Electron scattering on few-baryon systems at MAMI

Michael O. Distler

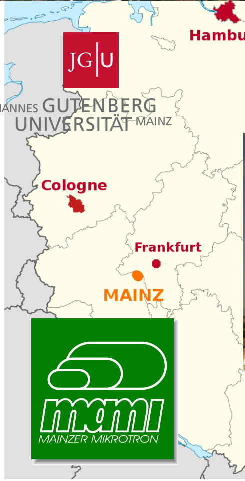
Institut für Kernphysik
Johannes Gutenberg-Universität Mainz

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Outline

- The Mainz Microtron and the Three Spectrometer Facility
- Collaborative Research Centre 443 (1999-2010)
  - Form factor G_{en} – $^2H(\vec{e}, e'\vec{n})$ and $^3\vec{He}(\vec{e}, e'n)$
  - Nuclear structure – $^3\vec{He}(\vec{e}, e'p)$
  - Triple measurement – $^3\vec{He}(\vec{e}, e'\vec{p})d$
  - (Correlations – $^3He(e, e'pn)$)
- The proton radius puzzle
- Collaborative Research Centre 1044 (2012–)
  - Form factors of D, $^{3,4}He$, $^{6,7}Li$
  - Inclusive measurements – $^{3,4}He(e, e')$
  - Neutron form factors – $^2H(\vec{e}, e'\vec{n})$
- PRISMA and MESA
- Summary

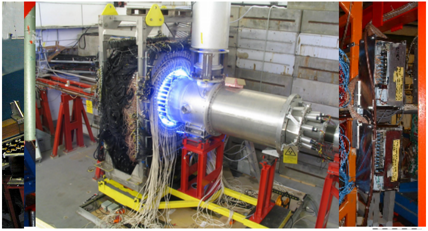
Location of Mainz, Germany

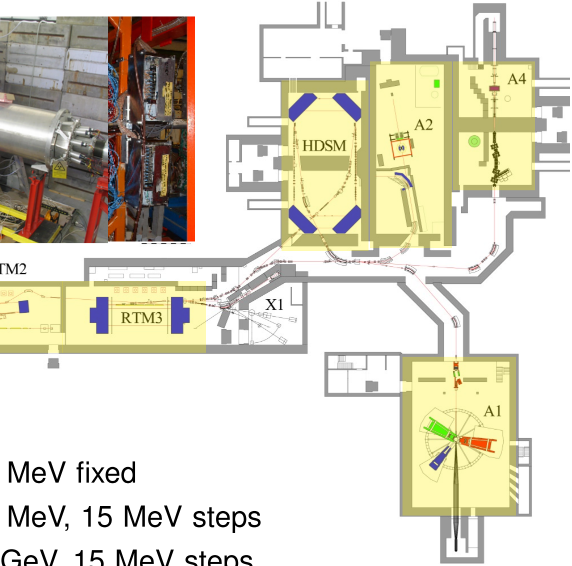


JG|U
JOHANNES GUTENBERG
UNIVERSITÄT MAINZ

mami
MAINZER MIKROTRON

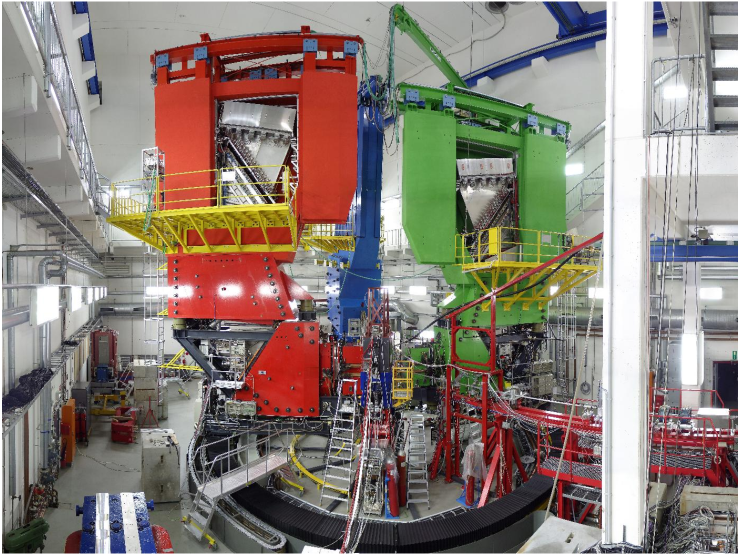
The Mainz Microtron MAMI





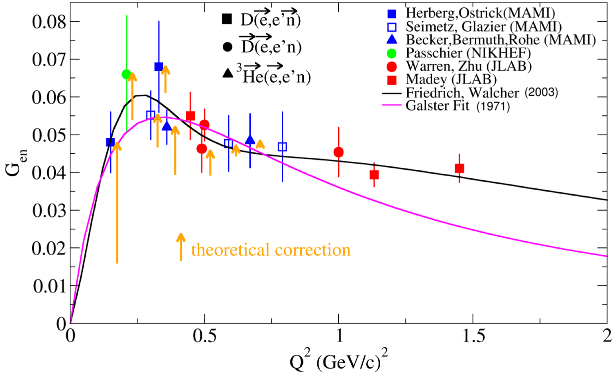
- MAMI-A: 180 MeV fixed
- MAMI-B: 855 MeV, 15 MeV steps
- MAMI-C: 1.6 GeV, 15 MeV steps

Three spectrometer facility of the A1 collaboration



^{3}He as effective neutron target

The electric form factor of the neutron (G_{en}) from polarisation experiments



J. Friedrich und Th. Walcher, Eur.Phys.J. **A17**, 607 (2003)

Electric form factor of the neutron

Problem:

- no free neutron target available
- G_{en} small compared to G_{mn}.
  Rosenbluth separation gives big errors:

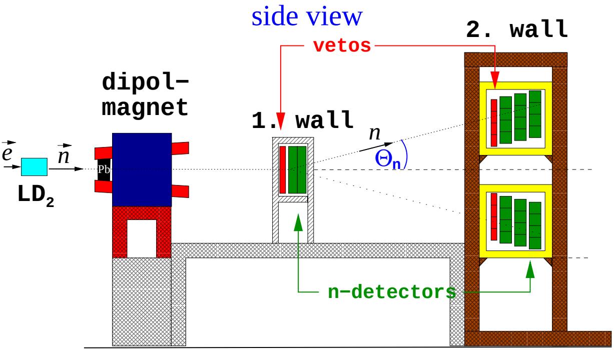
$$\frac{d\sigma}{d\Omega} \sim a G_{\mathrm{e}}^2(q) + b G_{\mathrm{m}}^2(q)$$

Solution:

Double polarization experiments on ^{2}H or ^{3}He.

