

PRECISION FEW-BODY EXPERIMENTS WITH ELECTRON BEAMS

Harald Merkel

Johannes Gutenberg-Universität Mainz

The 22nd European Conference on Few-Body Problems in Physics
Kraków, Poland, 10 September, 2013

- Motivation
- Form Factor of the Proton
 - ▶ Why still form factors? The “Proton Radius Puzzle”
 - ▶ New experimental approaches
- Few body Form Factors
 - ▶ Deuteron charge radius
 - ▶ Neutron form factor
- Concepts for tests of Ab-Initio-Calculations
 - ▶ MESA Accelerator
- Summary

Form Factor of the Nucleon

Elastic Cross Section (Rosenbluth-Formula):

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

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

$G_E(Q^2)$: Electric Form Factor → related to charge distribution

$G_M(Q^2)$: Magnetic Form Factor → related to distribution of magnetic moments

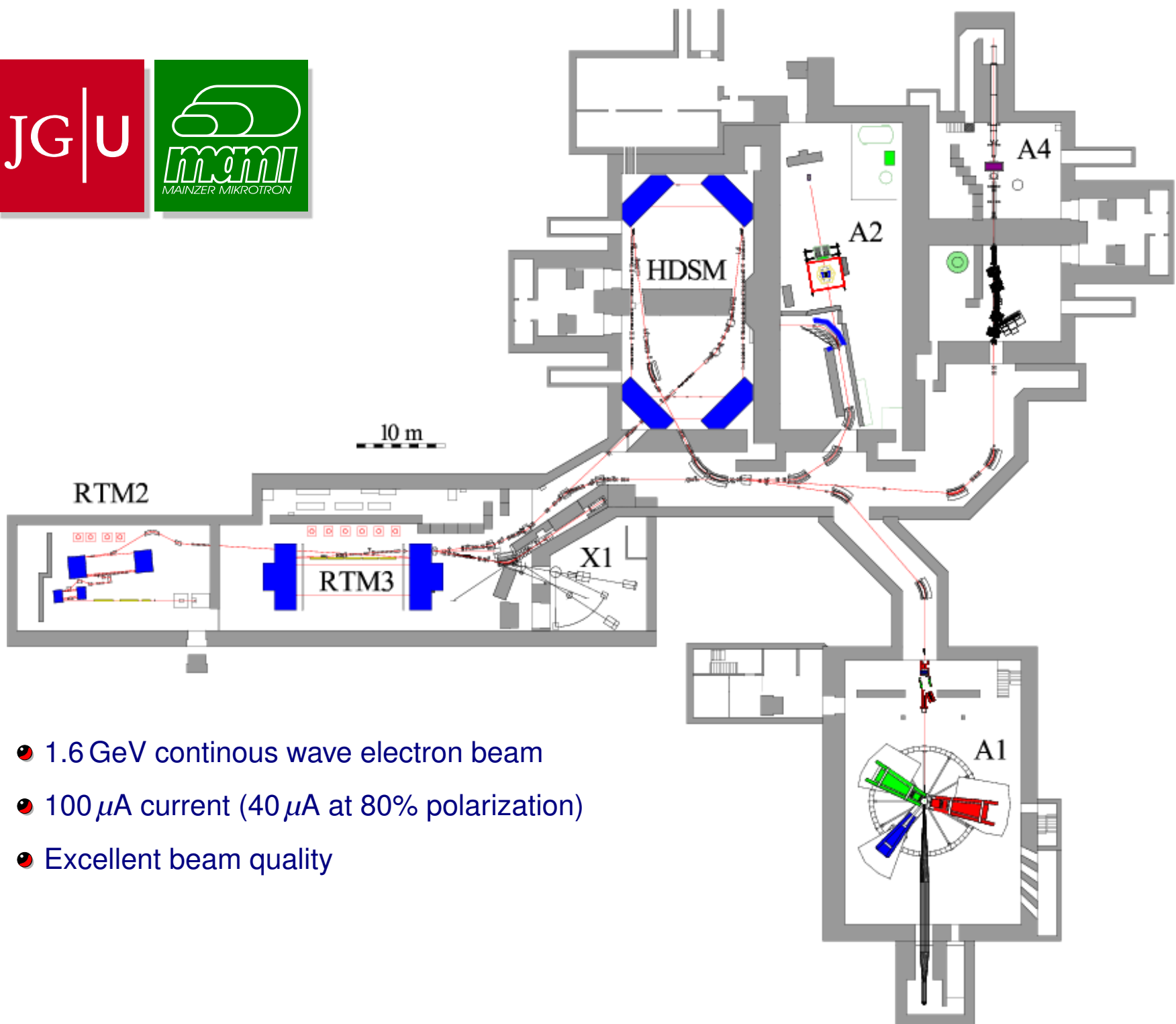
Normalization:

$$G_E^p(Q^2 = 0) = 1 \qquad G_E^n(Q^2 = 0) = 0$$
$$G_M^p(Q^2 = 0) = 2.79 \qquad G_M^n(Q^2 = 0) = -1.91$$

Root-Mean-Square Radius:

$$\langle r_E^2 \rangle = -6 \frac{d}{dQ^2} G_E(Q^2) \Big|_{Q^2=0}$$

$$\langle r_M^2 \rangle = -\frac{6}{\mu_p} \frac{d}{dQ^2} G_M(Q^2) \Big|_{Q^2=0}$$



- 1.6 GeV continuous wave electron beam
- 100 μA current (40 μA at 80% polarization)
- Excellent beam quality

A1: Spectrometer setup at MAMI



Spectrometer A:

$$\alpha > 20^\circ$$

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

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

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

Spectrometer B:

$$\alpha > 8^\circ$$

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

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

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

Spectrometer C:

$$\alpha > 55^\circ$$

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

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

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

$$\delta p/p < 10^{-4}$$

Ingredients for a Precision Measurement

- Statistical error: 0.2% in less than 20 min!

