The MAMI Electron Scattering Program

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A1 Collaboration
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Workshop on Electron-Nucleus Scattering XIV
June 27-July 1, 2016 | Marciana Marina, Isola d'Elba

Mainz Microtron (MAMI) - Electron Accelerator

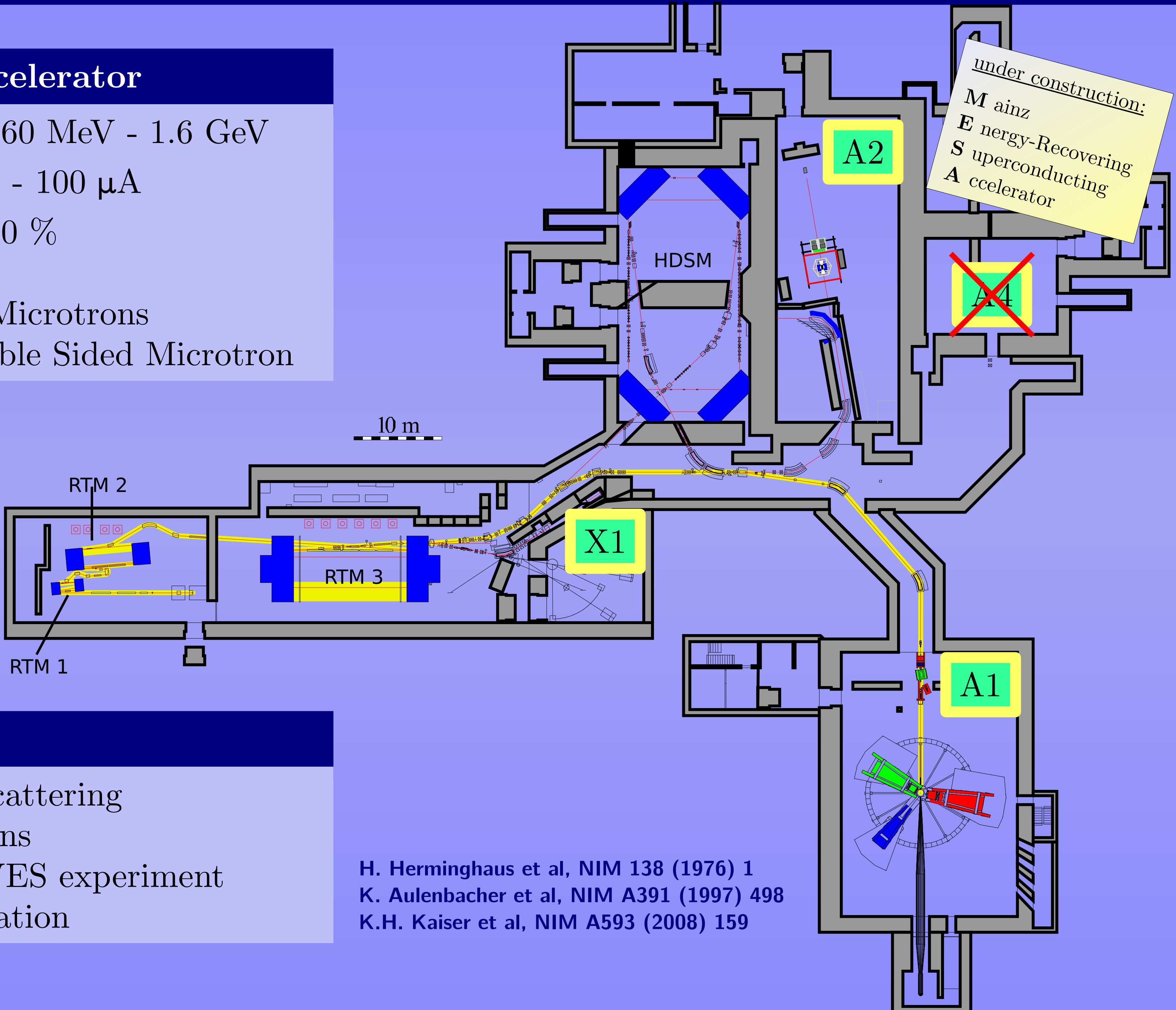
Komitee für Beschleunigerphysik KfB | www.beschleunigerphysik.de (2016)

Mainz Microtron

cw electron accelerator

- E_{beam}: 160 MeV - 1.6 GeV
- I_{beam}: 0 - 100 μA
- Polarization: 80 %

- 3 Race Track Microtrons
- Harmonic Double Sided Microtron

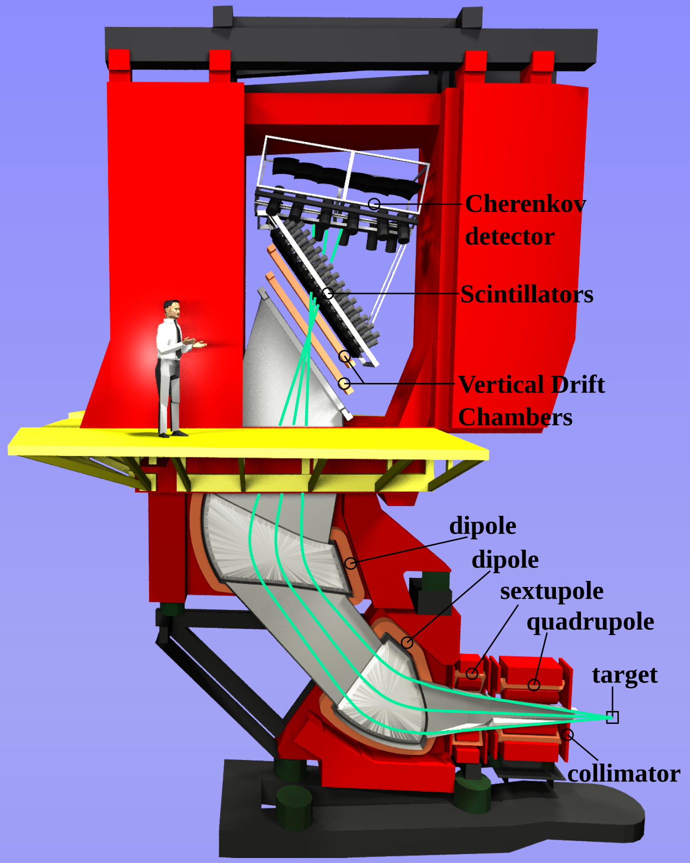


experiments

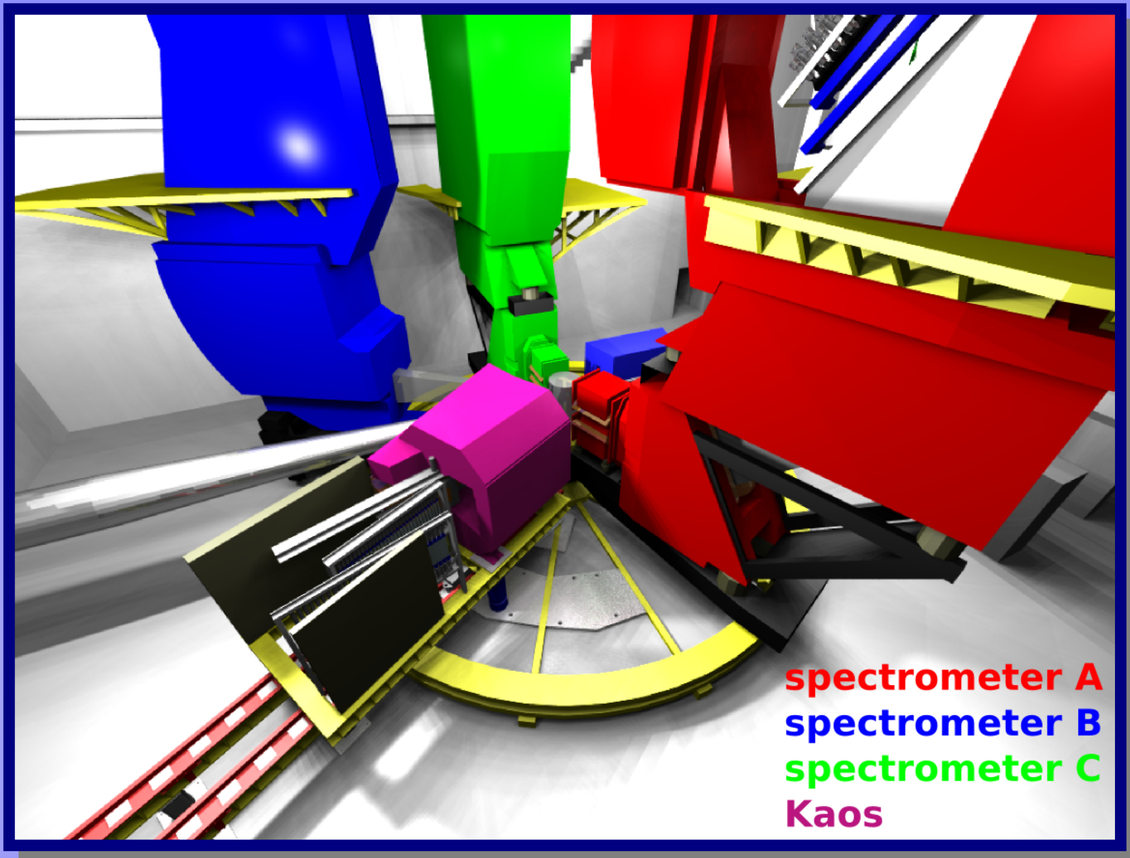
- A1: electron scattering
- A2: real photons
- A4: former PVES experiment
- X1: x-ray radiation

H. Herminghaus et al, NIM 138 (1976) 1
K. Aulenbacher et al, NIM A391 (1997) 498
K.H. Kaiser et al, NIM A593 (2008) 159

The A1 Setup



"Three-spectrometer facility"



	A	B	C	KAOS	SOS
magnets	QSDD	D	QSDD	D	D
$\Delta\Omega$ [msr]	28	5.6	28	10.4	4.8
ang. res [mrad]	<3	<3	<3	<3	1.3; 11
$p_{\max}$ [MeV/c]	735	870	551	1800	163
$\Delta p/p$	20%	15%	25%	50%	21%
$\delta p/p$	10^{-4}	10^{-4}	10^{-4}	10^{-3}	10^{-3}

additional detector systems

- kaon spectrometer (KAOS)
- pion spectrometer (SOS)
- neutron detectors
- hadron detector
- Si detector
- ...

specialities:

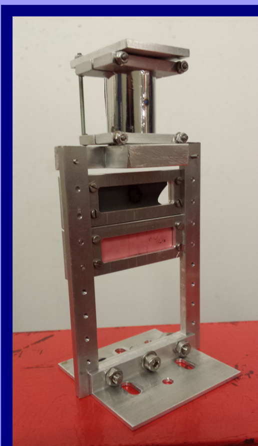
specA: proton polarimeter
specB: out of plane

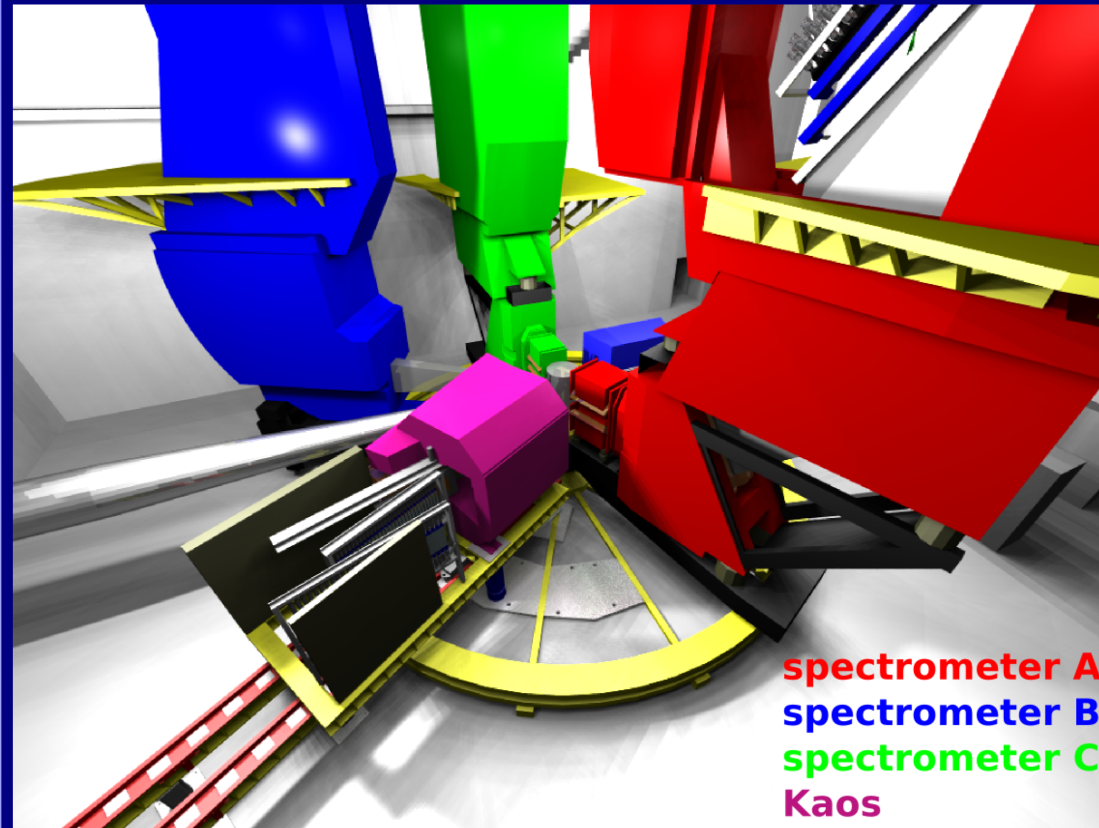
KAOS: 0°; double arm
SOS: 1.5m min. flight path

The A1 Setup

available targets

- solid state targets
  - carbon
  - tantalum
  - tungsten
  - plastic
  - ...
- liquid targets
  - hydrogen
  - deuterium
  - waterfall
- gas targets
  - helium-3
  - helium-4
  - ...





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Proton Charge Radius

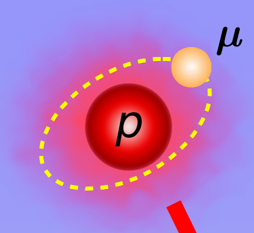
Proton radius problem

- Proton charge radius: important to atomic, nuclear, and particle physics
- discrepancy of radius measurement

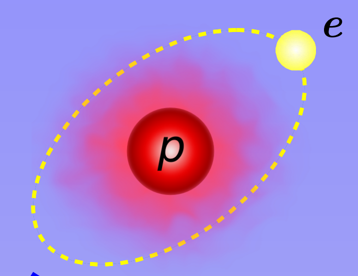
Active field

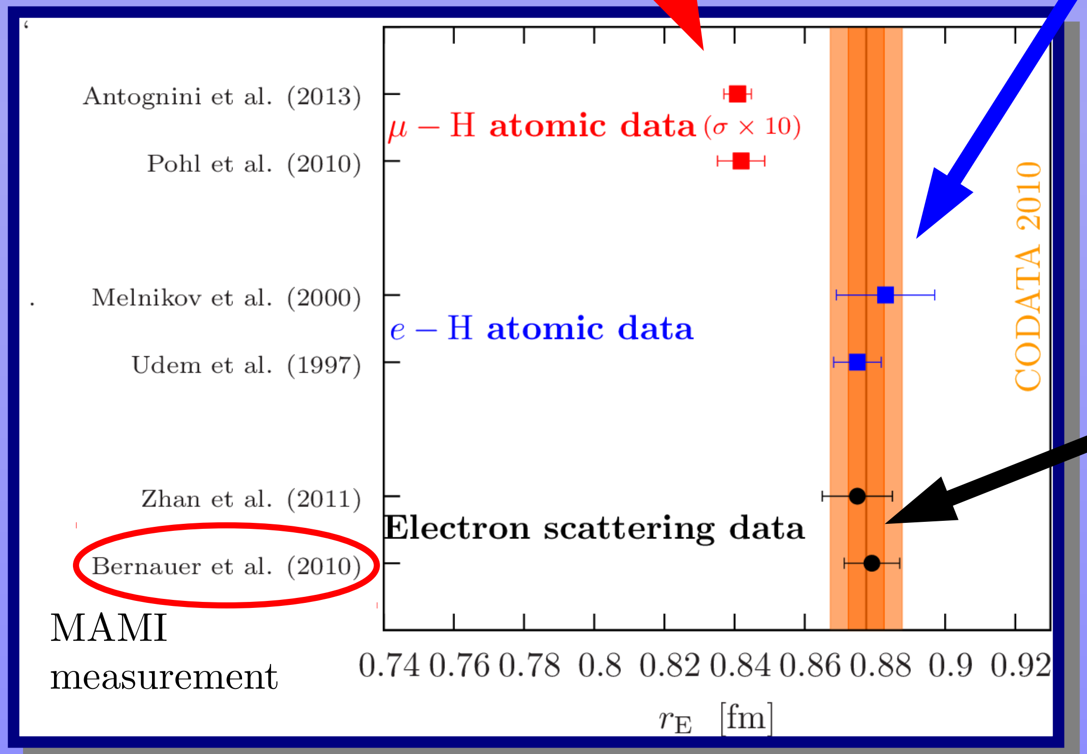
- reanalyses
- missing corrections?
- new physics?
- new e-H atomic data
- new scattering data
  - lower Q^2
  - muons (MUSE)
- (muonic) radii of other light nuclei

muonic hydrogen spectroscopy

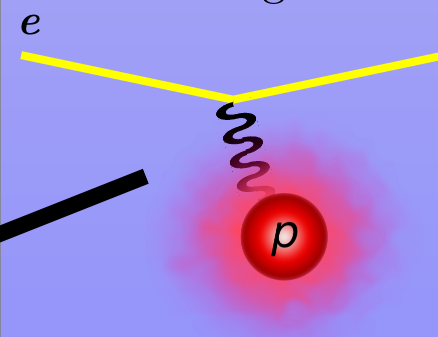


electronic hydrogen spectroscopy





electron-proton scattering



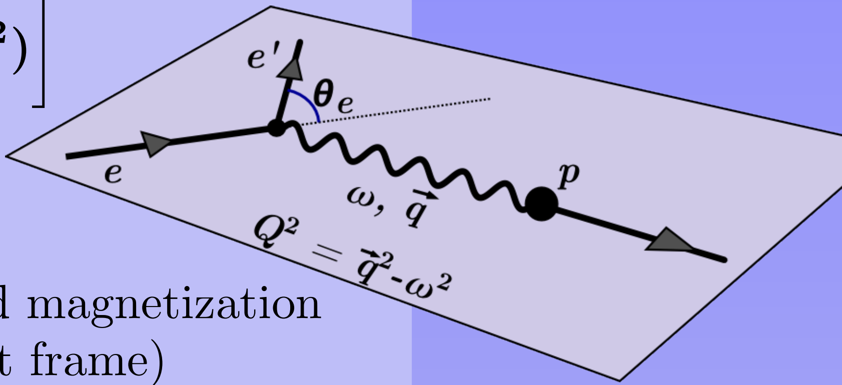
Proton Form Factors

elastic electron-proton scattering

- Cross section:

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

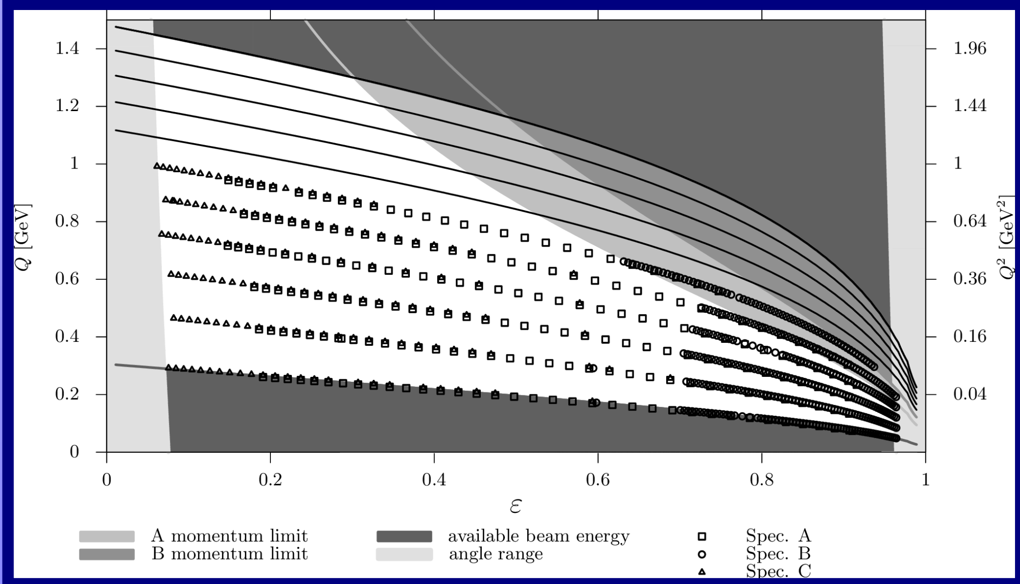
with $\tau = \frac{Q^2}{4m_p}, \qquad \frac{1}{\varepsilon} = 1 + 2(1+\tau)\tan^2\frac{\theta_e}{2}$



- Fourier-transform of G_E, G_M → spatial charge and magnetization distribution (Breit frame)
- disentangle G_E, G_M via Rosenbluth separation (varying ε)
- radius from slope: $\langle r_E^2 \rangle = -6\hbar^2 \left.\frac{\mathrm{d}G_E}{\mathrm{d}Q^2}\right|_{Q^2=0}$

Previous MAMI measurement

- around 1400 cross section measurements
- Q^2: 0.004 to 1 GeV^2
- published 2010



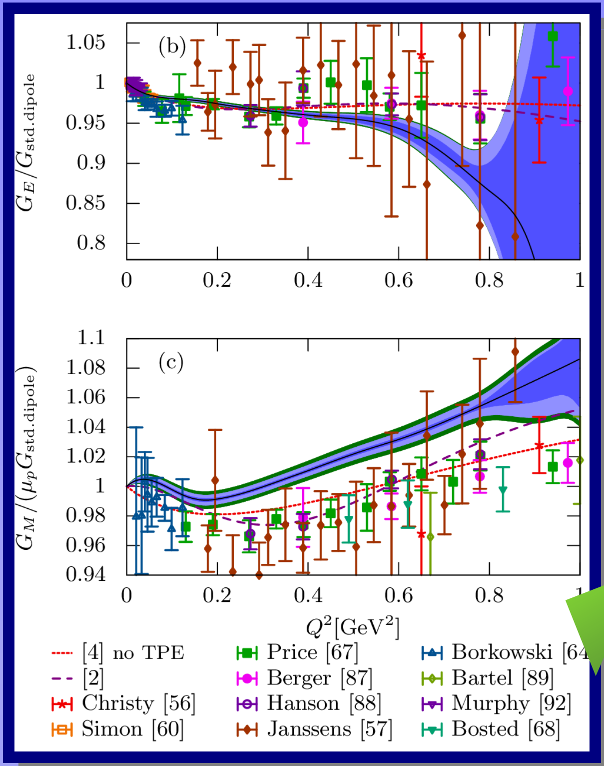
Proton Form Factors

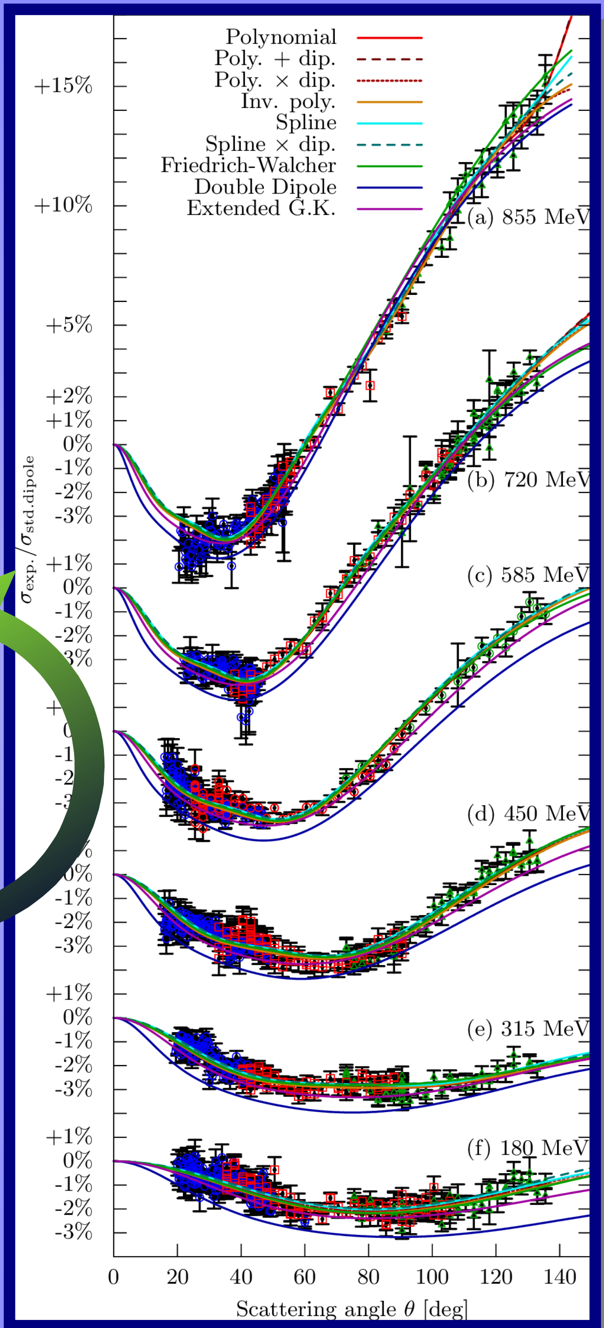
Form factor determination

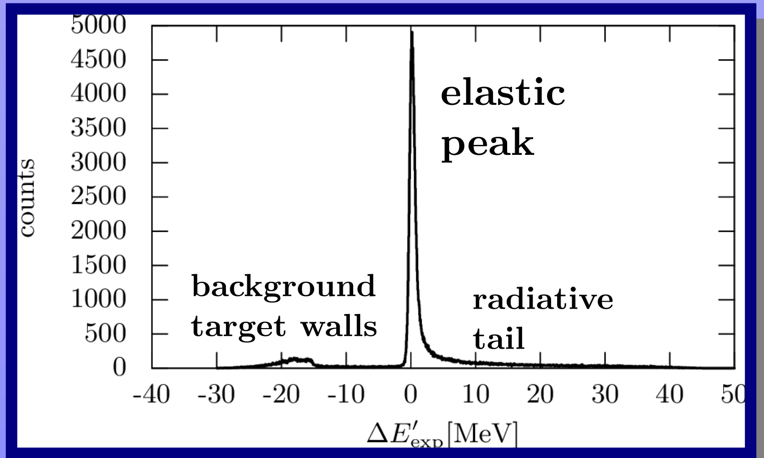
(1) measure elastic spectrum
(2) subtract background
(3) compare to simulation
(4) fit cross sections using appropriate form factor model(s)
(5) (determine radius from slope)

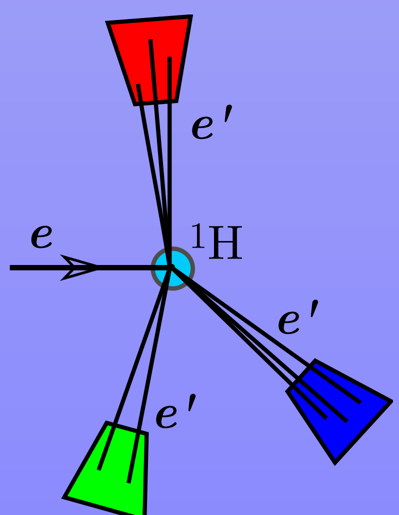
Extend Q2 range

- large Q^2: similar measurements, higher beam energies
- smaller Q^2: novel technique: ISR









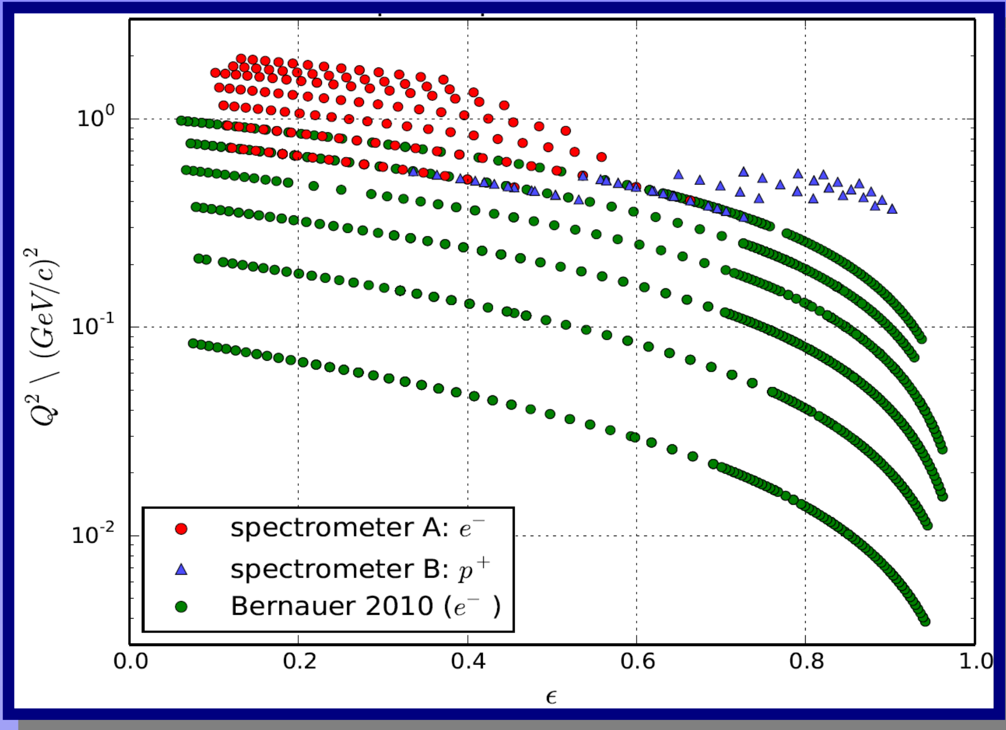
$\Delta E'$: measured - expected(elastic) electron energy

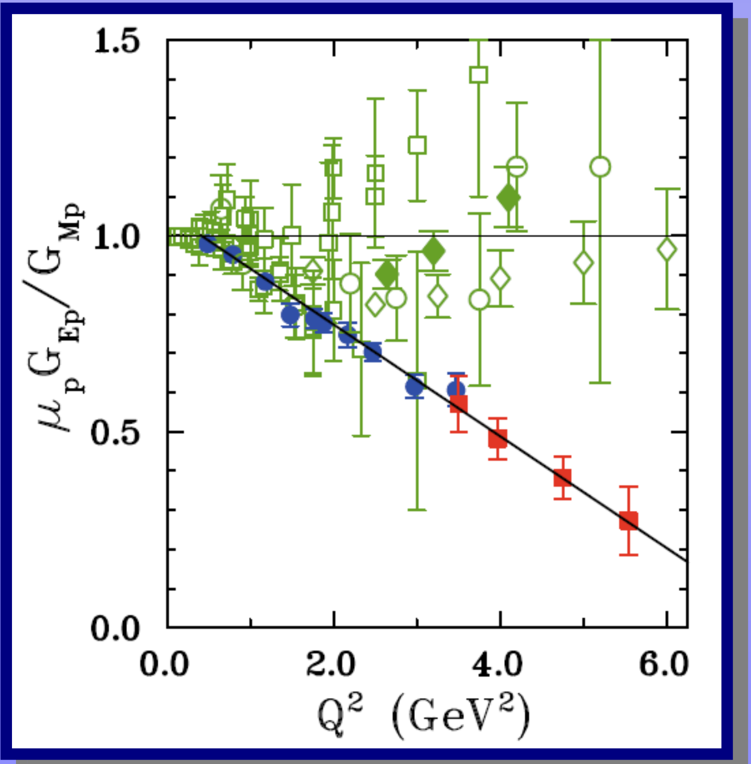
[J. C. Bernauer et al., Phys. Rev. C 90, 015206 (2014)]

Proton Form Factors: Q^2 range 0.5 to 2 GeV^2

Extend electron-proton settings

- Similar measurements at higher Q^2 (MAMI-C energies)
- Overlap with previous measurements
- Stat. error 0.2%
- G_M predominates
- Testwise: also H(e,p)



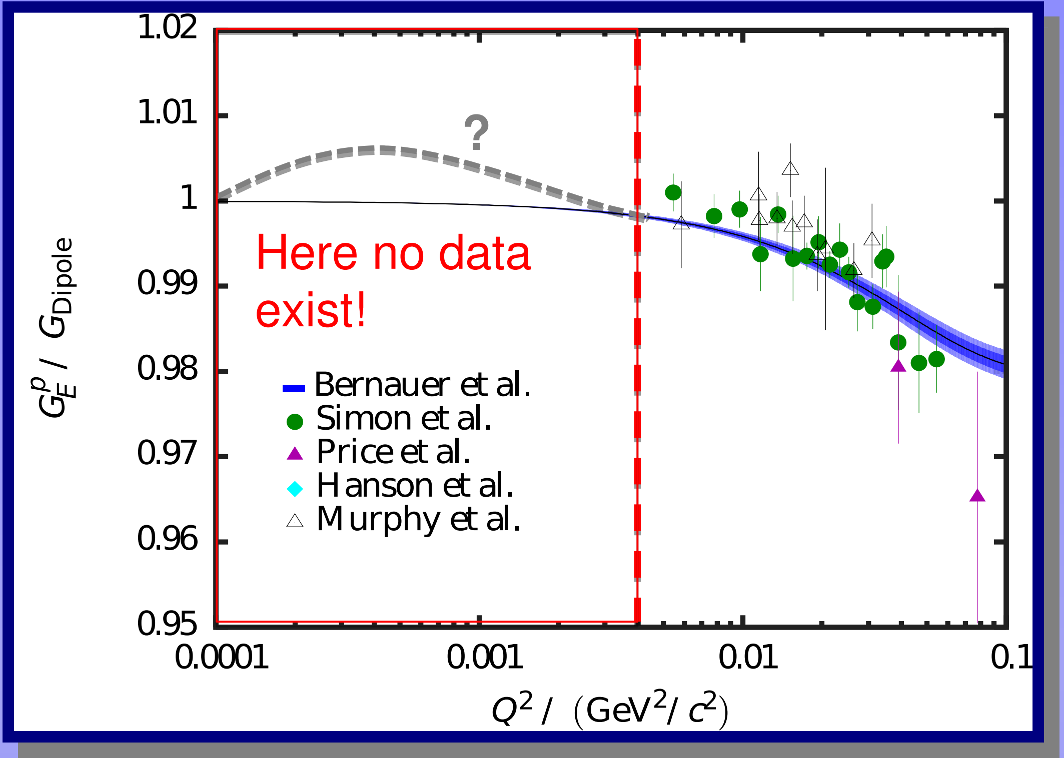


V. Punjabi et al, EPJ A (2015) 51

Will not resolve radius puzzle, but

- G_E/G_M: unpolarized vs. polarized data: test of radiative corrections
- discrepancy!
  - Two Photon Exchange? likely source of at least part of it
    - theoretical work ongoing
    - dedicated data, e.g. OLYMPUS
    - provide precise unpolarized data at Q^2=0.5 .. 2 GeV^2

Proton Form Factors: low Q^2



Low Q2 e-p experiments

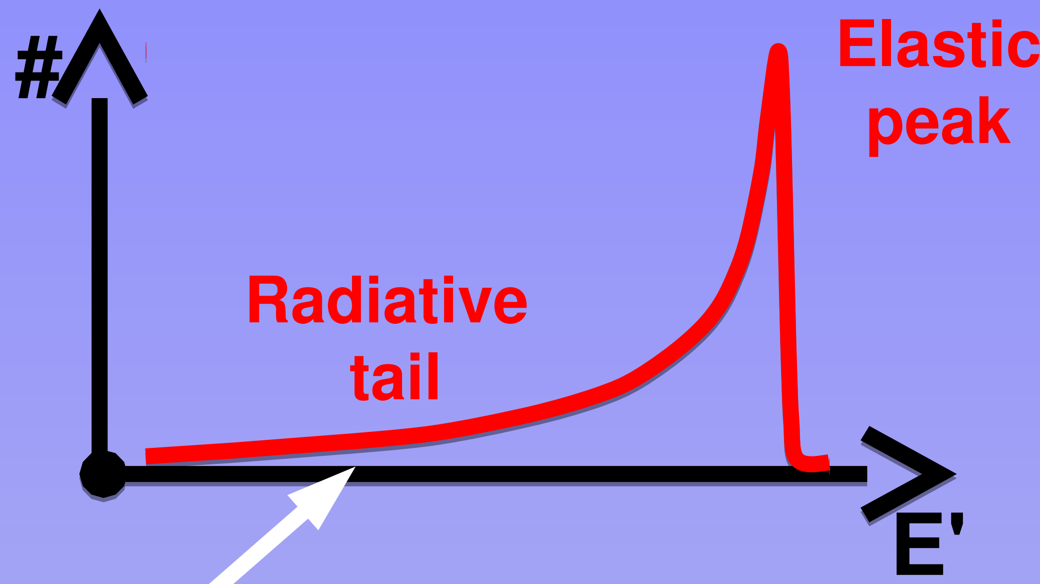
$$\langle r_E^2 \rangle = -6\hbar^2 \left. \frac{\mathrm{d}G_E}{\mathrm{d}Q^2} \right|_{Q^2=0}$$

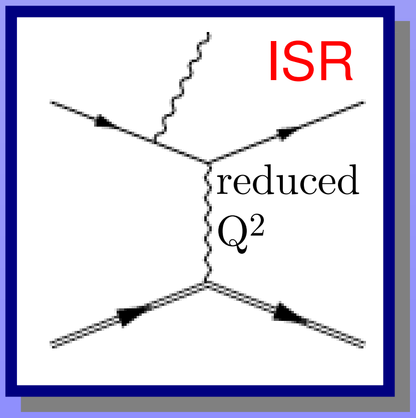
- Region of $Q^2 < 0.004$ GeV^2 extremely hard to reach
- For precise radius determination new measurements at even lower Q^2
  - PRAD (JLab)
    - low scattering angles -
  - **Initial State Radiation (MAMI)**
    - novel technique -

Initial State Radiation

Exploit information in radiative tail

- ISR:
  photon radiation takes energy out of electron → access to lower Q^2 at given scattering angle
- Allows investigating G_E at Q^2 down to 10^{-4} GeV^2
- Sophisticated simulation needed (FSR, ...)