- $^2\mathrm{H}(\vec{e}, e'\vec{n})$
- $^3\vec{\mathrm{He}}(\vec{e}, e'n)$

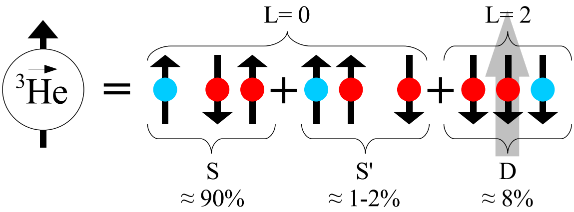
Double polarization experiments on ^{2}H



$$\tan\chi_0 = \frac{\mathcal{P}_n^x}{\mathcal{P}_n^z} = -\frac{1}{\sqrt{\tau + \tau(1+\tau)\tan^2\frac{\vartheta_e}{2}}}\frac{G_{E,n}}{G_{M,n}}$$

D.I.Glazier, M. Seimetz et al., EPJ **A24** (2005) 101

Double polarization experiments on ^{3}He



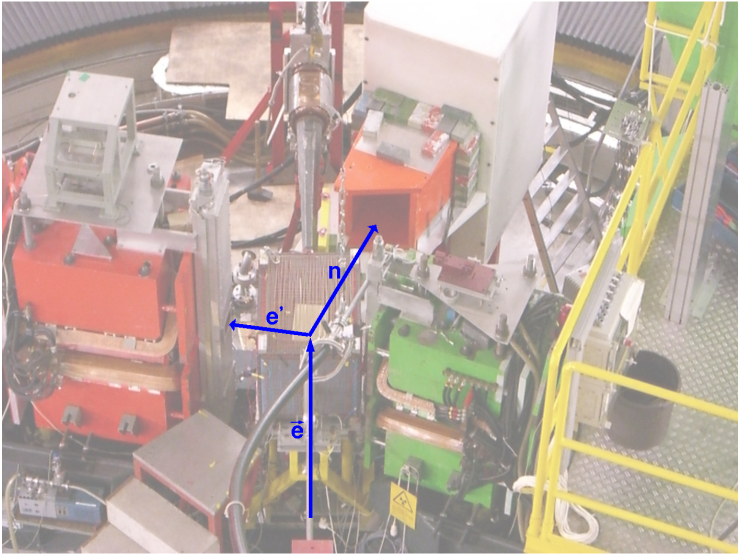
Beam target asymmetry:

$$A = \frac{N(\uparrow\uparrow) - N(\uparrow\downarrow)}{N(\uparrow\uparrow) + N(\uparrow\downarrow)} = \mathcal{P}_e\mathcal{P}_n \frac{a\, G_{E,n} G_{M,n} \sin(\theta)\cos(\theta) + b\, G^2_{M,n}\cos(\theta)}{c\, G^2_{E,n} + d\, G^2_{M,n}}$$

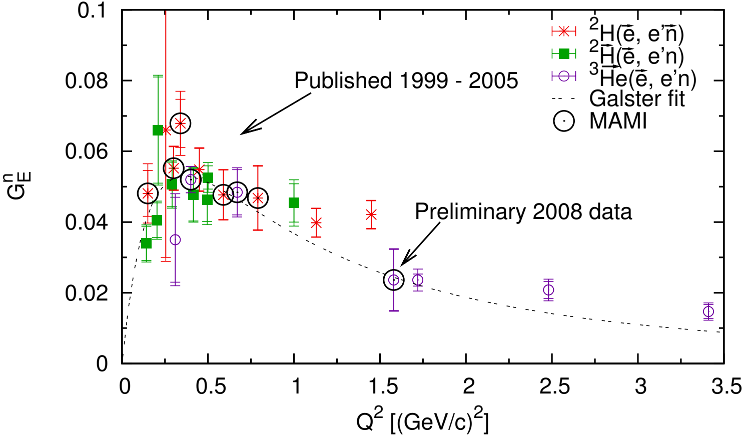
Ratio of asymmetries:

$$\frac{A(\theta = 90^\circ)}{A(\theta = 0^\circ)} = \frac{A_\perp}{A_\parallel} = \frac{a}{b}\frac{G_{E,n}}{G_{M,n}}$$

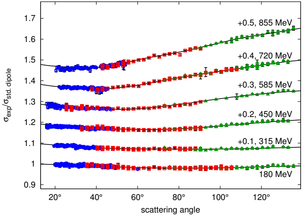
2008 measurement: G_{en} at $Q^2 \approx 1.5\,(\mathrm{GeV}/c)^2$



G_{en} from polarization experiments



S. Schlimme: PhD thesis, Mainz (2012).



Proton

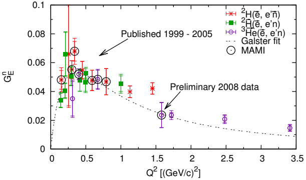
1 student (J. Bernauer)

1400 settings

Neutron

8 students (J. Becker, J. Bermuth, D. Glazier, C. Herberg, M. Ostrick, D. Rohe, S. Schlimme, M. Seimetz)

8 data points



$\hookrightarrow$ **dedicated neutron experiments**

Nuclear structure of ^{3}He

Are relativistic calculations important?

Experimental test: Beam-target asymmetries in the reaction $^3\vec{\mathrm{He}}(\vec{e}, e'p)$ at $Q^2 = 0.67\,(\mathrm{GeV/c})^2$

Theory (Faddeev method, realistic NN potentials):

Kamada, Glöckle, Golak, Elster: PRC66 (2002) 044010.

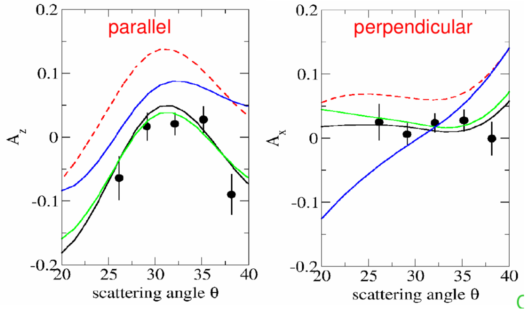
But: Incomplete treatment of FSI and MEC.

Available:

PWIA + FSI for the pn-nucleus (FSI23)

- relativistic 1-body current operator
- relativistic kinematics
- relativistic T-matrix acts on spectator
- relativistic ^{3}He ground state wave function

Are relativistic calculations important?



PWIA

current op.	kinematics
relativistic	relativistic
non-rel.	relativistic
relativistic	non-rel.

