Electrons for neutrinos at MAMI and MESA

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Lepton Interactions with Nucleons and Nuclei - Elba XVII

Cluster of Excellence PRISMA+ Precision Physics, Fundamental Interactions and Structure of Matter

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

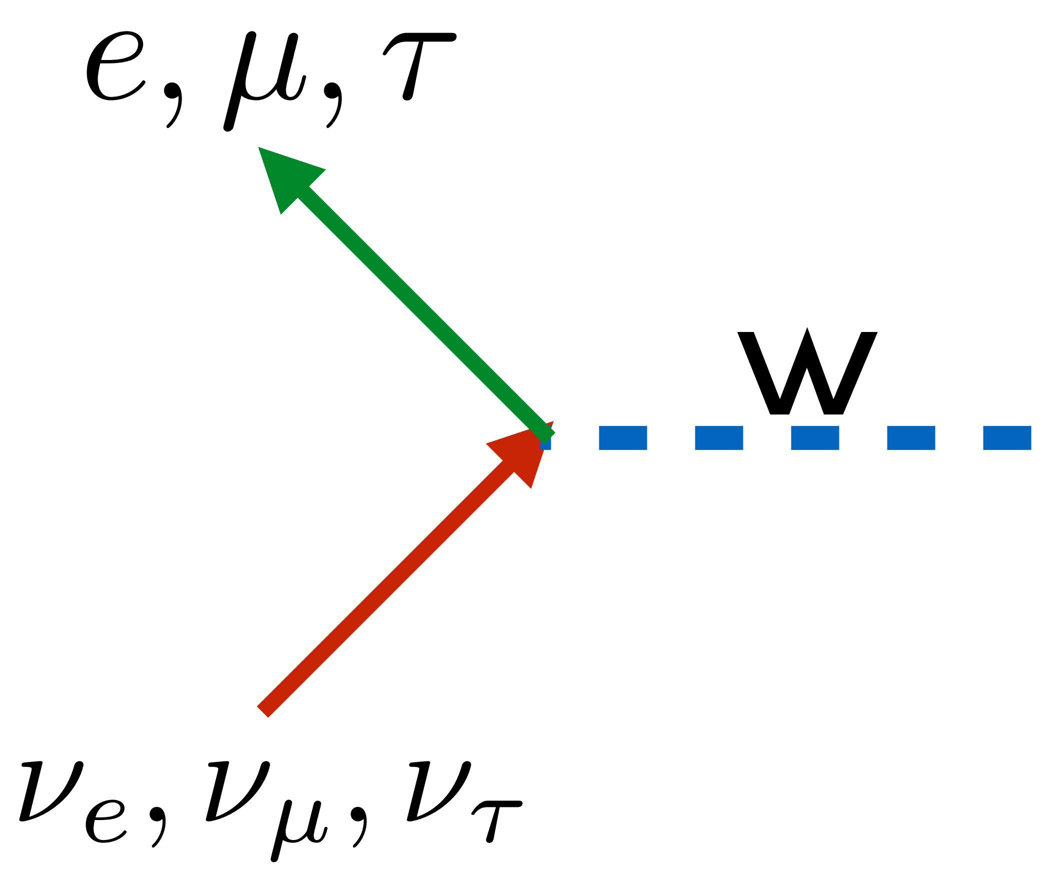
JG|U

Hadrons CRC 1660 Nuclei

Introduction

* Long-baseline Neutrino Experiments
* The role of nuclear physics
* Electron scattering at MAMI
* Future directions: MESA
* Summary

Neutrino Oscillations



- In the SM, neutrino come with 3 flavours 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 flavour and mass eigenstates:
  - The weak interaction produces weak eigenstates
  - Mass eigenstates evolve differently in time
  - Appearance of new flavour components (mixing)

- For two flavours:

$$\begin{pmatrix} \nu_\alpha \\ \nu_\beta \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \cdot \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

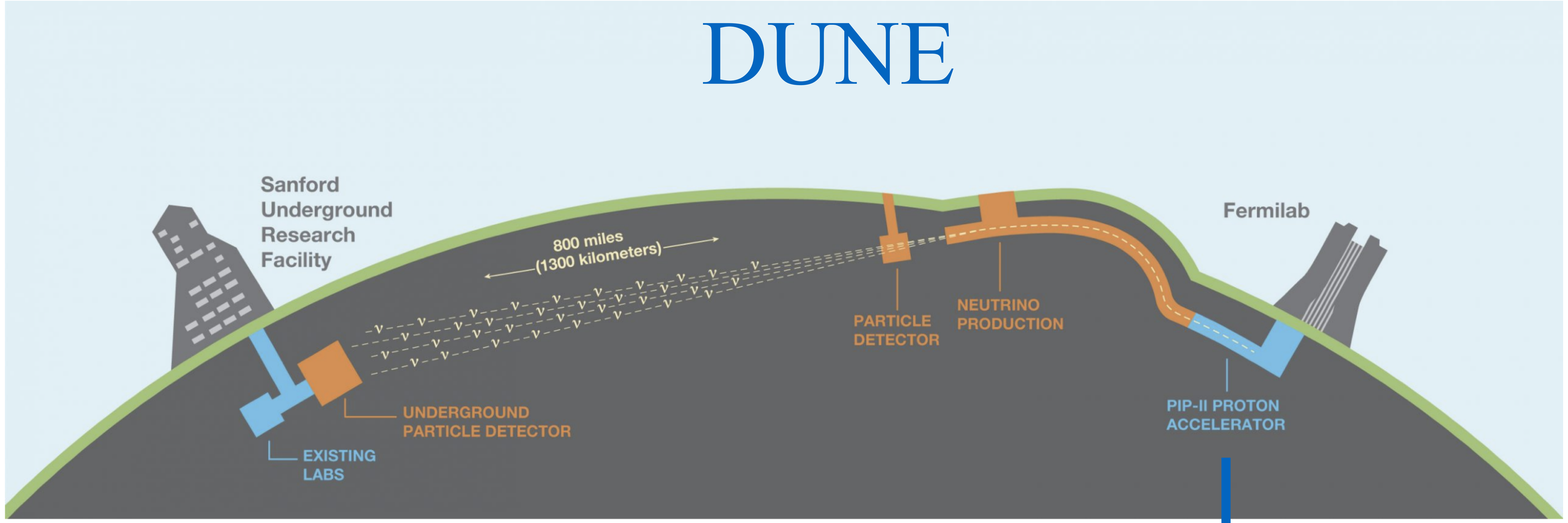
Flavour — Mixing — Mass

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

Oscill. probability

Knowledge of neutrino energy required.

How to measure oscillations: Long Base-Line Experiments



Near Detector

$$N_{ND}(\nu_\alpha, E_R) = \int dE_\nu \Phi_{\nu_\alpha}(E_\nu) \times \sigma(E_\nu) \times R_{\nu_\alpha}(E_\nu, E_R)$$

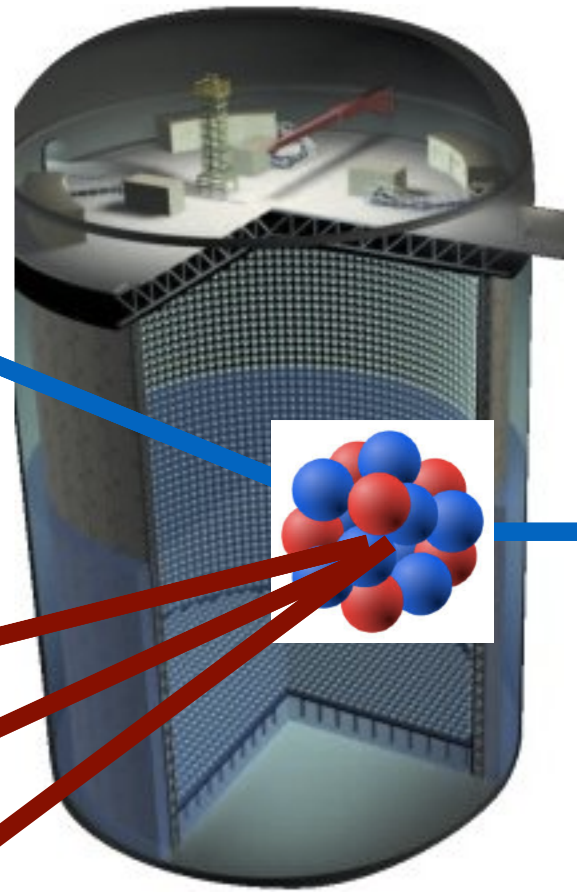
Far Detector

$$N_{FD}(\nu_\alpha \to \nu_\beta, E_R) = \int dE_\nu \Phi_{\nu_\alpha}(E_\nu) \times \sigma(E_\nu) \times R_{\nu_\alpha}(E_\nu, E_R) \times P(\nu_\alpha \to \nu_\beta, E_\nu)$$

Why nuclei are relevant for neutrino physics ?

Experiment

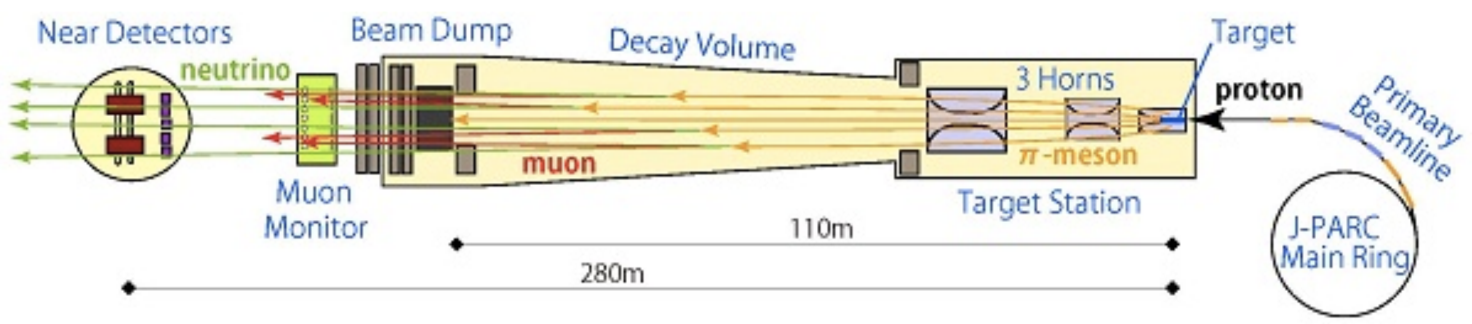
l



Oscillation

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}=\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{-i\delta} & 0 & c_{13}\end{pmatrix}\begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix}1 & 0 & 0\\ 0 & e^{i\alpha_1/2} & 0\\ 0 & 0 & e^{i\alpha_2/2}\end{pmatrix}\cdot\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

Production



ν_l

E_ν

π

p

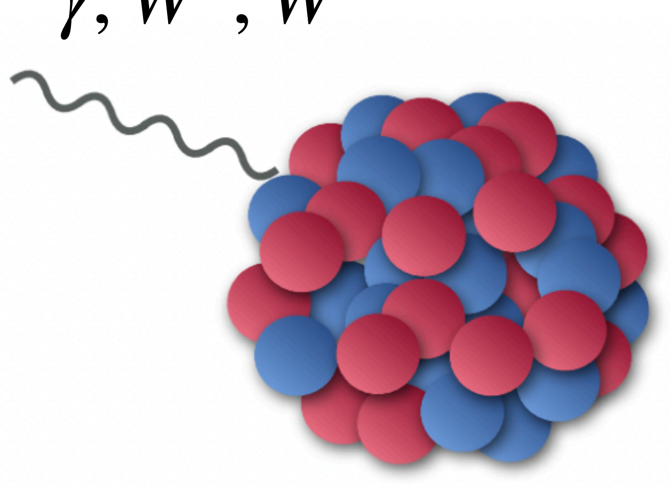
n

Detection

Analysis

Cross section model

$\sigma(E_\nu)$



Reconstruct

E_ν

Oscillation Parameters

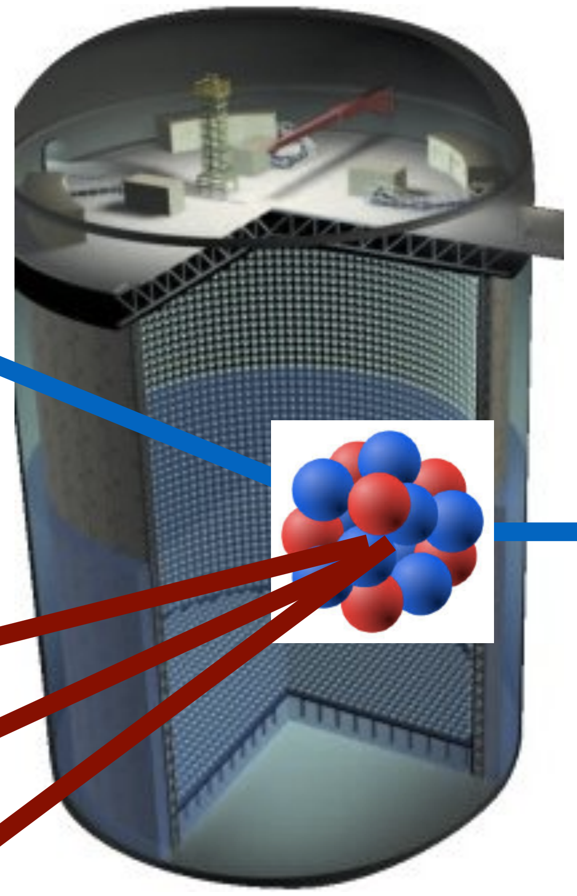
$\theta_e, \theta_\mu, \theta_\tau \quad \delta_{CP}$

$\Delta m_e^2, \Delta m_\mu^2, \Delta m_\tau^2$

Why nuclei are relevant for neutrino physics ?

Experiment

l



π

p

n

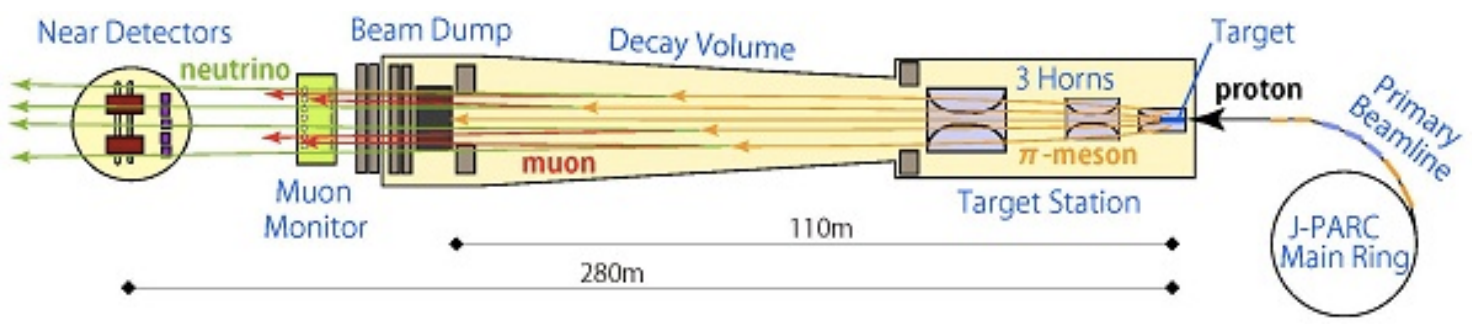
Detection

Oscillation

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix} c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{-i\delta} & 0 & c_{13}\end{pmatrix} \begin{pmatrix} 1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix} \begin{pmatrix} 1 & 0 & 0\\ 0 & e^{i\alpha_1/2} & 0\\ 0 & 0 & e^{i\alpha_2/2}\end{pmatrix} \cdot \begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

ν_l

Production

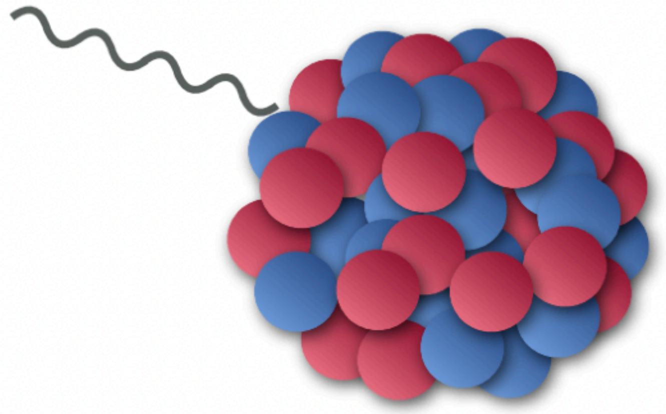


E_ν

Analysis

Cross section model

$\sigma(E_\nu)$



Reconstruct

E_ν

Oscillation Parameters

$\theta_e, \theta_\mu, \theta_\tau \quad \delta_{CP}$

$\Delta m_e^2, \Delta m_\mu^2, \Delta m_\tau^2$

Energy Reconstruction: Experimental Techniques

Kinematic Method

$$E_{Rec} = \frac{m_N E_\mu - m_\mu^2/2}{m_N - E_\mu + |\vec{p}_\mu| \cos\theta_\mu}$$

* Reconstruct outgoing lepton kinematics
* Assume only 1 knock-out nucleon
* No meson (pion) production
* Neglect nuclear recoil
* Used e.g. in Cherenkov detector like SuperKamiokande

Calorimetric Method

$$E_\nu^{\mathrm{cal}} = E_\ell + \epsilon_n + \sum_{i=1}^{n} (E_{\boldsymbol{p}'_i} - M) + \sum_{j=1}^{m} E_{\boldsymbol{h}'_j}$$

* Sums all the energies of measured particles
* Challenges: pions and neutrons
* Modeling important
* Proposed e.g. for DUNE

Generators

- Neutrino Experiments model neutrino interactions with "Generator" codes
- Challenging: they should work on a wide range of energies
- "Frankenstein" codes: patch together different models
- Wide market: Genie, NuWro, Neut, GiBUU , …
- Much more than cross-sections: must model full interactions:
  - -Detector efficiencies (dep. on energy, particle type, detector,…)
- Essential also for assessing systematic errors
- Essential for extracting the neutrino energy
- Many techniques:
  - -As good a physics model as possible
  - -Simple model with parameters adjusted to data
  - -On-line calculation or look-up tables
  - -Interpolation, scaling, …
  - -…

Generators and Neutrino Data

* Generators can be tested vs neutrino data
* Generators can be tuned on neutrino data
* Neutrino data:
  - Statistics is generally low
  - Limited kinematic range
* Uncertainties in the neutrino flux: what is the initial neutrino energy?
* On the bright side:
  - Events similar to what you need
  - Detectors similar to what you need

What about electrons ?

* Electron beams can be prepared with very precise energy (no “flux”)
* Statistics is not an issue
* Investigation of a large kinematic range possible + identification of reaction channels
* Stringent test of generators in electron-mode: necessary (but not sufficient) test.

Why electrons are relevant for neutrino physics ?

Neutrino-Nucleus scattering

$$\frac{d^2\sigma}{d\Omega_{k'}d\omega} = \sigma_0\left[L_{CC}R_{CC} + L_{CL}R_{CL} + L_{LL}R_{LL} + L_T R_T \pm L_{T'}R_{T'}\right]$$

(Unpolarized) Electron-Nucleus scattering

$$\frac{d^2\sigma}{d\Omega d\omega} = \left(\frac{d\sigma}{d\Omega}\right)_{Mott}\left[\frac{Q^4}{\vec{q}^4}R_L(q) + (\frac{1}{2}\frac{Q^2}{\vec{q}^2} + \tan^2\frac{\theta}{2})R_T(q)\right] = \left(\frac{d\sigma}{d\Omega}\right)_{Mott}\left[\sigma_L + \sigma_T\right]$$

Use electrons for testing and improving neutrino-nucleus interactions generators.