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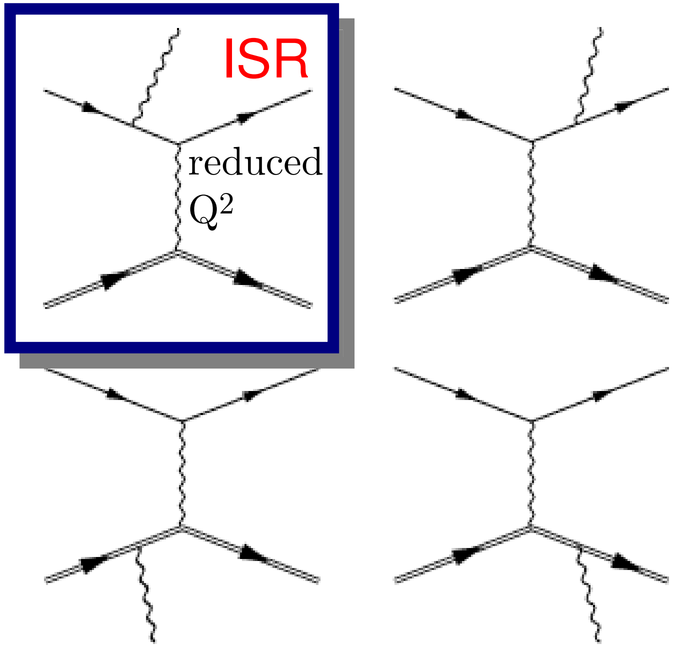
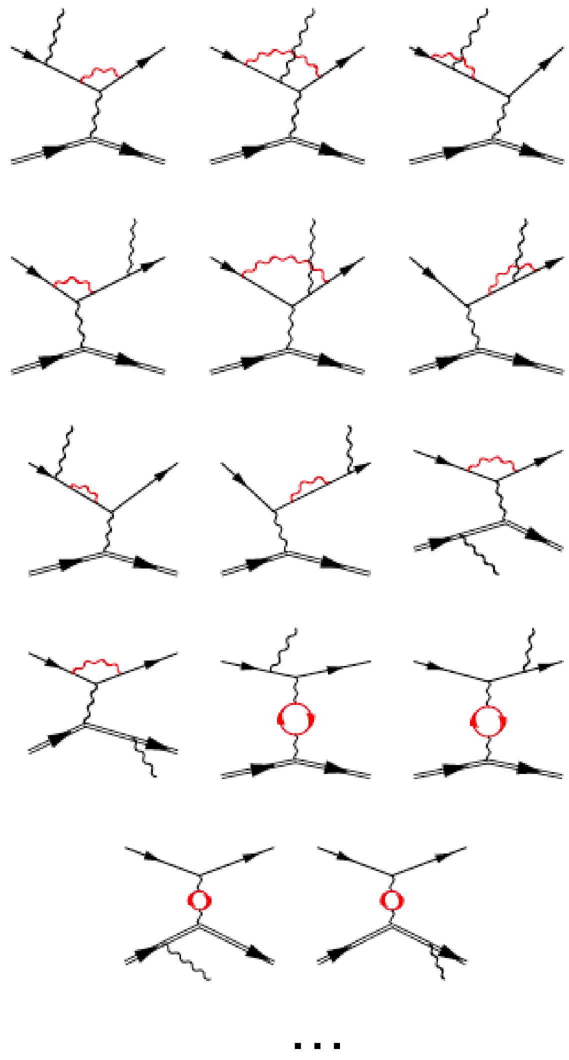


Exact calculation of LO diagrams



NLO virtual and real corrections included via effective corrections to cross-section

Initial State Radiation

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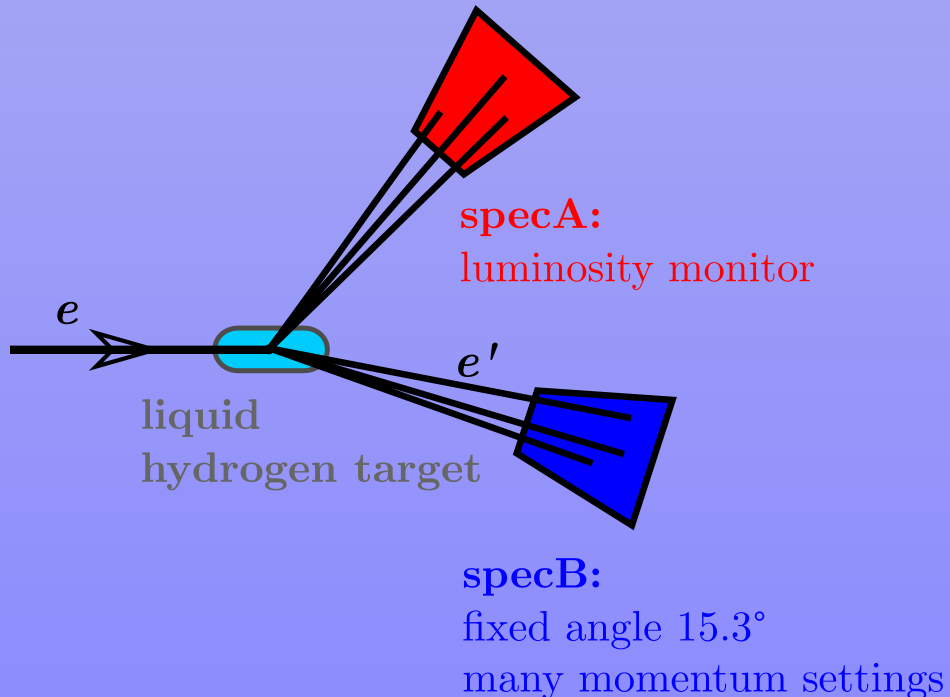
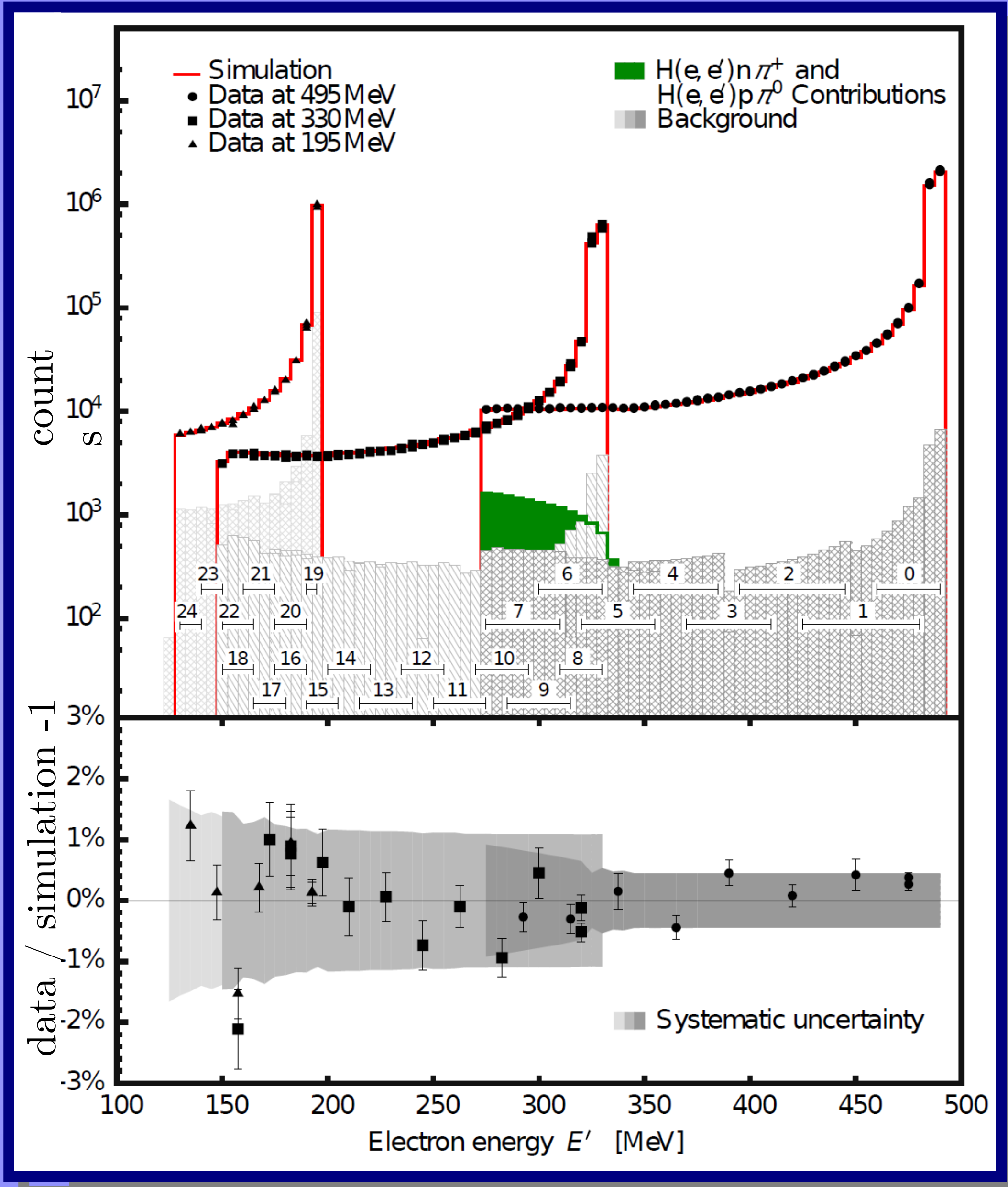
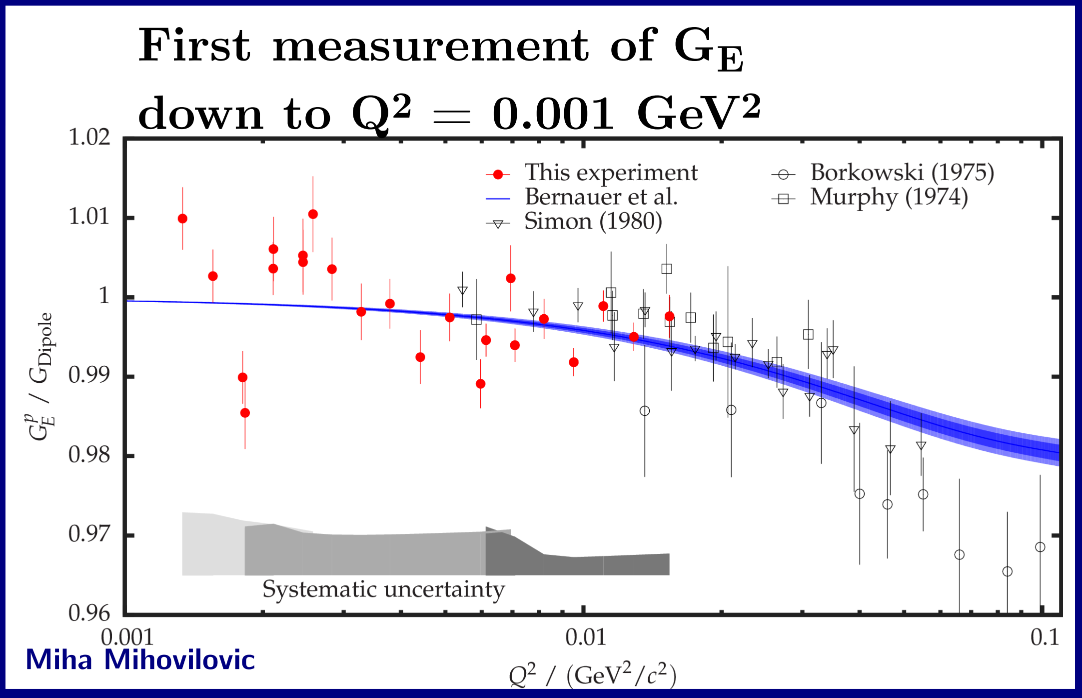




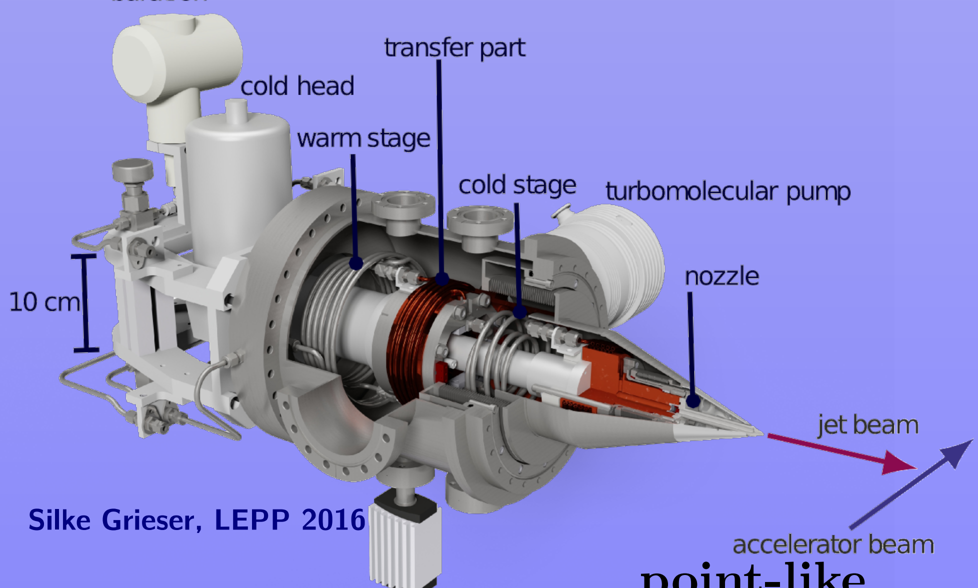
Initial State Radiation Experiment



planned improvements

- reduce background targetwalls
- reduce secondary scattering
  - target frame
  - spectrometer entrance structure