⟹ relativistic kinematics is important

Carasco et al., Phys. Lett. **B559** (2003) 41.

Study of the reaction mechanism

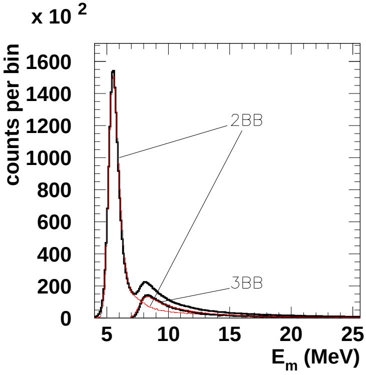
Experimental test: Beam-target asymmetries in the reaction $^3\vec{He}(\vec{e}, e'p)$ at $Q^2 = 0.31\ (\mathrm{GeV/c})^2$ in quasi-elastic kinematics.

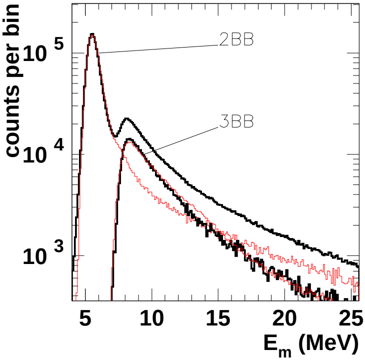
Analysis: Separation of 2- and 3-body breakup (2BB and 3BB)

$$^3\vec{He}(\vec{e}, e'p)d \Longleftrightarrow {}^3\vec{He}(\vec{e}, e'p)pn$$

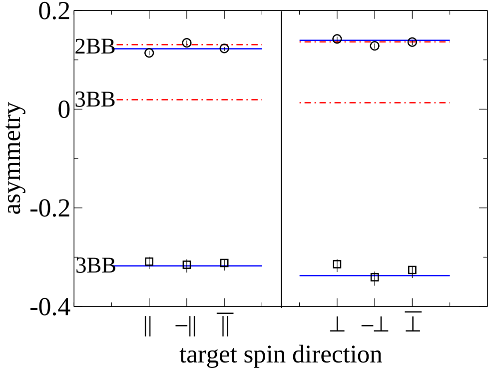
by reconstruction of the missing mass:

$$E_m = E_e - E_{e'} - T_{p'} - T_{A\text{-}1}$$


x 10 2
counts per bin
1600
1400
1200
1000
800
600
400
200
0
2BB
3BB
5
10
15
20
25
E_m (MeV)


counts per bin
10 5
10 4
10 3
2BB
3BB
5
10
15
20
25
E_m (MeV)

Nuclear structure of ^{3}He



FSI + MEC

PWIA

Achenbach et al.,
EPJ **A25** (2005) 177.

very good agreement between data and theory
(calculations by J. Golak)

- FSI: strong influence in 3BB
- MEC: negligible

Nuclear structure of ^{3}He

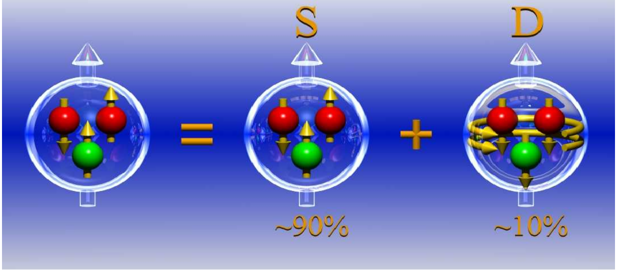
Interpretation:

- 2BB:
  $\longrightarrow$ polarized proton target
  $P_{2BB} = (-)\frac{1}{3}$ (simple Clebsch-Gordan relation)

  Experiment: $A_{\parallel} = 12.3\,\%$
  PWIA ($P_p = 100\,\%$): $A_{\parallel} = 39.2\,\%$
- 3BB:
  in PWIA: both protons are in S-state
  $\longrightarrow$ no polarization

FSI: mainly rescattering of the spectators
direct FSI of the knocked-out proton with the spectators is small (2BB and 3BB).

Nuclear structure of ^{3}He



Applications:

- Polarized neutron target (G_{en} measurement)
- Use polarized ^{3}He as polarized proton target?

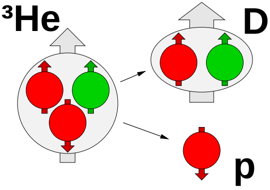
Spin structure of ^{3}He

Spin coupling:

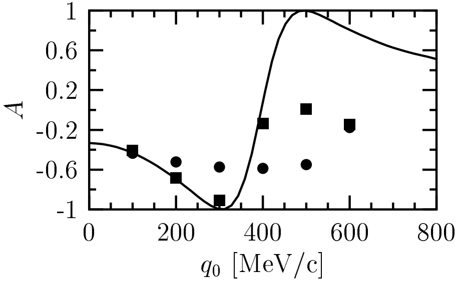
$$\left|\left(1,\frac{1}{2}\right)\frac{1}{2}\;\frac{1}{2}\right\rangle = \sqrt{\frac{2}{3}}|1,1\rangle\left|\frac{1}{2},-\frac{1}{2}\right\rangle - \sqrt{\frac{1}{3}}|1,0\rangle\left|\frac{1}{2},\frac{1}{2}\right\rangle$$

$$A \equiv \frac{\mathcal{Y}\left(M=\frac{1}{2},\ M_d=0,\ m=\frac{1}{2};|\vec{q}_0|\hat{z}\right) - \mathcal{Y}\left(M=\frac{1}{2},\ M_d=1,\ m=-\frac{1}{2};|\vec{q}_0|\hat{z}\right)}{\mathcal{Y}\left(M=\frac{1}{2},\ M_d=0,\ m=\frac{1}{2};|\vec{q}_0|\hat{z}\right) + \mathcal{Y}\left(M=\frac{1}{2},\ M_d=1,\ m=-\frac{1}{2};|\vec{q}_0|\hat{z}\right)}$$

Polarized proton target?



Prediction of the spin-dependend momentum distribution in ^{3}He:
J. Golak et al.:
Phys. Rev. C**65** (2002) 064004.