- Systematic error:

 - ▶ Detector efficiency

 - ⇒ Overlap in acceptance (every angle $4\times$)

 - ⇒ Where possible, every angle with two spectrometers

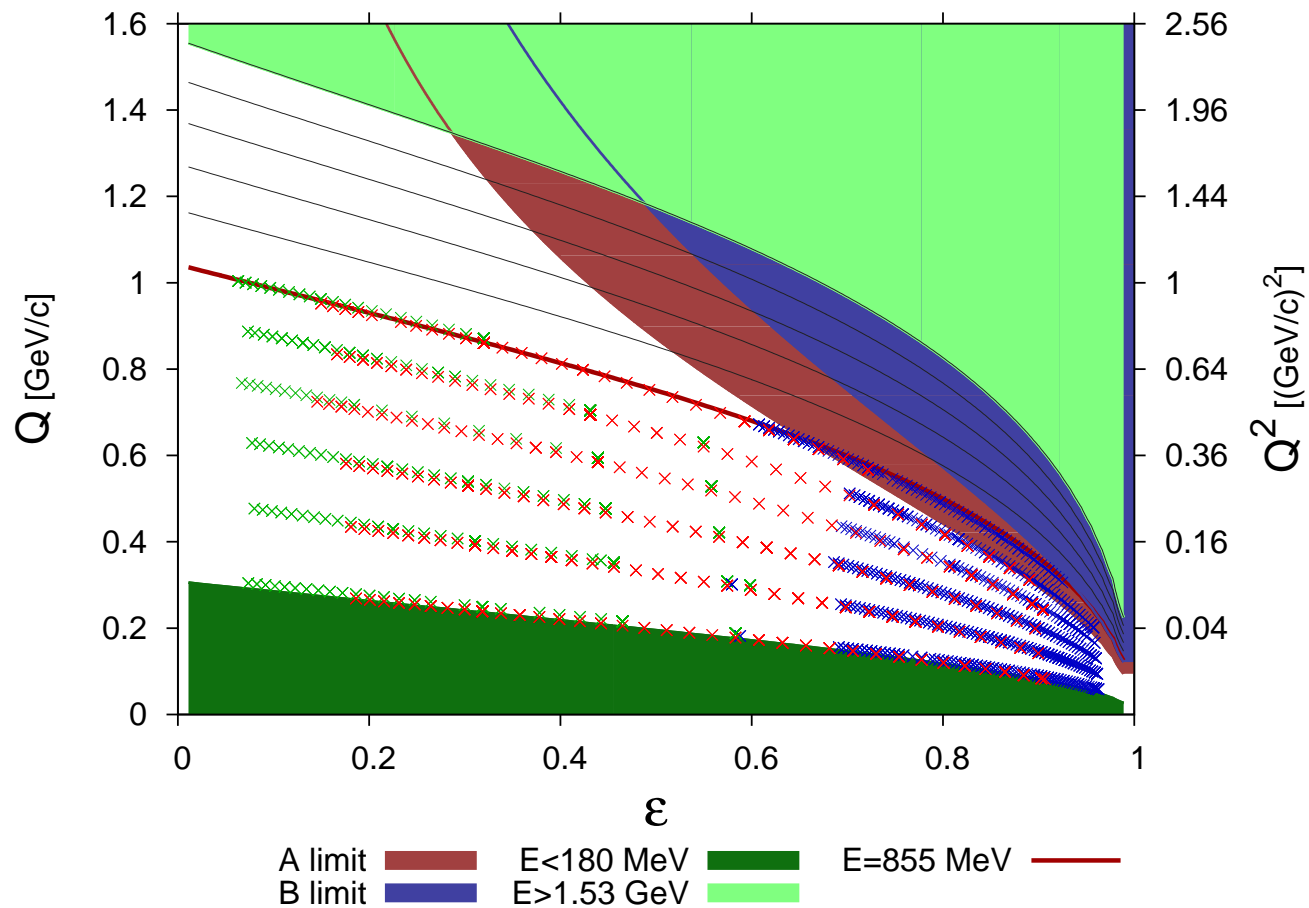
 - ▶ Luminosity over 4 orders of magnitude ($I_{\text{beam}} = 0.5 \text{ nA} - 10 \mu\text{A}$)

$$L \propto I_{\text{beam}} \times \rho_{\text{target}} \times l_{\text{target}}$$

 - ⇒ Current with Foerster probe (flux-meter, 90 turns in MAMI)
Pico-ampere Meter (direct measurement)

