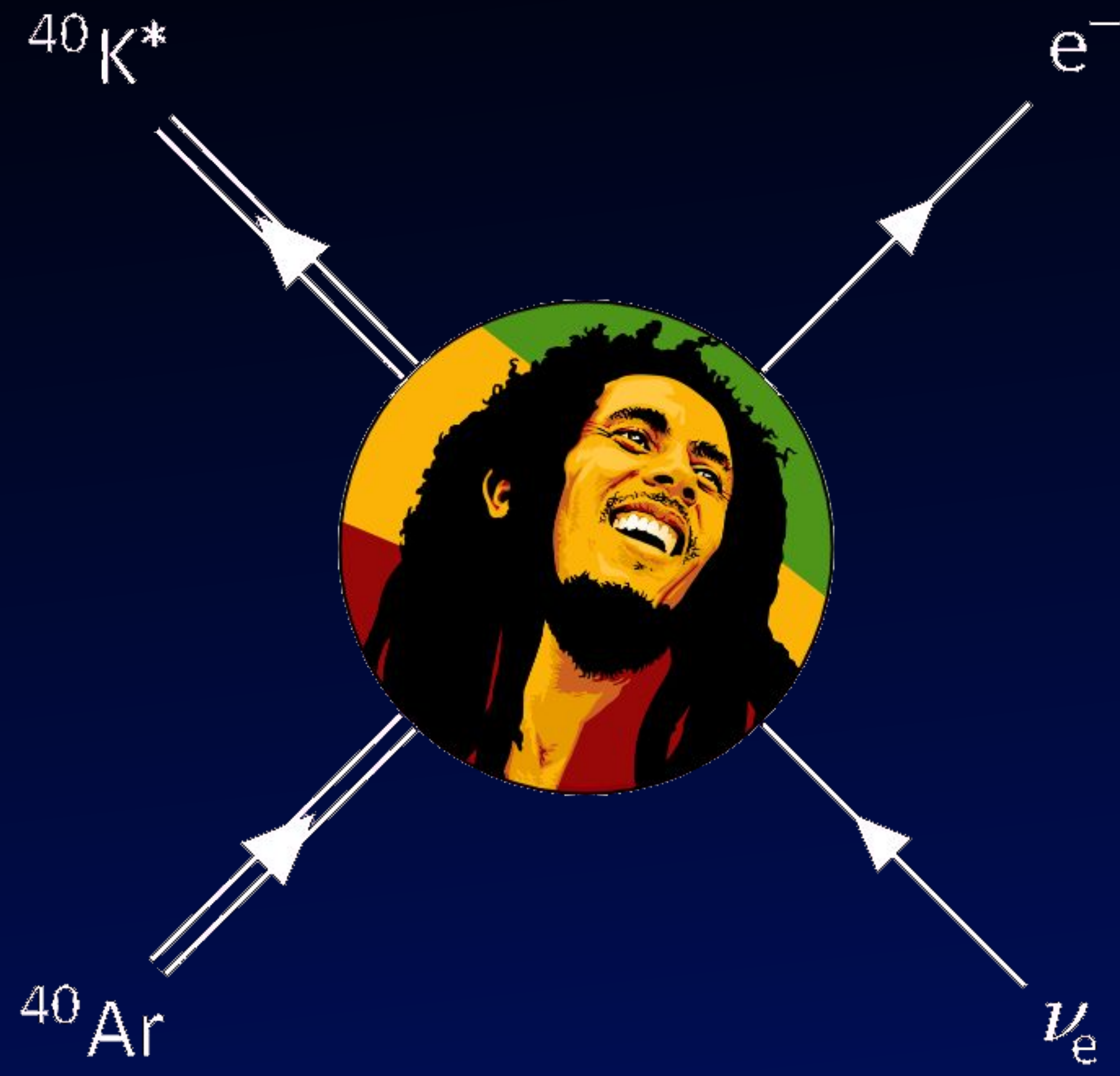


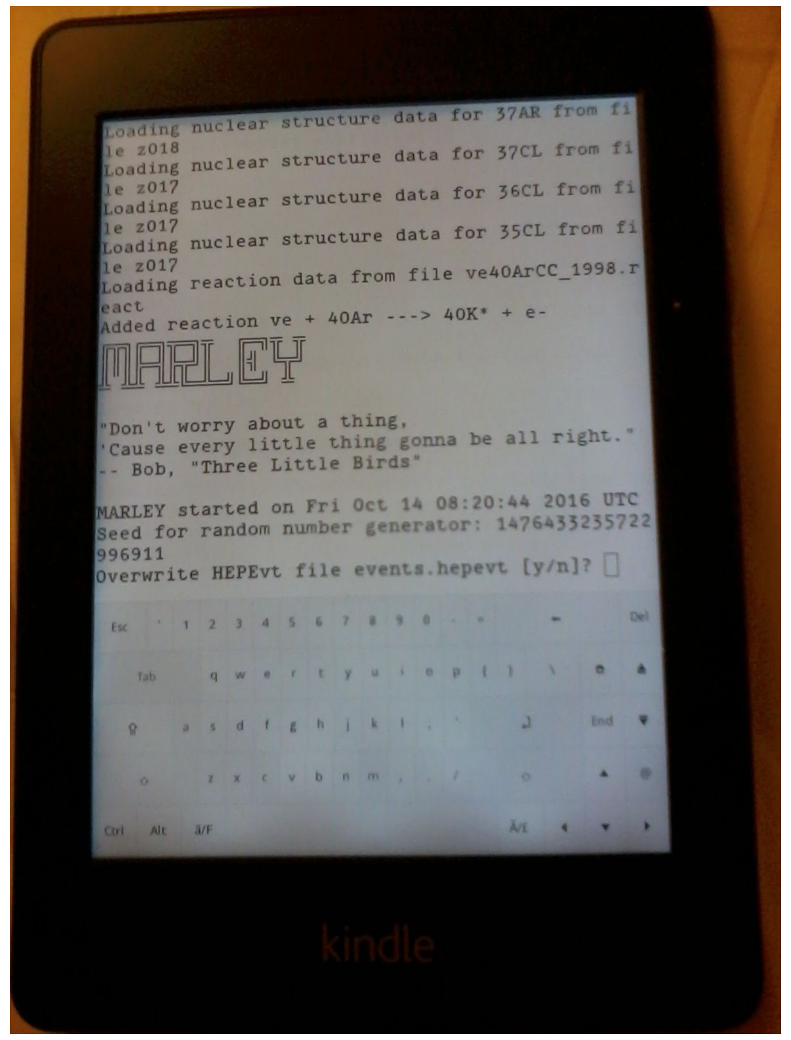
Physics modeling improvements in the MARLEY neutrino event generator

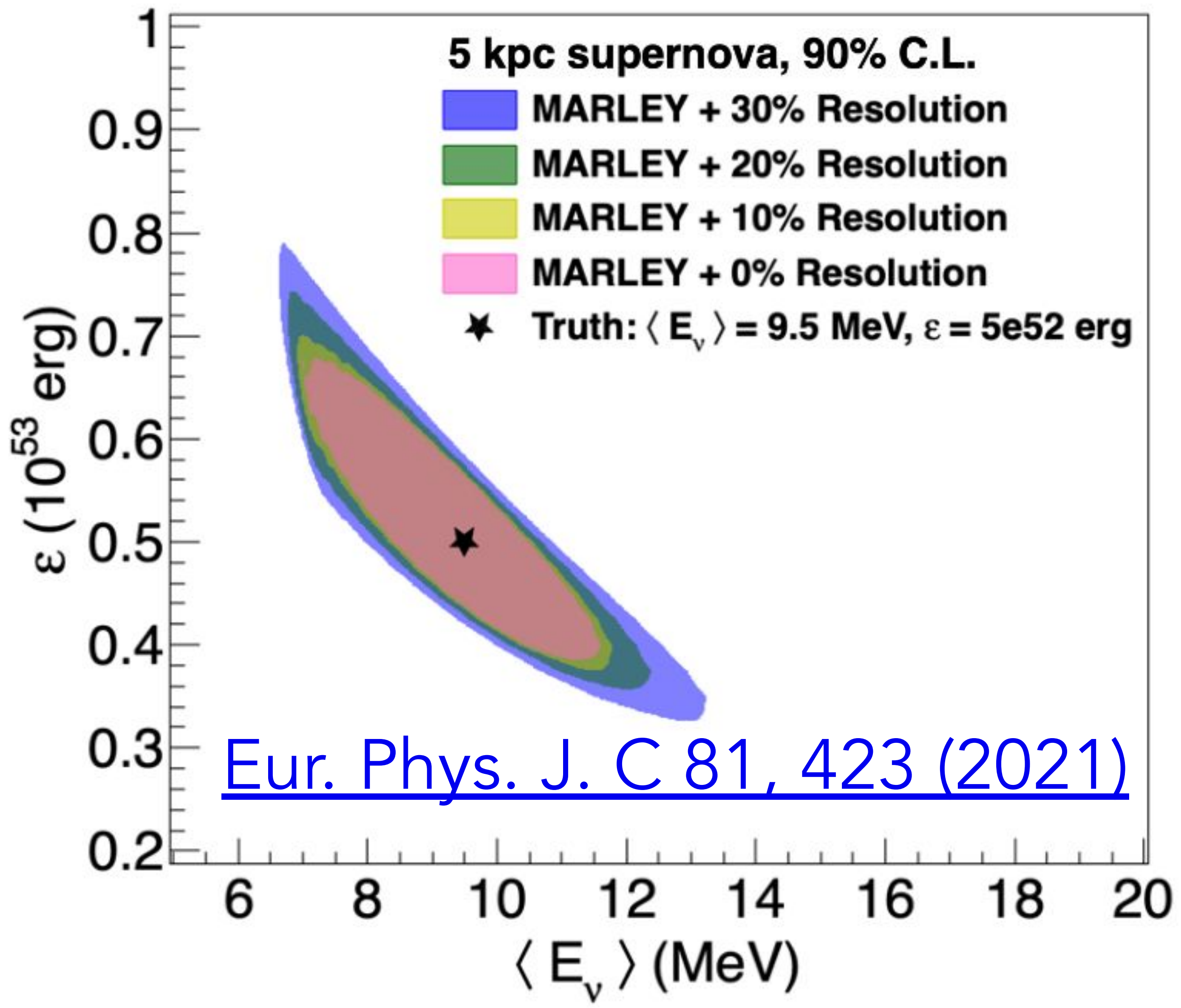
Steven Gardiner, Pablo Barham Alzás, Luca Abu El-Haj

25th International Workshop on Neutrinos from Accelerators (NuFact 2024)
Argonne National Laboratory, 17 September 2024

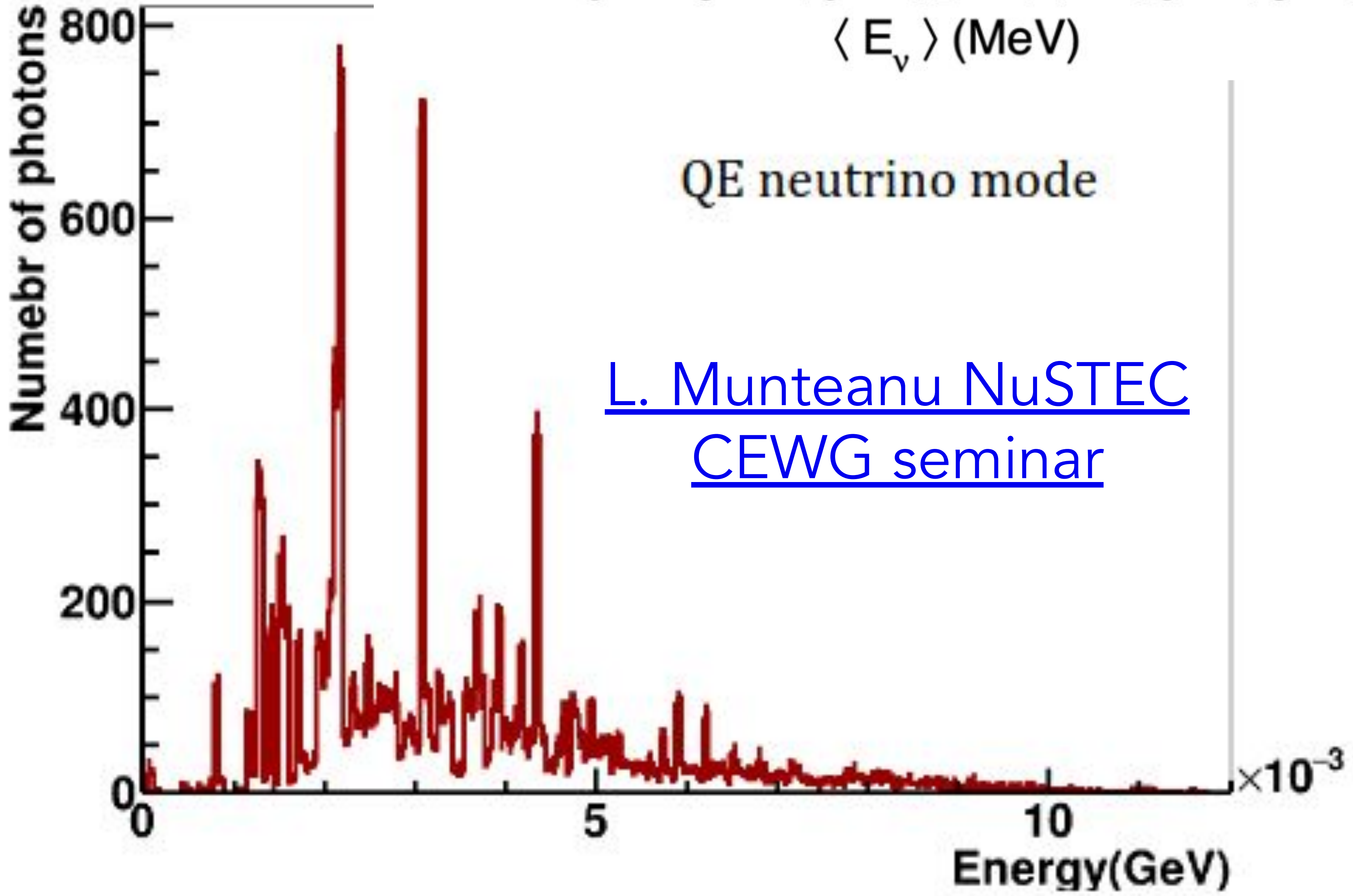
Model of Argon Reaction Low Energy Yields (MARLEY)

- Event generator for **MeV-scale** neutrino interactions
  - DUNE sensitivity to **supernova + solar neutrinos**
  - COHERENT backgrounds to CEvNS and efficiencies for inelastic cross sections
  - DUNE+SBN **de-excitation γ-rays** in new GENIE model set ("AR23_20i_00_000")
- Current release is **version 1.2.1** (marleygen.org)
  - Interaction model: Phys. Rev. C 103, 044604 (2021)
  - C++14 implementation: Comput. Phys. Commun. 269, 108123 (2021)