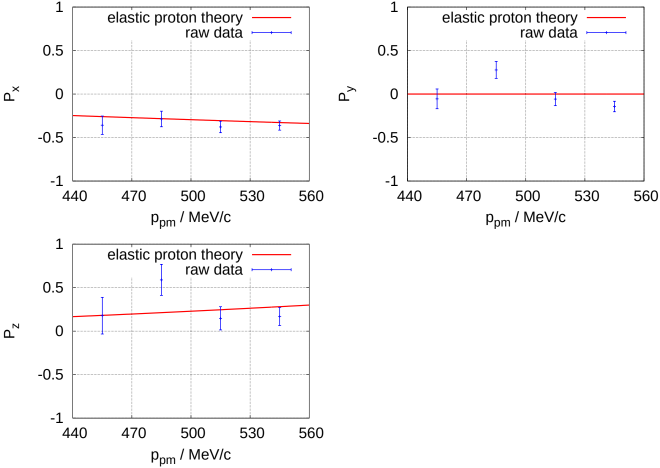
$^3\vec{He}(\vec{e}, e'\vec{p})d$

First triple polarization experiment

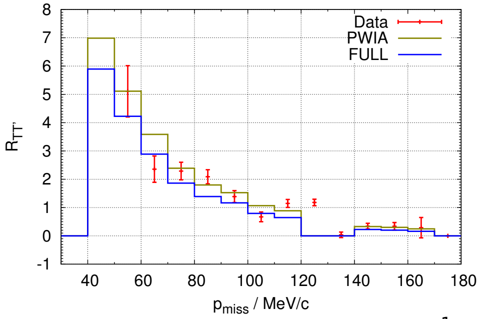
M. Weinriefer, PhD thesis, Mainz (2011)

Polarized proton target?

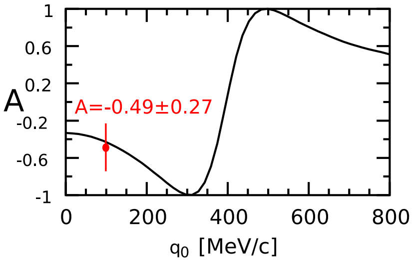
Comparison of the polarization:
Free proton $H(\vec{e}, e'\vec{p})$ (theory) –
Recoil proton from $^3He(\vec{e}, e'\vec{p})d$ (A1 experiment)



Preliminary results on $^3\vec{\mathrm{He}}(\vec{\mathrm{e}}, \mathrm{e}'\vec{\mathrm{p}})\mathrm{d}$



Structure function $R_{TT'}$

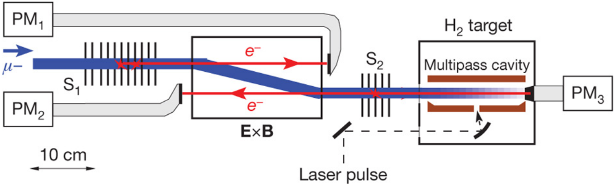


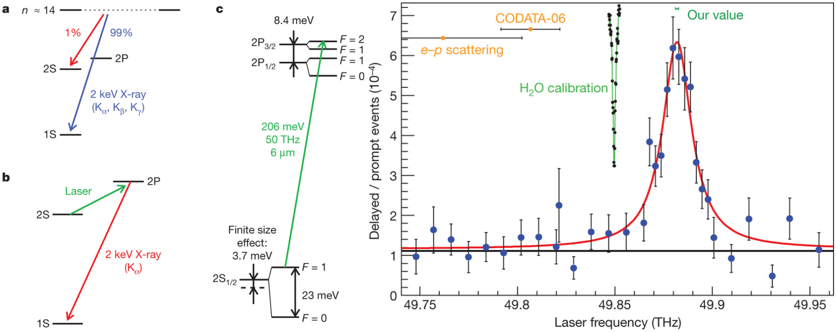
Spin-dependend momentum distribution

press any key

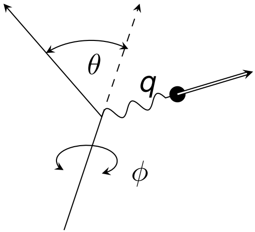
The radius puzzle – Lamb shift in μH

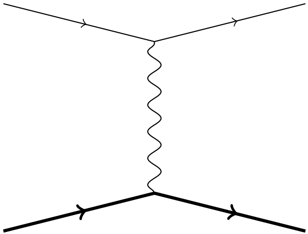
Nature **466**, 213-216 (8 July 2010)





Cross section and form factors for elastic e-p scattering





The cross section:

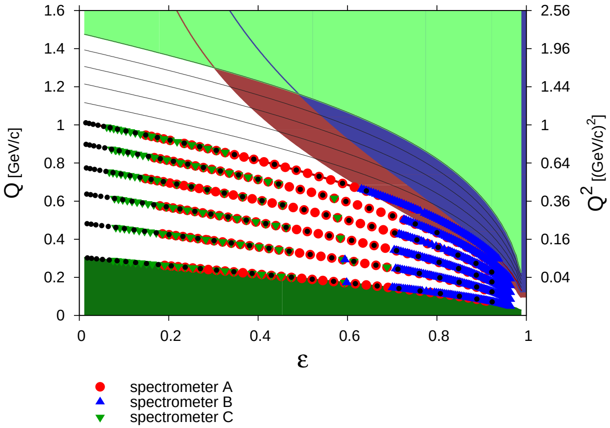
$$\frac{\left(\frac{d\sigma}{d\Omega}\right)}{\left(\frac{d\sigma}{d\Omega}\right)_{Mott}} = \frac{1}{\varepsilon\left(1+\tau\right)}\left[\varepsilon G_E^2\left(Q^2\right) + \tau G_M^2\left(Q^2\right)\right]$$

with:

$$\tau = \frac{Q^2}{4m_p^2}, \quad \varepsilon = \left(1 + 2\left(1+\tau\right)\tan^2\frac{\theta_e}{2}\right)^{-1}$$

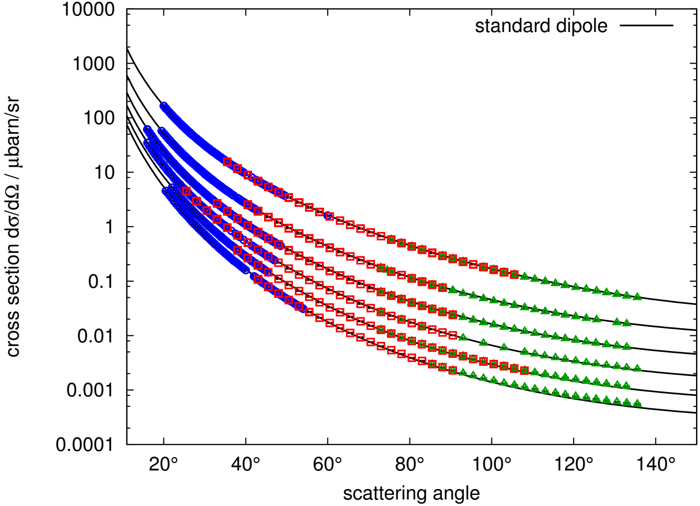
Measured settings and future (high Q^2) expansion