Why electrons are relevant for neutrino physics ?

Neutrino-Nucleus scattering

$$\frac{d^2\sigma}{d\Omega_{k'}d\omega} = \sigma_0 [L_{CC}R_{CC} + L_{CL}R_{CL} + L_{LL}R_{LL} + L_T R_T \pm L_{T'}R_{T'}]$$

(Unpolarized) Electron-Nucleus scattering

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Use electrons for testing and improving
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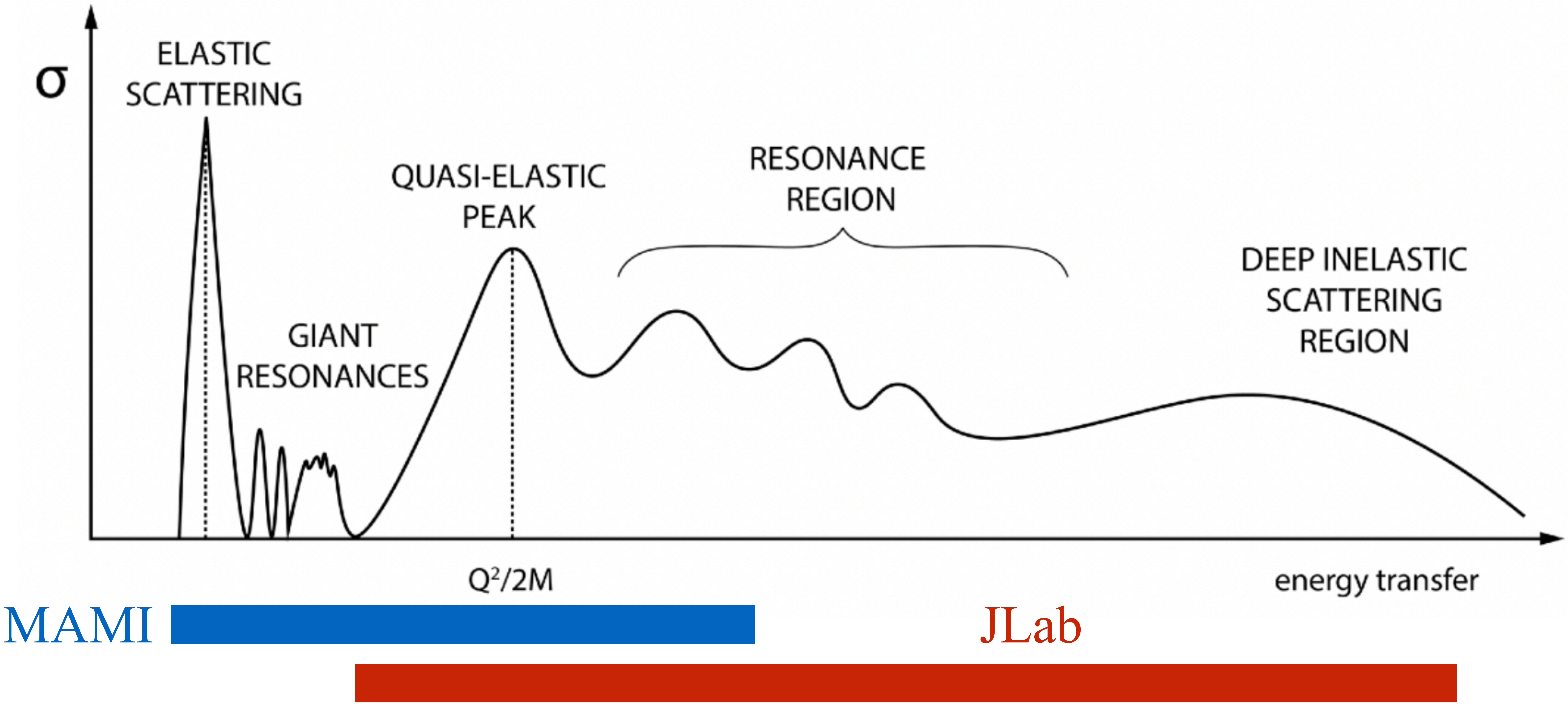
Why electrons are relevant for neutrino physics ?

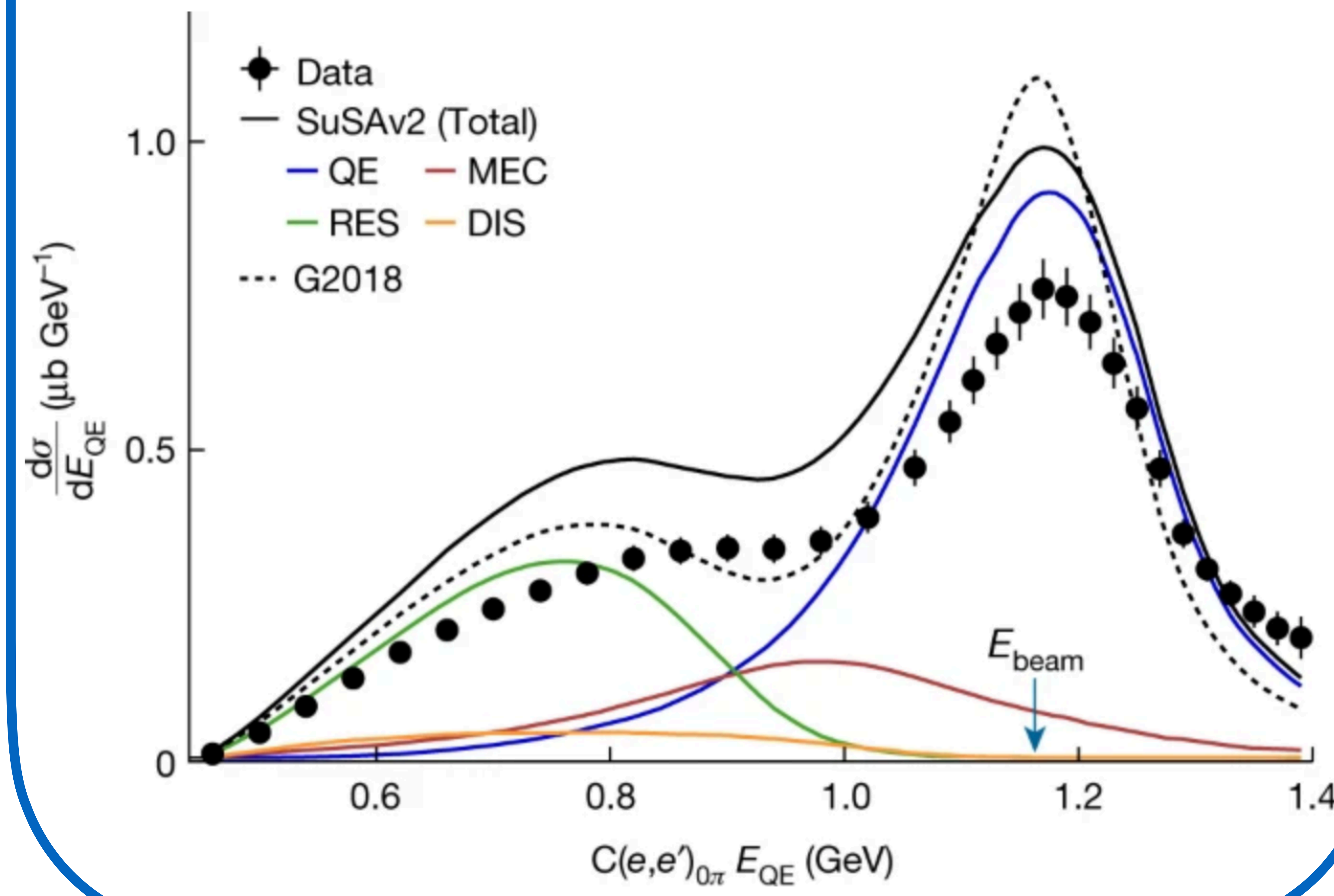


Growing and successful community

Article | Published: 24 November 2021

Electron-beam energy reconstruction for neutrino oscillation measurements

M. Khachatryan, A. Papadopoulou, A. Ashkenazi, F. Hauenstein, A. Nambrath, A. Hrnjic, L. B. Weinstein, O. Hen, E. Piasetzky, M. Betancourt, S. Dytman, K. Mahn, P. Coloma, the CLAS Collaboration & e4ν Collaboration*



Electron Scattering and Neutrino Physics

A NF06 Contributed White Paper

Submitted to the Proceedings of the US Community Study on the Future of Particle Physics (Snowmass 2021)

A. M. Ankowski*[1], A. Ashkenazi*[2], S. Bacca*[3,4], J. L. Barrow*[2,5], M. Betancourt*[6], A. Bodek*[7], M. E. Christy*[8,9], L. Doria*[3], S. Dytman*[10], A. Friedland*[1], O. Hen*[5], C. J. Horowitz*[11], N. Jachowicz*[12], W. Ketchum*[6], T. Lux*[13], K. Mahn †[14], C. Mariani*[15], J. Newby*[16], V. Pandey ‡[17], A. Papadopoulou*[5], E. Radicioni*[18], F. Sánchez*[19], C. Sfienti*[3], J. M. Udías*[20], L. Weinstein*[21],

L. Alvarez-Ruso[22], J. E. Amaro[23], C. A. Argüelles[24], A.B. Balantekin[25], S. Bolognesi[26], V. Brdar[6,27], P. Butti[1], S. Carey[28], Z. Djurcic[29], O. Dvornikov[30], S. Edayath[31], S. Gardiner[6], J. Isaacson[6], W. Jay[5], A. Klustová[32], K. S. McFarland[7], A. Nikolakopoulos[6], A. Norrick[6], S. Pastore[33], G. Paz[28], M. H. Reno[34], I. Ruiz Simo[23], J. E. Sobczyk[3], A. Sousa[35], N. Toro[1], Y.-D., Tsai[36], M. Wagman[6], J. G. Walsh[14], and G. Yang[37]

2022

- March 1 – April 1, 2022, "NuSTEC workshop: Improving the art of neutrino nuclei modelling with charged lepton scattering data", Tel Aviv, Israel
- January 17-21, 2022, "Neutrino–Nucleus Interactions in the Standard Model and Beyond", CERN

2021

- November 12, 2021, "Snowmass21 NF06: Low Energy Neutrino and Electron Scattering Workshop, online
- August 23-25, 2021, "Snowmass21 NF06, TF05, TF11, and RF04: Theoretical tools for neutrino scattering: the interplay between lattice QCD, EFTs, nuclear physics, phenomenology, and neutrino event generators", online
- May 10-12, 2021, "Third Nuclear and Particle Theory Meeting: Beyond the Standard Model Physics with Nucleons and Nuclei", Washington University in St. Louis, online
- March 15-18, 2021, "New Directions in Neutrino-Nucleus Scattering", online

2020

- Dec. 14, 2020, "Snowmass21 NF06: Electron Scattering Workshop", online
- Sept. 21-23, 2020, "Snowmass21 TF11: Mini-Workshop on Neutrino Theory", online
- Sept. 3-4, 2020, "Snowmass21 NF06: Neutrino Cross Section Data Usage and Archival", online
- Jan. 8-10, 2020, "Generator Tools Workshop", Fermilab, USA

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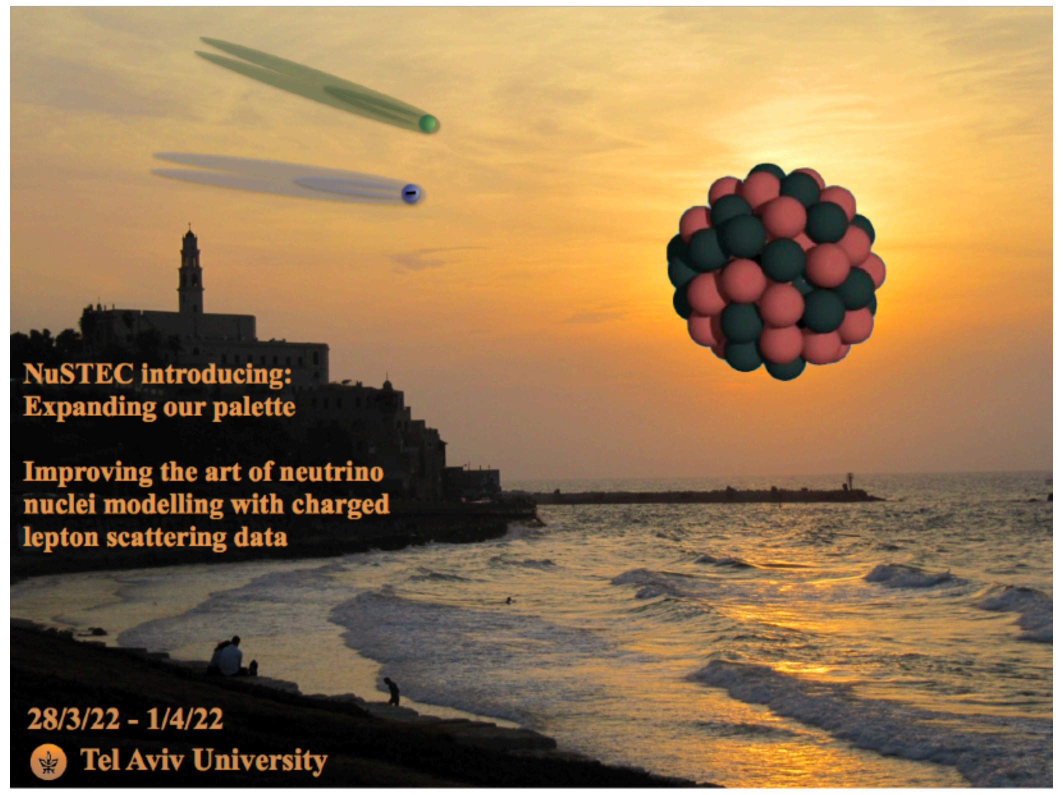
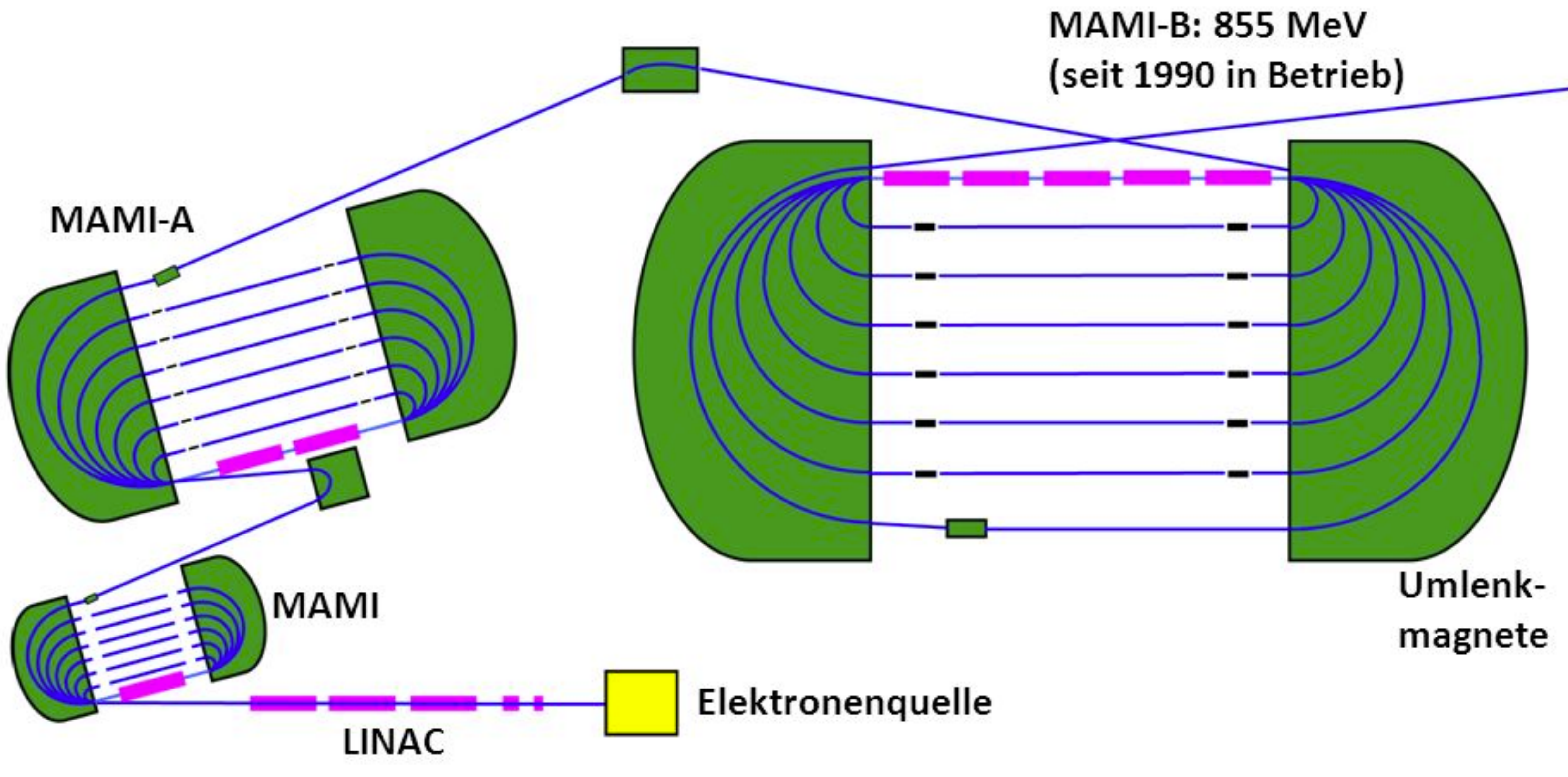
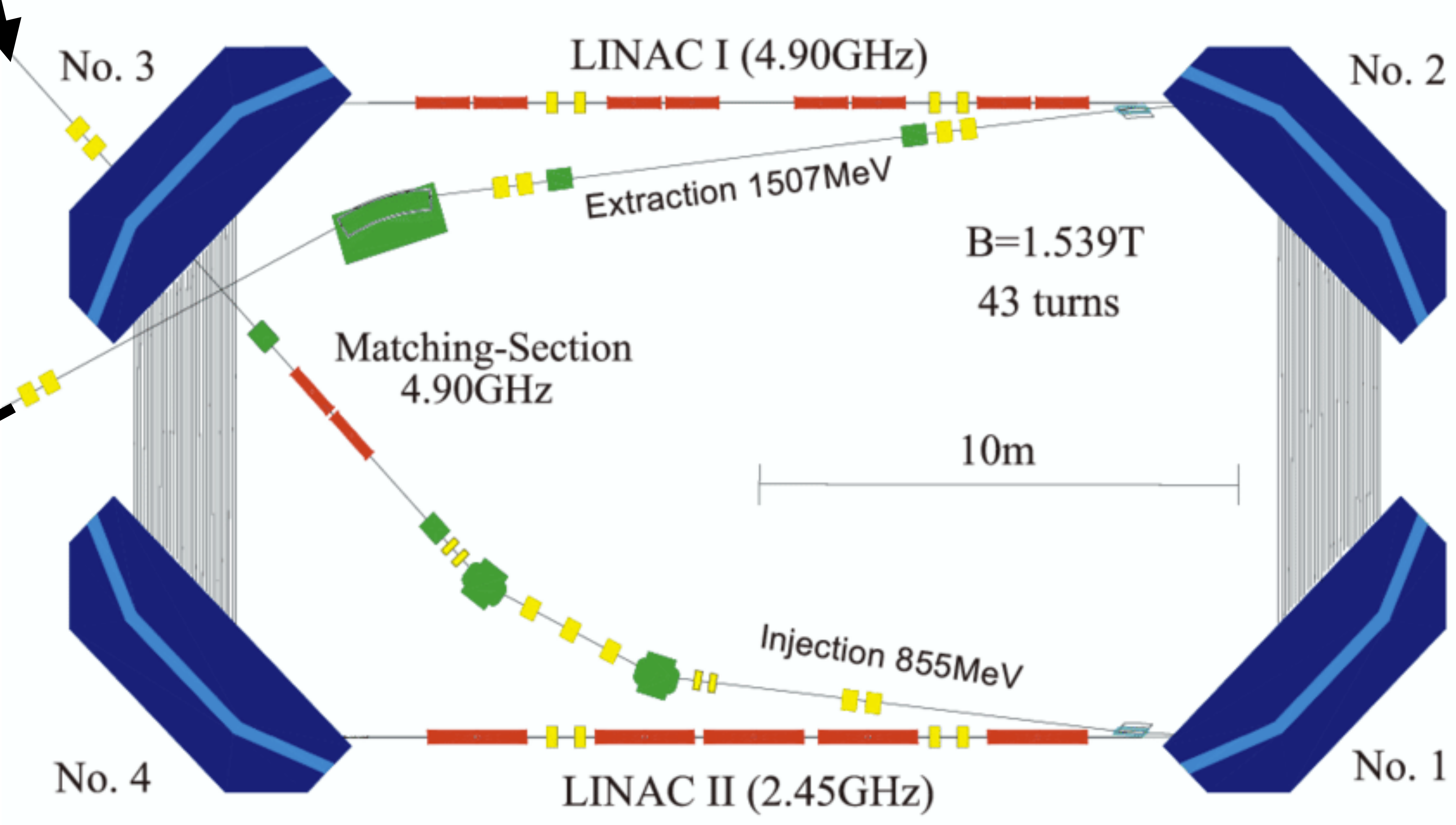