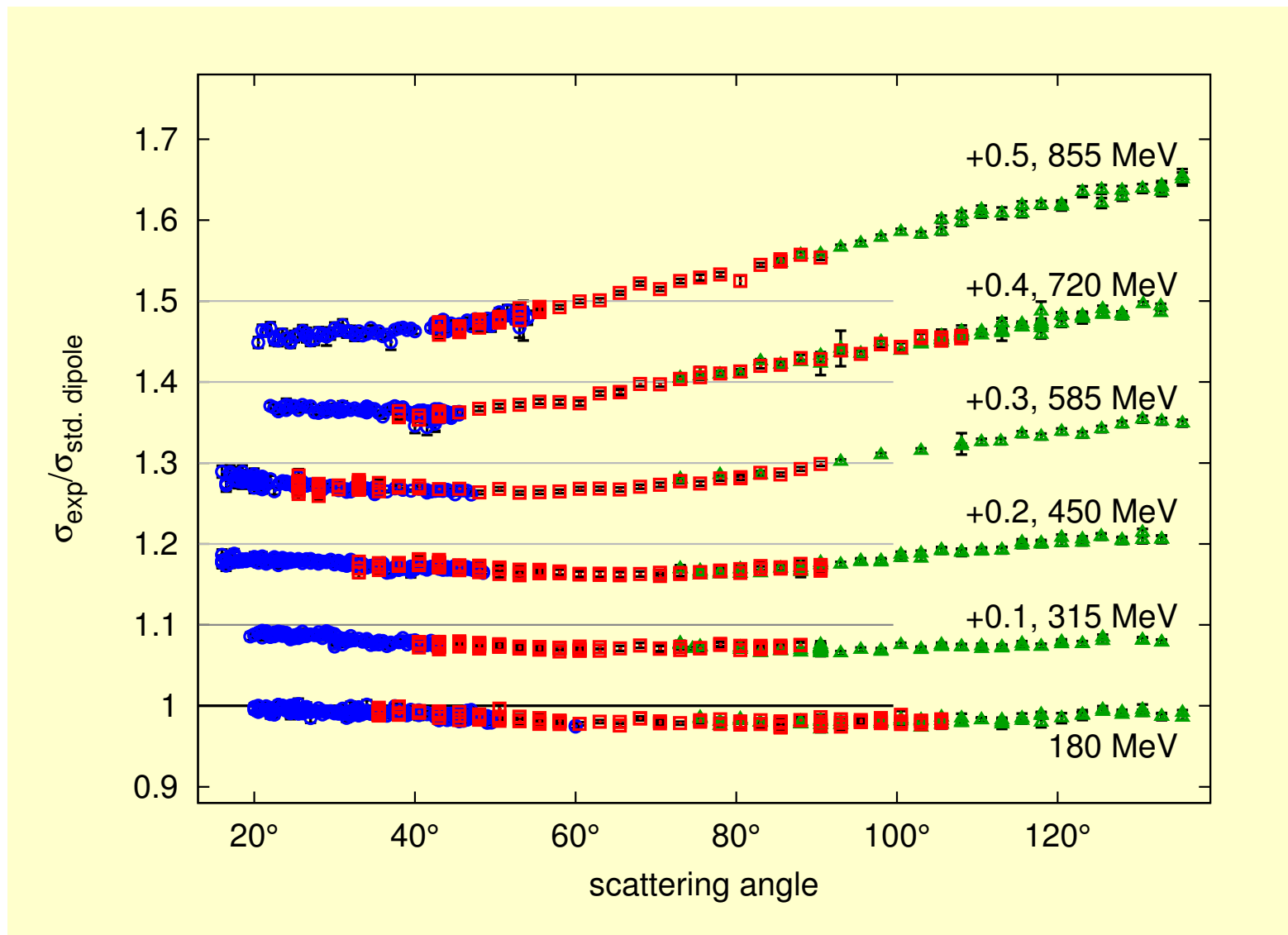
 - ⇒ Two spectrometer for measurement, third at fixed position

