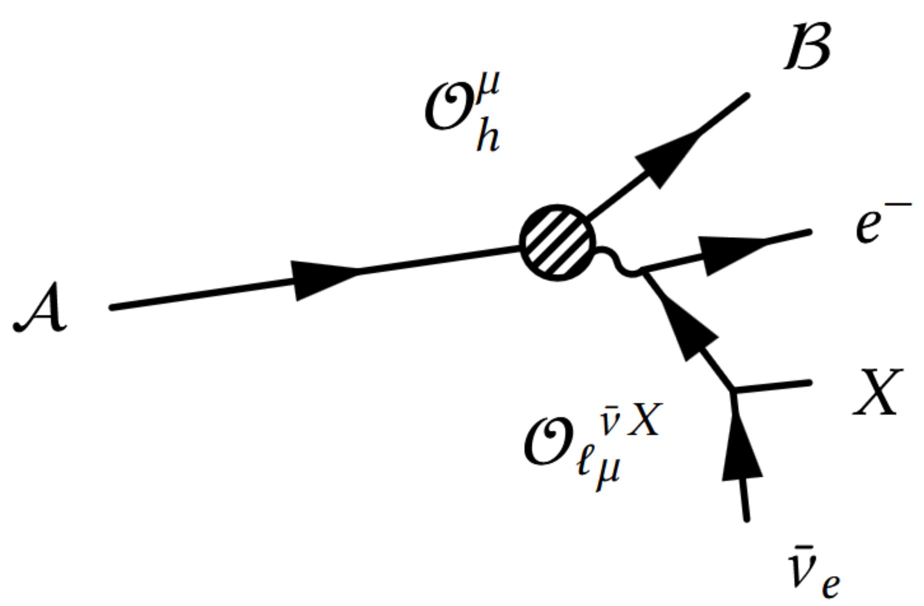
→ Consequence: spectral modification due to emission of the additional real particle *X*

1. *dynamics*: special coupling structures, virtual intermediate leptons
2. *kinematics*: shifted endpoint, four-body final state

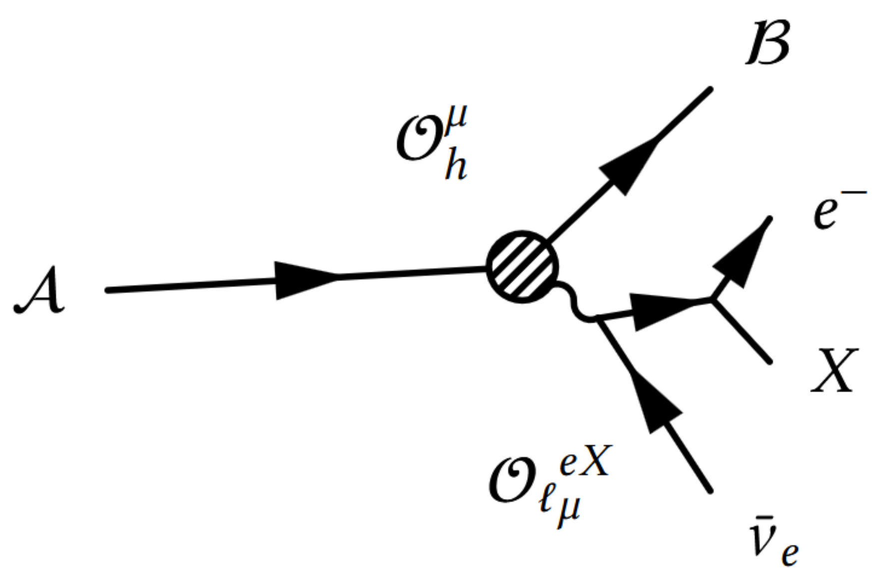
$$\mathrm{d}\Gamma = \frac{(2\pi)^4}{2m_\mathcal{A}}\overline{|\mathcal{M}|^2}\,\mathrm{d}\Phi$$

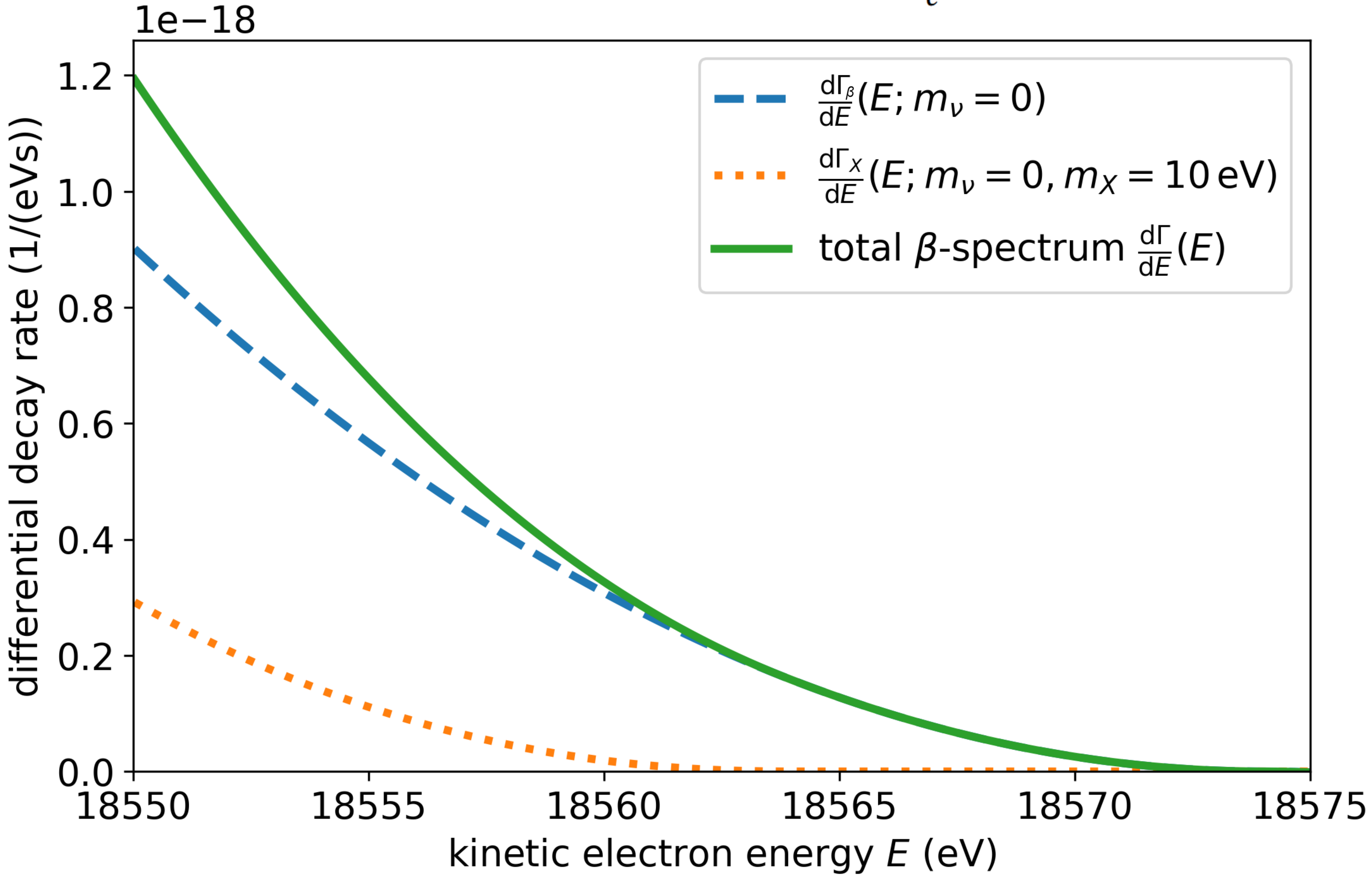
Spectral modifications with light bosons

→ Additional decay channdel $\mathrm{d}\Gamma_{fX}$: $\frac{\mathrm{d}\Gamma}{\mathrm{d}E_e} = \frac{\mathrm{d}\Gamma_\beta}{\mathrm{d}E_e} + \frac{\mathrm{d}\Gamma_{fX}}{\mathrm{d}E_e} \geq \frac{\mathrm{d}\Gamma_\beta}{\mathrm{d}E_e}$



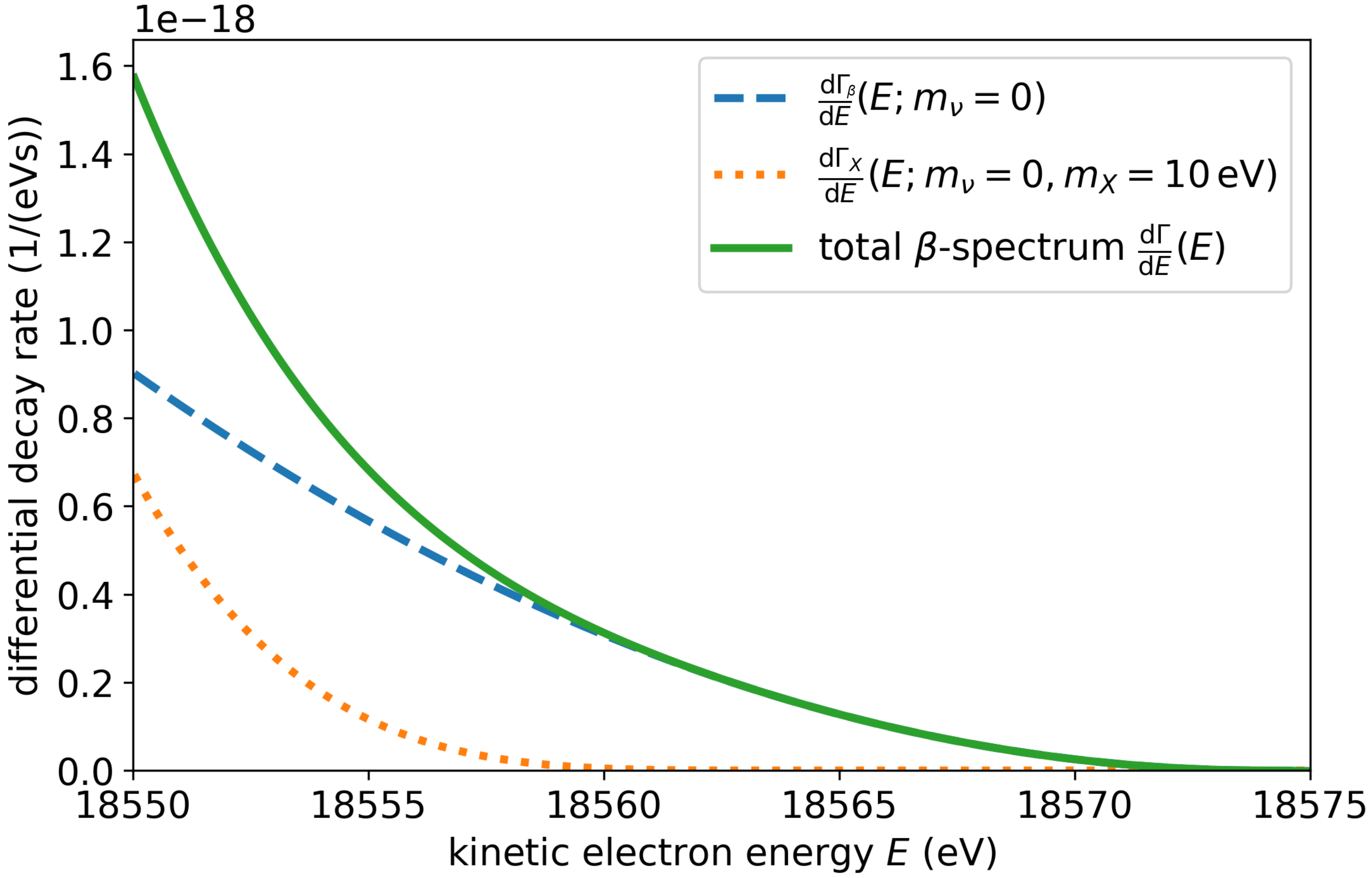
Example scenarios:
pseudoscalar couplings
$\mathcal{L} \supset \mathrm{i}g_X\bar{\nu}\gamma_5\nu X,\ \mathrm{i}g_X\bar{e}\gamma_5 eX$





tree-level process:
$\Gamma \propto g_X^2$ 💡

→ two parameters:
m_X and g_X



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Search for light bosons with KATRIN