The MAMI Facility

The Racetrack Microton (Institute for Nuclear Physics, U. Mainz)



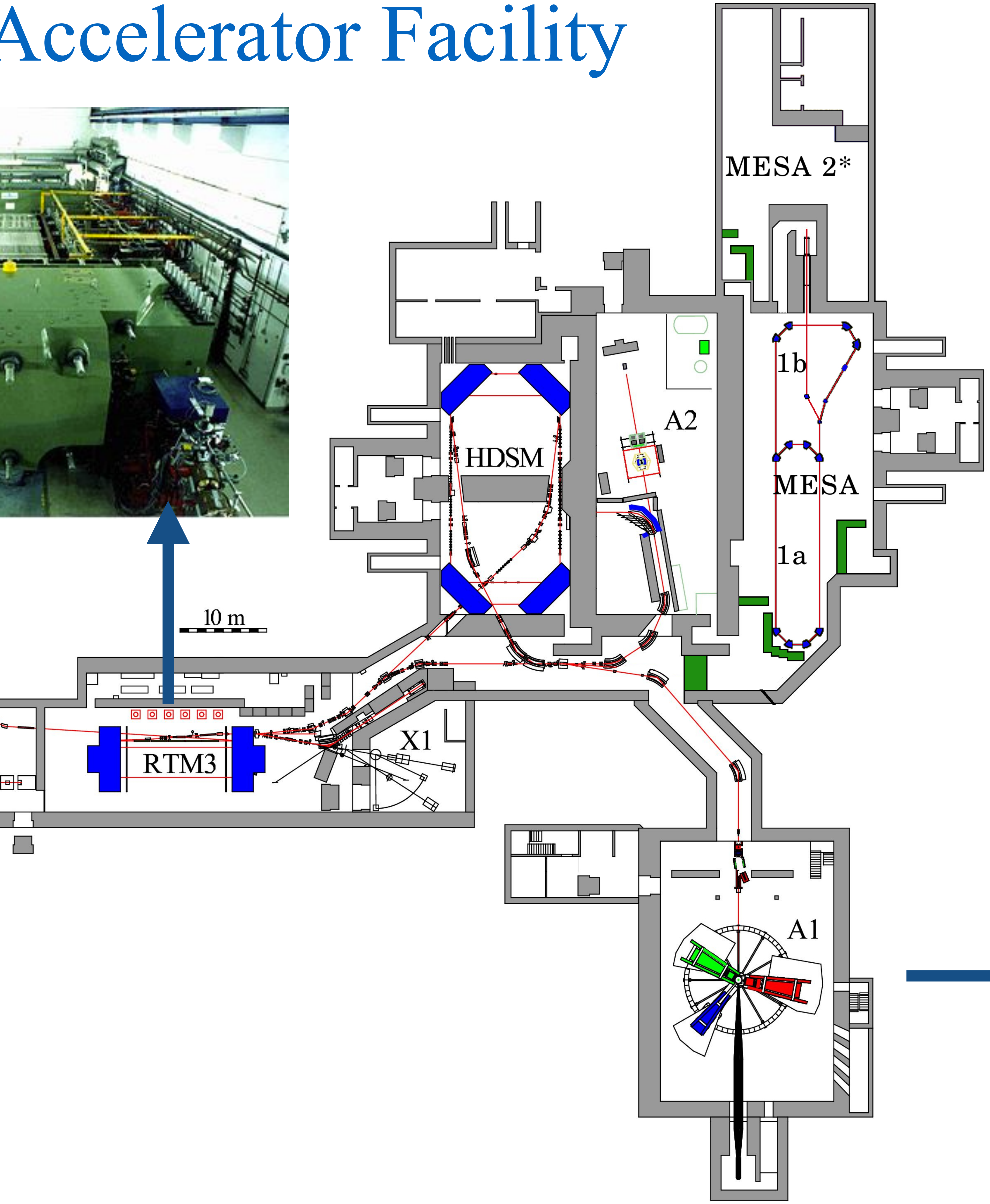
up to 855 MeV



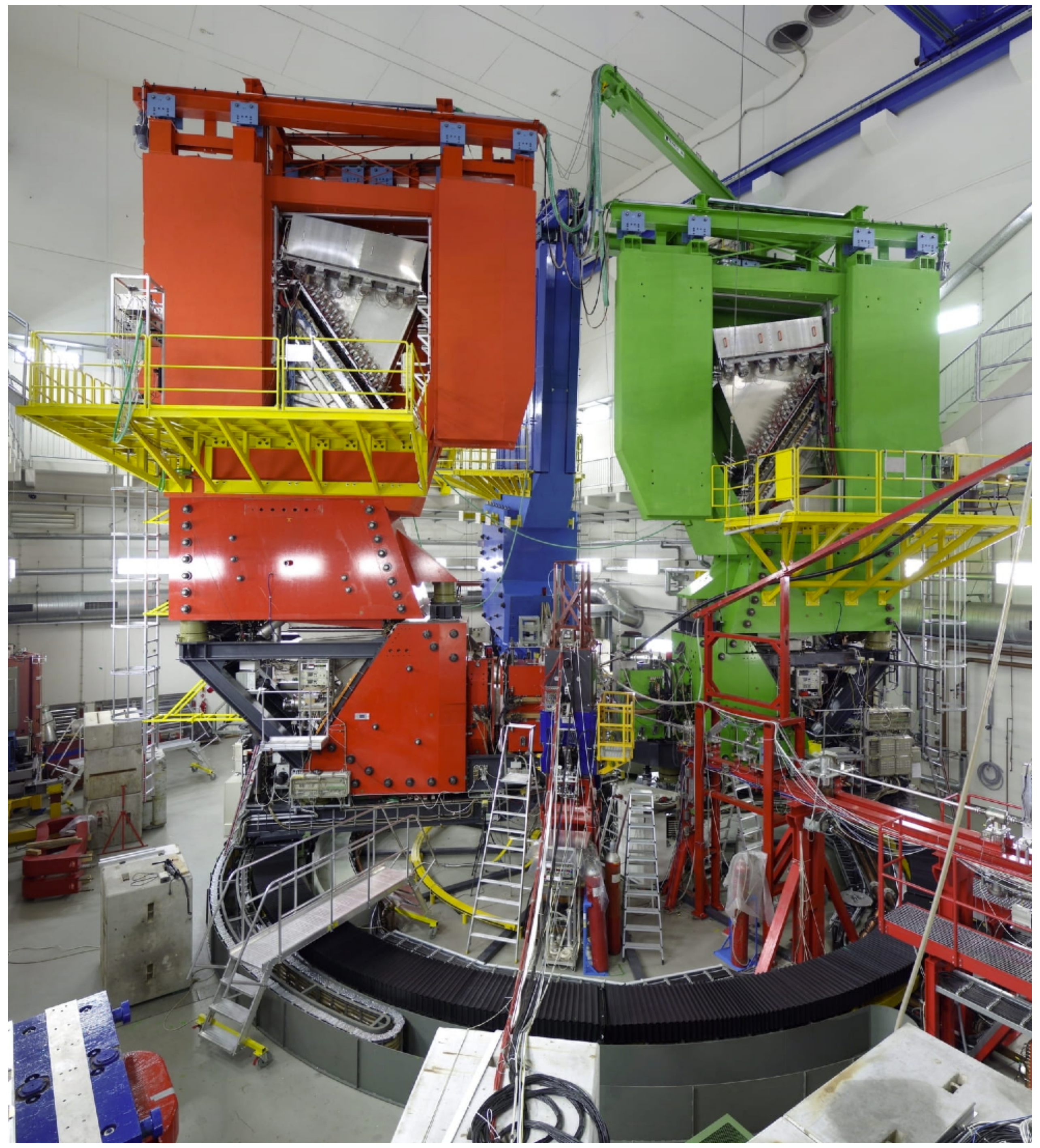
- CW electron beam
- Up to 100 uA current
- 80% polarization
- dE <13 keV

up to 1.6 GeV

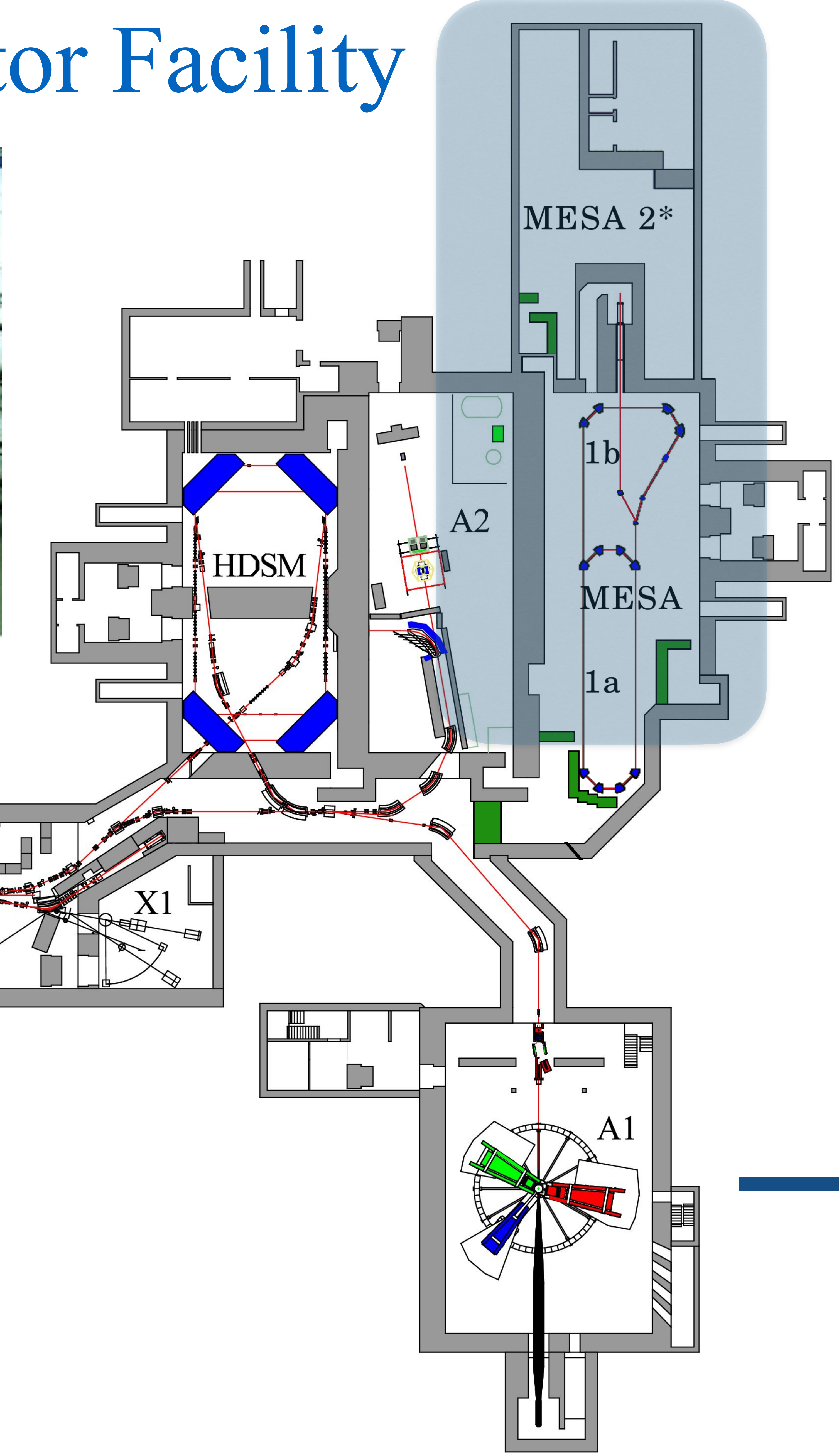
The MAMI Accelerator Facility



A1 Collaboration
3-Spectrometers Setup



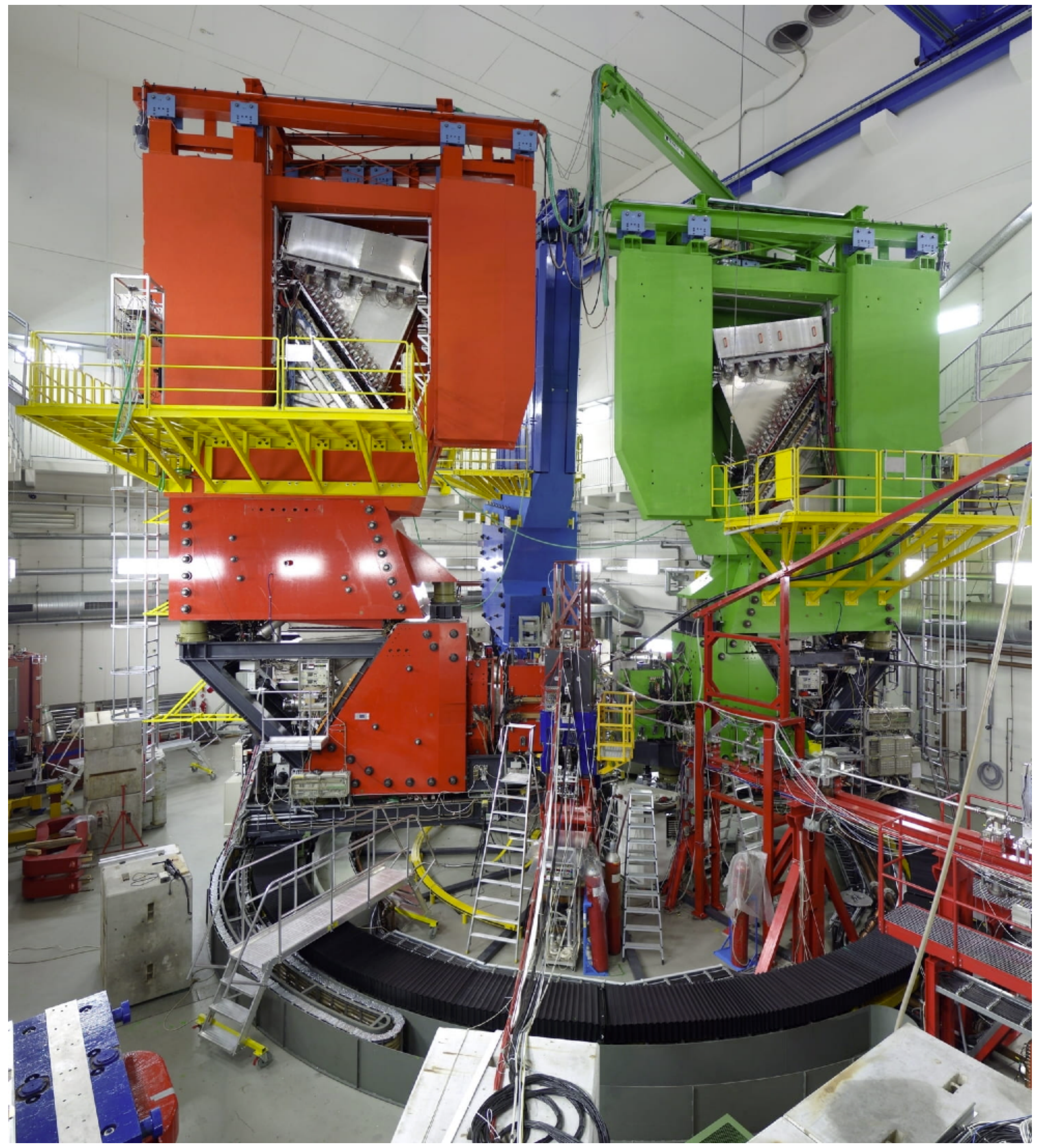
The MAMI Accelerator Facility



MESA

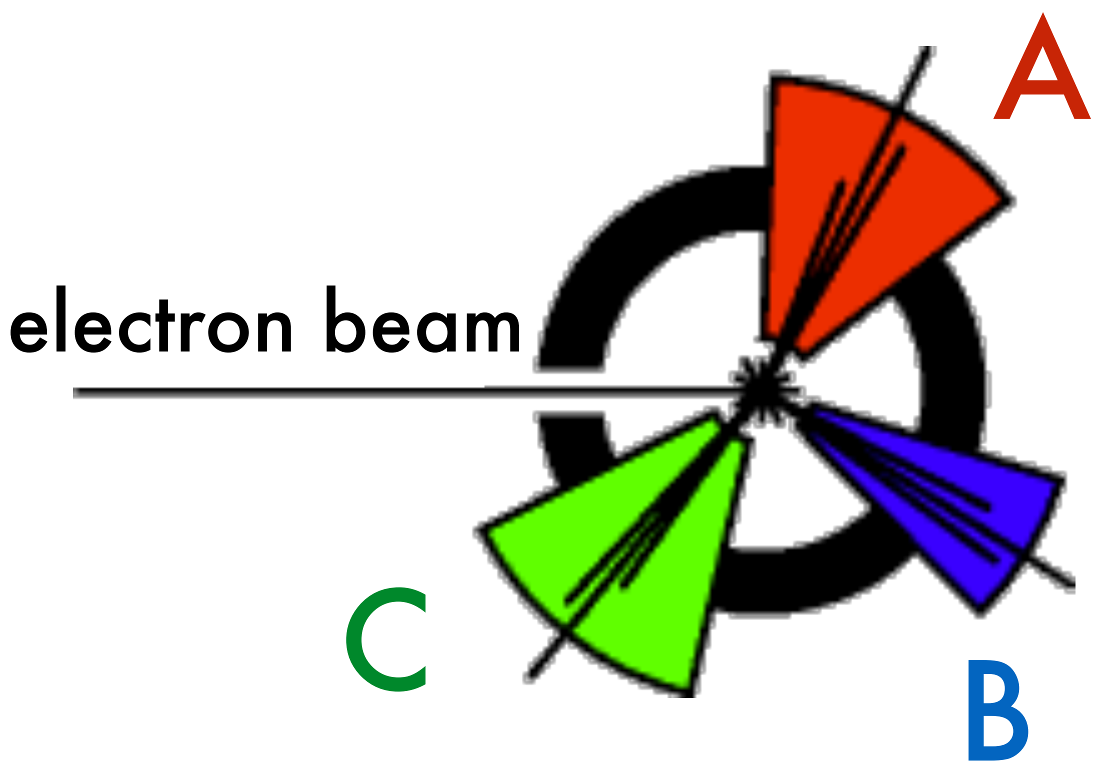
Mainz
Energy-recovery
Superconducting
Accelerator