→ borrow (cluster) jet target of planned MAGIX experiment at MESA

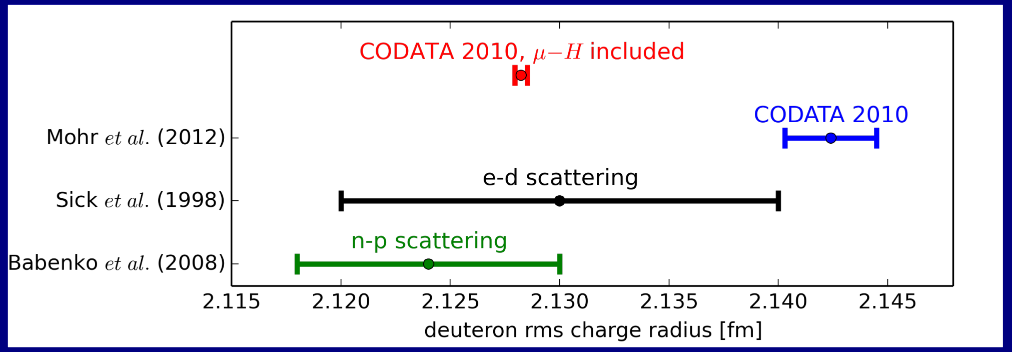


point-like
no walls

Deuteron Charge Form Factor

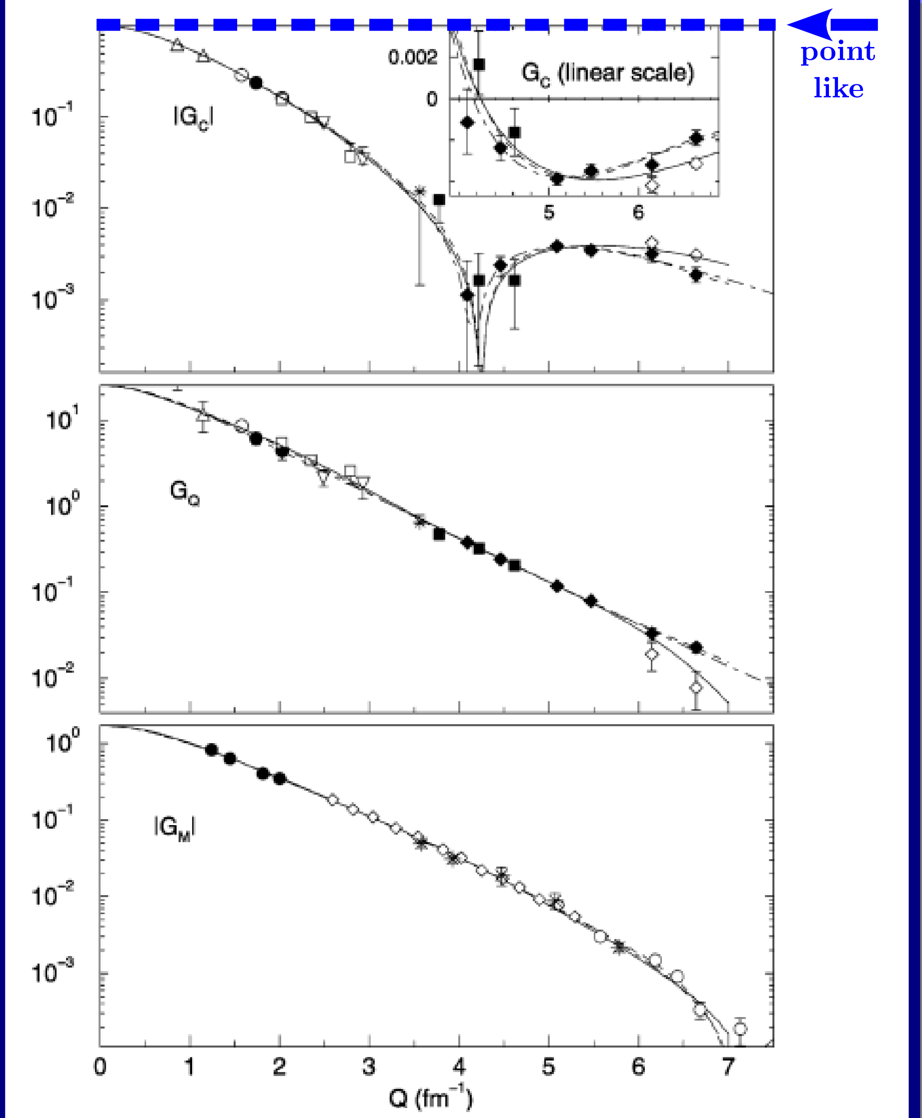
determination d-radius in e-d scattering

- proton radius puzzle → deuteron radius
  - radius measurement μD (CREMA)
  - improve e-d scattering result



MAMI e-d measurement

- elastic e-d scattering
- 3 e.m. form factors: G_C, G_Q, G_M
- low Q2
  - charge form factor predominates
  - extract deuteron radius



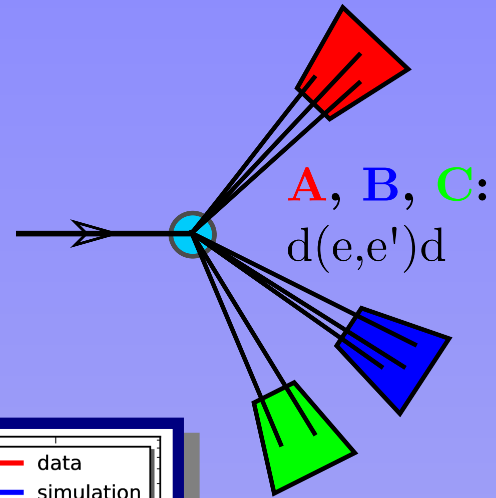
D.Abbott et al, EPJ A 7 (2000) 421

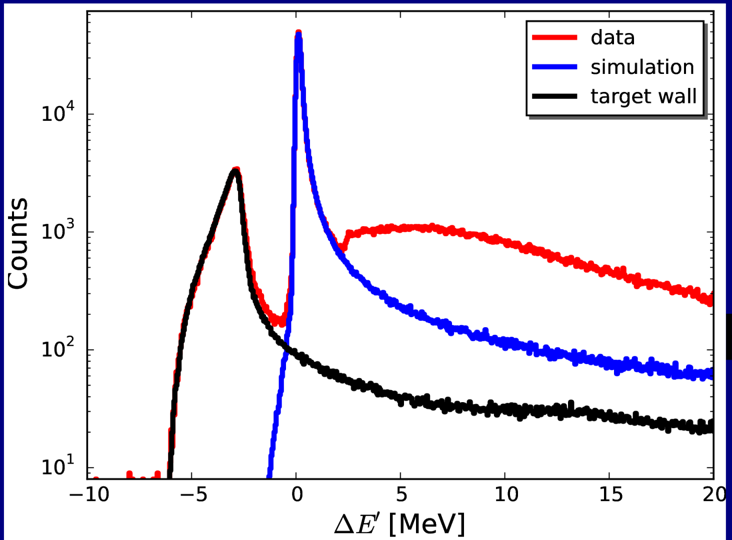
$$\langle r^2 \rangle = -6\hbar^2 \left. \frac{dG_C}{dQ^2} \right|_{Q^2=0}$$

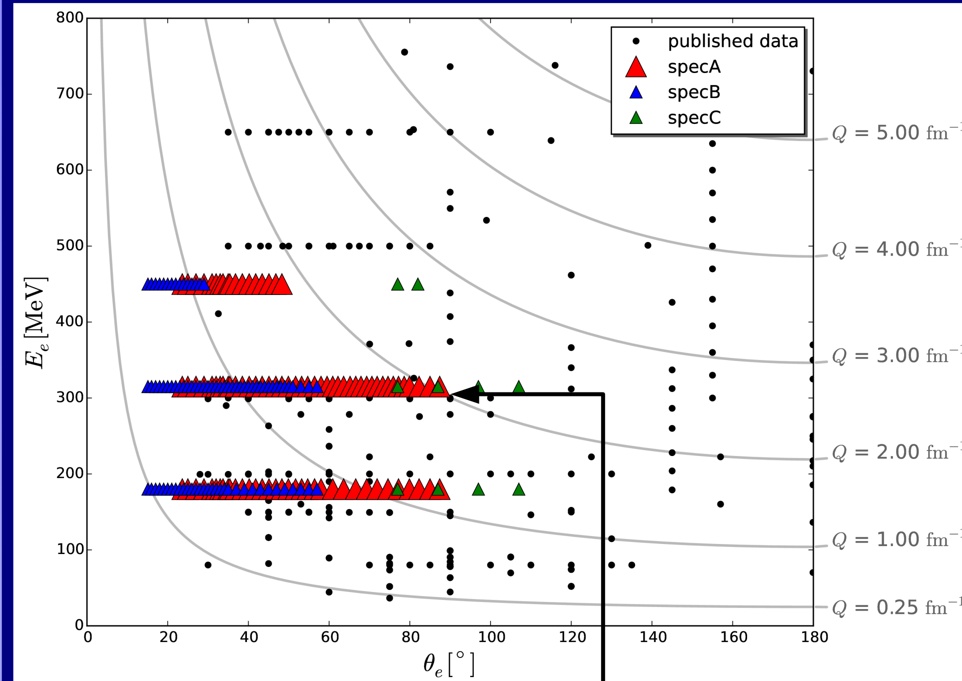
Deuteron Charge Form Factor

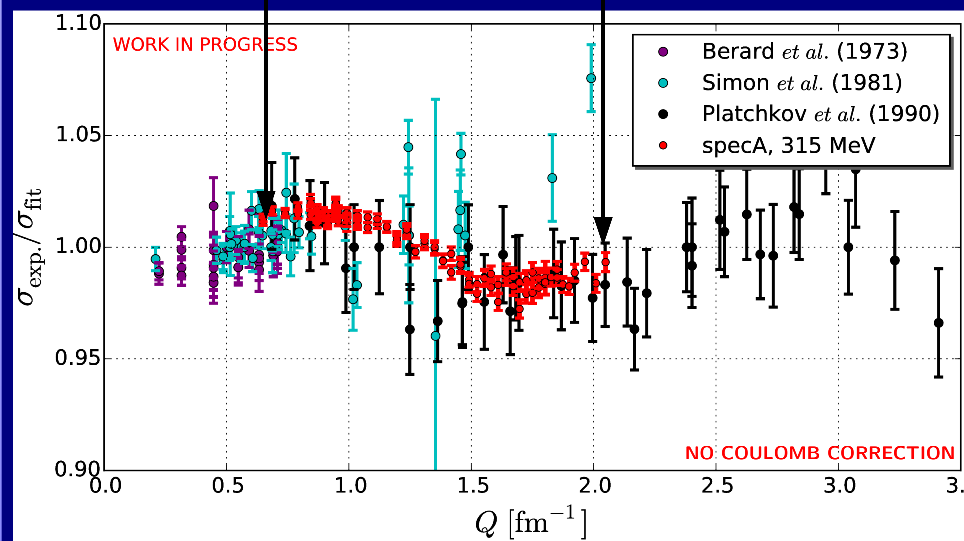
MAMI d(e,e')d measurement

- 200 settings
- high redundancy
- down to $Q^2 = 0.0022\ GeV^2$









follow-up experiments

- precise study of *d*-breakup reaction
  - deuteron polarizability
- similar ^{3}He form factor measurements
  - μ-He was also measured

Few-Baryon Systems

Basic picture of nucleus

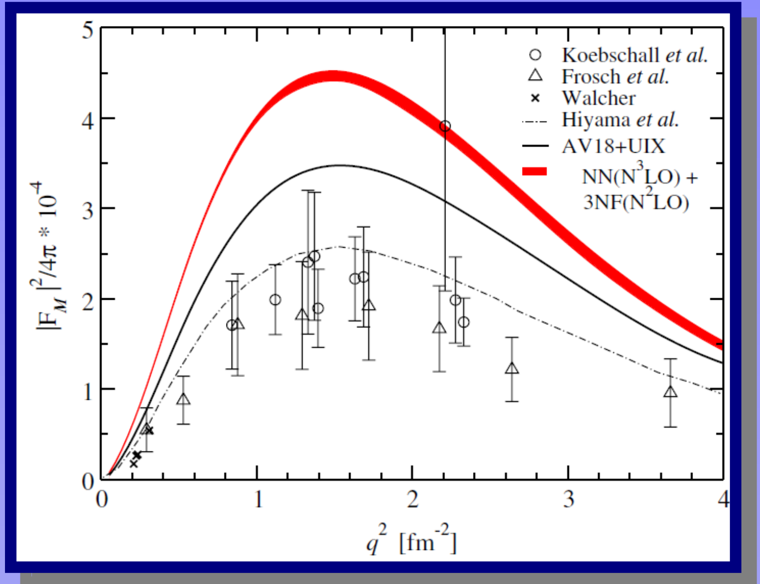
- Non-relativistic system of nucleons
  - interacting via known NN force
  - non-nucleonic d.o.f? rel. effects? ...

Testing nuclear forces

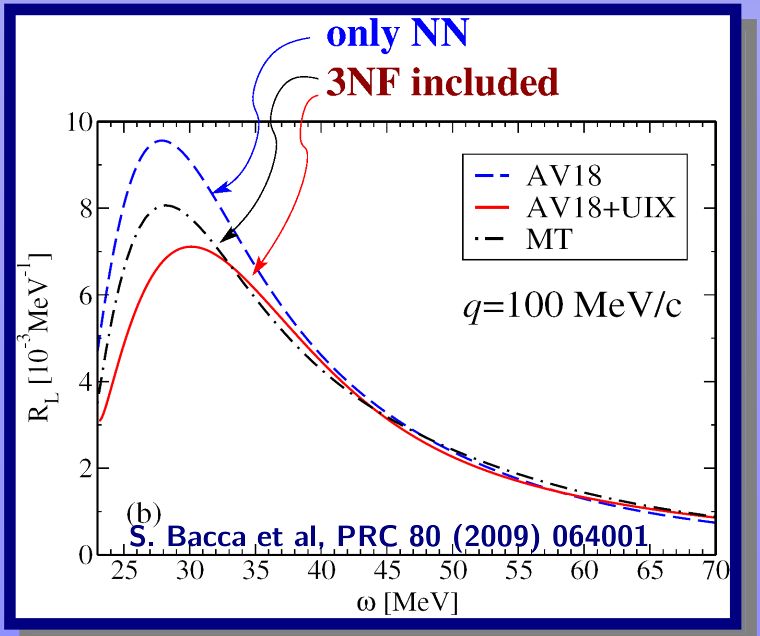
- models/theory/potentials
  should reproduce basic quantities
- NN
  - binding energies, deuteron radius, ...
  - precise NN potentials available
- 3N forces (naturally enter in EFT)
  - ^{3}H, ^{3}He, ...

Observables to test 3NF

- binding energies, ...
- excitation of light nuclei with e.m. probes
  - ^{4}He transition form factor to resonant state 0^+
  - inclusive measurements ^{3}He, ^{4}He
  - inclusive measurements Lithium

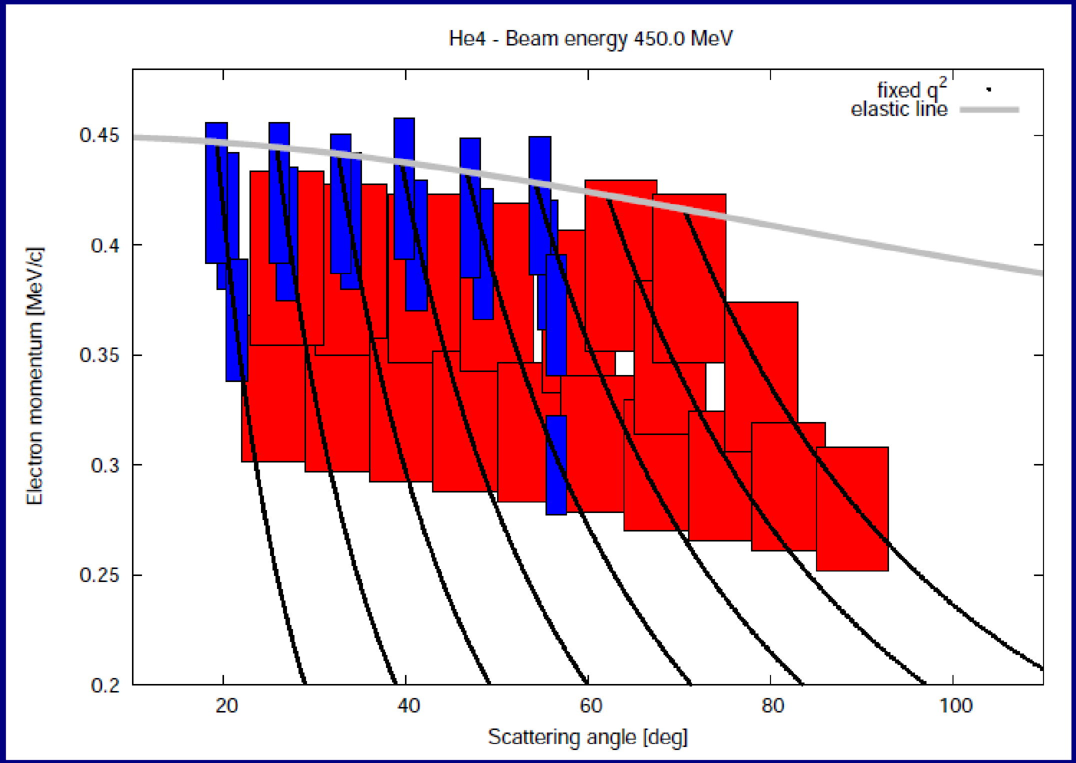


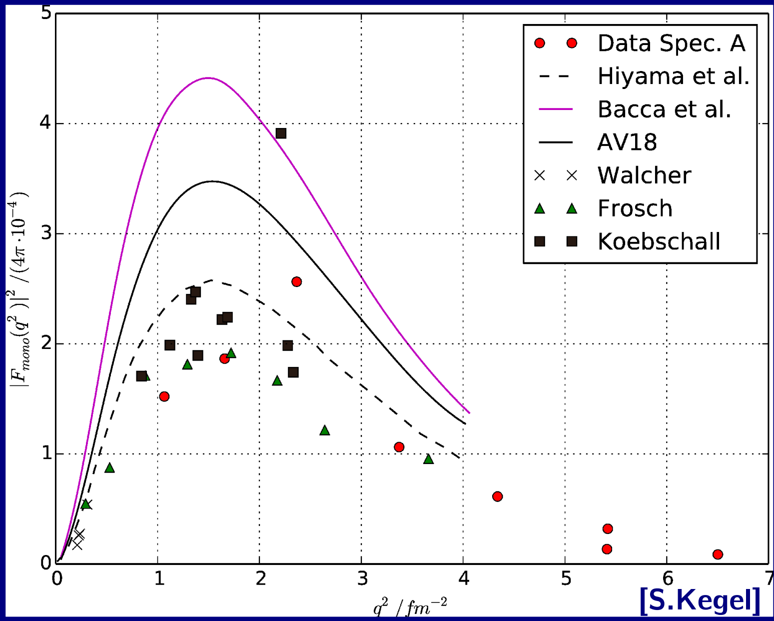
S. Bacca et al, PRL 110 (2013) 042503 (2013)