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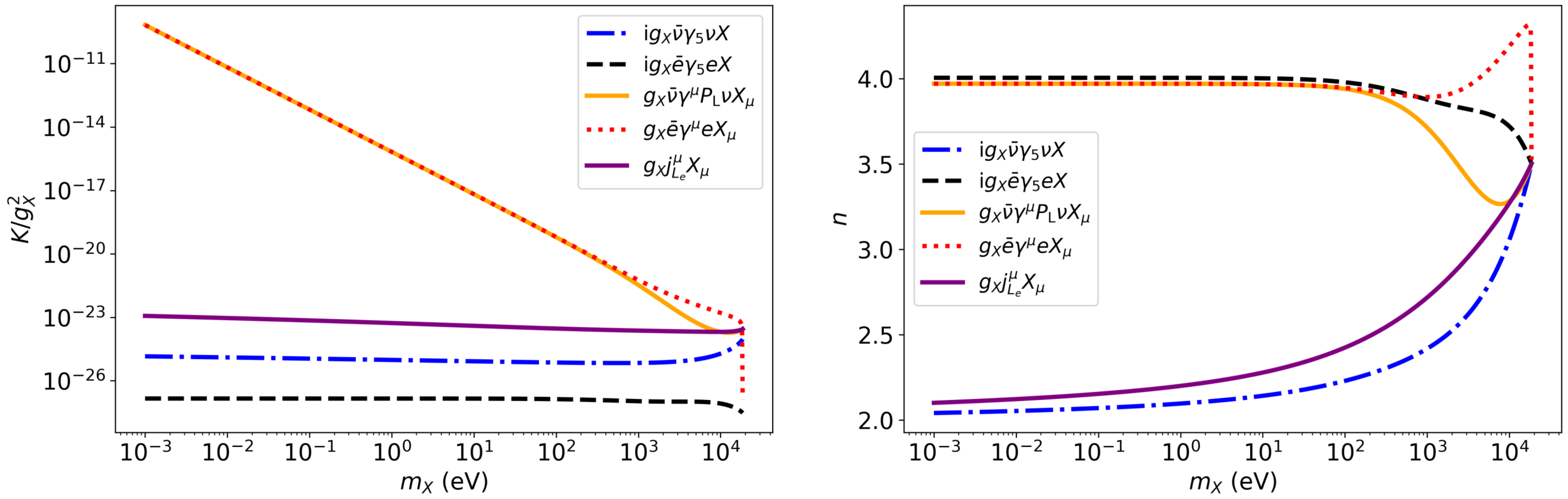


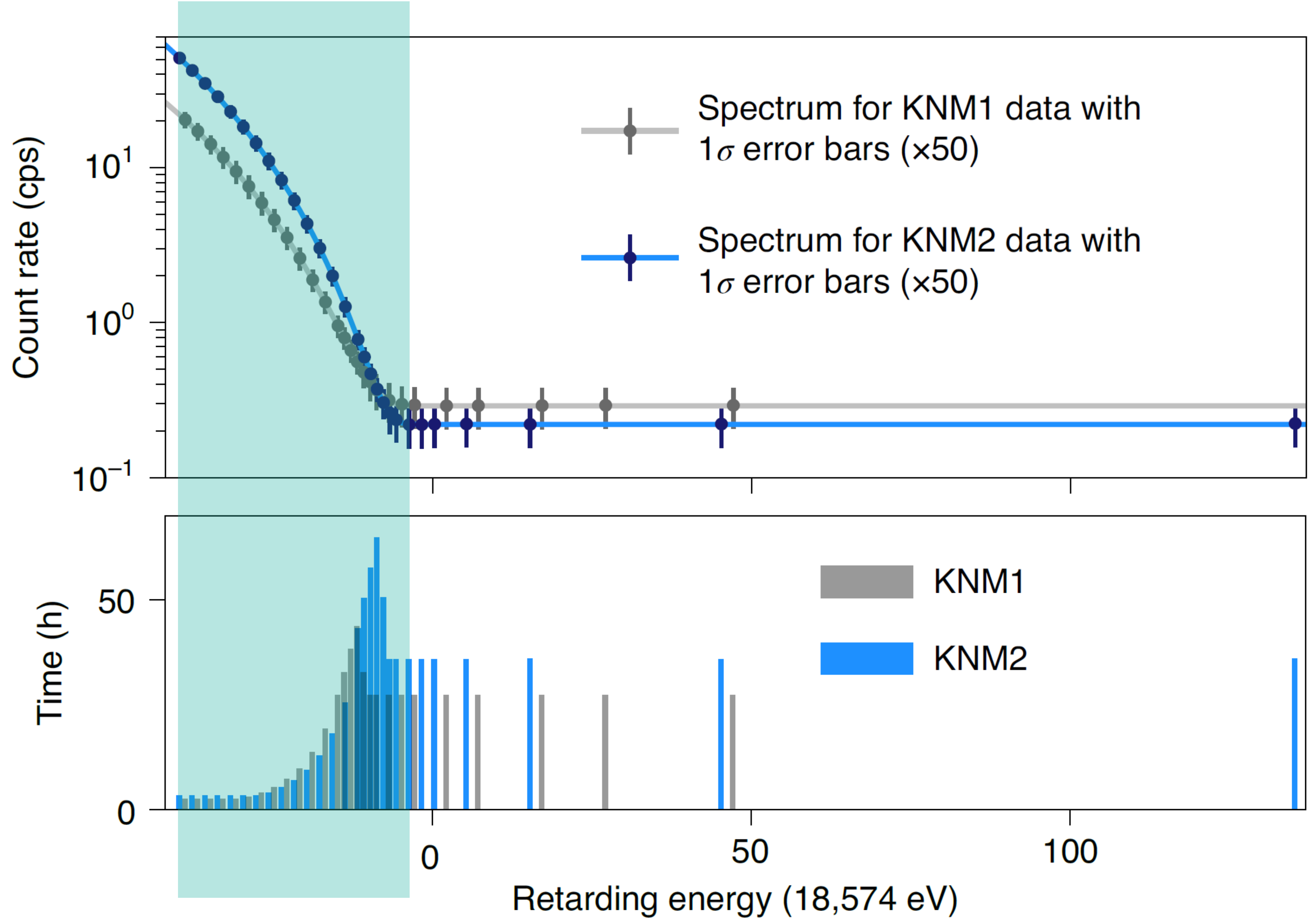
- No general analytic expression for the (differential) rate exists

→ Empirical parametrization by Julian Heeck:

$$\frac{\mathrm{d}\Gamma}{\mathrm{d}E} = K\sqrt{\frac{E}{m_e}}\left(\frac{E_{\max}-E}{E_{\max}+m_e}\right)^n$$

- Semi-analytic approach for evaluation at certain energies E (with $m_\nu = 0$) → fit of K, n

- Analysis procedure for KATRIN: **likelihood scan** over parameter grid in $(\boldsymbol{m_X}, \boldsymbol{g_X})$

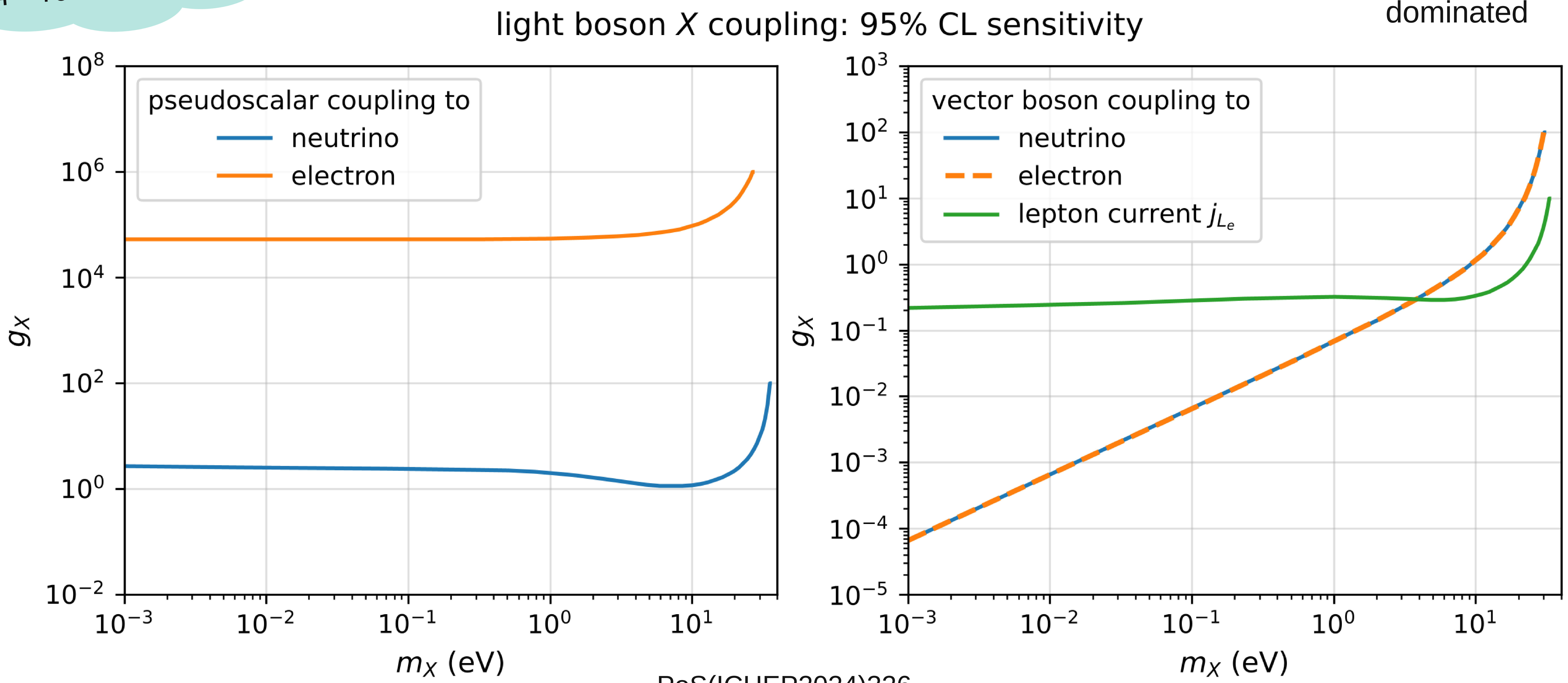


→ current KATRIN: masses $\boldsymbol{m_X} \lesssim$ **40 eV**

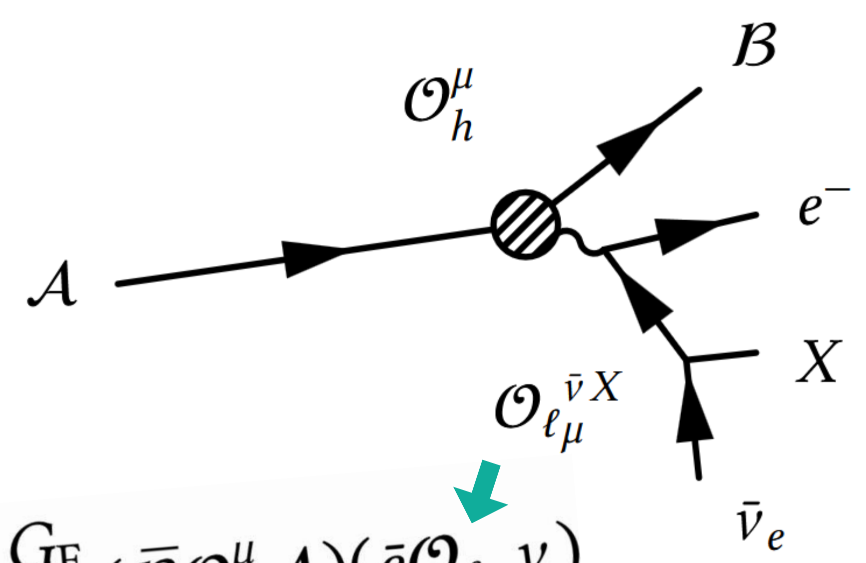
Reference-based light boson *sensitivity* of KATRIN ($m_\nu = 0$)