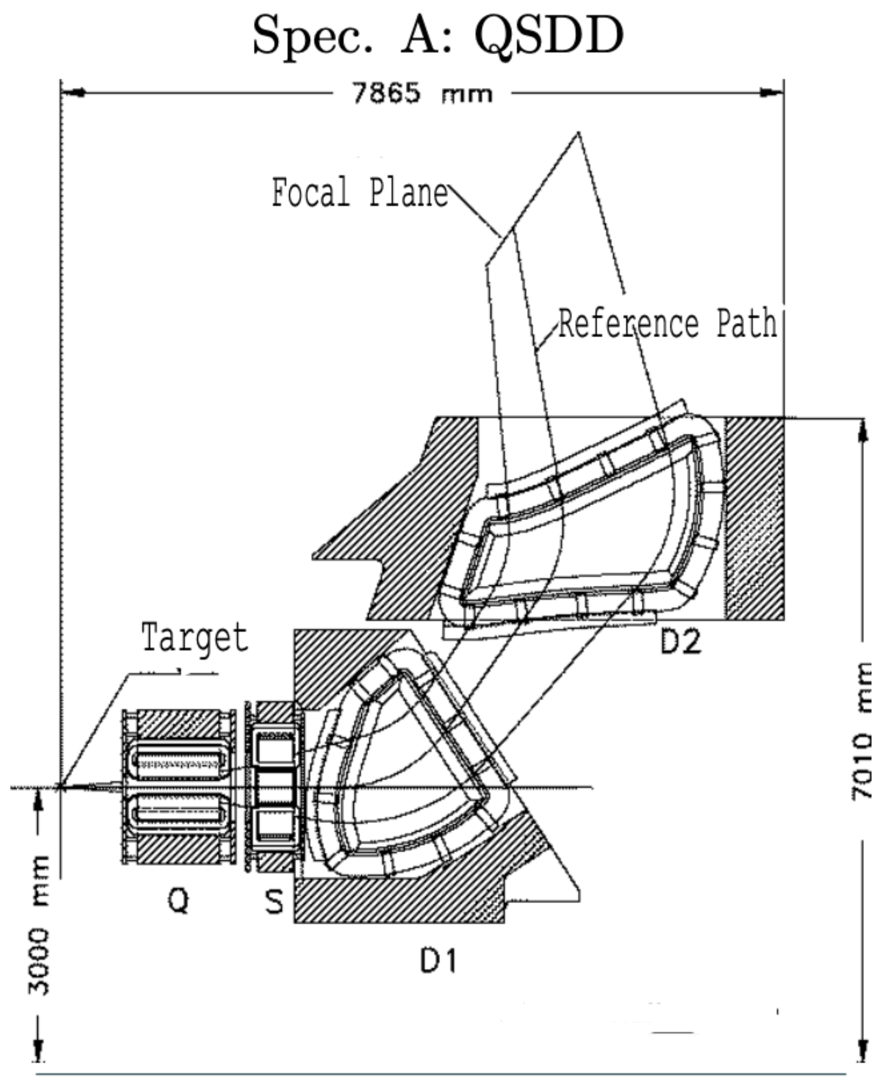
A1 Collaboration
3-Spectrometers Setup

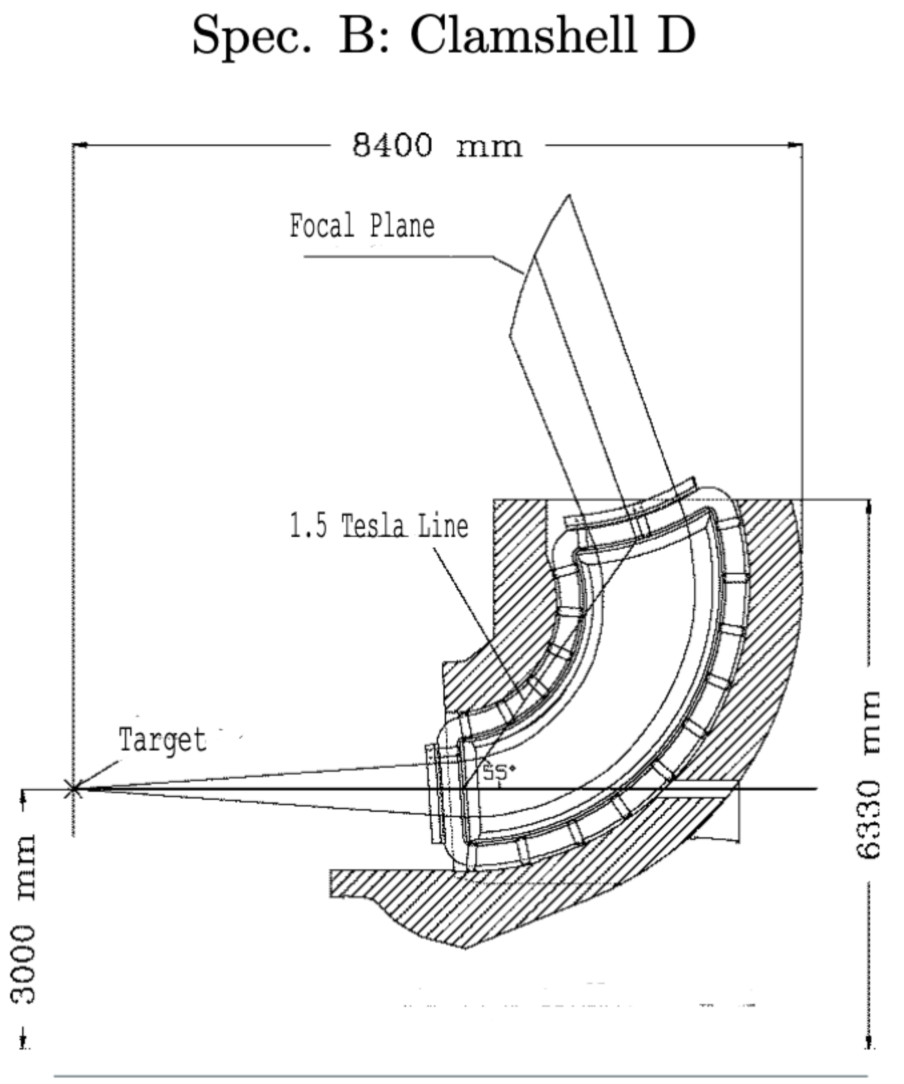


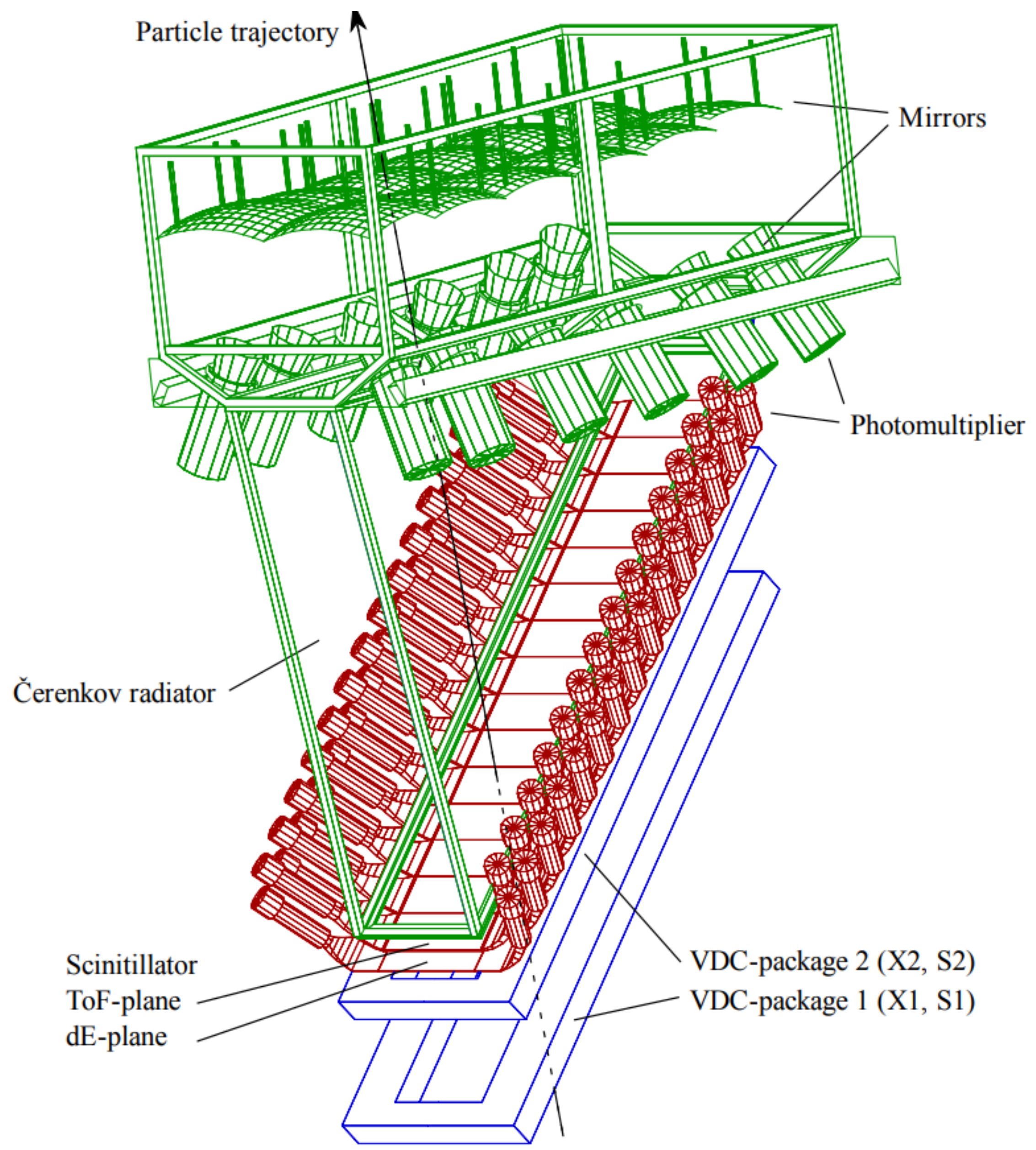
A1 Spectrometer Facility

	A	B	C
Configuration	QSDD	D	QSDD
Max.Momentum (MeV)	735	870	551
Solid Angle (msr)	28	5,6	28
Mom. Resolution	10^{-4}	10^{-4}	10^{-4}
Pos. Res at Target (mm)	3-5	1	3-5

