

Form factors and proton radius with elastic scattering and Initial State Radiation at MAMI

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for the A1 collaboration

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Introduction

Experimental setup

Proton form factors and radius

Initial State Radiation

Deuteron charge form factor

Neutron electric form factor

Summary

Nucleon form factors

Elastic electron scattering: Cross section and form factors

Cross section:

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega} \right)_{\text{Mott}} \cdot \frac{\epsilon G_E^2(Q^2) + \tau G_M^2(Q^2)}{\epsilon (1 + \tau)}$$

with:

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

Fourier transform of G_E , $G_M \rightarrow$ spatial distribution (Breit frame)

Electric and magnetic radius:

$$\langle r_E^2 \rangle = -6\hbar^2 \left. \frac{dG_E}{dQ^2} \right|_{Q^2=0} \quad \langle r_M^2 \rangle = -6\hbar^2 \left. \frac{d(G_M/\mu)}{dQ^2} \right|_{Q^2=0}$$

Nucleon form factors

Experimental methods: Elastic $p(e, e')p$ scattering

Two classes of experimental methods:

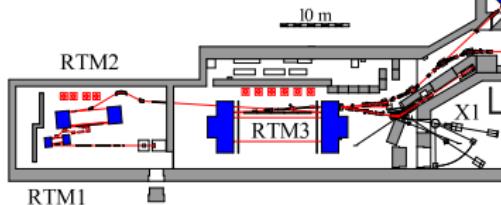
- ▶ Unpolarized scattering: “Rosenbluth separation”
Separated $G_E(Q^2)$ and $G_M(Q^2)$,
but contribution from two photon exchange (TPE)
- ▶ Polarized scattering:
 - ▶ polarized electrons scattered from polarized targets
 - ▶ polarization transfer from electron to nucleon

Only ratio $G_E(Q^2)/G_M(Q^2)$,
little contribution from two photon exchange (TPE)?

The Mainz Microtron MAMI

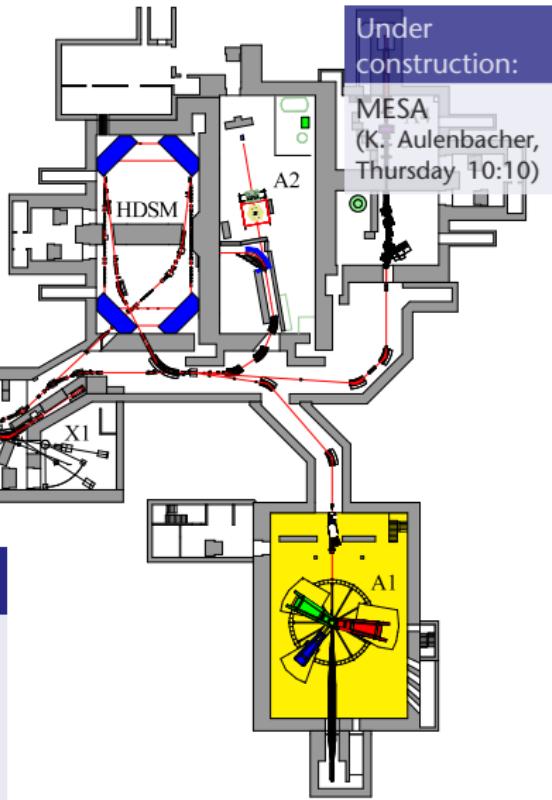
MAMI C

Beam energy max. **1600 MeV**
CW beam $100 \mu\text{A}$ unpolarized
 $40 \mu\text{A}$ at 80 % polarization
Excellent beam quality



Experiments

- A1: Electron scattering
- A2: Real photons
- A4: Parity violation (dismantled)
- X1: X-ray radiation



Three-spectrometer setup of the A1 collaboration



Spectrometer A:

$$\alpha > 20^\circ$$

$$p < 735 \text{ MeV}/c$$

$$\Delta\Omega = 28 \text{ msr}$$

$$\Delta p/p = 20\%$$

Spectrometer B:

$$\alpha > 8^\circ$$

$$p < 870 \text{ MeV}/c$$

$$\Delta\Omega = 5.6 \text{ msr}$$

$$\Delta p/p = 15\%$$

Spectrometer C:

$$\alpha > 55^\circ$$

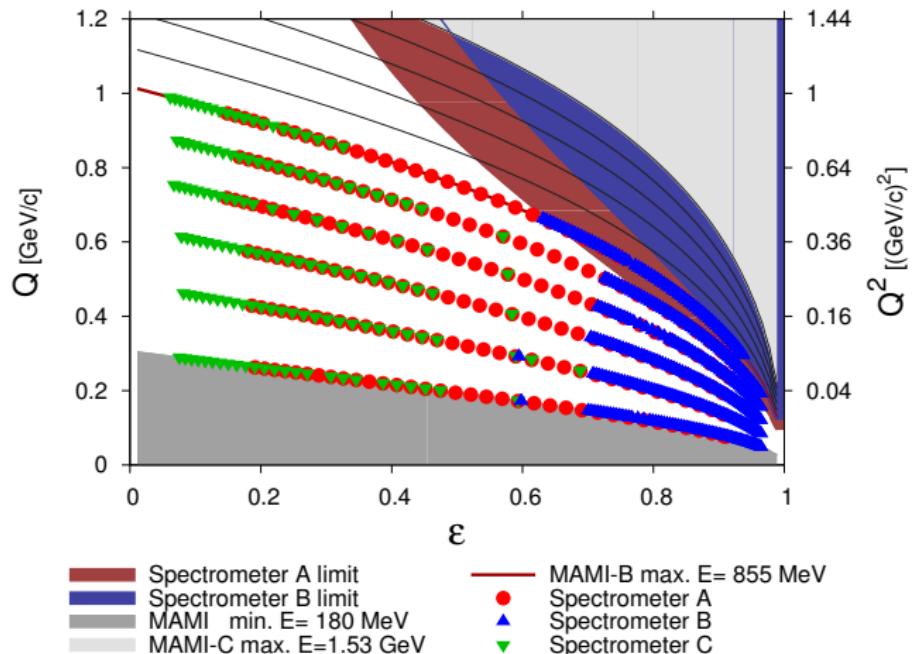
$$p < 655 \text{ MeV}/c$$

$$\Delta\Omega = 28 \text{ msr}$$

$$\Delta p/p = 25\%$$

Proton form factors: Measured settings

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega} \right)_{\text{Mott}} \cdot \frac{\epsilon G_E^2(Q^2) + \tau G_M^2(Q^2)}{\epsilon (1 + \tau)}$$