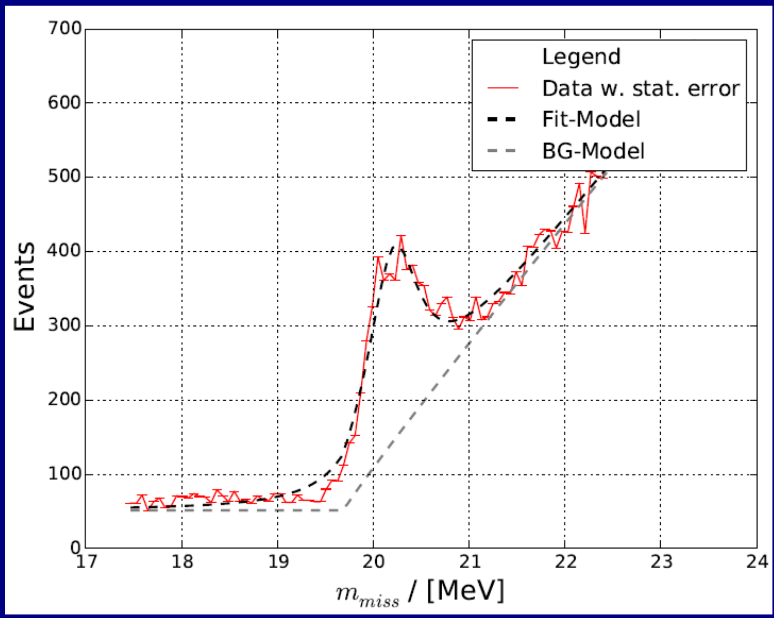


Ab initio calculations (LIT) for longitudinal response function $e + {}^4\text{He} \to e' + X$

Few-Baryon Systems







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  - inclusive measurements ^{3}He, ^{4}He
  - inclusive measurements Lithium

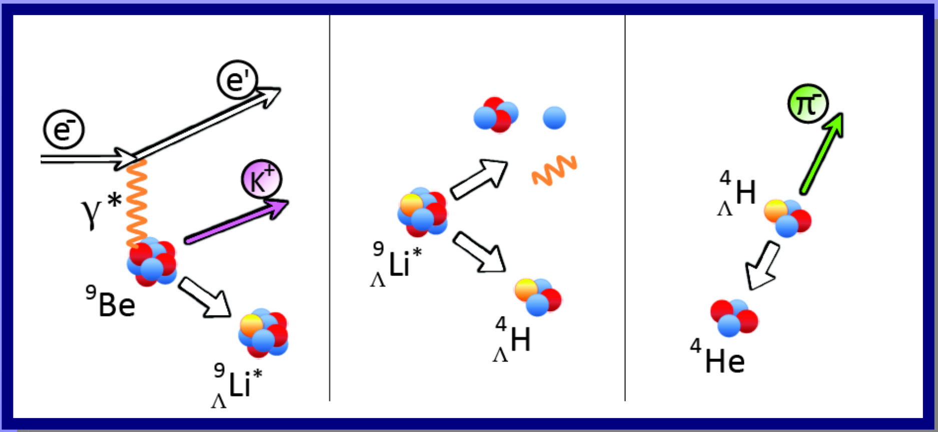
Few-Baryon Systems: Hypernuclei

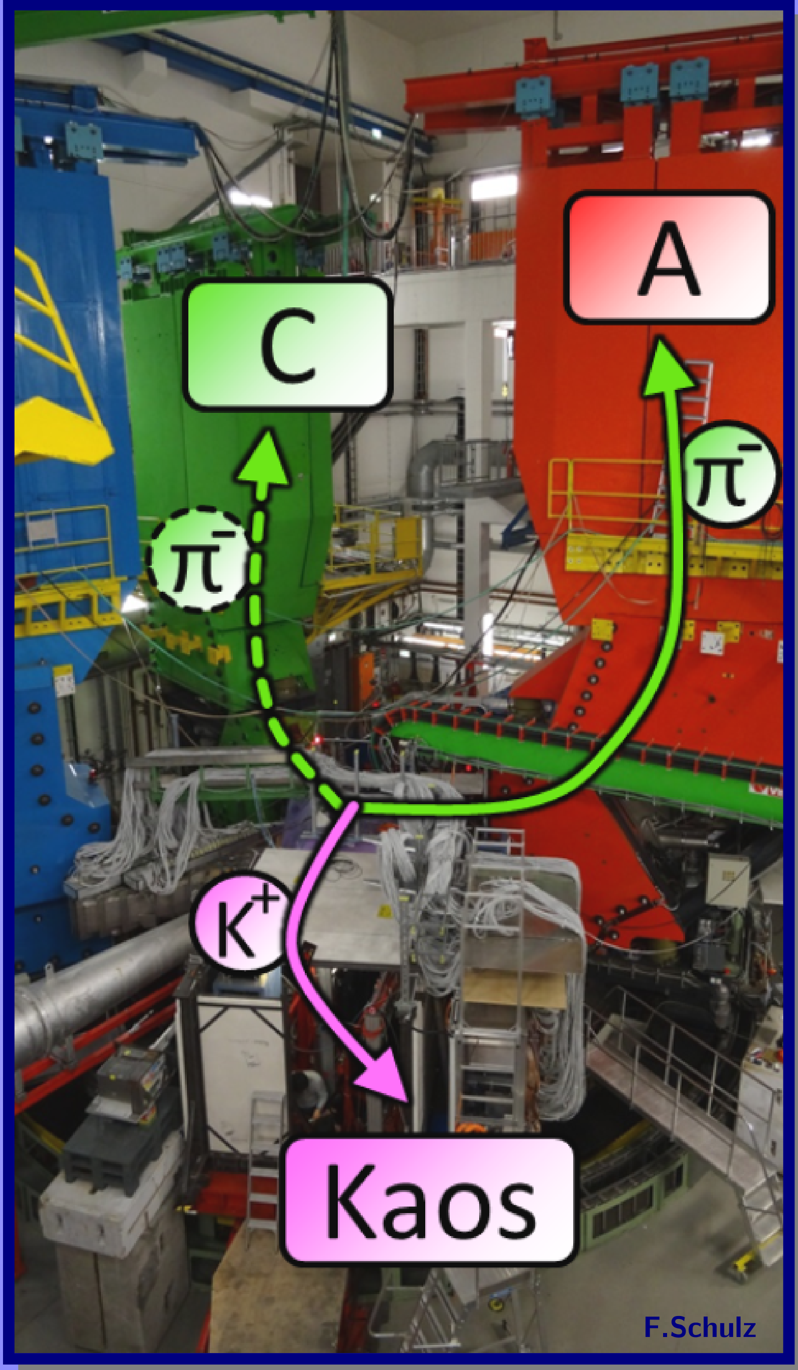
YN interaction, charge symmetry breaking

- new measurement of ${}^{4}_{\Lambda}$H binding energy
  - comparison to ${}^{4}_{\Lambda}$He
  - difference Λn and Λp interaction?
  - emulsion data: large difference!
    data quality: not perfect

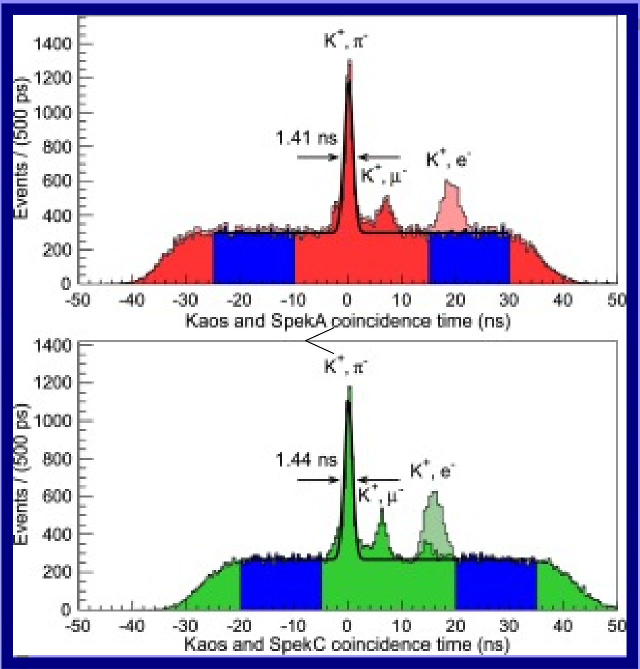
pion decay spectroscopy

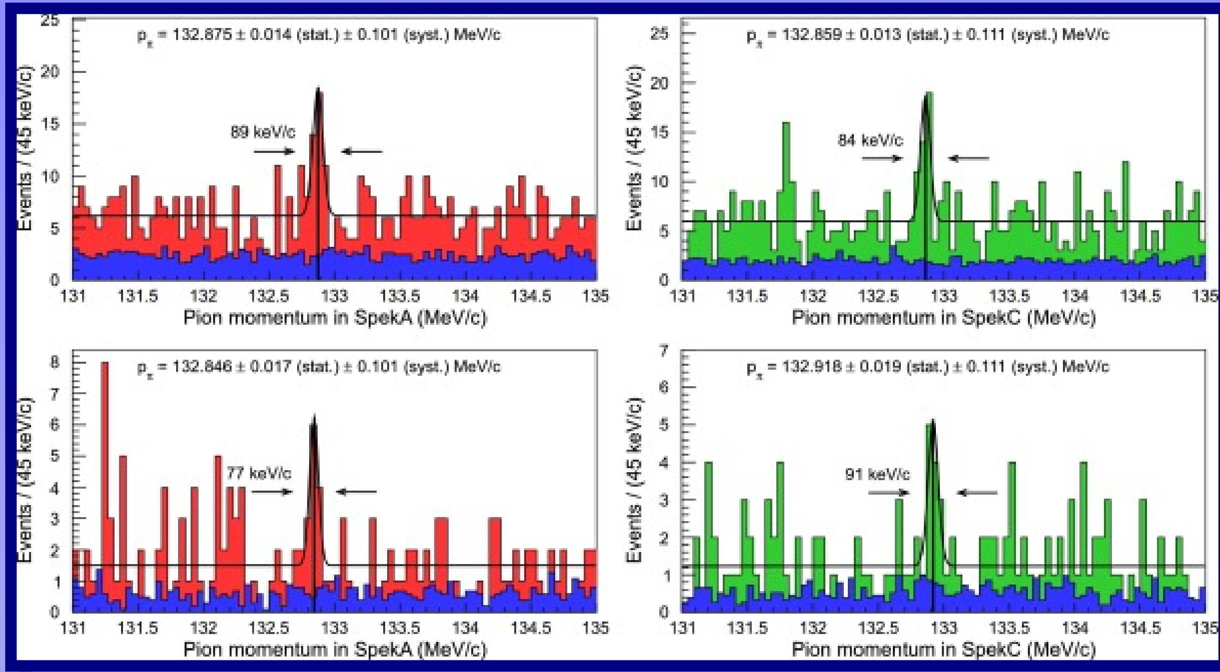
- production of ${}^{4}_{\Lambda}$H
- pionic two-body decay
- coincident detection of
  - K^+ (strangeness tagging)
  - π^- (decay product)
- momentum measurement of π^-
  - Λ binding energy ${}^{4}_{\Lambda}$H





Few-Baryon Systems: Hypernuclei

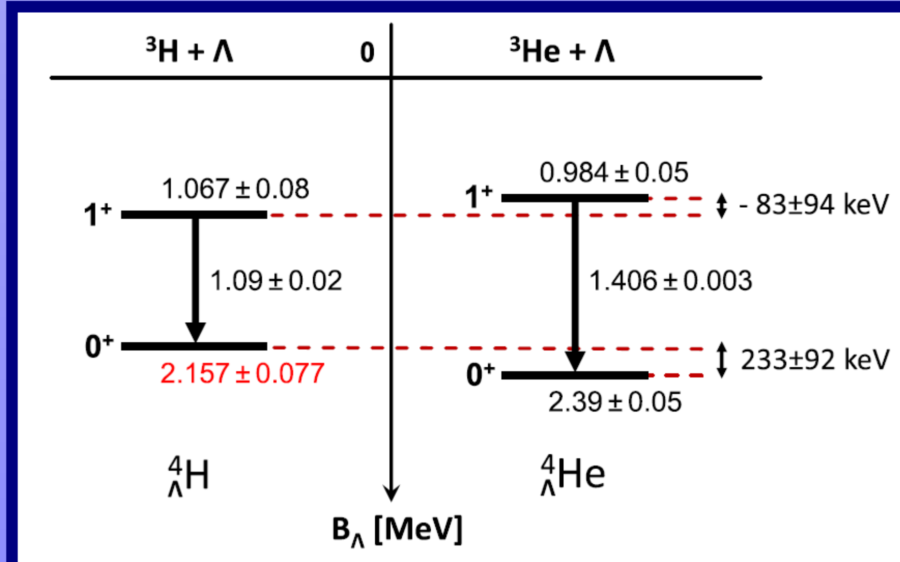




results 2012, 2014 data

- large charge symmetry breaking effect confirmed
- reduction systematics (absolute momentum calibration!) ongoing

A.Esser, S.Nagao, F.Schulz et al, Phys. Rev. Lett. 114 (2015) 232501
F. Schulz et al, Nucl. Phys. A (2016) in press



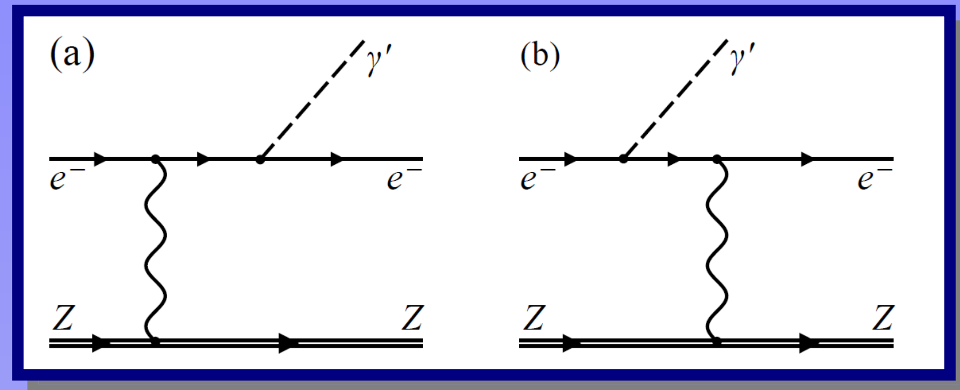
Dark photon search

Dark photon search

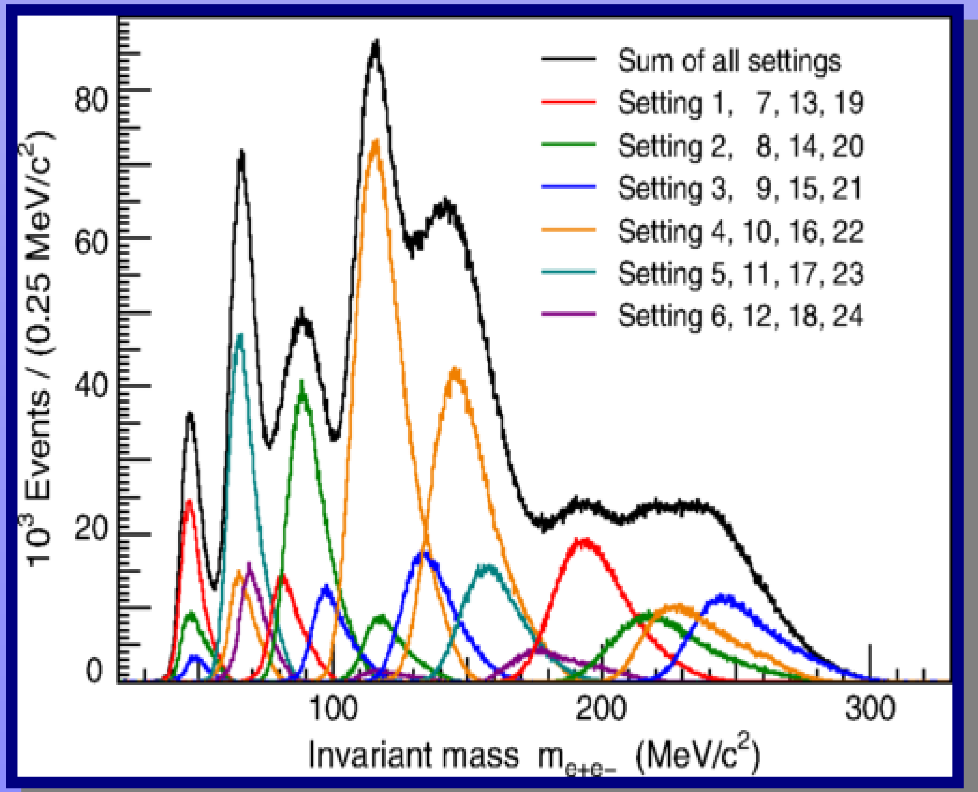
- Radiative production of a Dark Photon

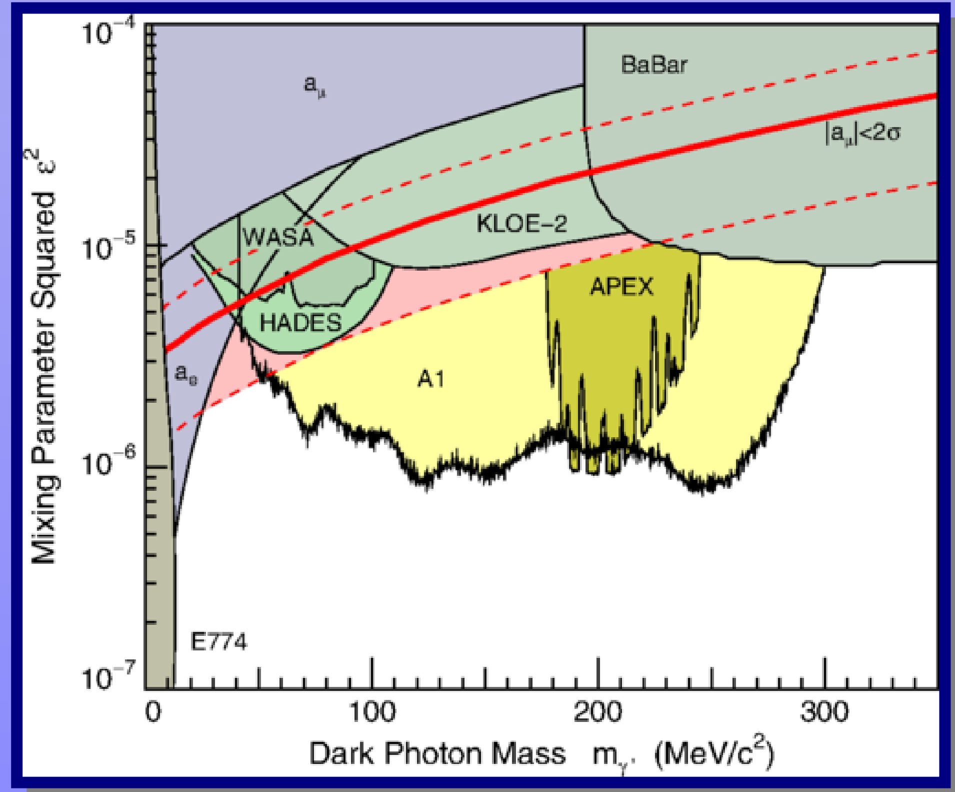
$$e + Z \to e + Z + \gamma'$$
$$\hookrightarrow e^+ + e^-$$