2nd science run:
4×10^6 electrons

statistics dominated



Exact derivation of the spectra



$$\mathcal{M} = -\frac{G_F}{\sqrt{2}}(\bar{\mathcal{B}}\mathcal{O}_h^\mu \mathcal{A})(\bar{e}\mathcal{O}_{\ell_\mu}\nu)$$

- **Goal:** extension to explicitly **massive neutrino** ($m_\nu \neq 0$, as opposed to reference)

→ calculation of the spectra from first principle (tree-level): $\mathrm{d}\Gamma = \frac{(2\pi)^4}{2m_{\mathcal{A}}} \overline{|\mathcal{M}|^2}\, \mathrm{d}\Phi$

Dynamics:

- *Mathematica* with package *FeynCalc* is used to perform the operations for $\overline{|\mathcal{M}|^2} = \overline{\sum} |\mathcal{M}|^2 = \frac{1}{2}\sum_{\text{spins}} |\mathcal{M}|^2$

Kinematics:

- Parmaterization: 5 independent many-particle mass-squares $M_{i\ldots j}^2 = \left(\sum_{k=i\ldots j} p_k\right)^2 = (E_i + \ldots + E_j)^2 - (\vec{p}_i + \ldots + \vec{p}_j)^2$

$$\frac{\mathrm{d}\Gamma}{\mathrm{d}E_e} = \frac{1}{2^5(2\pi)^6 m_{\mathcal{A}}^2} \int_{M_{12-}^2}^{M_{12+}^2(E_e)} \int_{M_{34-}^2(E_e,M_{12}^2)}^{M_{34+}^2(E_e,M_{12}^2)} \int_{M_{134-}^2(M_{12}^2,M_{34}^2)}^{M_{134+}^2(M_{12}^2,M_{34}^2)} \int_{M_{14-}^2(E_e,M_{12}^2,M_{34}^2,M_{134}^2)}^{M_{14+}^2(E_e,M_{12}^2,M_{34}^2,M_{134}^2)} \frac{\overline{|\mathcal{M}|^2}}{\sqrt{-B}} \mathrm{d}M_{12}^2 \mathrm{d}M_{34}^2 \mathrm{d}M_{134}^2 \mathrm{d}M_{14}^2$$

$$\bar{\nu} \to 1, \quad X \to 2, \quad e \to 3, \quad \mathcal{B} \to 4$$

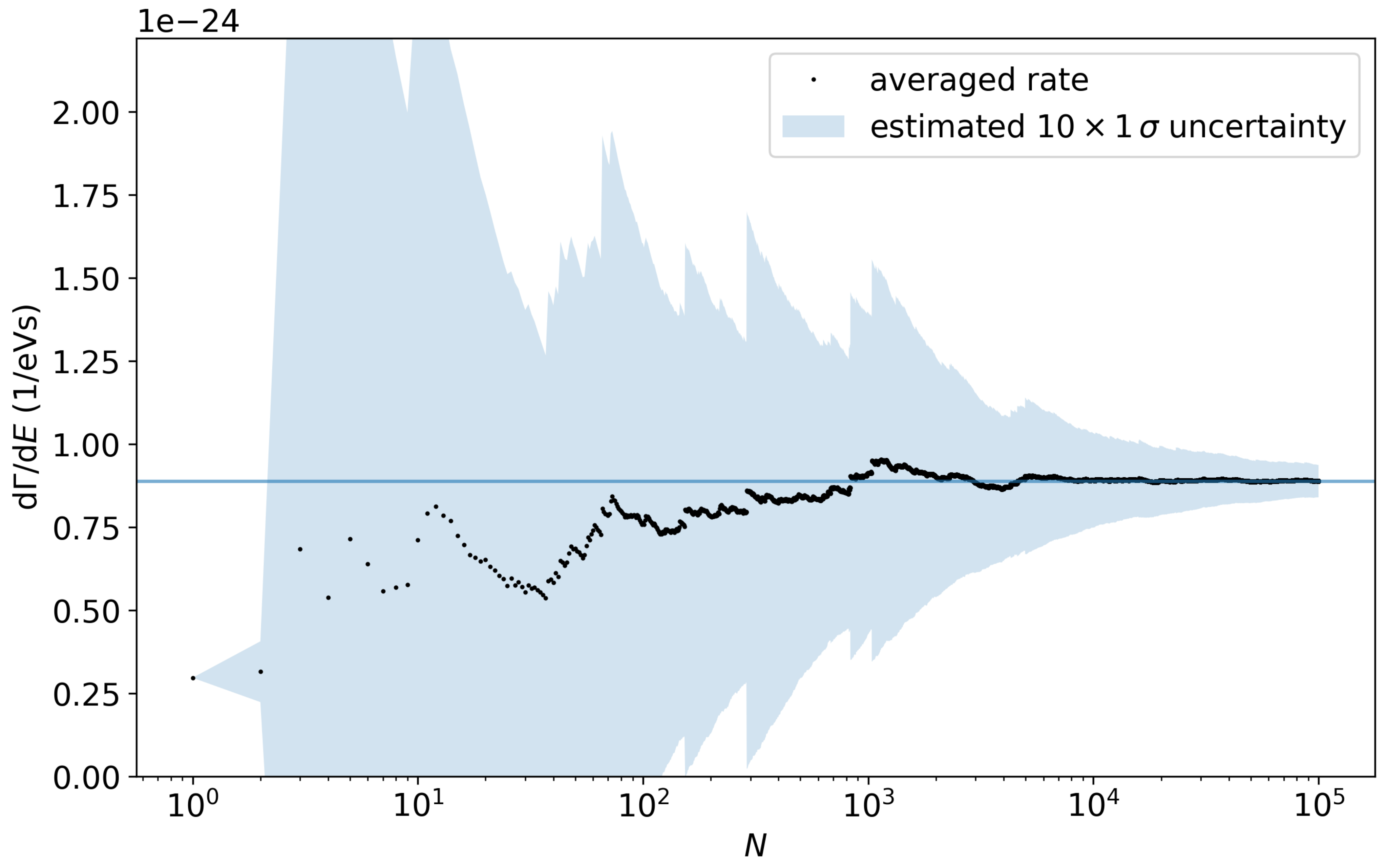
Spectrum calculation – *numerical integration*

$$\frac{\mathrm{d}\Gamma}{\mathrm{d}E_e} = \frac{1}{2^5(2\pi)^6 m_{\mathcal{A}}^2} \int_{M_{12-}^2}^{M_{12+}^2(E_e)} \int_{M_{34-}^2(E_e,M_{12}^2)}^{M_{34+}^2(E_e,M_{12}^2)} \int_{M_{134-}^2(M_{12}^2,M_{34}^2)}^{M_{134+}^2(M_{12}^2,M_{34}^2)} \int_{M_{14-}^2(E_e,M_{12}^2,M_{34}^2,M_{134}^2)}^{M_{14+}^2(E_e,M_{12}^2,M_{34}^2,M_{134}^2)} \frac{\overline{|\mathcal{M}|^2}}{\sqrt{-B}} \mathrm{d}M_{12}^2 \mathrm{d}M_{34}^2 \mathrm{d}M_{134}^2 \mathrm{d}M_{14}^2$$

- No general exact analytic solution for the integral was found
- Highest level of flexibility and modularity: **MC sampling** of entire phase space

  → statistically converging approximation of the integral, uncertainty $\propto 1/\sqrt{N}$

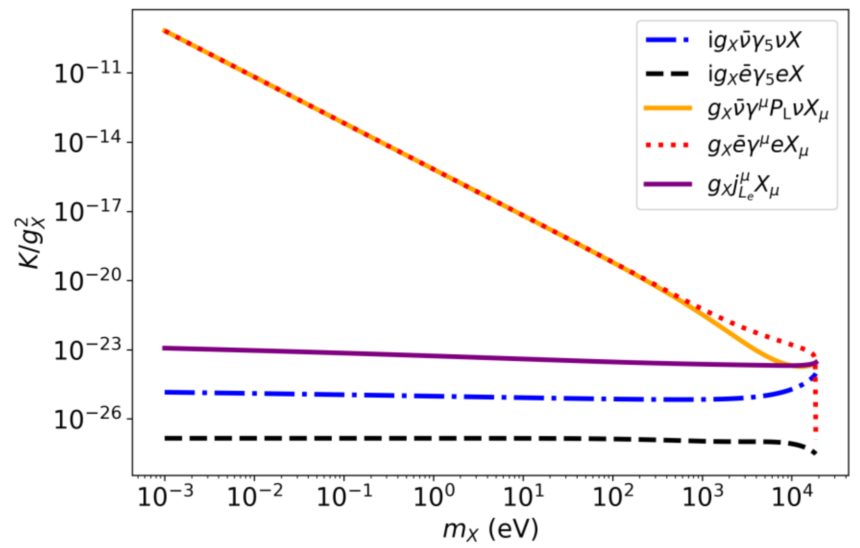
Performance example

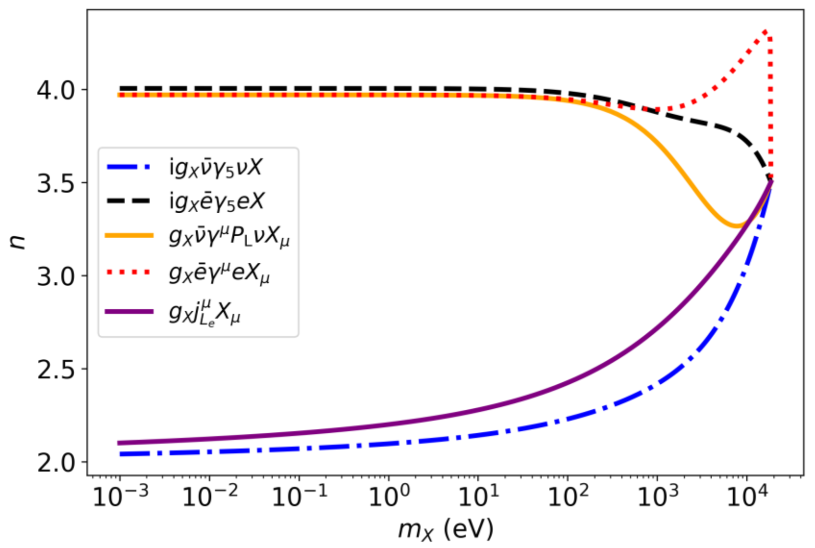


- Computation: **C++** framework with *GNU Multiple Precision Arithmetic Library* (**GMP**) → numerically extremely stable
- **Downside:** expensive computation for precise calculation at *single electron energy* ≠ spectrum

