Physics Highlights and Perspectives with Electron Beams in Mainz

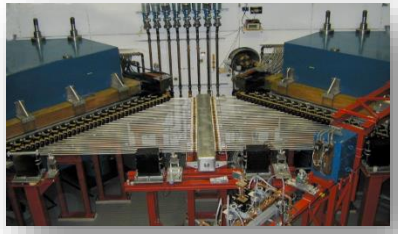
Patrick Achenbach

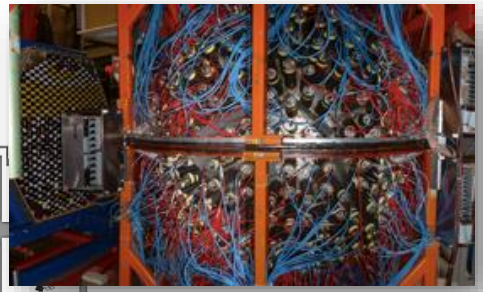
U Mainz

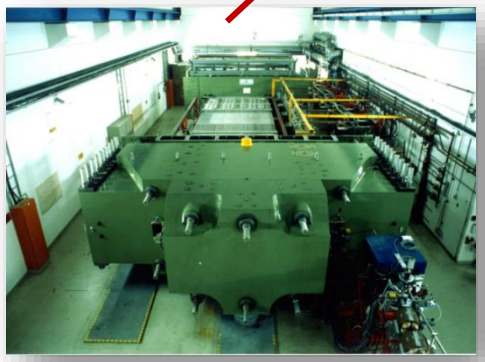
July 2o22

Experimental Opportunities at Mainz University

From established high-precision experiments at Mainz Microtron MAMI …

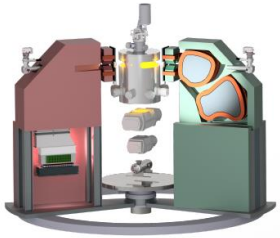




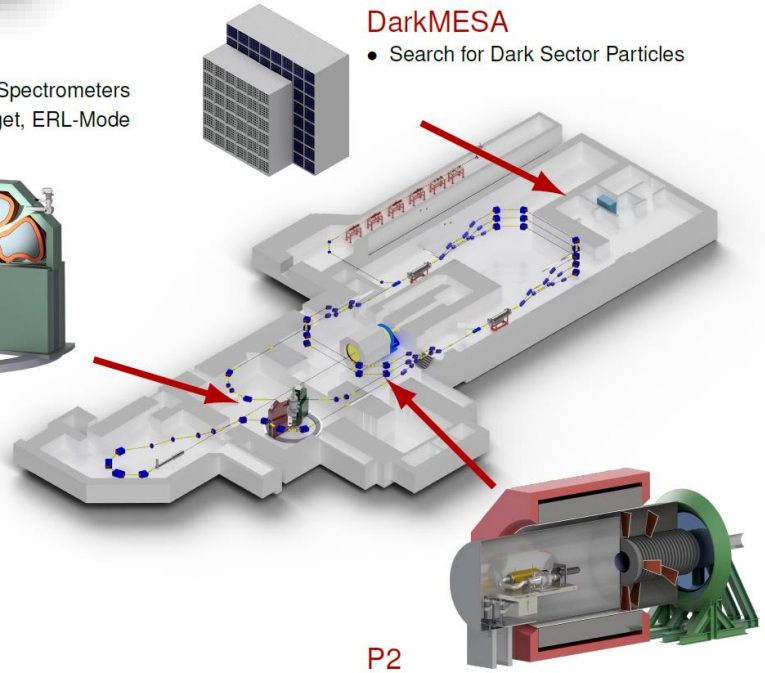


… to the energy recovering superconducting accelerator MESA in the new Center for Fundamental Physics

MAGIX
- High Resolution Spectrometers
- Internal Gas Target, ERL-Mode

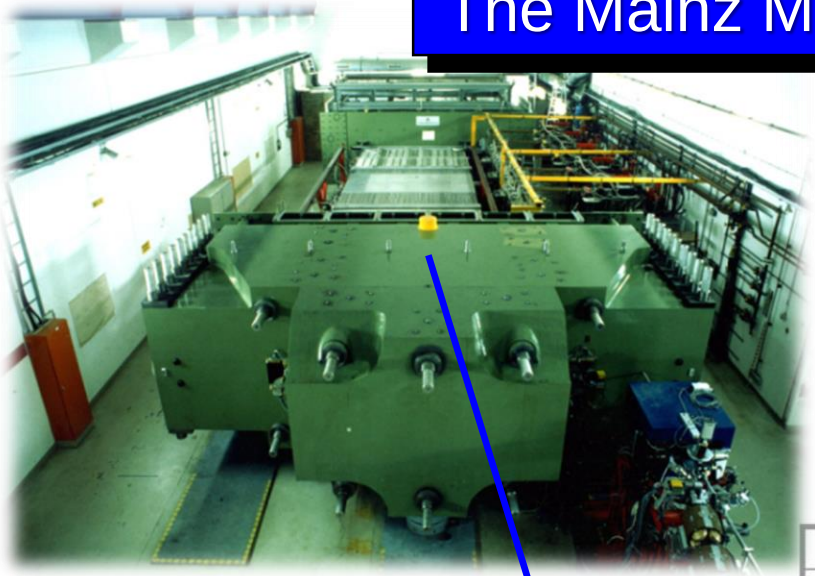


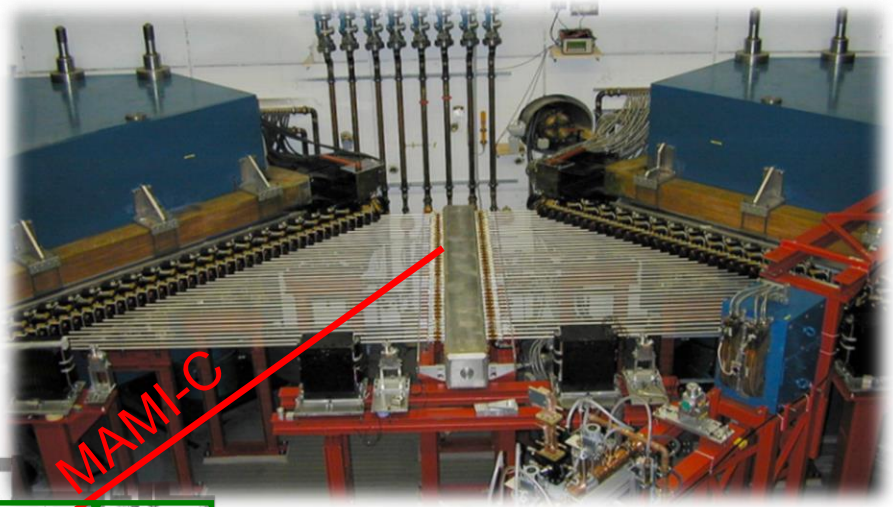
DarkMESA
- Search for Dark Sector Particles



P2
- Parity-Violating $\vec{e}$-scattering
- Extracted Beam (155 MeV, 150 μA)

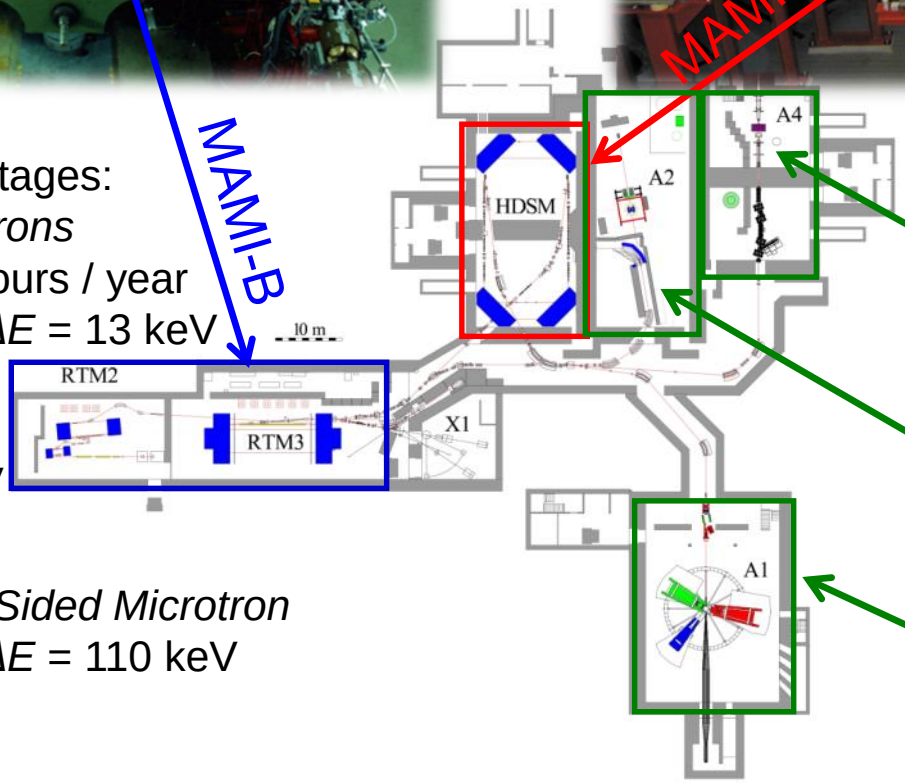
The Mainz Microtron until the 2010s





MAMI-B:
Three cascading stages:
Race Track Microtrons
Runtime > 7000 hours / year
Energy definition ΔE = 13 keV
I = 100 µA c.w.
Polarization 85%
E = 180...883 MeV

MAMI-C:
Harmonic Double-Sided Microtron
Energy definition ΔE = 110 keV
E = 1604 MeV



Ultrafast calorimeter

Photon Tagger &
4π Detector

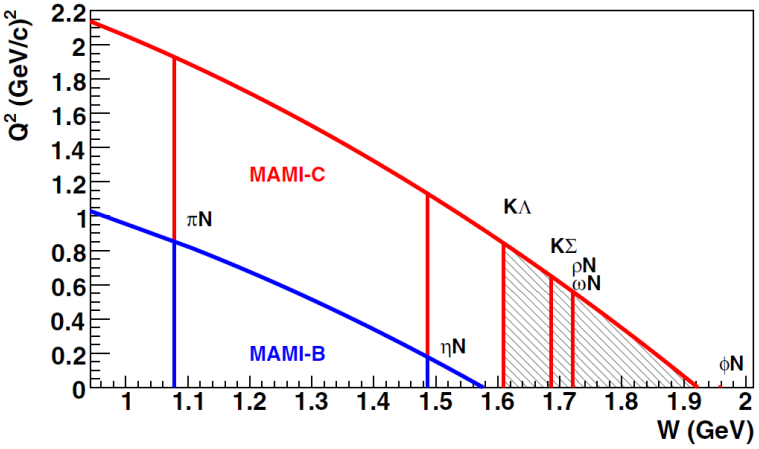
Electron scattering
spectrometer facility