- Detection of the decay to lepton pair with high resolution spectrometers A, B



H. Merkel et al, PRL 112 (2014) 221802
H. Merkel et al, PRL 106 (2011) 251802



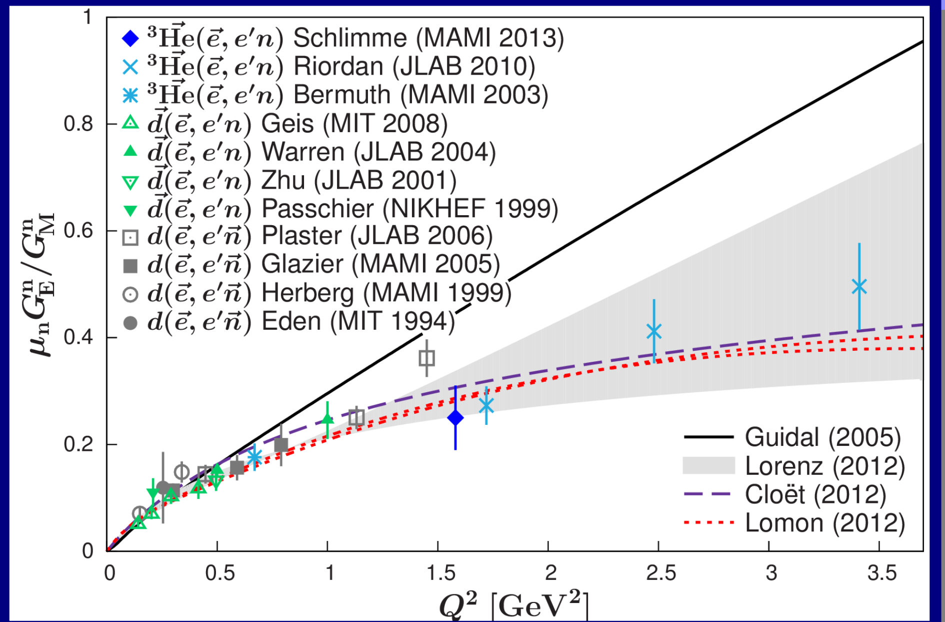


Neutron Form Factors

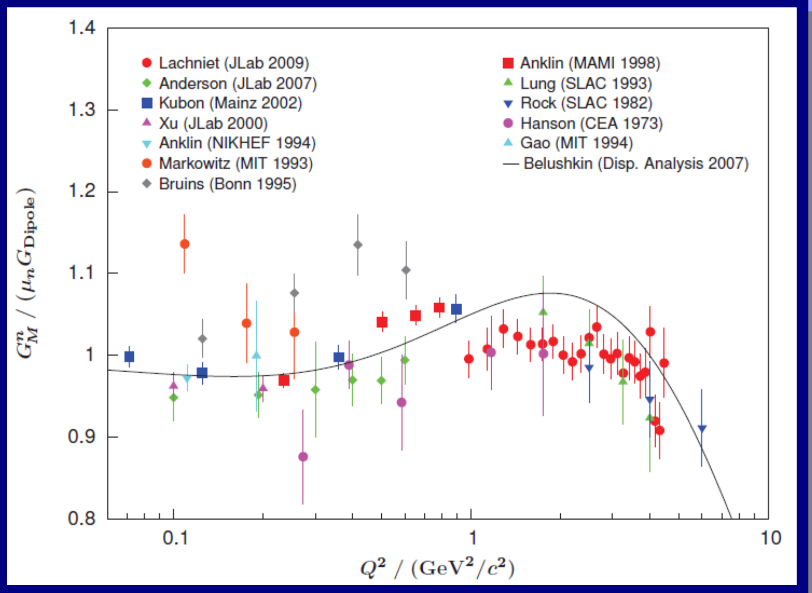
Experimental complications

- no free neutron target
  - eff. target (D, ^{3}He), binding effects, large proton background → neutron det.
- G^n_M: cross section measurement, but neutron det. efficiency
- $G^n_E \ll G^n_M$
  - double polarization observables
    - polarized target
    - neutron recoil polarization

  $\rightarrow G^n_E / G^n_M$



B.S. Schlimme et al, PRL 111 (2013) 132504



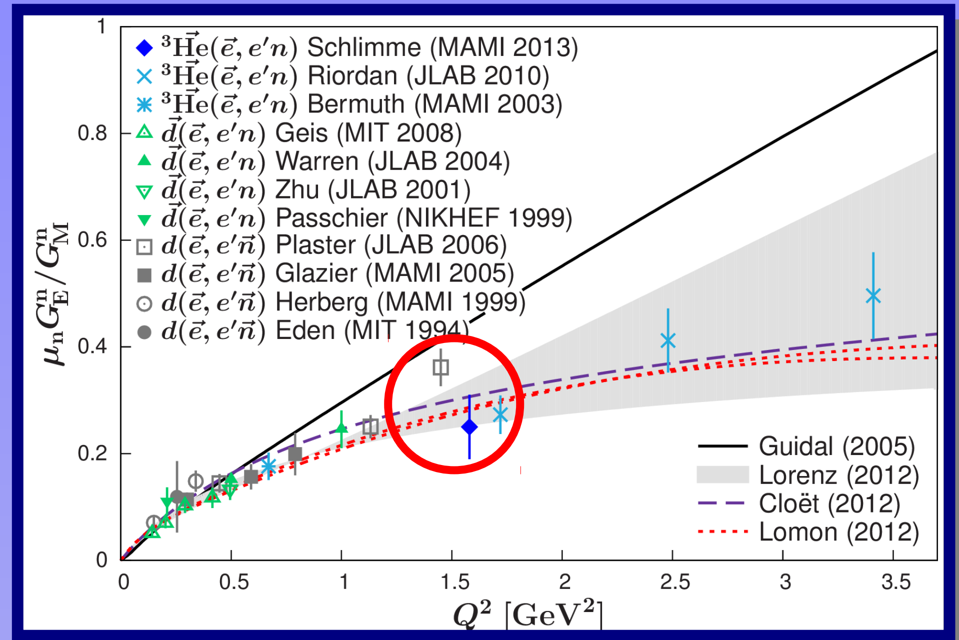
Neutron Form Factors

G_E^n/G_M^n from double pol. experiments

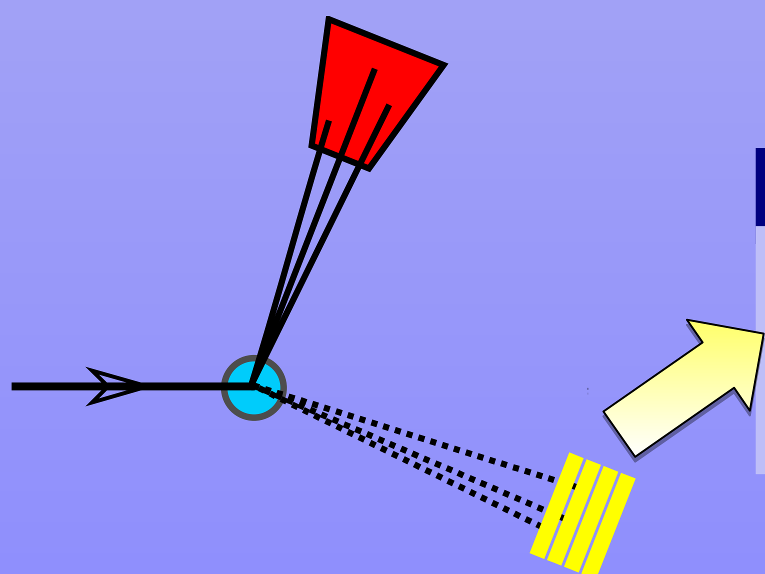
- tension between deuteron and helium data at 1.5 GeV^2

	$^3\vec{\mathrm{He}}(\vec{e},e'n)$	$d(\vec{e},e'\vec{n})$
JLAB	2011	2006
MAMI	2013	×

- consistent measurements Q^2=0.2 - 1.5 GeV^2
  - G_E^n/G_M^n asymmetry measurements
  - G_M^n (rel.) cross sections



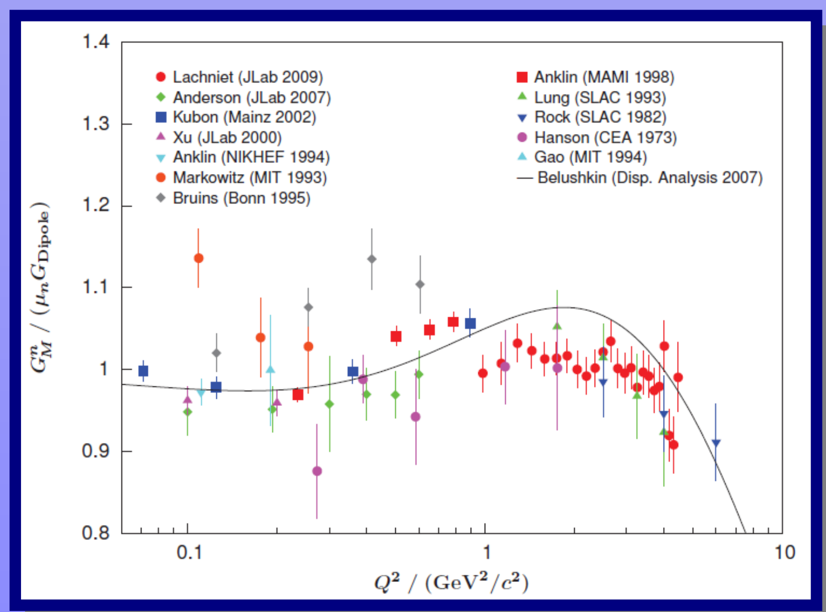
B.S. Schlimme et al, PRL 111 (2013) 132504



neutron detector

- multi purpose
- high efficiency
- high rate cap.
- high resolution

neutron detector: vacant position



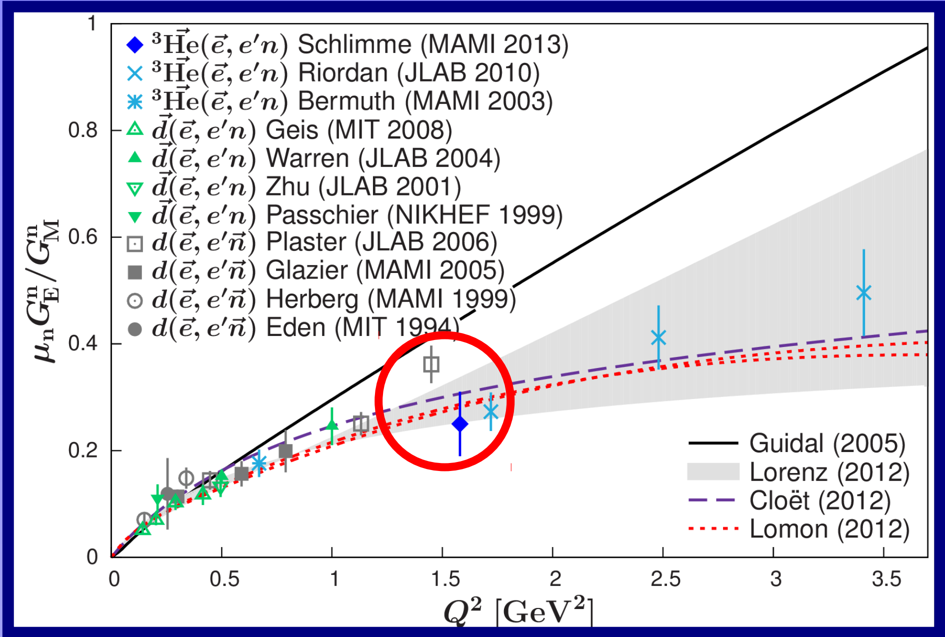
Neutron Form Factors

G_E^n/G_M^n from double pol. experiments

- tension between deuteron and helium data at 1.5 GeV^2

	$^3\vec{He}(\vec{e},e'n)$	$d(\vec{e},e'\vec{n})$
JLAB	2011	2006
MAMI	2013	×

- consistent measurements Q^2=0.2 - 1.5 GeV^2
  - G_E^n/G_M^n asymmetry measurements
  - G_M^n (rel.) cross sections



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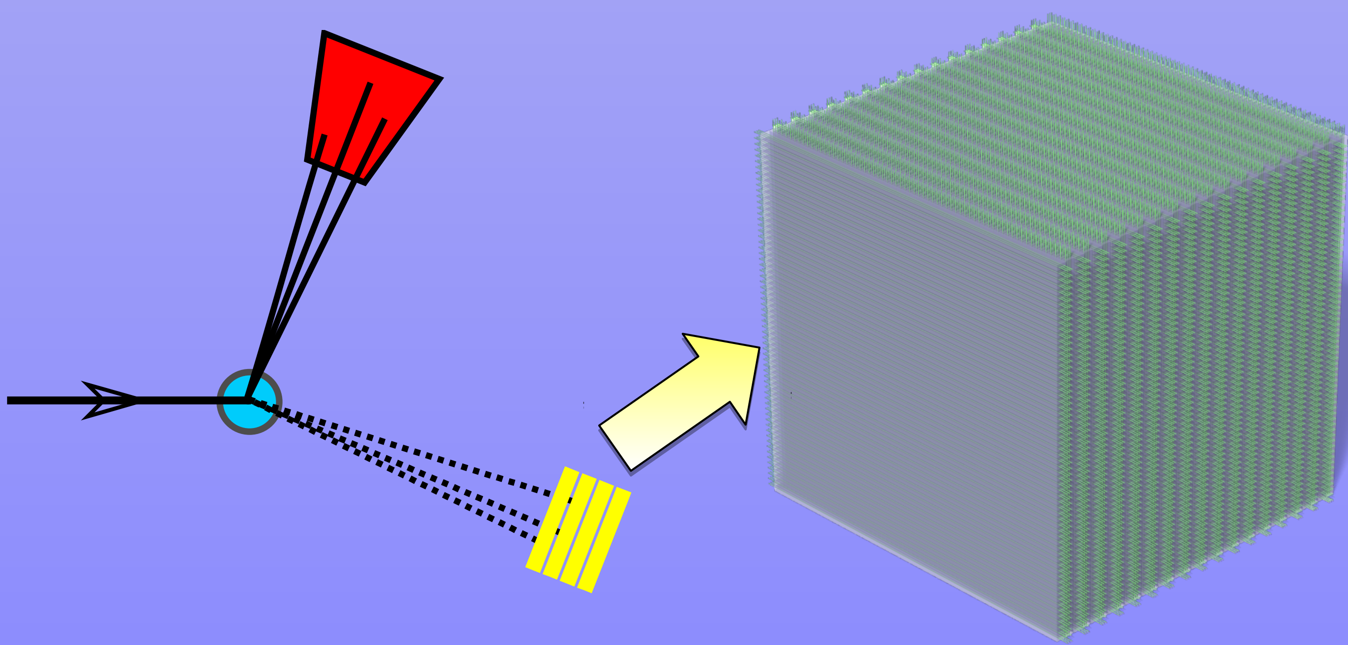
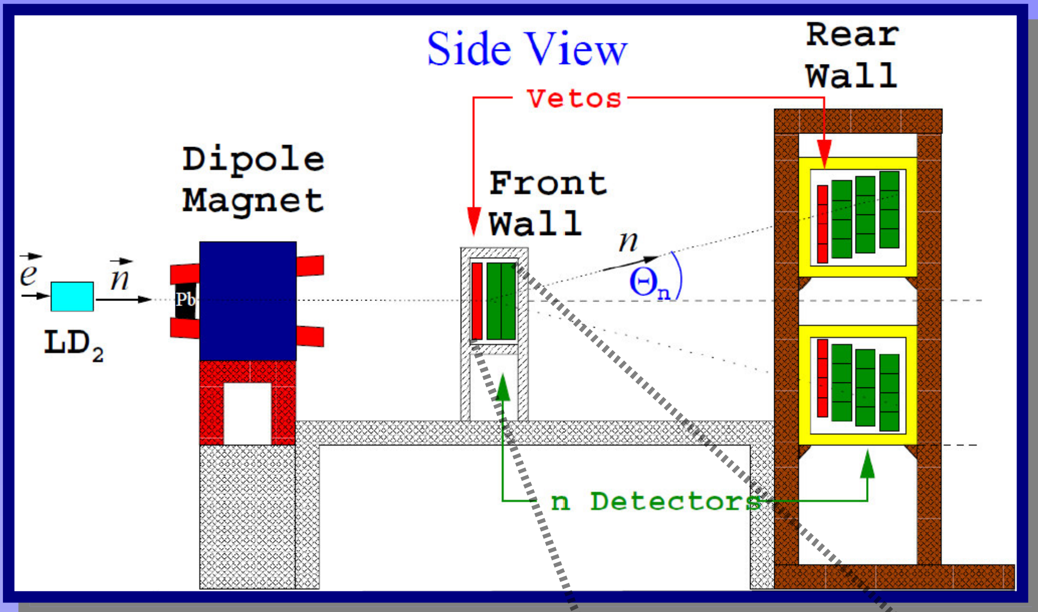
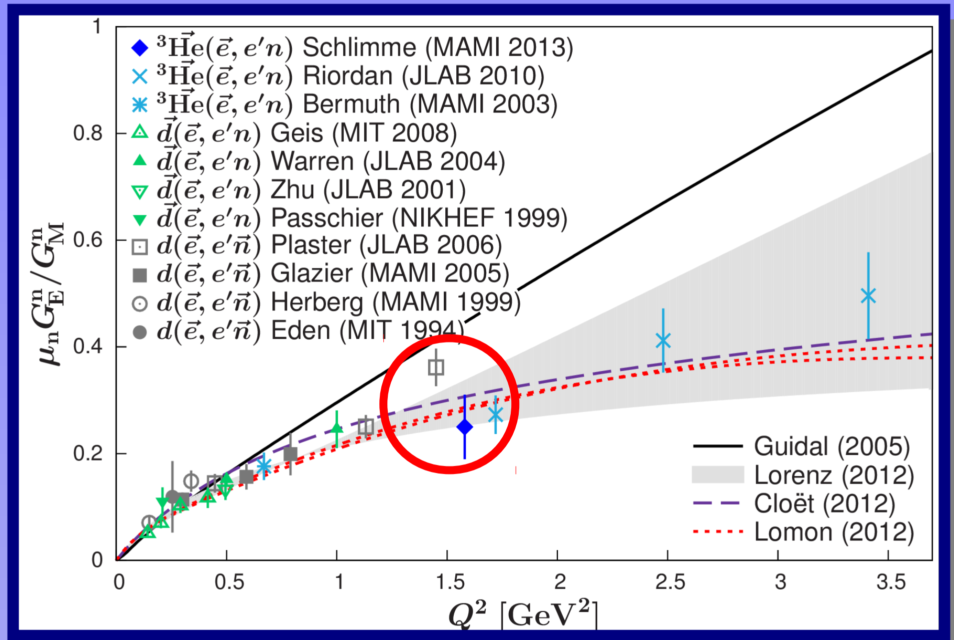


initial concept

- $1m^3$
- liquid scintillator
- high segmentation
  - 4500 channels
- wave length shifting fibers
- SiPMTs / MaPMTs