Kinematic Coverage



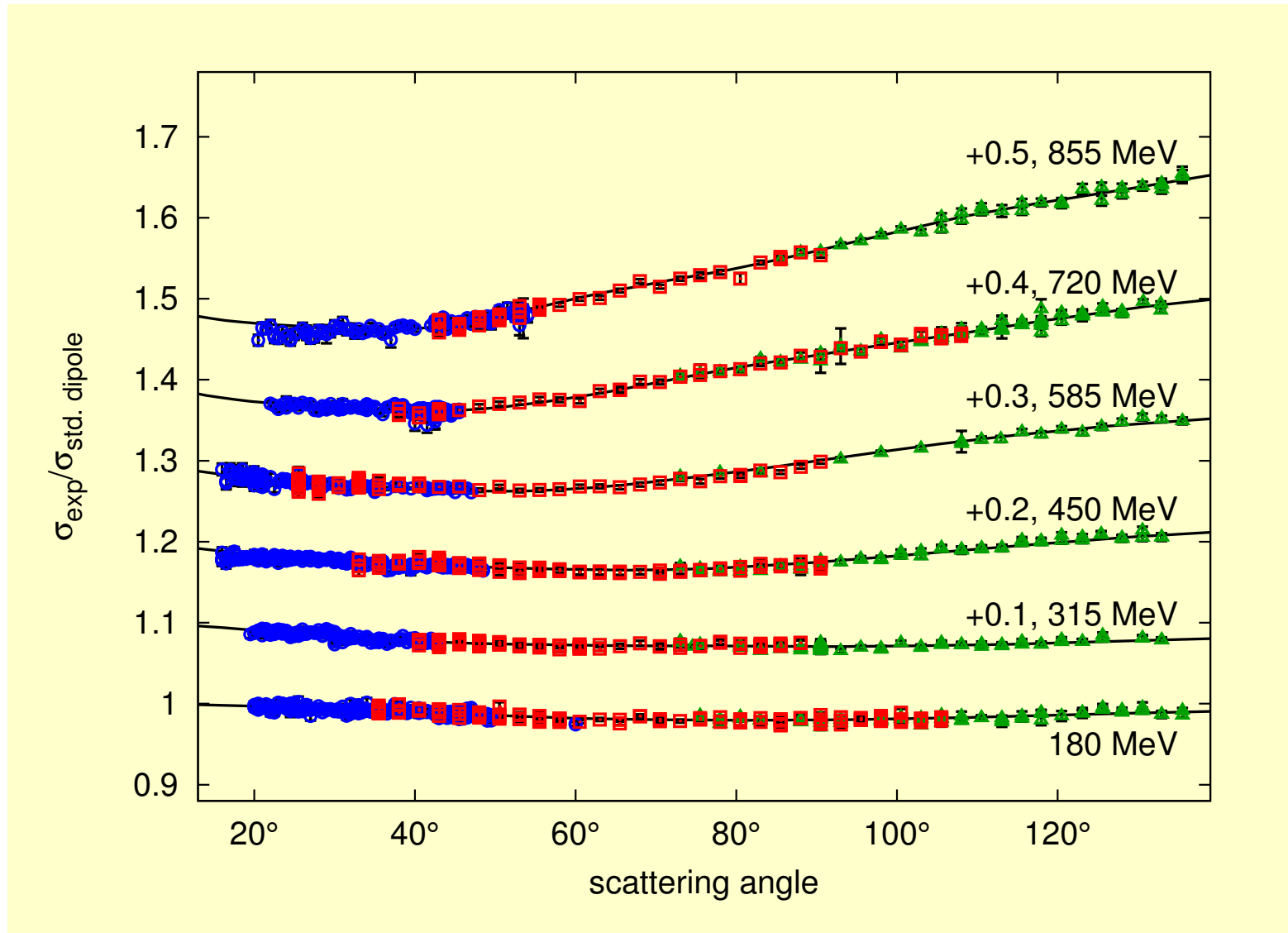
- ~ 1000 settings
- Remote control of the Spectrometer angles
- 10^9 Events

Cross Section Data



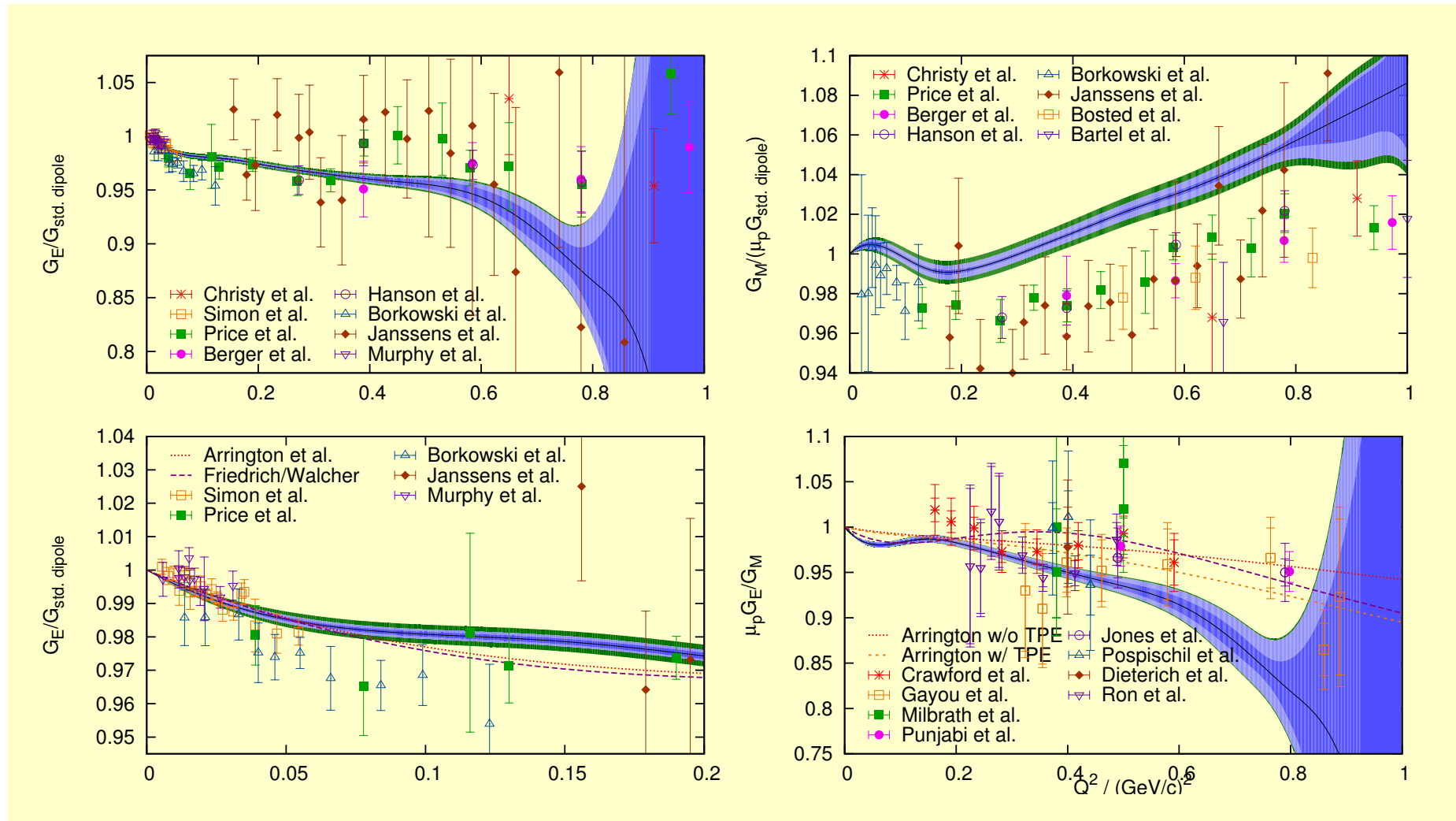
◆ ■ † Data spectrometer A, B, C, error bars by spread of data → 0.2% – 0.4% (stat.: 0.1% – 0.3%)

