Few-body electro-production experiments at MAMI

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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

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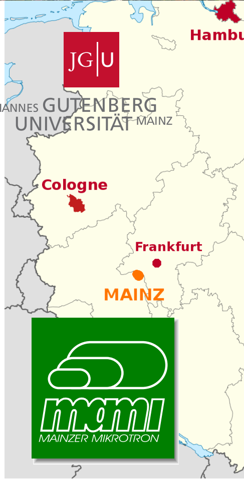

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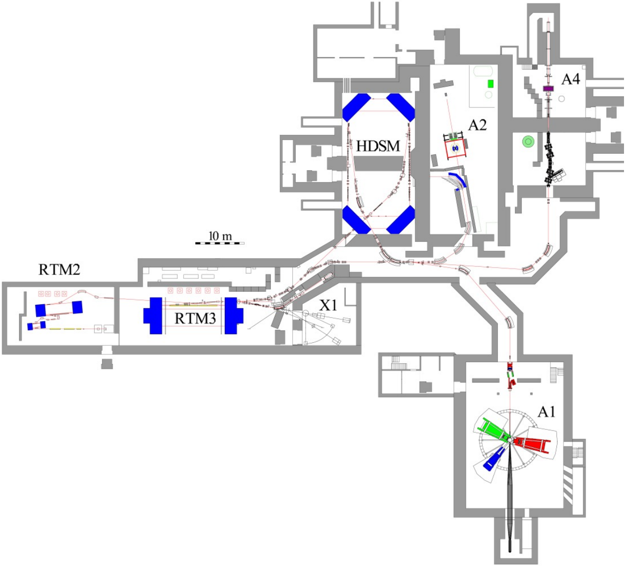
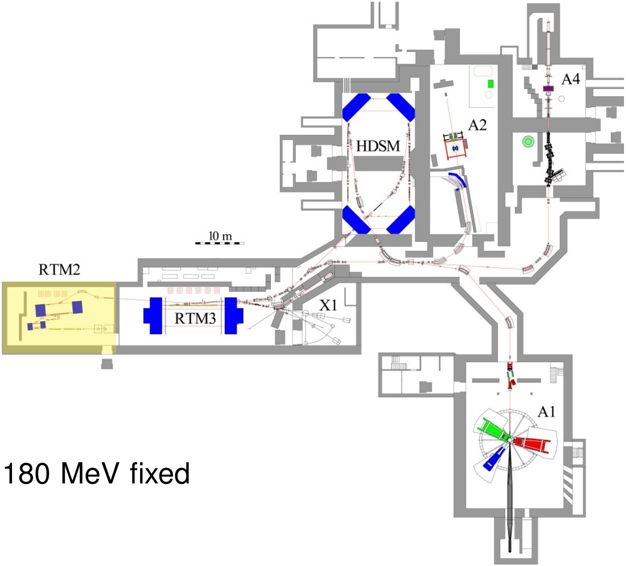
mami
MAINZER MIKROTRON

The Mainz Microtron MAMI

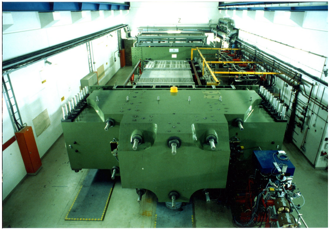


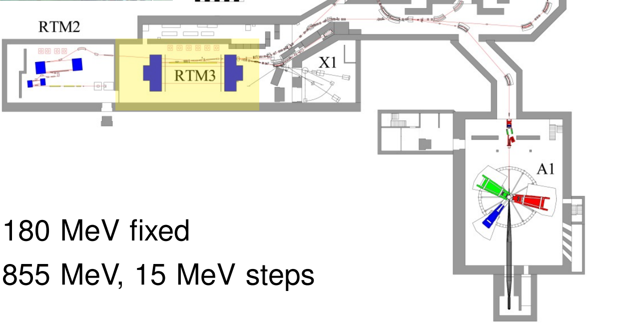
The Mainz Microtron MAMI



- MAMI-A: 180 MeV fixed

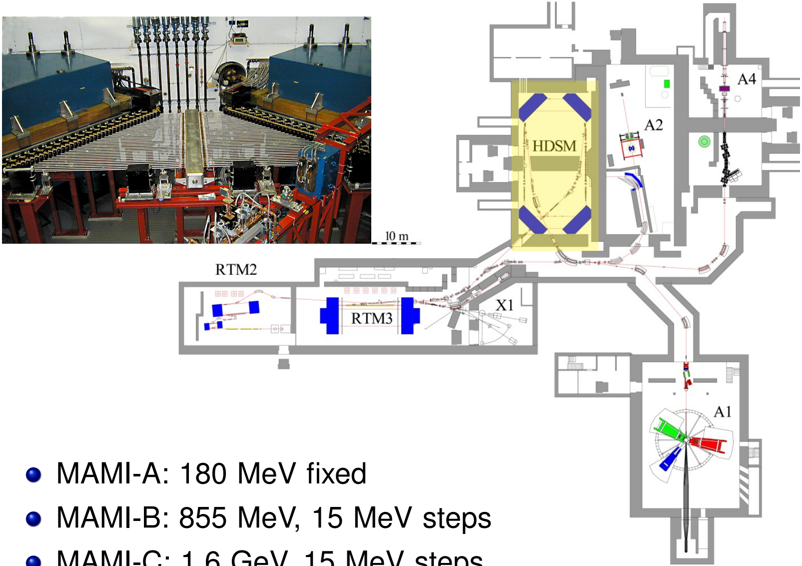
The Mainz Microtron MAMI





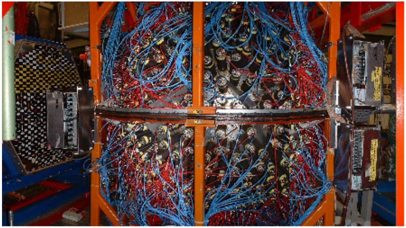
- MAMI-A: 180 MeV fixed
- MAMI-B: 855 MeV, 15 MeV steps

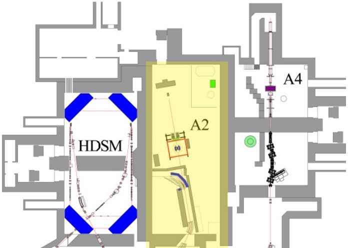
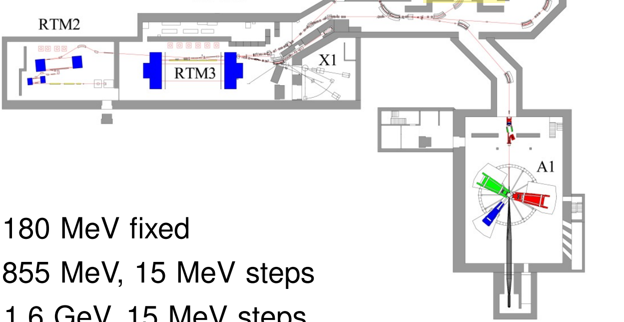
The Mainz Microtron MAMI



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

The Mainz Microtron MAMI



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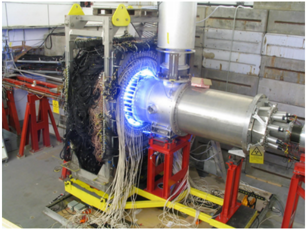