Eur. Phys. J. C 81, 423 (2021)

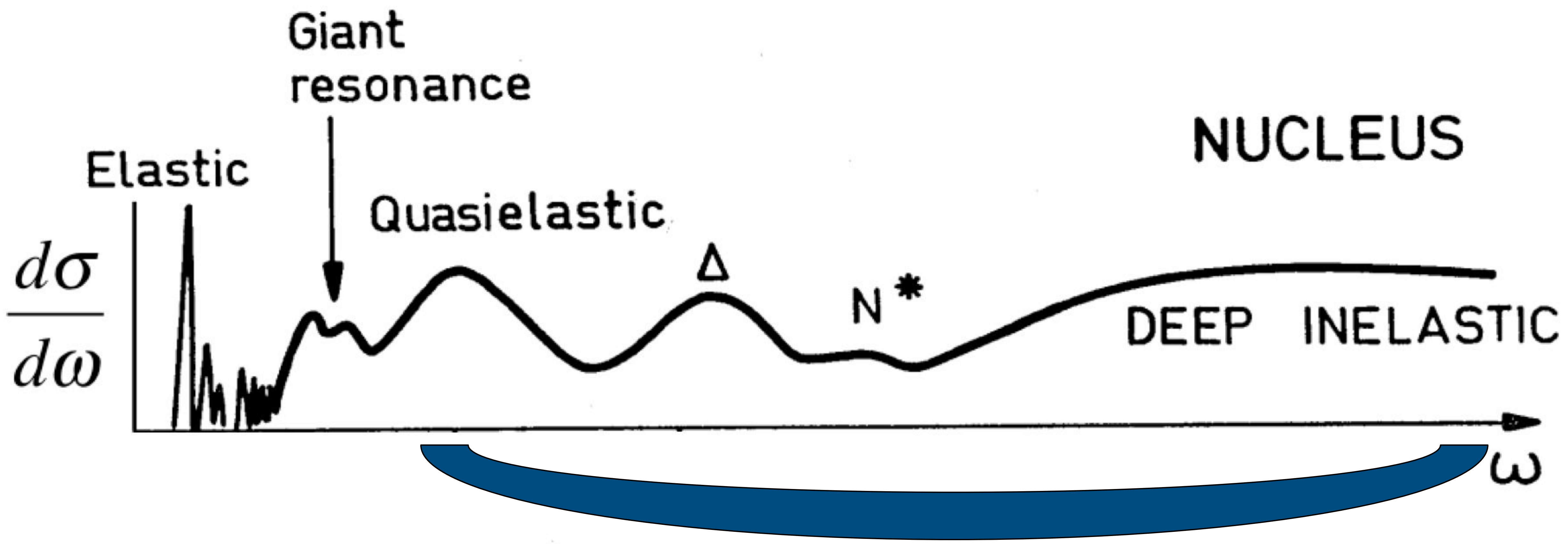


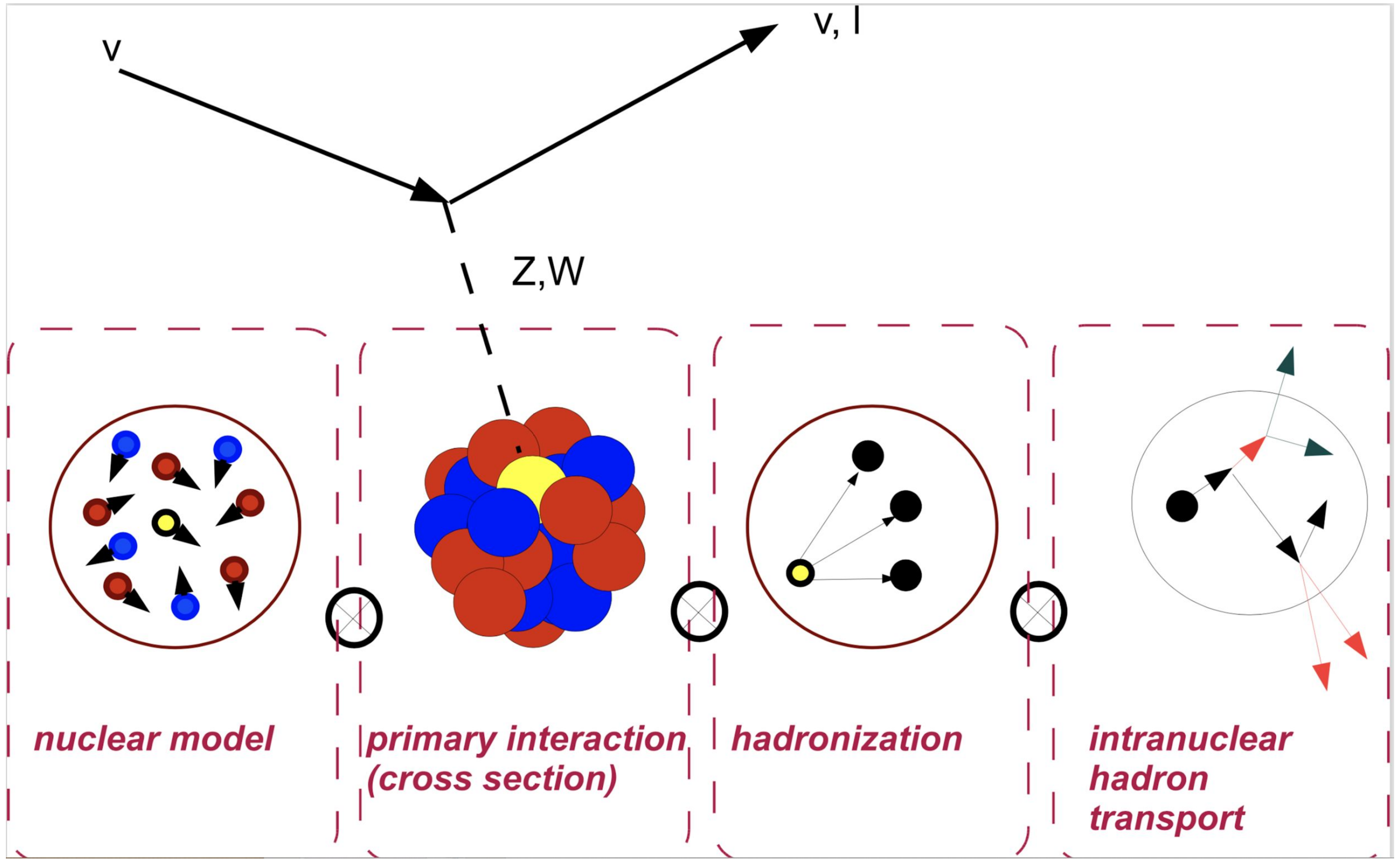
L. Munteanu NuSTEC CEWG seminar

Typical generator approach for the GeV scale

- Much attention given the needs of accelerator-based oscillation experiments

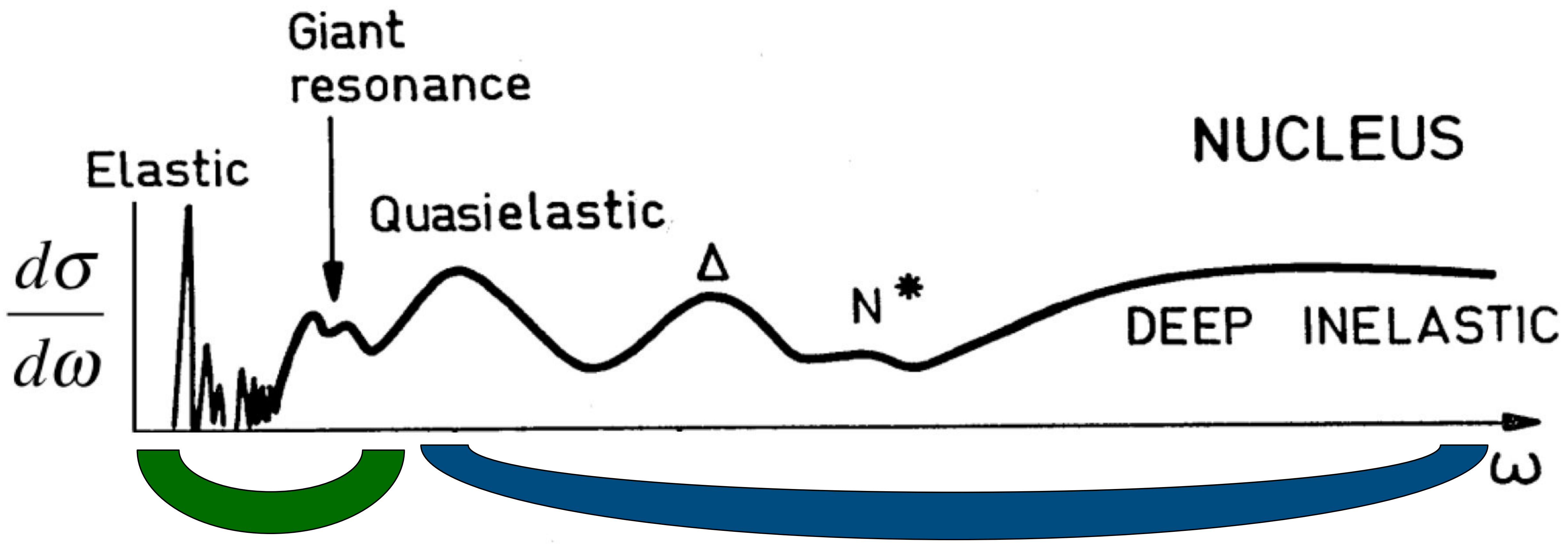
- **Direct nucleon knockout** with adjustments for nuclear effects (Fermi motion, FSI, etc.)