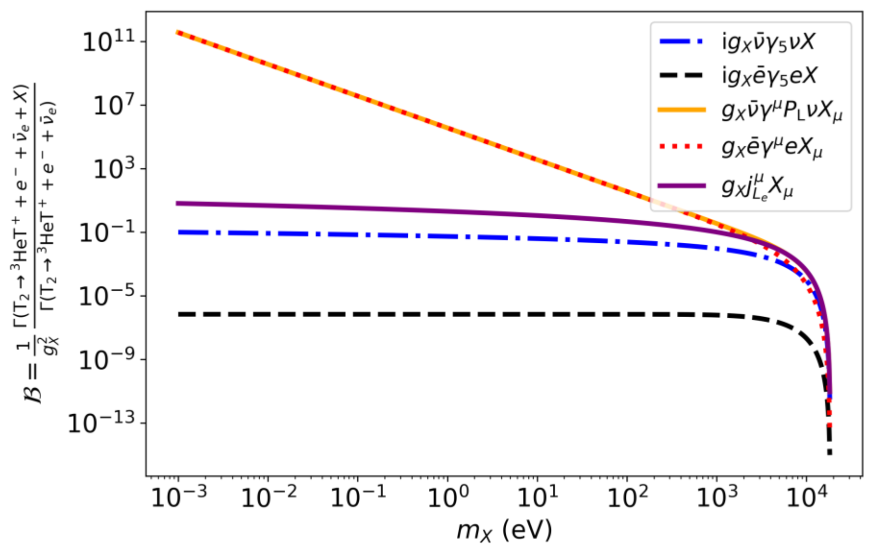
Results – *comparison*

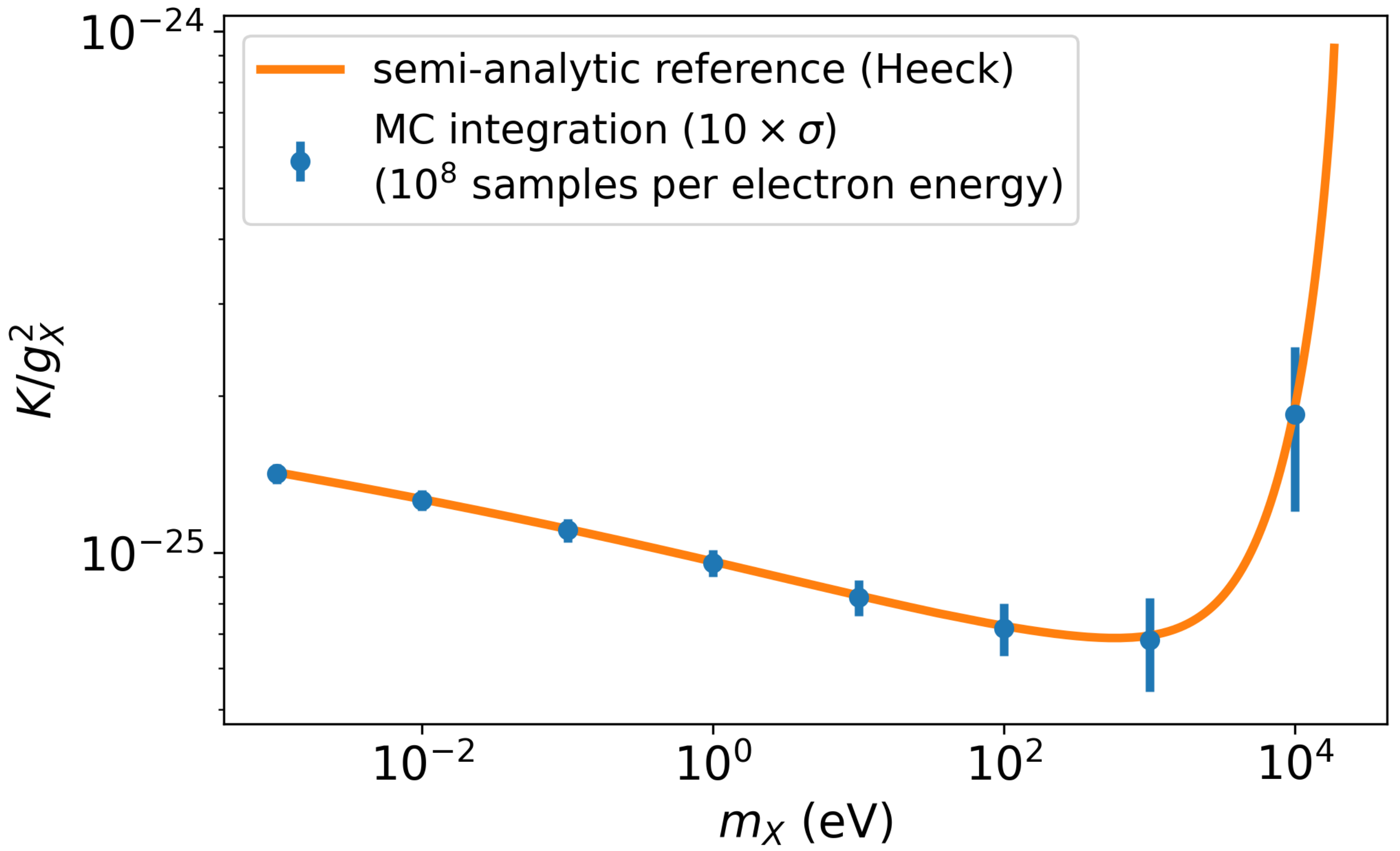
reference JHEP01(2019)206

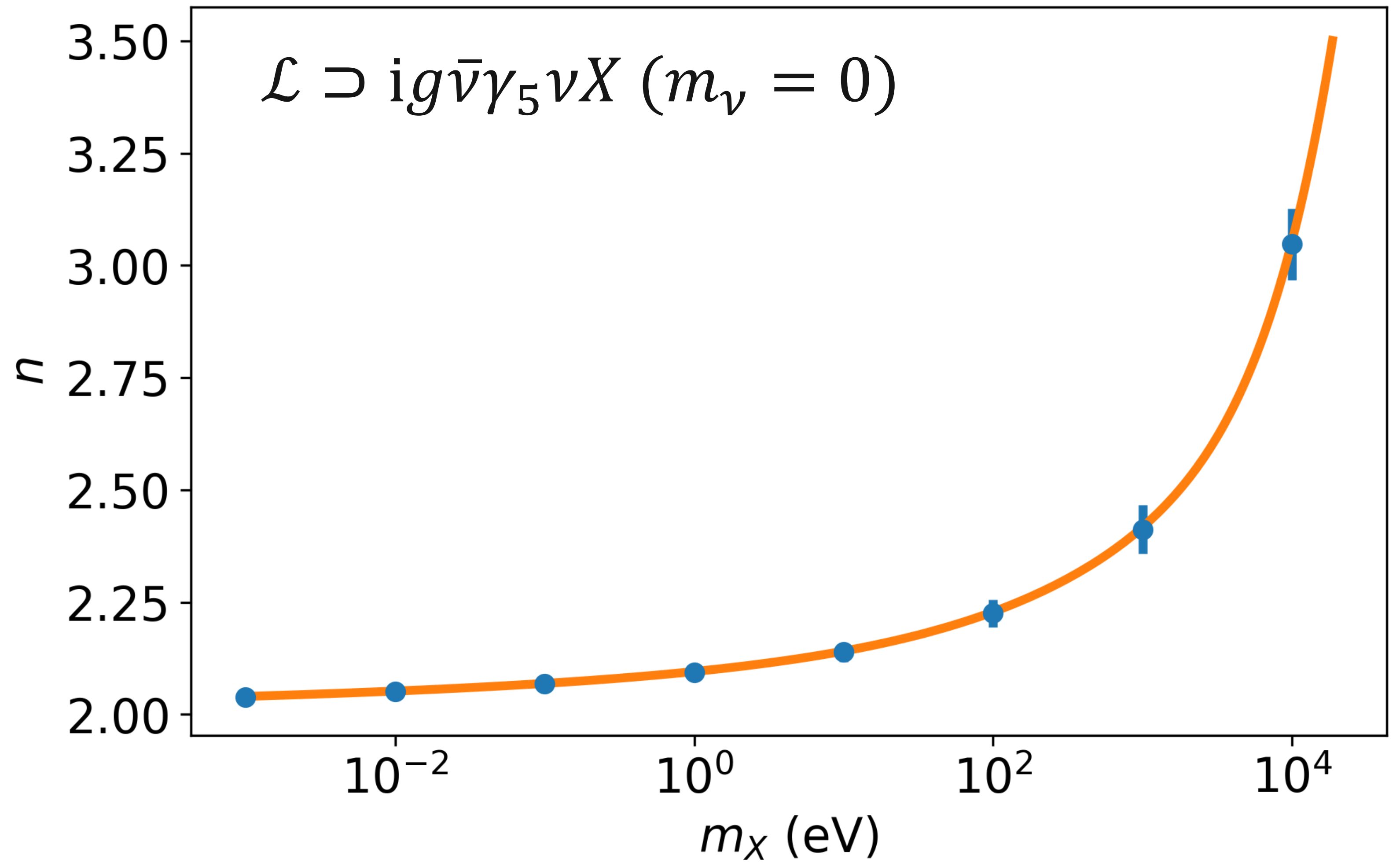




$$\frac{\mathrm{d}\Gamma}{\mathrm{d}E} = K\sqrt{\frac{E}{m_e}}\left(\frac{E_{\max}-E}{E_{\max}+m_e}\right)^n$$