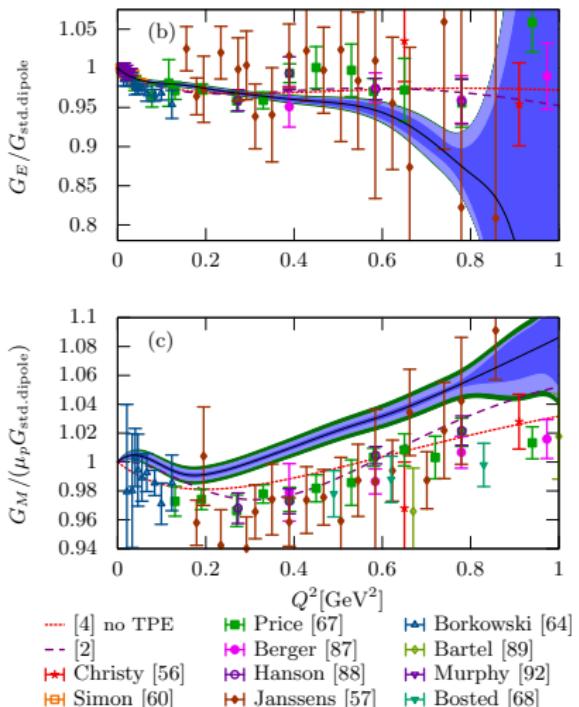
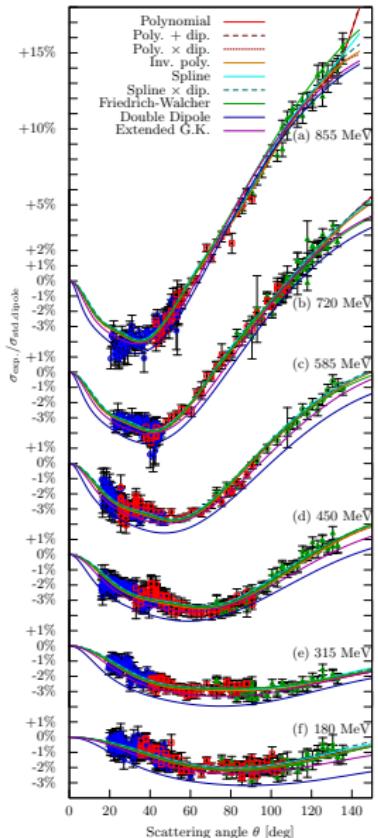
Extraction of form factors

- ▶ Measure elastic spectrum
- ▶ Subtract background from scattering at target walls
- ▶ Match to simulation of energy loss and small angle scattering

- ▶ Traditionally: Rosenbluth separation at constant Q^2
- ▶ "Super-Rosenbluth Separation":
fit of form factor models directly to the cross sections
 - ▶ Data at all Q^2 and ϵ values contribute to the fit
no projection to constant $Q^2 \Rightarrow$ no limit of kinematics
 - ▶ Easy fixing of normalization
 - ▶ Model dependence?

- ▶ For extraction of radius: Need a fit anyway!
- ▶ Classical Rosenbluth: Extracted G_E and G_M highly correlated
 \Rightarrow Error propagation very involved

Cross sections and proton form factor results



J. C. Bernauer et al., PRL 105 (2010) 242001

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

Radii of the proton from electron scattering

MAMI result with Coulomb correction (McKinley and Feshbach):

$$\begin{aligned}\langle r_E^2 \rangle^{1/2} &= 0.879 \pm 0.005_{\text{stat.}} \pm 0.004_{\text{syst.}} \pm 0.002_{\text{mod.}} \pm 0.004_{\text{grp.}} \text{ fm} \\ \langle r_M^2 \rangle^{1/2} &= 0.777 \pm 0.013_{\text{stat.}} \pm 0.009_{\text{syst.}} \pm 0.005_{\text{mod.}} \pm 0.002_{\text{grp.}} \text{ fm}\end{aligned}$$

Cross check: TPE/Coulomb correction

	r_e/fm	r_m/fm
(ours) McKinley, Feshbach	0.879	0.777
Borisuk, Kobushkin	0.876	0.803
Arrington, Sick	0.875	0.769
Blunden et al.	0.875	0.799

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Inclusion of world data

- ▶ Include world data for cross section and polarization
- ▶ Sparse data at high $Q^2 \rightarrow$ only fit special models
- ▶ Parameterize discrepancy between unpolarized and polarized measurements
- ▶ Radii from (variable knot) spline fit: $r_e = 0.878 \text{ fm}$, $r_m = 0.769 \text{ fm}$

Comparison with CLAS and VEPP-3 results

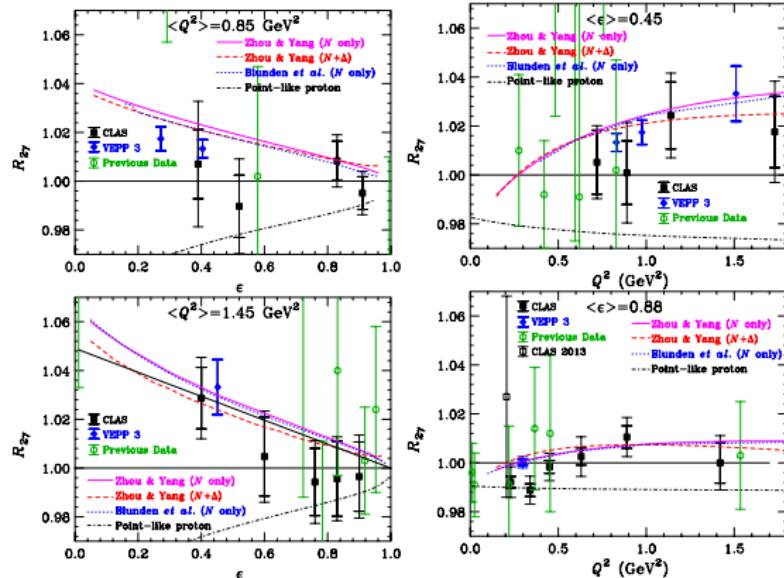
TPE corrections

Fit to world data set:

- ▶ CLAS: 12 data points
- ▶ VEPP-3: 4 data points

$$\chi^2/n_{\text{d.f.}}$$

Z & Y (N)	1.09
Z & Y ($N+\Delta$)	1.03
Blunden (N)	1.06
No TPE	2.10
Point-proton	6.96



D. Rimal et al., arXiv:1603.00315, D. Adikaram et al., PRL 114, 062003
VEPP-3 data: I. A. Rachev et al., PRL 114, 062005

Comparison with CLAS and VEPP-3 results

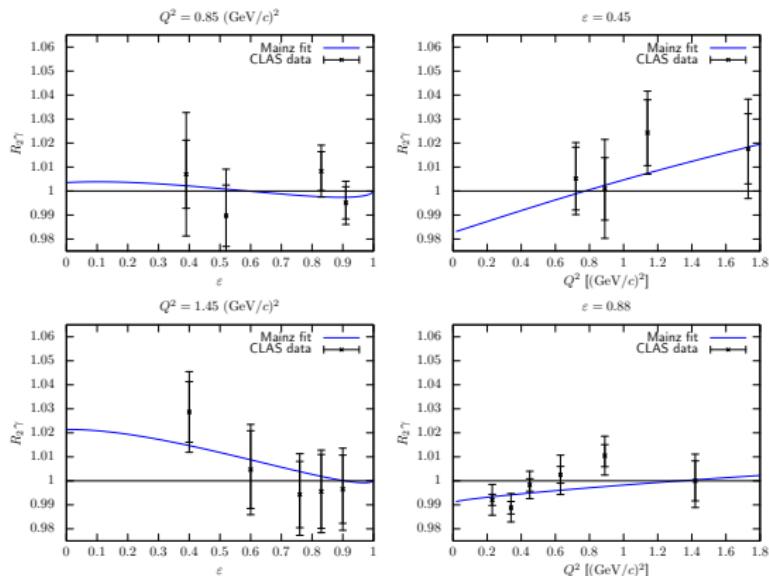
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Point-proton	6.96
Mainz	0.67