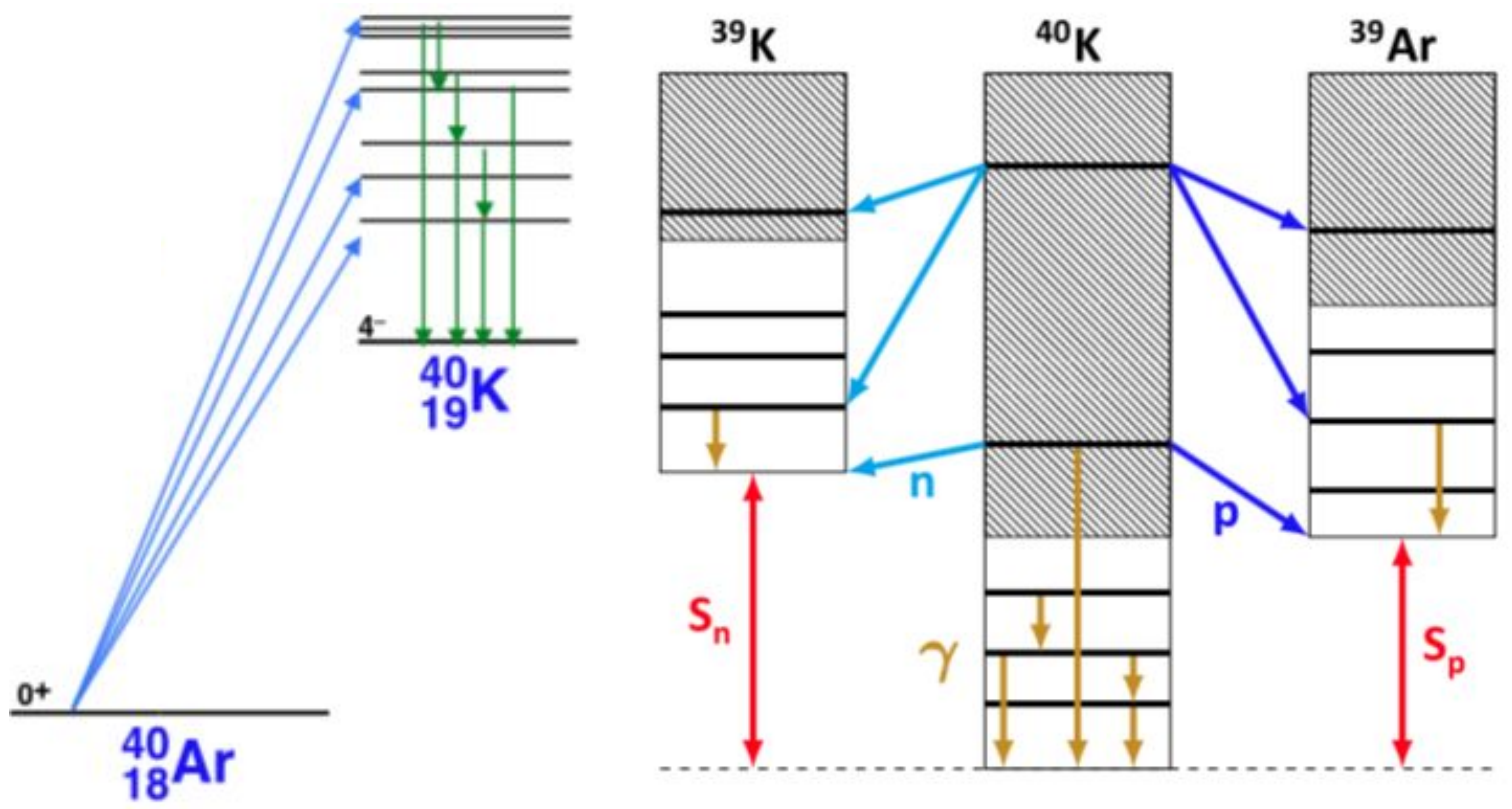




MARLEY's treatment is designed for a different regime

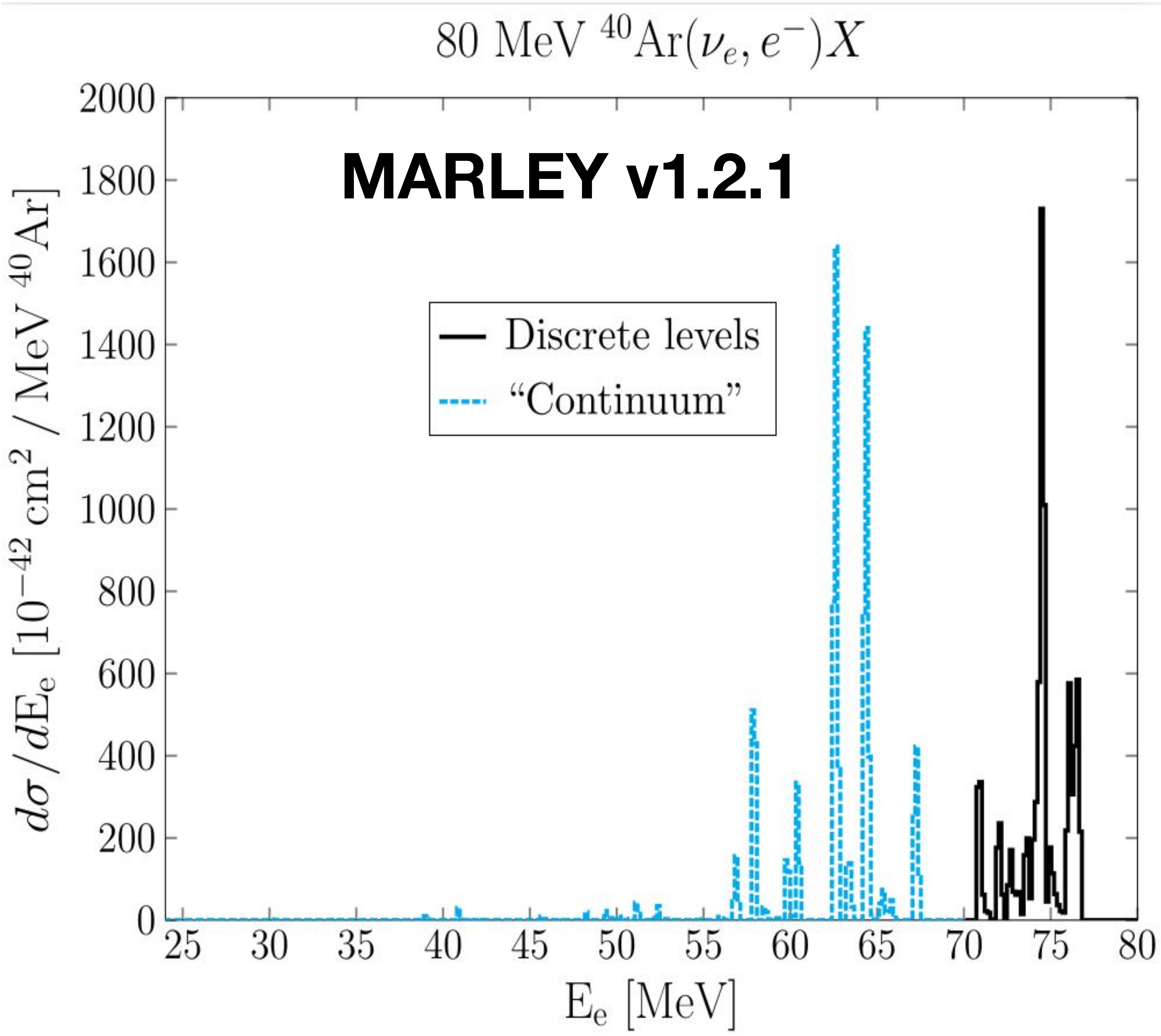
- Complements without competing
- Standard **two-step approach** $\lesssim$ 100 MeV
  - Induced transitions to nuclear excited states
  - Emission of de-excitation products





Physics limitations of MARLEY v1.2.1

- High-lying nuclear energy levels form a **continuum**
  - Existing cross-section model **pretends they are discrete**
- "Allowed approximation" evaluates matrix elements at zero momentum transfer
  - Forbidden contributions neglected
  - Allowed cross section overestimated due to missing q dependence
- No tools for uncertainty quantification
  - Capability needed for future analyses



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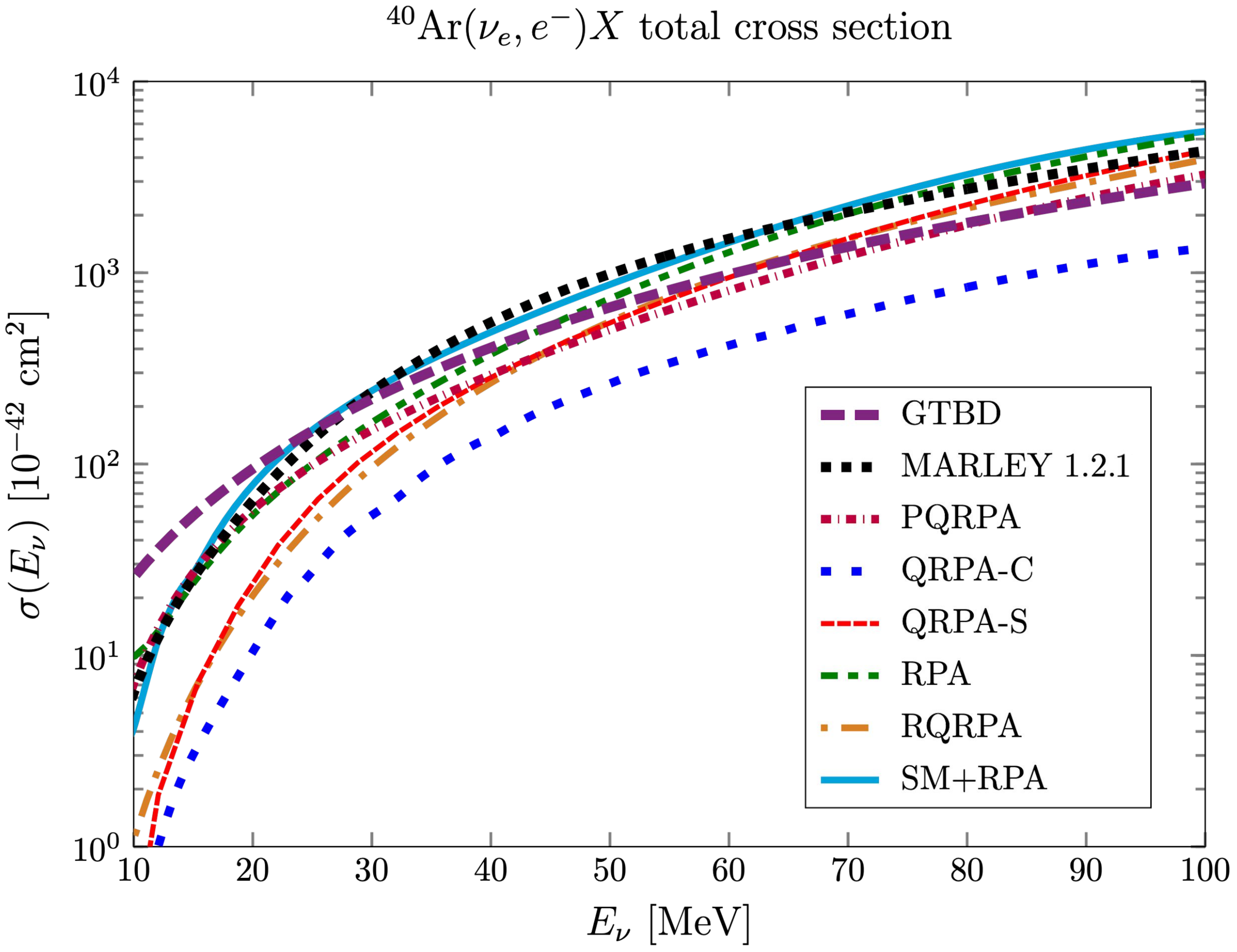
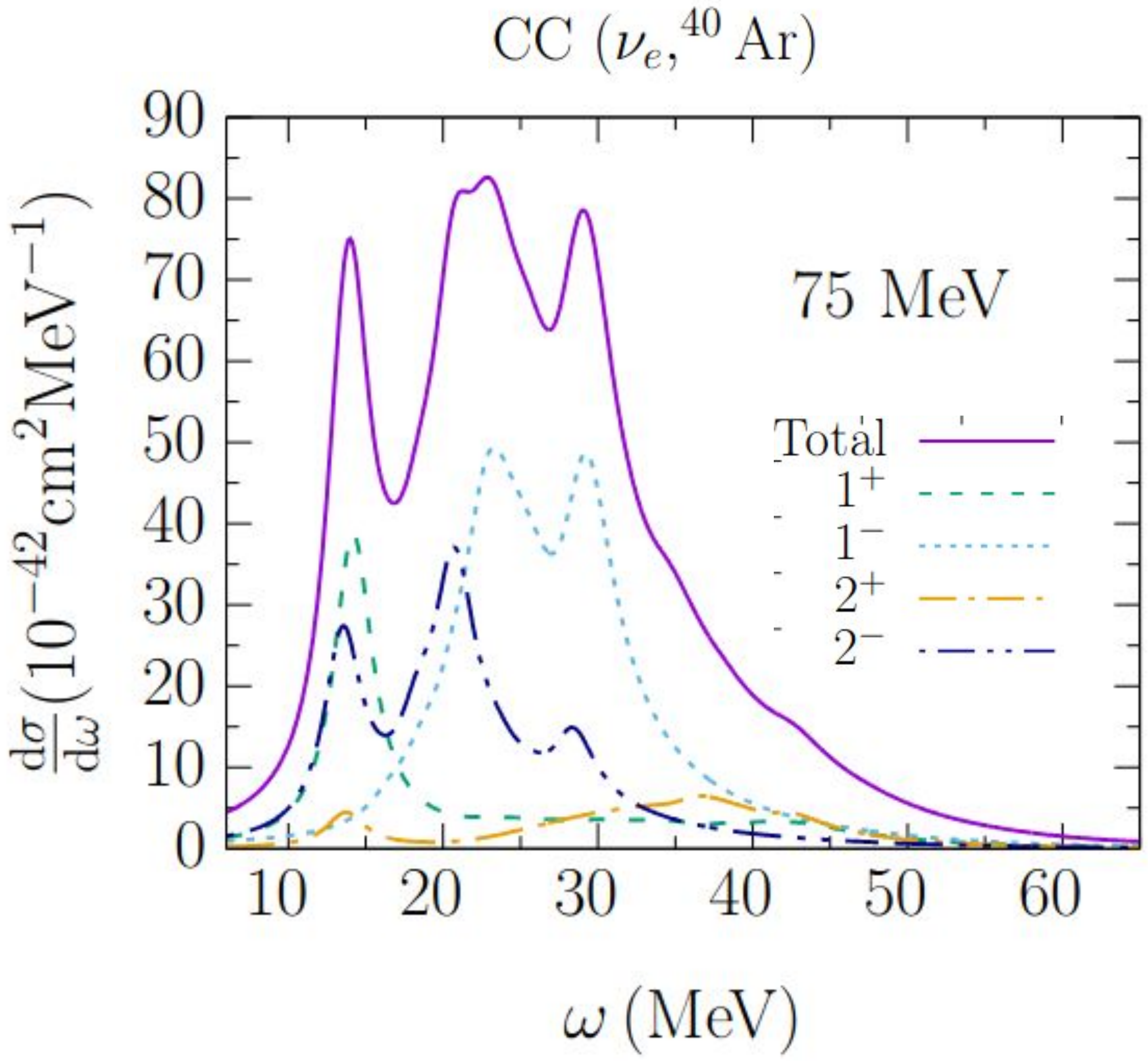


A real continuum for MARLEY: The HF-CRPA model

- Low-energy cross sections above the nucleon knockout threshold (~8 MeV)
  - See WG2 talk by Vishvas on Thursday afternoon
  - Developed by University of Ghent group: [Phys. Rev. C 100, 055503 (2019)]
- **Forbidden transitions** become important at several tens of MeV
  - Curves other than "1+" shown in the plot
- Implemented in MARLEY using tabulated nuclear responses
  - **Many thanks to Natalie Jachowicz, Alexis Nikolakopoulos, and Vishvas Pandey!**



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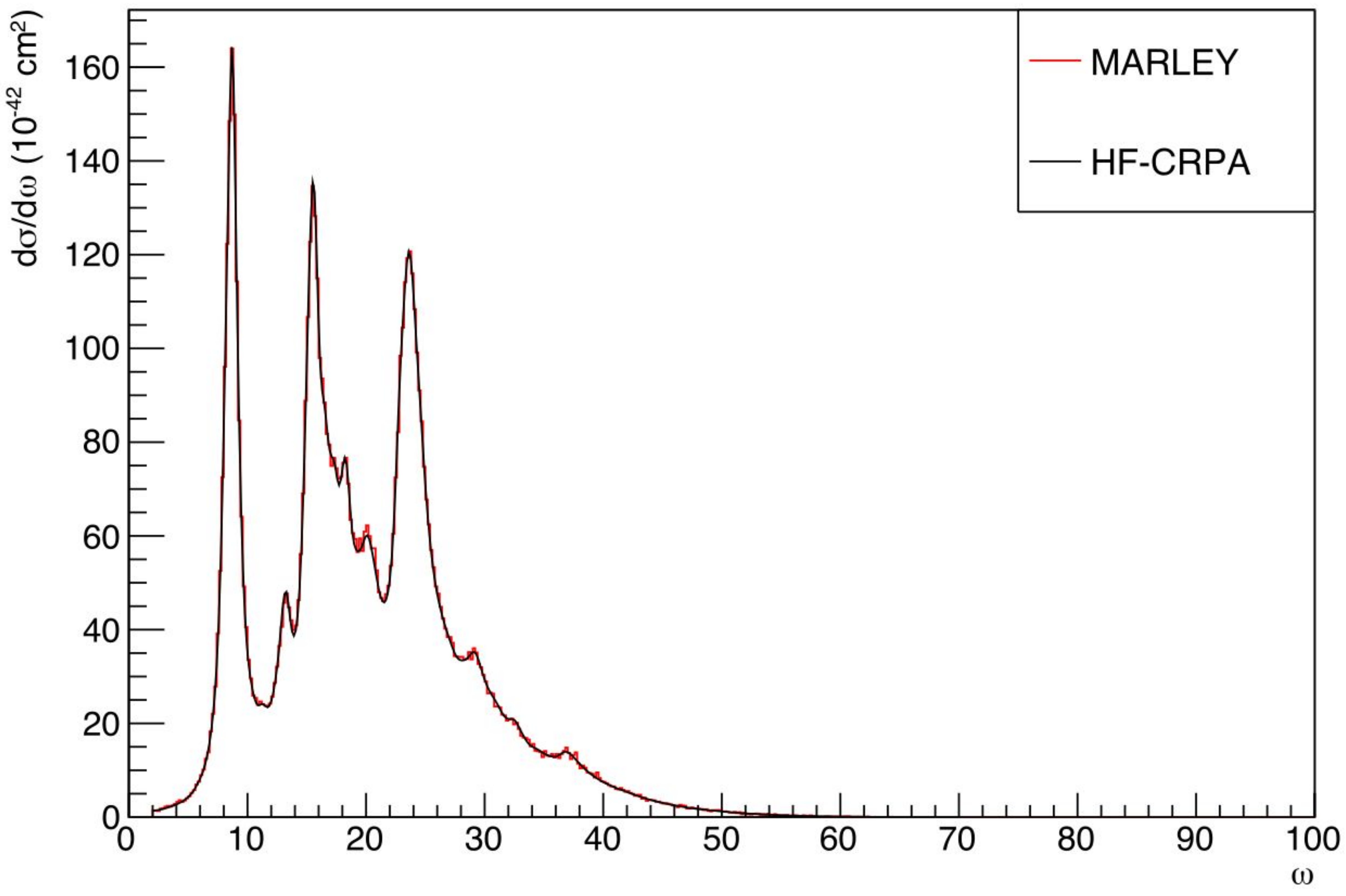
$$^{40}\mathrm{Ar}(\nu_e, e^-)X$$