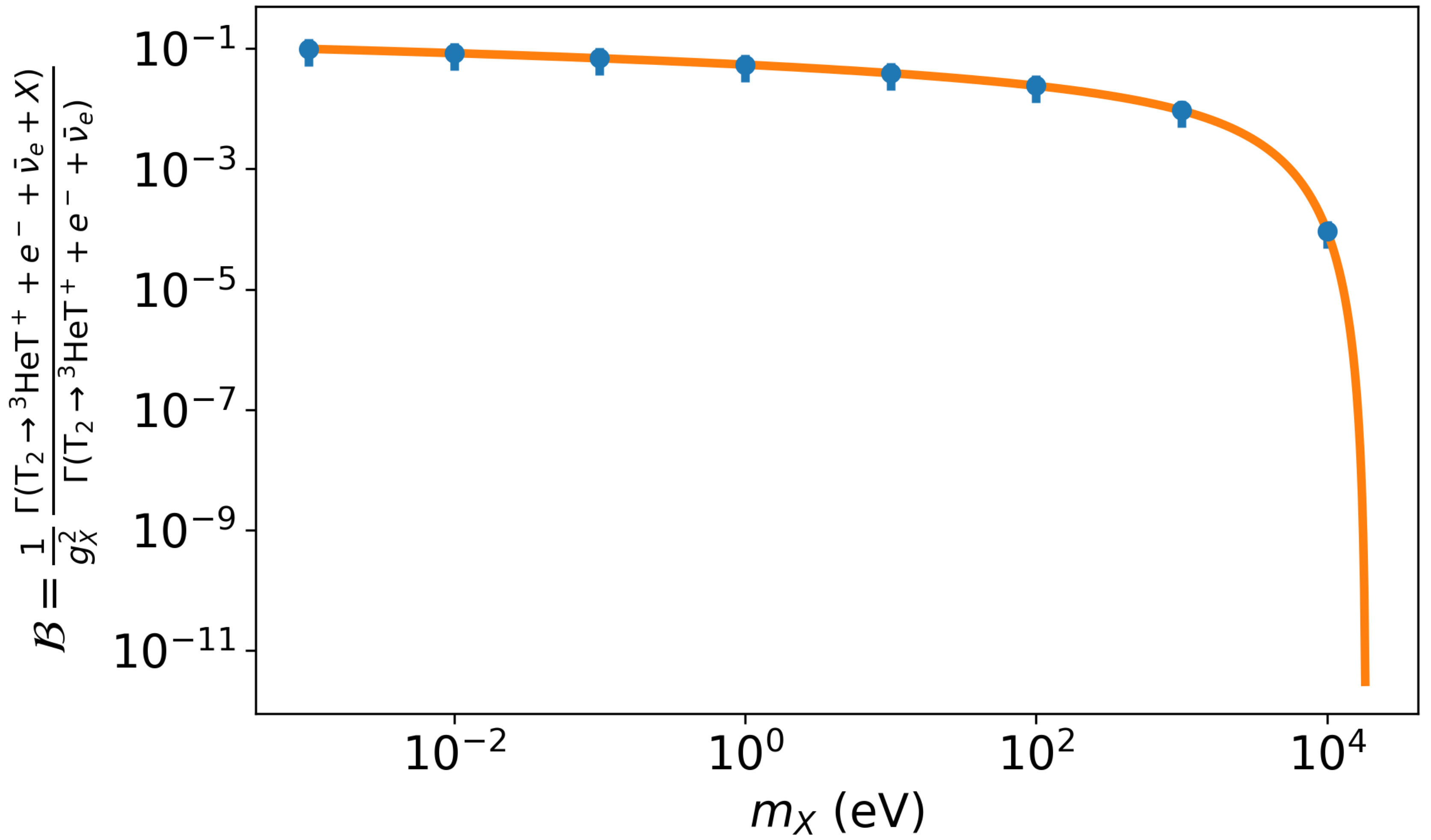


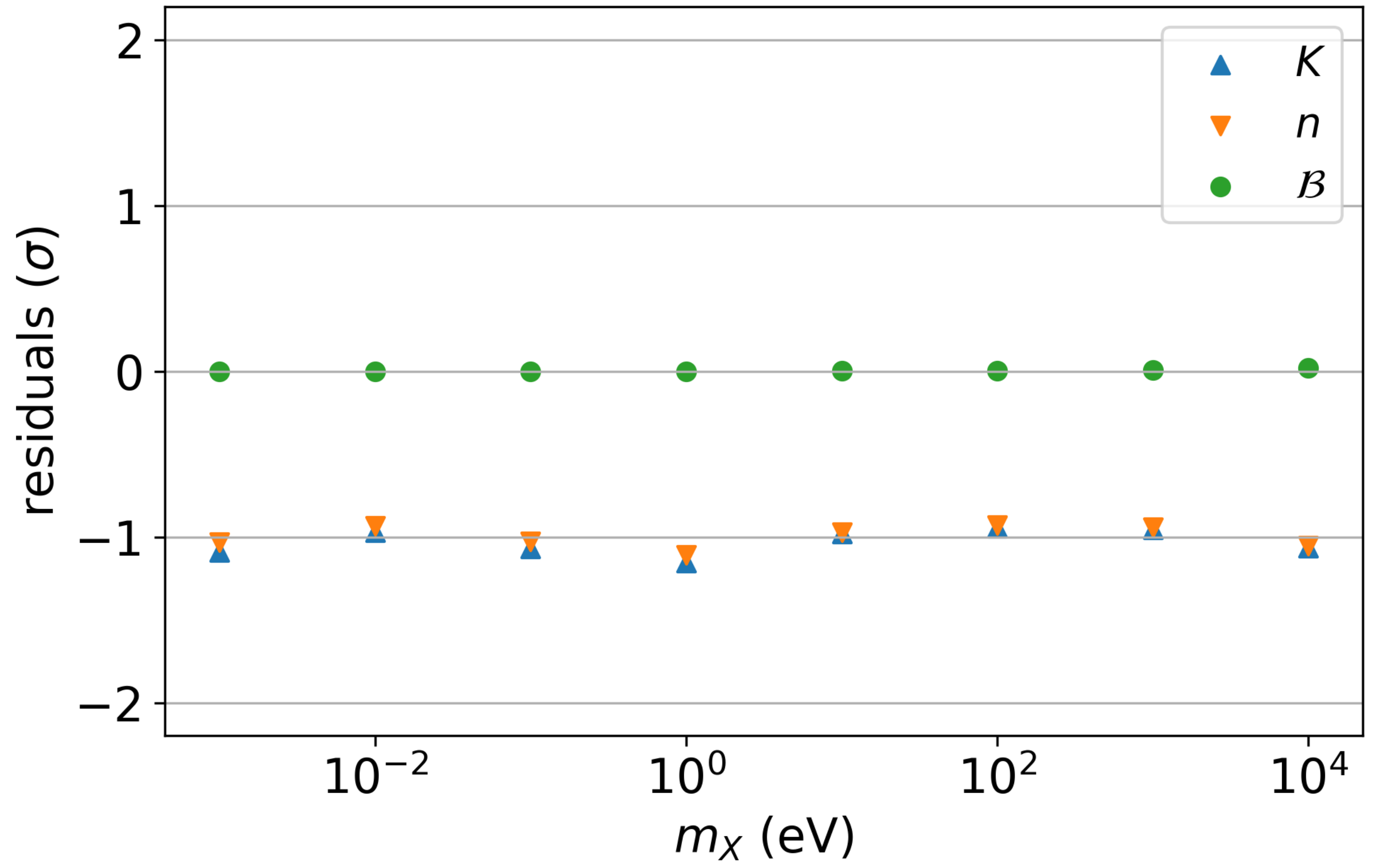




- **Good agreement** with reference
- **Problem:** assuming uniform weights instead of actual uncertainties

  → deviations at the endpoint (small contributions)

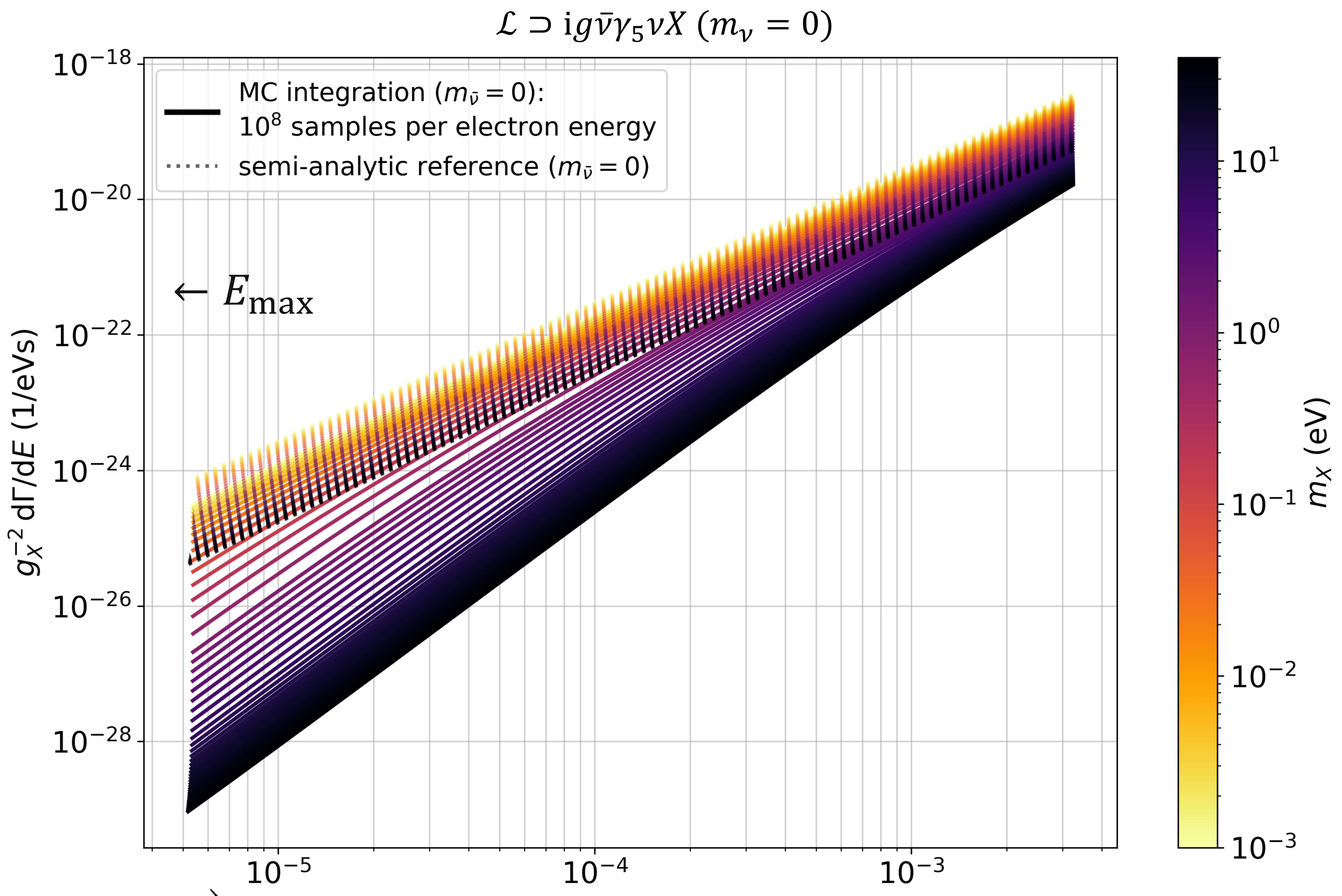




Endpoint studies

- **Goal:** precise description of the last 60 eV below the maximum energy E_{max}

  → parametrization not accurate in this region



- **Adapted ansatz:**

$$\ln\left(\frac{d\Gamma}{dE}\right) \propto \sum_{j=0}^{k} \theta_j \ln^j(x)$$

$$\Longrightarrow \frac{d\Gamma}{dE} \approx \exp\left(\sum_{j=0}^{k} \theta_j \ln^j(x)\right) = K \exp\left(\ln(x) \sum_{j=1}^{k} \theta_j \ln^{j-1}(x)\right)$$

$$x := \frac{E_{max} - E}{E_{max}} \in [0, 1]$$

$$= K\, x^{\sum_{j=1}^{k} \theta_j \ln^{j-1}(x)} = K \left(\frac{E_{max} - E}{E_{max}}\right)^{\overbrace{\sum_{j=0}^{k-1} \theta_{j+1} \ln^j(x)}^{n(E)}}$$

Refined parametrization

- Numerical results are fitted with ansatz of order *k:*

$$\frac{\mathrm{d}\Gamma}{\mathrm{d}E} \approx \exp\left(\sum_{j=0}^{k} \theta_j \ln^j(x)\right)$$

- Parameters K and $n(x)$ are extracted:

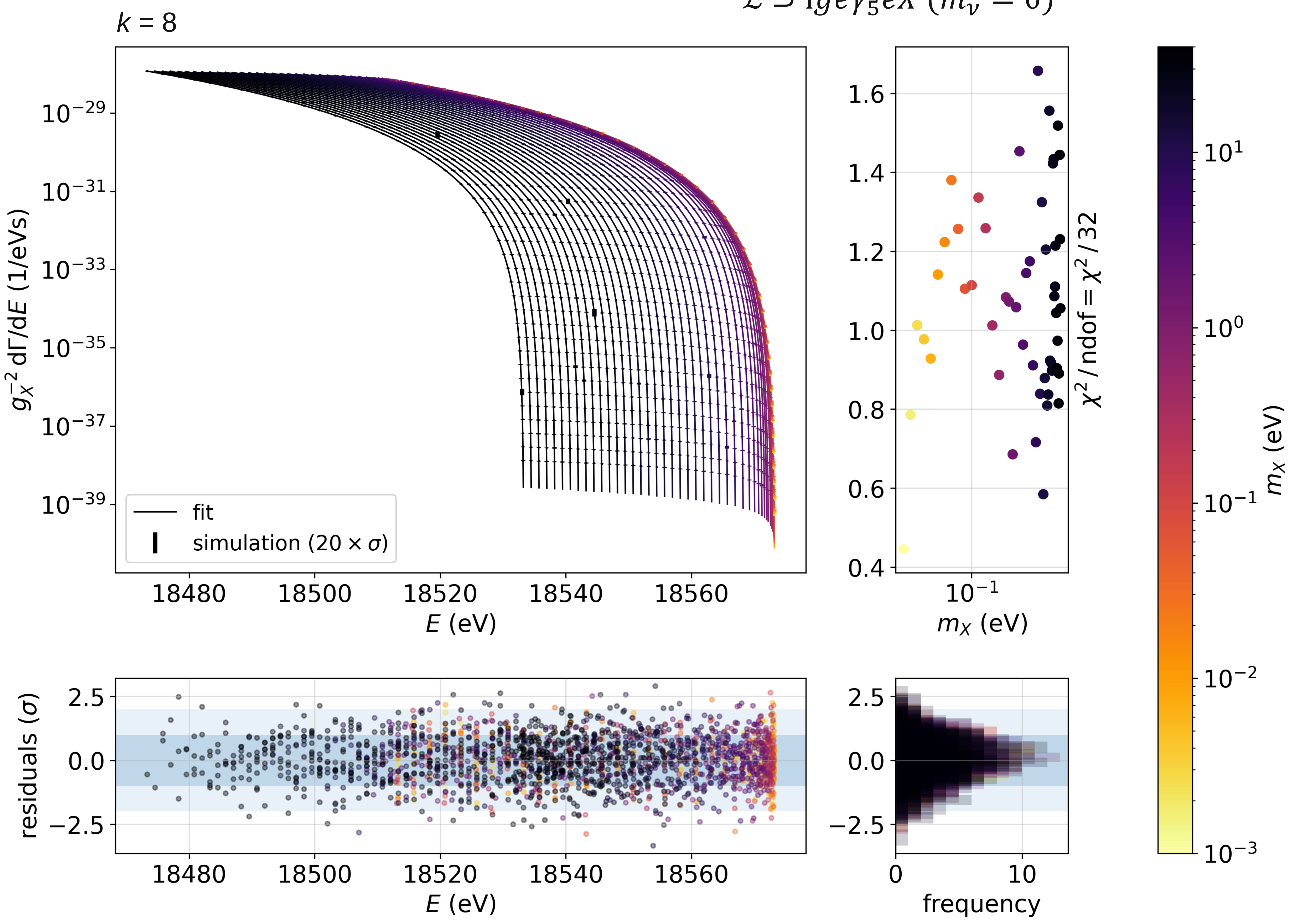
$$K\left(\frac{E_{\max}-E}{E_{\max}}\right)^{\overbrace{\sum_{j=0}^{k-1}\theta_{j+1}\ln^j(x)}^{n(E)}}$$