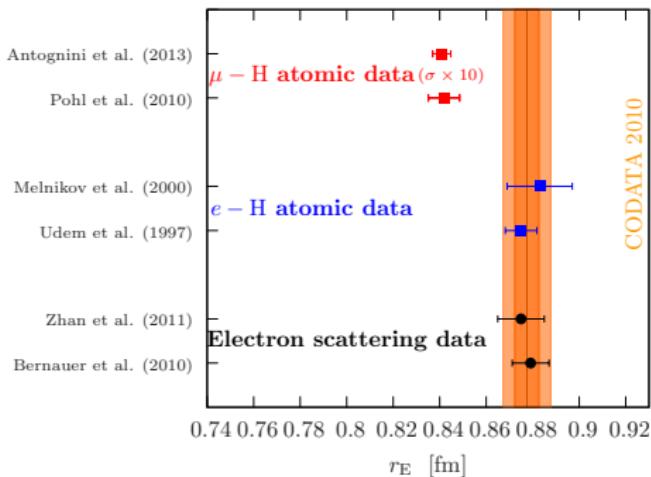


D. Rimal et al., arXiv:1603.00315, D. Adikaram et al., PRL 114, 062003
VEPP-3 data: I. A. Rachev et al., PRL 114, 062005

Proton charge radius

Proton radius puzzle

- ▶ Proton charge radius: important quantity in several fields
- ▶ Significant discrepancy between measurements
 - ▶ Missing corrections?
 - ▶ New physics?
 - ▶ Experimental error?



Ongoing research

- ▶ Electron scattering at low Q^2
- ▶ Muon scattering (MUSE)
Talk by C. Collicott, Tuesday 12:15
- ▶ Other muonic atoms (D, He)

A1 form factor experiments

Proton: Extend Q^2 range

- ▶ Q^2 up to $2 \text{ GeV}^2/c^2$ for $p(e, e')p \rightarrow$ magnetic form factor G_M^p
- ▶ Q^2 down to $0.001 \text{ GeV}^2/c^2$ with Initial State Radiation \rightarrow proton radius

Deuterium and other light nuclei

- ▶ Elastic scattering on deuteron $\rightarrow G_C^d$ and radius

Neutron

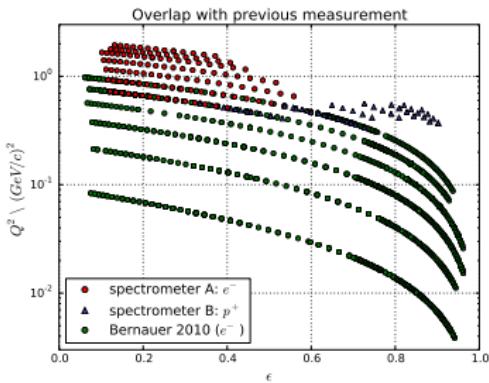
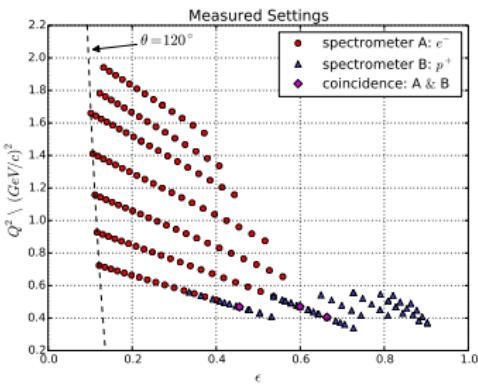
- ▶ Double polarization experiment $\rightarrow G_E^n$

Elastic: Extension to higher Q^2

Extend electron-proton measurement

- ▶ Setting at higher Q^2 (MAMI C)
- ▶ 7 beam energies: 720–1508 MeV
- ▶ Overlap with previous measurement for 720 and 855 MeV
- ▶ Čerenkov trigger for background reduction
- ▶ Statistical error 0.2%
- ▶ Dominated by G_M
- ▶ Also (e, p) and $(e, e'p)$

Data taking completed in June 2015
Julian Müller, PhD thesis

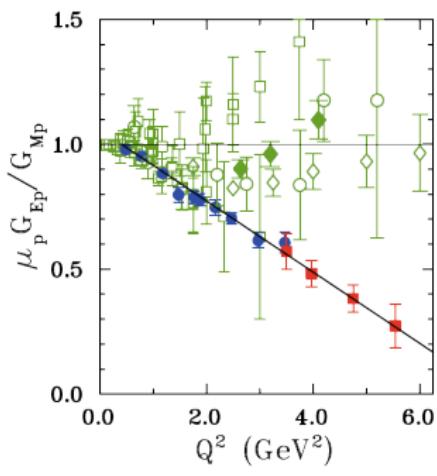


Elastic: Extension to higher Q^2

Will not resolve radius problem, but:

- ▶ Provide precise unpolarized data up to $2 \text{ GeV}^2/c^2$
- ▶ G_E/G_M unpolarized vs. polarized: test of radiative corrections
- ▶ Two-photon exchange? Likely cause for at least part of the discrepancy
- ▶ Theoretical work ongoing
- ▶ Dedicated experiment (OLYMPUS)

Talk by B. Henderson, Tuesday 17:05



V. Punjabi et al.,
EPJ A 51 (2015) 79

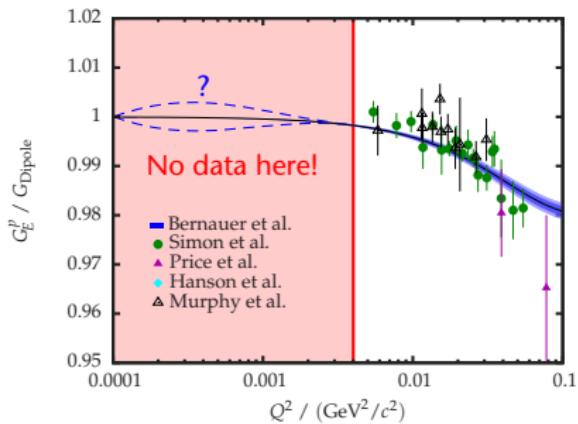
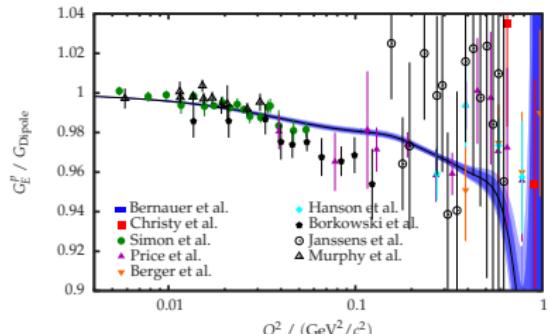
ISR: Proton electric form factor