Discrete transitions in MARLEY v1.2.1: Allowed approximation

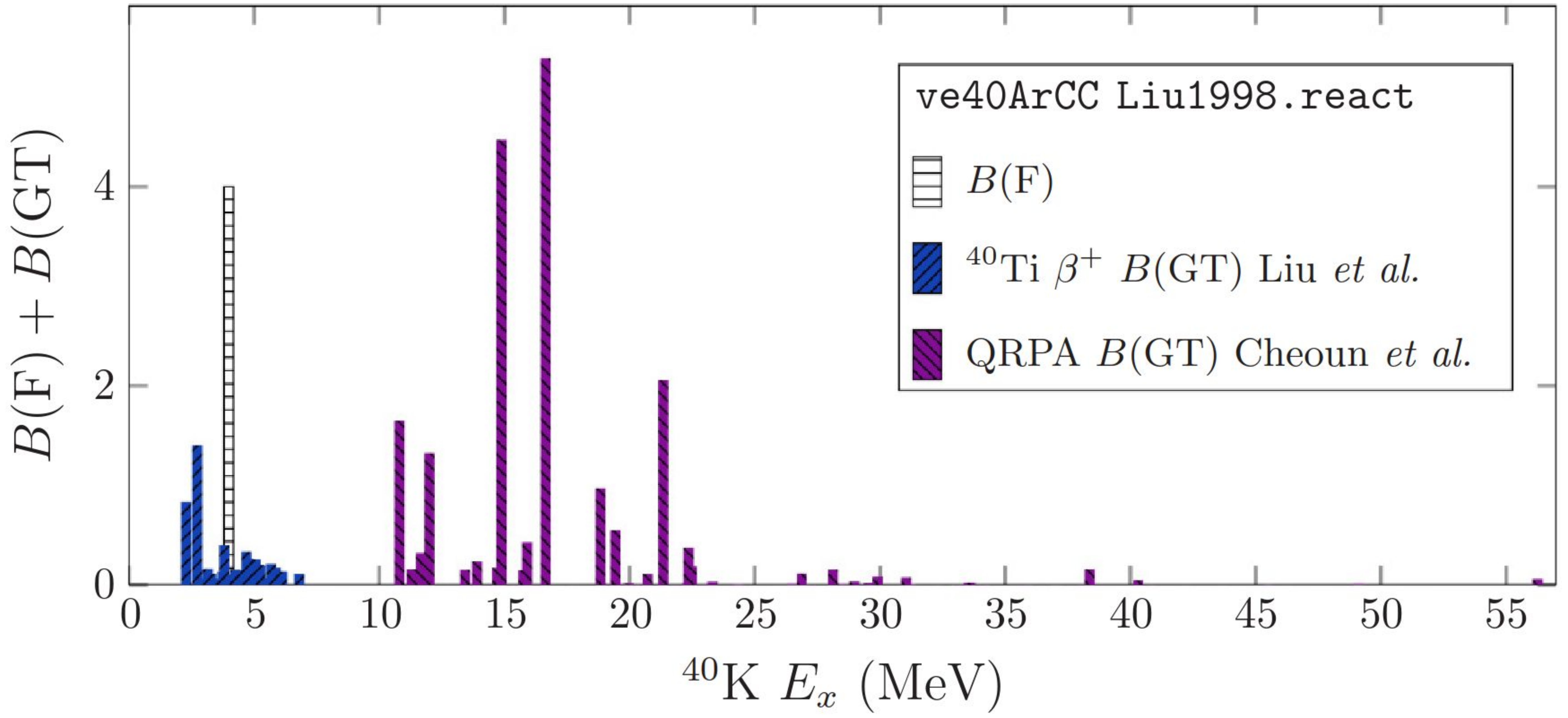
Differential cross section can be written in the form $$\frac{d\sigma}{d\cos\theta_\ell} = \frac{G_F^2\,|V_{ud}|^2}{2\,\pi}\,F_C\left[\frac{E_i\,E_f}{s}\right]E_\ell\,|\mathbf{k}'|\cdot \mathsf{v}_{\mu\nu}\,\mathsf{R}^{\mu\nu}$$

AA evaluates the nucleon current under two limits:

Long-wavelength limit: $q \to 0$

$$j^t = g_V\,t_\mp \qquad j^a = -\sigma^a\,g_A\,t_\mp$$

Slow nucleon limit: $\frac{|\mathbf{p}_{N_i}|}{m_N} \to 0$



Tensor contraction evaluated using Fermi and Gamow-Teller strengths, from data where available

$$\mathsf{v}_{\mu\nu}\,\mathsf{R}^{\mu\nu} = \left(1 + \beta_\ell\cos\theta_\ell\right)B(\mathrm{F}) + \left(1 - \frac{1}{3}\,\beta_\ell\cos\theta_\ell\right)B(\mathrm{GT})$$

[Phys. Rev. C 103, 044604 (2021)]

Improved discrete treatment

- Dependence on momentum transfer κ = |**q**| needed for compatibility with HF-CRPA
    - Current operators now evaluated to order $1/m_N$
- Data-driven approach retained
    - "Old MARLEY" preserved in AA limits
    - Input B(F) and B(GT) scaled by relevant form factors dependent on Q^2
- j_0 dependence is roughly approximated in nuclear matrix element:

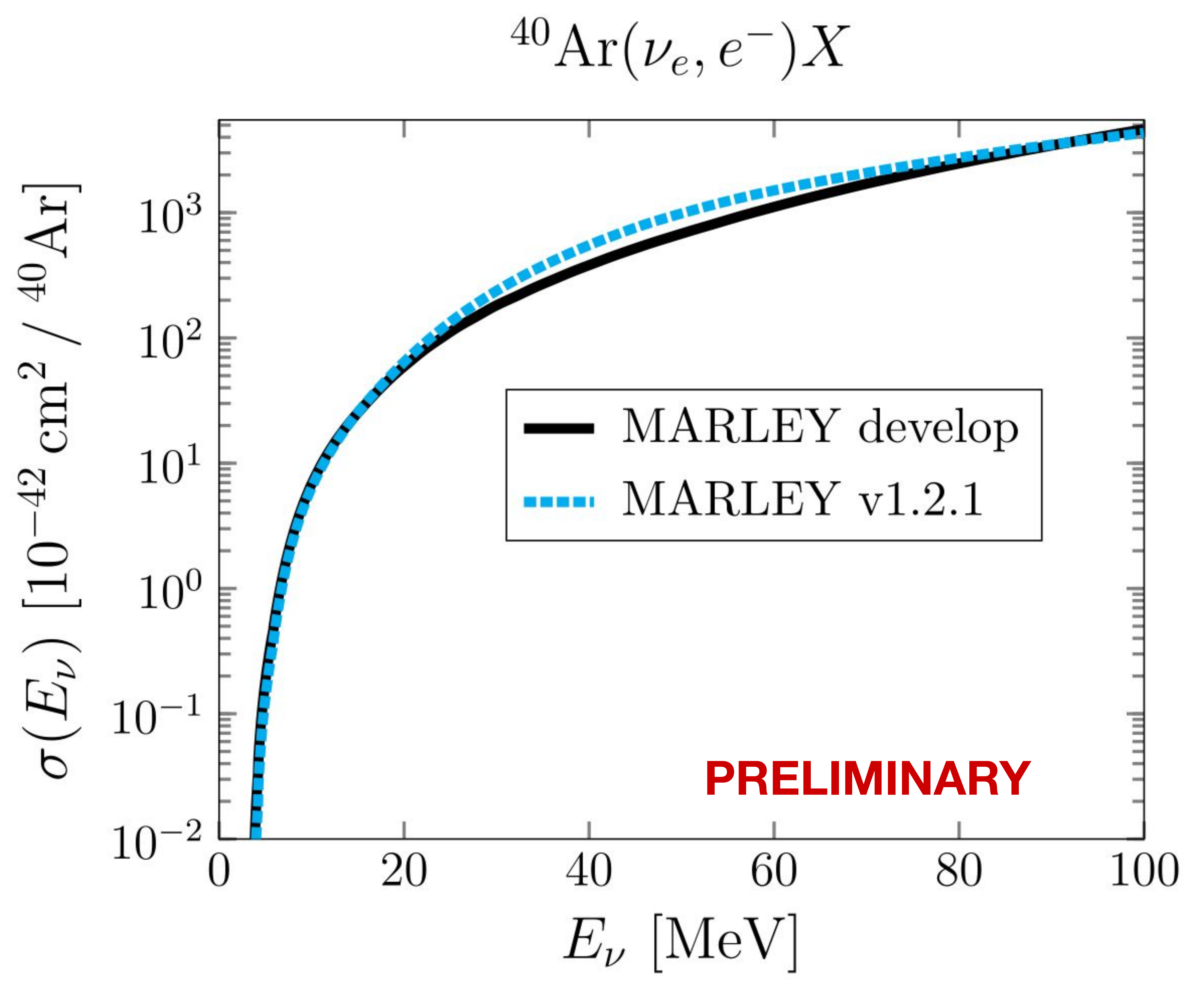
$$\left\langle J_f \left|\left| \sum_{k=1}^{A} j_0(\kappa r_k) t_-(k) \right|\right| J_i \right\rangle \simeq \left(\frac{1}{N} \sum_{k \in \text{neutrons}} j_0(\kappa r_k) \right) \left\langle J_f \left|\left| \sum_{k=1}^{A} t_-(k) \right|\right| J_i \right\rangle$$

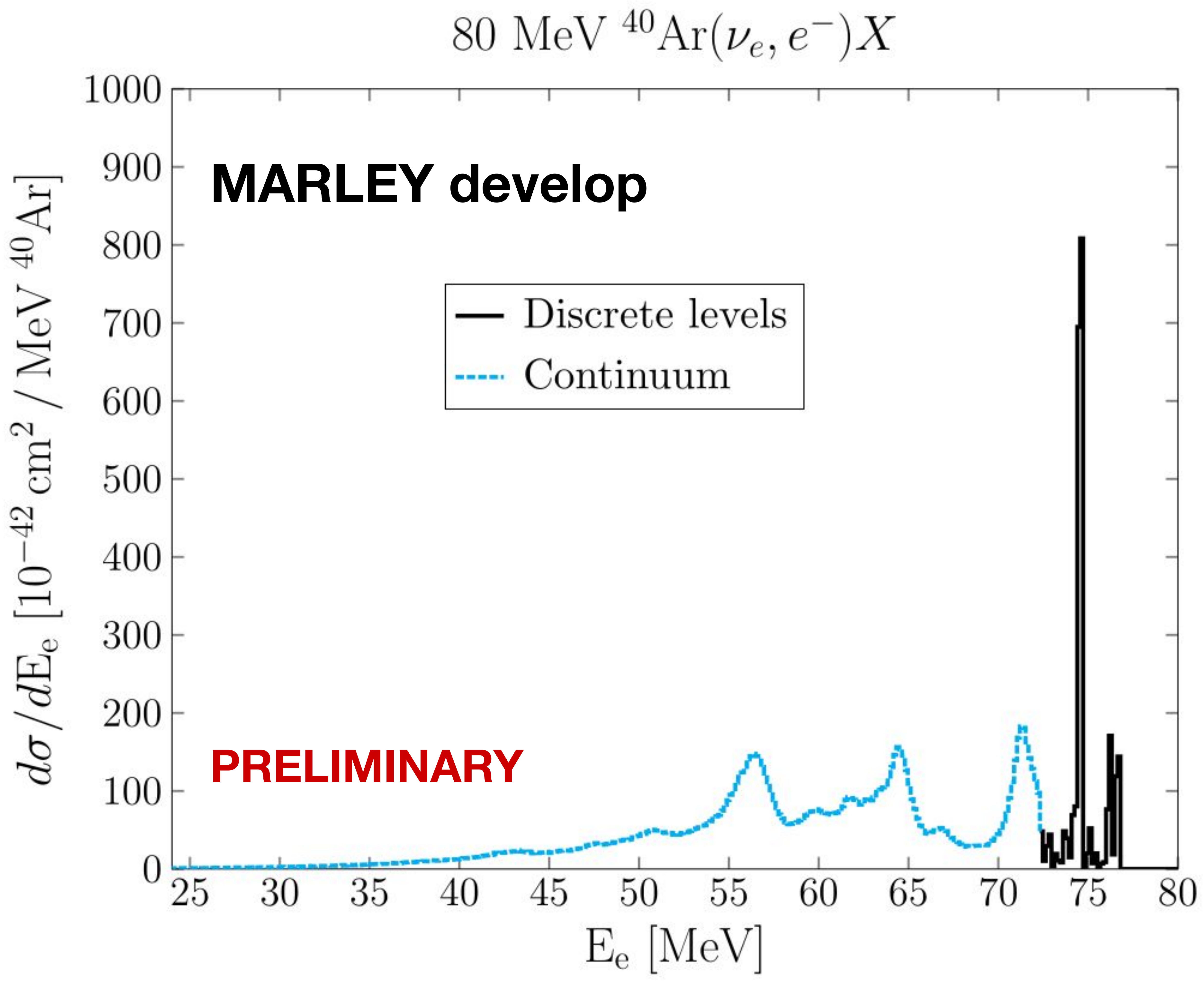
$$\begin{aligned} \mathrm{v}_{\mu\nu}\, \mathrm{R}^{\mu\nu} = {} & F_1^2\, \mathcal{B}_F \left[v_{CC} + \frac{\kappa}{m_N}\, v_{CL} + \frac{\kappa^2}{4\, m_N^2}\, v_{LL} \right] \\ & + F_A^2\, \mathcal{B}_{GT} \left[\frac{\kappa^2}{12\, m_N^2} \left(1 - 2\,\omega\, F_{PA} + \omega^2\, F_{PA}^2\right) v_{CC} \right. \\ & + \frac{\kappa}{3 m_N} \left(1 - \left[\omega + \frac{\kappa^2}{2 m_N}\right] F_{PA} + \frac{\omega\, \kappa^2}{2\, m_N}\, F_{PA}^2 \right) v_{CL} \\ & + \left(\frac{1}{3} - \frac{\kappa^2}{3\, m_N}\, F_{PA} + \frac{\kappa^4}{12\, m_N^2}\, F_{PA}^2 \right) v_{LL} \\ & \left. + \left(\frac{2}{3} + \frac{\kappa^2}{6\, m_N^2}\, F_{12A}^2 \right) v_T - h\, \frac{2\kappa}{3 m_N}\, F_{12A}\, v_{T'} \right] \end{aligned}$$