Neutron Form Factors





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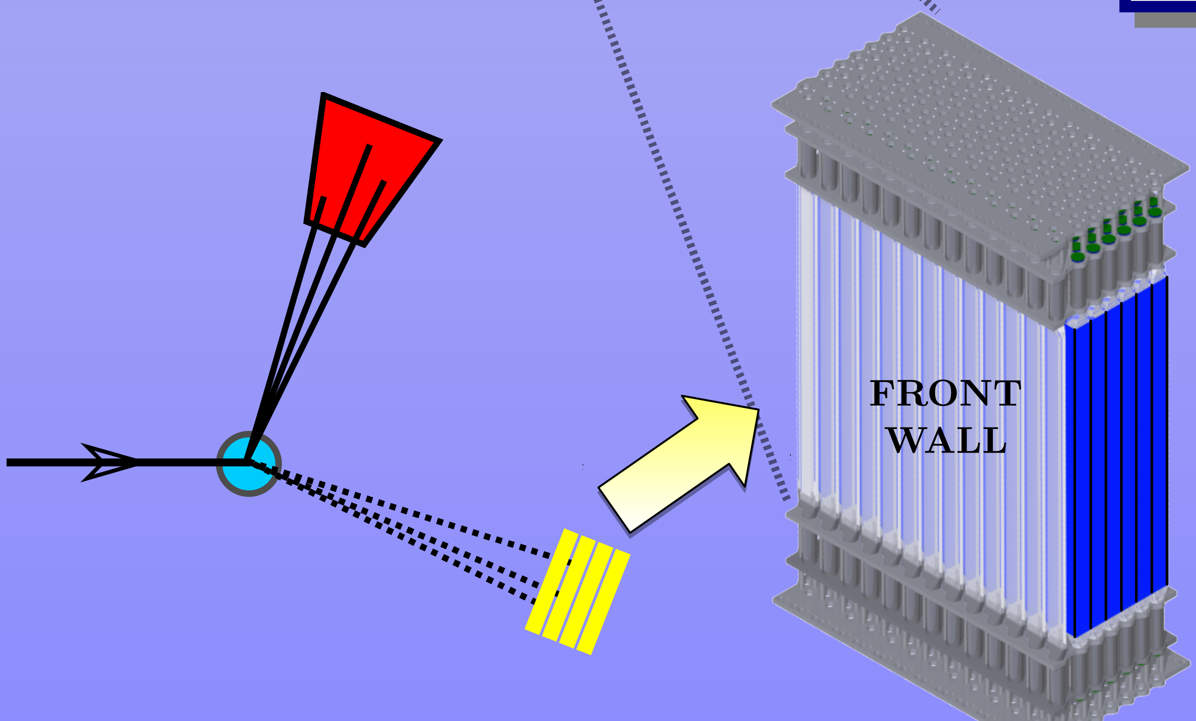


Matthias Hoek

final design

- 300 bars × 2PMTs
  - scintillator: EJ-200
  - PMT: 9142SB
- NINO discriminator card
- TDC readout board
- resolutions 15mm, 160ps
- (multi purpose)
- optimize for G_E^n / G_M^n

Proton Form Factors: Bound vs Free

problem

- Bound nucleon same properties as free one?
- *medium modifications* of form factors?

idea

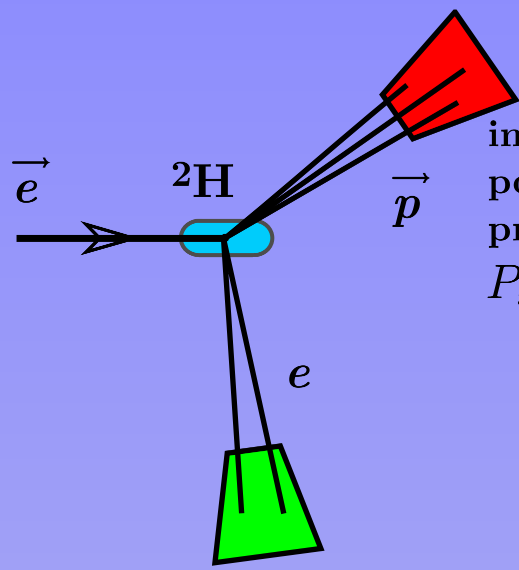
- Measure G_E/G_M free proton
- Measure G_E/G_M bound proton
- compare

finding, ^{2}H

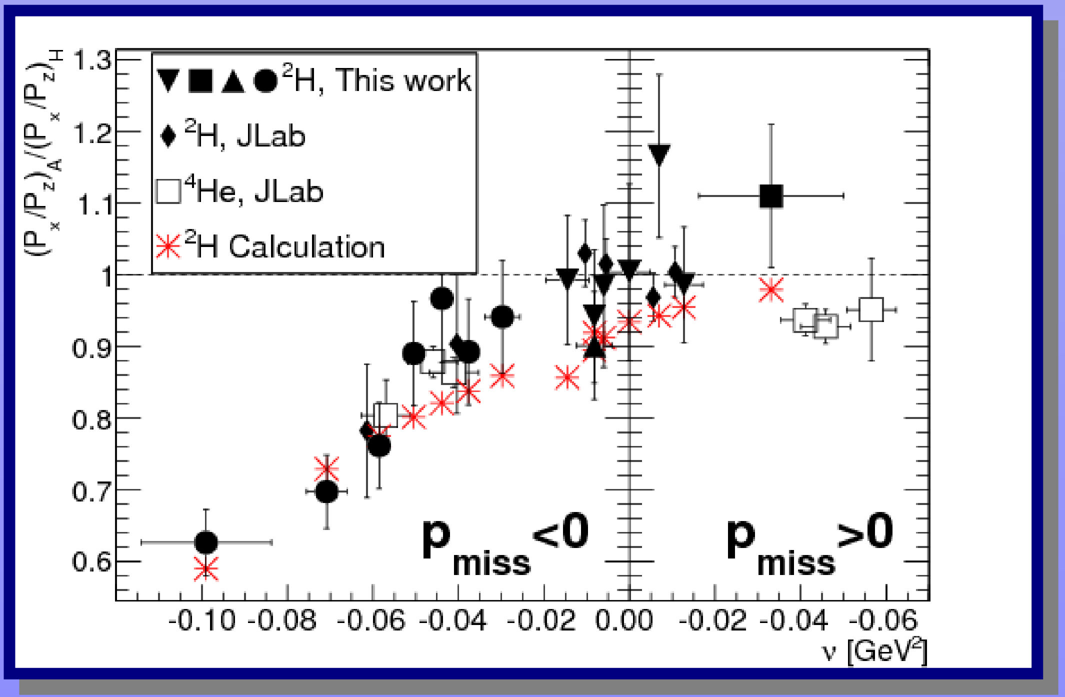
- 10% difference
- may point to *nuclear medium modifications*
- agreement with ^{4}He JLab data
  - effect due to proton virtuality ν, not due to average nuclear density!?

ongoing

- analysis ^{12}C (data taken)
- further data ^{2}H



including focal plane polarimeter;
proton recoil polarization:
$P_x/P_z \propto G_E/G_M$



I.Yaron et al, arXiv:1602.06104 [nucl-ex]

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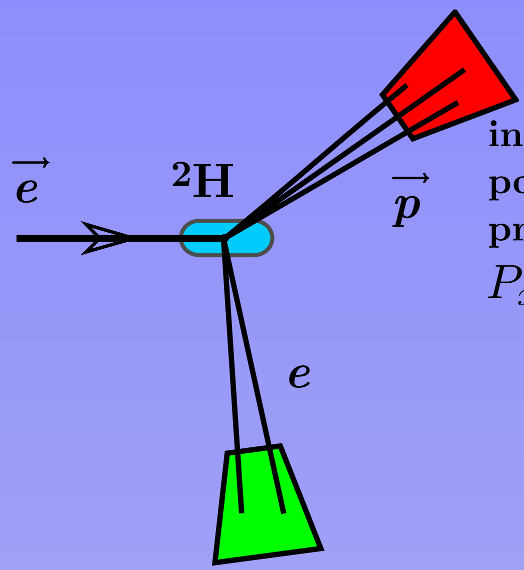

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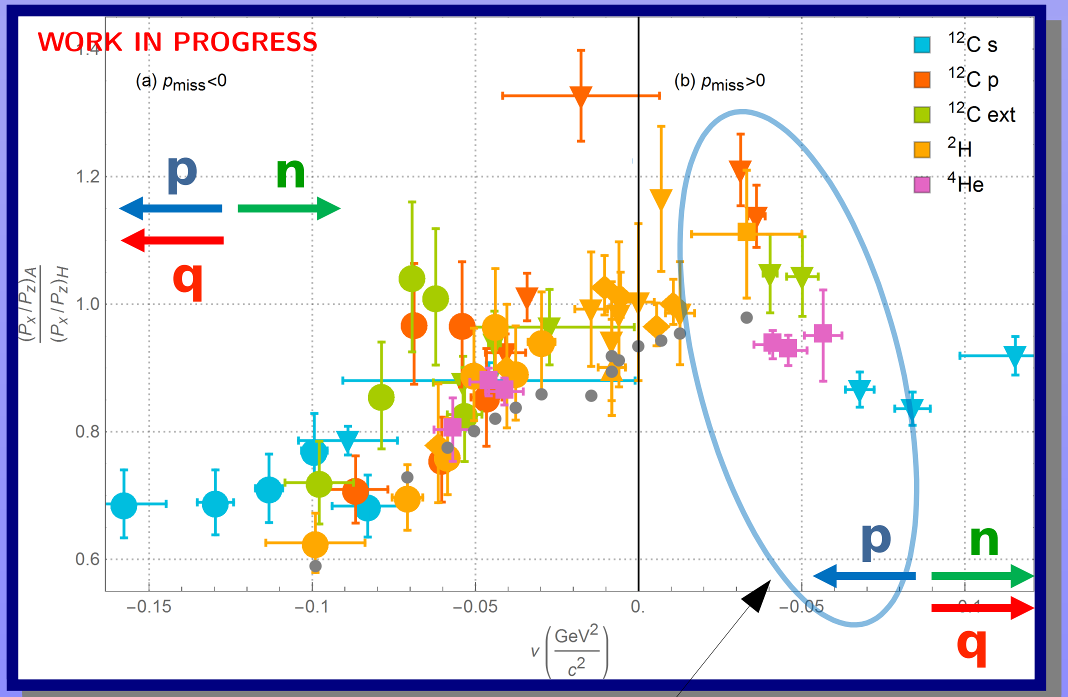


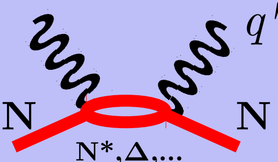
additional ^{2}H data here

Nucleon polarizabilities

nucleon polarizabilities: from γ to γ^*

reaction of nucleon under influence of EM field

Real
Compton Scattering



at q'=0: proton in applied EM field

↓

induced dipole:

$d_E = \alpha_E \cdot E$

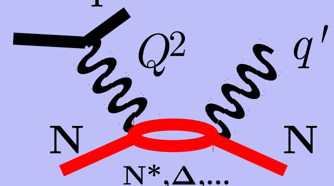
$d_M = \beta_M \cdot B$

$\alpha_E = (11.2 \pm 0.4) \cdot 10^{-4} fm^3$

$\beta_E = (\ 2.5 \pm 0.4) \cdot 10^{-4} fm^3$

PDG 2015

Virtual
Compton Scattering



at q'=0: proton in applied EM field

↓

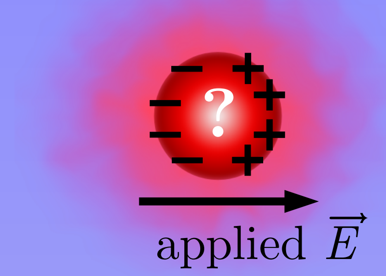
generalized polariz.:

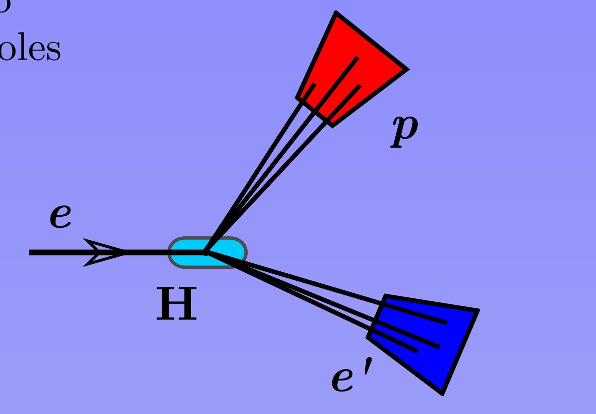
$\alpha_E(Q^2)$

$\beta_M(Q^2)$

- *form factor meas. in external field*
- Fourier transform of local distr. of polarizabilities

Polarizability: ability to form instantaneous dipoles





(partly out of plane)

GP determination

- measure d$\sigma(ep\gamma)$, different kinematics
- Analysis techniques:
  - Low Energy eXpansion
    - subtract BH+Born
    - separate structure functions
    - fix spin GP
- Dispersion Relations (model dep.)
  - fit paremeters Λ_α, Λ_β to measured cross section

$$\mathrm{d}\sigma(ep\gamma) = \mathrm{d}\sigma(\mathrm{BH}+\mathrm{Born}) + \Phi q'_{\mathrm{cm}}[\nu_{\mathrm{LL}}(P_{\mathrm{LL}} - P_{\mathrm{TT}}/\varepsilon) + \nu_{\mathrm{LT}} P_{\mathrm{LT}}] + \mathcal{O}({q'_{\mathrm{cm}}}^2)$$

LEX: dσ(BH+Born) ↓ known form factors (**huge background**); P_{LL} ↓ $\alpha_E(Q^2)$; P_{TT} ↓ spin GP; P_{LT} ↓ $\beta_M(Q^2)$ + spin GP

Nucleon polarizabilities

nucleon polarizabilities: from γ to γ*

reaction of nucleon under influence of EM field

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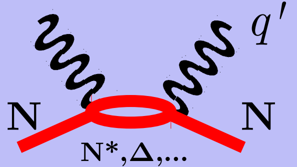
Compton Scattering



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PDG 2015

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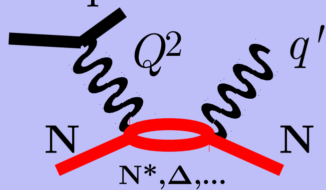
Compton Scattering



at q'=0: proton in applied EM field

↓

generalized polariz.:

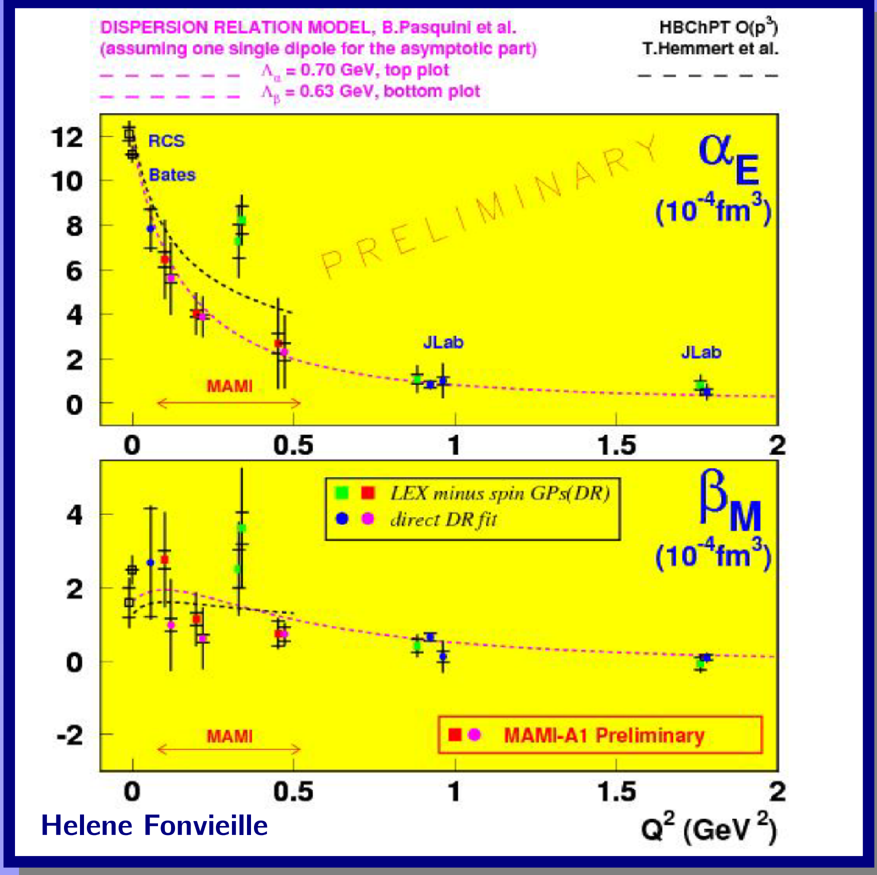
$\alpha_E(Q^2)$

$\beta_M(Q^2)$

- *form factor meas. in external field*
- Fourier transform of local distr. of polarizabilities

Double polarization observables

- linear combination of GPs via other structure function; Q^2=0.33GeV^2
  L. Doria et al., PRC 92 (2015) 054307



"vcsq2": 3 new MAMI points (prelim.)