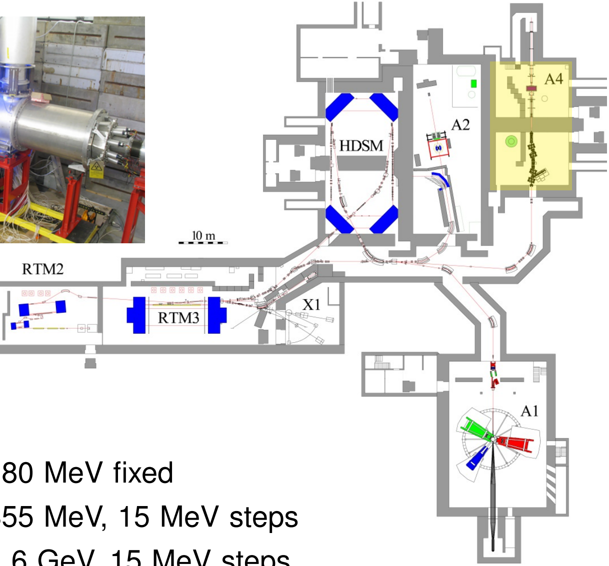

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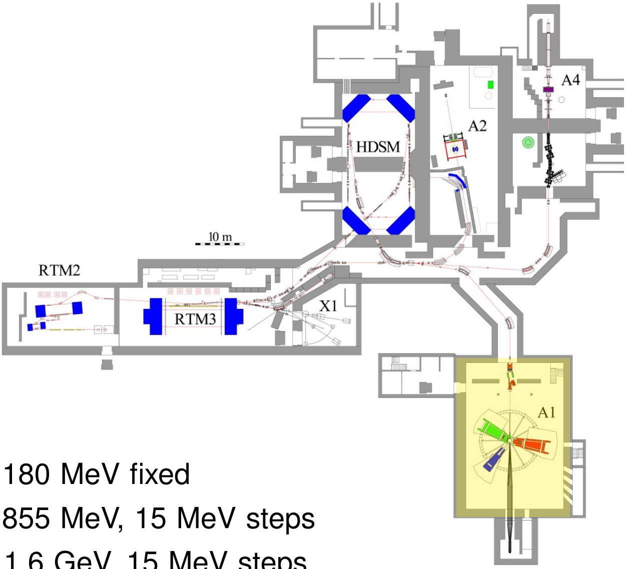

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- MAMI-B: 855 MeV, 15 MeV steps
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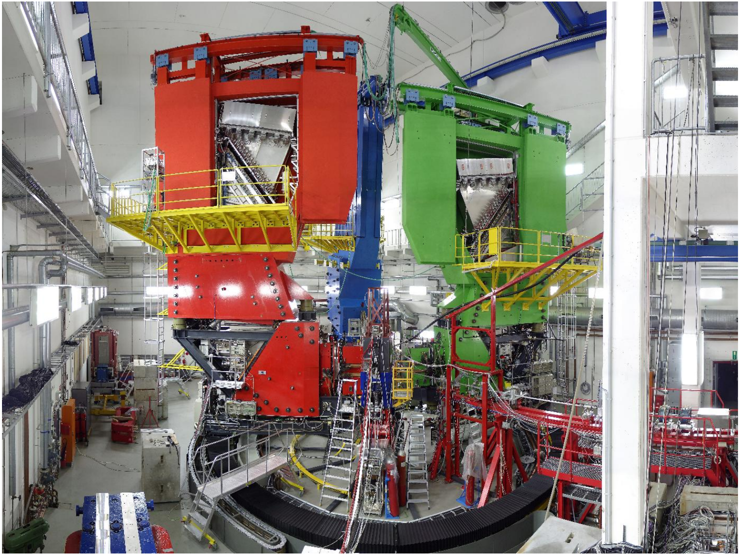
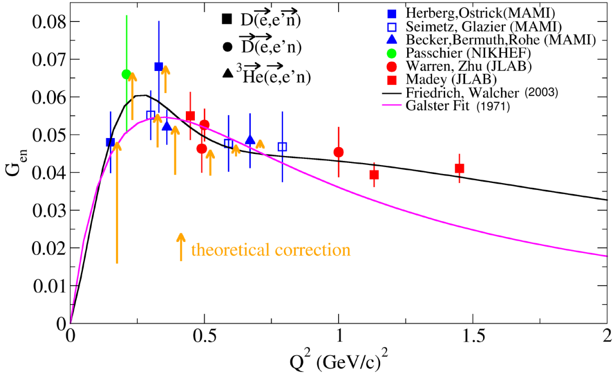
Three spectrometer facility of the A1 collaboration



^{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)

Introduction

- Few nucleon system serve as effective neutron targets.
- The understanding of hadronic systems is an important goal of nuclear physics.
- Fundamental theory: QCD
- Non perturbative regime: QCD not applicable.
$\longrightarrow$ Effective field theories use nucleons, mesons and isobars as effective degrees of freedom.
- Ideal to test EFTs: Few nucleon systems.

Electric form factor of the neutron

Problem:

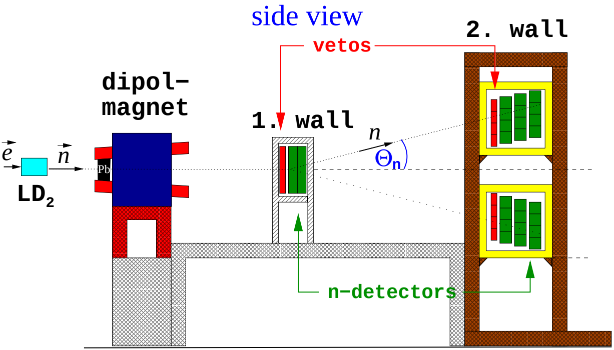
- no free neutron target available
- G_{en} small compared to G_{mn}.
  Rosenbluth separation gives big errors:

$$\frac{d\sigma}{d\Omega} \sim aG_e^2(q) + bG_m^2(q)$$

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

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

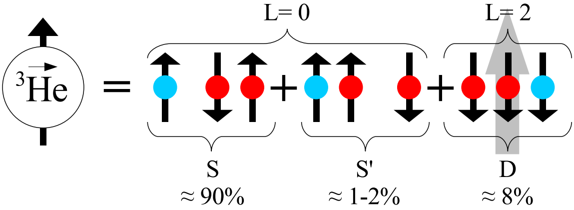
Double polarization experiments on ^{2}H



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

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

Double polarization experiments on ^{3}He



Beam target asymmetry:

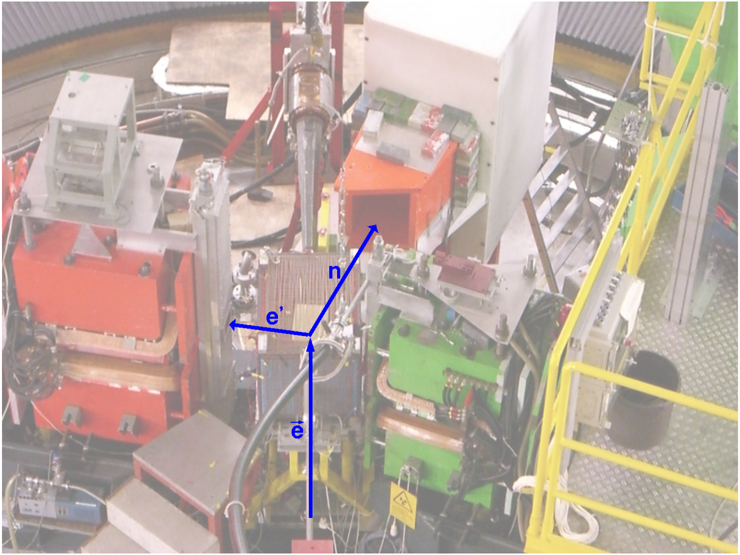
$$A = \frac{N(\uparrow\uparrow) - N(\uparrow\downarrow)}{N(\uparrow\uparrow) + N(\uparrow\downarrow)}$$