Elastic scattering:

- ▶ Data available only for $Q^2 > 0.004 \text{ GeV}^2/c^2$
- ▶ Extrapolation to zero needed
- ▶ May be source of systematic errors
- ▶ Very low Q^2 kinematic range not reachable with existing apparatus

Novel techniques needed to explore the low Q^2 regime

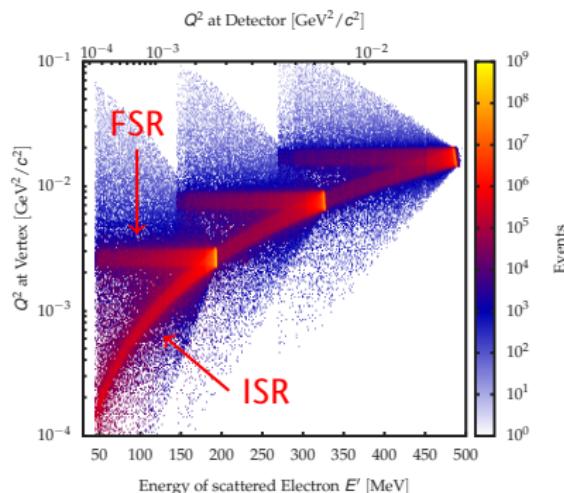
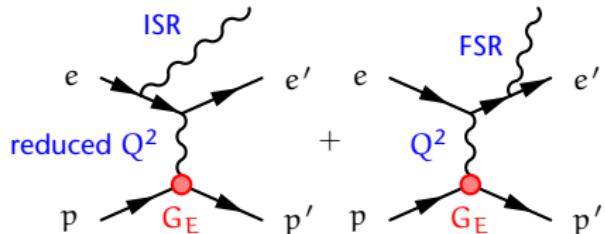
- ▶ Low scattering angles (PRad/JLab)
Talk by W. Xiong, Tuesday 12:35
- ▶ Initial State Radiation (MAMI)



ISR: Principle

Exploit information in radiative tail

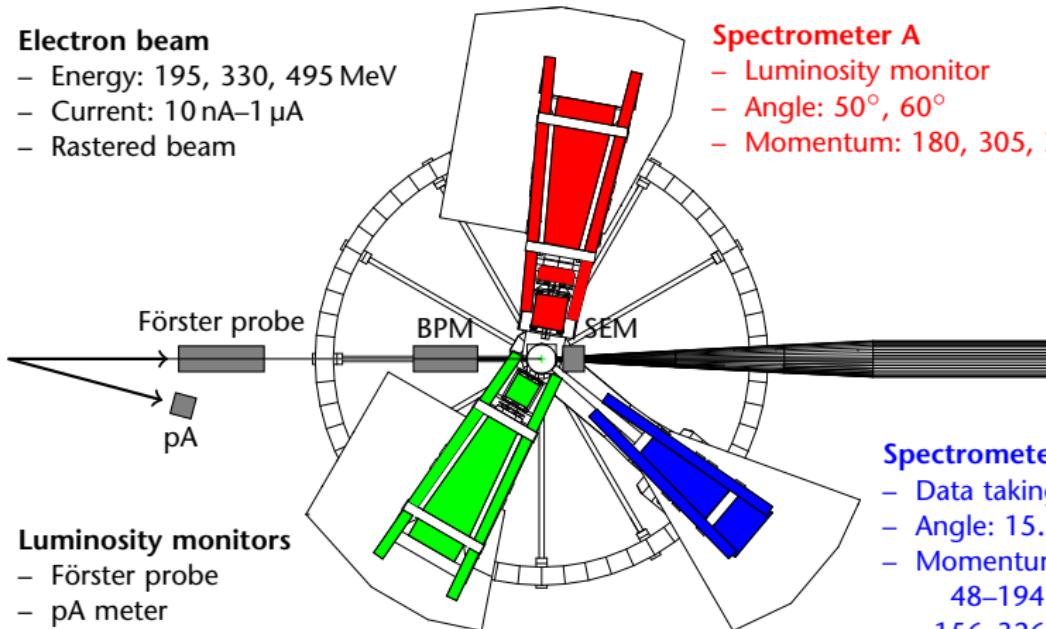
- ▶ Dominated by coherent sum of two Bethe-Heitler diagrams: **ISR** and **FSR**
- ▶ ISR: Electron energy reduced → Lower Q^2 at given scattering angle
- ▶ Investigate G_E down to $Q^2 = 10^{-4} \text{ GeV}^2/c^2$
- ▶ ISR and FSR cannot be distinguished → Sophisticated simulation needed



ISR: Experiment setup

Electron beam

- Energy: 195, 330, 495 MeV
- Current: 10 nA–1 µA
- Rastered beam



Spectrometer A

- Luminosity monitor
- Angle: 50°, 60°
- Momentum: 180, 305, 386 MeV/c

Luminosity monitors

- Förster probe
- pA meter
- SEM

Spectrometer C

- Not used

Spectrometer B

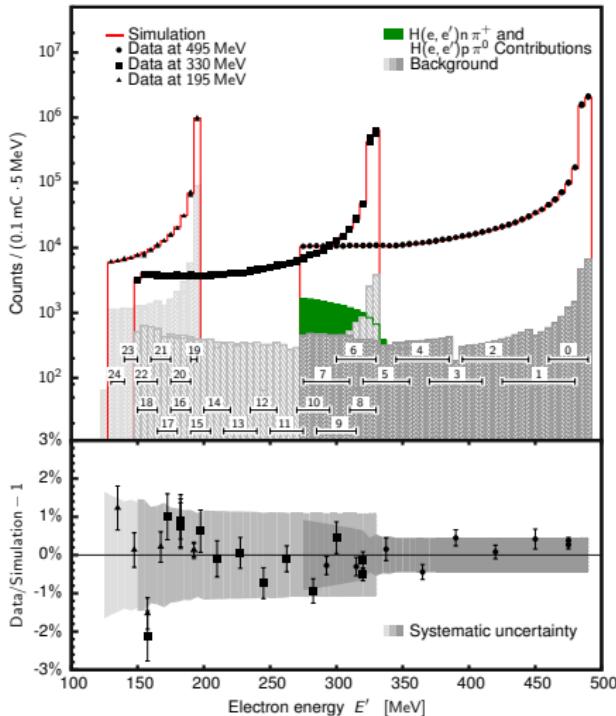
- Data taking
- Angle: 15.3°
- Momentum:
 - 48–194 MeV/c (35 setups)
 - 156–326 MeV/c (12 setups)
 - 289–486 MeV/c (9 setups)

Beam control module

- Beam stabilization via closed loop control
- Measure beam current (pA meter) and position every 3 minutes

