MARLEY updates

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DUNE Low-Energy Physics Working Group Meeting

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MARLEY paper news

- I recently made a big push to finally finish some papers about MARLEY
- **Physics paper: Phys. Rev. C 103, 044604 (2021)**
  - $^{40}\mathrm{Ar}(\nu_e, e^-)^{40}\mathrm{K}^*$ inclusive cross section
  - Nuclear de-excitation models
  - Brief discussion of impact on ν_e energy reconstruction
- **Implementation paper: arXiv:2101.11867**
  - Low-level guide to what the code does, step-by-step
  - User manual, instructions for interfacing with Geant4, etc.
  - Context in wider software landscape. Can't we just use GENIE?
  - Submitted to Computer Physics Communications on 3 February. Waiting on first round of referee comments.

Coulomb corrections are needed for CC cross section

- Dirac spinors are typically used for the leptonic part of the amplitude for CC ν-A scattering:

$$\bar{u}_e \gamma^\mu \left(1 - \gamma^5\right) u_{\nu_e}$$

- Cross section calculation involves the usual traces over these

- Outgoing electron subject to nuclear Coulomb potential
  - Not a free particle → use of a Dirac spinor is not fully correct
  - Most rigorous option: expand electron wave function in partial waves, use the distorted-wave born approximation (DWBA)

- Approximations are widely used instead. Standard approach is based on a paper by Jonathan Engel: **Phys. Rev. C 57, 2004 (1998)**.

MARLEY approach to Coulomb corrections (1)

- Correction factor F_C applied to the differential cross section
  - See the physics paper for definitions of all variables shown

$$\frac{d\sigma}{d\cos\theta_e} = F_C \frac{G_F^2 \, |V_{ud}|^2}{2\pi} \left[\frac{E_i E_f}{s}\right] E_e \, |\mathbf{p}_e| \left[(1+\beta_e \cos\theta_e) \, B(\mathrm{F}) + \left(1 - \frac{1}{3}\beta_e \cos\theta_e\right) B(\mathrm{GT})\right]$$

- **Low electron energies**: Fermi function

$$F_{\mathrm{Fermi}} = \frac{2\,(1+S)}{\left[\Gamma(1+2S)\right]^2} \left(2\gamma_{\mathrm{rel}}\,\beta_{\mathrm{rel}}\,m_e\,R\right)^{2S-2} e^{-\pi\eta} \left|\Gamma(S - i\eta)\right|^2$$

- **High electron energies**: Engel's "modified effective momentum approximation" (MEMA)

$$F_{\mathrm{MEMA}} = \frac{K_{\mathrm{eff}}\,E_{\mathrm{eff}}}{K\,E} \qquad E_{\mathrm{eff}} = E - V_C(0) \qquad V_C(0) \approx \frac{3\,Z_f\,z_e\,\alpha}{2\,R}$$