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

Ratio of asymmetries:

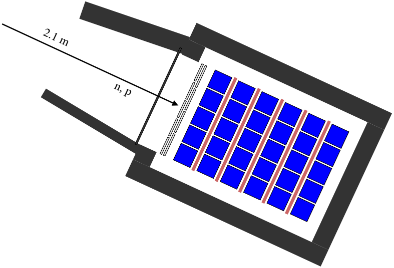
$$\frac{A(\theta = 90^\circ)}{A(\theta = 0^\circ)} = \frac{A_\perp}{A_\parallel} = \frac{a}{b} \frac{G_{E,n}}{G_{M,n}}$$

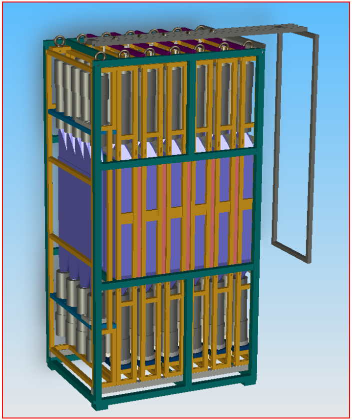
2008 measurement: Gen at $Q^2 \approx 1.5\,(\mathrm{GeV}/c)^2$



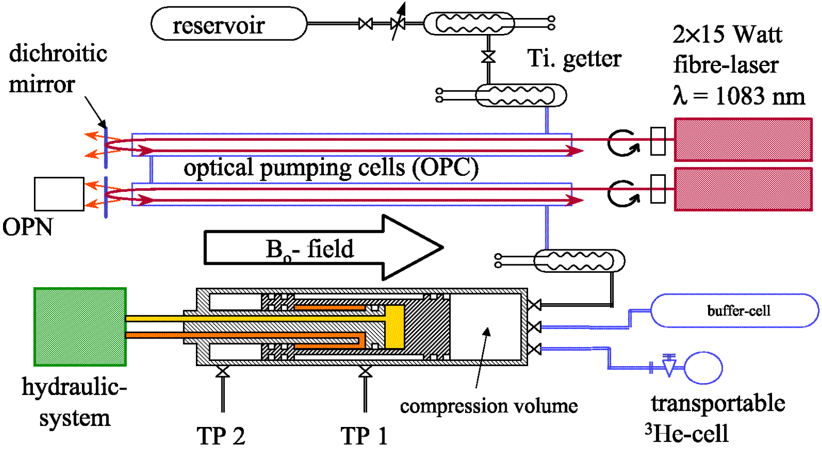
Neutron detection: Scintillator array

- Plastic scintillator matrix (BC 400)
  6 layers $\times$ 5 bars ($10 \times 10 \times 50\ \mathrm{cm}^3$))
  2 PMTs each
- 2 veto layers
- copper layers $\rightarrow$ increase neutron detection efficiency
- massive shielding
- 1 cm lead in front
  $\rightarrow$ p-n conversion





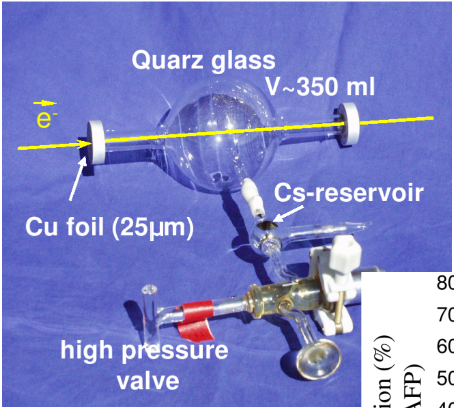
Polarized ^{3}He target - Institut für Physik (W. Heil)



J. Krimmer, MOD, W. Heil, S. Karpuk, D. Kiselev, Z. Salhia and E.W. Otten,
A highly polarized ^{3}He target for the electron beam at MAMI,
NIM **611** (2009) 18-24.

↪

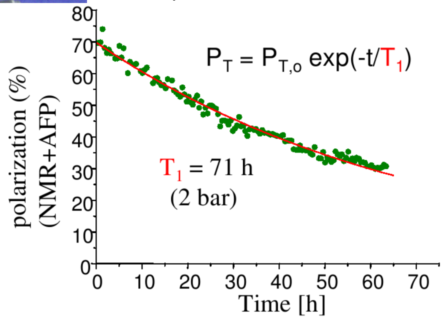
^{3}He cell



Relaxation due to

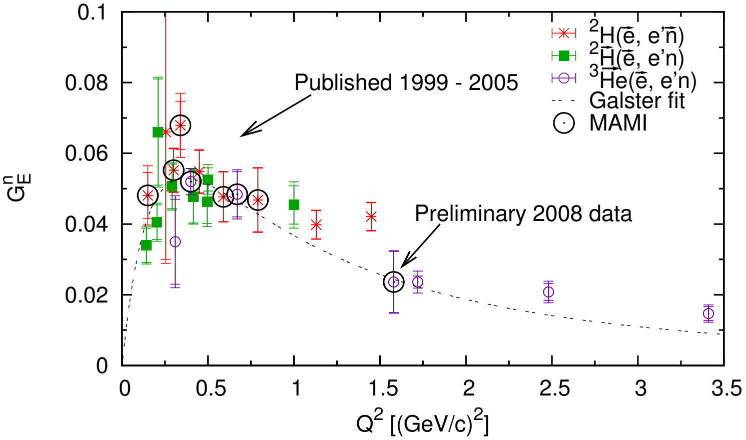
- surfaces
- pressure (5 bar)
- field gradients
- electron beam

$\longrightarrow T_1 \sim 45\,\mathrm{h}$



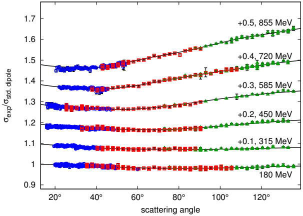
Change of the target cell
every 12 hours

G_{en} from polarization experiments



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

Form factor: Proton vs. Neutron



Proton

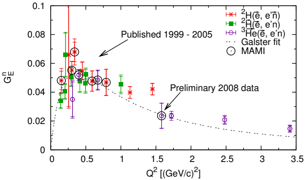
1 student (J. Bernauer)

1400 settings

Neutron

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

8 data points



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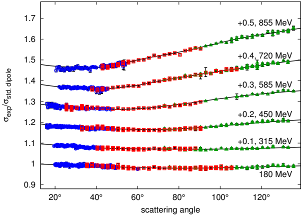

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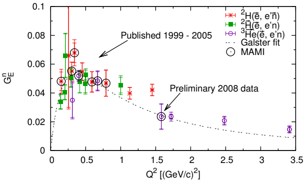


$\hookrightarrow$ **dedicated neutron experiments**

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.

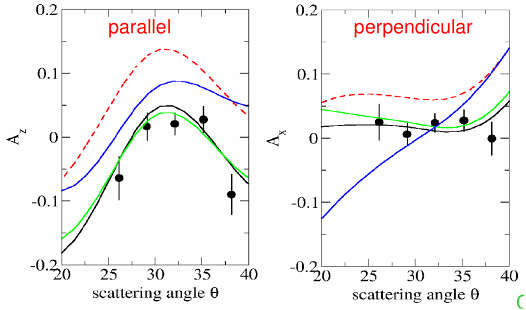
But: Incomplete treatment of FSI and MEC.

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.

$\Longrightarrow$ 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 $^3\vec{\mathrm{He}}(\vec{e}, e'p)$ at $Q^2 = 0.31\ (\mathrm{GeV/c})^2$ in quasi-elastic kinematics.