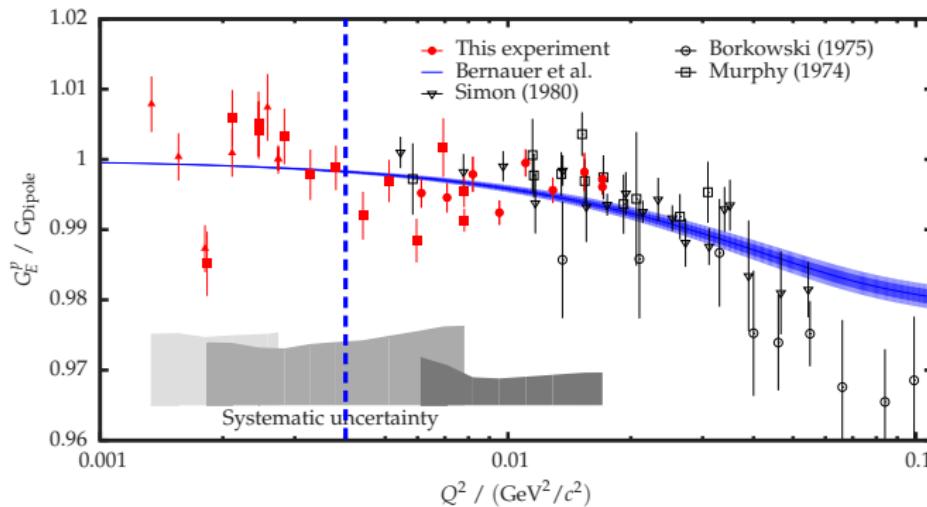
ISR: Preliminary results

- ▶ Existing apparatus limited to $Q^2 \gtrapprox 0.001 \text{ GeV}^2/\text{c}^2$
- ▶ Pion production contributes $\approx 10\%$ at lowest momenta
- ▶ Simulation performed with Bernauer parameterization of form factors
- ▶ Good agreement ($< 1\%$) between data and simulation validates ISR technique



ISR: Form factors

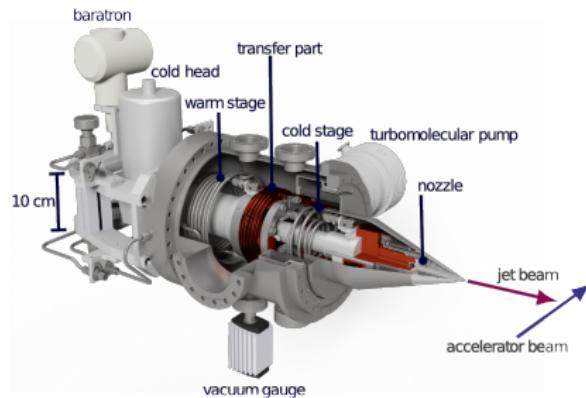
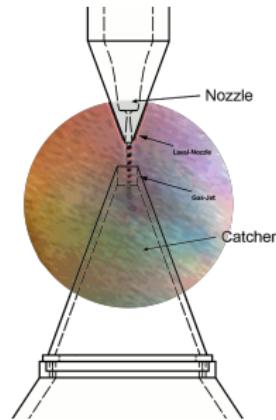
Preliminary – not for quotation!



- ▶ First measurement of G_E^p at $0.001 \text{ GeV}^2/c^2 \leq Q^2 \leq 0.004 \text{ GeV}^2/c^2$
- ▶ Final systematic checks still to be done
- ▶ Goal: Extraction of proton charge radius

ISR: Future plans

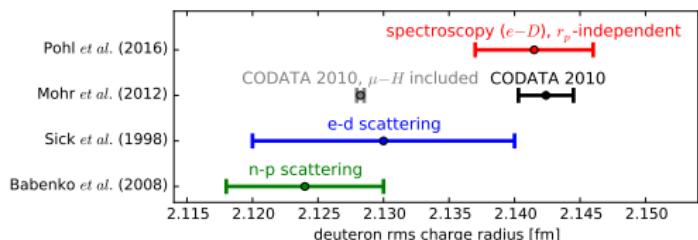
- ▶ Reduce background from target walls
- ▶ Reduce secondary scattering:
 - ▶ target frame
 - ▶ spectrometer entrance window
- ▶ → Use gas jet target of planned MAGIX experiment at MESA



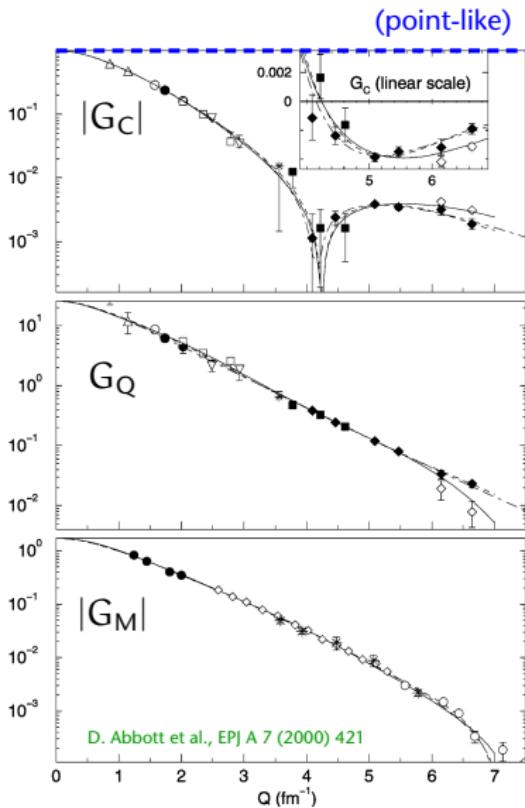
Deuteron charge form factor

Measurement of deuteron radius

- ▶ Proton radius puzzle → deuteron radius
- ▶ Radius from μ -deuterium (CREMA)
- ▶ Improve ed scattering result



- ▶ 3 e. m. form factors: G_C , G_Q , G_M
- ▶ $\langle r^2 \rangle = -6\hbar^2 \left. \frac{dG_C}{dQ^2} \right|_{Q^2=0}$
- ▶ Low Q^2 dominated by charge form factor (G_C vs. $Q^2 G_M$ vs. $Q^4 G_Q$)

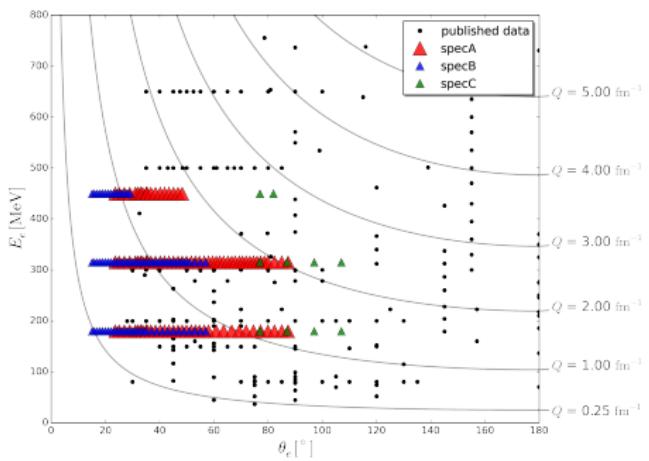


Deuteron charge form factor: Experiment

MAMI $d(e, e')d$ experiment

- ▶ 200 kinematics settings
- ▶ Small scattering angles preferred
- ▶ High redundancy
- ▶ Measure down to $Q^2 = 0.0022 \text{ GeV}^2/c^2$ or 0.057 fm^{-2}

Data taking completed in 2014



Kinematics settings vs. world data

Deuteron charge form factor: Data analysis

Preliminary – not for quotation!

