Electron Scattering Experiments at MAMI for Neutrino Physics and Nuclear Structure

Pillar H02

CRC 1660 Graduate School
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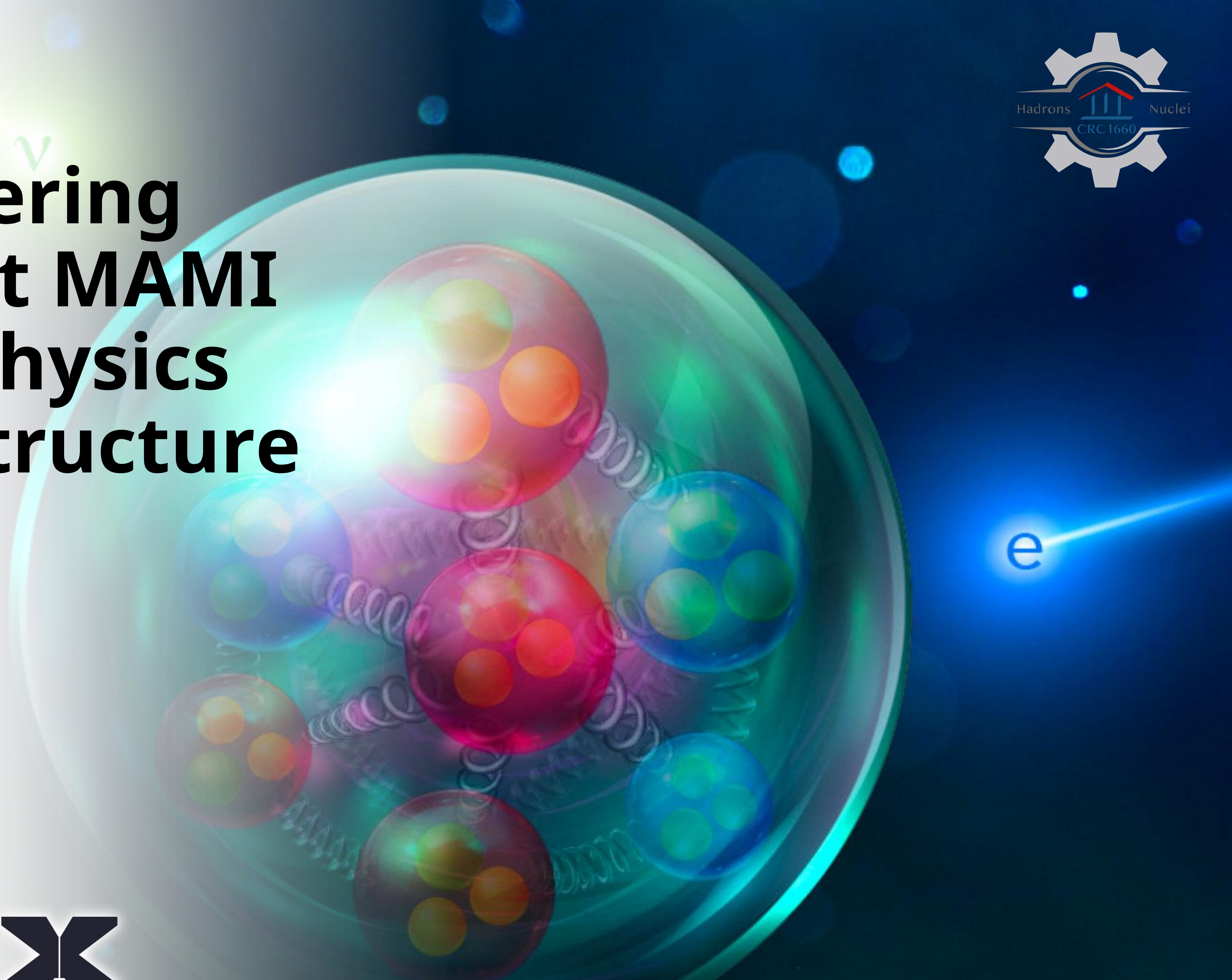
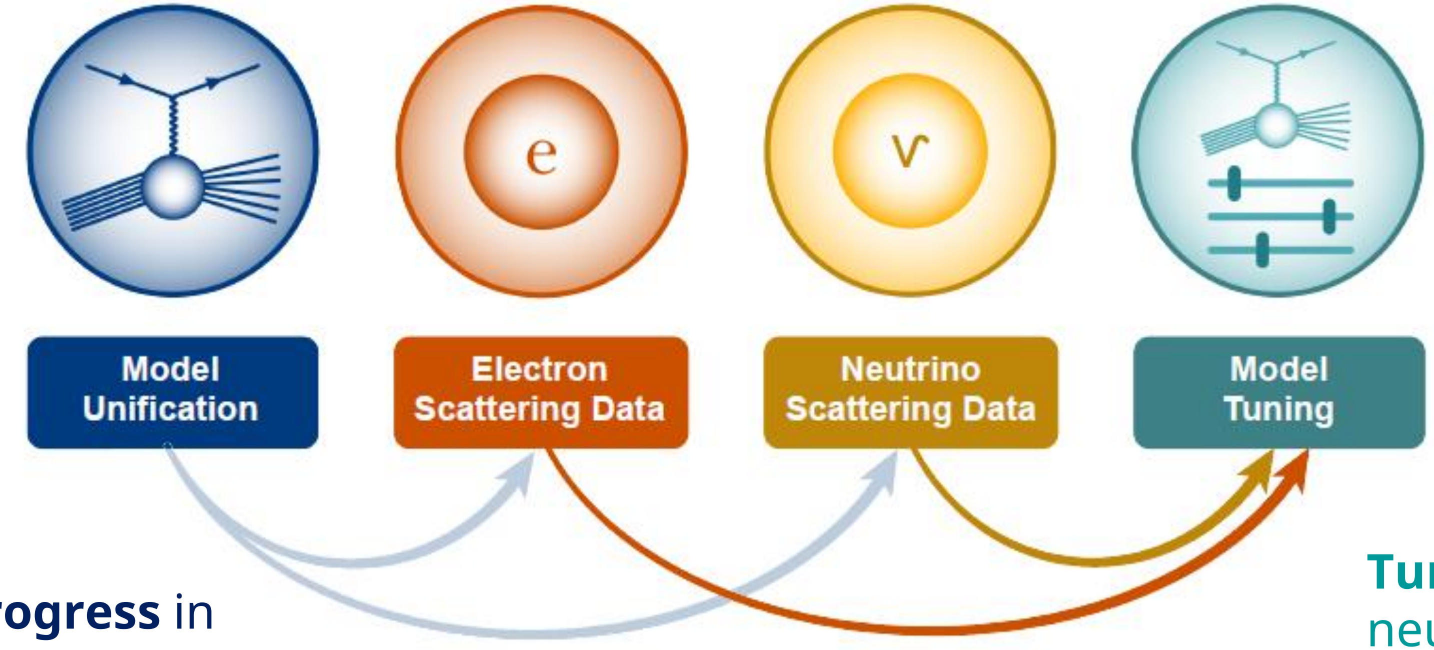


https://www.sci.news/physics/neutrino-argon-interaction-cross-sections-10707.html

Motivation

[1]



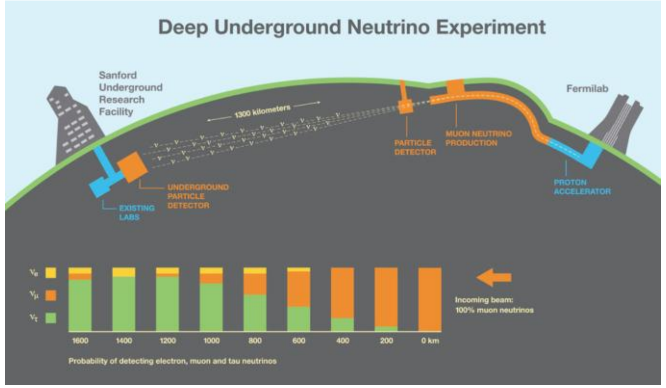
Progress in ab-initio calculations

Measure **new** inclusive cross-sections

New neutrino data

Tune neutrino generators

[2]