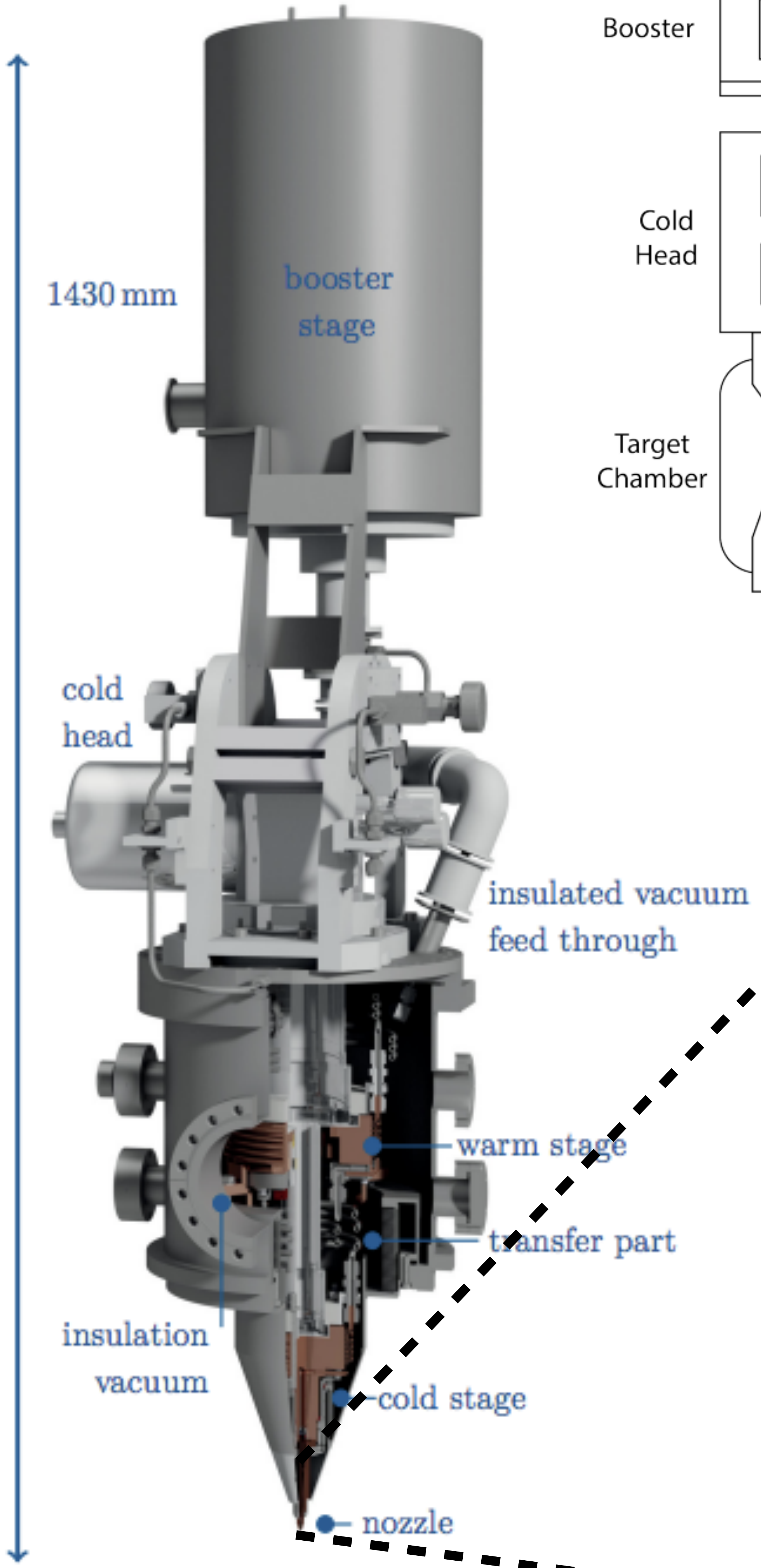


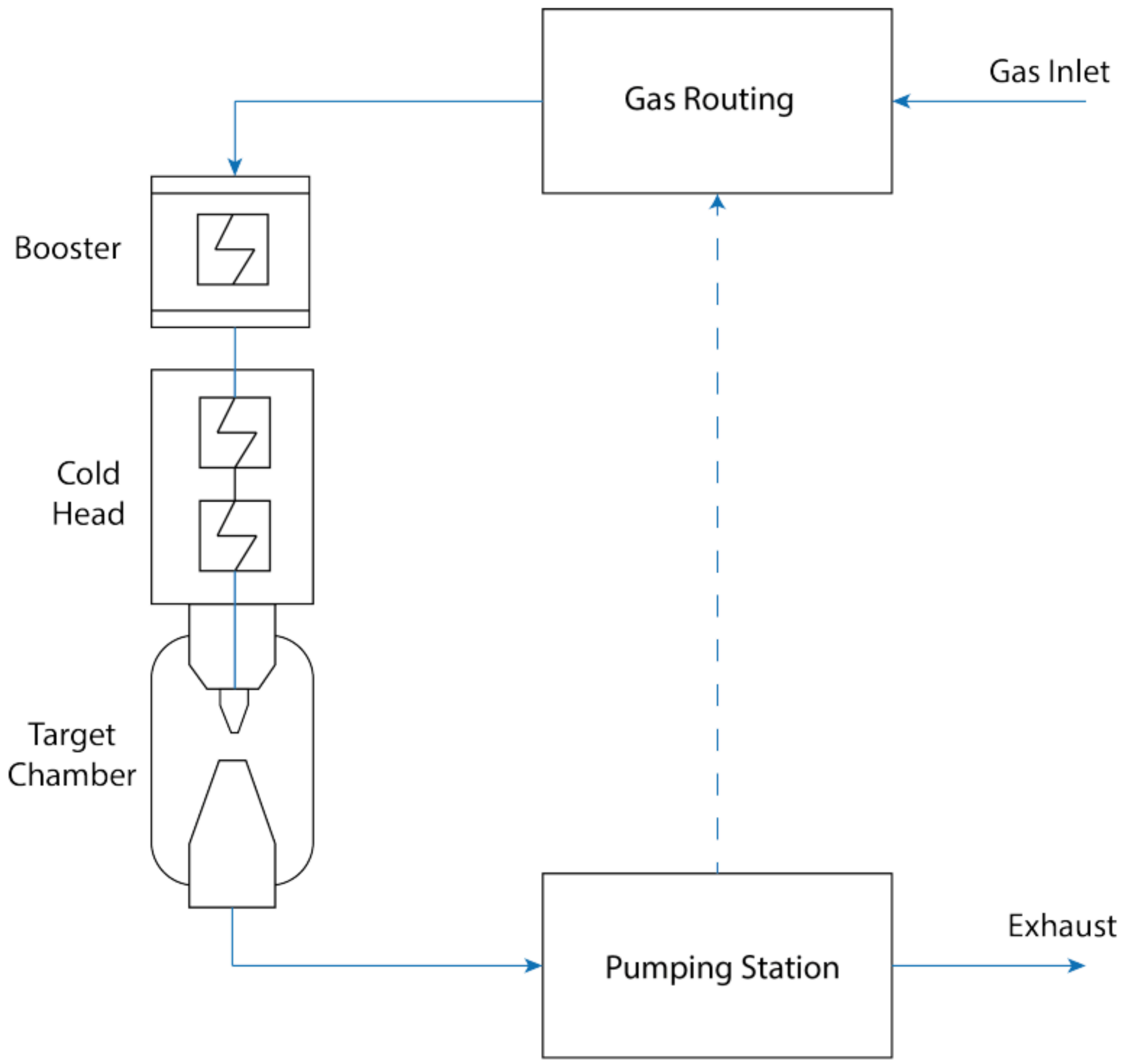






Jet Target

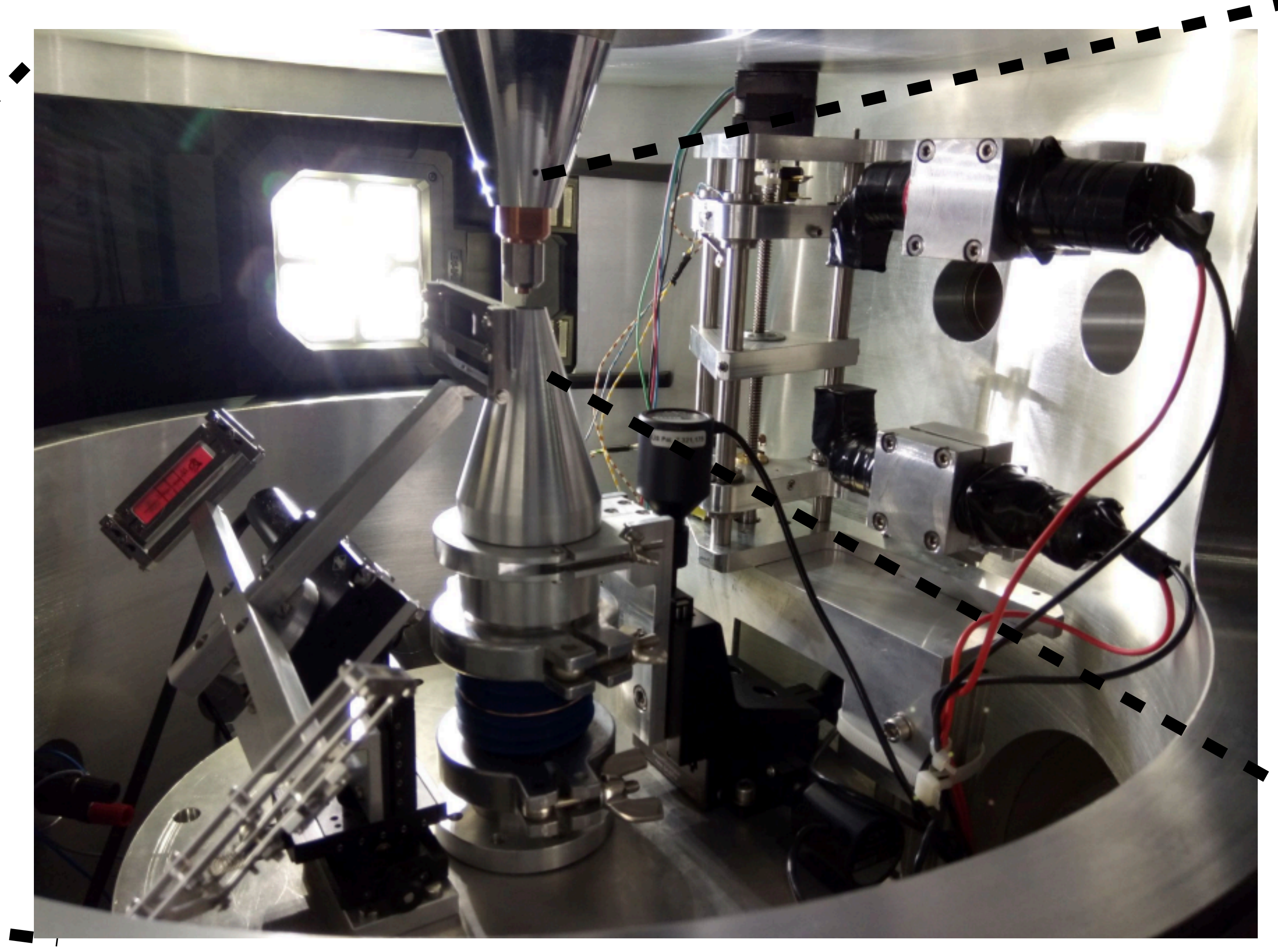


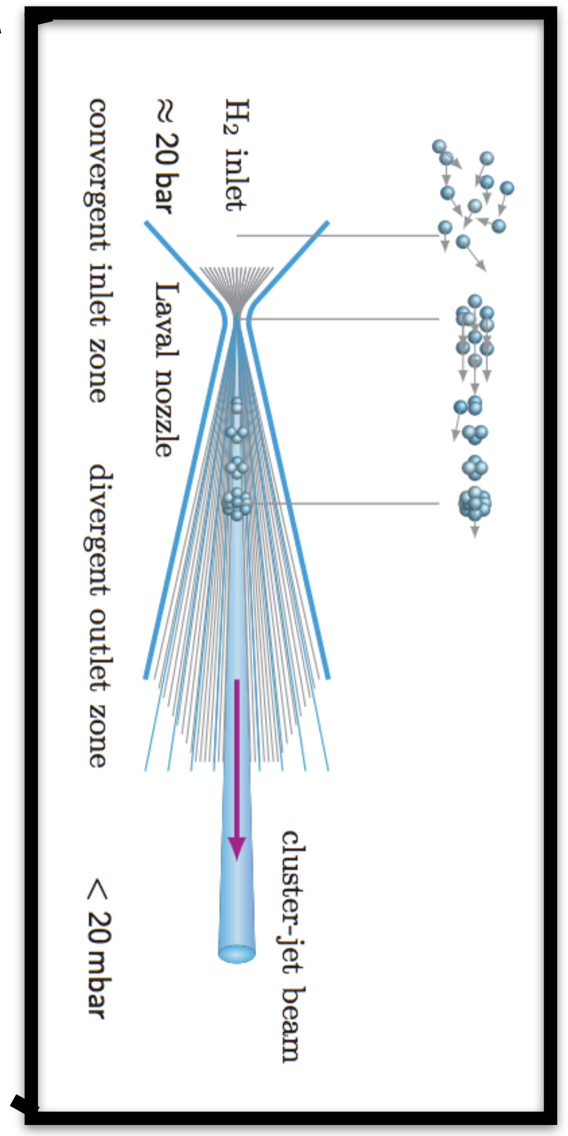


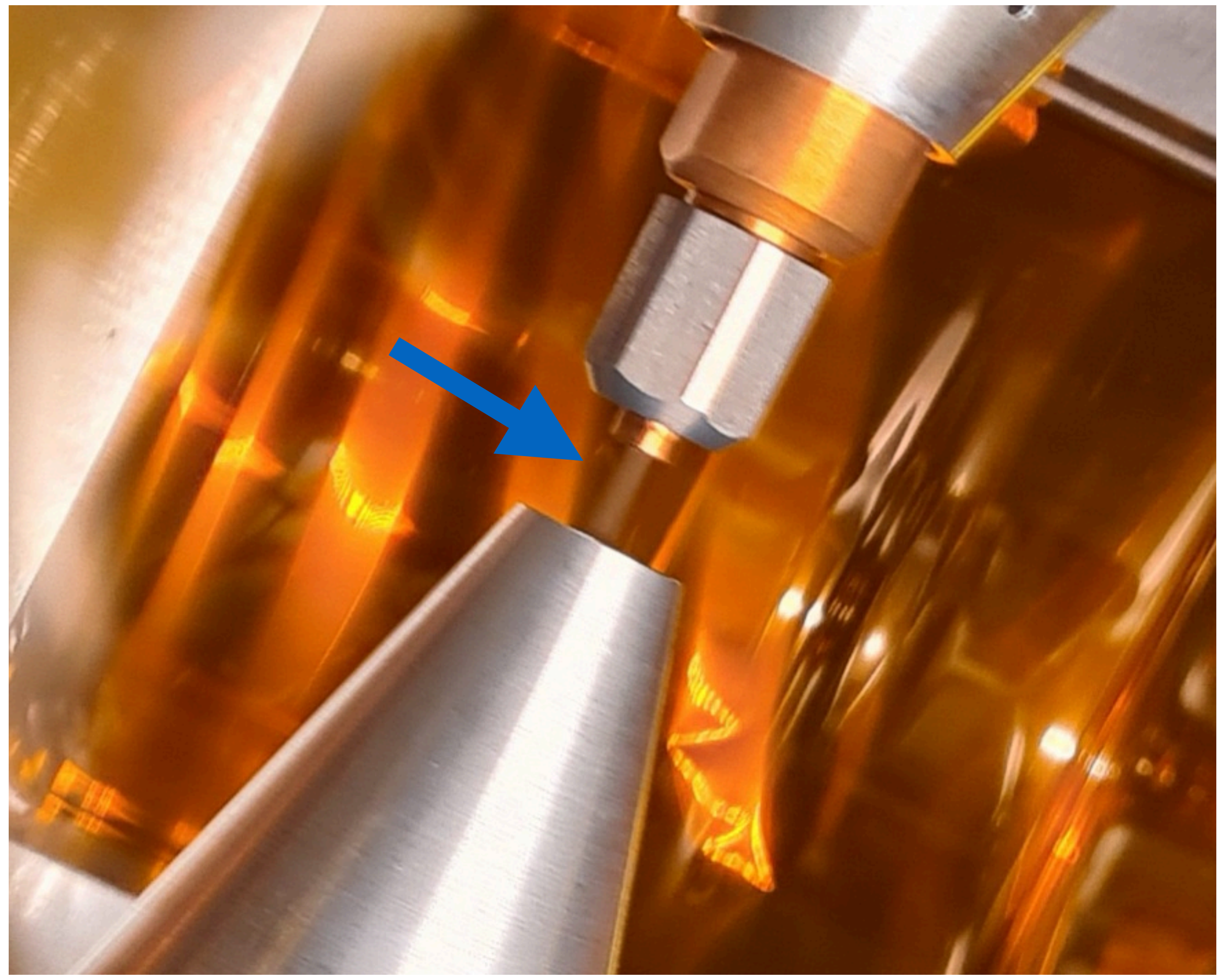
- Supersonic gas flow from Laval nozzle
- Supersonic shockwaves and clustering at cryogenic temperatures limit gas diffusion
- mm-wide collimated gas stream
- Well tested with hydrogen (“proton target”)
- Successfully operated with argon for the first time: milestone for MAGIX

B.S. Schlimme *et al.*, Nucl. Instr. Meth. Phys. Res. A 1013, 165668 (2021)

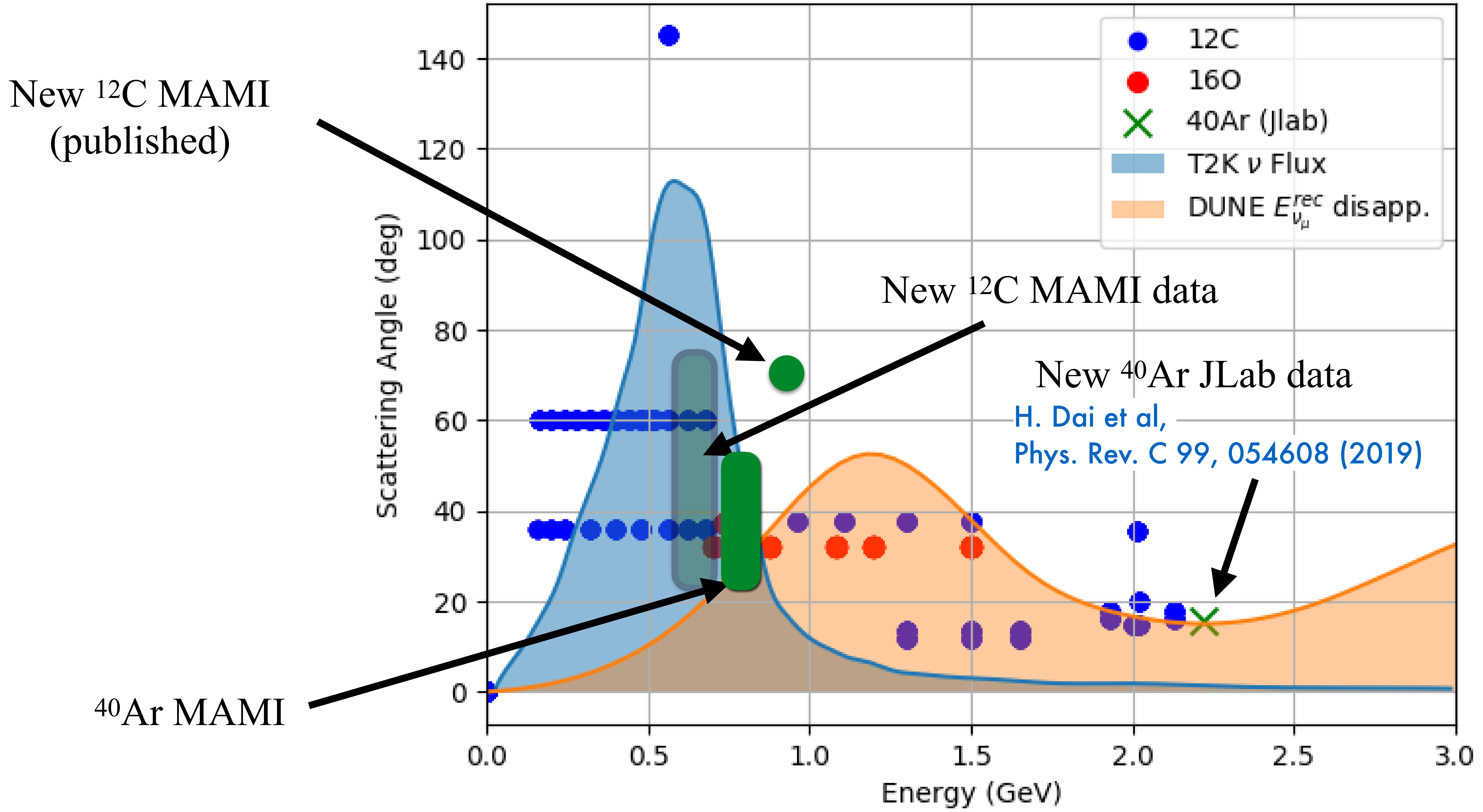
S. Grieser *et al.*, Nucl. Instr. Meth. A 906, 120-126 (2018)





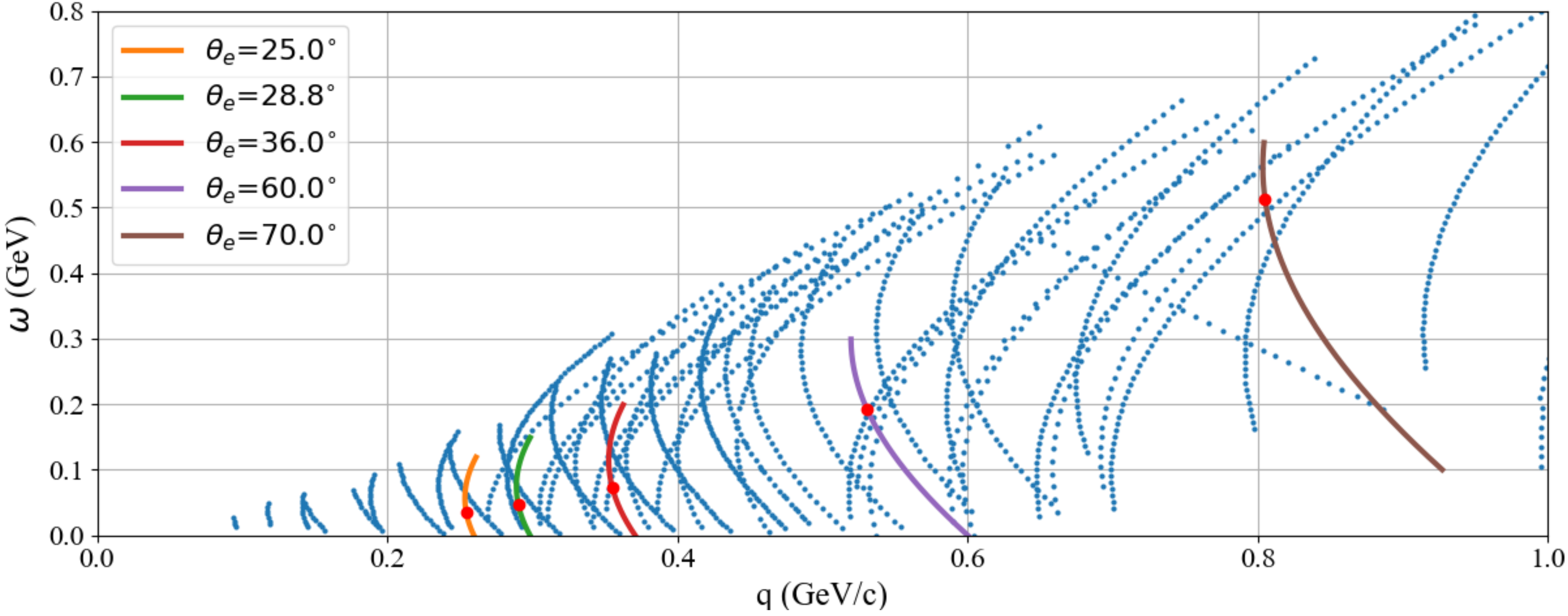


Electron Scattering Dataset vs Neutrino LB Experiments



Carbon
(Plastic Scints, Mineral Oils, …)