v factors are dimensionless functions of lepton kinematics

F_{PA} and F_{12A} are expressions involving multiple nucleon form factors

Inclusive cross-section results

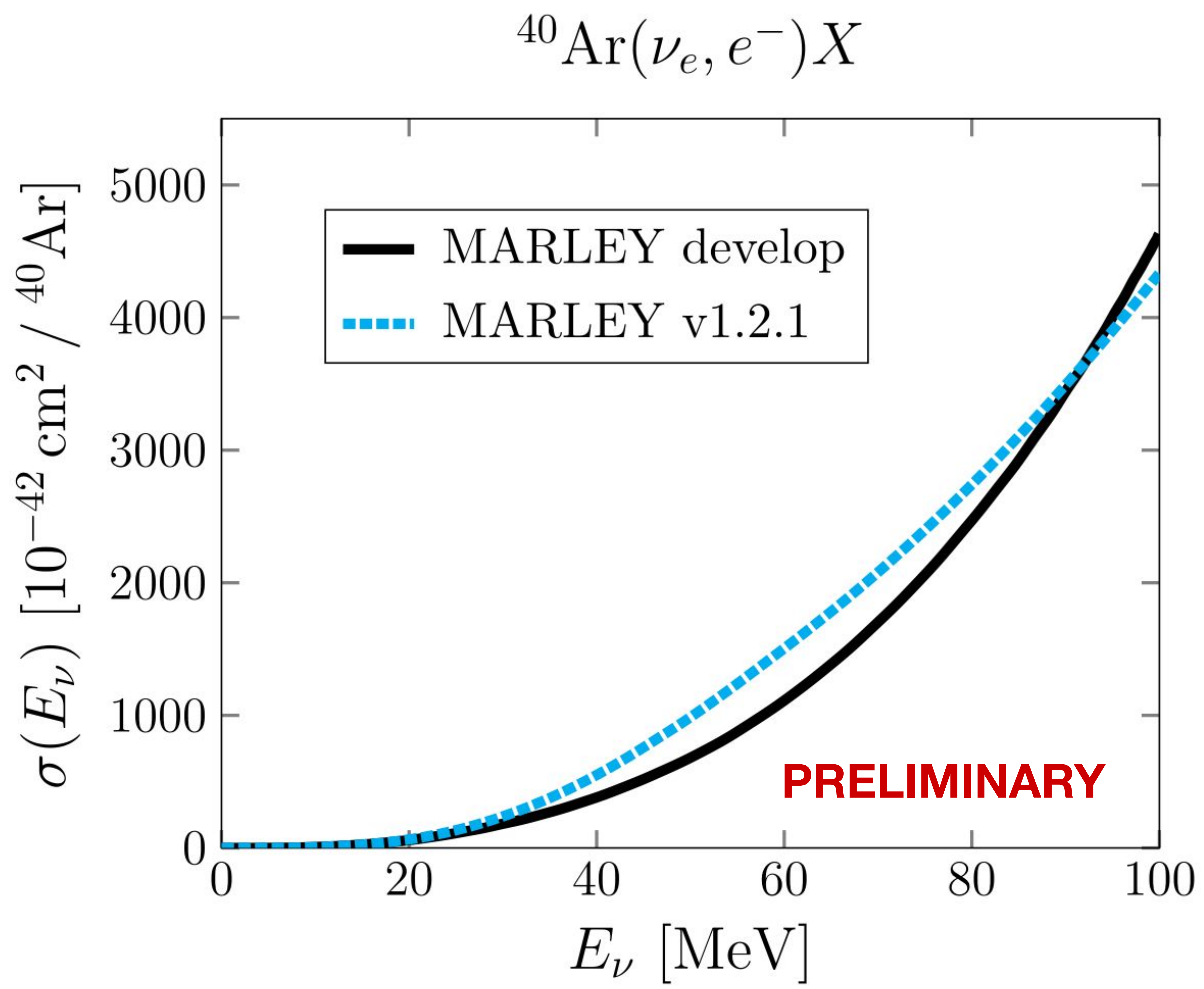




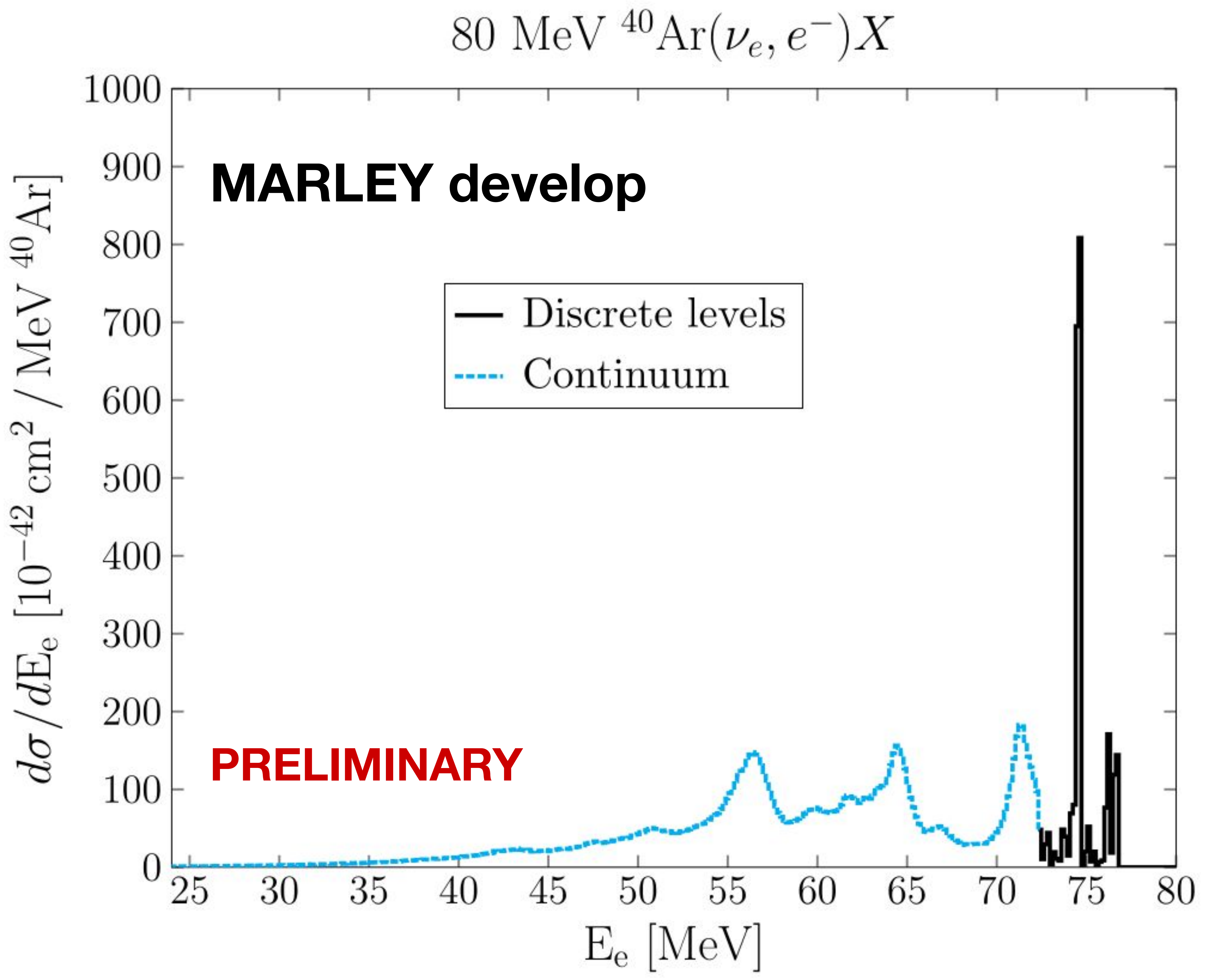
Reduction in σ(Eν) seen at a few tens of MeV

Continuum contributions now behave as expected

Inclusive cross-section results



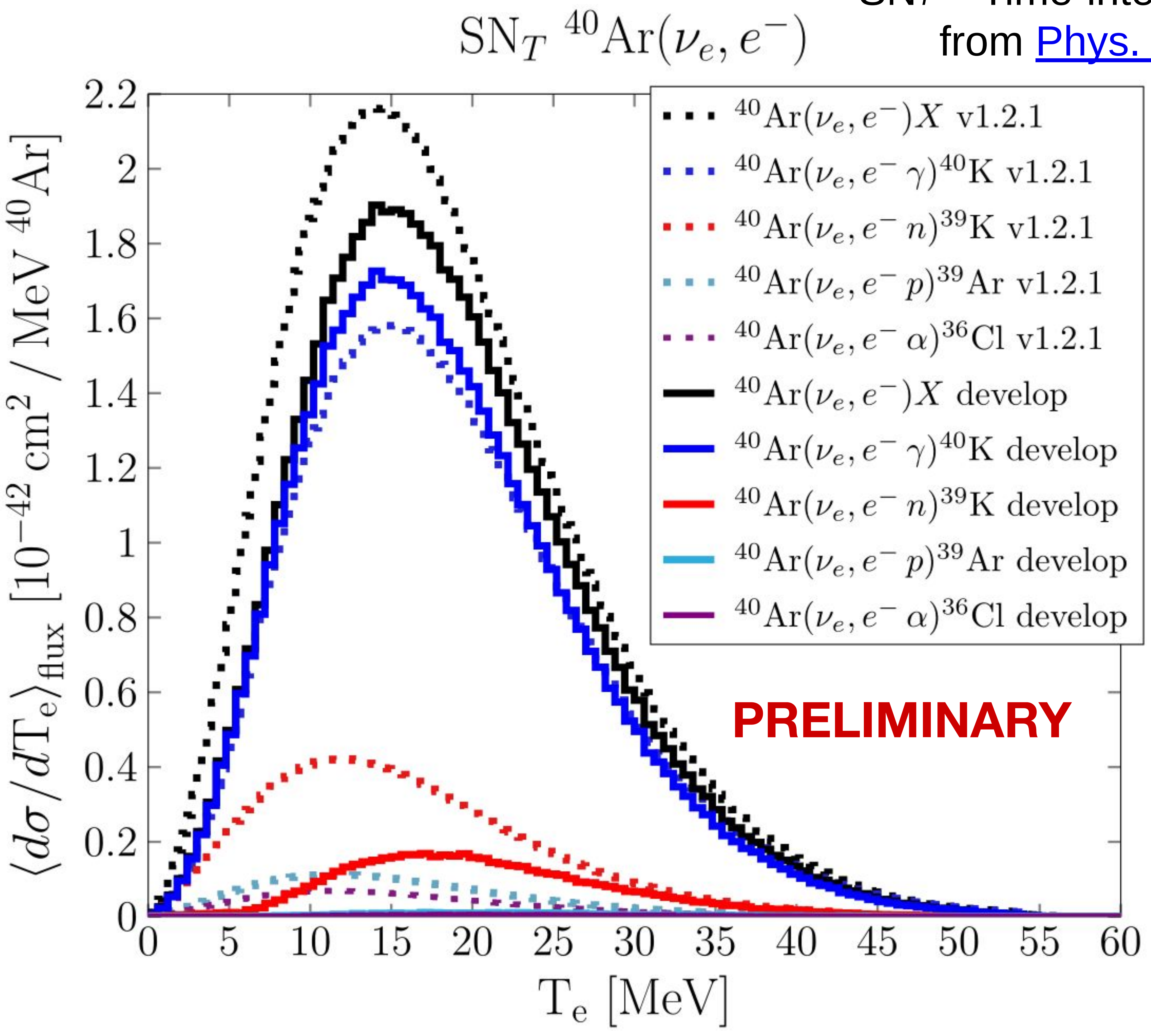
Reduction in σ(Eν) seen at a few tens of MeV



Continuum contributions now behave as expected

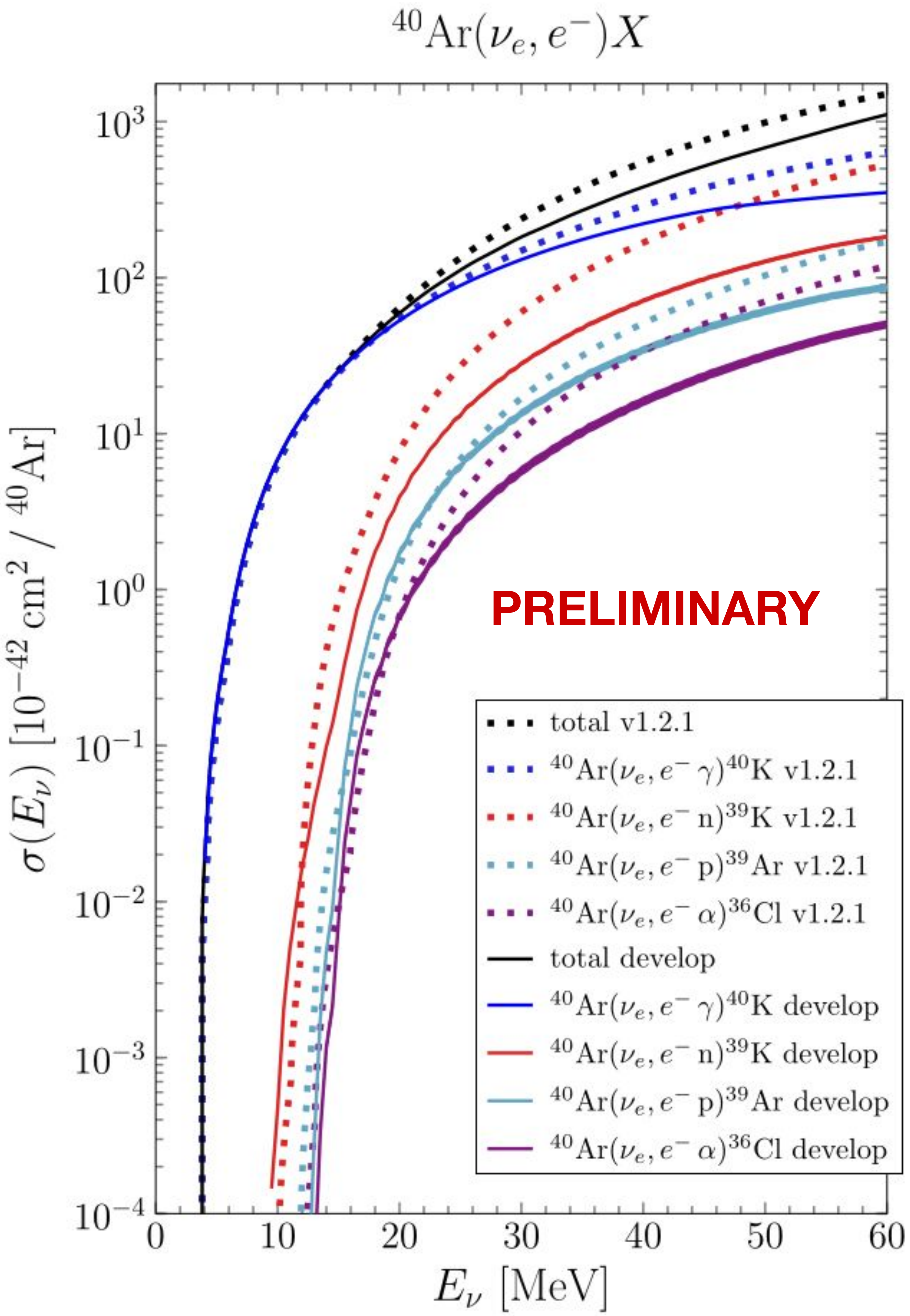
Exclusive predictions

SN_T = Time-integrated supernova ν_e spectrum from Phys. Rev. D 97, 023019 (2018)