Rosenbluth-Separation by Fit



• □ ▲ Data spectrometer A, B, C, error bars by spread of data → 0.2% – 0.4% (stat.: 0.1% – 0.3%)
— Spline fit

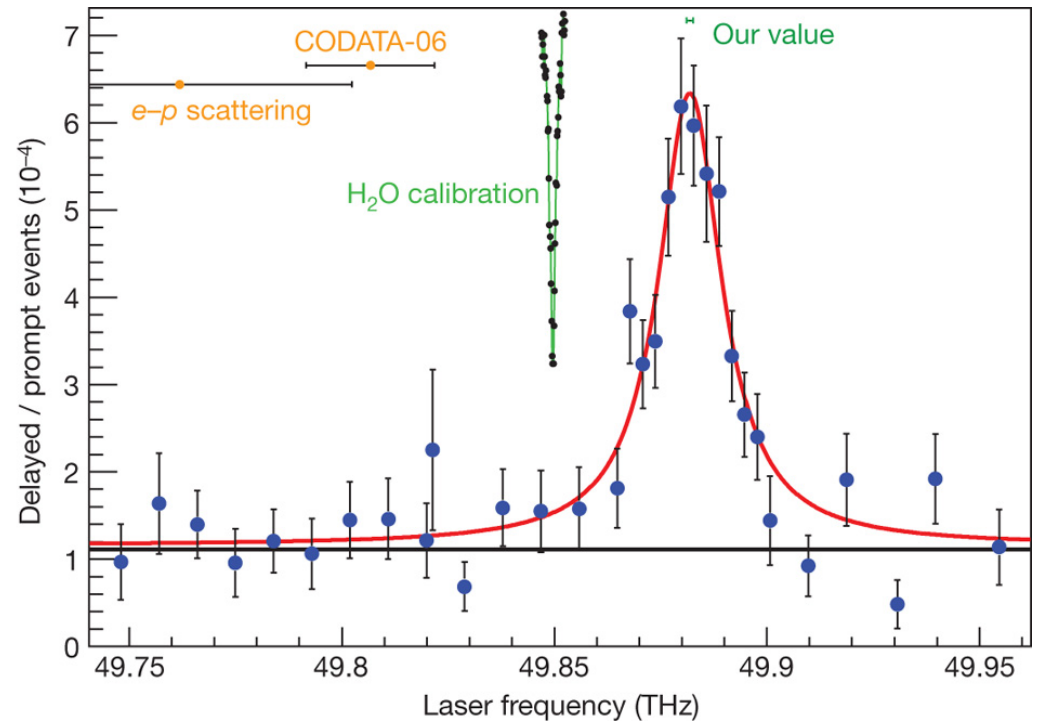
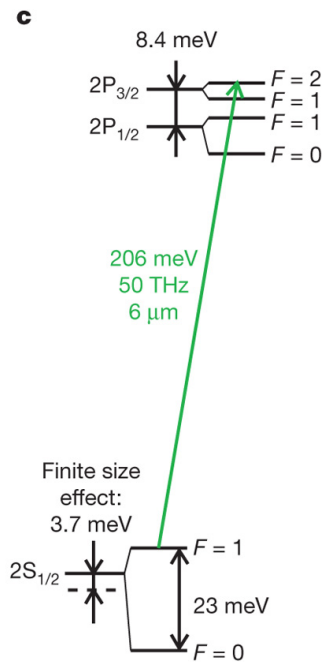
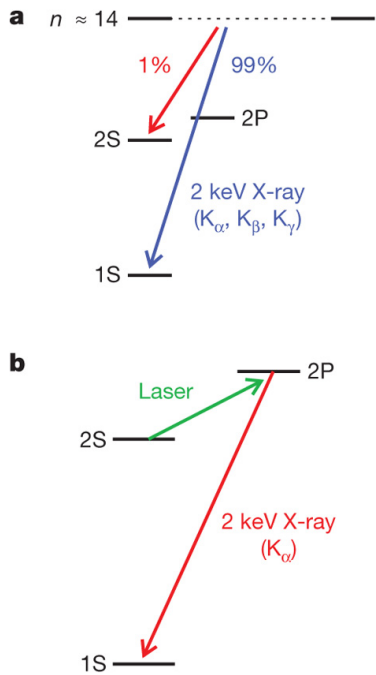
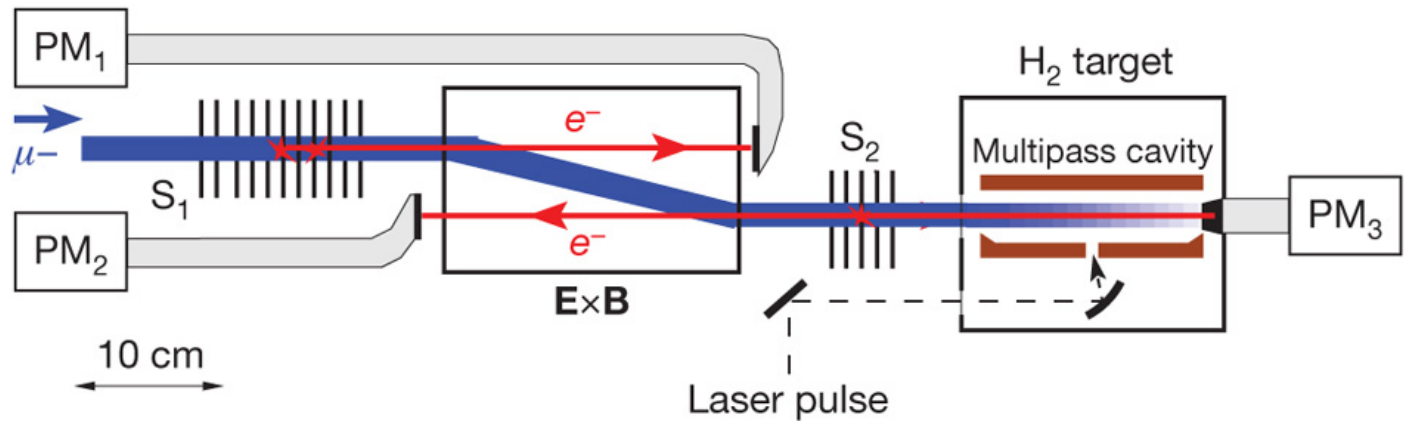
Form factor results