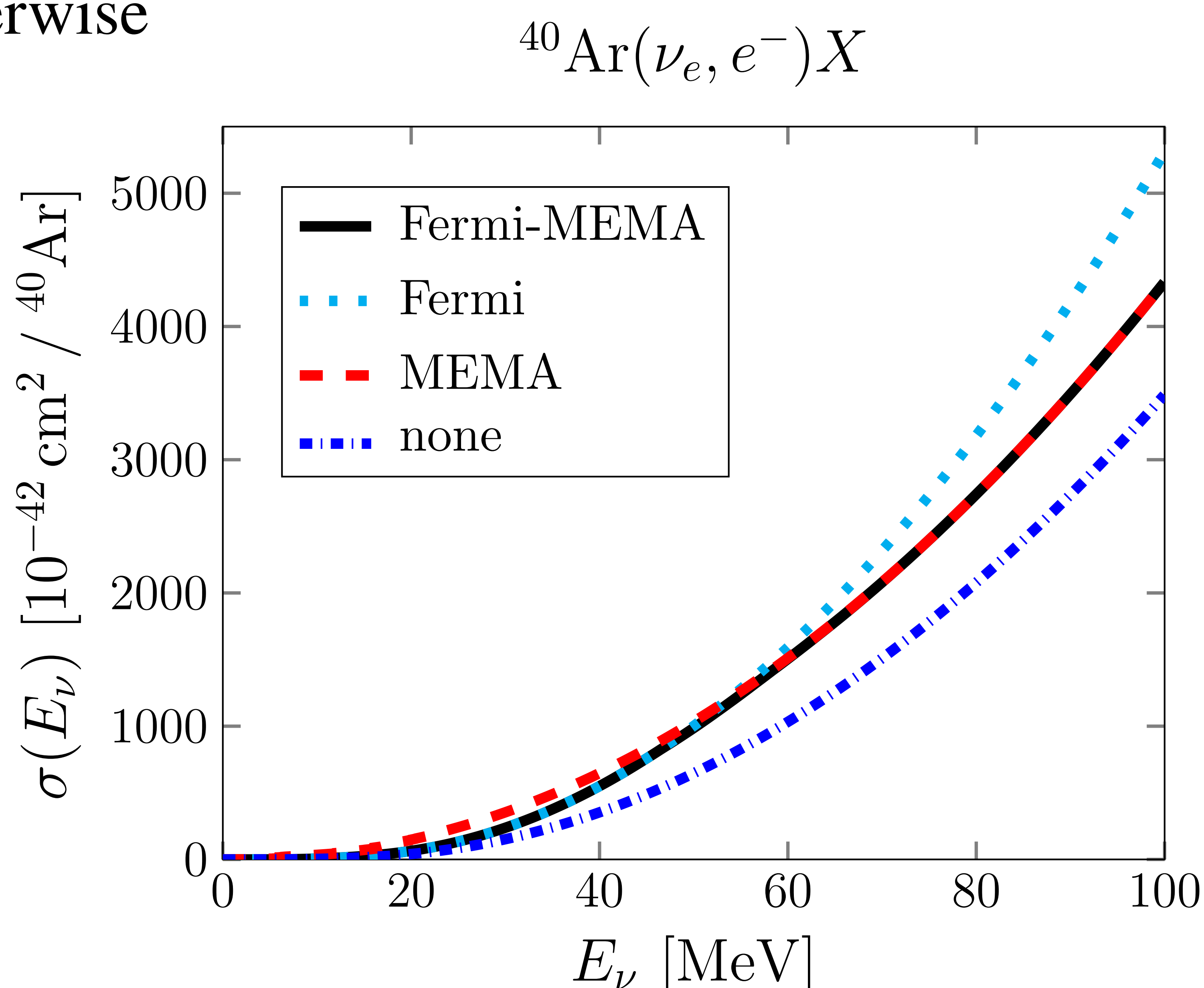
- Note that both depend on the nuclear radius R

MARLEY approach to Coulomb corrections (2)

- Each approach over-adjusts outside of its region of validity
- MARLEY solves this by choosing the smaller of the two corrections:

$$F_C = \begin{cases} F_{\text{Fermi}} & |F_{\text{Fermi}} - 1| < |F_{\text{MEMA}} - 1| \\ F_{\text{MEMA}} & \text{otherwise} \end{cases}$$

- The correction has a **sizable impact** on the CC total cross section:



Fermilab

MEMA bug in MARLEY v1.1.1

- Recent versions of LArSoft before v09_22_00 (the latest one) are built against MARLEY v1.1.1 (released 20 July 2019)
  - Physics content essentially identical to my PhD thesis
  - Minor updates to nuclear structure data and software framework
- While getting the papers ready, I noticed and fixed a problem in the code for the MEMA Coulomb correction (the Fermi function was okay)
  - Nuclear radius R used in the MEMA calculation was missing a factor of $\hbar c$ to convert to natural units:

$$R \approx \left(1.2\,\text{fm}\right) \cdot A^{1/3} \cdot \left(\hbar c\right)^{-1}$$

  - Since $\hbar c \approx 197\,\text{MeV} \cdot \text{fm}$, this causes the Coulomb potential to be far too small:

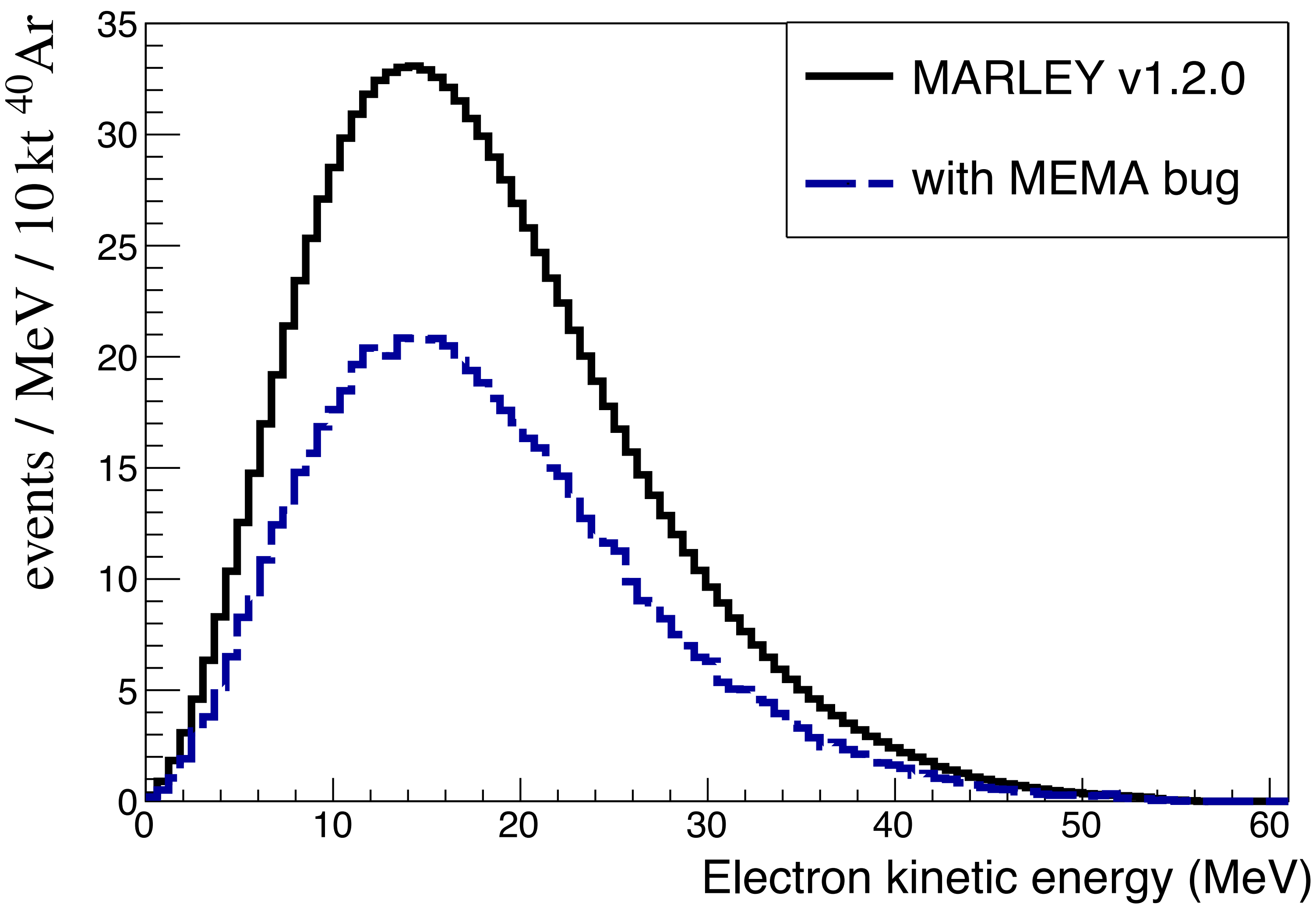
$$V_C(0) \approx \frac{3\,Z_f\,z_e\,\alpha}{2\,R}$$

Fermilab

Impact and fix

- This bug essentially turns the Coulomb corrections off in the v1.1.1 cross section
- Noticed and fixed on 2 April 2020, although full impact wasn't clear until later
- The current MARLEY release (v1.2.0) includes this fix and was used to generate all plots in the published paper
- Event rate estimates based on older versions of MARLEY were too low
- But, there is a silver lining for DUNE: more SN ve CC events according to the revised MARLEY estimate!
  - 680 events / 10 kt (v1.2.0)
  - 431 events / 10 kt (with bug)

Time-integrated SN ν_e flux from [Phys. Rev. D 97, 023019](). SN @ 10 kpc.



New comparison to competing models