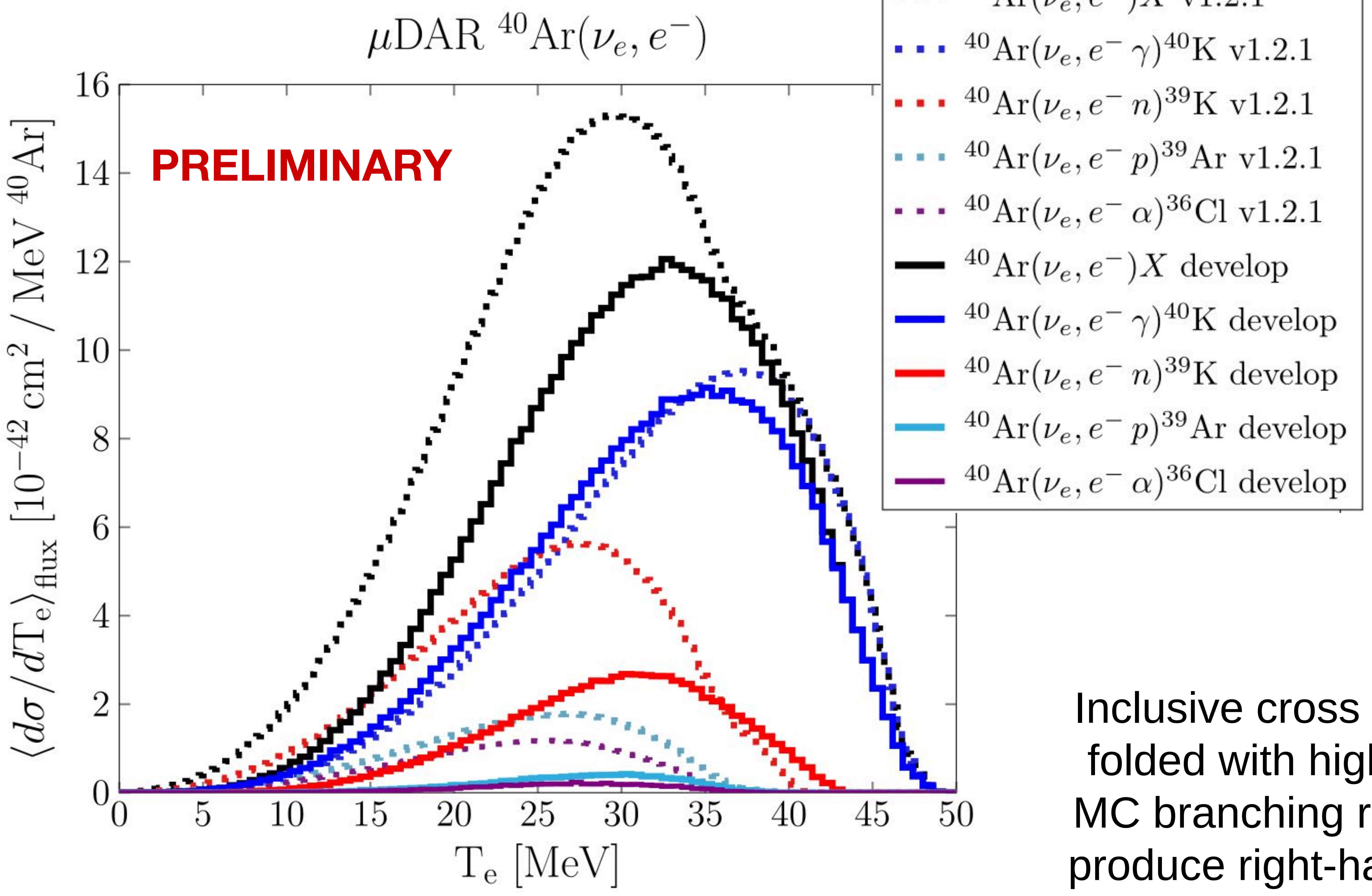
Neutron emission reduced in new calculation = less missing energy for DUNE

Inclusive cross section folded with high-stats MC branching ratios to produce right-hand plot



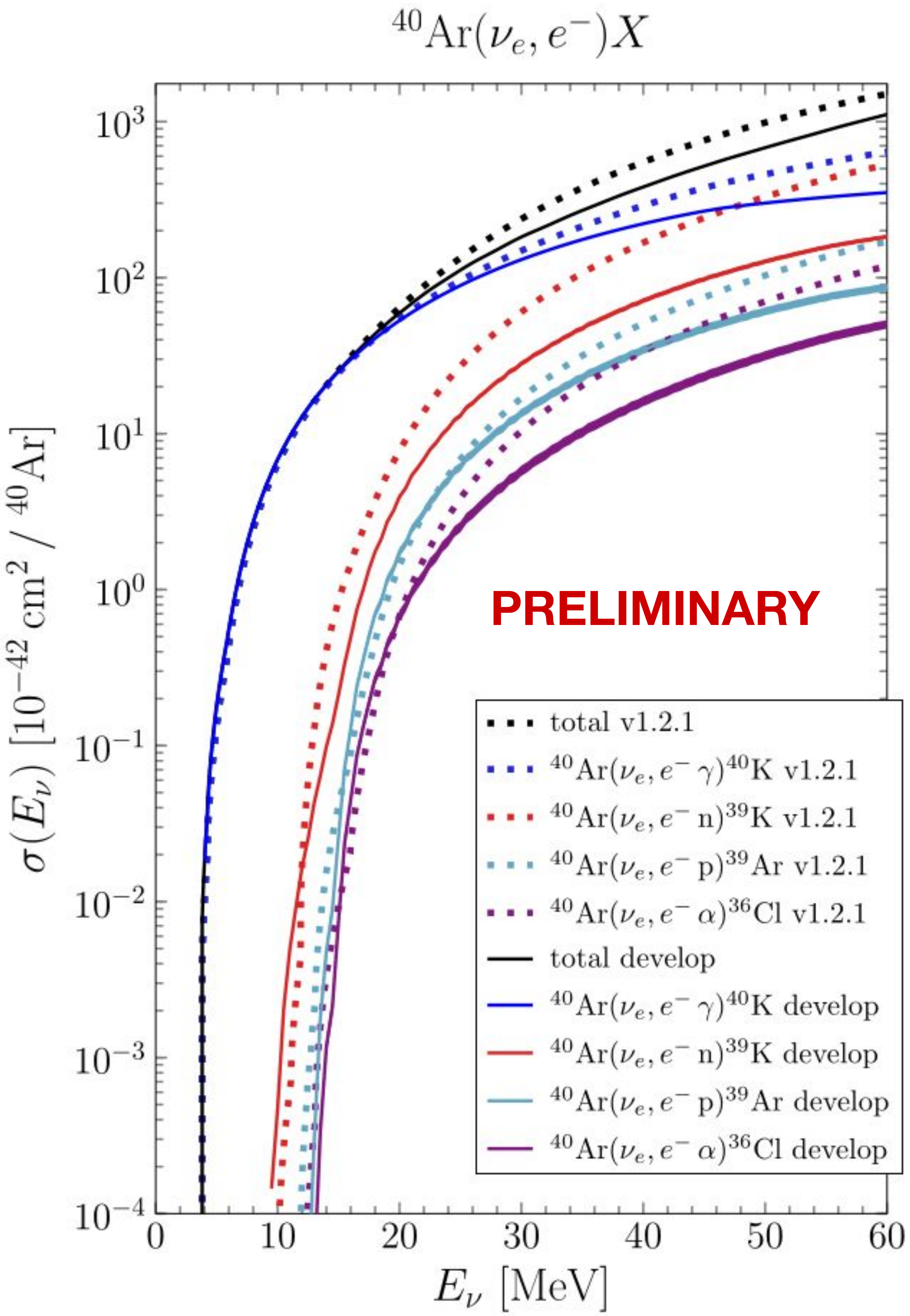
Exclusive predictions

μDAR = μ^+ decay-at-rest spectrum



Still almost entirely **1n** and **γ-only** final states in new calculation

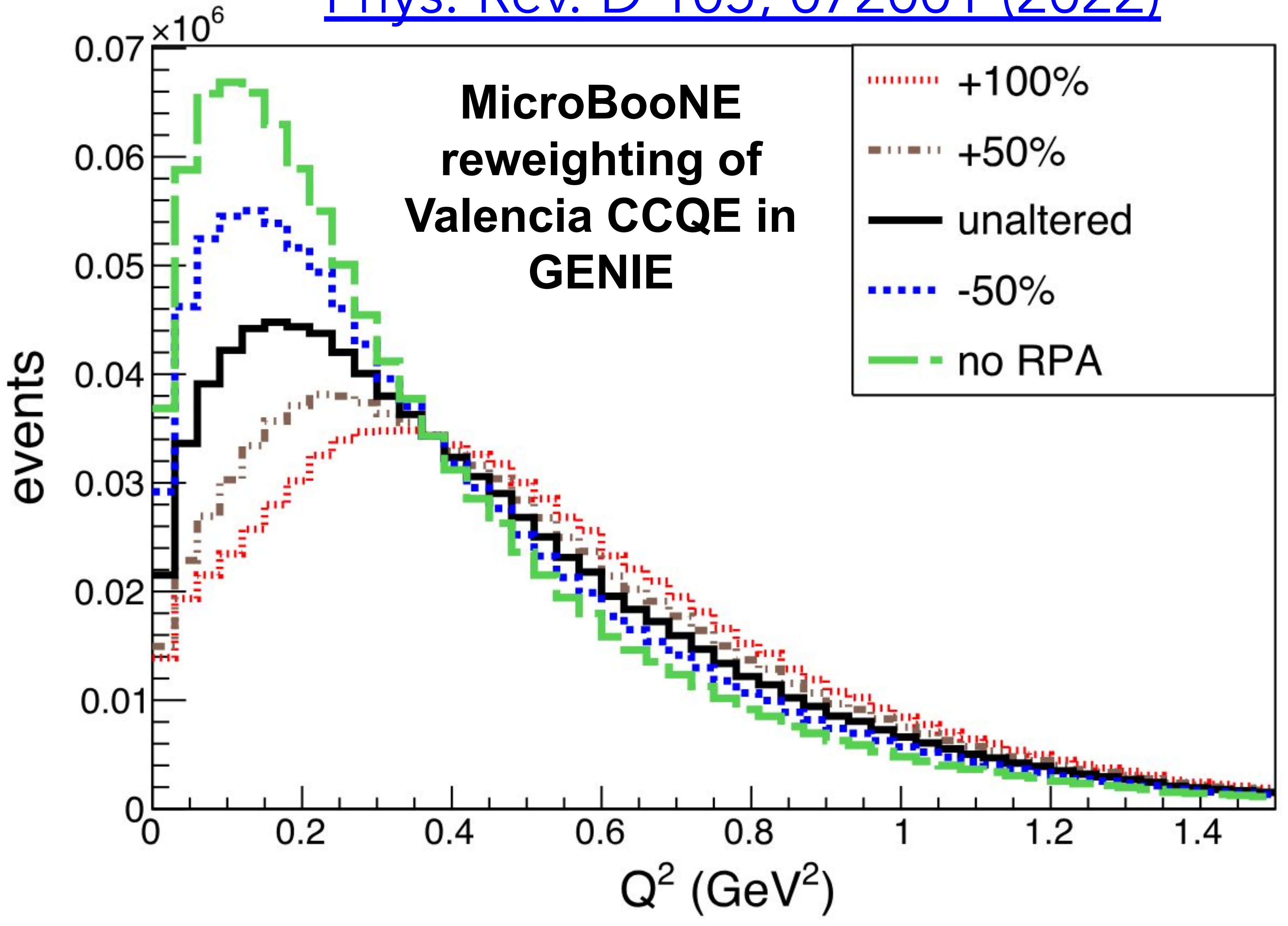
Inclusive cross section folded with high-stats MC branching ratios to produce right-hand plot

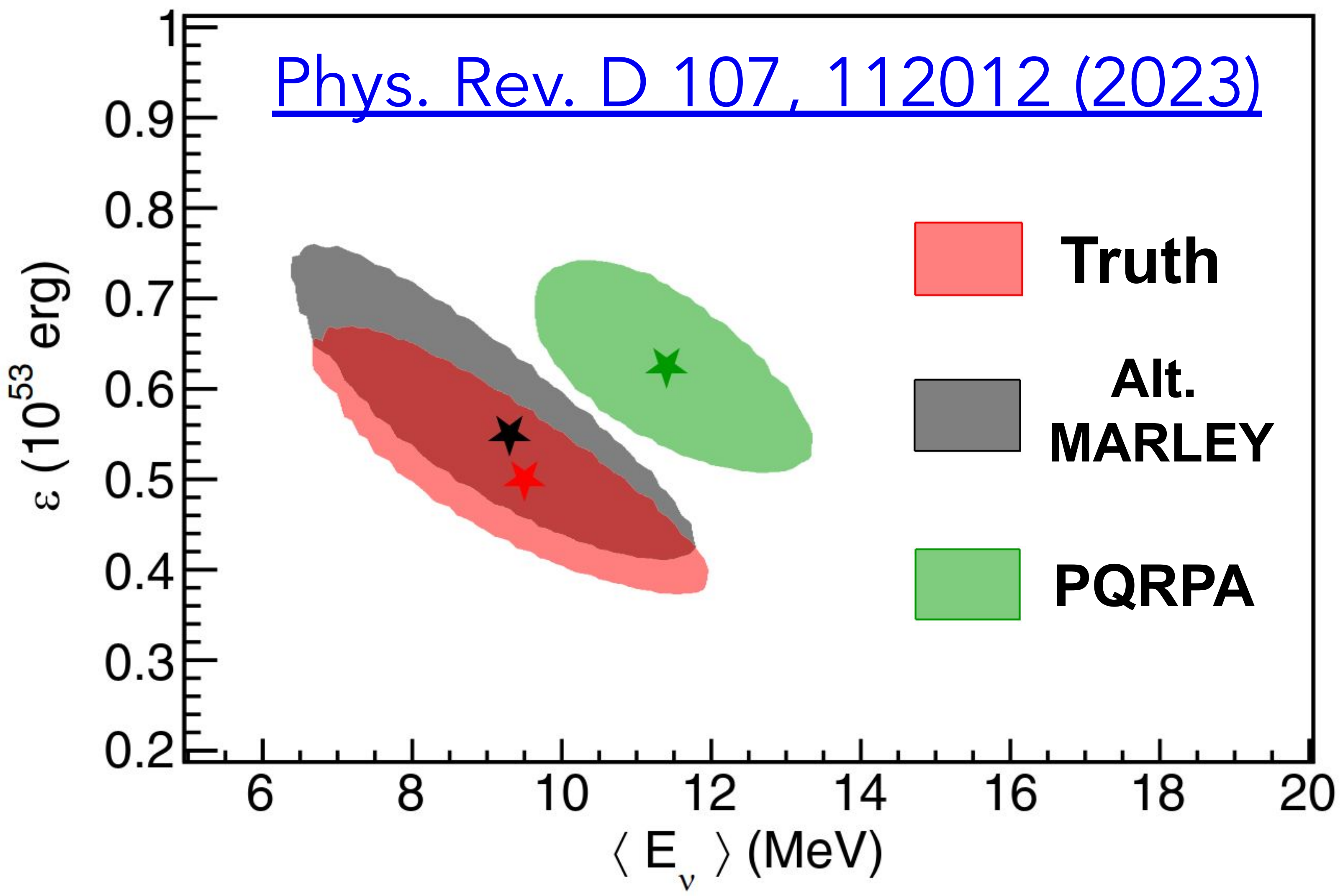


Reweighting for uncertainty quantification

- Standard "tool of the trade" at GeV energies
  - Weights assigned according to likelihood ratio between alternate and nominal physics models
- **Systematics** in future MARLEY-based analyses
  - Efficiency / purity / energy resolution for supernova ν_e detection in DUNE
  - Neutrino backgrounds for MeV-scale exotic physics searches
- Some **exploration of uncertainties** already
  - No technical infrastructure in MARLEY v1.2.1
  - $\sigma(E_\nu)$ uncertainty not rigorously quantified yet