The Radius Puzzle: Lamb shift in μH -Atom

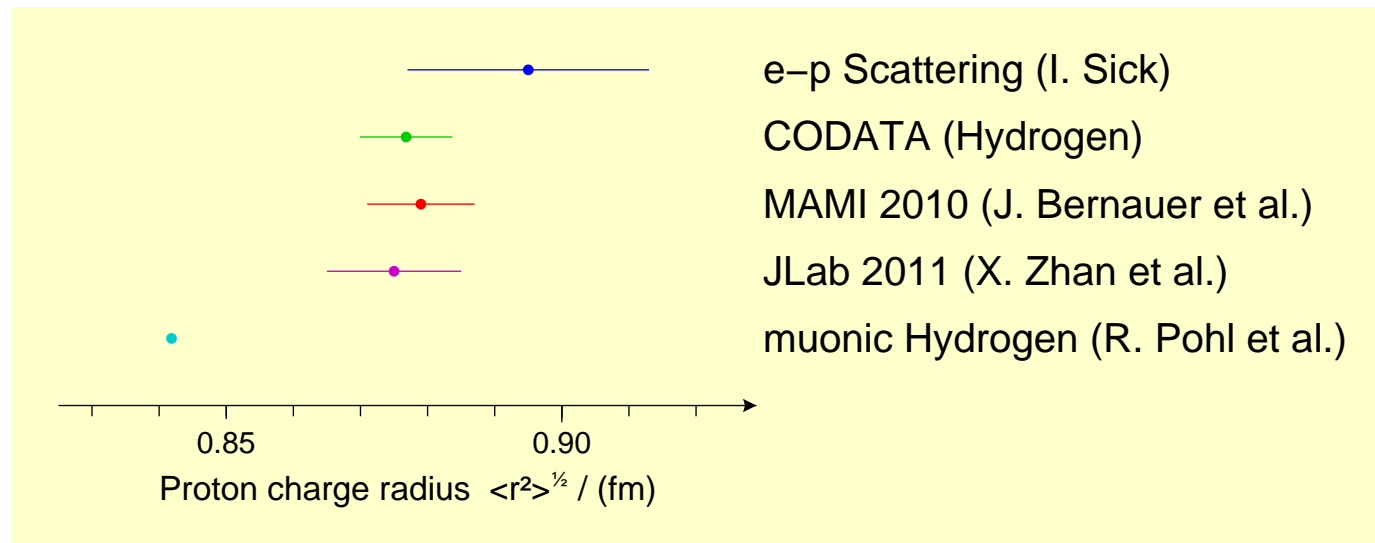


Nature **466**, 213-216 (8 July 2010)



Radius of the Proton

$$r_e = 0.879 \pm 0.005_{\text{stat.}} \pm 0.004_{\text{syst.}} \pm 0.002_{\text{model}} \pm 0.004_{\text{group}} \text{ fm},$$
$$r_m = 0.777 \pm 0.013_{\text{stat.}} \pm 0.009_{\text{syst.}} \pm 0.005_{\text{model}} \pm 0.002_{\text{group}} \text{ fm}.$$