→ Calculated for **any considered boson scenario** and neutrino masses $\boldsymbol{m_\nu}$ **from 0 to 1 eV**

→ Computations are running on the *bwForCluster NEMO* (Freiburg)

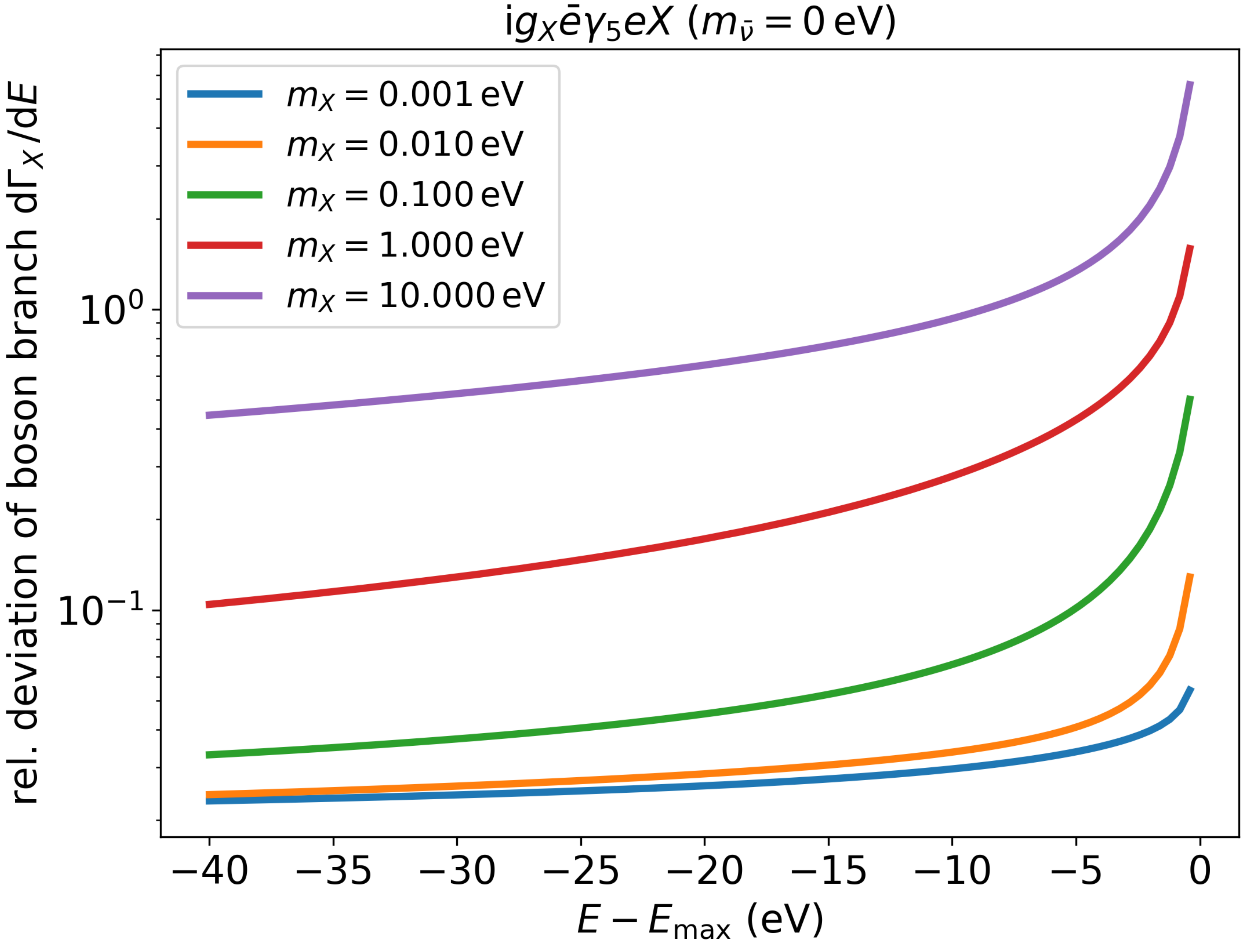
→ Precise analytic model in the sensitive region

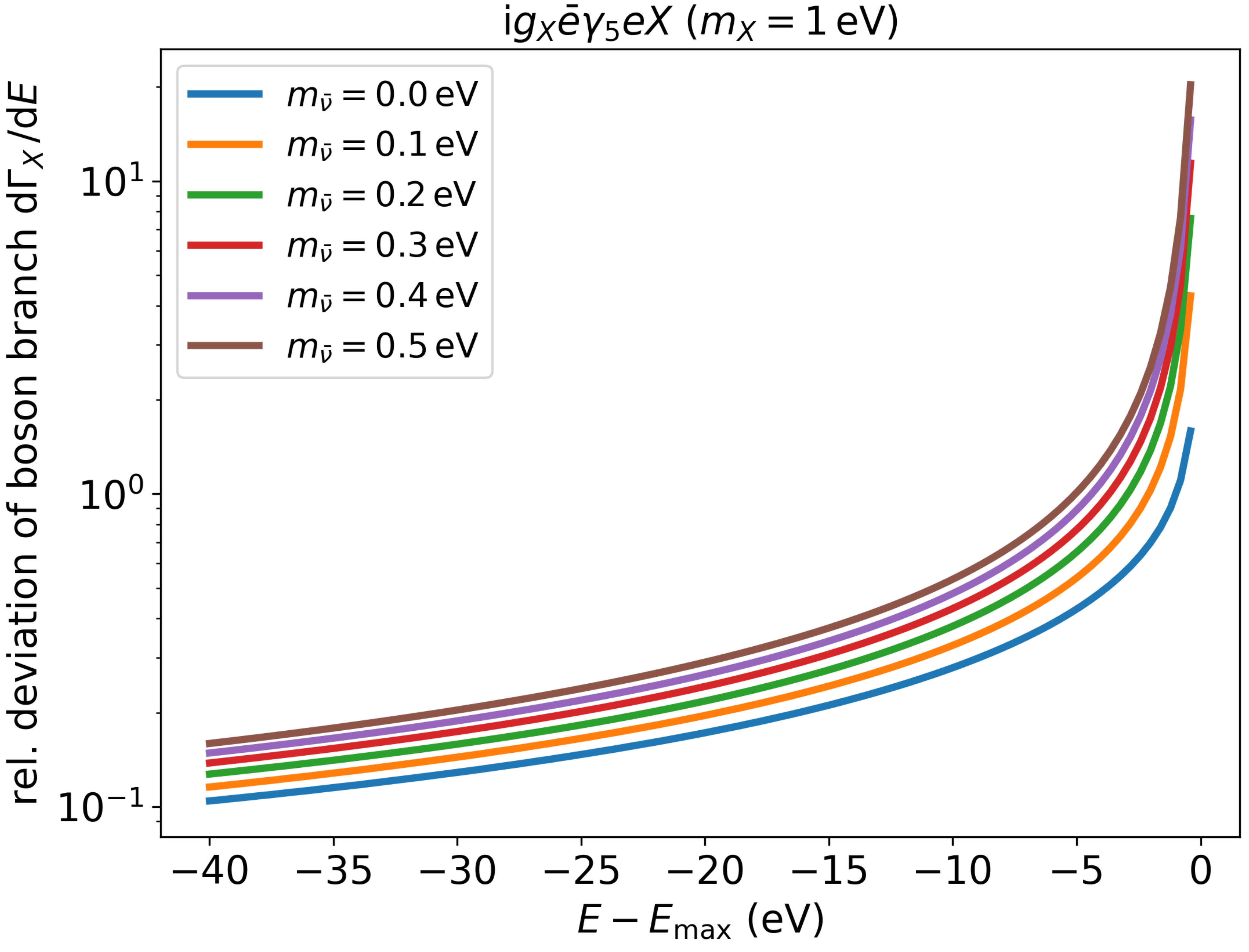
Example scenario:
electron-pseudoscalar coupling
$\mathcal{L} \supset \mathrm{i}g\bar{e}\gamma_5 eX\ (m_\nu = 0)$



New model: compensated deviations

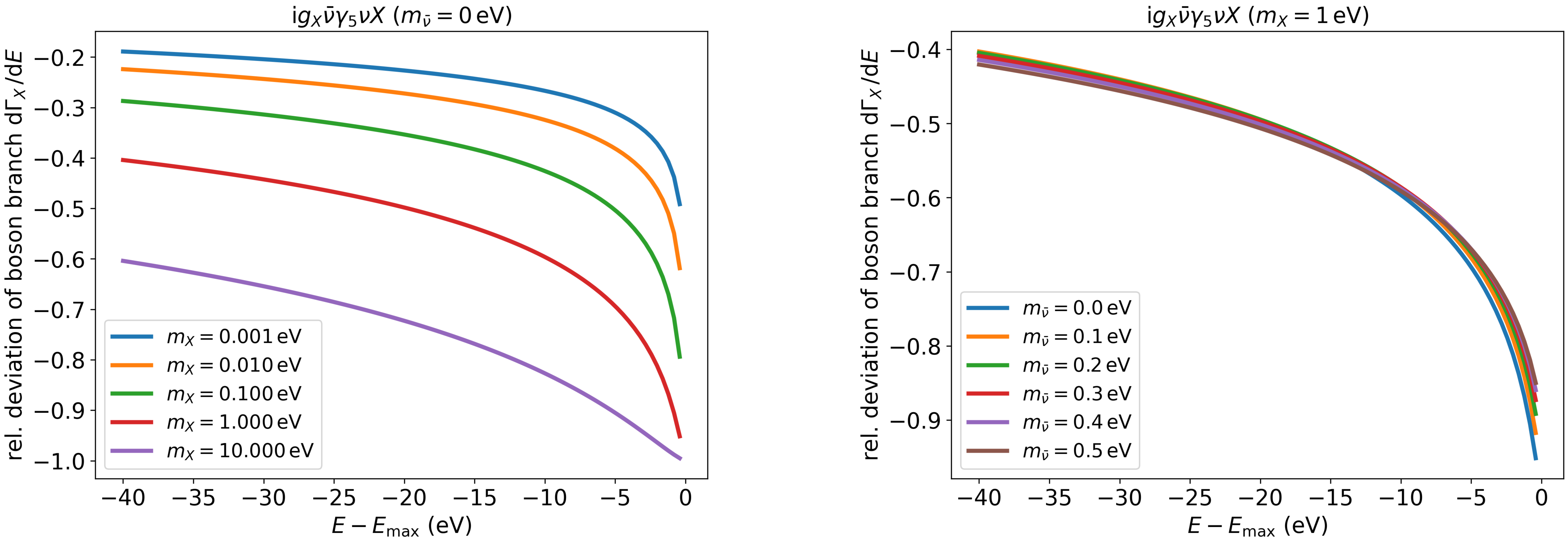
- Comparison: relative deviation of this work from the simplified model (reference)
- Scenario: **electron-pseudoscalar** coupling