Phys. Rev. D 105, 072001 (2022)





MARLEY nuclear de-excitation model

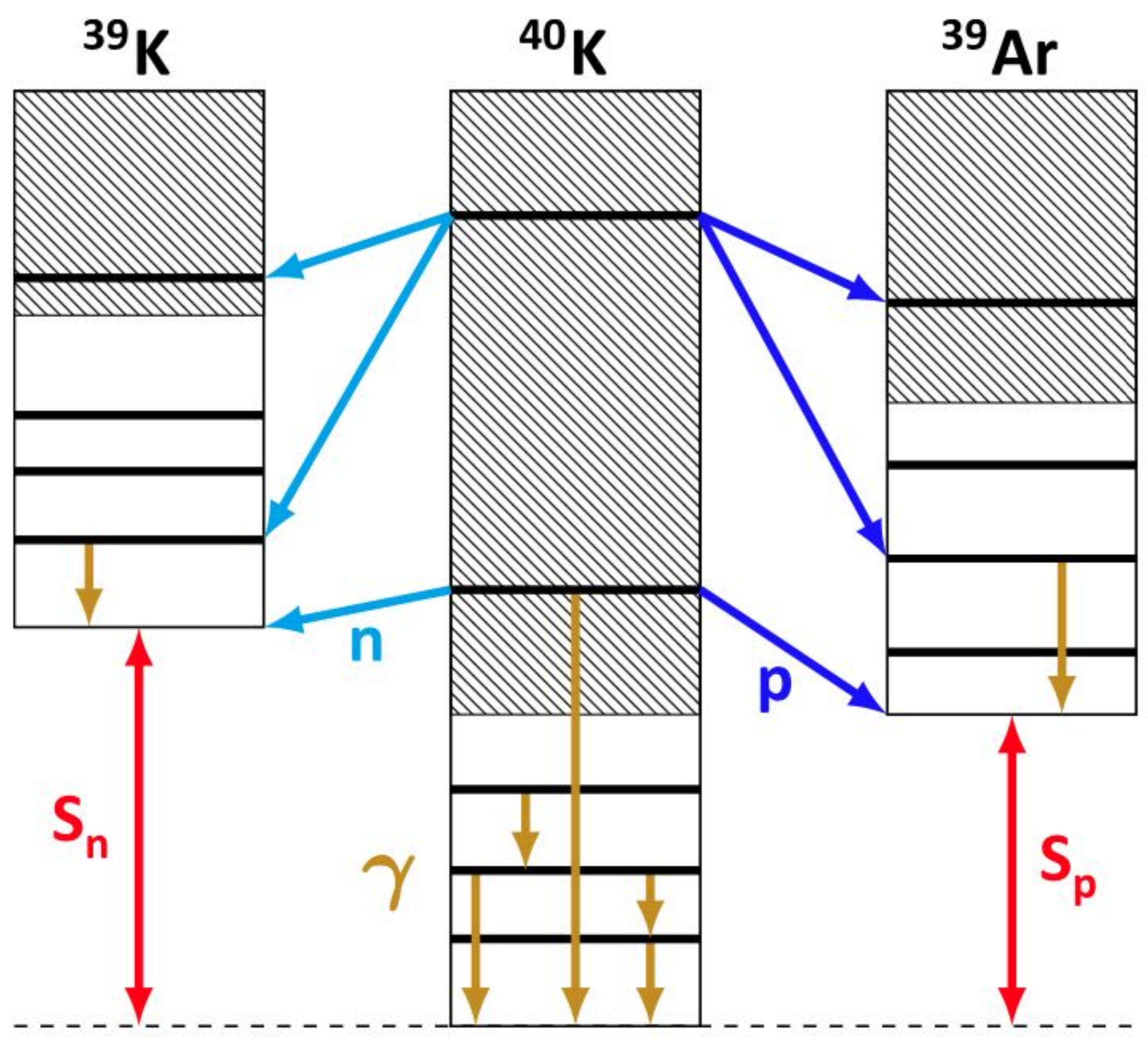
Hauser-Feshbach formalism for computing differential decay widths:

Differential decay width for emission of a nuclear fragment α (A ≤ 4 considered)

$$\frac{d\Gamma_\alpha}{dE'_x} = \frac{1}{2\pi\rho_i(E_x, J, \Pi)} \sum_{\ell=0}^{\ell_{\max}} \sum_{j=|\ell-s|}^{\ell+s} \sum_{J'=|J-j|}^{J+j} T_{\ell j}(\varepsilon)\, \rho_f(E'_x, J', \Pi')$$

Differential decay width for emission of a γ-ray

$$\frac{d\Gamma_\gamma}{dE'_x} = \frac{1}{2\pi\rho_i(E_x, J, \Pi)} \sum_{\lambda=1}^{\lambda_{\max}} \sum_{J'=|J-\lambda|}^{J+\lambda} \sum_{\Pi'\in\{-1,1\}} T_{X\lambda}(E_\gamma)\, \rho_f(E'_x, J', \Pi')$$



Phenomenological ingredients based on global fits to nuclear reaction data

Level density model: Back-shifted Fermi gas
Nucl. Data Sheets 110, 3107–3214 (2009)

Nuclear optical model potential: Koning & Delaroche,
Nucl. Phys. A 713, 231–310 (2003)

Gamma-ray strength function model: Standard Lorentzian
Nucl. Data Sheets 110, 3107–3214 (2009)

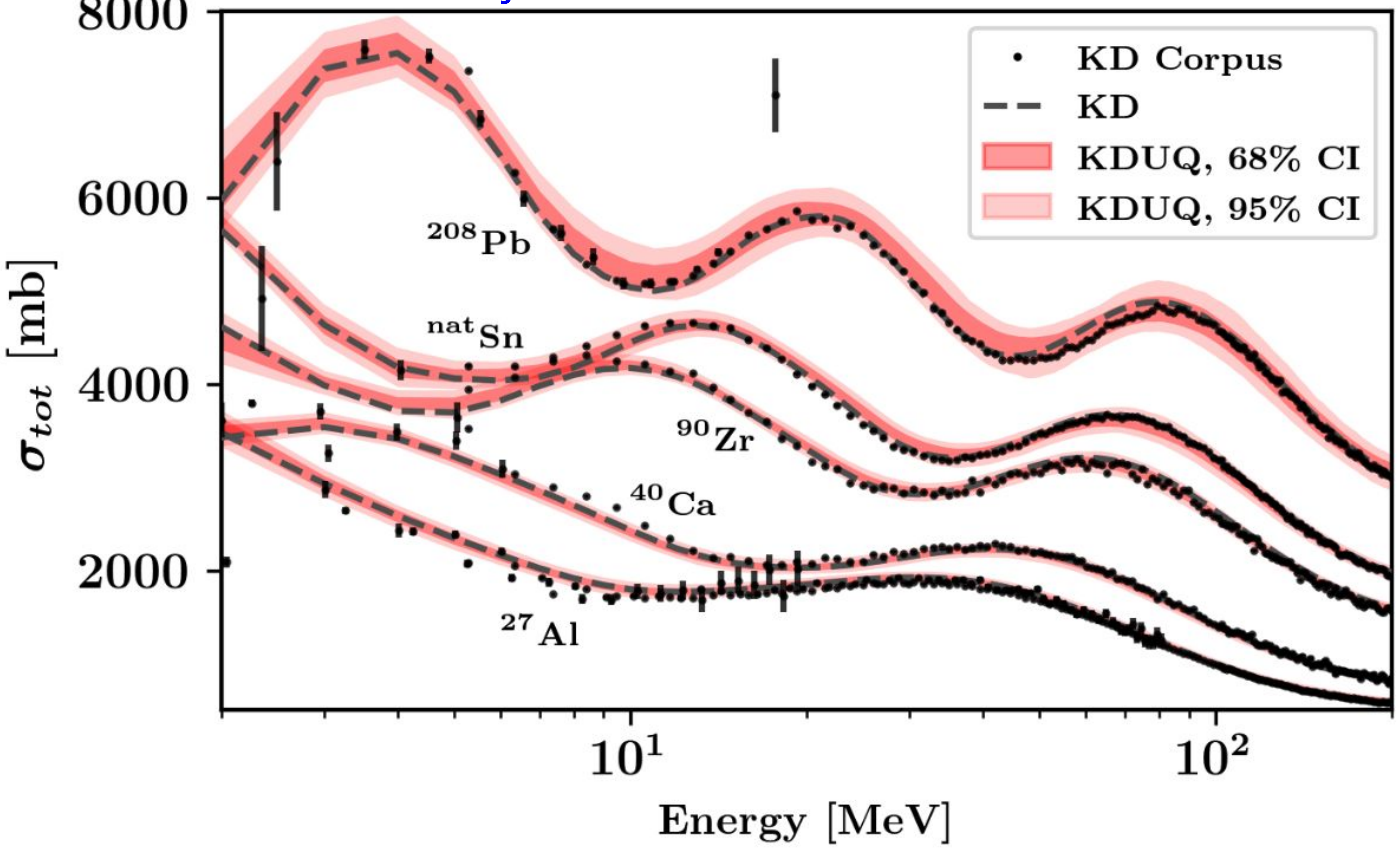
Supplemented with tabulated discrete levels and γ-rays for bound states (taken from TALYS 1.6).

Transitions from continuum to all accessible levels are explicitly treated.

Optical model potential uncertainties

- Original KD fit did not report these
- Revisited by Pruitt *et al.* (LLNL) in 2023
  - Motivated by applications to FRIB, etc.
  - KDUQ optical potential includes covariances between all 46 empirical parameters
- How do these impact calculations of exclusive O(10 MeV) neutrino cross sections?
  - Expected to be sub-leading at present
  - Well-justified by data, related uncertainties (level densities, etc.) under development
  - Starting point for MARLEY uncertainty toolkit

Phys. Rev. C 107, 014602 (2023)



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[Phys. Rev. C 107, 014602 (2023)]

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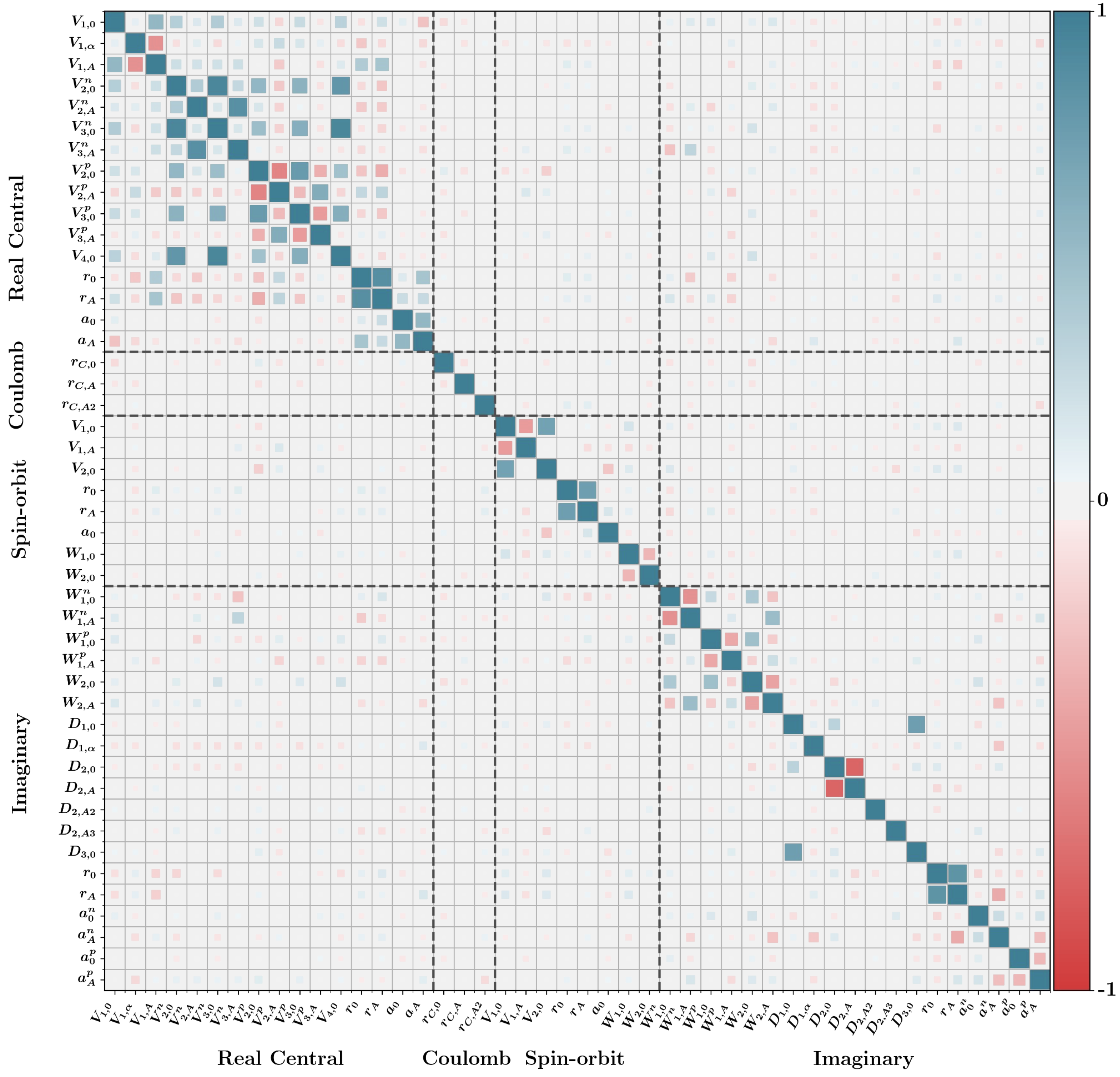