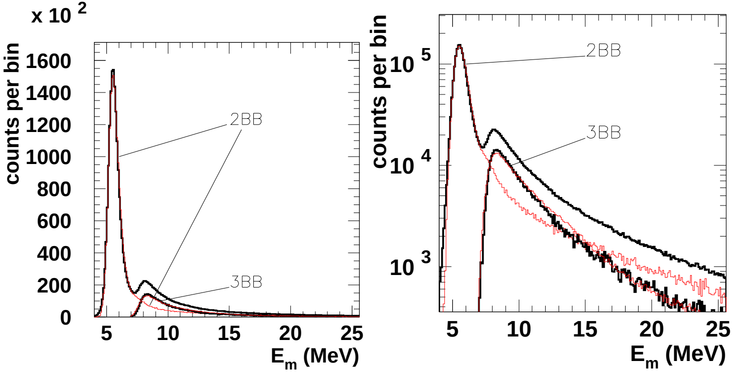
Analysis: Separation of 2- and 3-body breakup (2BB and 3BB)

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

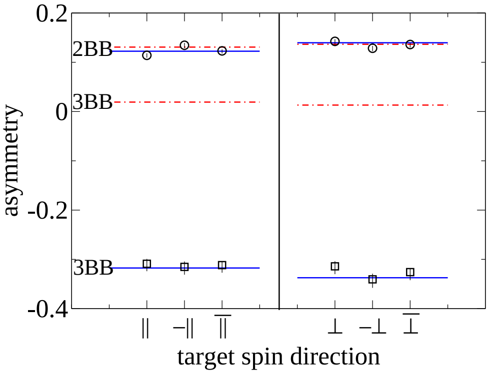
by reconstruction of the missing mass:

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

Nuclear structure of ^{3}He



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)

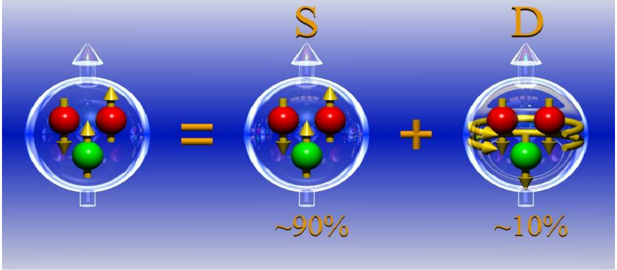
- FSI: strong influence in 3BB
- MEC: negligible

Interpretation:

- 2BB:
  $\longrightarrow$ polarized proton target
  $P_{2BB} = (-)\frac{1}{3}$ (simple Clebsch-Gordan relation)
  Experiment: $A_{\|} = 12.3\,\%$
  PWIA ($P_p = 100\,\%$): $A_{\|} = 39.2\,\%$
- 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:

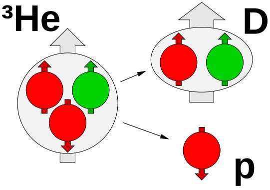
- Polarized neutron target (G_{en} measurement)
- Use polarized ^{3}He as polarized proton target?

Spin coupling:

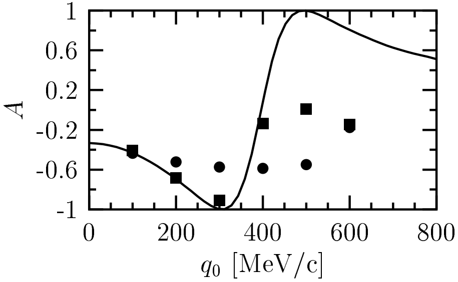
$$\left|\left(1, \frac{1}{2}\right) \frac{1}{2}\ \frac{1}{2}\right\rangle = \sqrt{\frac{2}{3}}|1,1\rangle \left|\frac{1}{2}, -\frac{1}{2}\right\rangle - \sqrt{\frac{1}{3}}|1,0\rangle \left|\frac{1}{2}, \frac{1}{2}\right\rangle$$

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

Polarized proton target?



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

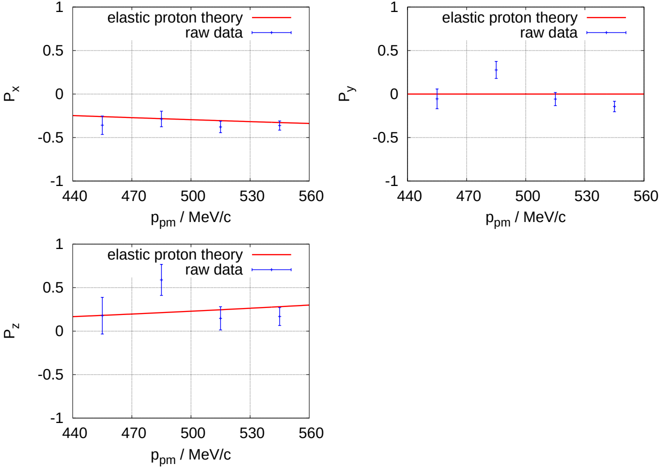


$^3\vec{\mathrm{He}}(\vec{\mathrm{e}}, \mathrm{e}'\vec{\mathrm{p}})\mathrm{d}$

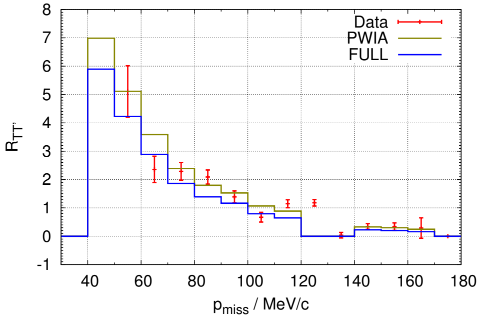
First triple polarization experiment
M. Weinriefer, PhD thesis, Mainz (2011)

Polarized proton target?

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

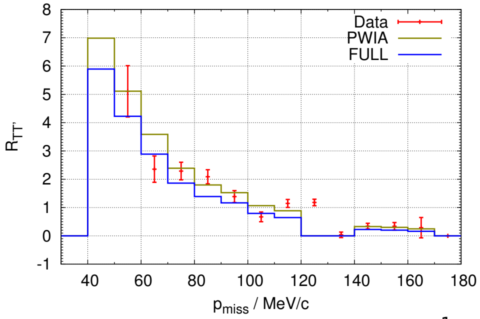


Preliminary results on $^3\vec{He}(\vec{e}, e'\vec{p})d$

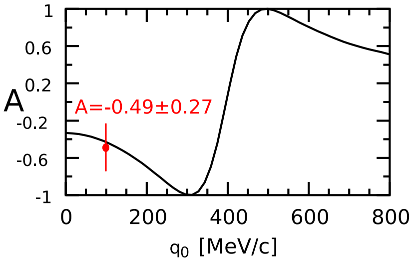


Structure function $R_{TT'}$

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

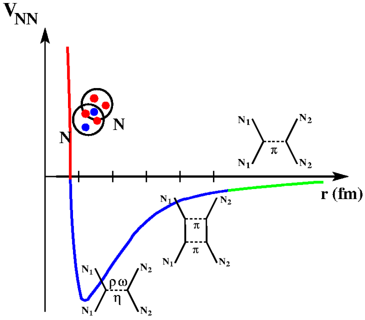


Structure function $R_{TT'}$



Spin-dependend momentum distribution

Correlations in ^{3}He

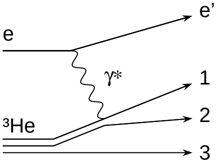


- Many nuclear models use the "mean field" ansatz: "Independent particle models".
- This picture accounts for long range, attractive forces.
- Short range forces, which are responsible for correlations, are often neglected.