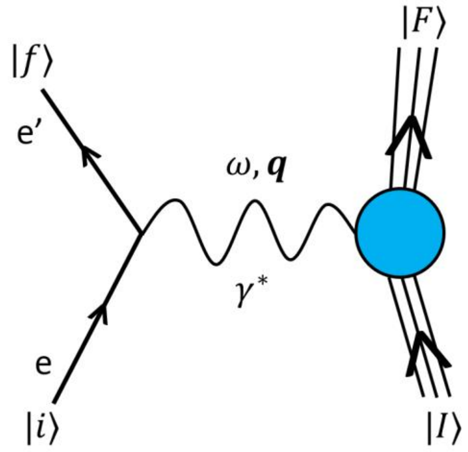


Achieve **higher precisions** in neutrino experiments

[1] Figure by Adi Ashkenazi
[2] DUNE, Fermilab

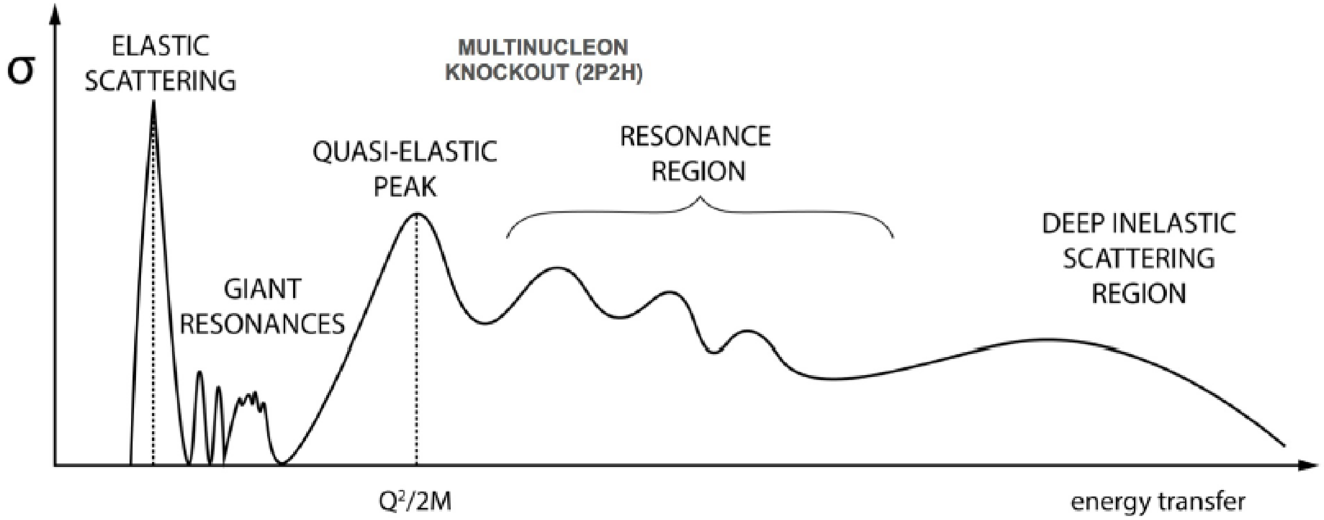
Electron Scattering
II. Electron Scattering

Electrons represent a very precise probe for the investigation of nuclei.



Electrons scatter on the Coulomb field of the nucleus.

Complex nuclear response phenomenology.



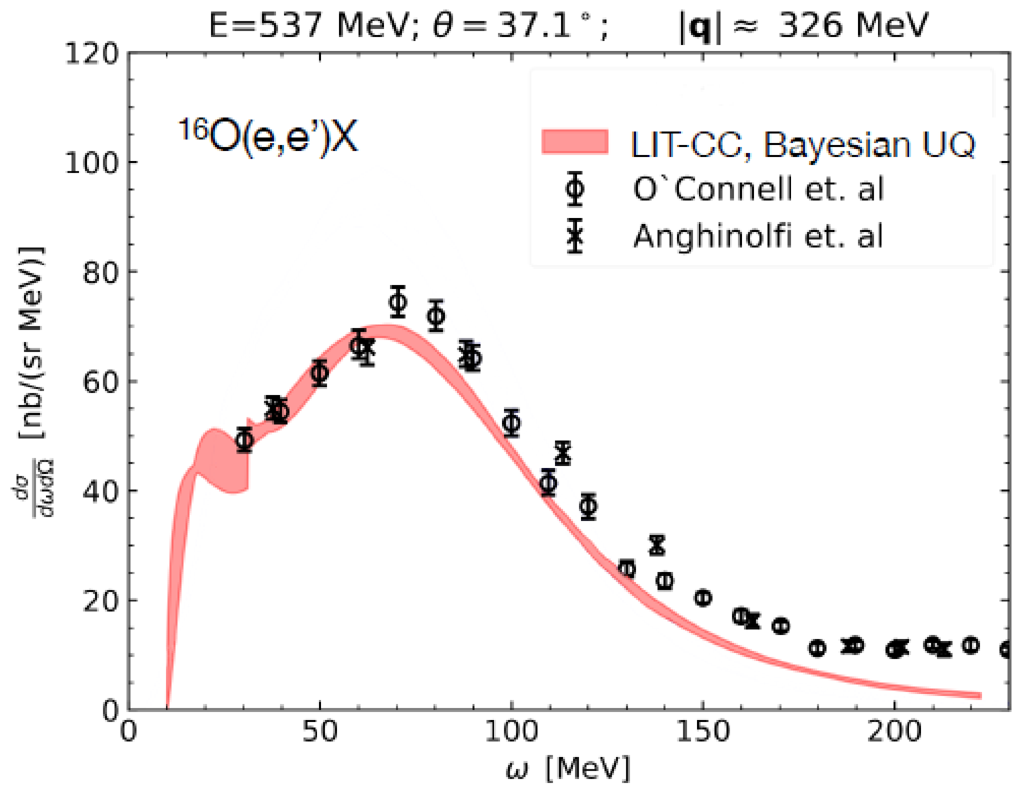
Nuclear Theory

II. Electron Scattering

- Exp. and theo. studies of electron scattering *on medium-mass nuclei*
- Theoretical ab-initio methods *extended* their reach to medium-mass nuclei
- *Better understanding* of the nuclear structure and dynamics governing lepton-nucleus cross-sections

Calculations will be challenged by our measurements at MAMI.

Acharya, Sobczyk, Bacca, Hagen, Jiang, PRL 134, 202501 (2025)

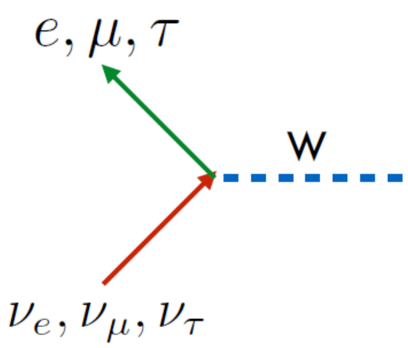


Neutrino Oscillation

III. Electrons for Neutrinos

In the SM, neutrinos come with 3 flavor eigenstates ν_e, ν_μ, ν_τ:

- Determined by their weak interaction properties
- Corresponding antineutrinos (Dirac/Majorana ?)



Three mass eigenstates ν_1, ν_2, ν_3: stationary under time evolution.