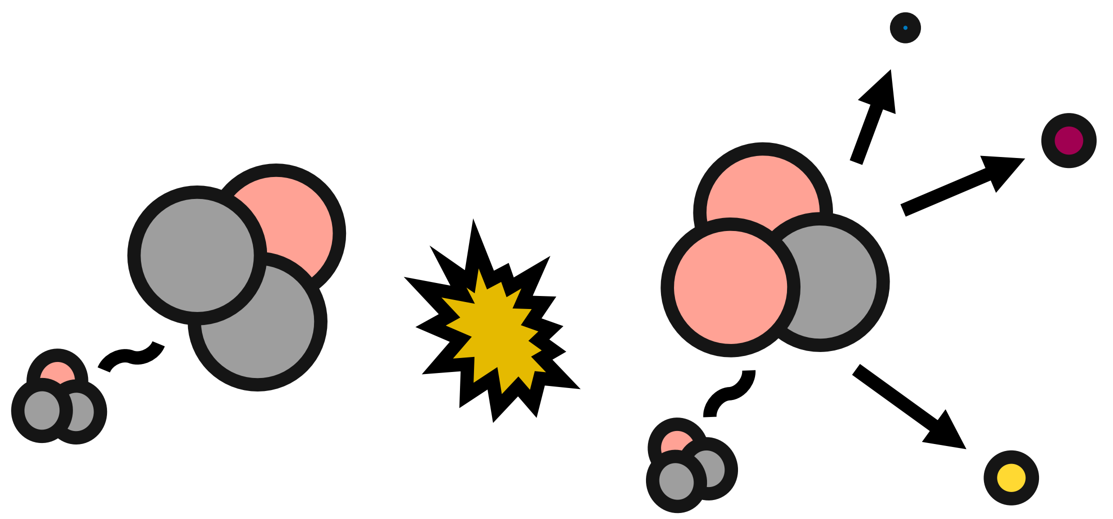
New model: compensated deviations

- Comparison: relative deviation of this work from the simplified model (reference)
- Scenario: **neutrino-pseudoscalar** coupling



Summary & outlook

- *This work:* a highly **adaptable and modular framework** for boson emission spectrum computation
- Reproduction of the reference values from JHEP01(2019)206, but **deviations in the endpoint region**
- **Refined parameterization** of the tree-level light boson branches compensates deviations close to E_{max}
- Extension to **explicitly massive neutrino** was performed



Outlook:

- Update **analysis framework** according to refined model
- Analysis of a **subset of our data** with respect to imprints of light bosons
- Comparison of **Majorana** neutrino case to current **Dirac** assumption

Acknowledgement

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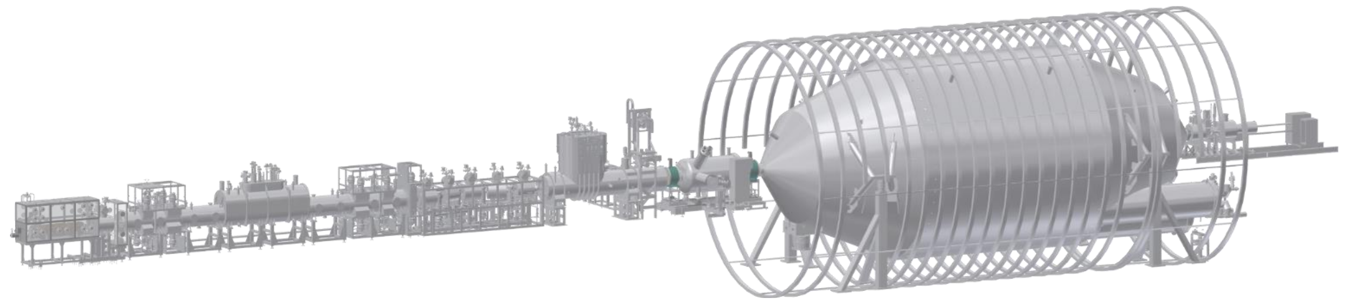
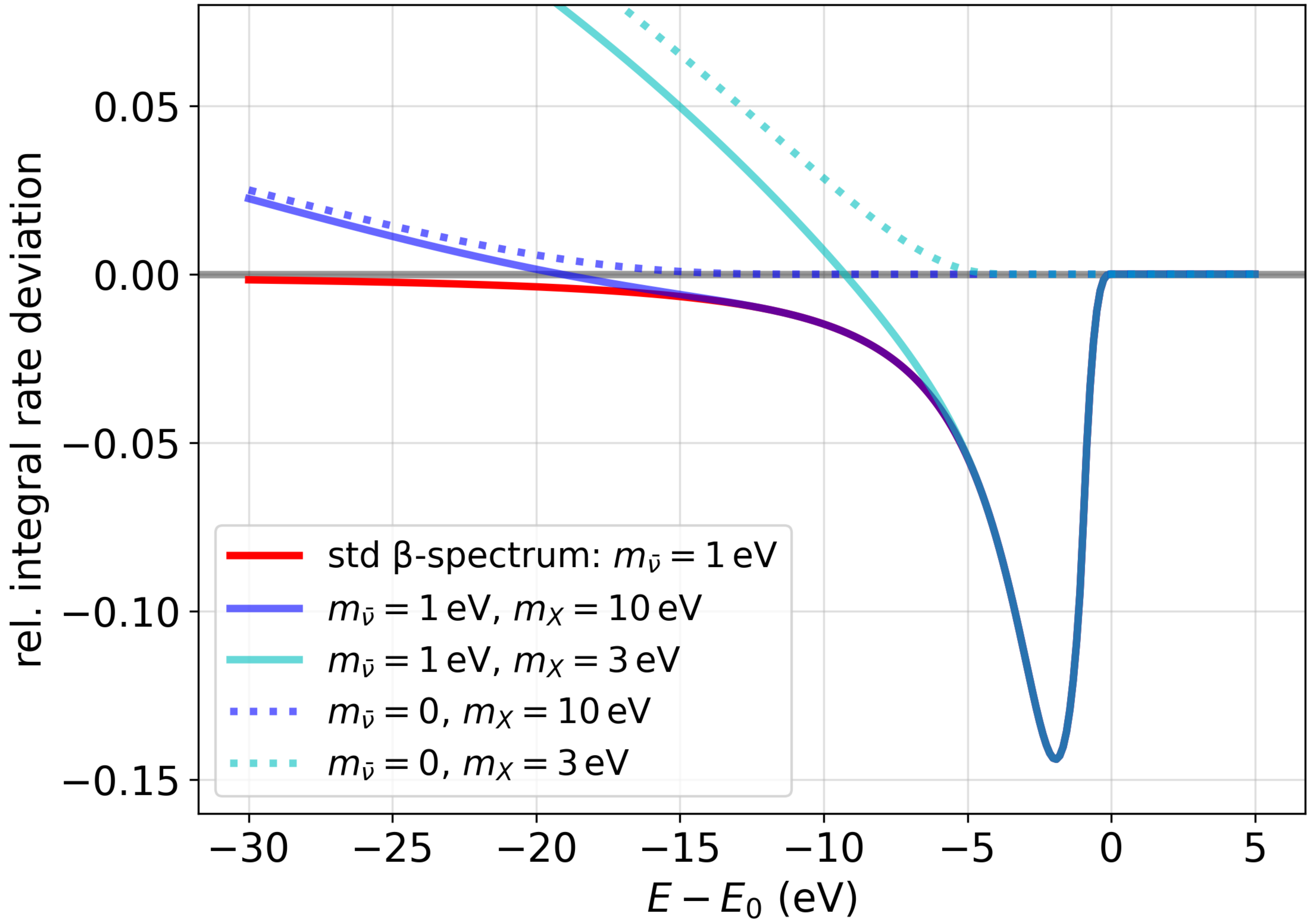
Backup

Refined boson signature



Example scenario:
neutrino-pseudoscalar coupling
$\mathcal{L} \supset ig\bar{\nu}\gamma_5\nu X \ (g_X = 5)$



- The neutrino mass is now respected explicitly in the underlying theory
- Assumption (so far): Dirac neutrino

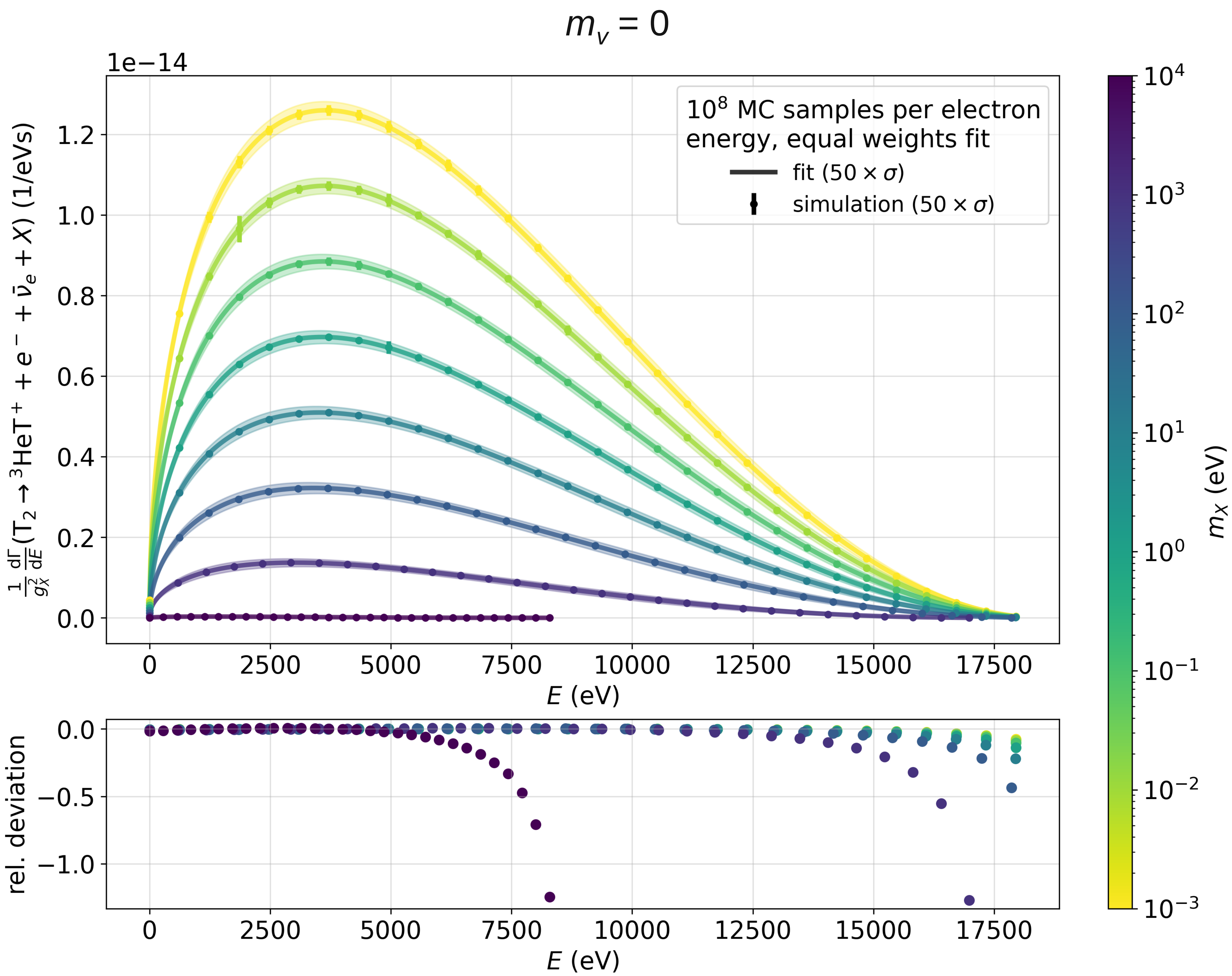
Fit results

- Fit of proposed relation to full spectra from MC integration:

$$\frac{\mathrm{d}\Gamma}{\mathrm{d}E} = K\sqrt{\frac{E}{m_e}}\left(\frac{E_{\max}-E}{E_{\max}+m_e}\right)^n$$