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

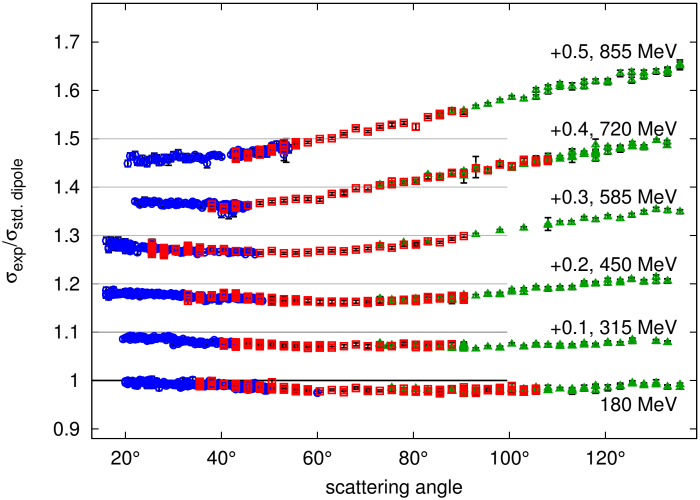


- ~90 GByte on disc
- ~1400 Settings
- $> 10^9$ events.

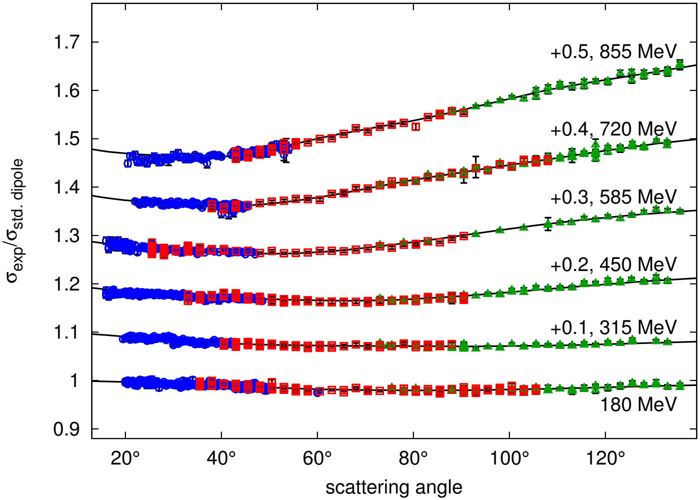
Cross sections



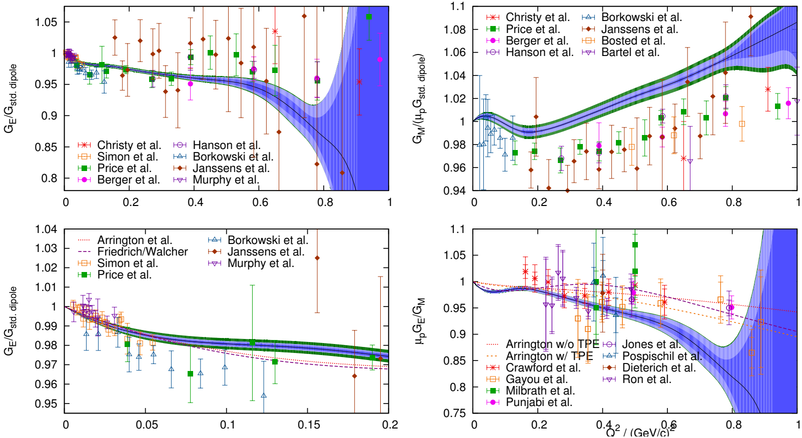
Cross sections / standard dipole



Cross sections + spline fit



Form factor results



Jan C. Bernauer *et al.*, "High-precision determination of the electric and magnetic form factors of the proton",

PRL 105, 242001 (2010), arXiv:1007.5076

Discussion of the Lamb shift / electron scattering discrepancy

- **Muonic hydrogen (Lamb Shift)**

  $r_p = 0.84184(67)\,\text{fm}$

  R. Pohl *et al.*, Nature **466**, 213-216 (2010)
- **Mainz form factor measurement**

  $r_p = 0.879(8)\,\text{fm}$

  J.C. Bernauer *et al.*, Phys. Rev. Lett. **105**, 242001 (2010).
- **Analysis of previous ep scattering data**

  $r_p = 0.895(18)\,\text{fm}$

  I. Sick, Phys. Lett. **B576** 62-67 (2003).
- **Electronic hydrogen - (CODATA)**
  (Hyperfine structure and Lamb shift)

  $r_p = 0.8768(69)\,\text{fm}$

  P.J. Mohr *et al.*, Rev. Mod. Phys. **80** 633-730 (2008).

Discrepancy is between
muonic **and** *electronic* **measurements**

The muonic/electronic puzzle of the charge radius

What could be wrong? or Is it “new” physics?
Akin to three standard deviations difference of magnetic moment of μ between experiment and theory?
electron scattering:

- very small $0 \leq Q^2 \lesssim 0.001\ (\mathrm{GeV/c})^2$ region not measured, extrapolation right?
  Only light particles contribute to the “long range structure”.
  Are *positrons* part of charge distribution?
- Models don’t extrapolate right to $Q^2 \rightarrow 0$?
  But, a plathora of models tried. All give same result.
- Coulomb corrections, resp. two photon exchange (TPE) is incomplete?
  But, effect on charge radius $< r_E >$ is negligible at $Q^2 \lesssim 1\ (\mathrm{GeV/c})^2$ for all TPE calculations.

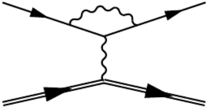
Possible explanations of the discrepancy

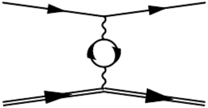
- **Exotic particles**
  e.g. V. Barger *et al.*, arXiv:1011.3519 and references.
  C. Carlson and B. Rislow, Phys.Rev. D86 (2012) 035013.
- **Contributions to the Lamb shift in μp**
  C.E. Carlson and M. Vanderhaeghen, arXiv:1101.5965
  U.D. Jentschura, Annals Phys. **326**, 500-515 (2011)
  E. Borie, arXiv:1103.1772
- **Higher moments of the charge distribution and Zemach radii**
  M.O.D., J.C. Bernauer, and Th. Walcher,
  Phys. Lett. **B696**, 343-347 (2011)

still an unsolved problem

Speculation about the discrepancy

- Reminder: The muon g-2 experiment has a $2-3\sigma$ discrepancy. Hadronic corrections may provide an explanation.
- The main contribution to the **Lamb shift** in …