- Q^2-behavior α_E: single dipole
- puzzle remains in Q^2=0.33 GeV^2 region
  - reanalyze (DR); new data

"vcsdelta": in W=Δ(1232) region

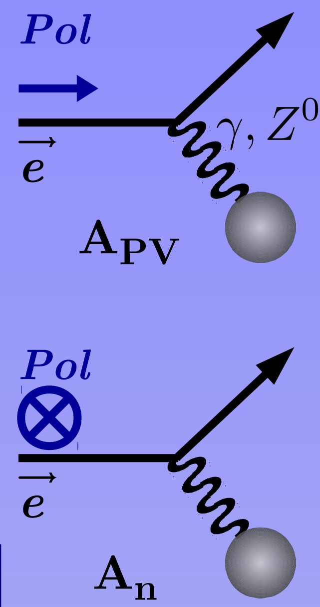
- α_E(0.2 GeV^2), analysis ongoing

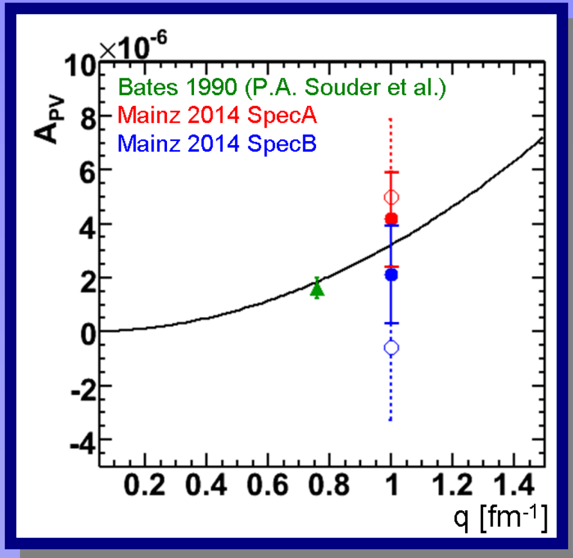
Parity-Violating Electron Scattering + Related

Long term plan in Mainz:

Neutron skin in heavy nuclei

- Difference between neutron and proton rms-radii inside nucleus
  - Important impact on nuclear theory, e.g. unique experimental constraint on symmetry energy of nuclear Equation Of State (EOS)
- $A_{\rm PV} = \frac{\sigma^{h+} - \sigma^{h-}}{\sigma^{h+} + \sigma^{h-}} \propto F_{\rm weak}(Q^2)$ sensitive to radius of neutron distribution (PREX)



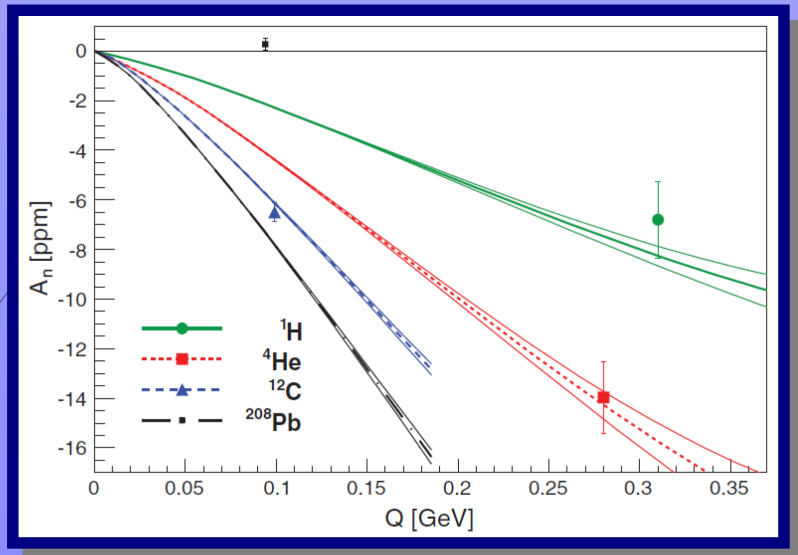


First A_{PV} experiment at A1

- PVES on 12C (1.8 cm target thickness!)
- Spectrometers to select elastic events
  - Quartz-Cherenkov detectors (high rates)
- Electronics of former A4 experiment
- It was demonstrated, for the first time by the A1 collaboration, that PV experiments are tough!

Beam-normal single spin asymmetry $A_n \gg A_{PV}$

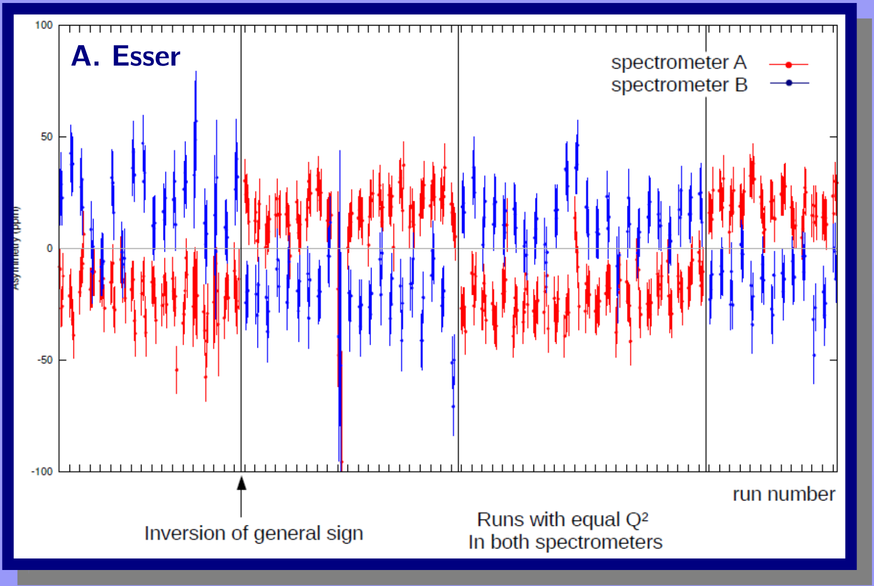
- Interference one- and multi-photon exchange terms
- Important background of PVES
- Unexpected feature: ^{208}Pb

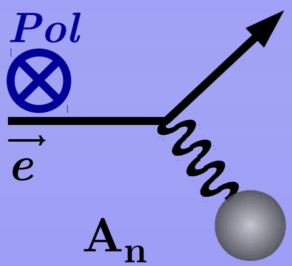


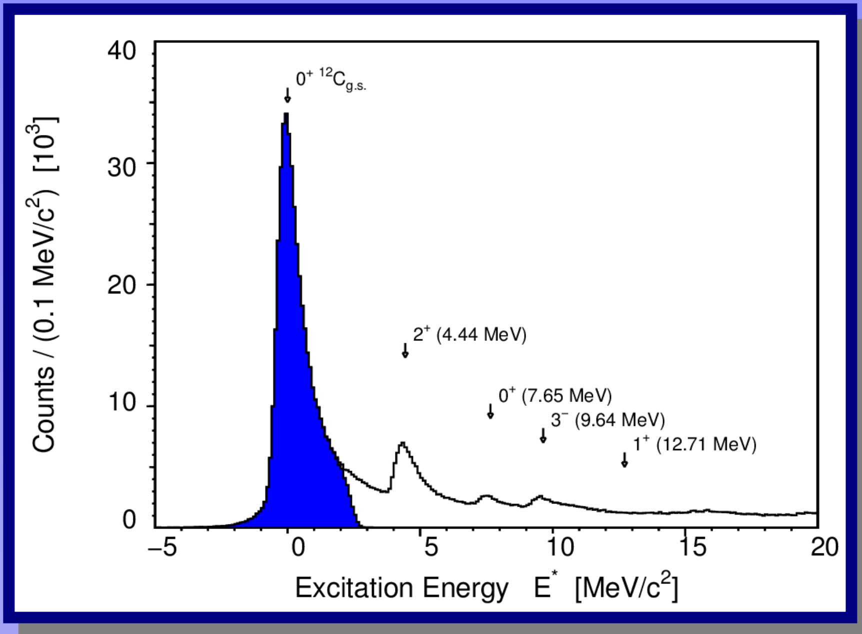
S.Abrahamyan et al, PRL 109 (2012) 192501

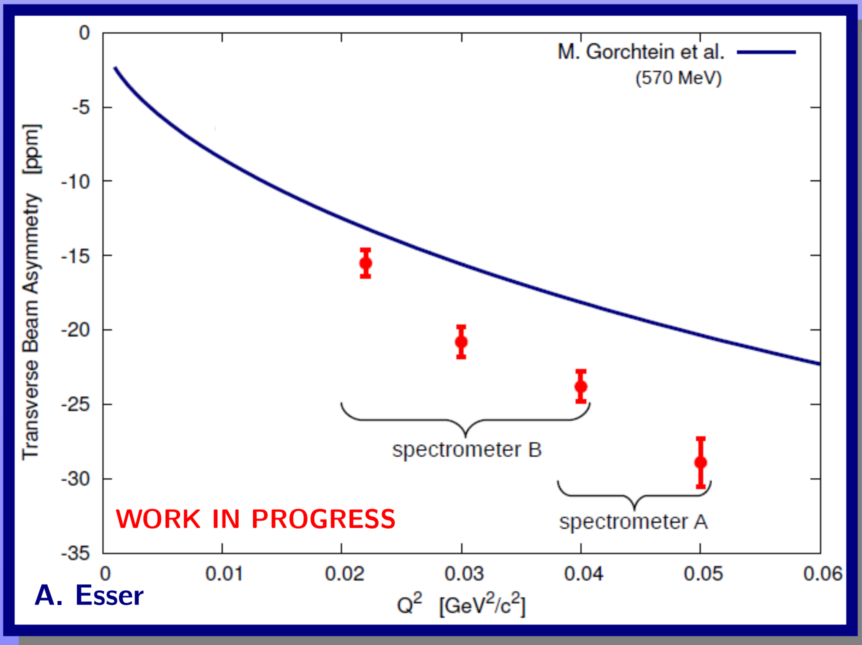
Beam-normal single spin asymmetry

- MAMI measurement:
  - ^{12}C, 4 different Q^2 values
  - analysis ongoing, promising!









possible continuation of program

- ^{12}C, energy dependence (fixed Q^2)
- Z dependence
  - ^{28}Si, ^{40}Ca, (^{208}Pb)

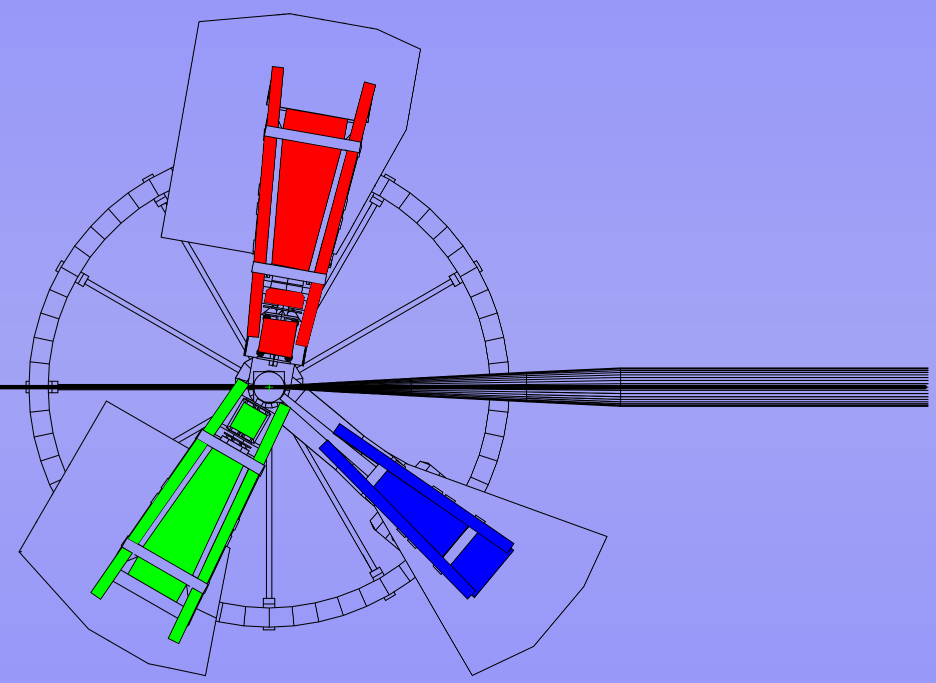
Summary

MAMI

e, $\vec{e}$ ~~low beam quality~~ ~~medium beam quality~~ high beam quality → ↑⊗ 80% Pol 160 MeV - 1.6 GeV 0 - 100 μA

A1 spectrometer hall

- 3 × High Resolution Spectrometer
- 1 × Pion Spectrometer
- 1 × Kaon Spectrometer
- Various additional detector systems
- Various targets



experimental studies

- proton structure
- neutron structure
- in-medium modifications
- structure of light nuclei
- dark photon search
- pion production
- strangeness production

25 YEARS 1991 2016

Jan. 29., 1991

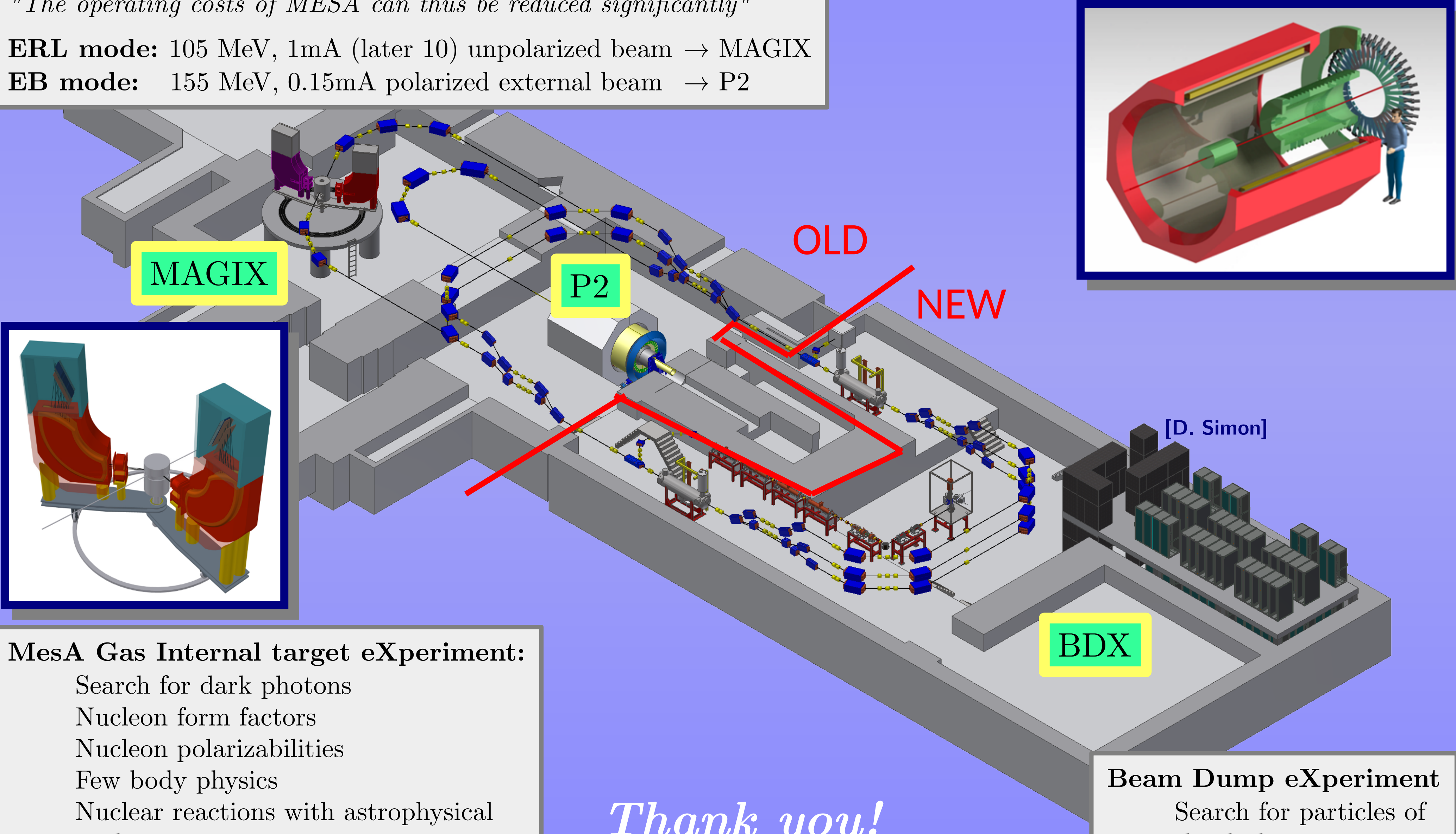
Ceremonial opening of MAMI B, Completion of the new hall for experiments of collaboration A1

Outlook - MESA

Mainz Energy-Recovering Superconducting Accelerator
will be world's first superconducting energy-recovering accelerator dedicated to research
"The operating costs of MESA can thus be reduced significantly"

ERL mode: 105 MeV, 1mA (later 10) unpolarized beam → MAGIX
EB mode: 155 MeV, 0.15mA polarized external beam → P2

P2: 0.13% measurement of $\sin^2\theta_W$
MREX: neutron skin studies



MesA Gas Internal target eXperiment:
- Search for dark photons
- Nucleon form factors
- Nucleon polarizabilities
- Few body physics
- Nuclear reactions with astrophysical relevance

Thank you!

Beam Dump eXperiment
Search for particles of the dark sector