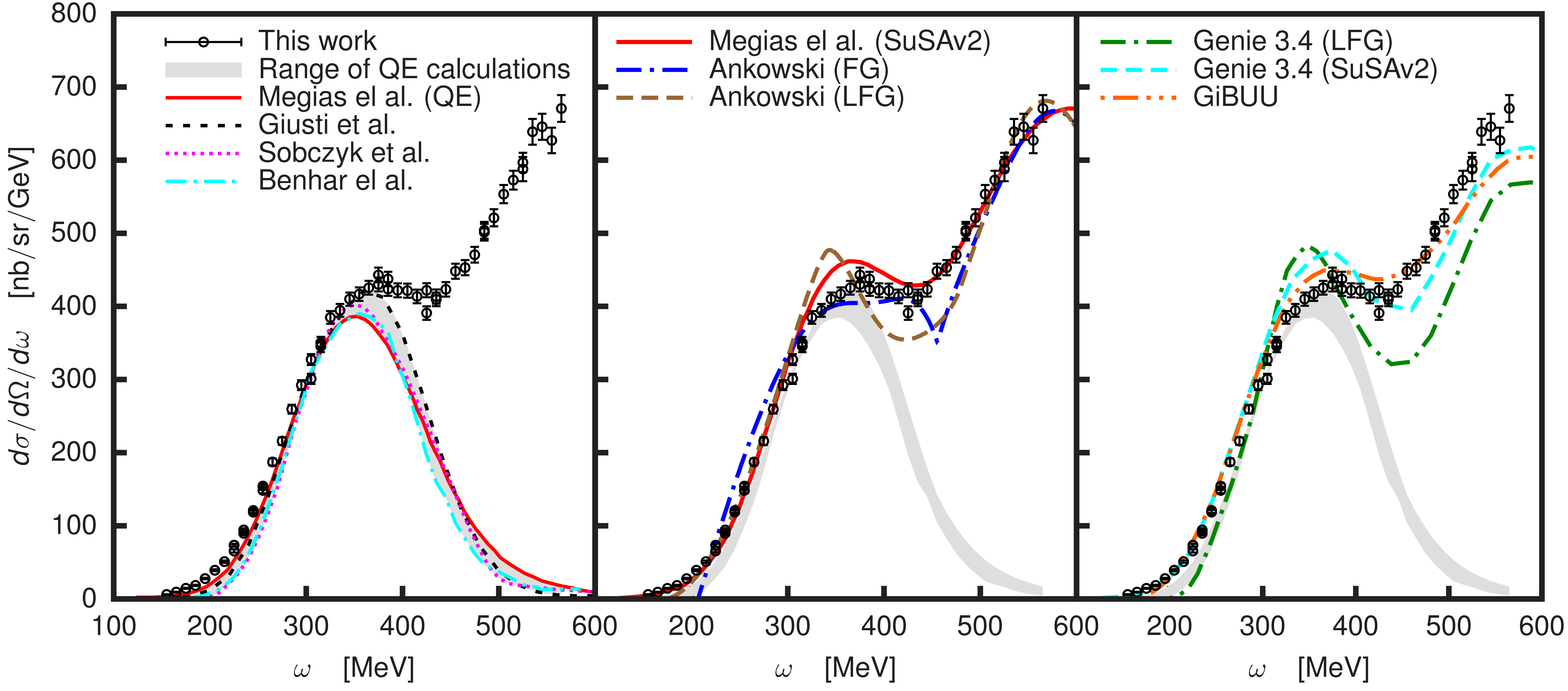
Electron Scattering ^{12}C Dataset



MAMI ^{12}C data

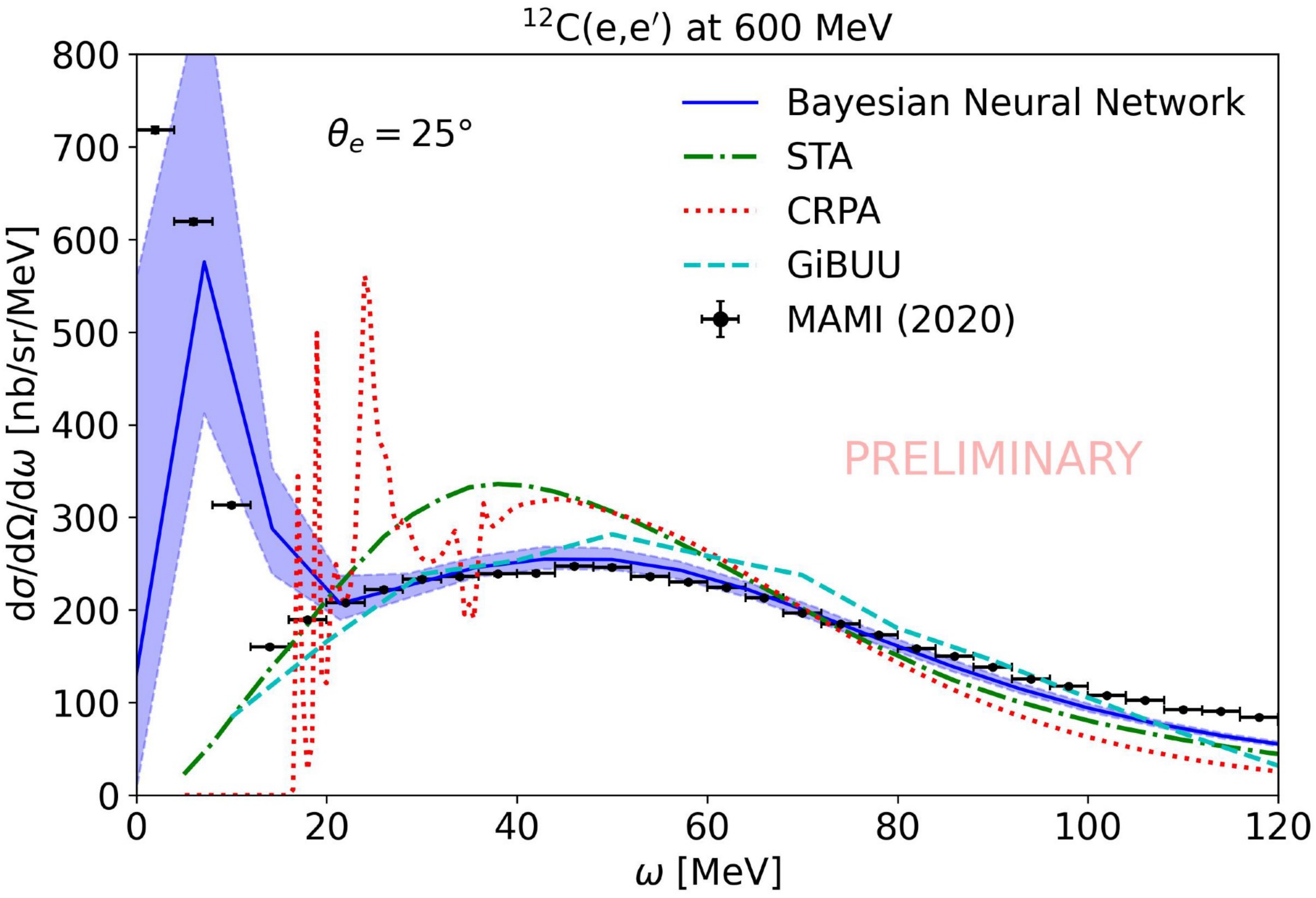
E=705 MeV , θ_e=70°

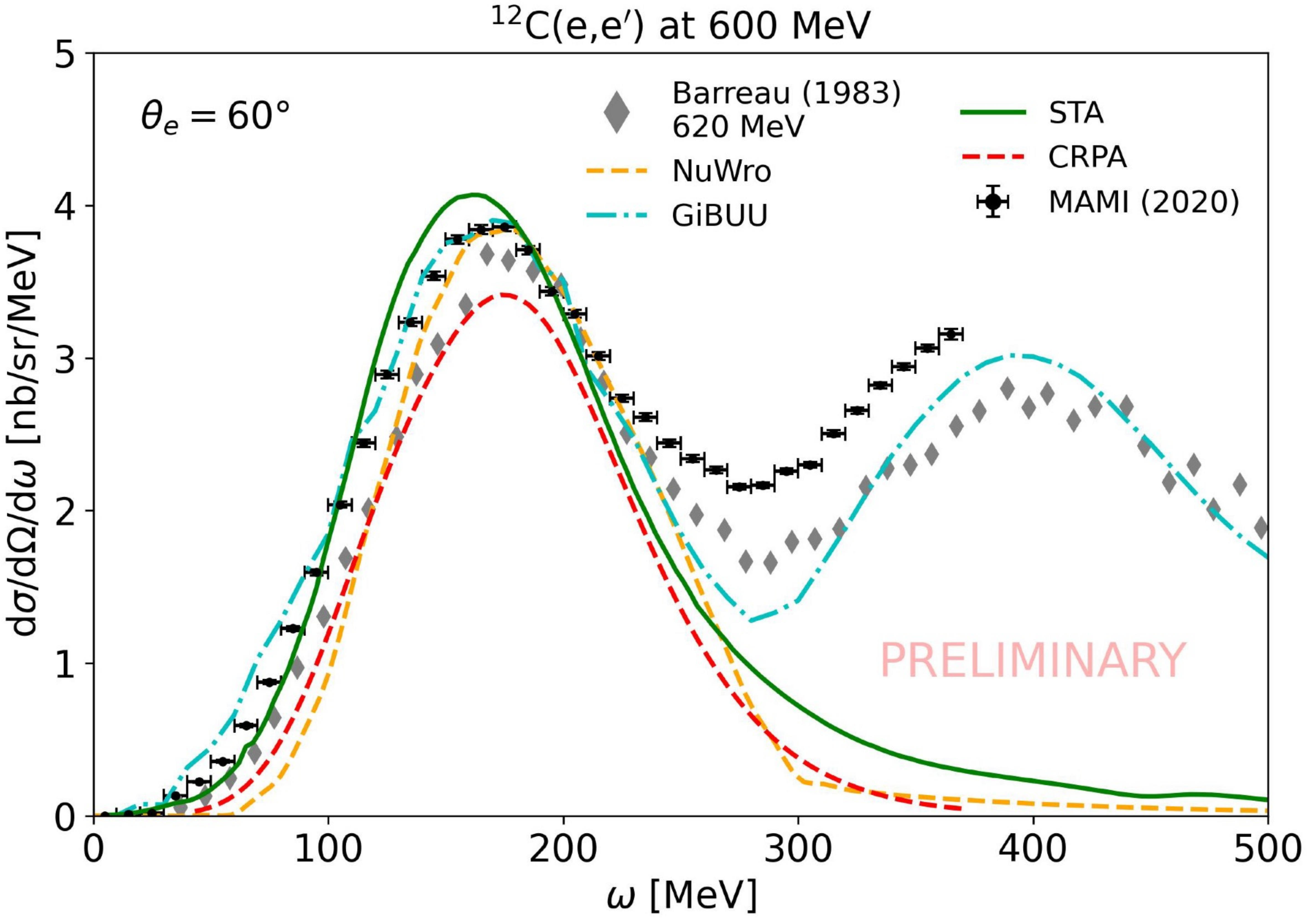
M Mihovilovič, LD, et al. , Few-body systems 65 (3), 78 (2024)



- Analysis: M. Mihovilovic (J.Stefan Inst.)
- GENIE (2.x tune) from A.Ankowski
- MEC / Resonance region more difficult to describe
- Quasi-Elastic region well described by theory

MAMI ^{12}C data





- Available data: E_0=600 MeV , $\theta_e = 25^o, 28.8^o, 36^o, 60^o ,70^o$
- Analysis: L. Wilhelm (JGU Mainz)

Argon
(SB Program@FNAL, DUNE)

MAMI (elastic) ^{40}Ar data

Assume hom. cyl. jet:

$$\rho_{\text{areal}} = 4N_{\text{mol}} \frac{q_V}{\pi d v} \frac{p_N N_A}{T_N R}$$

$$v_{\text{gas}} = \sqrt{\frac{2\kappa}{\kappa - 1} \frac{RT_0}{M}} \qquad v_{\text{liq}} > \sqrt{\frac{2p_0}{\rho(p_0, T_0)}}$$

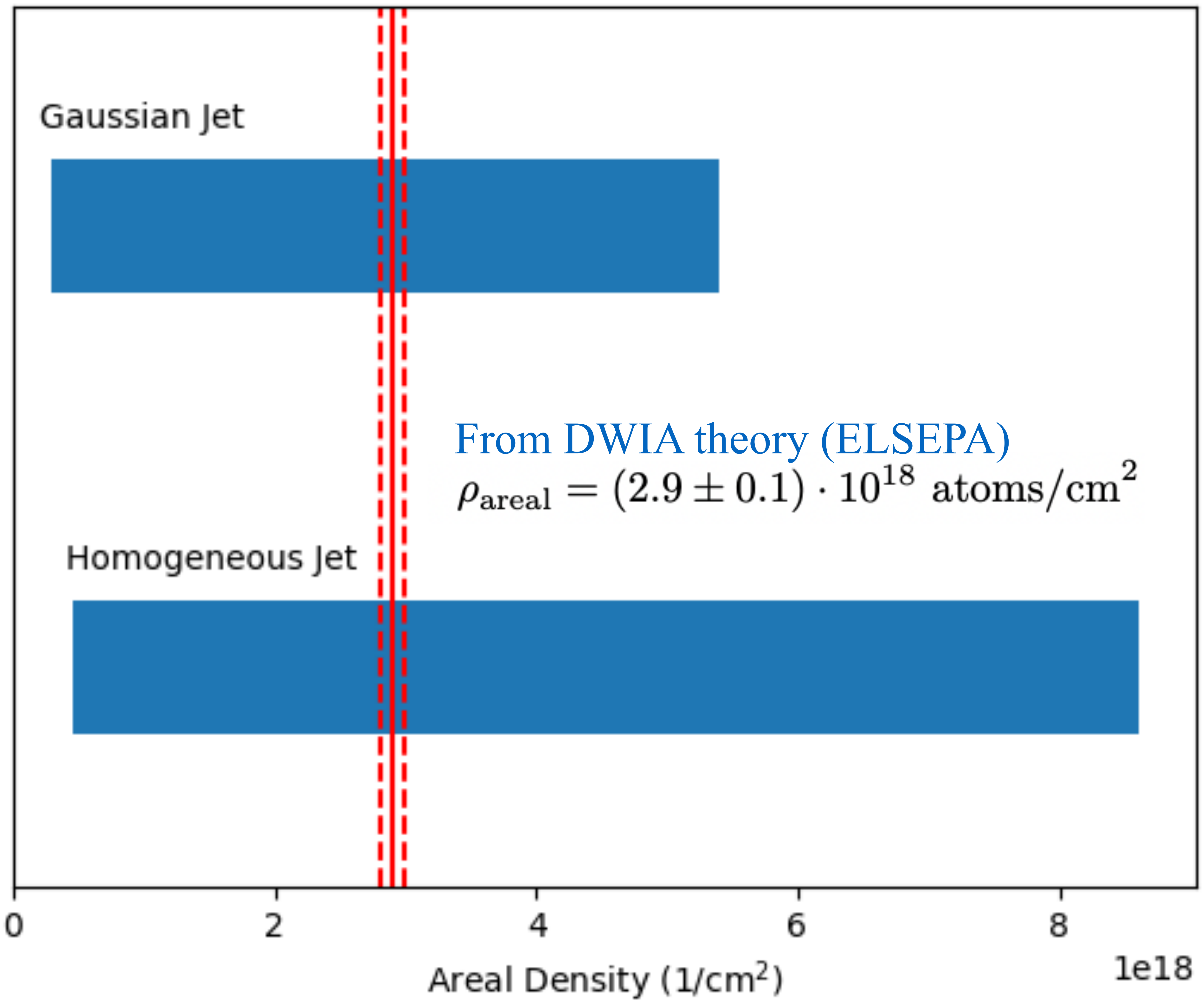
Gaussian case: $\pi d \longrightarrow \sqrt{2\pi\sigma^2}$

Results:

$$\rho_{\text{areal}}(\text{gas}) = 0.46 \cdot 10^{18} \text{ atoms/cm}^2$$

$$\rho_{\text{areal}}(\text{liquid}) < 8.62 \cdot 10^{18} \text{ atoms/cm}^2$$

* Theoretical calculation: ELSEPA
  https://github.com/eScatter/elsepa

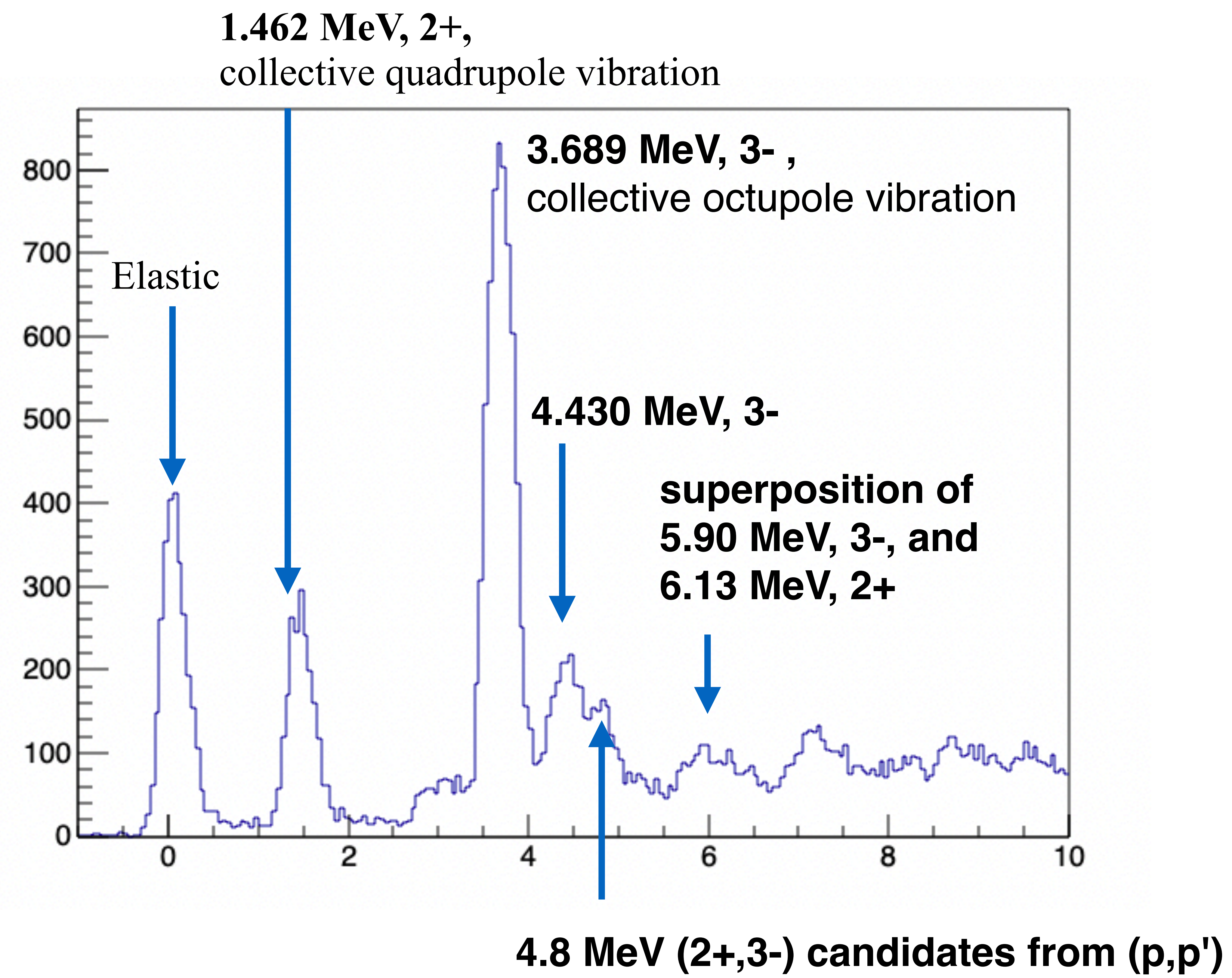


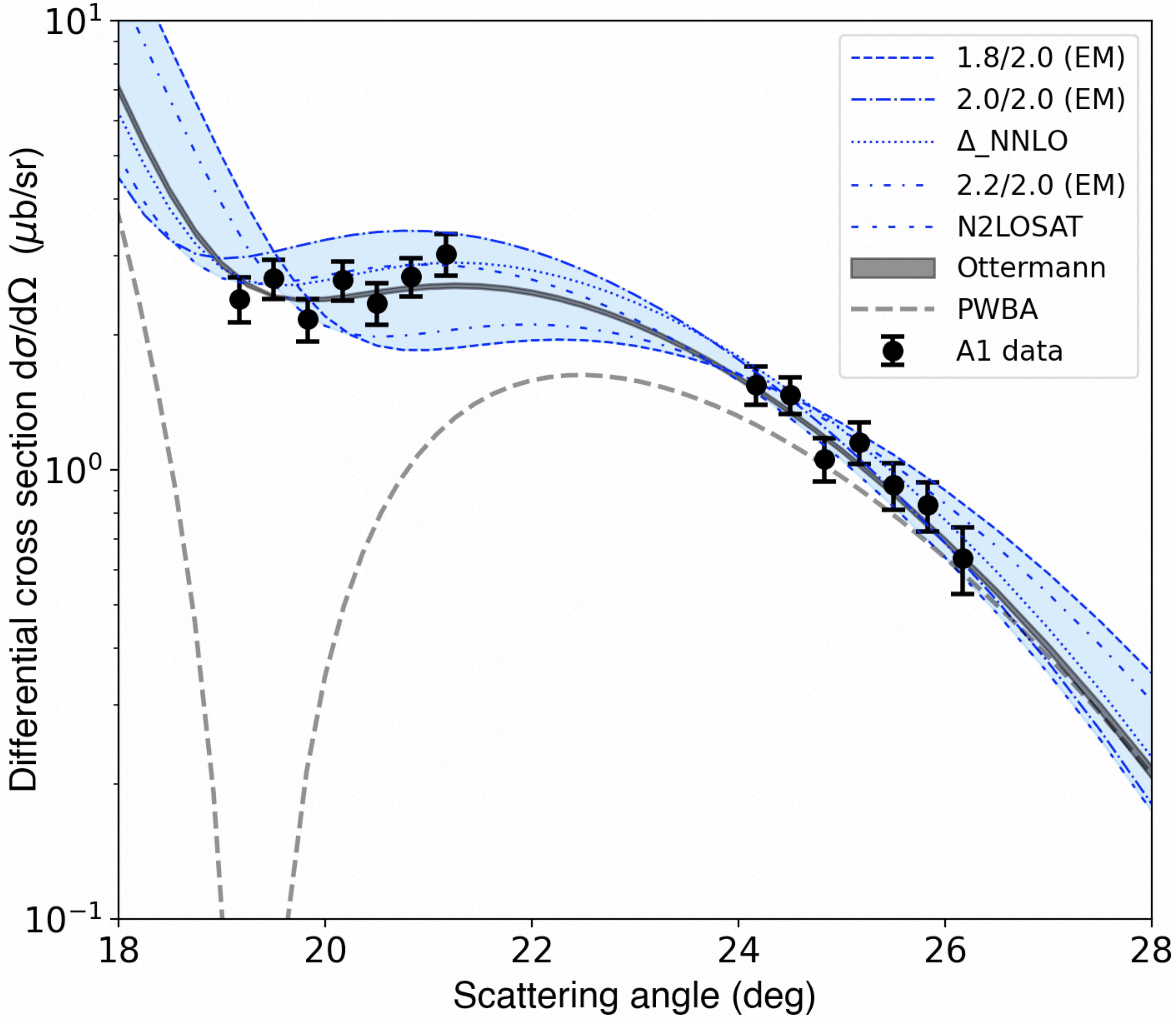
MAMI (elastic) ^{40}Ar data

M. Littich, LD, et al, arXiv:2503.18965 (accepted on EPJA)

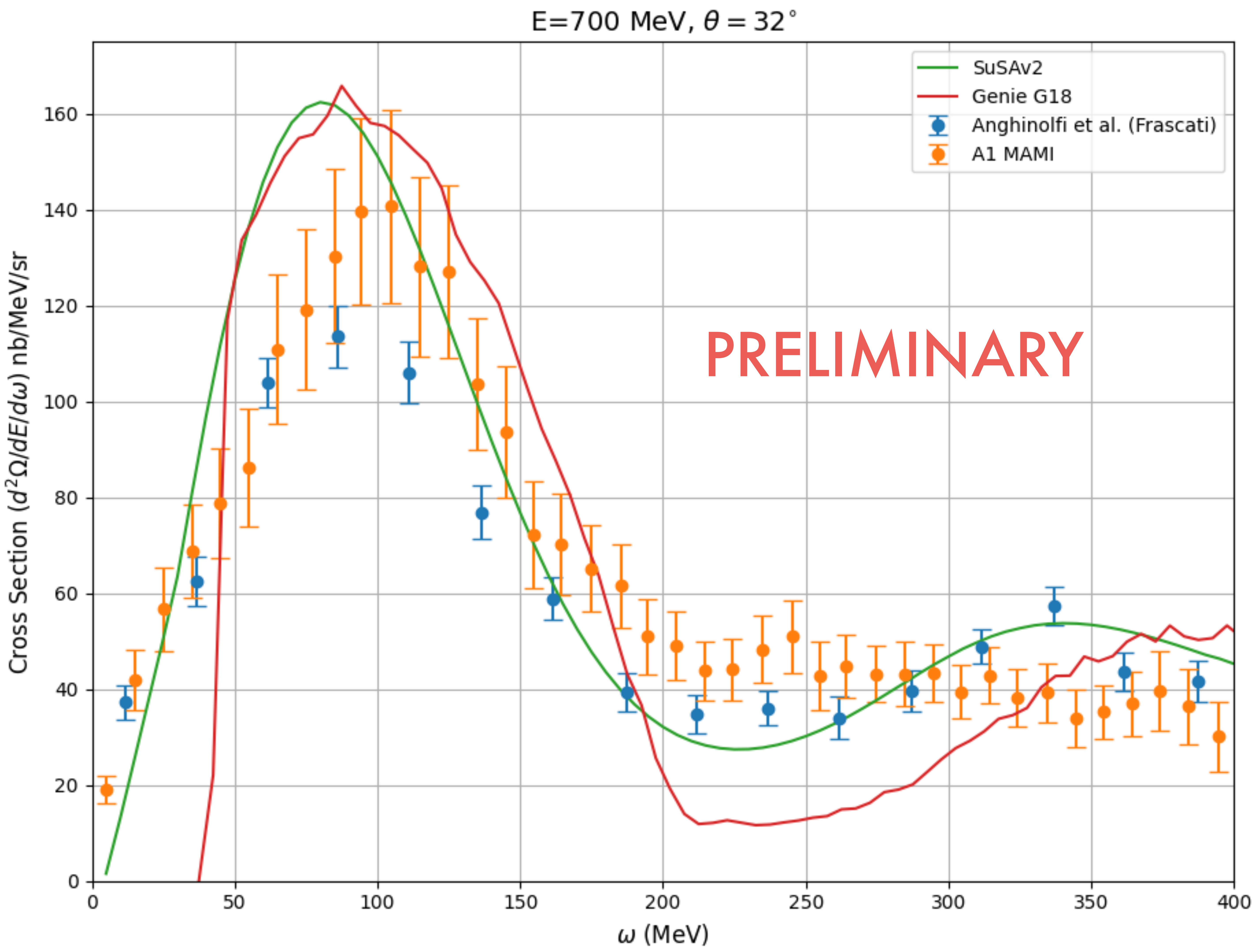
C.R. Ottermann et al. Nucl. Phys. A, 379(3):396–406, 1982

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





MAMI (inelastic) ^{40}Ar data

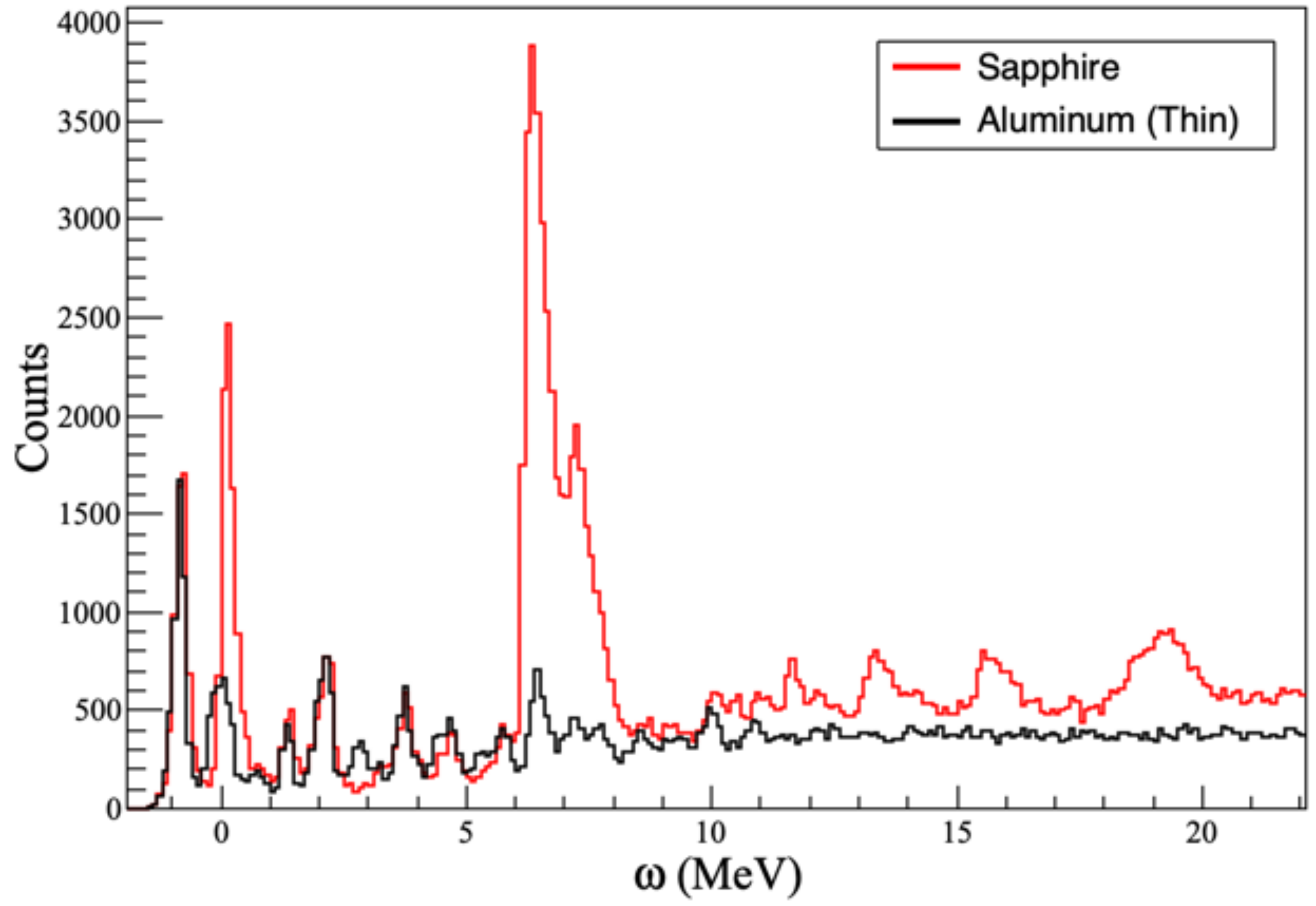


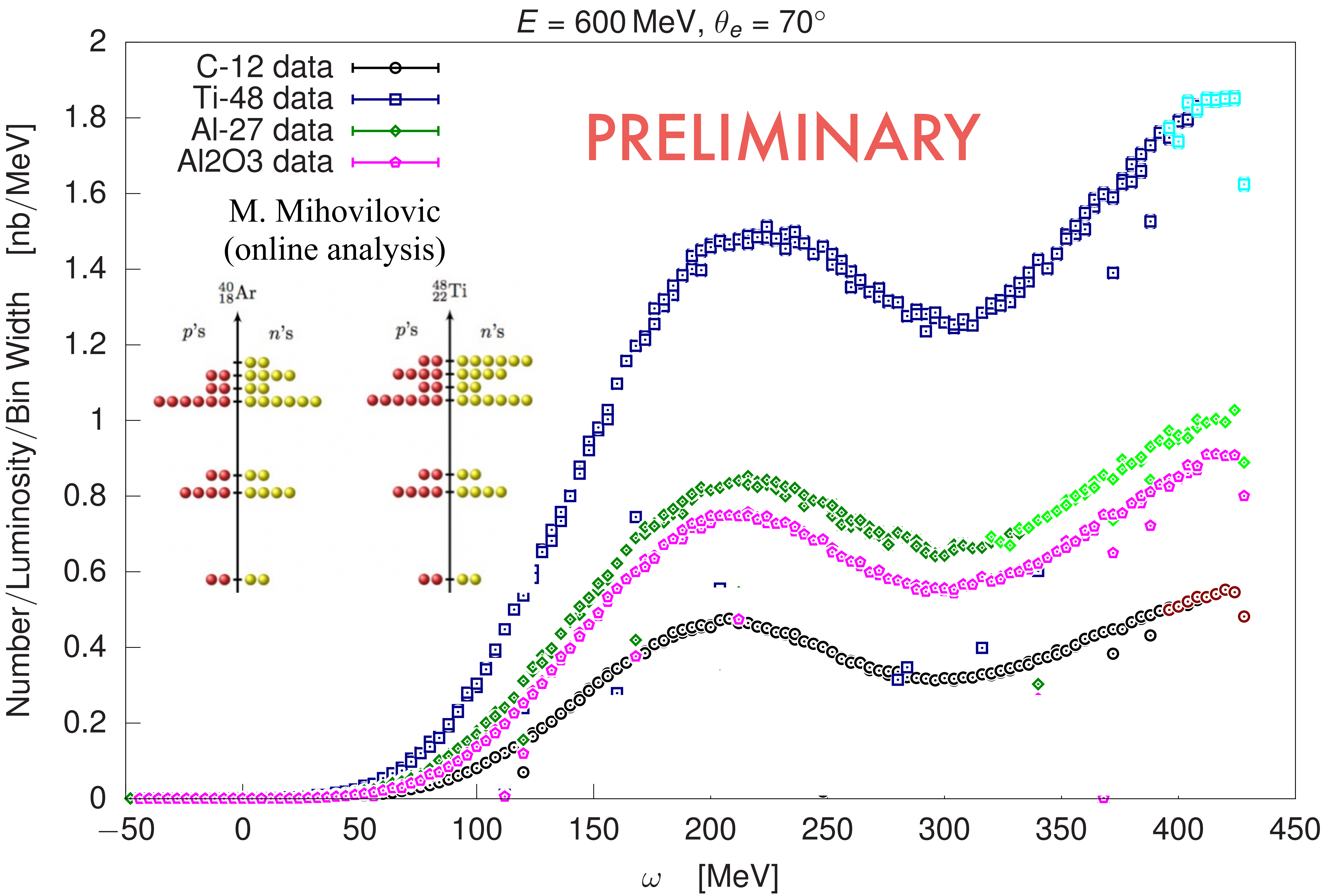
✱ Analysis: M. Littich (JGU Mainz)

Oxygen
(Cherenkov Detectors, T2K/HyperK, …)