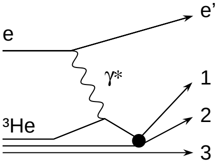
Correlations in ^{3}He

One-body currents:

Central and tensor correlations

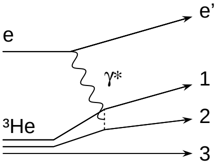


Final state interactions (FSI):

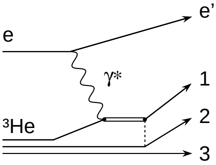


Two-body currents:

Meson Exchange currents (MEC)



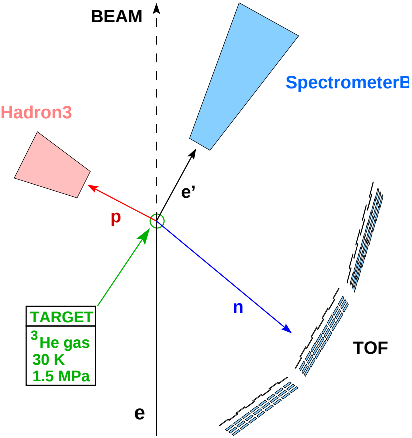
Δ-excitations. Isobar currents (IC)



Disentangle contributions via comparison of pp (^{3}He(e, e′pp)) and pn (^{3}He(e, e′pn)) knockout.

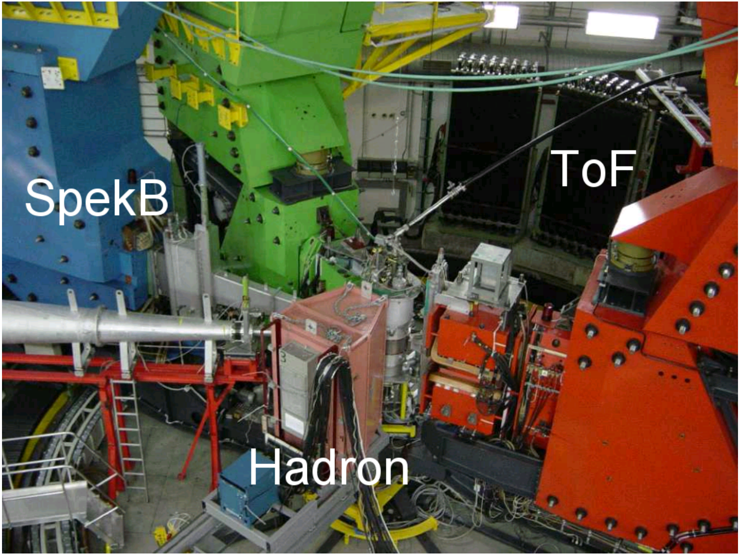
^{3}He(e, e′pn) - Experimental setup

Amsterdam - Glasgow - Tübingen - Mainz

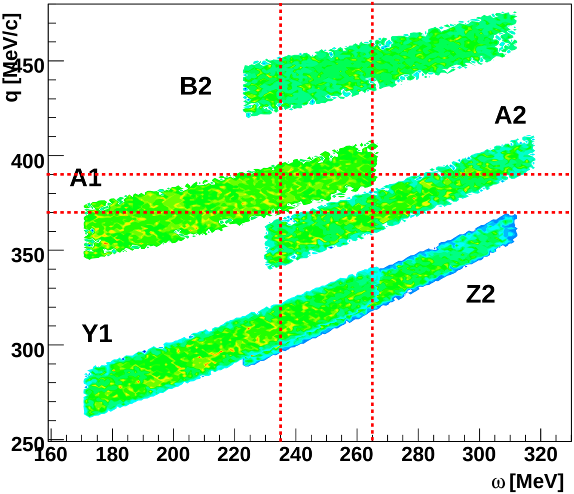


- ^{3}He(e, e′pp) (Nikhef) Groep et al.: PRC 63 (2000) 014005.
- Magnetic spectrometers for electron detection
- Scintillator hodoscope (Amsterdam): Proton
- TOF (Glasgow, Tübingen): Neutron
- High pressure cryo target

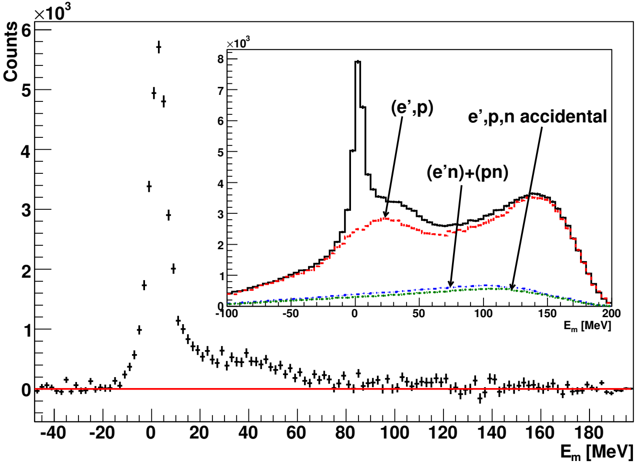
^{3}He(e, e′pn) - Experimental setup



$^3He(e, e'pn)$ - Kinematical region

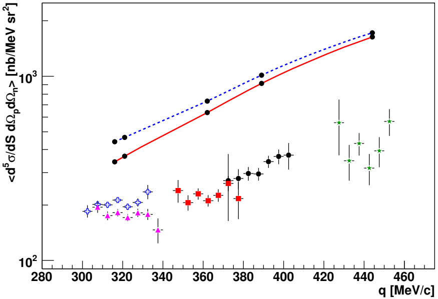


^{3}He(e, e′pn) - missing-energy (Em) distribution



D. G. Middleton *et al.*, Phys. Rev. Lett. **103** (2009) 152501.

^{3}He(e, e′pn) - cross section vs. momentum transfer

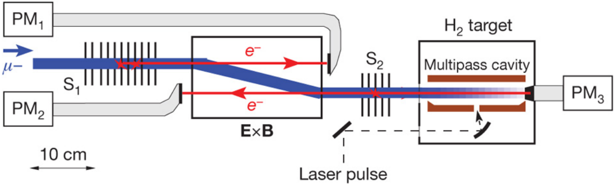


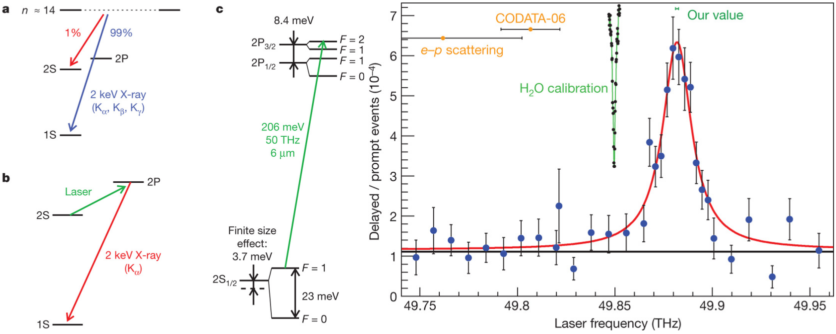
- *q* tests, how the photon couples to the nucleus.
- A small increase of the cross section is seen.
- ^{3}He(e, e′pp) showed a decrease.

press any key

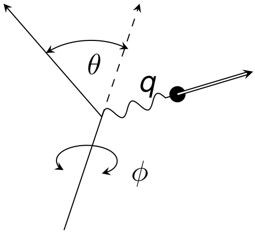
The radius puzzle – Lamb shift in μH

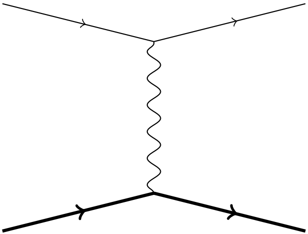
Nature **466**, 213-216 (8 July 2010)