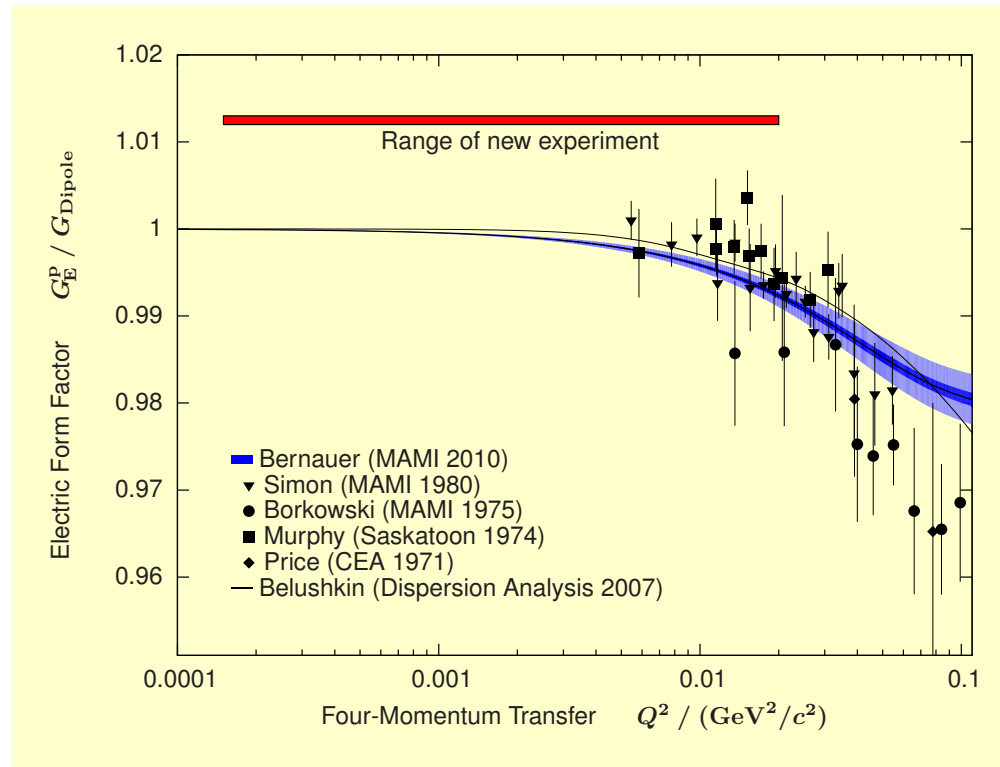


- $e - p$ results are consistent!
- $e - p$ results are consistent with hydrogen atoms
- Significant discrepancy to **muonic hydrogen atoms**
- Challenge to precision QED calculations

(→ I. Sick, Session C5)