MAMI ^{16}O data

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



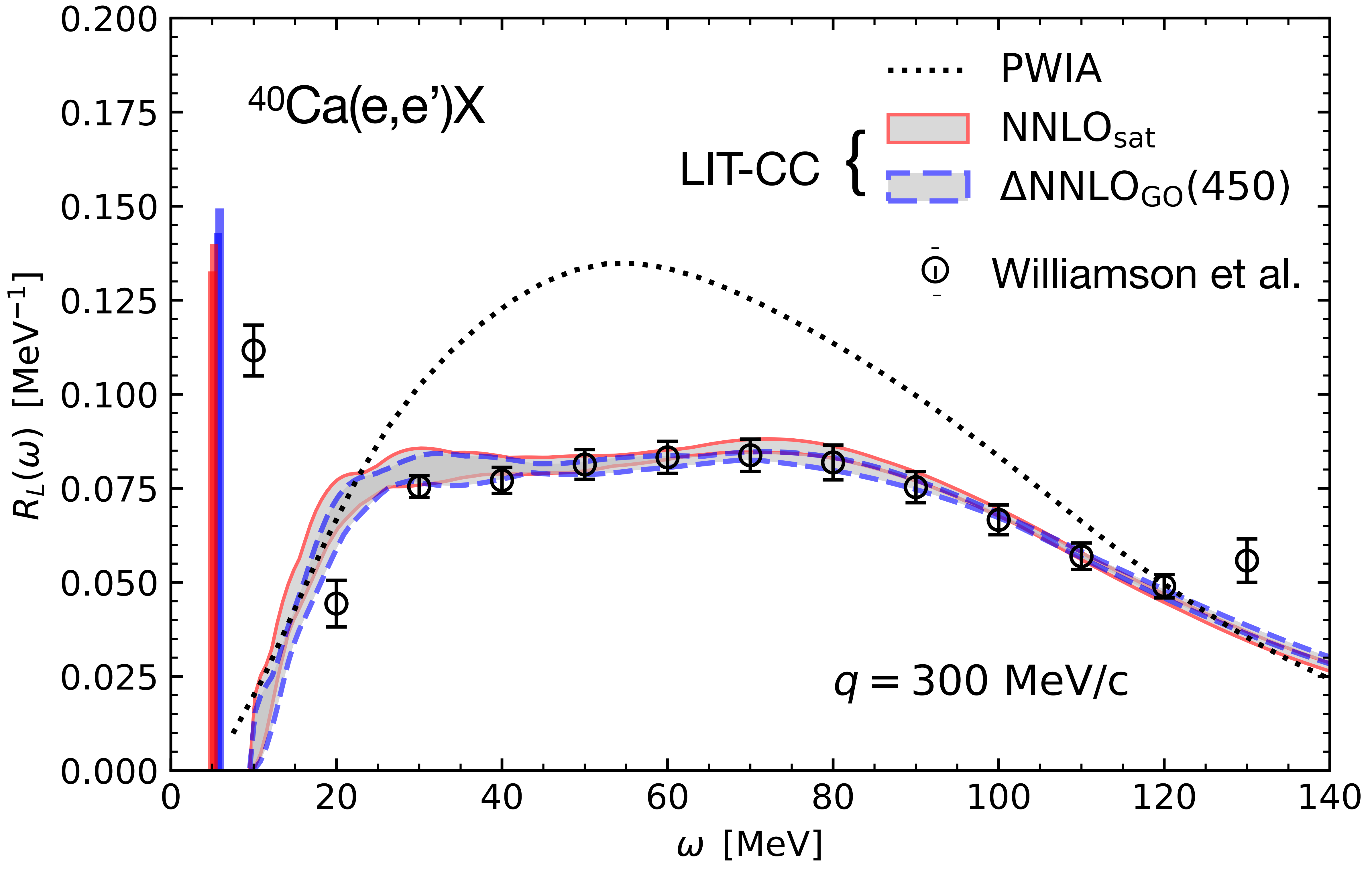


- Analysis: K. I. Hassan

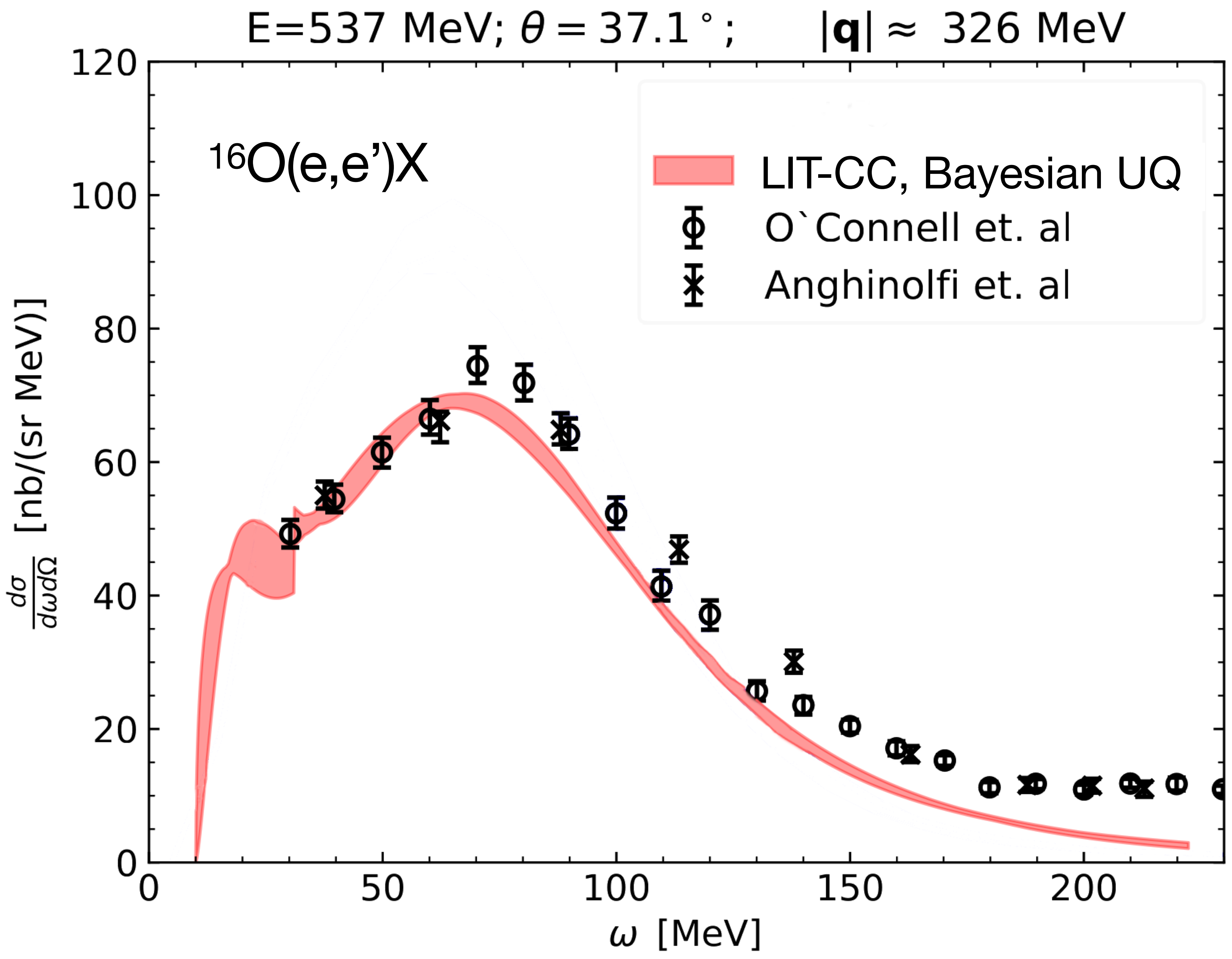
Support from ab-initio nuclear theory

Lorentz integral transform with coupled-cluster theory ➞ LIT-CC

Sobcyzk, Acharya, Bacca, Hagen, PRL 127 (2021) 7, 072501

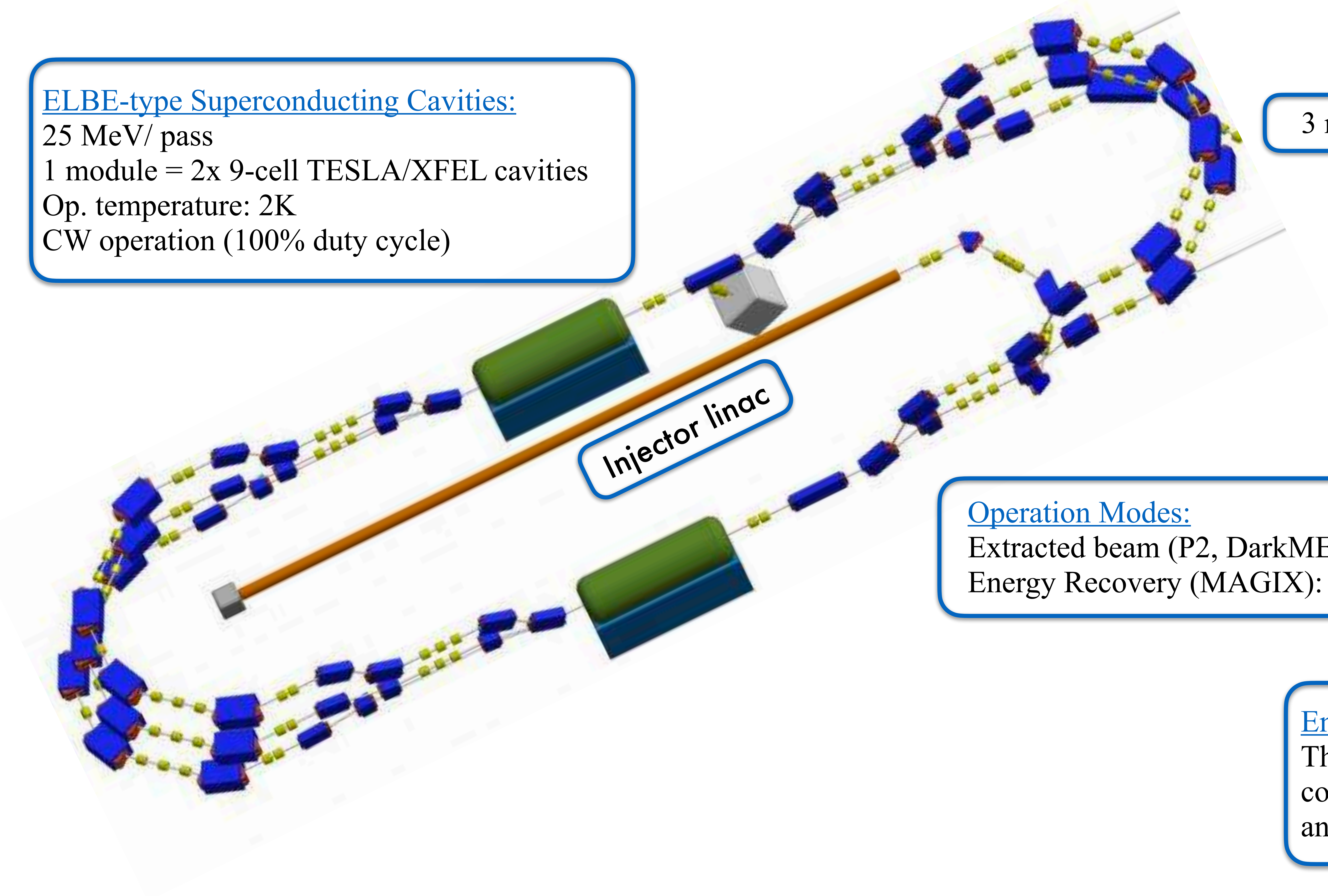


Acharya, Sobczyk, Bacca, Hagen, Jiang, PRL 134, 202501 (2025)



Future:
The MESA Facility

MESA: Mainz Energy-Recovery Superconducting Accelerator



ELBE-type Superconducting Cavities:
25 MeV/ pass
1 module = 2x 9-cell TESLA/XFEL cavities
Op. temperature: 2K
CW operation (100% duty cycle)

3 recirculation arcs

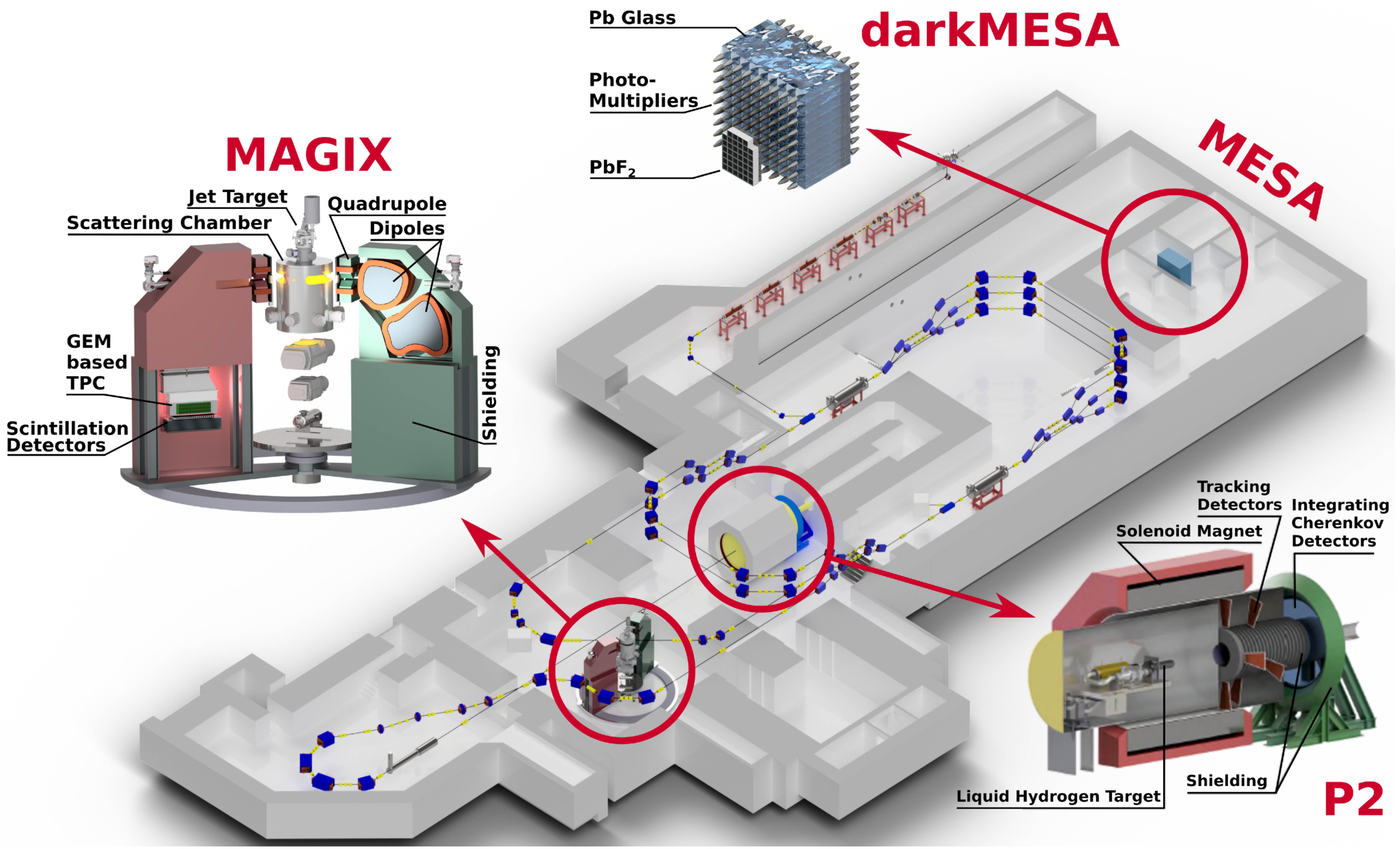
Operation Modes:
Extracted beam (P2, DarkMESA): E_{beam} = 155 MeV, I_{beam} = 150uA
Energy Recovery (MAGIX): E_{beam} = 105 MeV, I_{beam} = 1mA

Energy Recovery mode:
The beam is reinserted after 3 recalculations in couterphase: the energy goes back to the cavities and the beam is dumped at 5 MeV.

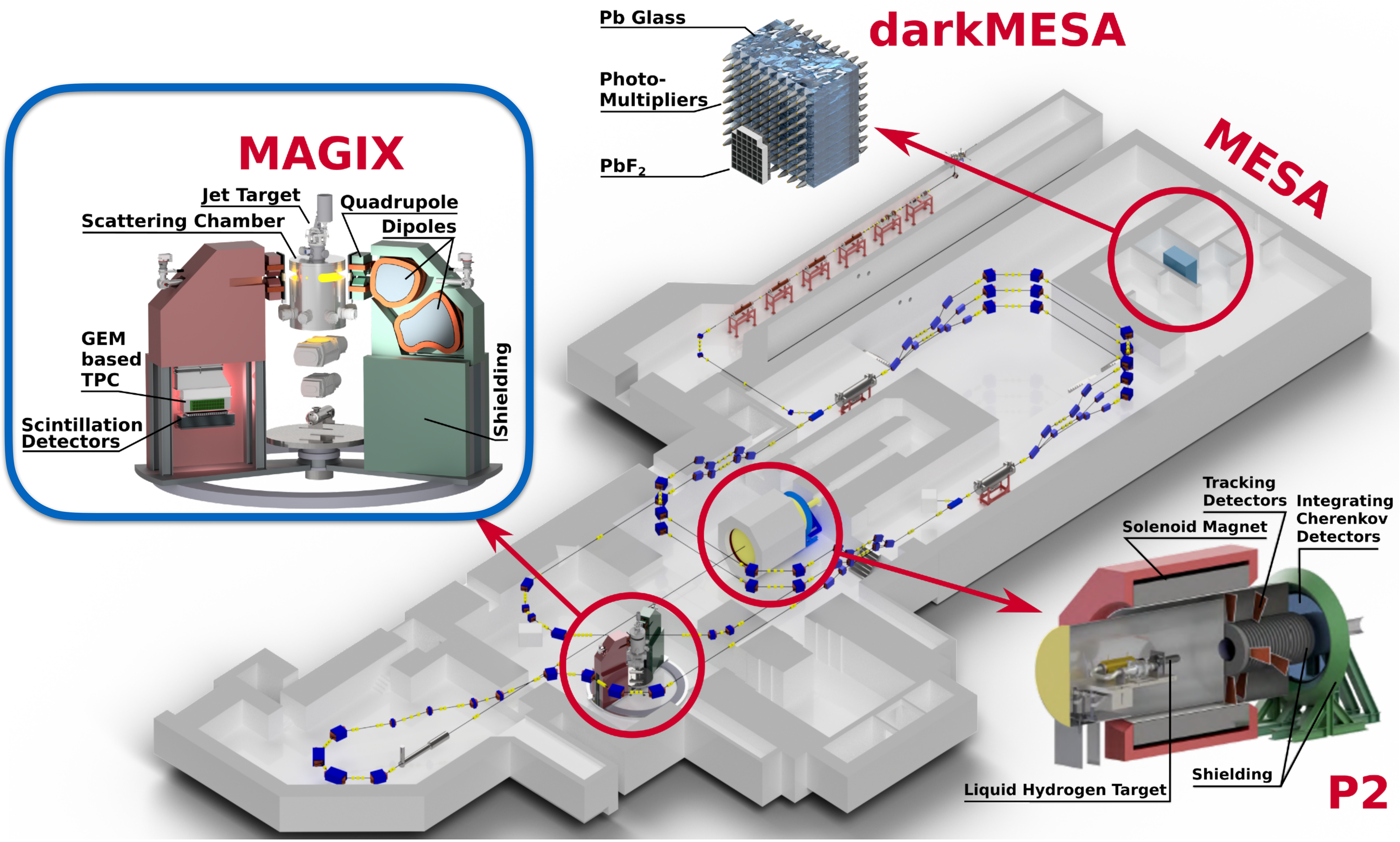
MESA: Mainz Energy-Recovery Superconducting Accelerator

MESA: Mainz Energy-Recovery Superconducting Accelerator

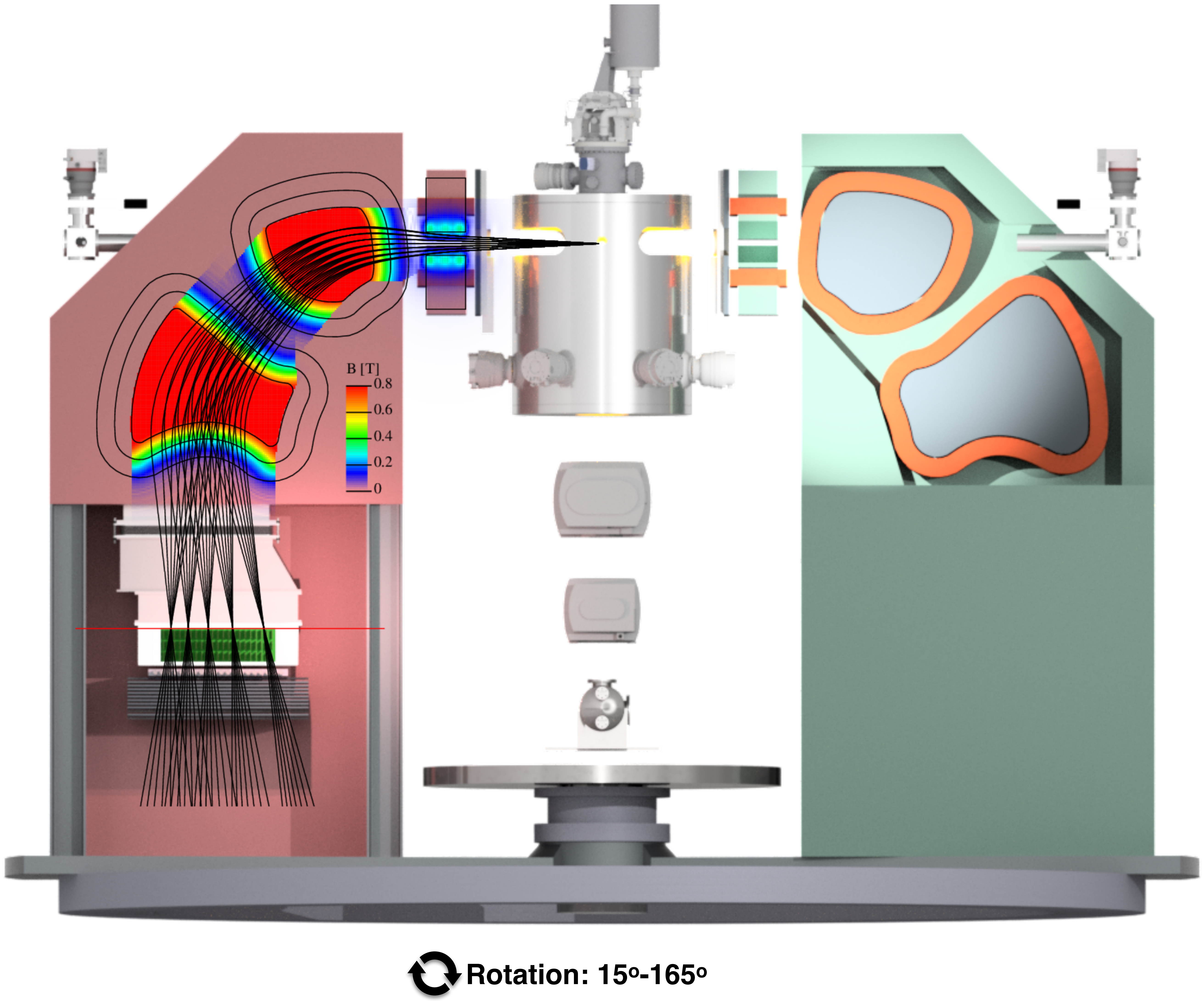
The MAGIX experiment



The MAGIX experiment



The MAGIX experiment



Detectors:

- Low-mass GEM-based TPC.
- Plastic Scintillators for triggering and veto.

Timing

- TPC trigger: ~1 ns
- coincidence time STAR↔PORT: ~100 ps

Focal Plane resolutions (*p*-dependent etc)

- positions: ~100 μm angles: ~3.5 mrad

Expected Resolution

- dp/p: 6×10^{-5}
- in-plane angle φ_0: 6.5 mrad
- oop angle θ_0: 1.6 mrad vertex y_0: 60 μm

Acceptances

- momentum acceptance: ± 15 %
- solid angle: 18 msr

Summary and Future plans

Facilities in Mainz:

MAMI, up to 1.6 GeV / 10-100 uA current / CW beam / polarized
MESA (under construction) 150 MeV / mA currents / CW beam / polarized

Physics:

Long-baseline neutrino oscillation experiments (DUNE, HyperK, …)
Supernova neutrinos.

Electrons for Neutrinos Program

Started with inclusive measurements on targets of interest for neutrino physics.
Goal: start exclusive measurements (1p, 1n, 2p, pion channels, ..).
Complementarity with a JLab program at higher energies
Interesting for nuclear structure and reactions physics (modern ab-initio theory)