- Assumption: **equal weight** for each point

  → extraction of parameters K, n

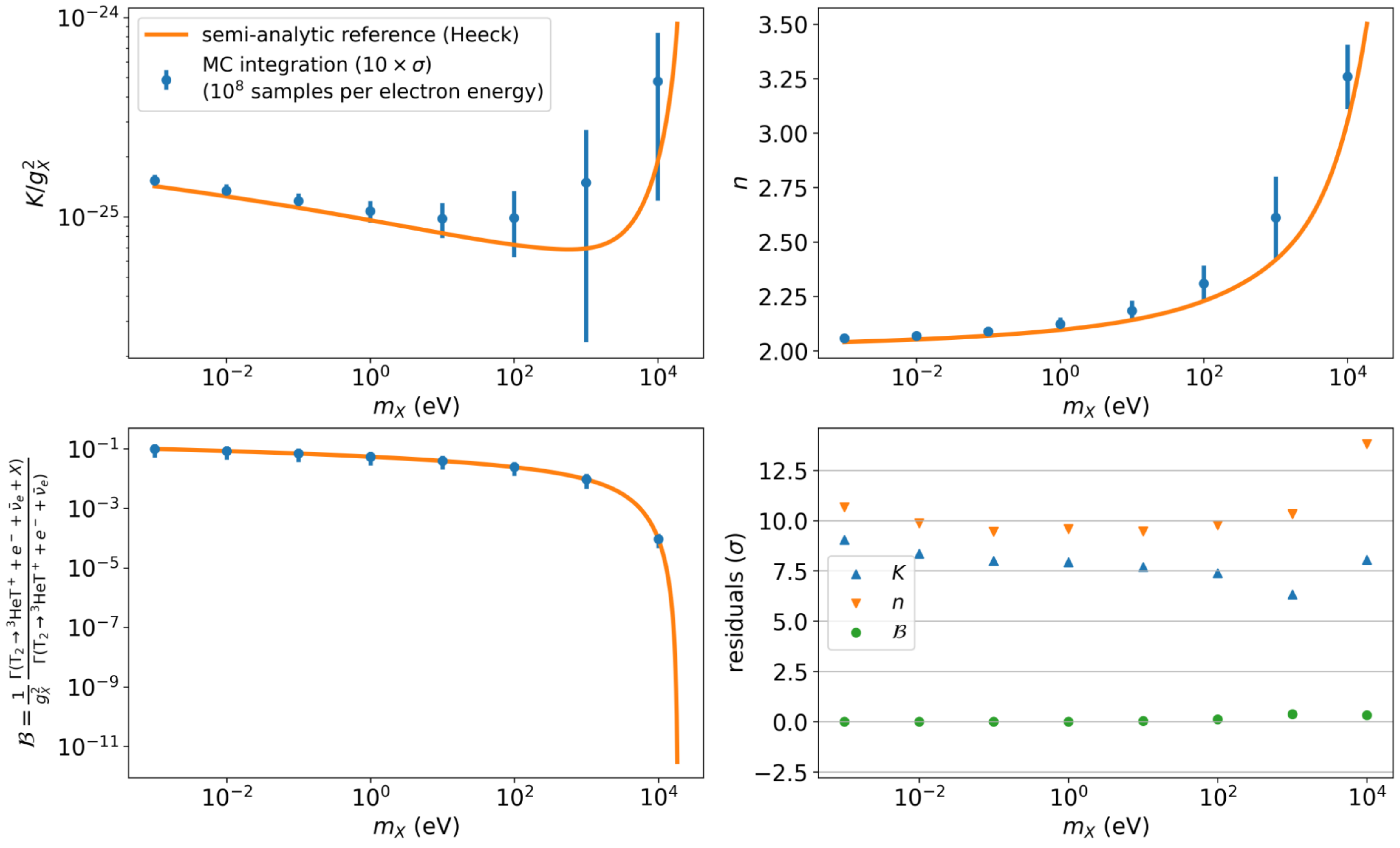


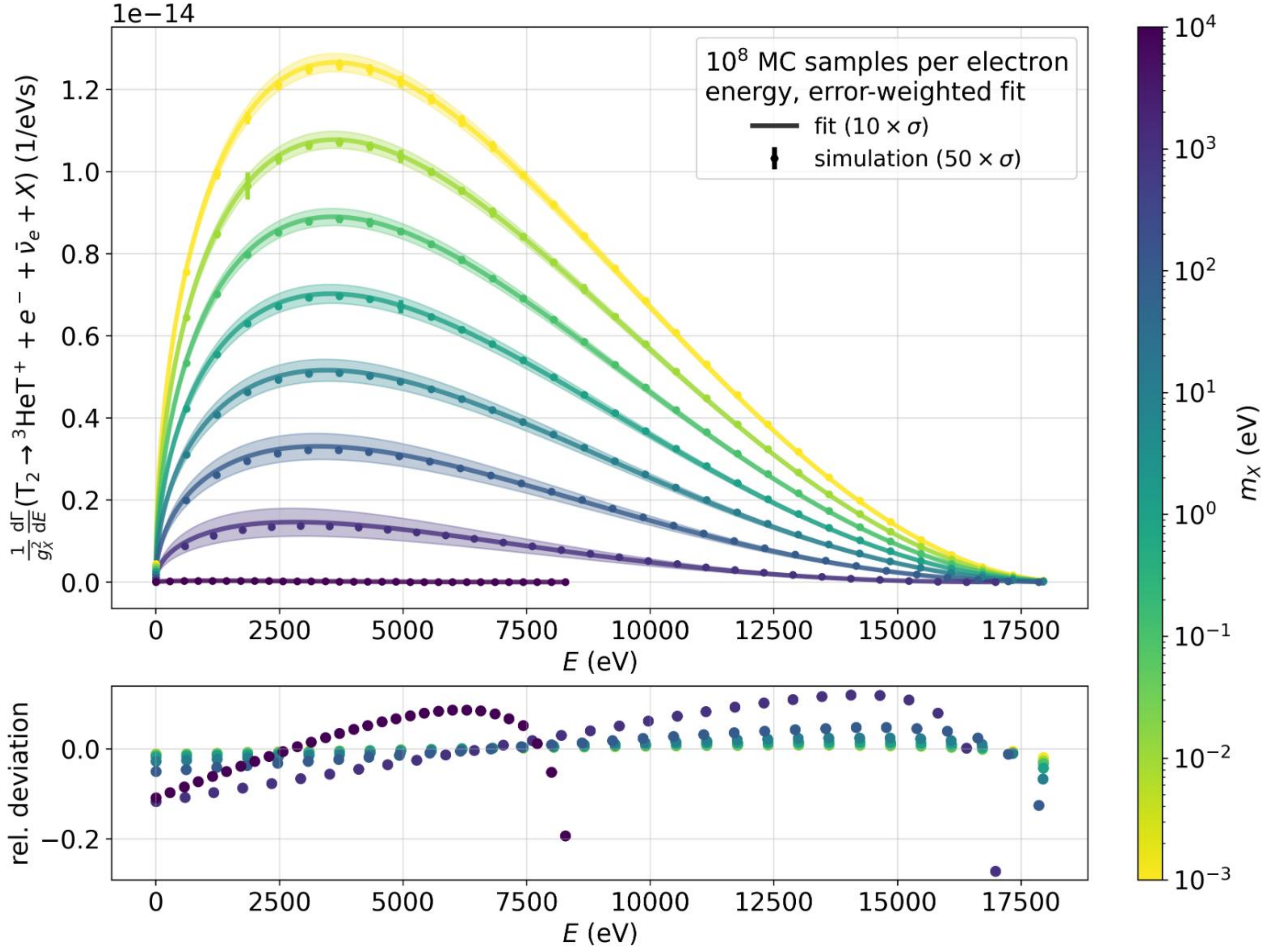
Example scenario:
neutrino-pseudoscalar coupling
$\mathcal{L} \supset \mathrm{i}g\bar{\nu}\gamma_5\nu X$

$m_\nu = 0$

$$\frac{d\Gamma}{dE} = K\sqrt{\frac{E}{m_e}}\left(\frac{E_{\max} - E}{E_{\max} + m_e}\right)^n$$

- Fit: each point **weighted with uncertainty**





Example scenario:
neutrino-pseudoscalar coupling
$\mathcal{L} \supset ig\bar{\nu}\gamma_5\nu X$

$$
\begin{aligned}
B=&[M^2Q^2+N^2P^2+M^2R^2+N^2R^2+P^2Q^2]-2[M^2QR+N^2PR+MNR^2+MPQ^2+NP^2Q]\\
&+2[MNPQ+MNPR+MNQR+MPQR+NPQR]-2[M^2Qm+N^2Pn+M^2Rm+N^2Rn+MQ^2q\\
&+NP^2p+MR^2r+NR^2r+P^2Qp+PQ^2q]-2[MNPm+MNQn+MPRp+NQRq+PQRr]\\
&+2[MNR(m+n-2r)+MPQ(m+p-2q)+NQP(n+q-2p)+QRM(q+r-2m)+PRN(p+r-2n)]\\
&+[M^2m^2+N^2n^2+P^2p^2+Q^2q^2+R^2r^2]+2[MNmn+MPmp+NQnq+PRpr+QRqr]\\
&+2[MQ(mq+mn+qn+mp+qr-pr)+NP(np+nm+pm+pr+nq-qr)+MR(mr+mp+rp+mn+rq-nq)\\
&+NR(nr+nq+rq+nm+rp-mp)+PQ(pq+pr+qr+pm+qn-mn)]-2[Mm(mp+mn+qr-pr-nq+2np)\\
&+Nn(nm+nq+pr-pm-qr+2mq)+Pp(pm+pr+nq-mn-qr+2mr)+Qq(qn+qr+mp-mn-pr+2nr)\\
&+Rr(rp+rq+mn-mp-nq+2pq)]+[m^2n^2+m^2p^2+n^2q^2+p^2r^2+q^2r^2]-2[m^2np+mn^2q+mp^2r+nq^2r+pqr^2]\\
&+2[mnpq+mnpr+mnqr+mpqr+npqr], \qquad (7)
\end{aligned}
$$

where the symbols are defined by

$$M=M_{12}{}^2,\quad N=M_{34}{}^2,\quad P=M_{124}{}^2,\quad Q=M_{134}{}^2,\quad R=M_{14}{}^2;$$

$$m=m_3{}^2,\quad n=m_2{}^2,\quad p=m_1{}^2,\quad q=m_4{}^2,\quad r=E^2.$$

$$\bar{\nu}\to 1,\quad X\to 2,\quad e\to 3,\quad \mathcal{B}\to 4$$

scalar product	IKV representation
$p_1\cdot p_2$	$\frac{1}{2}\left(M_{12}^2-m_1^2-m_2^2\right)$
$p_1\cdot p_4$	$\frac{1}{2}\left(M_{14}^2-m_1^2-m_4^2\right)$
$p_3\cdot p_4$	$\frac{1}{2}\left(M_{34}^2-m_3^2-m_4^2\right)$
$p_2\cdot p_3$	$\frac{1}{2}\left(M_{14}^2-M_{124}^2-M_{134}^2+m_{\mathcal{A}}^2\right)$
$p_1\cdot p_3$	$\frac{1}{2}\left(M_{134}^2-M_{14}^2-M_{34}^2+m_4^2\right)$
$p_2\cdot p_4$	$\frac{1}{2}\left(M_{124}^2-M_{12}^2-M_{14}^2+m_1^2\right)$
$p_{\mathcal{A}}\cdot p_2$	$\frac{1}{2}\left(m_{\mathcal{A}}^2+m_2^2-M_{134}^2\right)$
$p_{\mathcal{A}}\cdot p_3$	$\frac{1}{2}\left(m_{\mathcal{A}}^2+m_3^2-M_{124}^2\right)$
$p_{\mathcal{A}}\cdot p_1$	$\frac{1}{2}\left(M_{134}^2+M_{12}^2-M_{34}^2-m_2^2\right)$
$p_{\mathcal{A}}\cdot p_4$	$\frac{1}{2}\left(M_{124}^2+M_{34}^2-M_{12}^2-m_3^2\right)$

Light bosons: sensitivity comparison

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