Kinematic Reach of MAMI

Kinematic plane in electroproduction:

$$Q^2 = -q^2 = (q_e^\mu - q_{e'}^\mu)^2 \quad W^2 = s = (q^\mu + p_{target}^\mu)^2$$

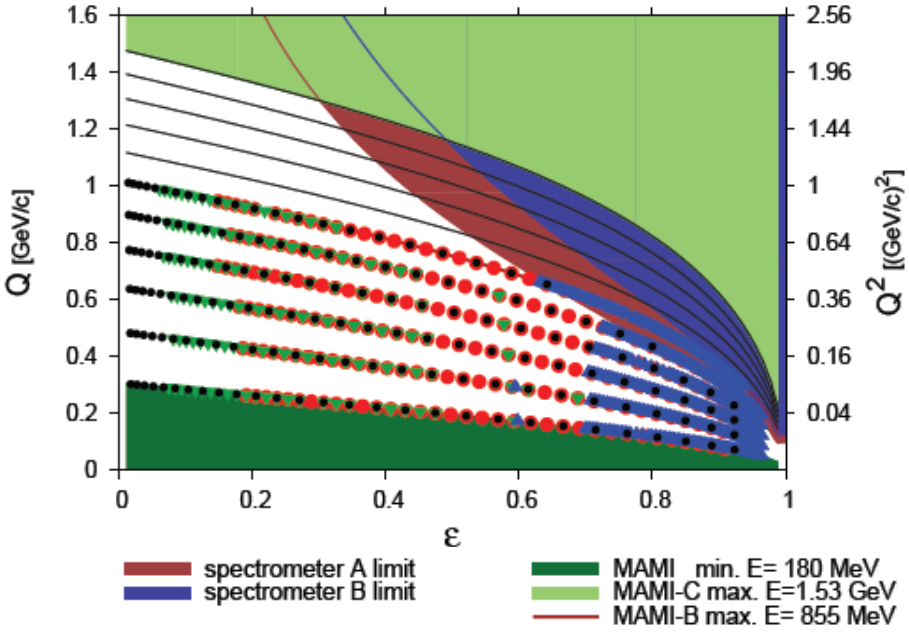
P. Achenbach, EPJ ST198, 307 (2011)



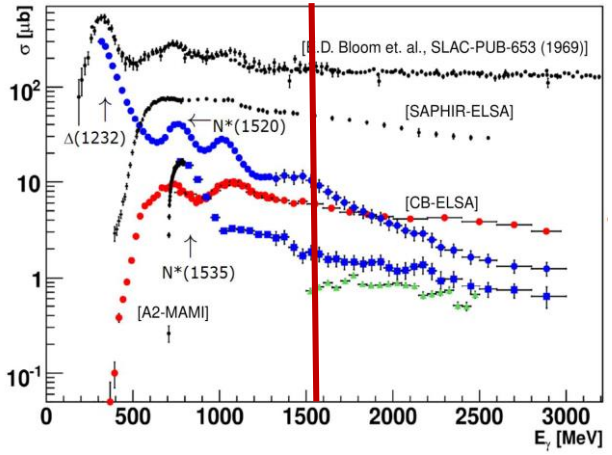
Kinematic plane in elastic scattering:

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{Mott} \frac{1}{\varepsilon(1+\tau)} \left[\varepsilon G_E^2(Q^2) + \tau G_M^2(Q^2)\right]$$

J. C. Bernauer et al. (A1 Collab.), PRC 90, 015206 (2014)



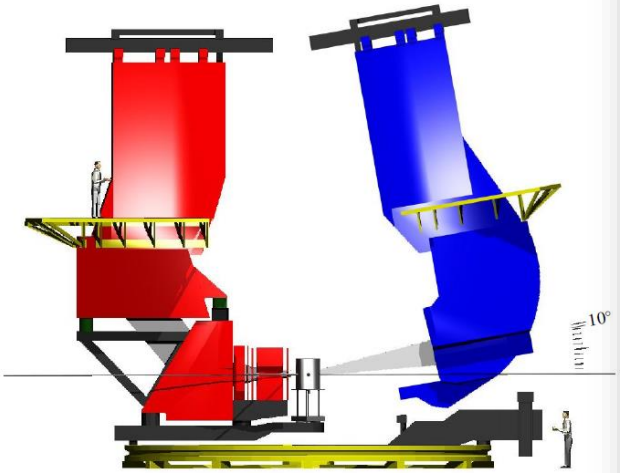
Excitation range in photoproduction:



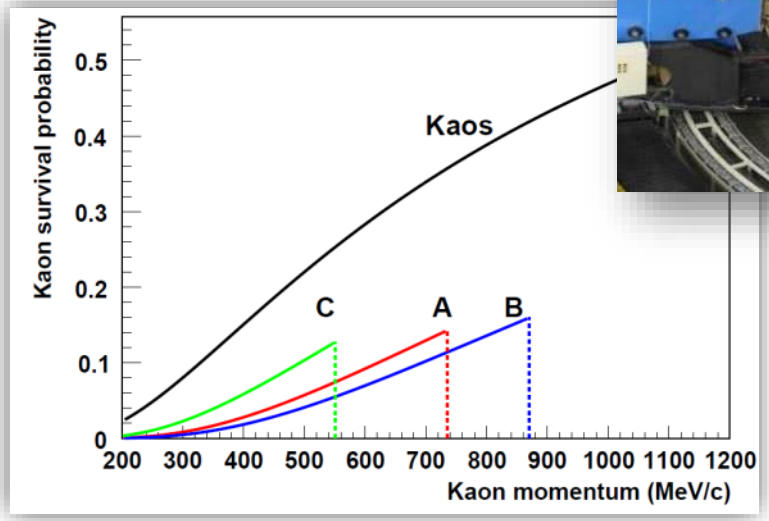
- Full coverage of nucleon structure physics
- Probing many aspects of QCD bound states

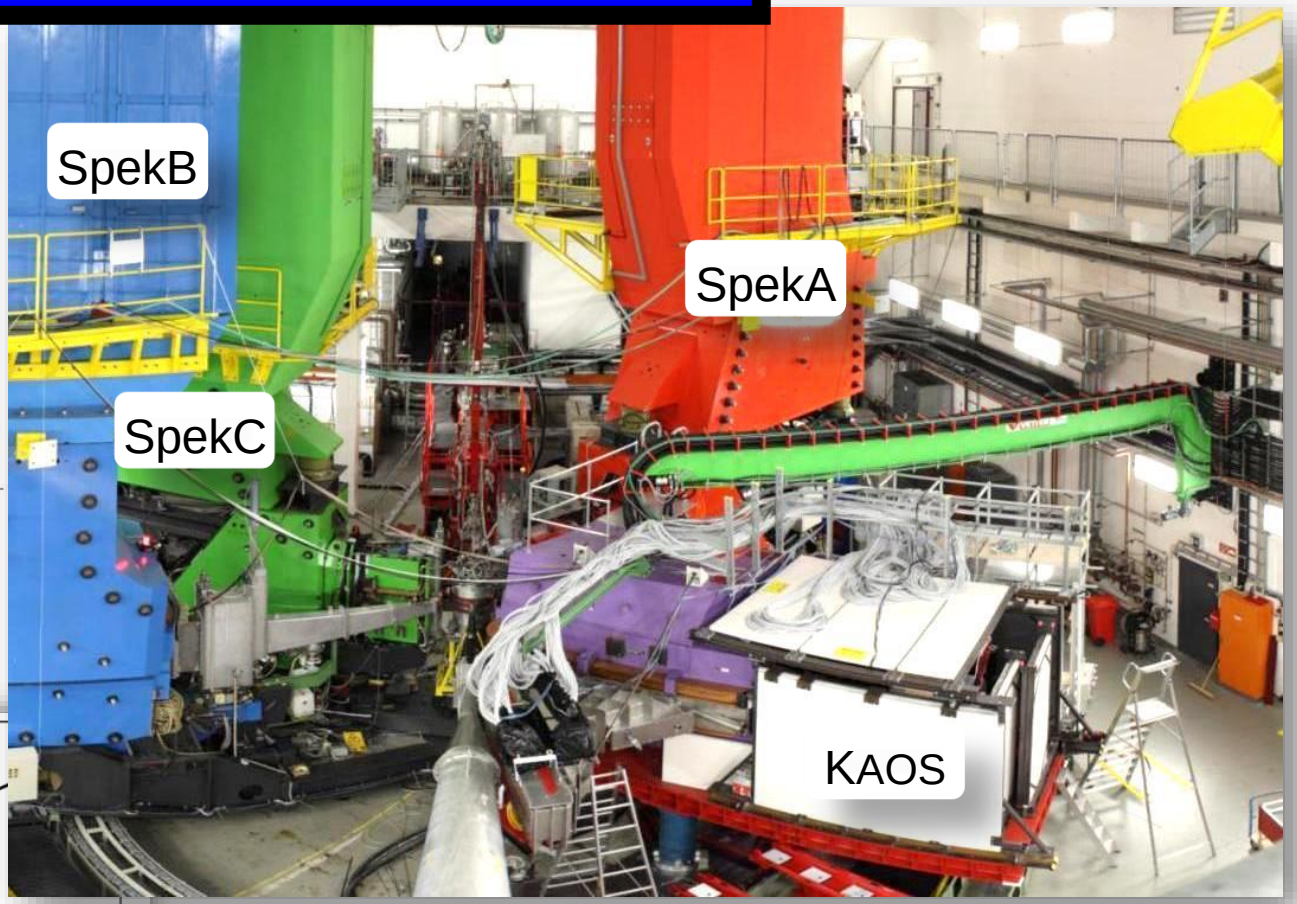
Spectrometer Facility at MAMI

Out-of-plane capability:



Kaon detection capability:

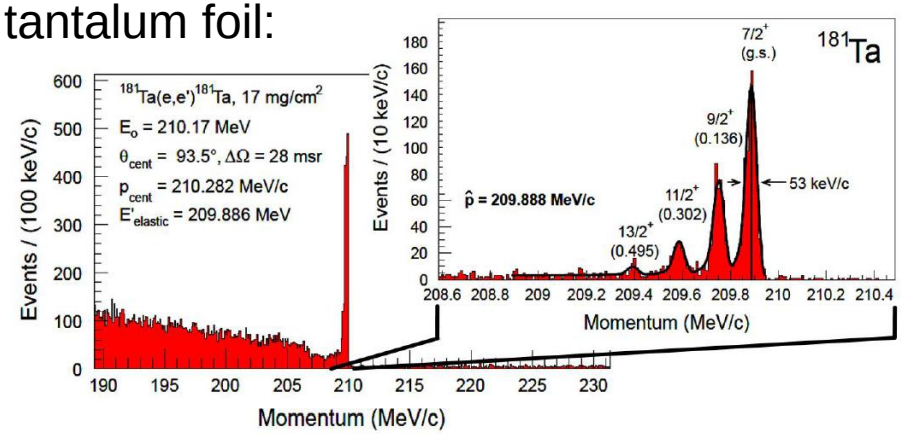




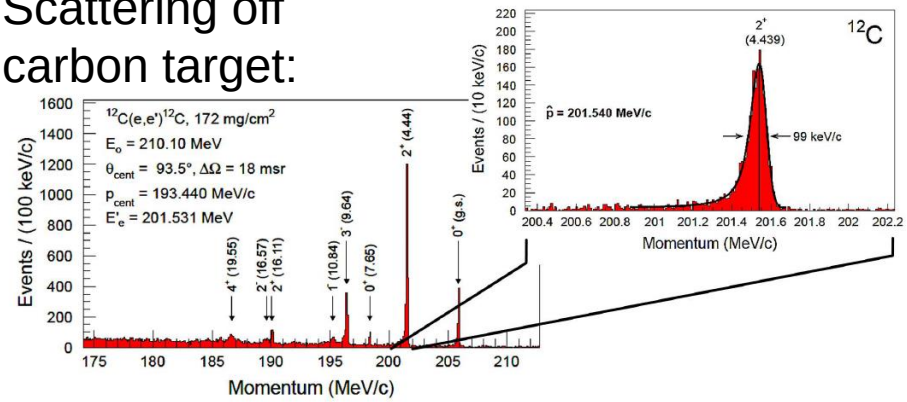
- Three high-resolution spectrometers
- One short-orbit spectrometer

The Role of Precision

Scattering off thin tantalum foil:



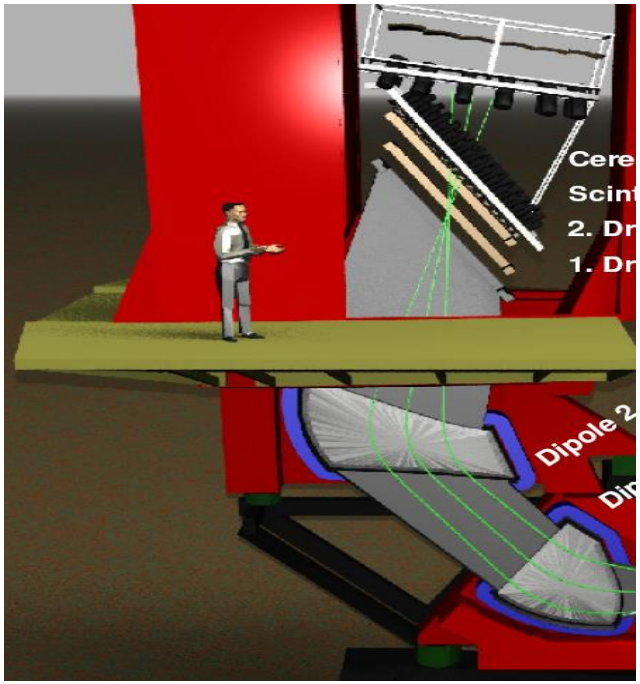
Scattering off carbon target:



FWHM of 53 keV/*c* → $\delta p/p \sim 2 \cdot 10^{-4}$

Systematic calibrations → $\delta p_{calib} \sim 5$ keV/*c*

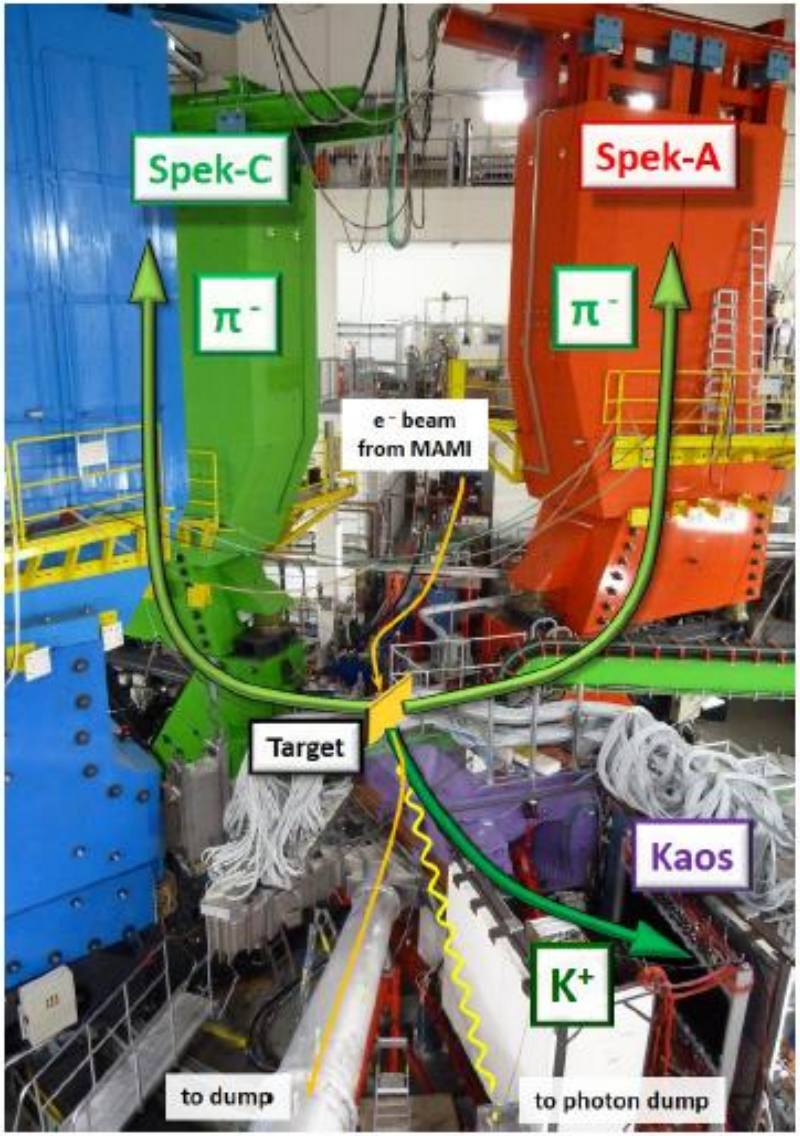
High-order corrections for superb optics:

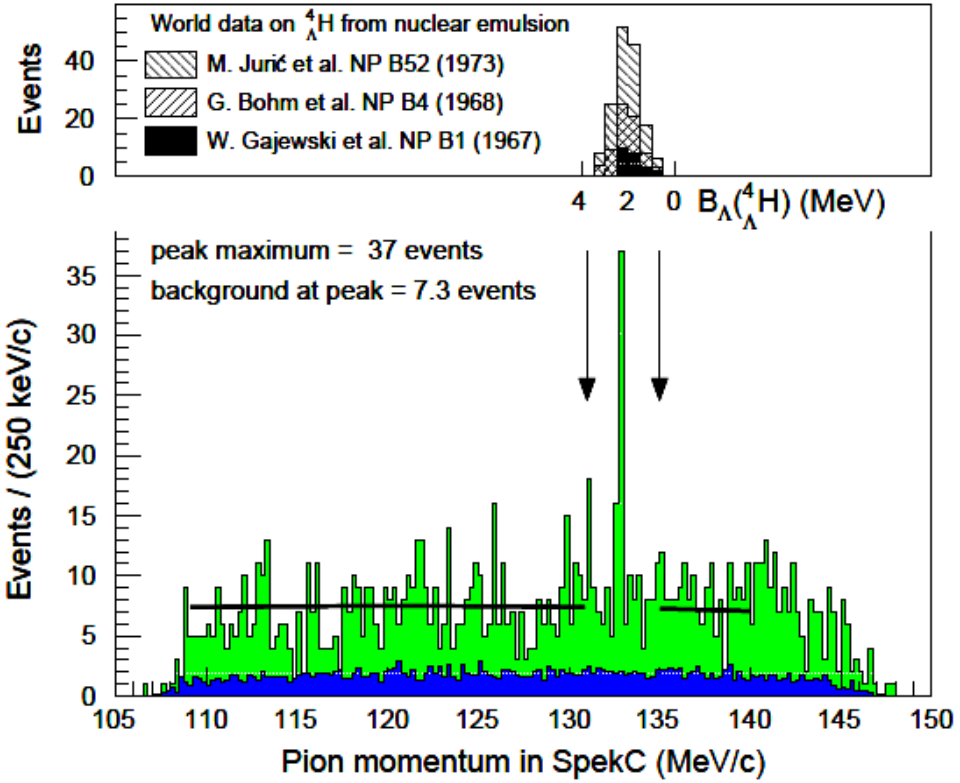


- Large solid angle accept.: 28 msr
- Large momentum accept.: up to 25 %
- High vertex resolution: 3 – 5 mm
- Good angular resolution: < 3 mrad
- Long target acceptance: 50 mm
- Large angular range: 15° – 160°