Mixing between flavor and mass eigenstates:

- Weak interaction produces weak eigenstates
- Mass eigenstates evolve differently in time
- Appearance of new flavor components (mixing)

Mixing is described by the PMNS matrix U_{PMNS}:

$$\underbrace{\boxed{\begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \\ |\nu_\tau\rangle \end{pmatrix}}}_{\text{Flavor ES}} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \underbrace{\boxed{\begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \\ |\nu_3\rangle \end{pmatrix}}}_{\text{Mass ES}}$$

Neutrino Oscillation

III. Electrons for Neutrinos

$$\begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \\ |\nu_\tau\rangle \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \\ |\nu_3\rangle \end{pmatrix}$$

The PMNS matrix can be parameterized with 3 angles $\theta_{21}, \theta_{31}, \theta_{32}$, 3 phases:

$$U = \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{Solar Neutrinos}} \underbrace{\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix}}_{\text{Reactor Neutrinos}} \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ -s_{12} & c_{12} & 0 \end{pmatrix}}_{\text{Atmospheric/Accel. Neutrinos}} \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha_1/2} & 0 \\ 0 & 0 & e^{i\alpha_2/2} \end{pmatrix}}_{\text{Majorana Phases}}$$

- With $s_{ij} = \sin\theta_{ij}$ and $c_{ij} = \cos\theta_{ij}$

Mixing angle θ: how much mass ES ν_i component is in the flavor ES ν_α

Phases: Dirac CP-violating δ and Majorana $\alpha_{1,2}$

Oscillation probability depends on neutrino energy E_ν and propagation length L:

$$\underbrace{\begin{pmatrix} \nu_\alpha \\ \nu_\beta \end{pmatrix}}_{\text{Flavour}} = \underbrace{\begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}}_{\text{Mixing}} \cdot \underbrace{\begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}}_{\text{Mass}}$$

$$\underbrace{P(\nu_\alpha \to \nu_\beta)}_{\text{Oscill. probability}} = \sin^2 2\theta \sin^2\left[1.27 \cdot \frac{\Delta m_{21}^2\ (\mathrm{eV}^2)}{E\ (\mathrm{GeV})} L\ (\mathrm{km})\right]$$

Knowledge of neutrino energy required.

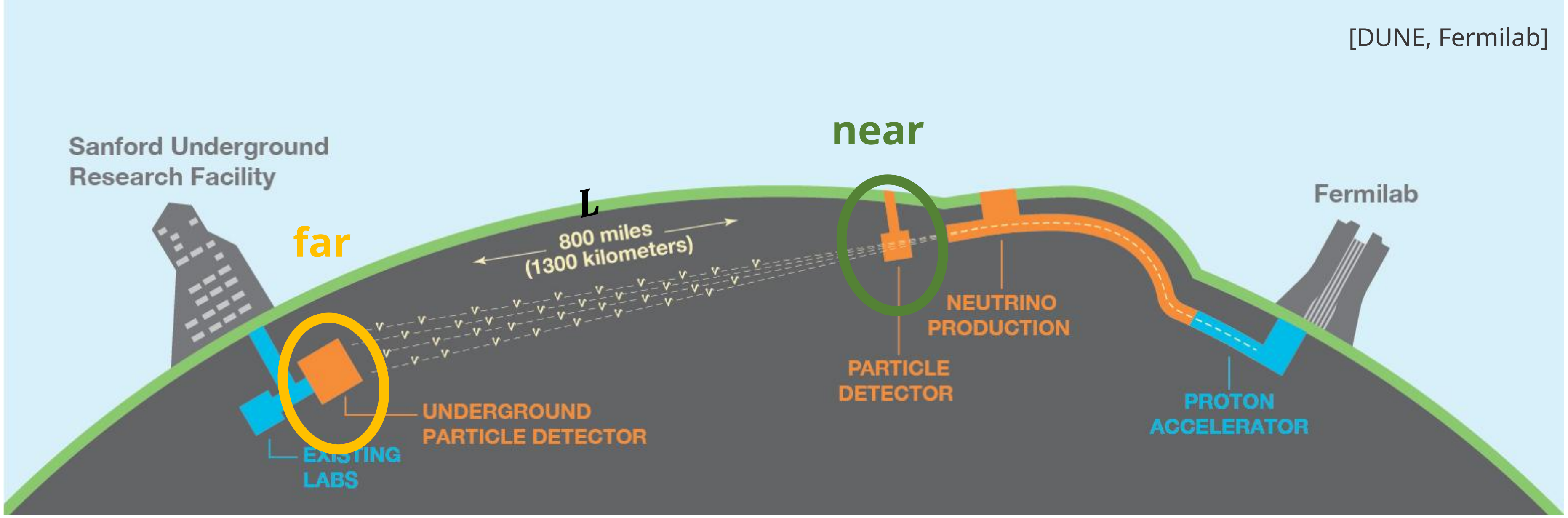
Neutrino Experiments

III. Electrons for Neutrinos

$$P(E_\nu, L)_{\nu_\alpha \to \nu_\beta} \approx \sin^2(2\theta_e)\sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right)$$

Long-baseline (LBL) neutrino experiments: e.g., DUNE (US), HyperK (Japan)

- observe and detect neutrino oscillations, **near** & **far** detector
- mostly limited by statistical uncertainties and lack of knowledge of neutrino flux
- nuclear effects are main component of the systematic error



Electrons for Neutrinos

Why using electrons for neutrino physics:

- Similar properties:
  - Identical initial nuclear state
  - Same final state interactions
  - Similar interactions (vector vs. vector + axial)

$$\left(\frac{d^2\sigma}{d\Omega d\omega}\right)_e = \sigma_M \left[A_L R_L + A_T R_T \right] \qquad \left(\frac{d^2\sigma}{d\Omega d\omega}\right)_{\nu/\bar{\nu}} = \sigma_0 \left[A_{CC} R_{CC} + A_{CL} R_{CL} + A_{LL} R_{LL} + A_T R_T \pm A_{T'} R_{T'} \right]$$

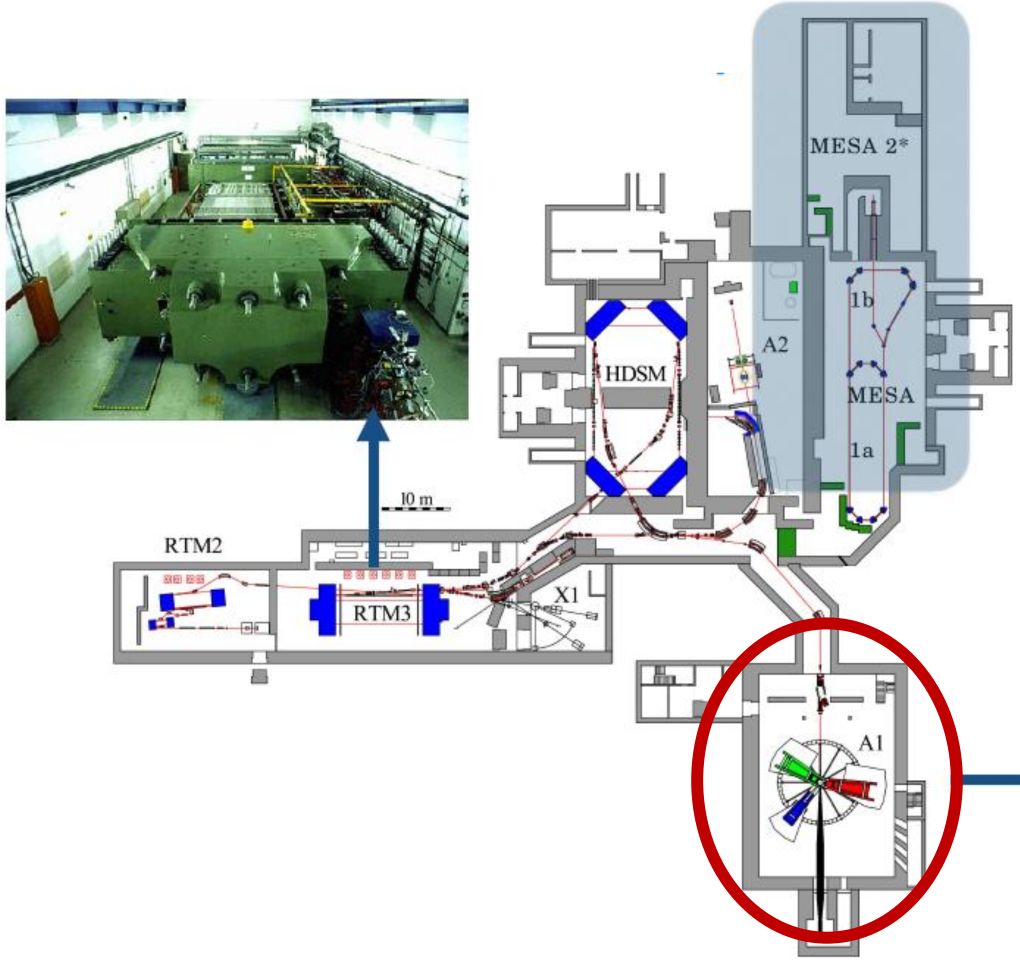
- Similarities are useful to constrain neutrino model uncertainties
  - Neutrino generators must describe at least electron data → Benchmark