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

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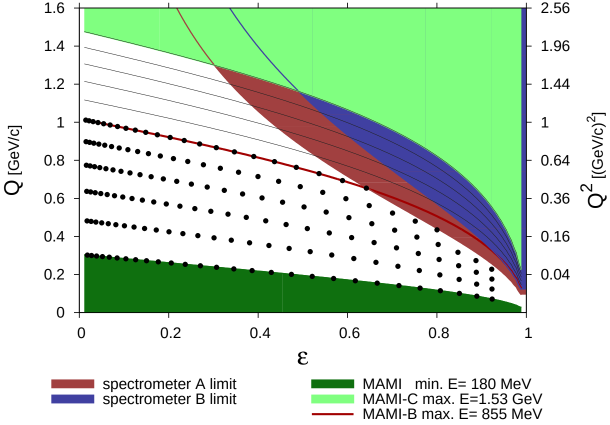

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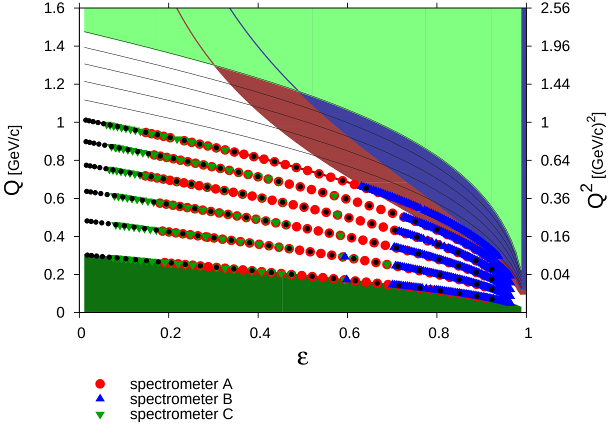
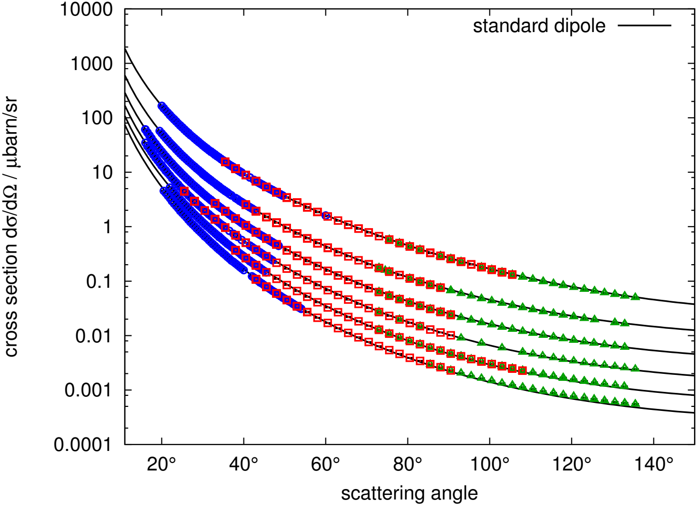
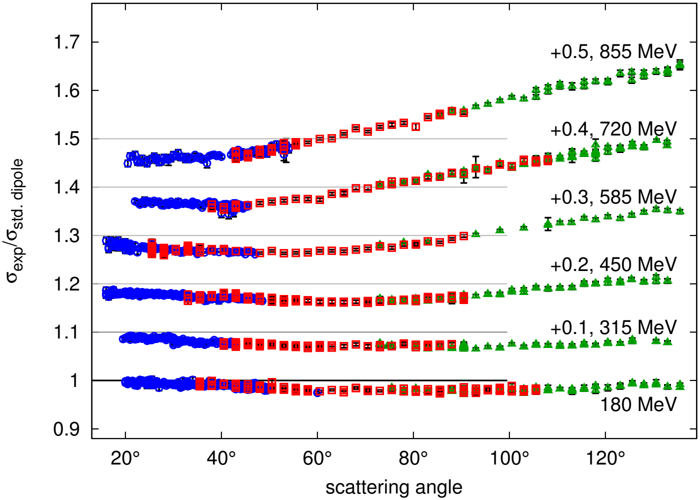


- ~90 GByte on disc
- ~1400 Settings
- $> 10^9$ events.

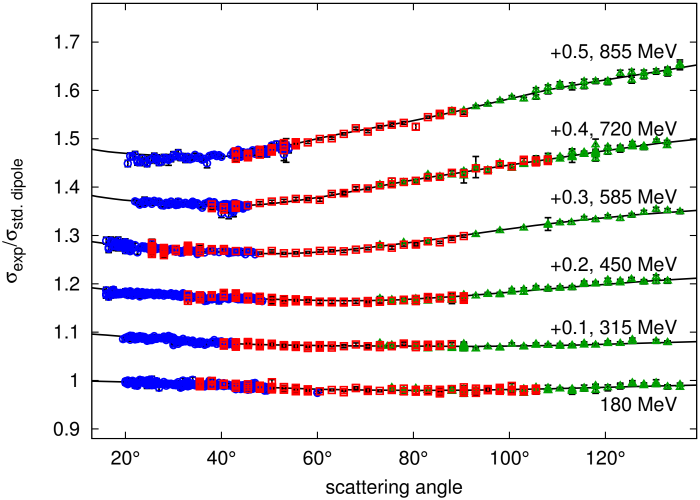
Cross sections



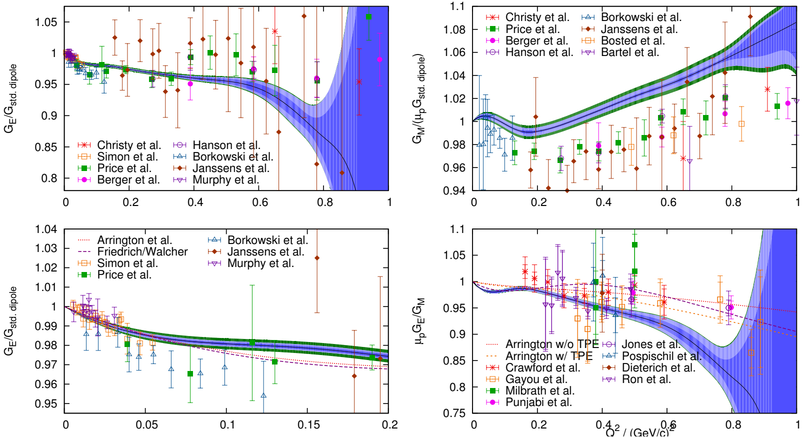
Cross sections / standard dipole



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)**
  $r_p = 0.84184(67)\,\text{fm}$
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Discrepancy is between
***muonic* and *electronic* measurements**

What could be wrong?

What could be wrong? or Is it “new” physics?

The muonic/electronic puzzle of the charge radius

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Akin to three standard deviations difference of magnetic moment of μ between experiment and theory?

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  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.
- **Contributions to the Lamb shift in μp**
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  U.D. Jentschura, Annals Phys. **326**, 500-515 (2011)
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still an unsolved problem

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Perturbative approximation for QED is not valid for bound system?

Some issues concerning the proton charge radius puzzle.