K. I. Blomqvist et al. (A1 Collab.), NIM A 403, 263 (1998)

Selected Result: Hypernuclear Binding Energy

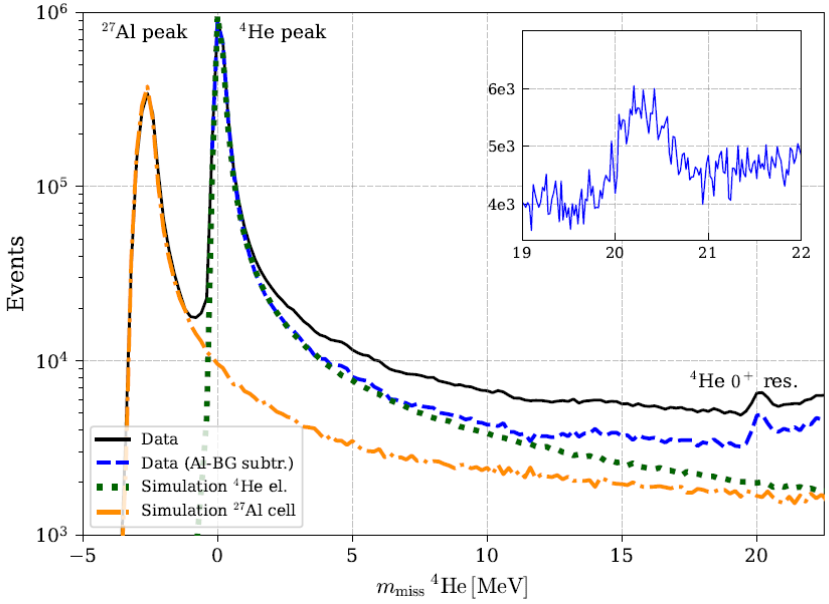


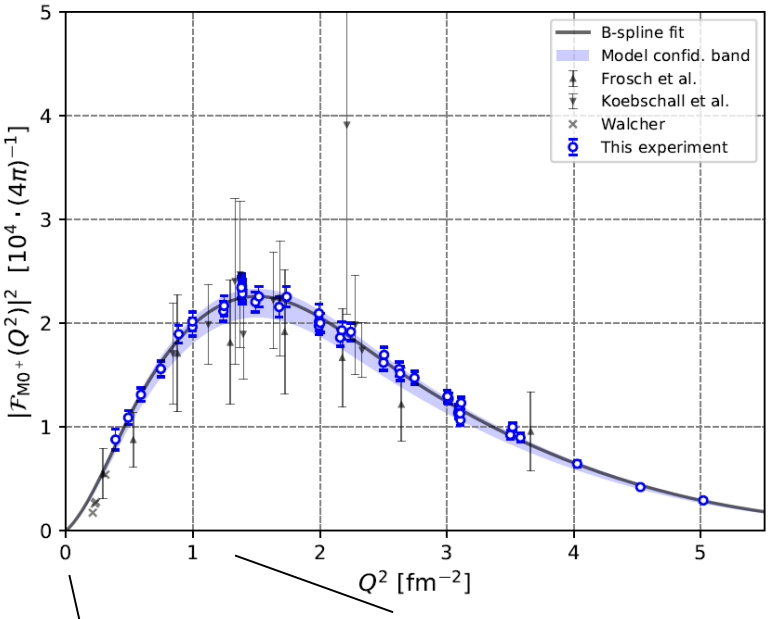


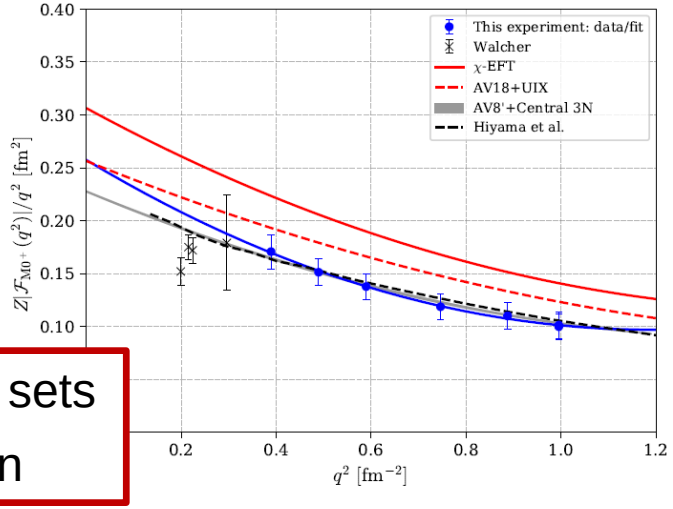
A. Esser et al. (A1 Collab.), PRL 114, 232501 (2015)

- High-resolution decay-pion spectroscopy of light hypernuclei pioneered at MAMI
- Charge symmetry breaking considerably stronger in hyper- than in ordinary nuclei

Selected Result: Monopole Transition in ^{4}He



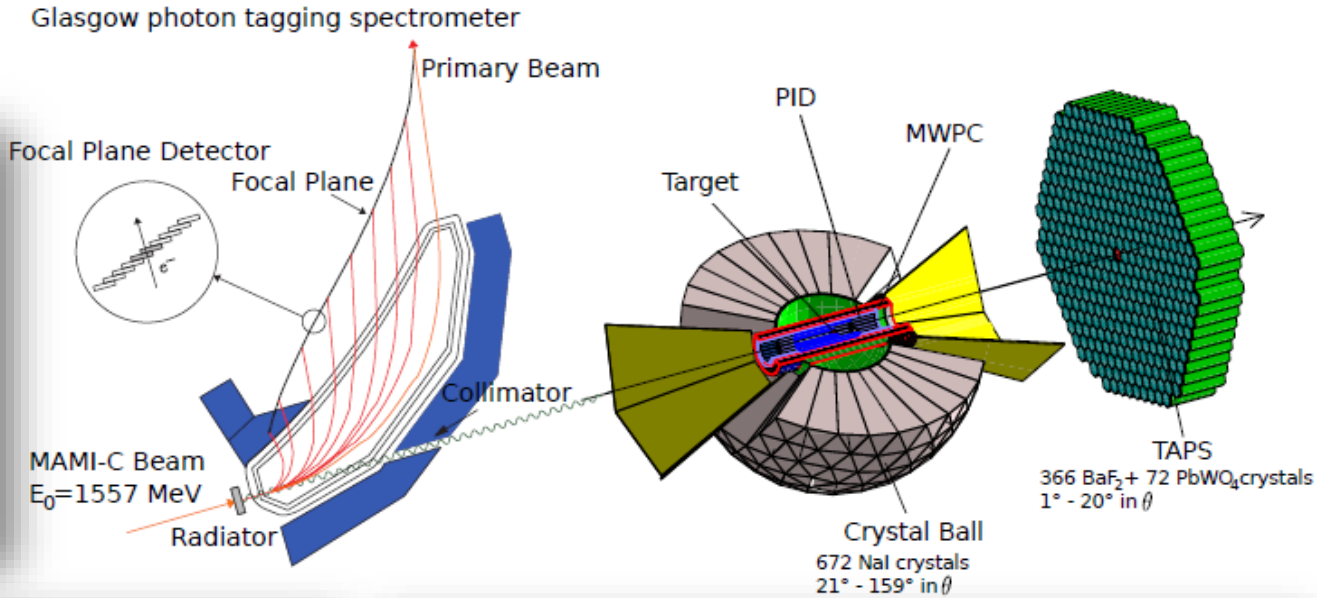


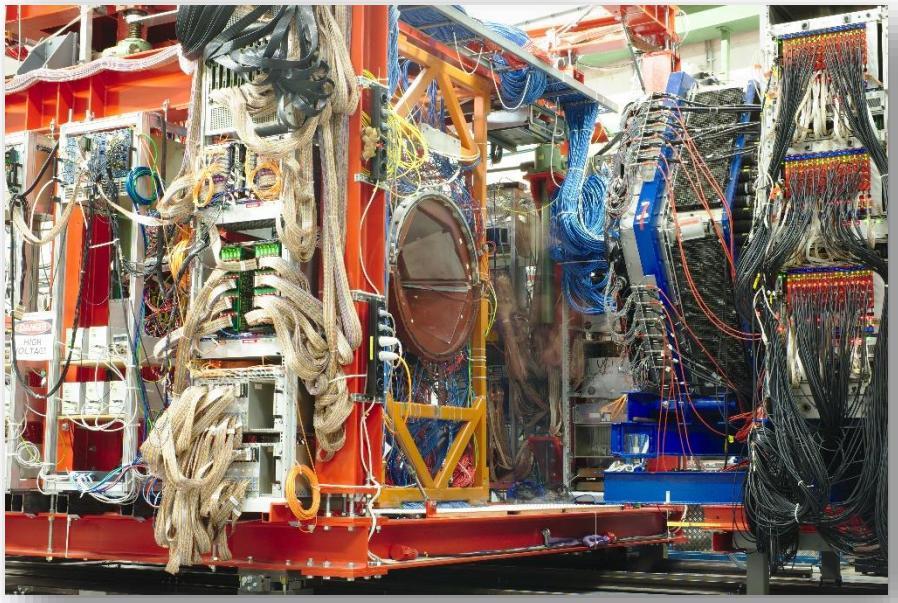


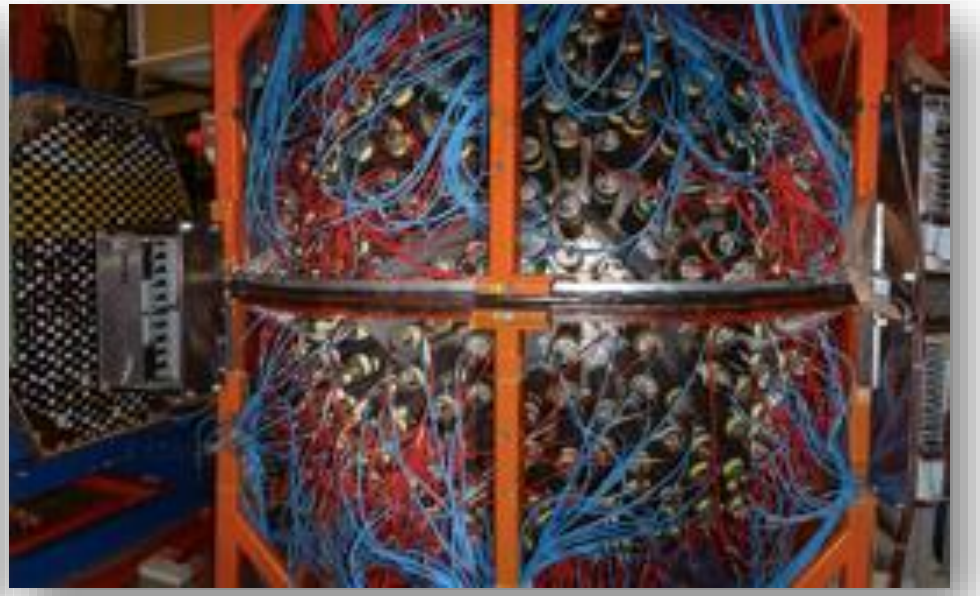
- Broad range in Q^2 covered: 0.5 to 5.0 fm
- Use of cryogenic helium gas in Al cell

- Precision dramatically supersedes that of older data sets
- Modern nuclear forces fail to reproduce the excitation