- Electrons have precisely known energies
  → Test incoming energy reconstruction methods

The MAMI Accelerator Facility

IV. Electron-Nucleus Cross-Section Measurements at MAMI

[L. Doria]



MESA
Mainz
Energy-recovery
Superconducting
Accelerator

A1 Collaboration
3-Spectrometers Setup

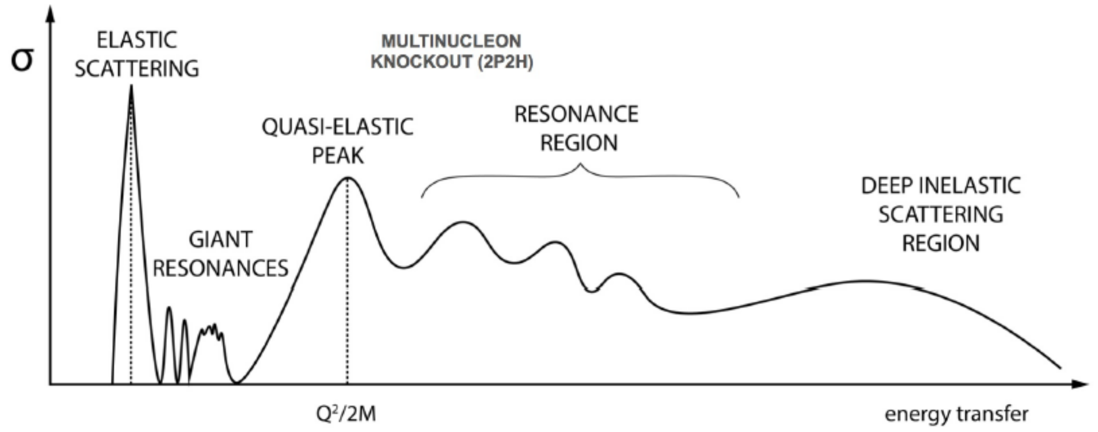
Experiments in Mainz @ A1

IV. Electron-Nucleus Cross-Section Measurements at MAMI

A1 3-spectrometer setup is a unique tool for electron for neutrino experiments:

- allows *inclusive and exclusive* measurements
- covers a broad range of *scattering angles*
- *beam energies* from 180 MeV to 1.6 GeV

→ possible to investigate different nuclear effects



Electrons for Neutrinos in Mainz
IV. Electron-Nucleus Cross-Section Measurements at MAMI

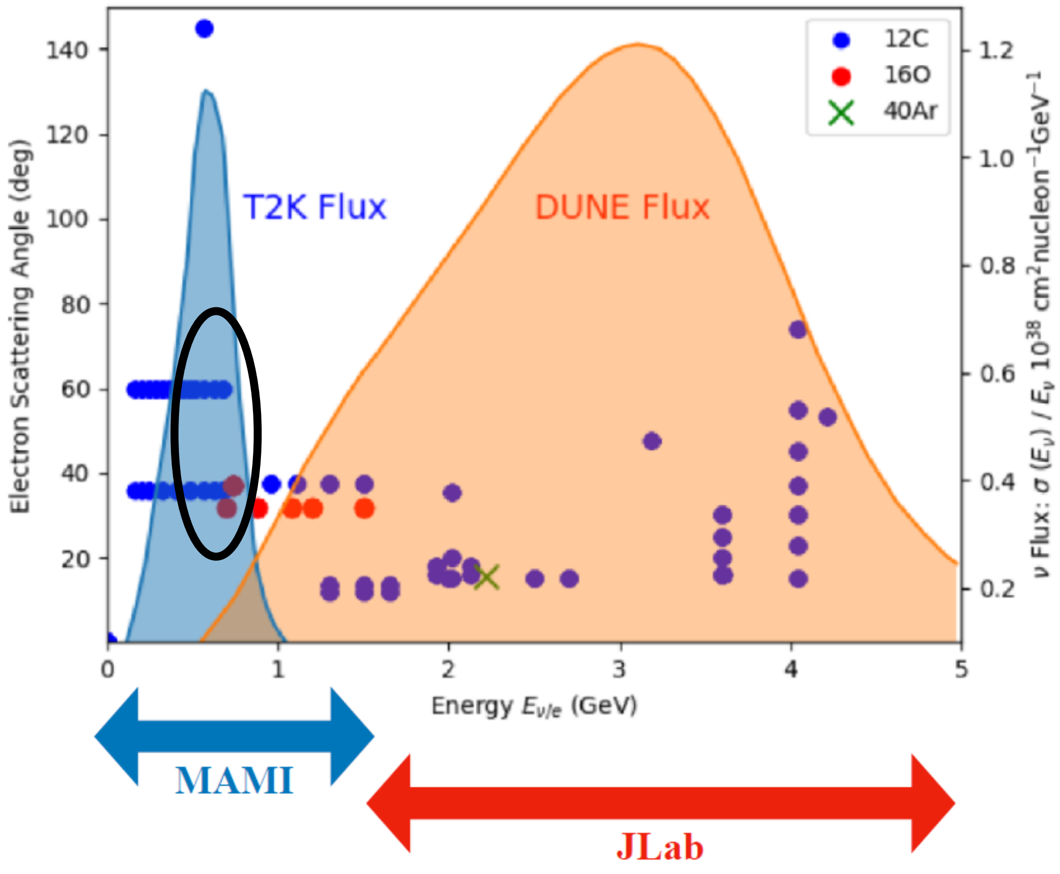
Existing inclusive data for relevant 'electrons for neutrinos' - target nuclei

Target nuclei used in LBL experiments:

- ^{12}C, ^{16}O and ^{40}Ar

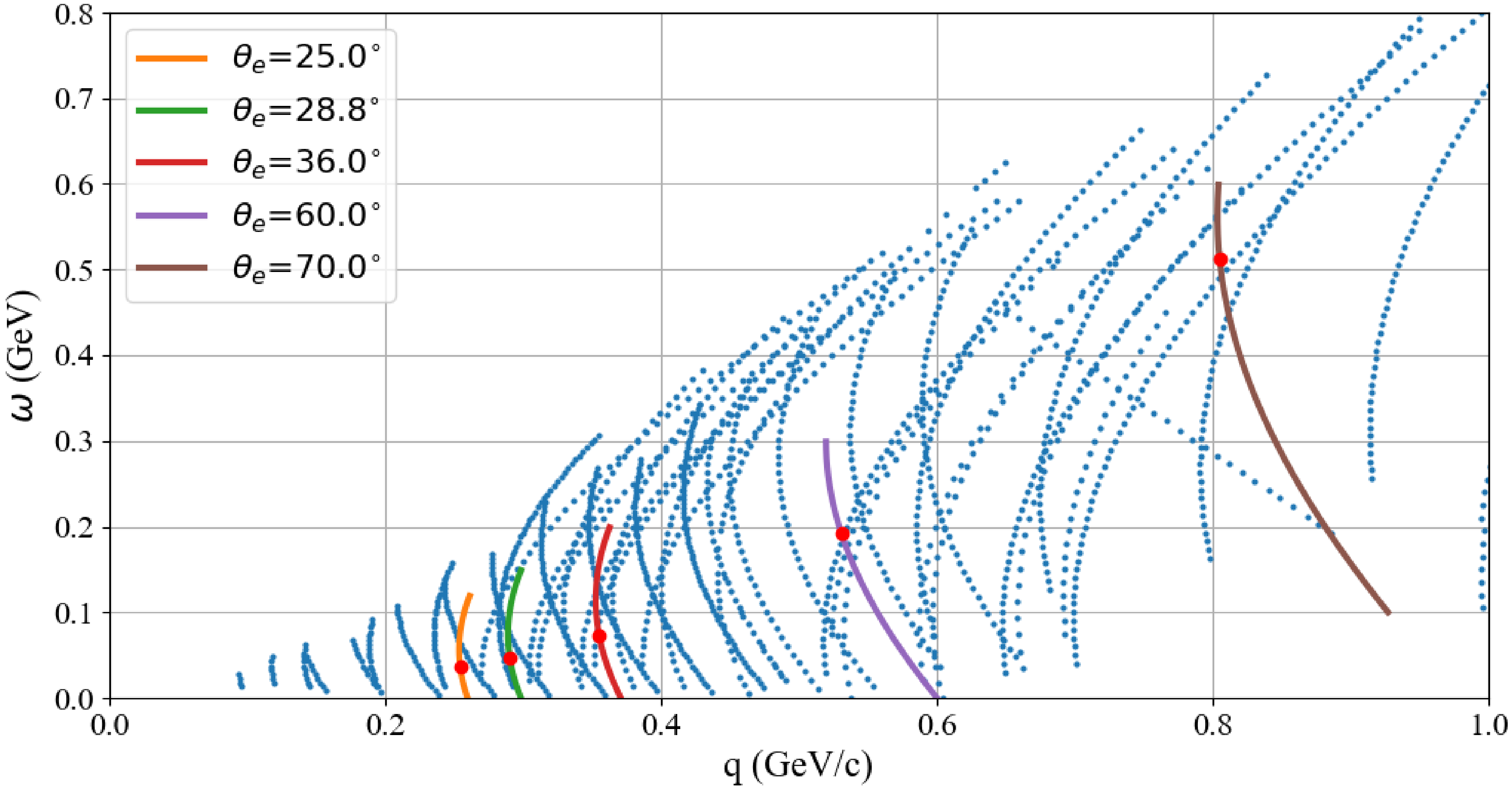
At MAMI, we performed measurements for:

- ^{12}C: @ 600, 855 MeV
- ^{40}Ar: @ 705 MeV
- ^{16}O: @ 600 MeV



Electron Scattering ^{12}C Dataset @ A1

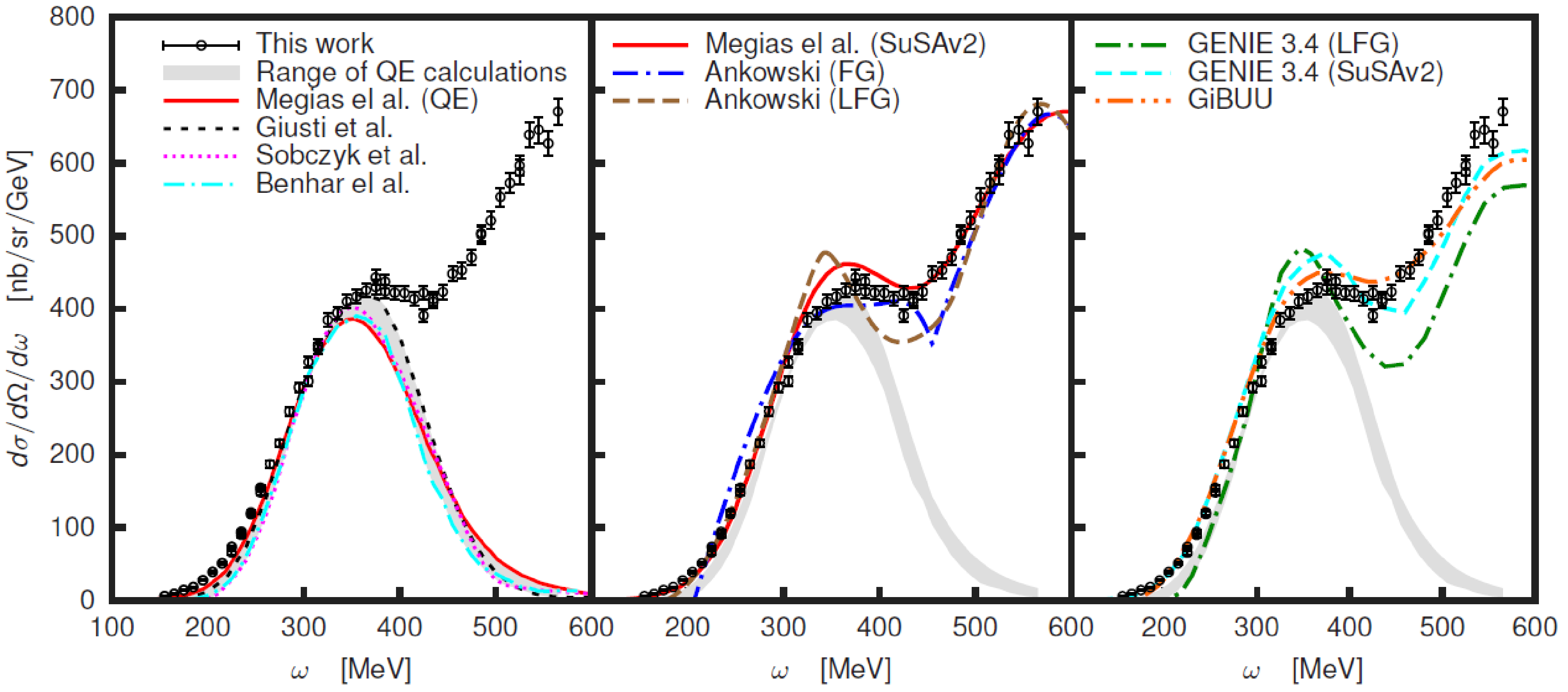
IV. Electron-Nucleus Cross-Section Measurements at MAMI



^{12}C data @ A1

IV. Electron-Nucleus Cross-Section Measurements at MAMI

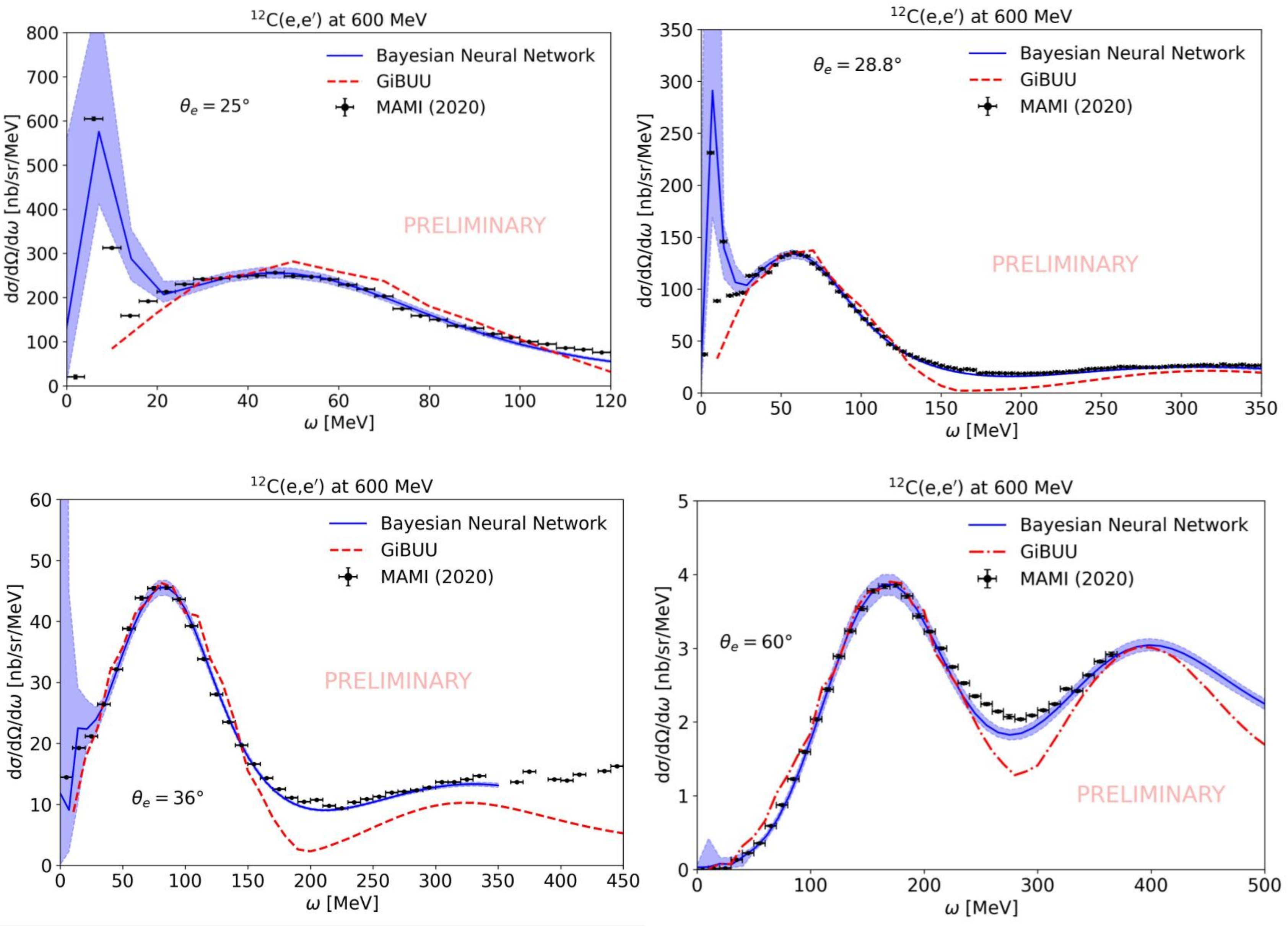
M Mihovilovič, et al. Few-body systems 65 (3), 78 (2024) $E_0 = 855\ MeV, \theta_e = 70°$