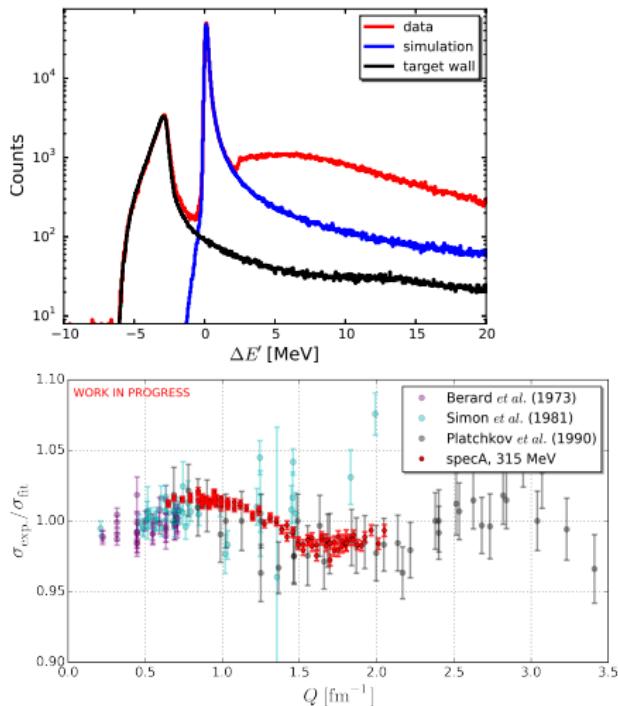
MAMI $d(e, e')d$ experiment

- ▶ Data analysis ongoing
- ▶ Additional backgrounds (as compared to $p(e, e')p$):
 - ▶ Target walls ($m_d \approx 2m_p$)
 - ▶ Deuteron breakup

Yvonne Kohl, PhD thesis

Follow-up experiments

- ▶ Precise study of deuteron breakup
→ deuteron polarizability
- ▶ Form factor of ^3He



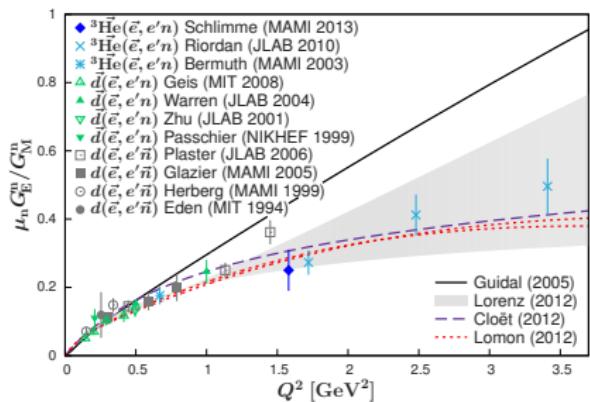
Electric form factor of the neutron

Motivation:

- ▶ Consistent data for large Q^2 range
- ▶ Structure in G_E^n at $0.3 \text{ GeV}^2/c^2$?
- ▶ Tension between D and ${}^3\text{He}$ data

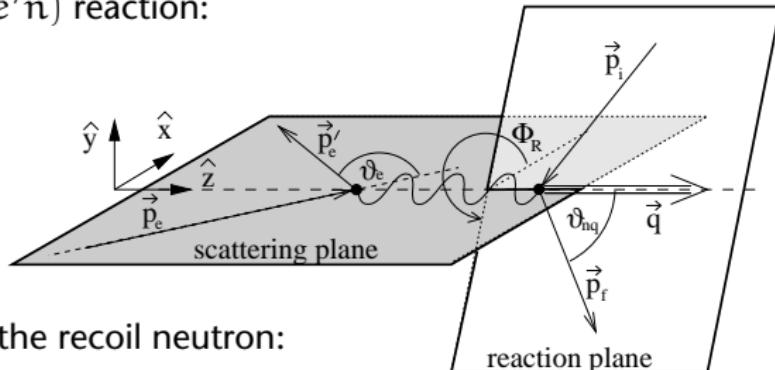
Experimental intricacies:

- ▶ No free neutron target
- ▶ $G_E^n \ll G_M^n$
⇒ Rosenbluth method infeasible
- ▶ Double polarization experiments
 ${}^2\text{H}(\vec{e}, e' \vec{n})$ or ${}^3\text{He}(\vec{e}, e' \vec{n})$



Double polarization experiments

Kinematics of the $n(\vec{e}, e'n)$ reaction:



Polarization transfer to the recoil neutron:

Arnold, Carlson, Gross, PRC 23 (1981) 363

$$P_x = -P_e \frac{2\sqrt{\tau(1+\tau)} \tan(\theta/2) G_E G_M}{G_E^2 + \tau G_M^2 (1 + 2(1+\tau) \tan^2(\theta/2))}$$