	'electronic' hydrogen	muonic hydrogen
vertex and self-energy	$1011.41\,\mathrm{MHz}$	
vacuum polarization	$-27.13\,\mathrm{MHz}$	$-205.028\,\mathrm{meV}$
anom. magn. moment	$67.82\,\mathrm{MHz}$	
+ higher order		
theoretical value	$1057.864(14)\,\mathrm{MHz}$	$-206.057\,\mathrm{meV}$
experimental value	$1057.862(20)\,\mathrm{MHz}$	$\Delta: 0.341\,\mathrm{meV}$

Collaborative Research Centre 1044 (2012–)

The Low-Energy Frontier of the Standard Model

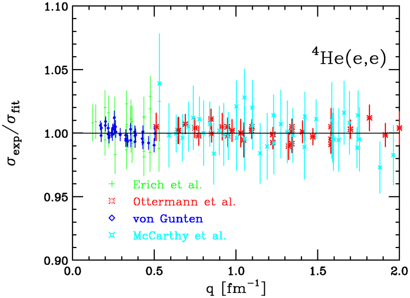
From Quarks and Gluons to Hadrons and Nuclei

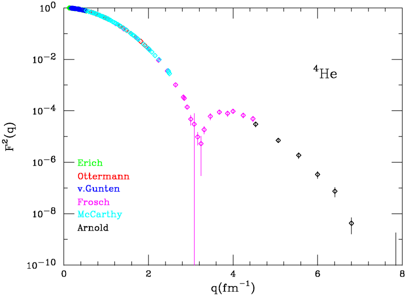
Project N: Interactions in few-baryon systems

Helium-4

Interest

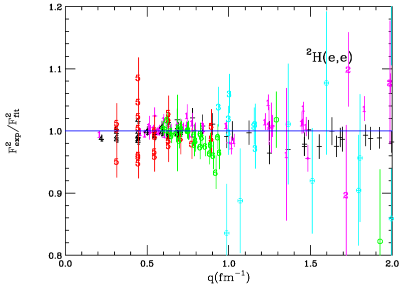
- precise isotope shifts available up to ^{8}He.
- candidate for μHe Lamb shift measurement
- candidate for measurement with ^{4}He$^+$

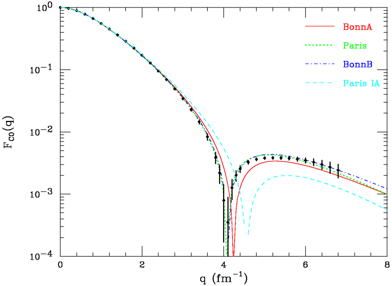


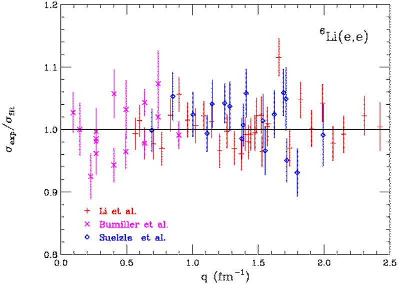


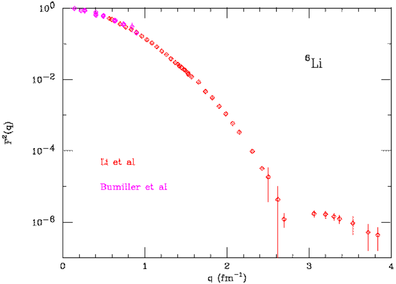
Ingo Sick, PSAS 2012

Hydrogen-2 and Lithium-6









Mainz Microtron MAMI

Collaboration: A1

Spokesperson: H. Merkel

Title: Measurement of the elastic $A(q^2)$ form factor of the deuteron at very low momentum transfer and the extraction of the monopole charge radius of the deuteron

Authors: P. Achenbach[1], R. Böhm[1], D. Bosnar[2], J. Beričič[3], L. Debenjak[3], A. Denig[1], M. O. Distler[1], A. Esser[1], H. Fonvieille[4], I. Friščić[2], M. Gómez Rodríguez[1], K. Griffioen[5], S. Kegel[1], Y. Kohl[1], H. Merkel[1], M. Mihavilovič[1], U. Müller[1], J. Pochodzalla[1], T. R. Saito[1], B. S. Schlimme[1], M. Schoth[1], F. Schulz[1], C. Sfienti[1], I. Sick[6], S. Širca[3], M. Thiel[1], A. Weber[1]

[1] Institut für Kernphysik, Johannes Gutenberg-Universität, Mainz

[2] Department of Physics, University of Zagreb, Croatia

[3] University of Ljubljana and Institute "Jožef Stefan", Ljubljana, Slovenia

[4] IN2P3-CNRS, Université Blaise Pascal, Clermont-Ferrand, France

[5] Department of Physics, College of William and Mary, Williamsburg, VA

[6] Departement für Physik, Universität Basel, Switzerland

Contactpersons: M. O. Distler, K. Griffioen

Abstract of physics: We propose to perform a high precision measurement of the elastic cross section in the reaction ^{2}H(e,e'd) at very low 4-momentum transfer. The data will be used to extract the elastic $A(q^2)$ and $G_C(q^2)$ form factors of the deuteron and the monopole charge radius. The contributions of the magnetic and the quadrupole form factor in the low q^2 region are small and known to a good precision from previous measurements. There is renewed interest in the charge radius of the deuteron as it may help to solve the proton radius puzzle in combination with new Lamb shift measurements at PSI.

Abstract of equipment: Standard A1 equipment with the liquid deuterium target.

MAMI specifications :

beam energy:	min. 180 MeV	max. 450 MeV
beam current:	min. 25 nA	max. 15 μA
time structure:	continuous beam	
polarization:	no	

Experiment specifications:

targets and chamber:	liquid deuterium target, 5cm cell
hall:	spectrometer hall
beam line:	standard to spectrometer hall

spectrometer:	particles:	range of angles:	out of plane:
SpekA	e,p	$18^\circ - 160^\circ$	—
SpekB	e,p	$7^\circ - 62^\circ$	—
SpekC	e	$18^\circ - 160^\circ$	—

Beam time request :