Thomas Walcher[1]

[1]*Institut für Kernphysik, Johannes Gutenberg-Universität Mainz, 55099 Mainz, Germany.*

(Dated: July 23, 2012)

An explanation of the difference of the charge radius of the proton as determined from the Lamb shift in electronic hydrogen and from elastic electron scattering off the proton on the one side and the recent high precision determination with muonic hydrogen on the other side is presented. It is shown that the modification of the $2S_{1/2}$ and $2P_{3/2}$ wave functions by the "Uehling potential" yields a correction to the theoretical Lamb shift of $\delta(\Delta E_{\mathrm{Lamb}}) = 0.302\,\mathrm{meV}$ which has to be compared to $\delta(\Delta E_{\mathrm{Lamb}}) = 0.322(46)\,\mathrm{meV}$ equivalent to the stated radius difference. The explanation is based on the realization that the bound state wave functions modified by the external "Uehling potential" have to be propagated by the vacuum polarization propagator in order to give the correct leading order Lamb shift. It is argued that a conflicting relativistic calculation neglects this propagation aspect. The explanation demonstrates that the Lamb shift is dynamically induced through the QED vacuum polarization and is not only the result of a static external "Uehling potential" probed by a test charge.

arXiv:1207.4901

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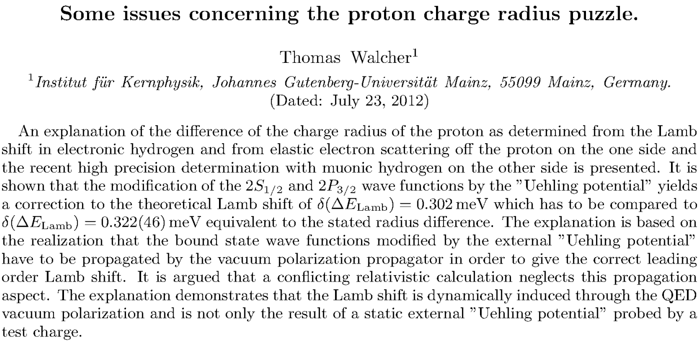
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Speculation about the discrepancy

- 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 ...

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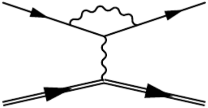
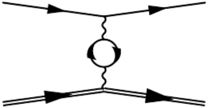
	'electronic' hydrogen	muonic hydrogen
		
vertex and self-energy	1011.41 MHz	
vacuum polarization	$-27.13\,\mathrm{MHz}$	$-205.028\,\mathrm{meV}$
anom. magn. moment	67.82 MHz	
+ higher order		
theoretical value	1057.864(14) MHz	$-206.057\,\mathrm{meV}$
experimental value	1057.862(20) MHz	Δ : 0.341 meV

Collaborative Research Centre 1044 (2012–)

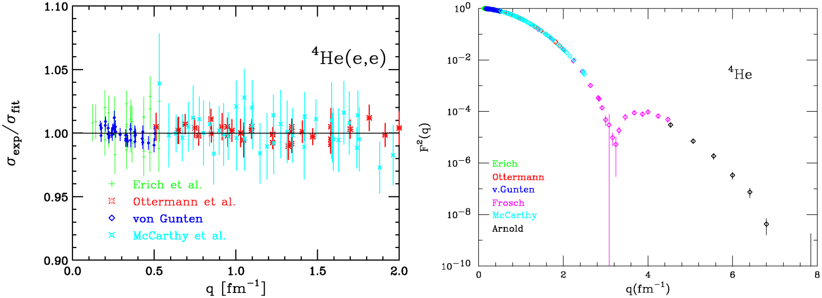
The Low-Energy Frontier of the Standard Model From Quarks and Gluons to Hadrons and Nuclei

Project N: Interactions in few-baryon systems

Helium-4

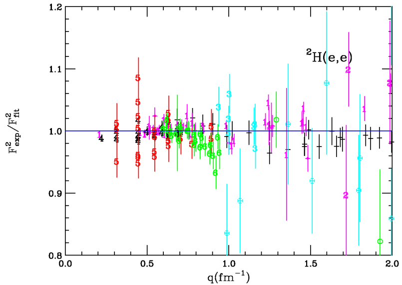
Interest

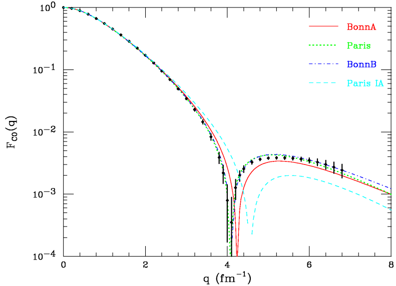
- precise isotope shifts available up to ^{8}He.
- candidate for μHe Lamb shift measurement
- candidate for measurement with ^{4}He$^+$

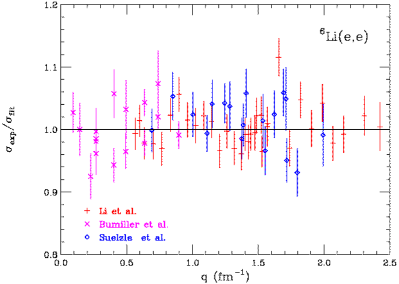


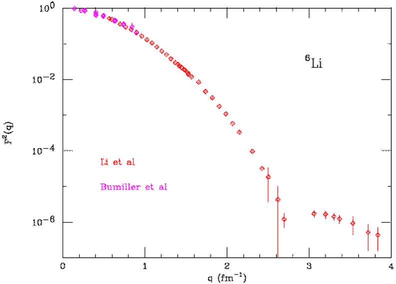
Ingo Sick, PSAS 2012

Hydrogen-2 and Lithium-6

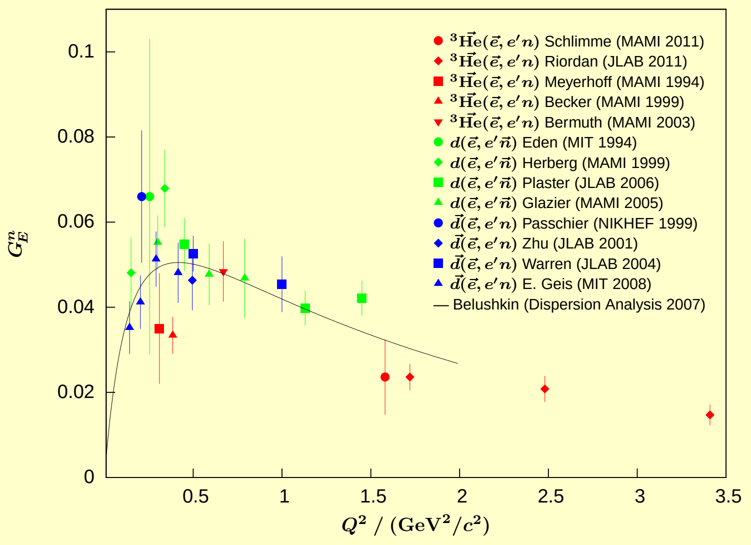






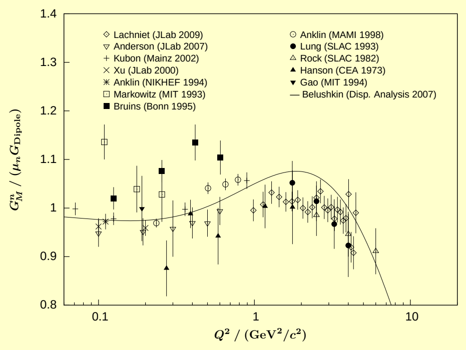


Electric form factor of the neutron: G_{en}



Only double polarization measurements!