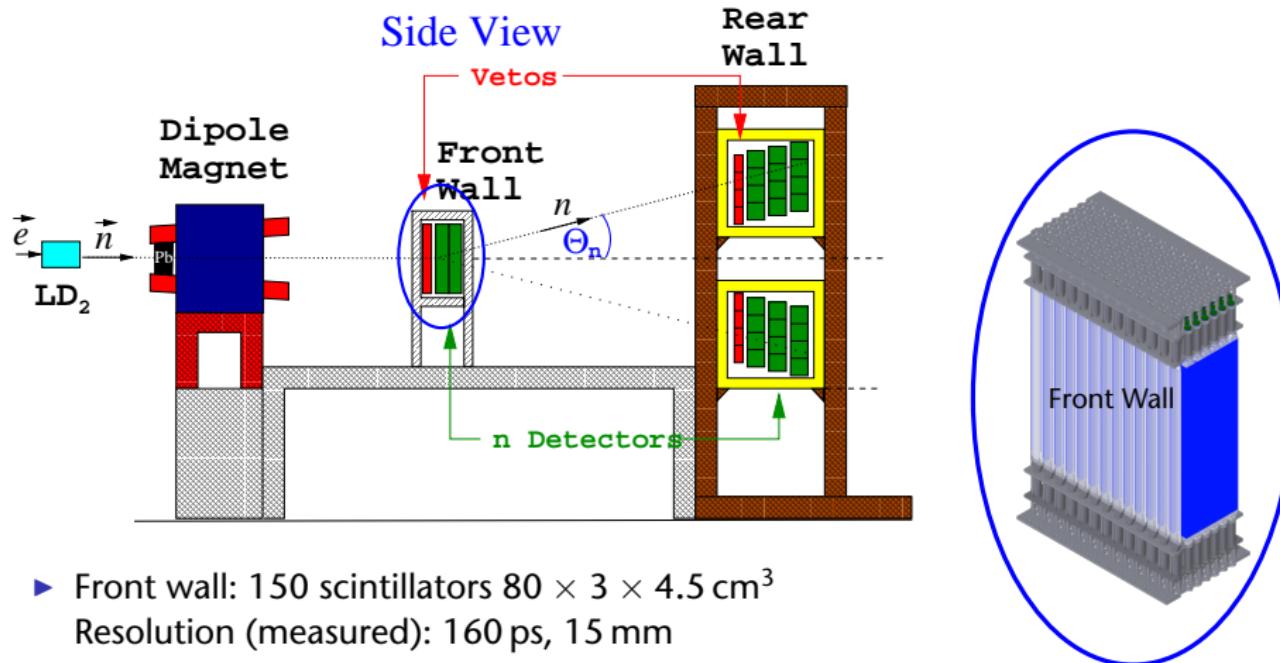
$$P_y = 0$$

$$P_z = P_e \frac{2\tau\sqrt{1+\tau + (1+\tau)^2 \tan^2(\theta/2)} \tan(\theta/2) G_M^2}{G_E^2 + \tau G_M^2 (1 + 2(1+\tau) \tan^2(\theta/2))}$$

P_x contains interference term $G_E^n G_M^n$.

Equivalent terms appear for the asymmetry in $\vec{n}(\vec{e}, e'n)$ scattering.

Design of the A1 neutron recoil polarimeter



- ▶ Front wall: 150 scintillators $80 \times 3 \times 4.5 \text{ cm}^3$
Resolution (measured): 160 ps, 15 mm
- ▶ Rear wall: 96 scintillators $170 \times 10 \times 10 \text{ cm}^3$
(with gap at height of beam)
- ▶ Veto scintillators in front of each wall

Summary

Elastic electron-proton scattering

- ▶ High precision data from MAMI: Q^2 range from 0.004 to 1 GeV^2/c^2
- ▶ Data taken up to $Q^2 = 2 \text{ GeV}^2/\text{c}^2$, results upcoming

Initial State Radiation

- ▶ Successful pilot experiment for Q^2 down to 0.001 GeV^2/c^2
- ▶ Next generation experiments with gas jet target planned at MAMI and MESA
→ Will eliminate background from target walls

Deuteron charge radius

- ▶ Data analysis ongoing
- ▶ Follow-up experiments on other light nuclei

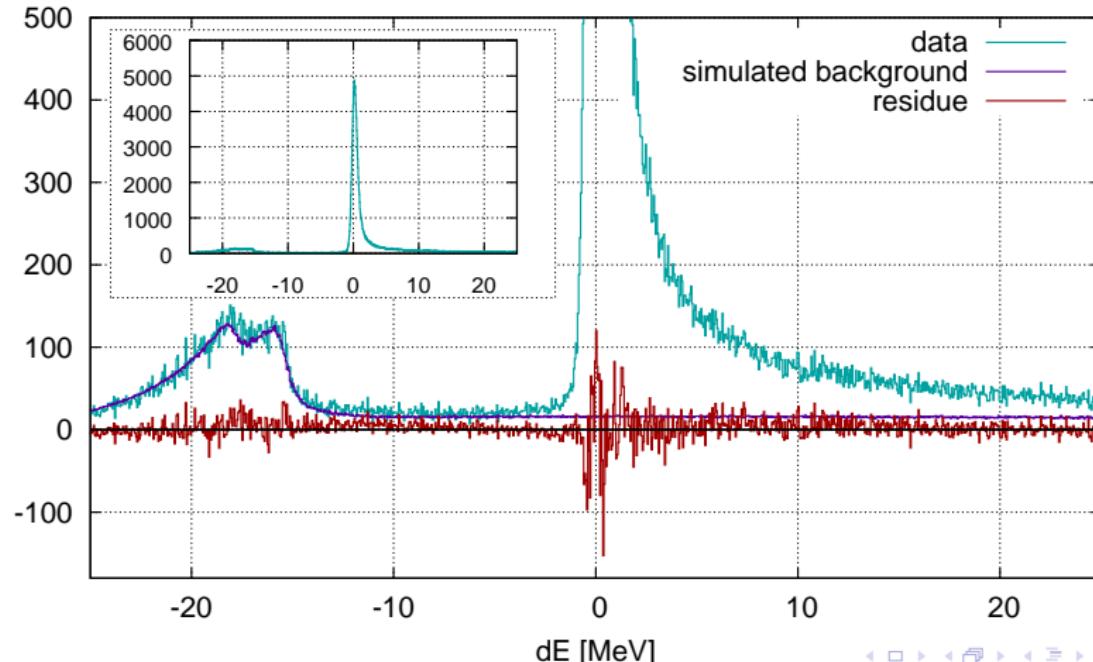
Neutron electric form factor

- ▶ New highly segmented neutron polarimeter under construction

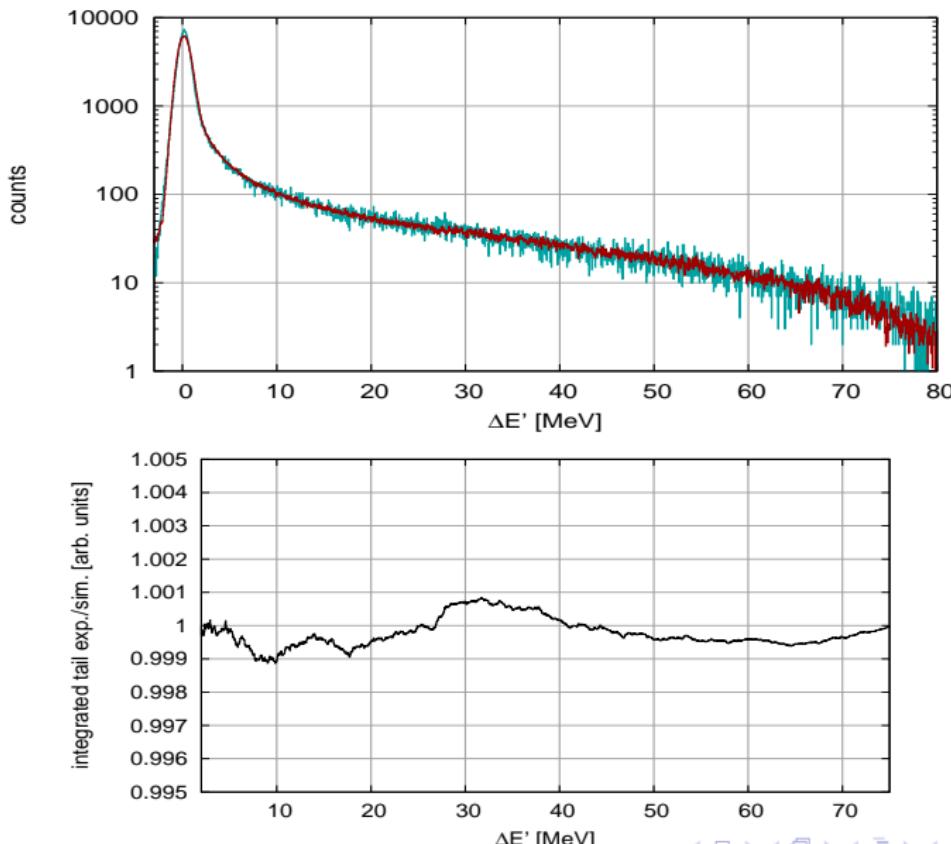
Proton form factors: Background subtraction