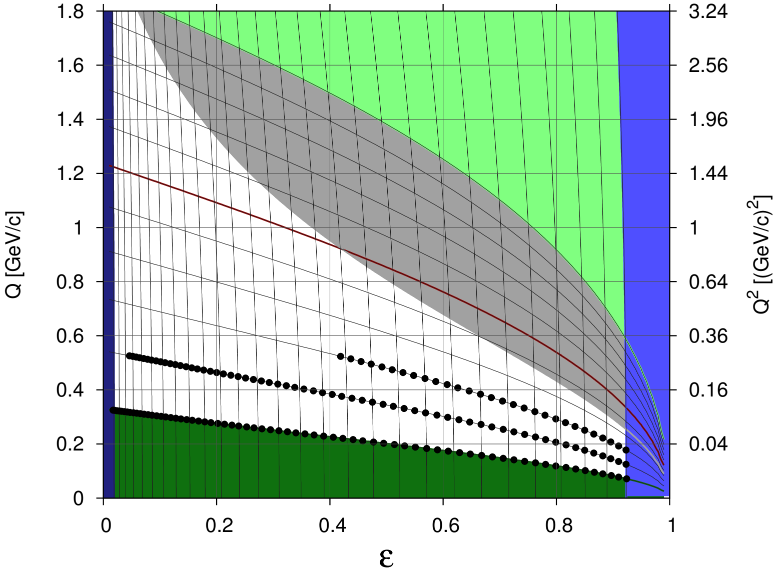
set-up without beam:	4 days
set-up with beam:	90 h
data taking:	160 h

Elastic scattering from the spin-1 deuteron

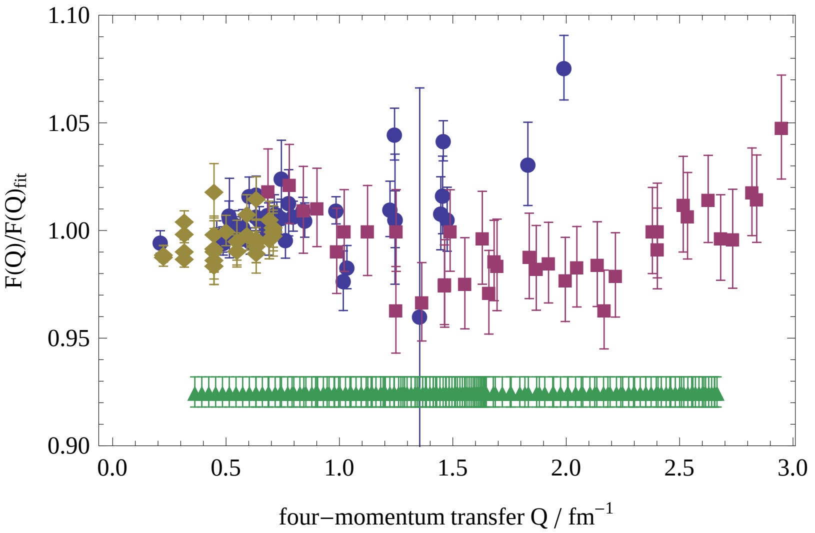
$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}} \left[A(Q^2) + B(Q^2)\tan^2\frac{\theta}{2}\right]$$

$$\begin{aligned} A(Q^2) &= F_{C0}^2(Q^2) + (M_d^2 Q_d)^2 \frac{8}{9}\eta^2 F_{C2}^2(Q^2) \\ &\quad + \left(\frac{M_d}{M}\mu_d\right)^2 \frac{2}{3}\eta(1+\eta) F_{M1}^2(Q^2) \\ B(Q^2) &= \left(\frac{M_d}{M}\mu_d\right)^2 \frac{4}{3}\eta(1+\eta)^2 F_{M1}^2(Q^2) \end{aligned}$$

Kinematical coverage – ^{2}H(e,e')d @ MAMI

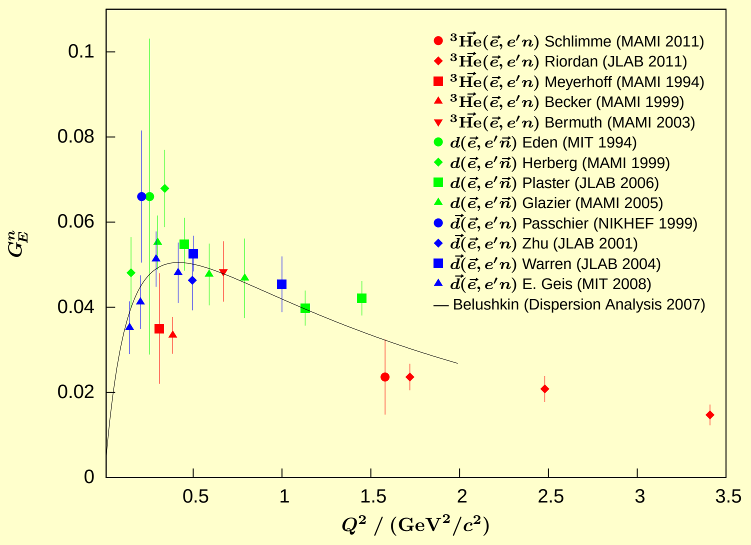


Estimated errors – $^2H(e,e')d$ @ MAMI



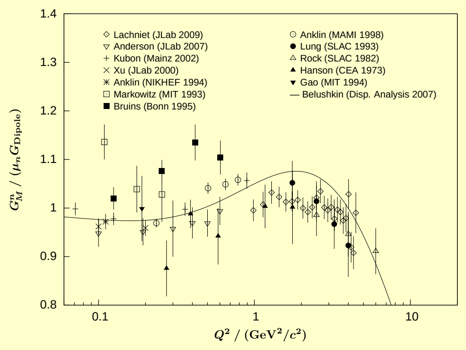
♦ Berard (1973), • Simon (1981), ■ Platchkov (1990), ▲ MAMI

Electric form factor of the neutron: G_{en}



Only double polarization measurements!

Magnetic form factor of the neutron

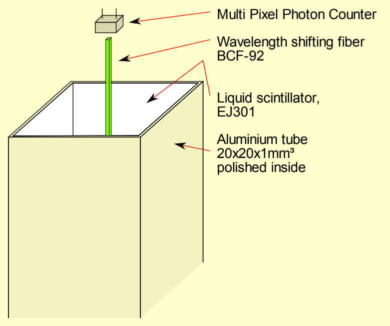


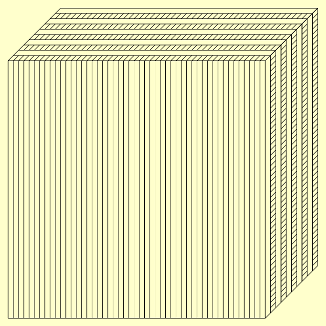
- Discrepancy BLAST $\leftrightarrow$ CLAS
- Data consistency
- Observable: $R = \frac{^2H(e,e'n)p}{^2H(e,e'p)n}$
- Normalization of neutron detector
  - *In situ* calibration (background, count rate, n-momentum)
  - Continuous monitoring of efficiency

Electric form factor of the neutron

- Well suited for low Q^2: Recoil polarimetry on Deuteron
- Goal: half error bar, cover range $0.1\,\mathrm{GeV}^2$–$2\,\mathrm{GeV}^2$
- $\Rightarrow$ Experimental requirements:
  - Improved statistics $\times 20$
    - Improved efficiency: 15% $\rightarrow$ 80%
    - Improved beam current: $3\,\mu$A$\rightarrow$ $20\,\mu$A
    - Improved resolution $\rightarrow$ reduced background
    - Just more beam time...
  - Improved systematics
  - Improved mechanical design
- $\Rightarrow$ A new, highly segmented neutron detector!