pure QE calculations | full theoretical calculations | MC neutrino generators

IV. Electron-Nucleus Cross-Section Measurements at MAMI

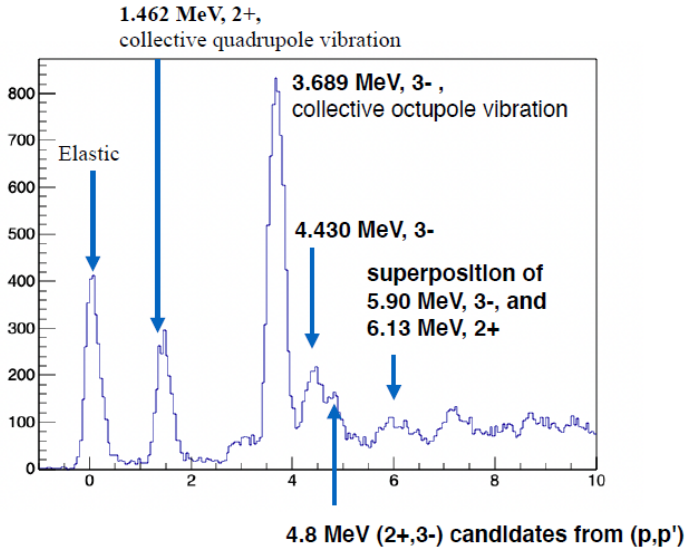
Experiments in Mainz
^{12}C data @ A1

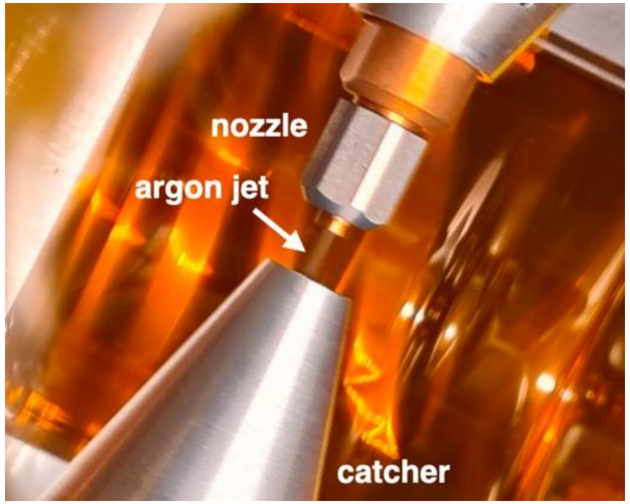


^{40}Ar elastic data @ A1

IV. Electron-Nucleus Cross-Section Measurements at MAMI

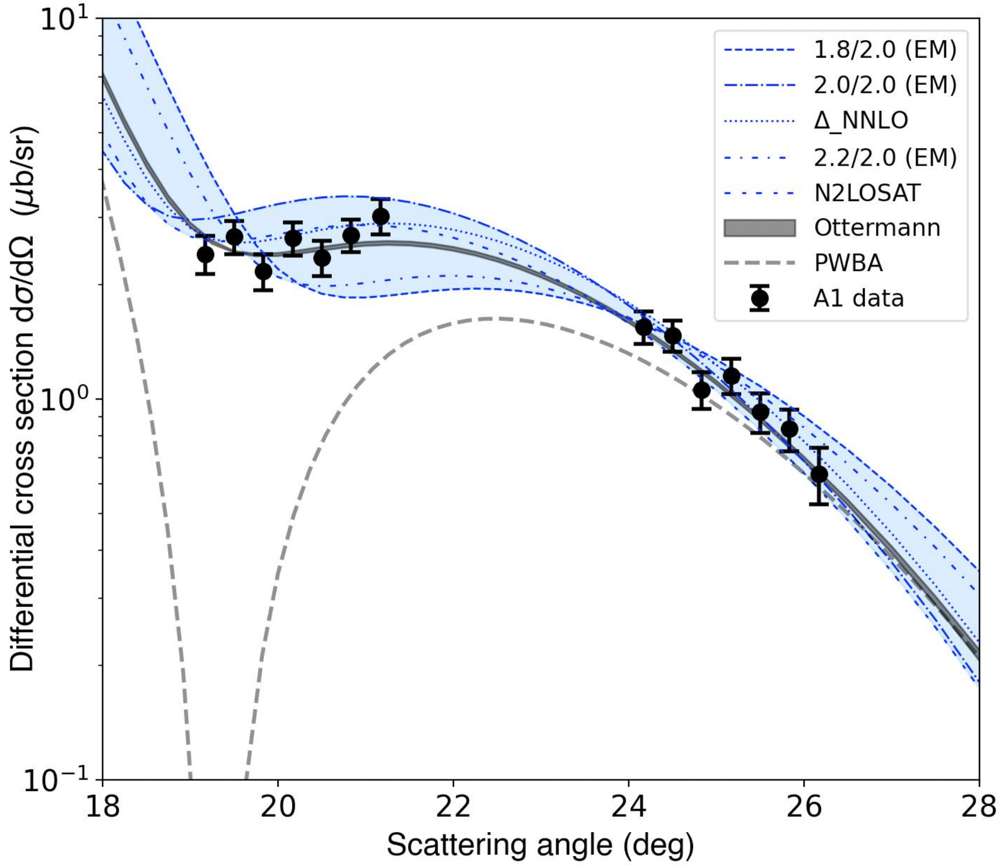
- Data taken in 2022
- First measurement on argon with *gas jet target*
  - Key milestone for MAGIX
  - Very low background