Photon Beam Facility at MAMI

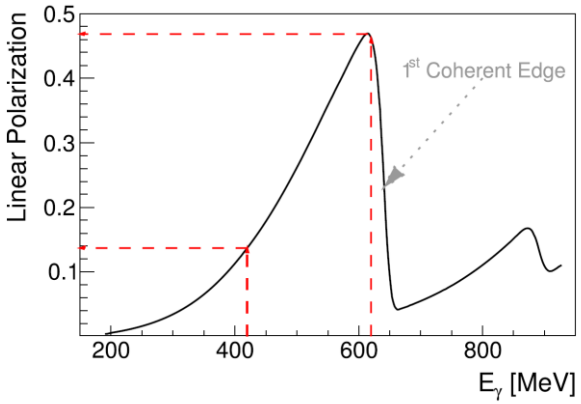


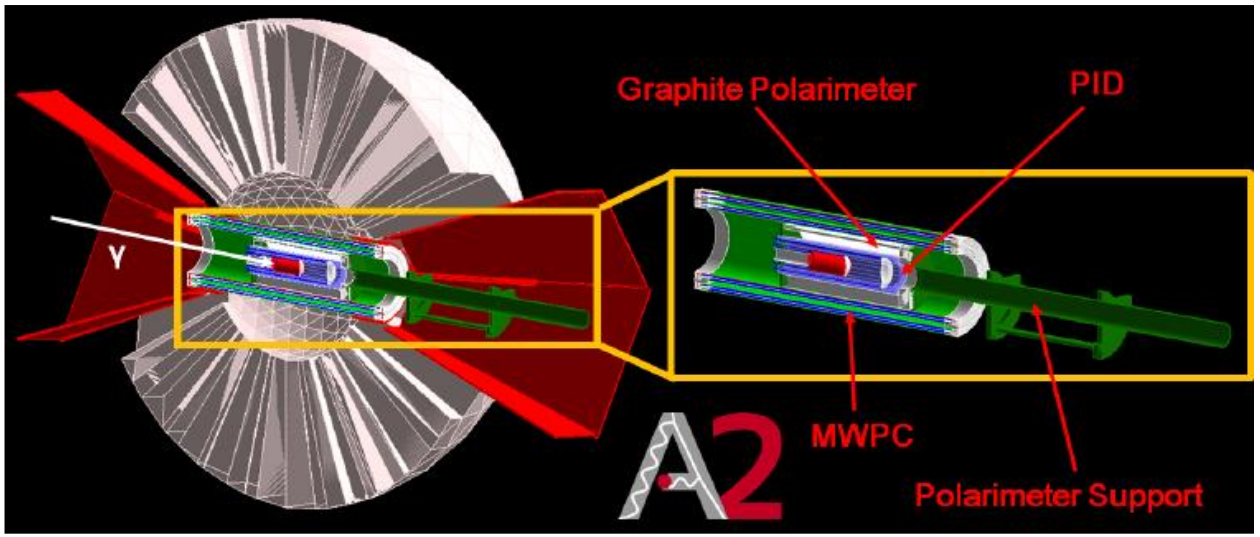




Selected Results: Deuteron Photodisintegration

Polarization observables

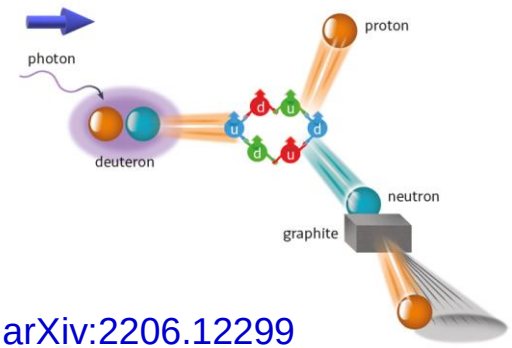




- Study of beam-spin asymmetry Σ → M3 transition
- Ancillary large-acceptance nucleon polarimeter surrounding deuterium target
- Study of polarisation transfer from circularly-polarised photon to final state neutron

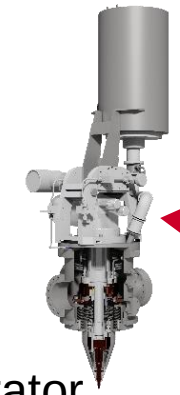
  → Both p and n highly polarised in d* resonance region

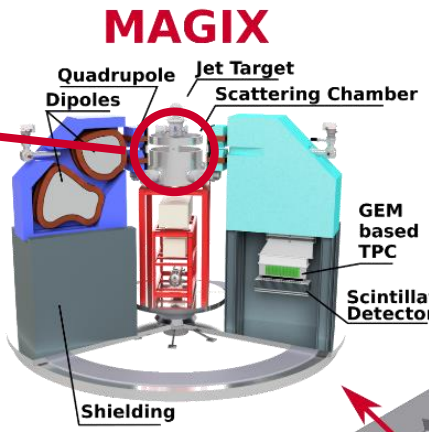
Signatures for the existence of an exotic quark configuration in light-quark sector



M. Bashkanov et al. (A2 Collab.), PRL 124, 132001 (2020); PLB789, 7 (2019); arXiv:2206.12299

Mainz Energy-Recovering Superconducting Accelerator





MESA accelerator

- 1.3 GHz c.w. beam
- Normal conducting injector
- 2 superconducting cavities
- Several recirculations

Two main operation modes

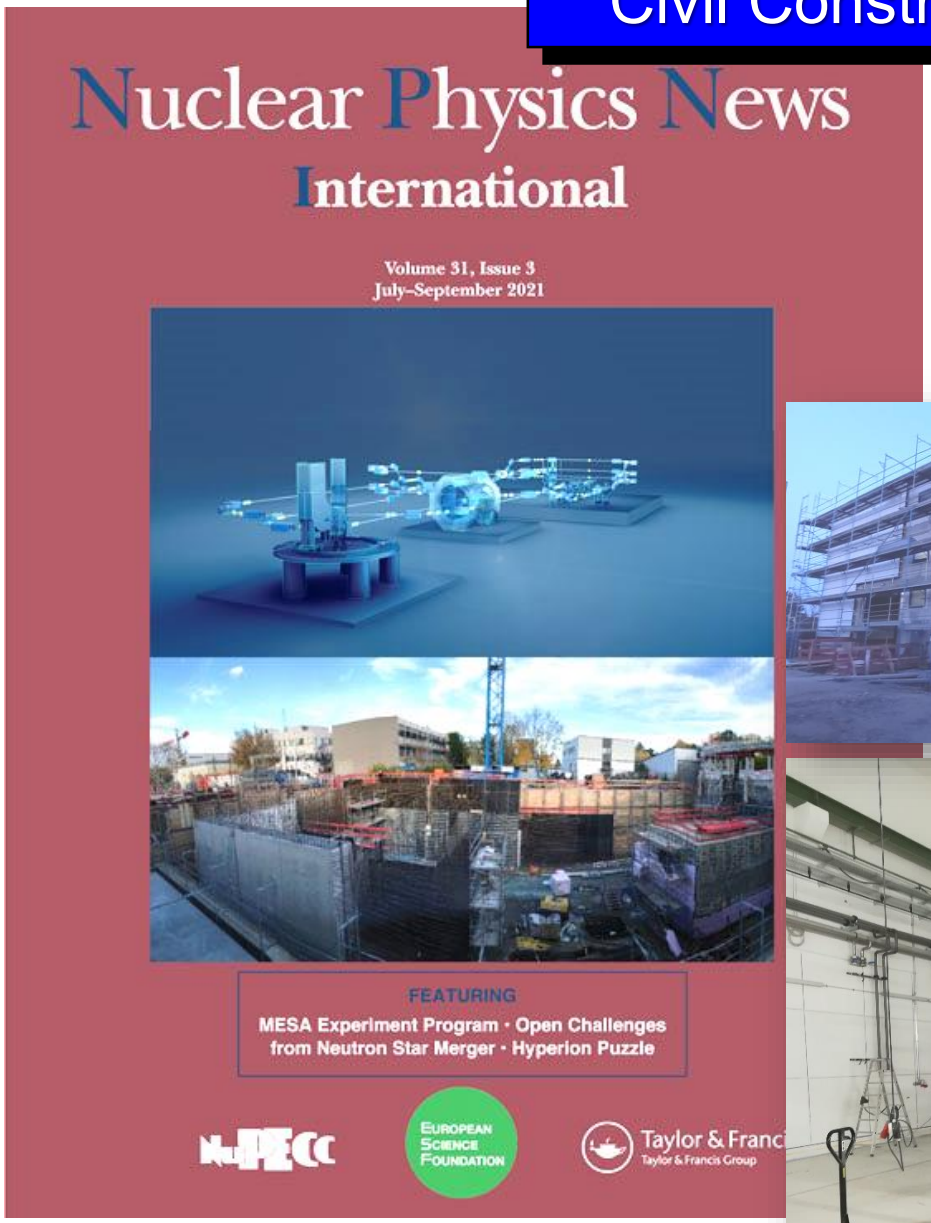
1. Energy recovery mode, 30–105 MeV, 10000 μA: internal target + spectrometers
2. External mode, polarized, 155 MeV, 150 μA: thick targets + solenoid
   + parasitic beam dump experiment

Realization of MESA on Mainz University Campus

- Funding of PRISMA and PRISMA+ Cluster of Excellence
- Funding of Major Research Investments in 2019
- New Centre for Fundamental Physics (CFP I + II buildings)

- New accelerator workshop and storage buildings finished in 2019
- Ground breaking for new underground hall in spring 2019

Civil Construction 2021–22



Nucl. Phys. News 31 (2021)

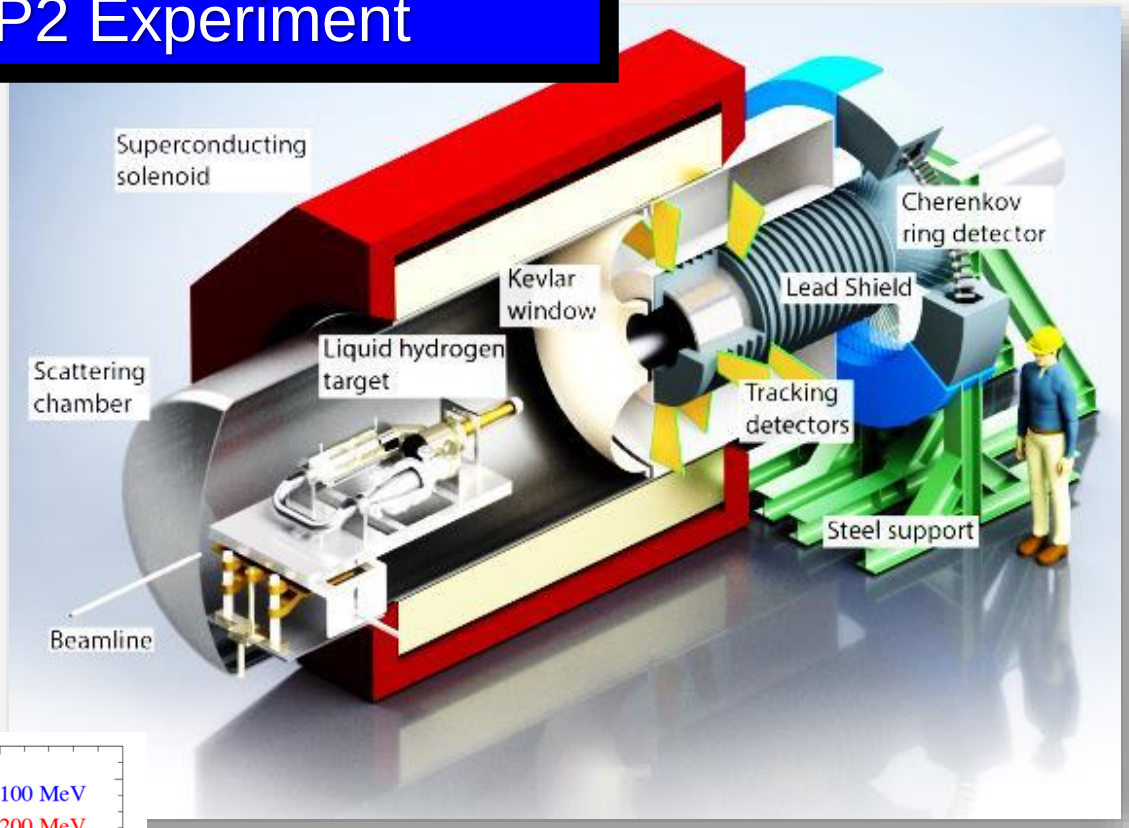
- **2022:** Handover of experimental halls
- **March 2023:** Delivery of STAR/PORT
- **Early 2023:** Start of MESA assembly
- **Early 2025:** First beam for experiment