Design of a new Neutron detector

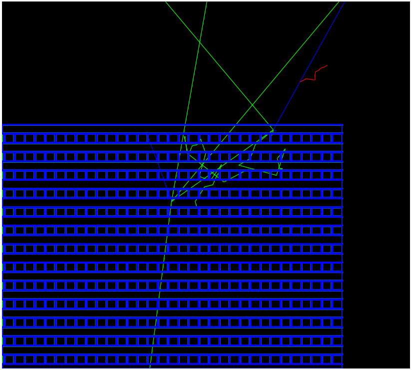




- Aim: Costs per module ≈200€
- Block: ≈1 m^3 ⇒ 48×48 Modules
- Segmenting improved ≈ 10×
- Closer to target with same ToF-resolution

⇒ High rates, large solid angle, good resolution, high efficiency

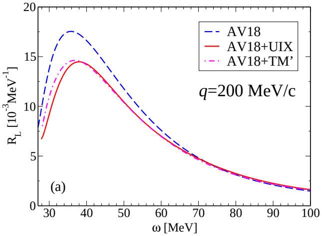
Simulation (Geant4)



- Momentum range 300 MeV/c – 1500 MeV/c
- Below 300 MeV/c bad position resolution
- Approx. 80% Efficiency, 2% Momentum resolution (ToF), 2 mrad Angular resolution
- Preliminary design, first test modules are built

Search for three-nucleon force effects in ^{3,4}He

Sonia Bacca, Nir Barnea, Winfried Leidemann, Giuseppina Orlandini, Phys.Rev.C80:064001 (2009), Phys.Rev.Lett.102:162501 (2009).

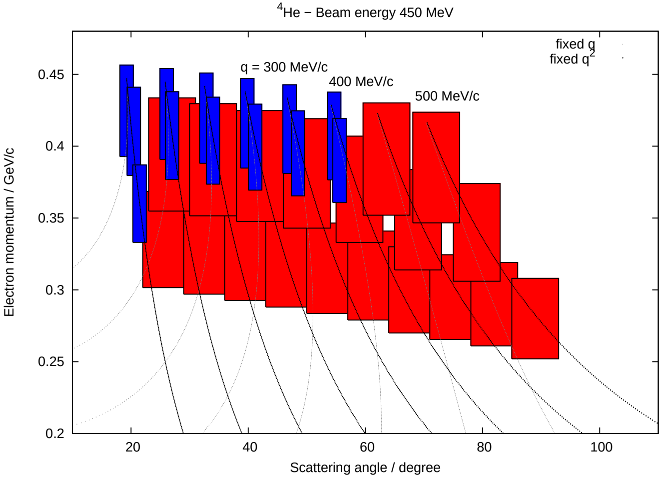


- Lorentz integral transform
- ab initio calculation using realistic NN potentials
- data missing at low q

Inclusive measurement ^{3,4}He(e, e') in 2009.

- 5 beam energies, 250 settings
- LT-separation

Example of kinematic coverage



Johannes Gutenberg University Mainz: Precision Physics, Fundamental Interactions and Structure of Matter (PRISMA)

Research Areas

- What is the origin of particle masses?
- How do the properties of bound states emerge from fundamental interactions?
- Why does the Universe contain more matter than anti-matter?
- Which phenomena will we encounter beyond the Standard Model?
- What is the nature of the dark components of the Universe?
- Are fundamental symmetries exact on all length scales?

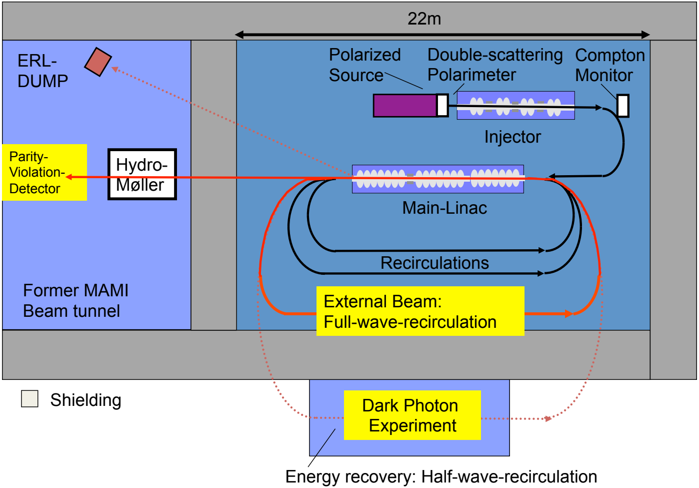
Johannes Gutenberg University Mainz:
Precision Physics, Fundamental Interactions and Structure of Matter (PRISMA)

Methods

- **accelerator-based experiments**
- neutrino telescopes and **dark matter experiments**
- atom and ion traps
- reactor-based experiments with cold and ultra-cold neutrons

PRiSMA

MESA Accelerator (preliminary design)



Energy recovering superconduction linac $\Rightarrow L = 10^{35}\mathrm{s}^{-1}\mathrm{cm}^{-2}$ with internal hydrogen target

Summary

Experiments on few-nucleon systems at MAMI

$^3\vec{He}(\vec{e}, e'n)$, $^2H(\vec{e}, e'\vec{n})$, $^3\vec{He}(\vec{e}, e'p)$, $^3He(e, e'pn)$, $^3\vec{He}(\vec{e}, e'\vec{p})d$

- Extensive program to measure nucleon form factors
- Nuclear structure of ^3He
- (Correlations in ^3He)

Plans for the future

- May $^3\vec{He}$ be used as effective polarized proton target? Use EFT to understand medium effects.
- Build an improved neutron detector for G_{en}
- Form factor and inclusive measurements on $^{6,7}Li$
- Help resolve the proton radius puzzle (Zemach-moments, form factors, and polarizibilities of D, $^{3,4}He$).
- Study three body forces in $^{3,4}He$
- (Study of light hypernuclei)