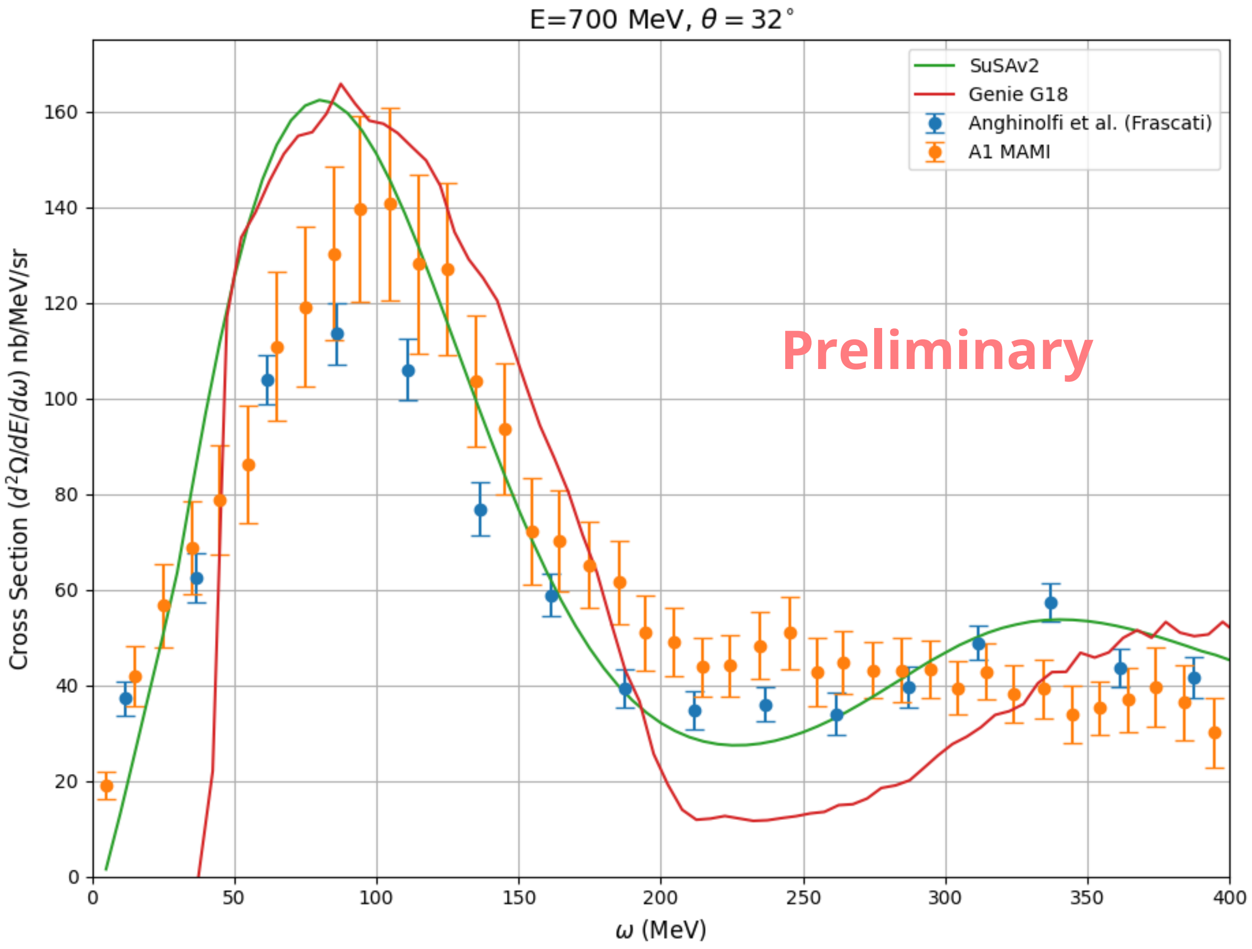
B.S. Schlimme et al., Nucl. Instr. Meth. Phys. Res. A 1013, 165668 (2021)
S. Grieser et al., Nucl. Instr. Meth. A 906, 120-126 (2018)

M. Littich, LD, et al, arXiv:2503.18965 (accepted on EPJA)
C.R. Ottermann et al. Nucl. Phys. A, 379(3):396–406, 1982



^{40}Ar data @ A1

IV. Electron-Nucleus Cross-Section Measurements at MAMI

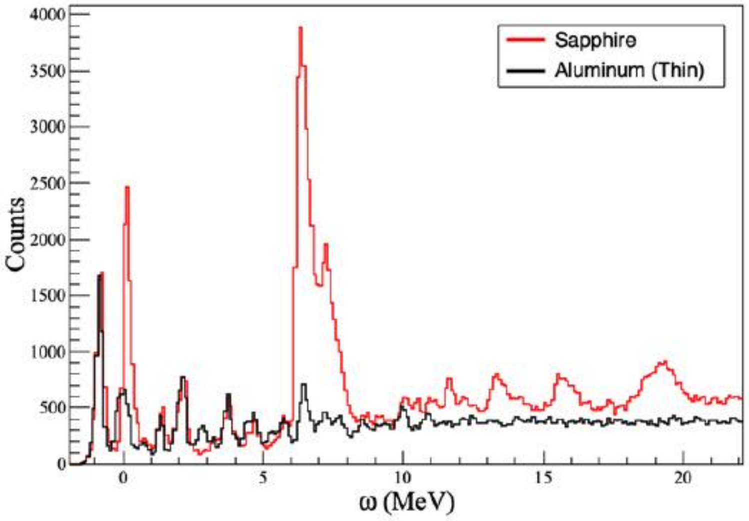


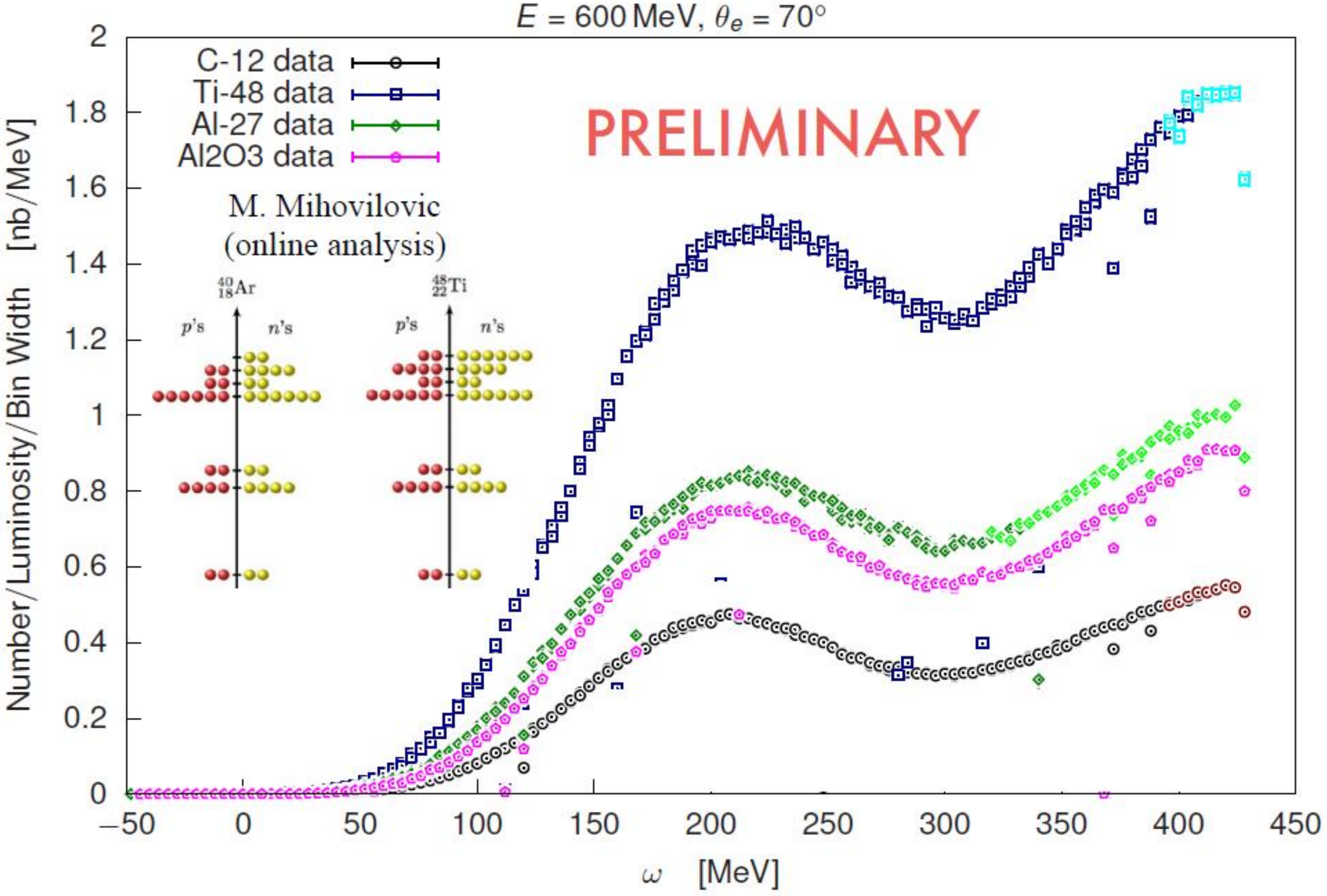
Analysis: M. Littich (JGU Mainz)

^{16}O data @ A1

IV. Electron-Nucleus Cross-Section Measurements at MAMI

- Data taken in 2024
- Target: Sapphire (Al_2O_3)
- Additional Target: ^{48}Ti
  - Same p-shell structure as ^{40}Ar
- Al to be subtracted:



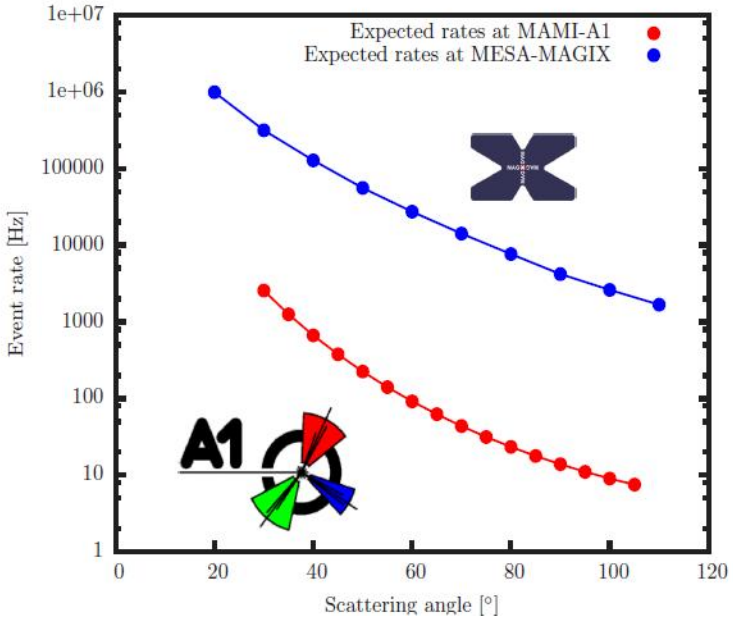


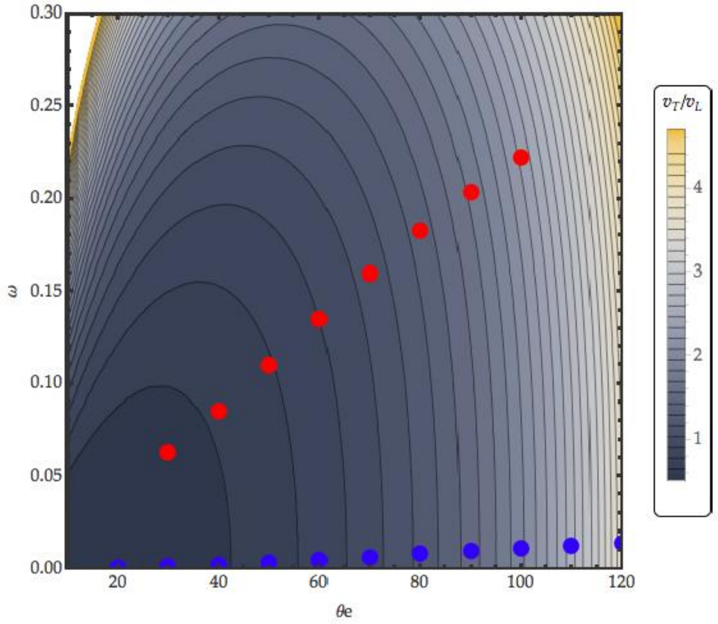
Analysis: K.I. Hassan (JGU Mainz)

Future A(e,e') experiments @ MAGIX

IV. Electron-Nucleus Cross-Section Measurements at MAGIX

- Accessing $\boldsymbol{R_L}$ (charge) and $\boldsymbol{R_T}$ (EM currents).
- Much higher rates.
- New precise measurements at low Q^2 and small ω.
- Energy regime of supernova (SN) neutrinos





This is interesting for 10s MeV neutrino physics.

[Miha Mihovilovič]

https://www.sci.news/physics/neutrino-argon-interaction-cross-sections-10707.html

V. Summary

- ✓ **Precise electron data help tuning neutrino generators and benchmark nuclear theory**

- ✓ **A1 setup is a unique tool for electron for neutrino experiments**

- ✓ **Started with inclusive measurements on targets of interest for neutrino physics**
- ✓ **Goal: start exclusive measurements (1p, 1n, 2p, pion channels, …)**

⇒ Interesting for nuclear structure and reactions physics (modern ab-initio theory)

- ✓ **New ^{12}C and ^{40}Ar data from Mainz**
- ✓ **^{16}O data in progress…**

Thank you for your attention!

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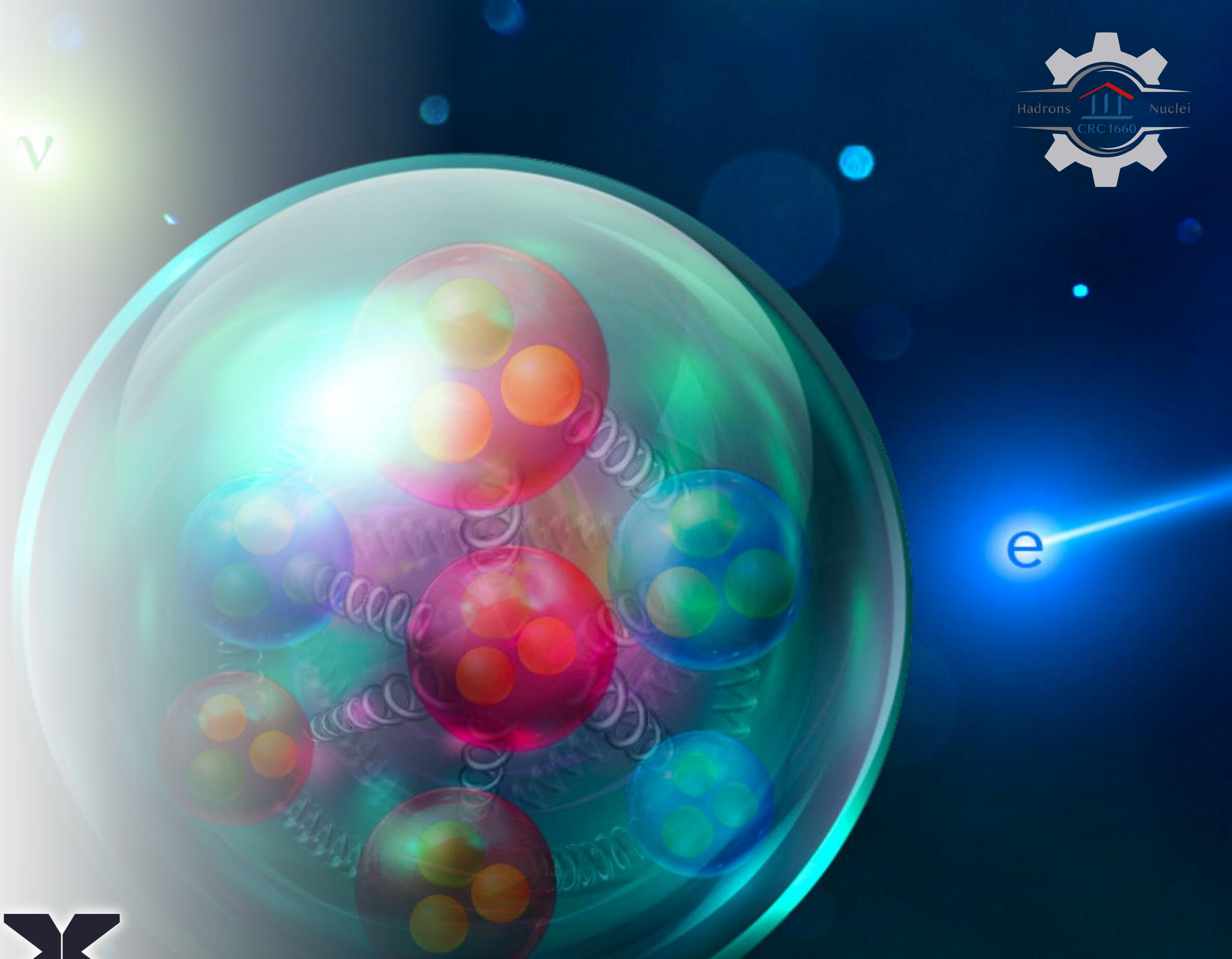

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