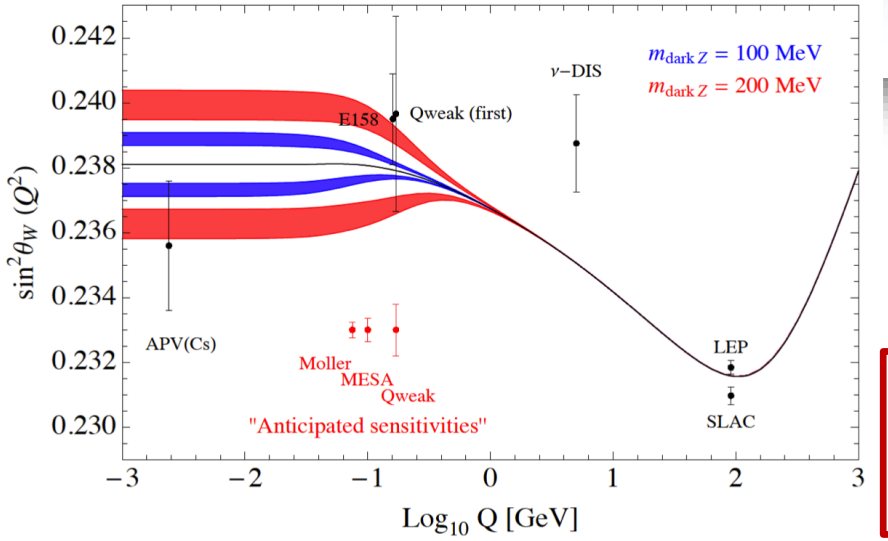
The P2 Experiment

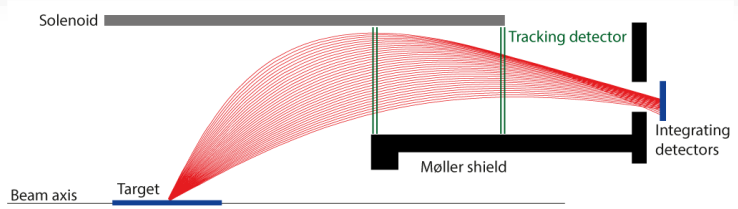
- Weinberg angle central parameter of Standard model
- Cross section asymmetry in elastic scattering of 40×10^{-9}
- Precision goal:

$\delta \sin^2\theta_W \sim 0.0003$ (< 2 ‰)

D. Becker et al. (P2 Collab.)
EPJ A 54, 208 (2018)





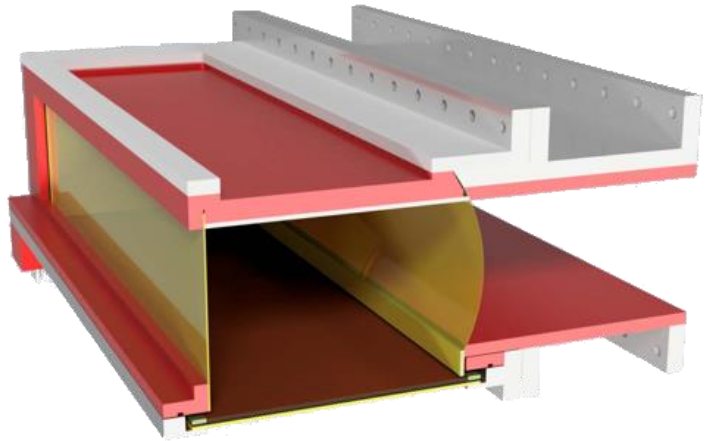


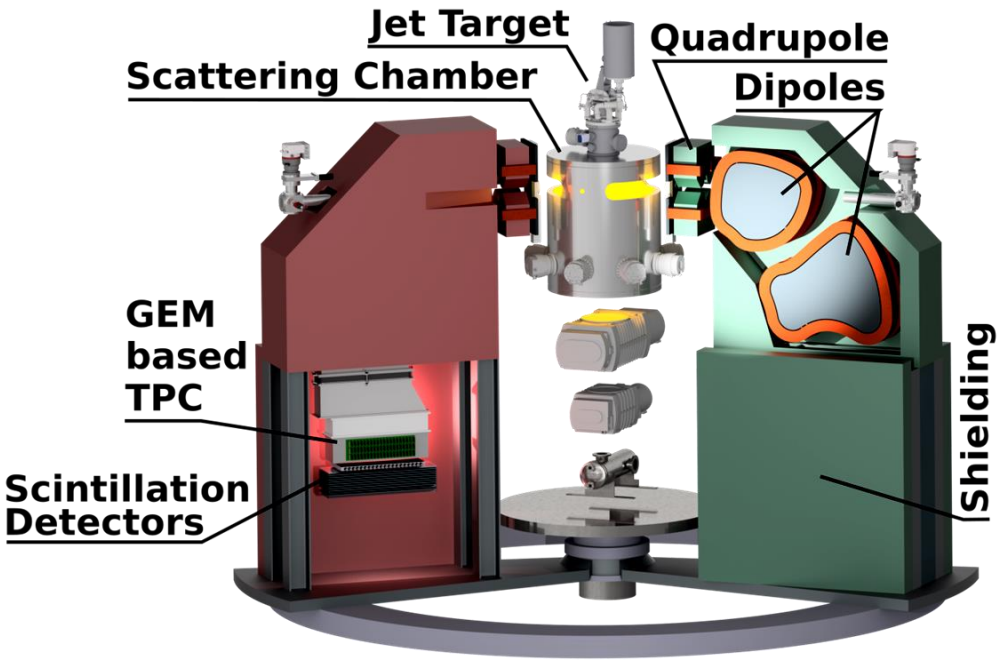
Low-energy measurement with high sensitivity to new phenomena

The MAGIX Spectrometers

High resolution spectrometers STAR/PORT

- Double-arm, compact design
- Momentum resolution: $\Delta p/p < 10^{-4}$
- Innovative GEM-TPC focal plane detector

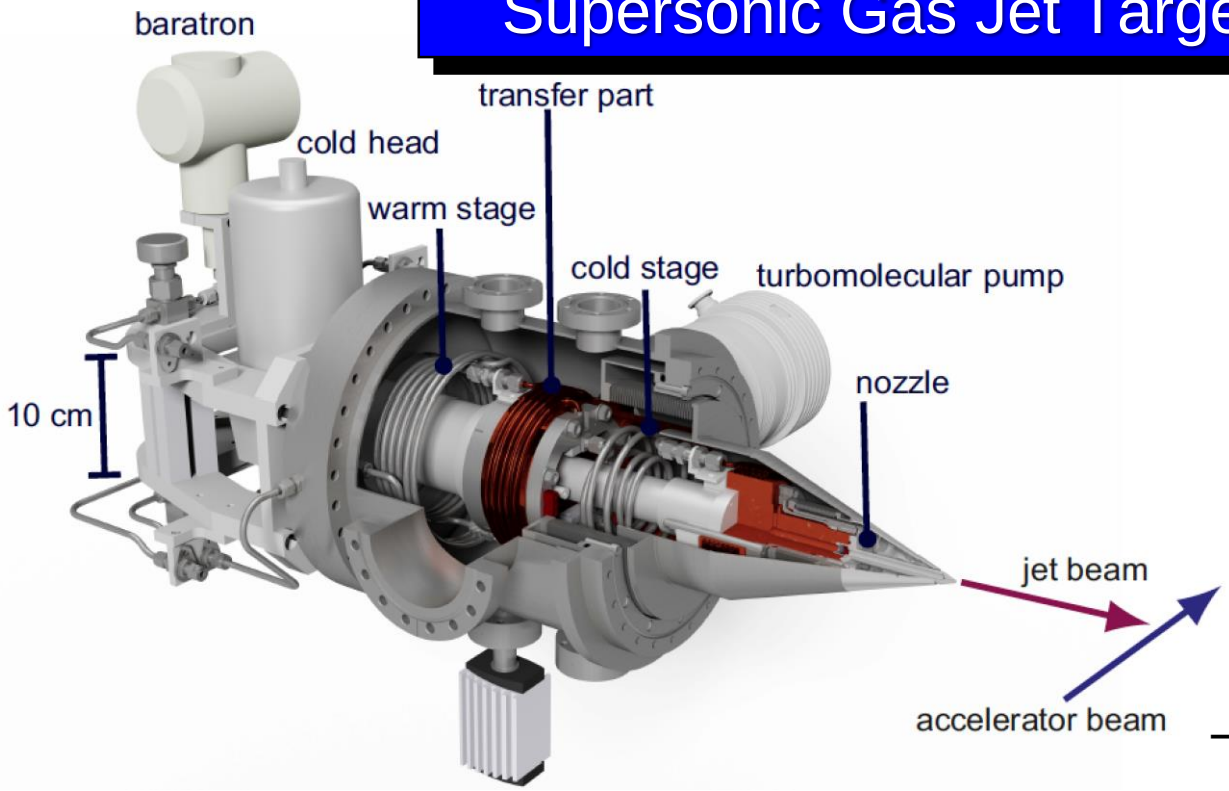


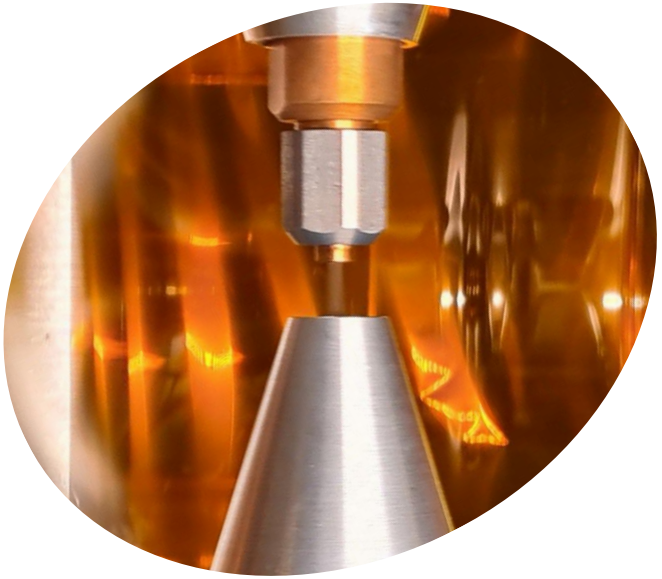


- Gas jet (or polarized gas) target

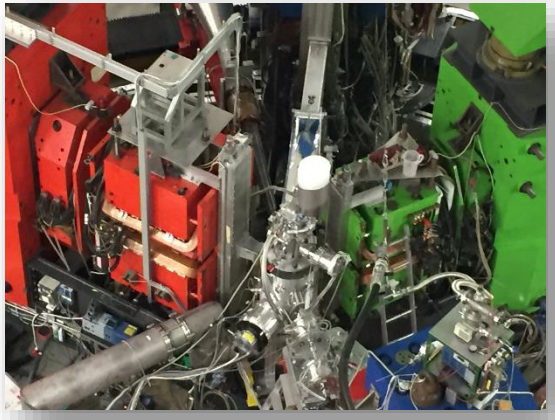
- Dark photon search - visible decay
- Dark photon search - invisible decay
- Proton electromagnetic form factors
- Deuteron electrodisintegration
- Transition form factor of ^{12}C Hoyle state
- Nuclear astrophysical (γ,n) reactions
- S-factor of the $^{12}C(\alpha,\gamma)^{16}O$ - reaction
- Knockout reactions from light nuclei
- Exclusive measurements on $^{3}He/^{4}He$
- Inclusive measurements on ^{4}He, ^{16}O
- Charge radius of deuteron, ^{4}He
- Electrons for neutrino physics