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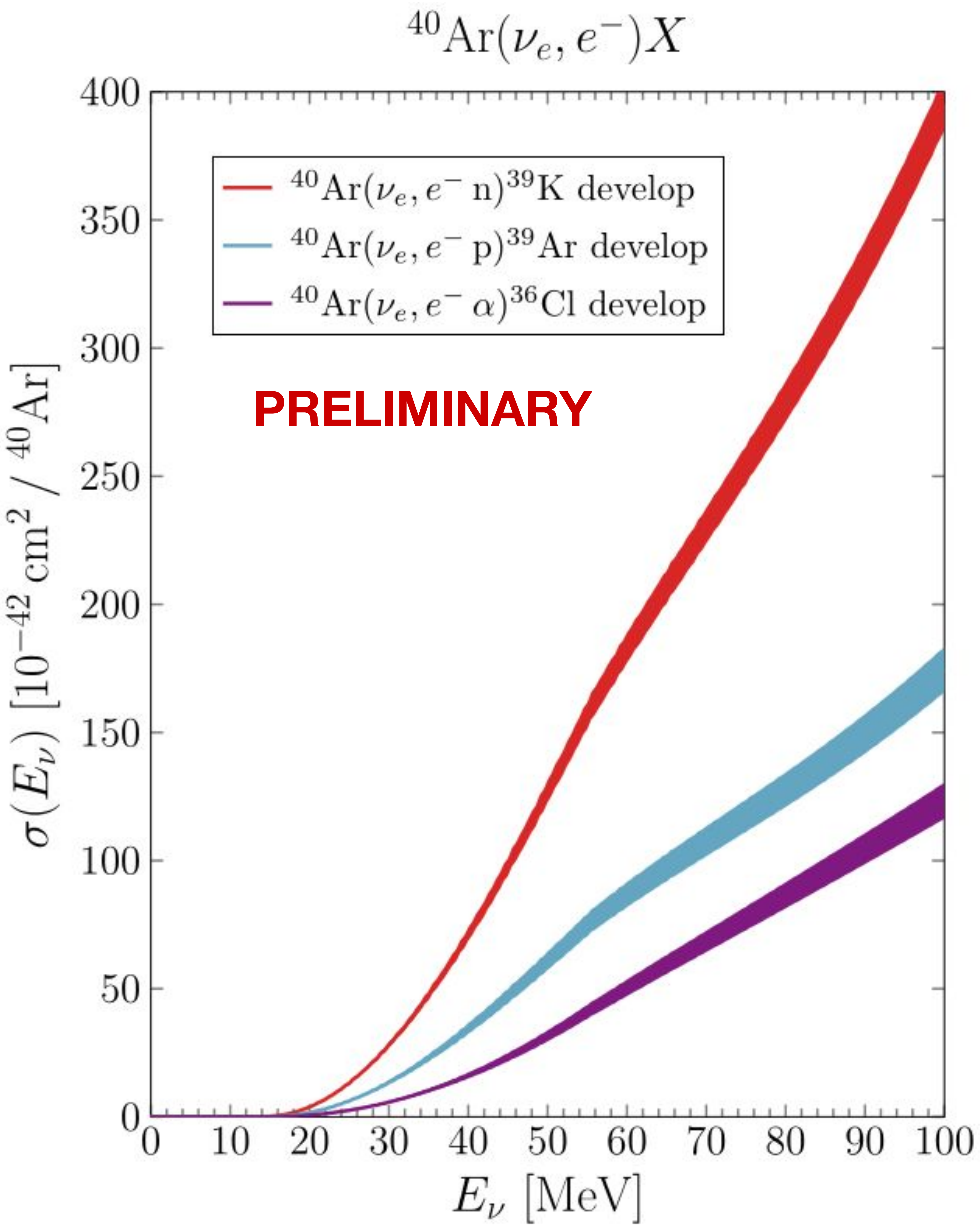
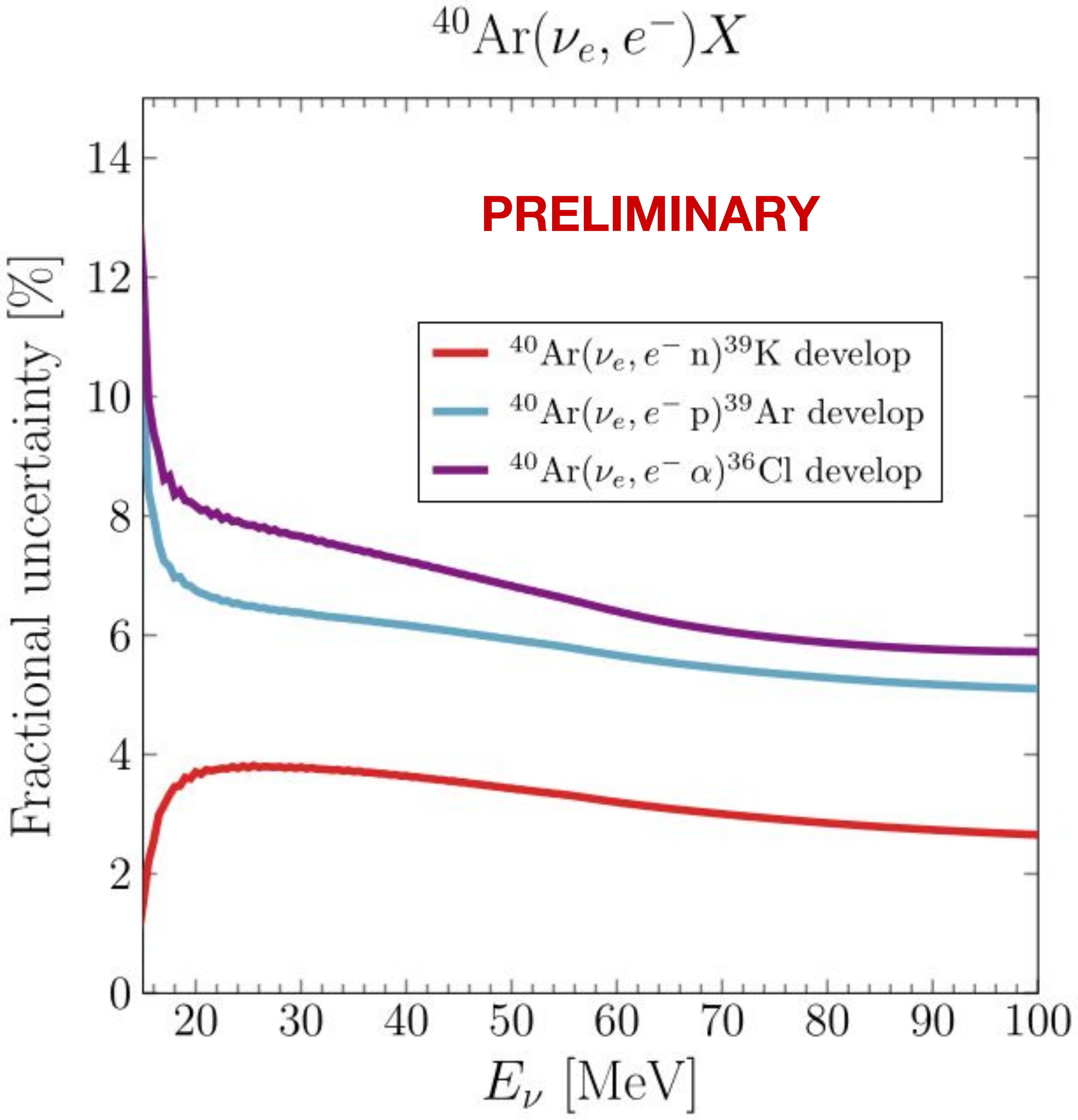


γ-only cross section dominated by discrete levels. OMP uncertainty nonzero but tiny!

1α has modestly higher fractional uncertainty → sensitive to both p and n OMP parameters



Towards MARLEY v2.0.0

- Many technical enhancements in addition to physics topics addressed in this talk

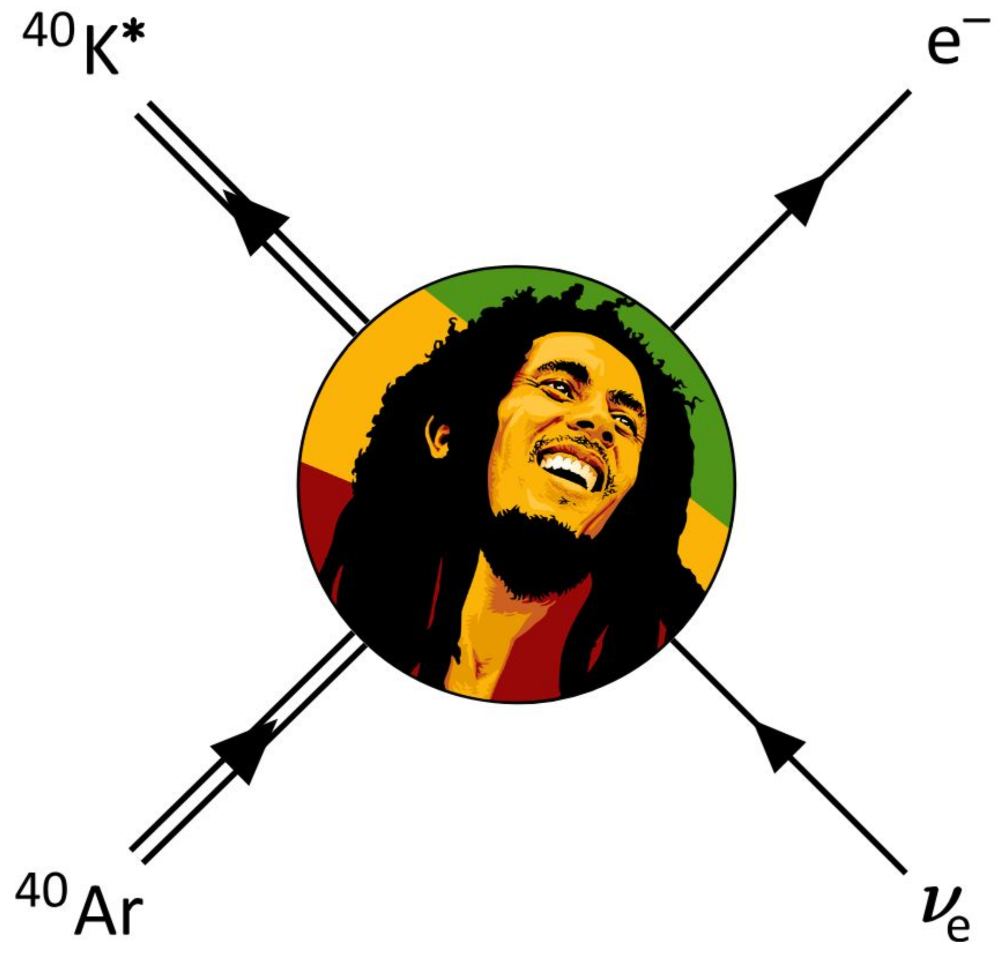
- **NuHepMC**: Universal neutrino generator event format
  - Adopted internally and in MARLEY output
  - Directly enables reweighting, other new features
  - Automated, generator-agnostic **analysis of results**
  - Could enable interoperability
    (e.g., delegate de-excitations to MARLEY)

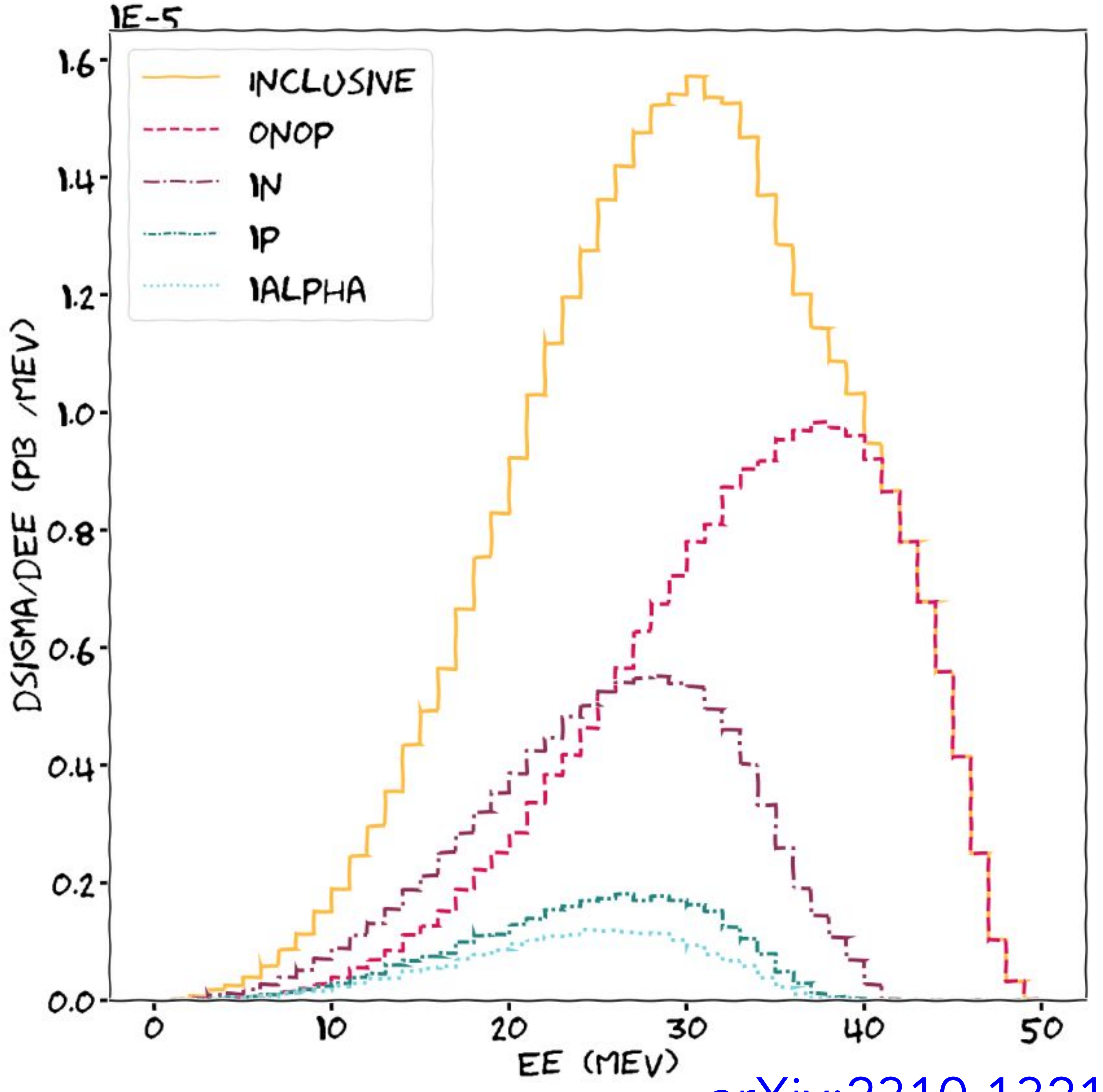
- **mardecay**: Standalone simulation of de-excitation step only

- **marreweight**: Apply new weights to existing MC sample

- Speedup of optical model calculations (~30x!)

- **New major release** (v2) anticipated in the coming months
  - Development team remains small ($\ll$ 1 FTE)
  - New collaborators are always welcome! (gardiner@fnal.gov)





arXiv:2310.13211

Backup