Simulation:

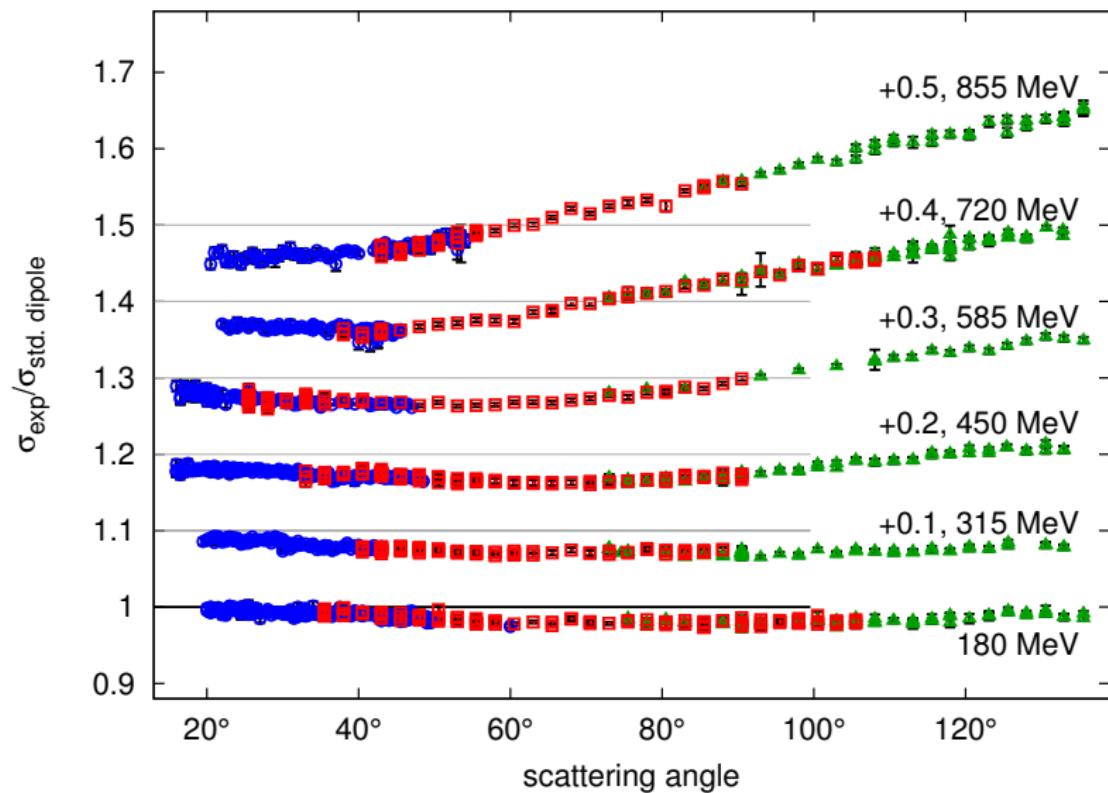
- ▶ Background from elastic and quasi-elastic scattering at target walls
- ▶ Model for energy loss and small angle scattering
- ▶ Input: momentum-, angular-, vertex resolution



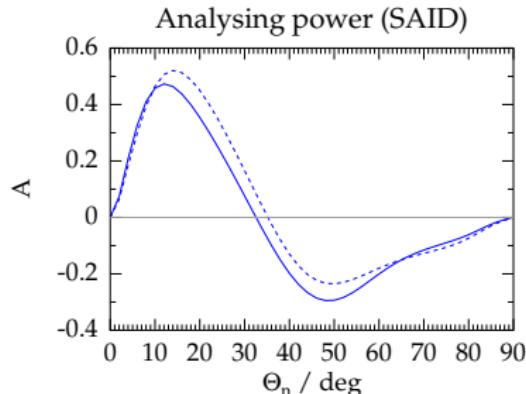
Description of the radiative tail



Cross sections / standard dipole



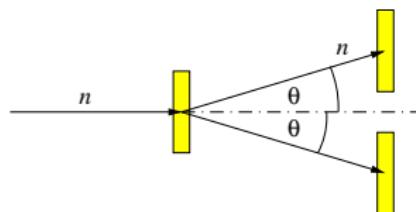
Neutron polarimetry



Elastic scattering of polarized neutrons at unpolarized protons has analysing power $\epsilon(\theta_n)$ due to spin-orbit term V_{LS} in NN interaction: This leads to a ϕ asymmetry for the outgoing neutron:

$$I(\theta_n) = I_0 \cdot [1 + \epsilon(\theta_n)(P_x \cos \phi_n + P_y \sin \phi_n)] \underbrace{= 0}_{= 0}$$

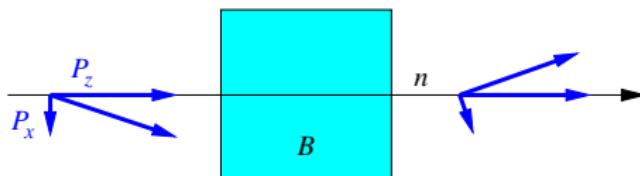
- ▶ Analysing reaction $p(n, n'p)$ in scintillation detector
- ▶ Detection of outgoing neutron (or proton) in second scintillator



Problem: Also reactions $^{12}\text{C}(n, n'p)$ in scintillator with unknown analysing power.
Effective analysing power has to be calibrated!

Spin precession method

Calibration of the analysing power can be avoided by rotating the neutron spin direction in the xz plane:



Precession angle:

$$\chi = \frac{2\mu_n}{\hbar c} \cdot \beta_n^{-1} \int B dl = \frac{-35.02^\circ}{Tm} \cdot \beta_n^{-1} \int B dl$$

Transverse polarization (and therefore asymmetry) after the magnet:

$$P_{\perp} = P_x \cos \chi - P_z \sin \chi$$

The **zero crossing** angle χ_0 with asymmetry $A_{\perp}(\chi_0) = 0$ is determined by the ratio A_x/A_z :

$$\tan \chi_0 = \frac{A_x}{A_z} = \frac{P_e \epsilon_{\text{eff}}}{P_e \epsilon_{\text{eff}}} \cdot \frac{-1}{\sqrt{\tau + \tau(1 + \tau) \tan^2(\theta/2)}} \cdot \frac{G_E^n}{G_M^n}$$

independent of the effective analysing power ϵ_{eff} .