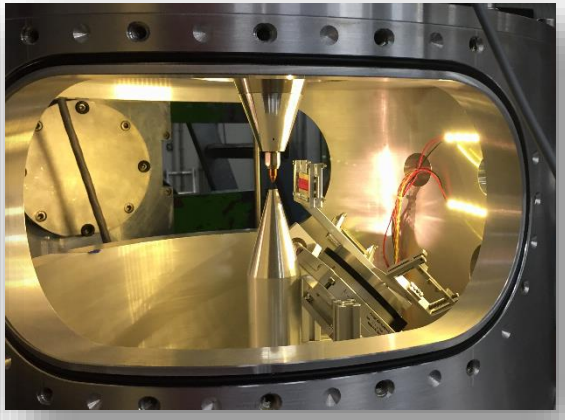
Supersonic Gas Jet Target





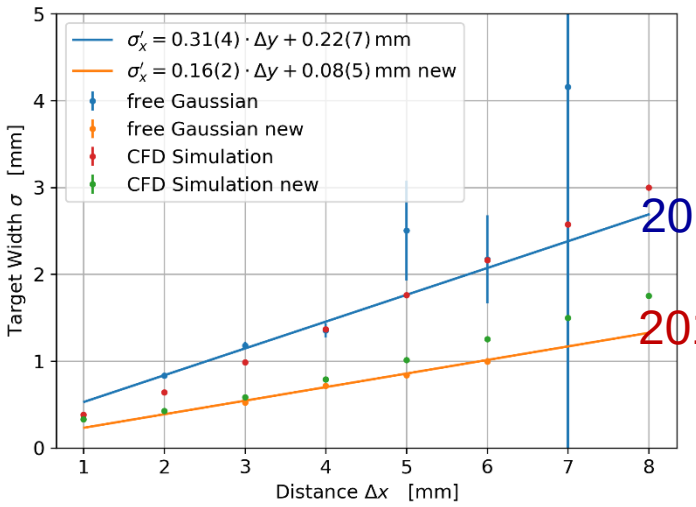
Commissioned at MAMI in 2017/18

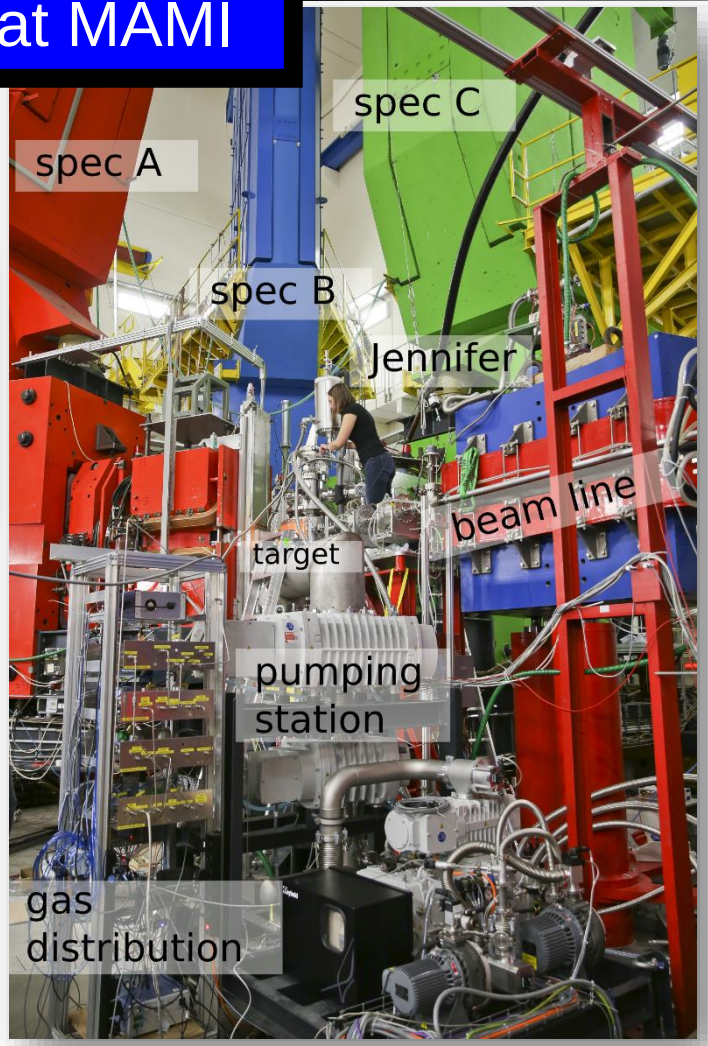


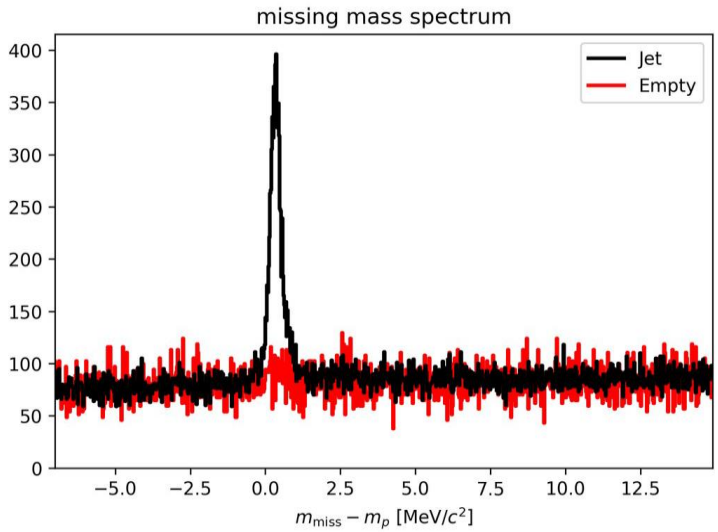


- Windowless design
- Supersonic gas jet
- Gas density $O(10^{19}/cm^2)$
- Beam size O(mm)
- H_2, ^3He, ^4He, O_2, ….., Xe
- Luminosity $O(10^{35}\ cm^{-2}\ s^{-1})$ @ $10^{19}/cm^2$