Magnetic form factor of the neutron

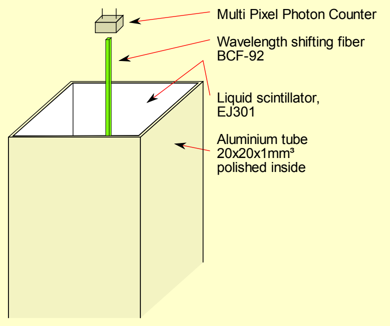


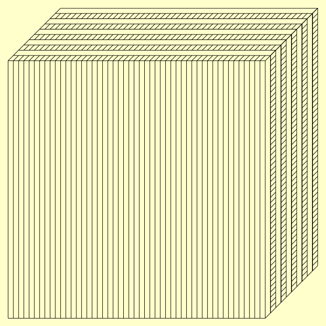
- Discrepancy BLAST $\leftrightarrow$ CLAS
- Data consistency
- Observable: $R = \frac{^2H(e,e'n)p}{^2H(e,e'p)n}$
- Normalization of neutron detector
  - *In situ* calibration (background, count rate, n-momentum)
  - Continuous monitoring of efficiency

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

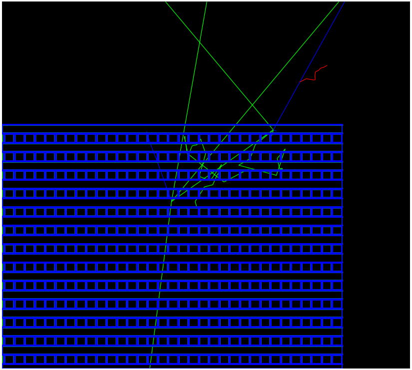




- Aim: Costs per module ≈200€
- Block: ≈1 m^3 ⇒ 48×48 Modules
- Segmenting improved ≈ 10×
- Closer to target with same ToF-resolution

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

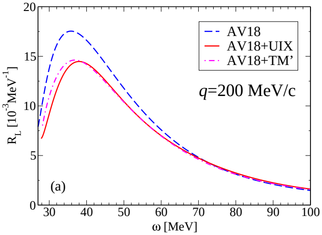
Simulation (Geant4)



- 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
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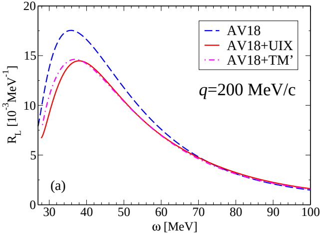

- Lorentz integral transform
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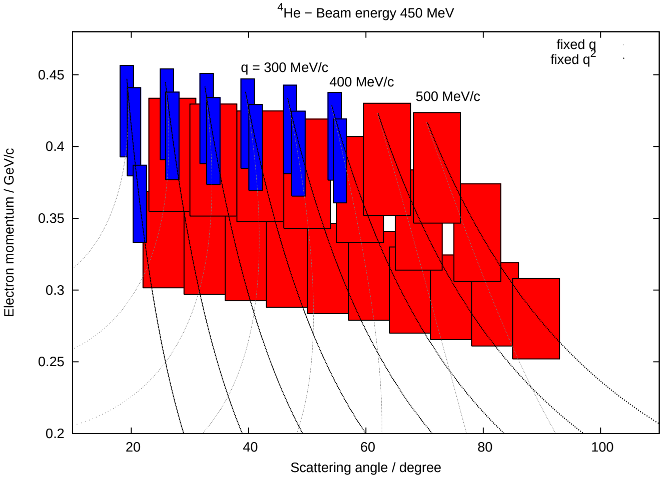
Inclusive measurement ^{3,4}He(e, e') in 2009.

- 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?

PRISMA

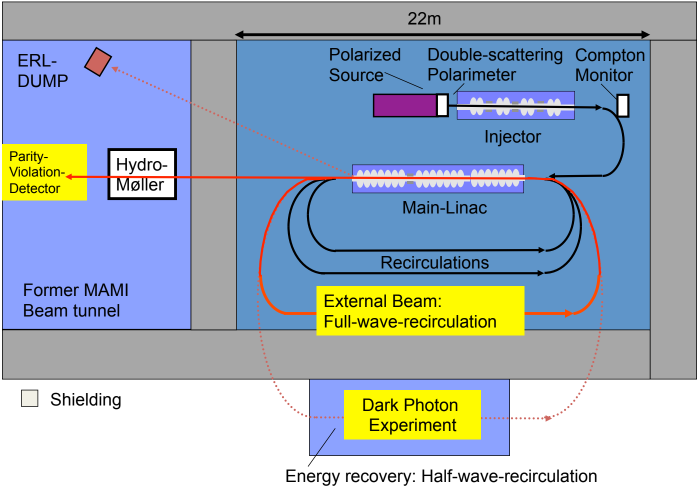
Johannes Gutenberg University Mainz:
Precision Physics, Fundamental Interactions and Structure of Matter (PRISMA)

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 $\Rightarrow L = 10^{35}\text{s}^{-1}\text{cm}^{-2}$ with internal hydrogen target

Summary

Experiments on few-nucleon systems at MAMI

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

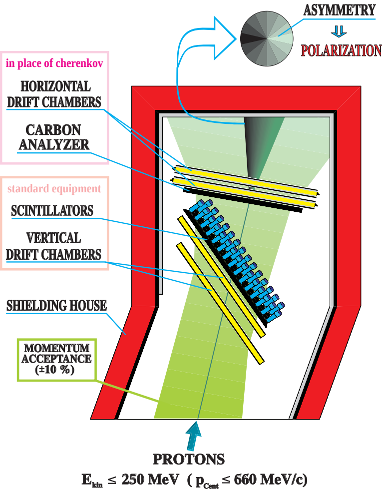
- Extensive program to measure nucleon form factors
- Nuclear structure of ^3He
- Correlations in ^3He

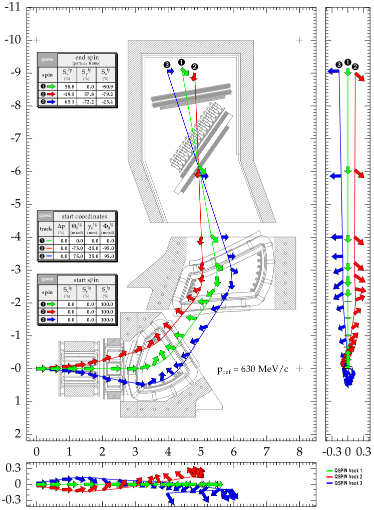
Plans for the future

- 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)

press any key

The focal plane proton polarimeter

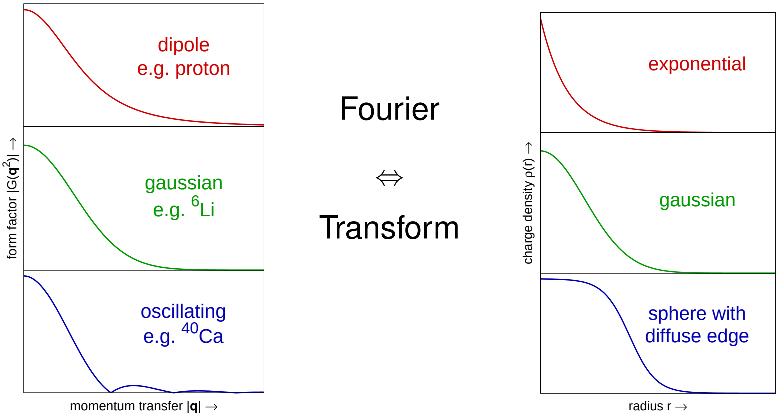




T. Pospischil et al., *The focal plane proton polarimeter for the three spectrometer setup at MAMI*, NIM A483 (2002) 713

Classical picture

form factor: $G(q^2) = \frac{1}{e} \int_0^\infty \rho(r) \frac{\sin qr}{qr} 4\pi r^2 \, dr$



charge distribution: $\rho(r) = \frac{e}{(2\pi)^3} \int_0^\infty G(q^2) \frac{\sin qr}{qr} 4\pi q^2 \, dq$