Target Performance at MAMI



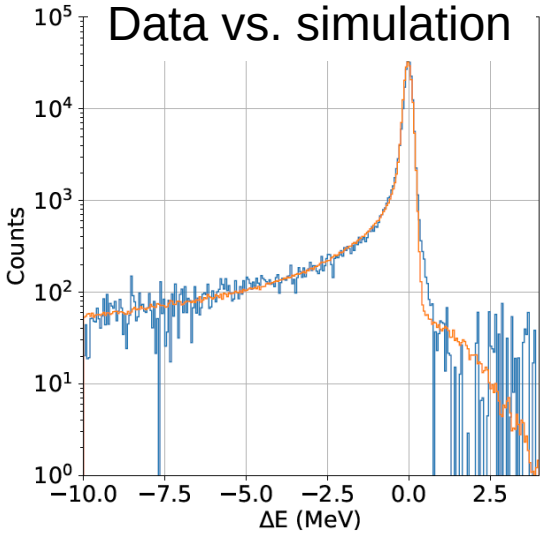


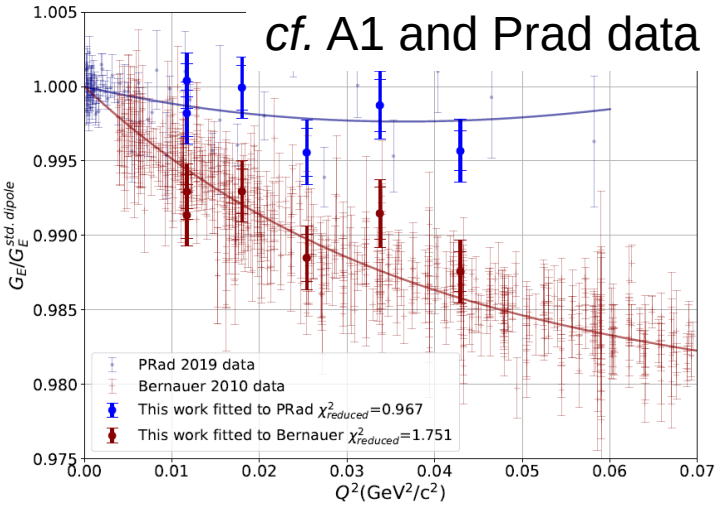


B. S. Schlimme et al. (A1 & MAGIX Collab.) NIM A1013, 165668 (2021)

- Ultimate precision in elastic scattering
- Target system commissioned for MESA

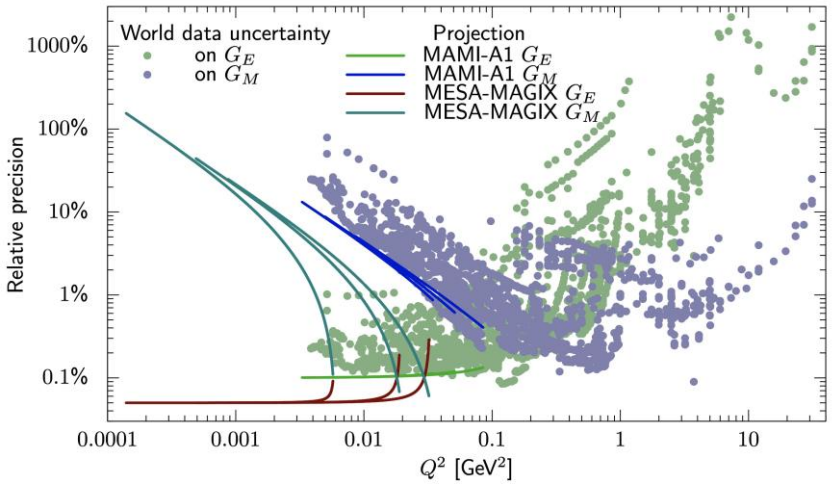
Proton Elastic Scattering

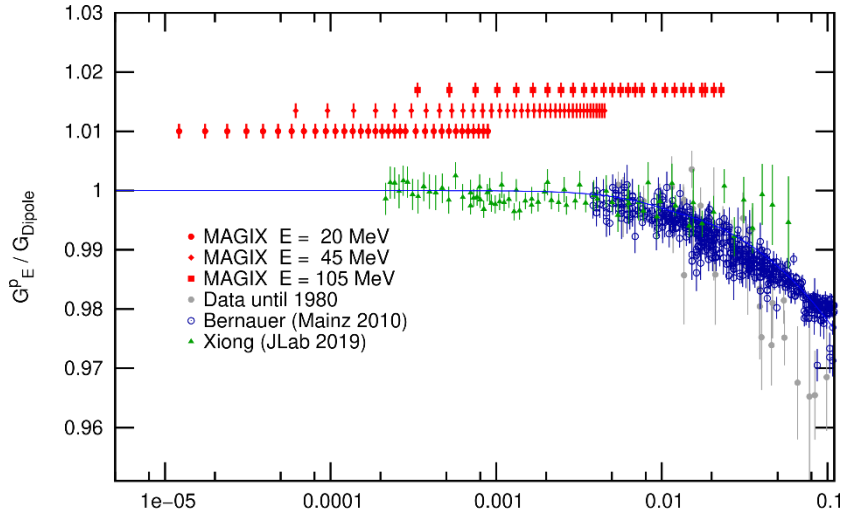




Y. Wang, publication preprint 2022

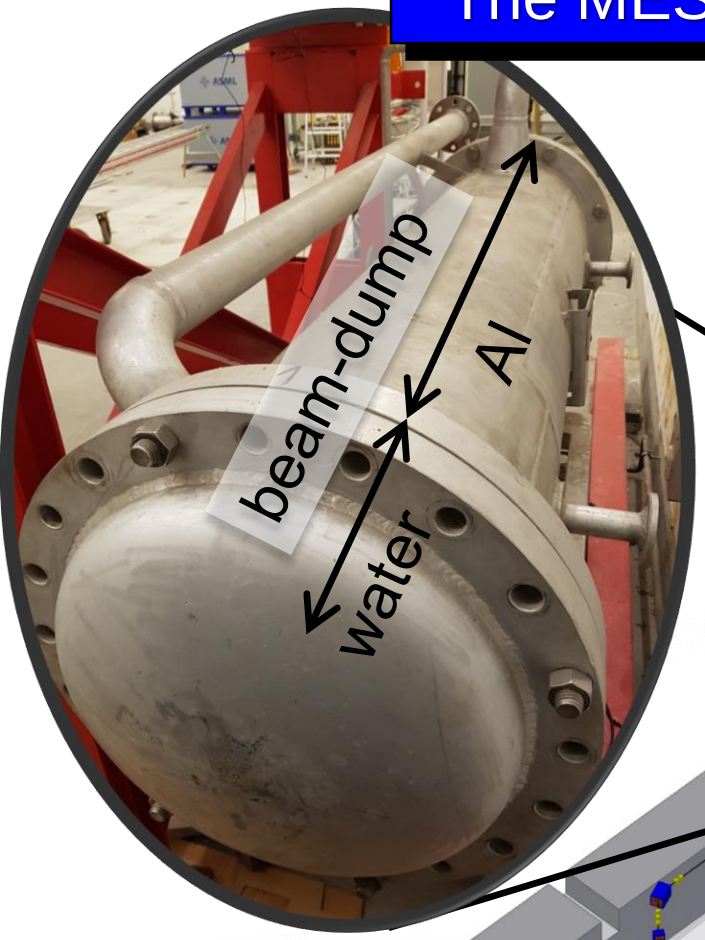
Projections



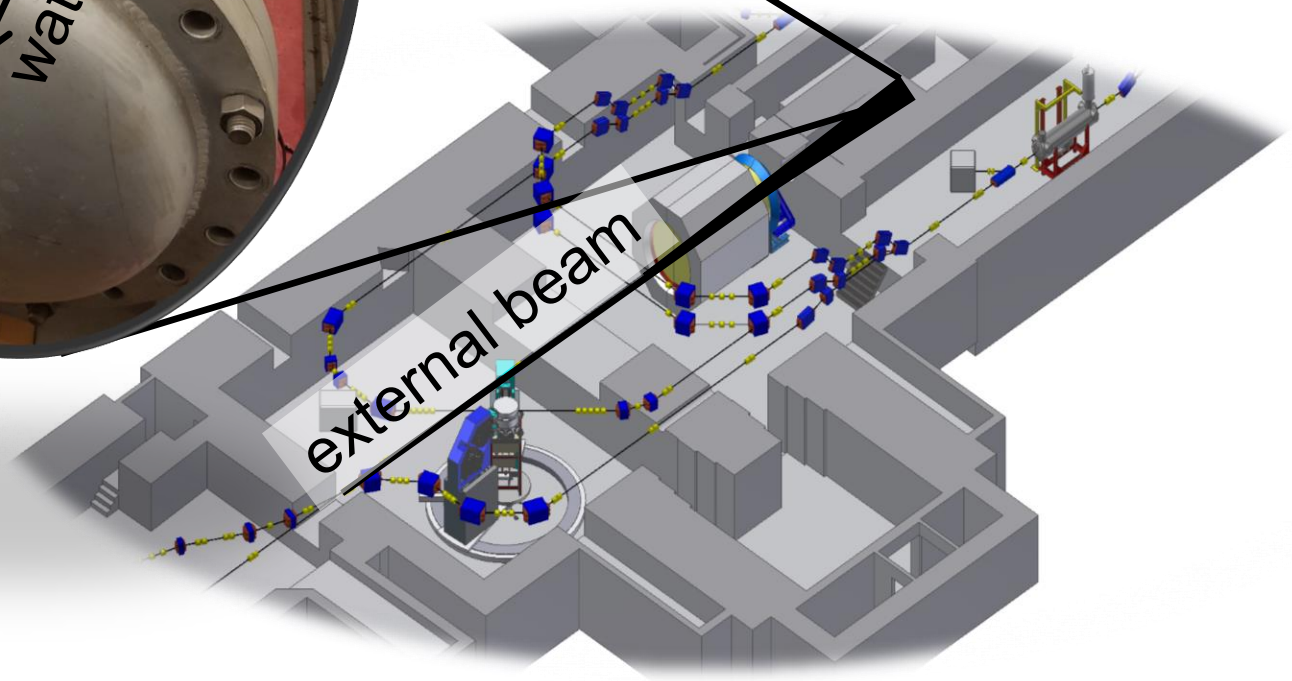


Significant improvement of data at low Q^2

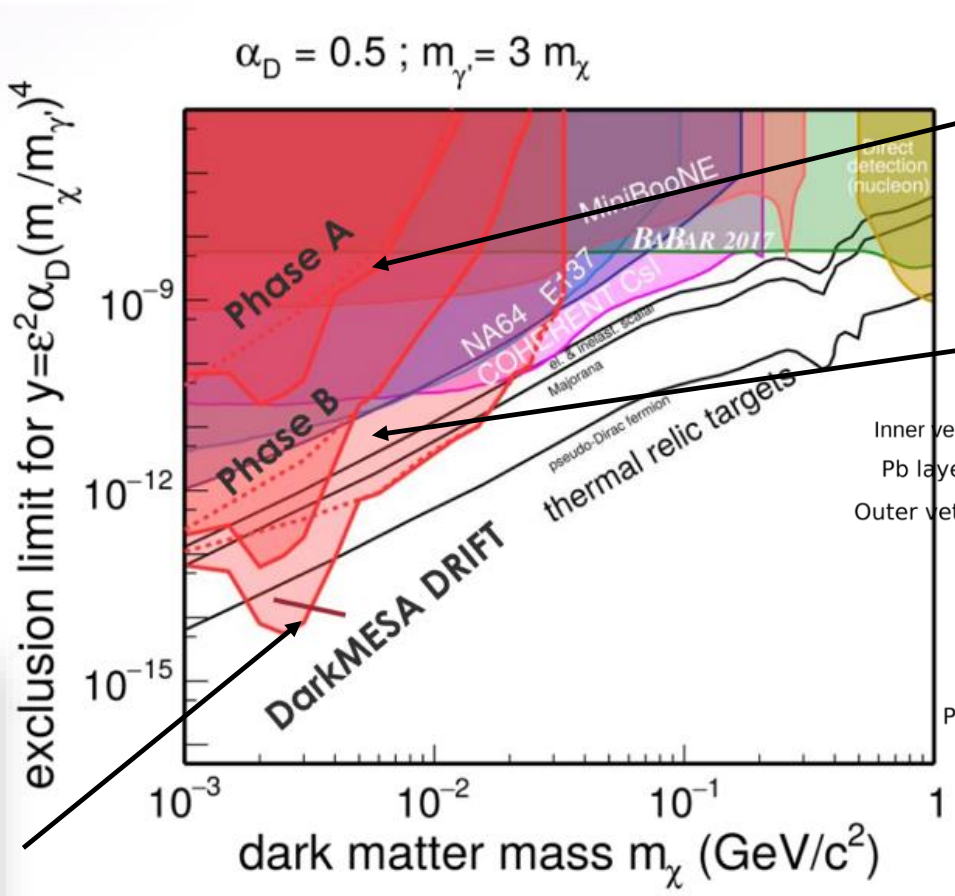
The MESA Beam Dump Experiment



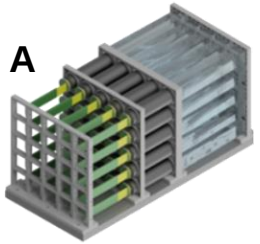
- Beam current ~ 150 µA
- Beam energy ~ 150 MeV
- e p → e n π^+ threshold at 152 MeV
- 10 000 h beam ~ 3 x 10^{22} EOT



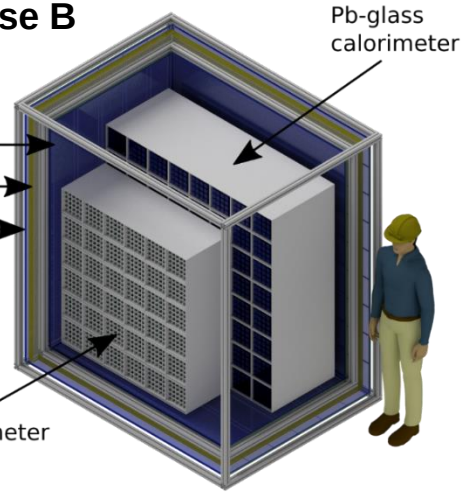
Projected Exclusion Limits for DarkMESA



Phase A



Phase B



DRIFT

- DarkMESA has the potential to cover thermal relic targets
- Different types of experiments are sensitive to different models

Summary

MAMI electron accelerator: E ~ 185 - 1600 MeV

- Strong history of low-energy hadron physics results

Energy-recovering MESA accelerator: E < 155 MeV

- Up to 10 mA beam current
- Extracted beam mode & energy recovering mode
- Start of MESA data in 2023

MAGIX experiment at MESA

- High beam intensities and windowless internal target
- Operation with gases from H_2 to Xe
- First physics results in 2025

Thank you for your attention!