r_p via Initial State Radiation

Possible Improvements on Proton Radius

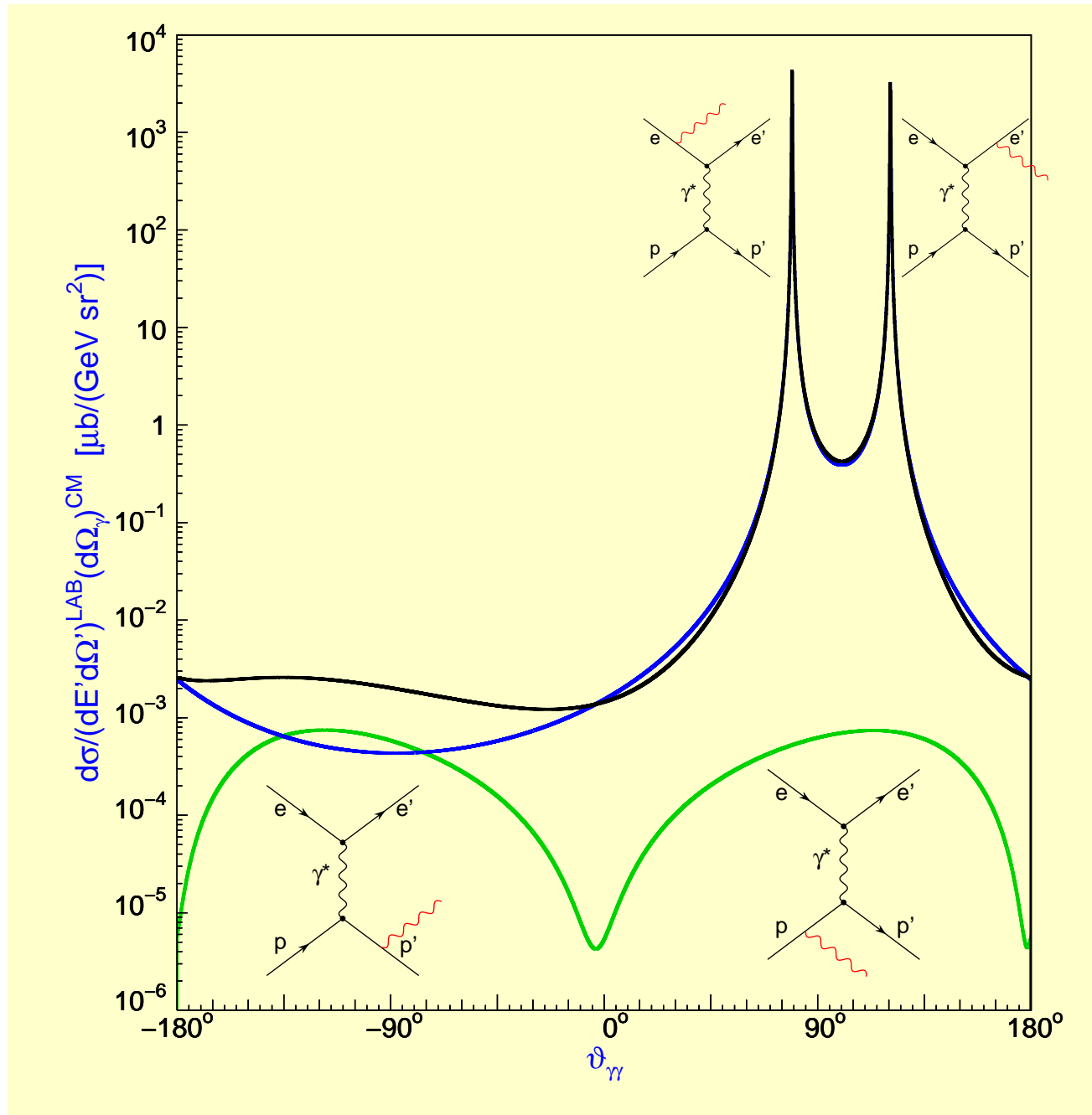


Where should we determine the root-mean-square-radius?

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

- Extrapolation to $Q^2 = 0$, no absolute cross section!
- Sufficient “Lever arm” for radius determination $\rightarrow Q^2 \approx 0.2 \text{ GeV}^2/c^2$
- Reduction of higher orders \rightarrow linear fit

Virtual Compton Cross Section $H(e, e')p\gamma$



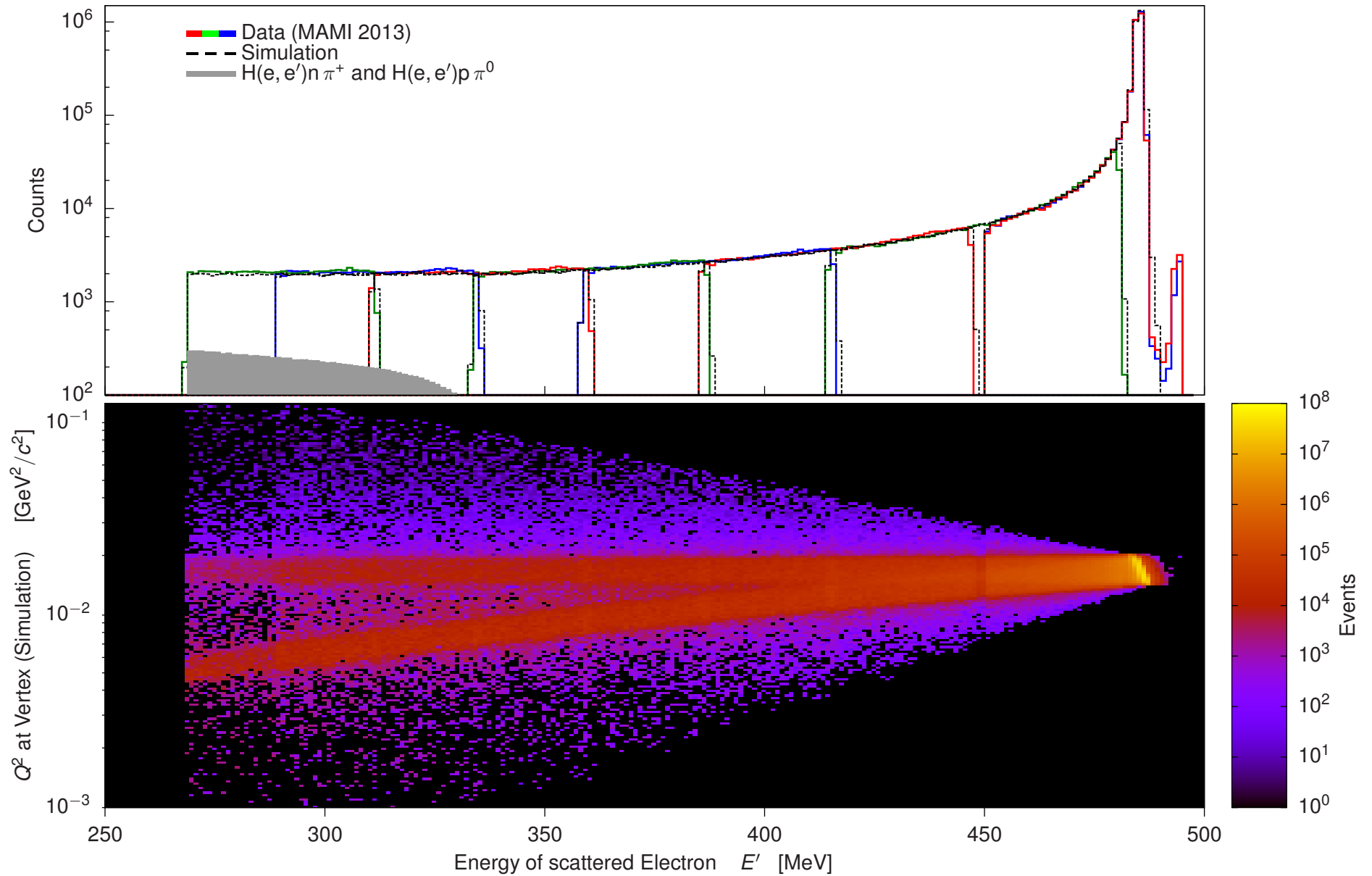
Initial state radiation

$$d\sigma \approx \left| \begin{array}{c} \text{Diagram 1: } e \text{ emits } \gamma \text{ before } \gamma^* \text{ exchange} \\ \text{Diagram 2: } e \text{ emits } \gamma \text{ after } \gamma^* \text{ exchange} \end{array} \right|^2$$

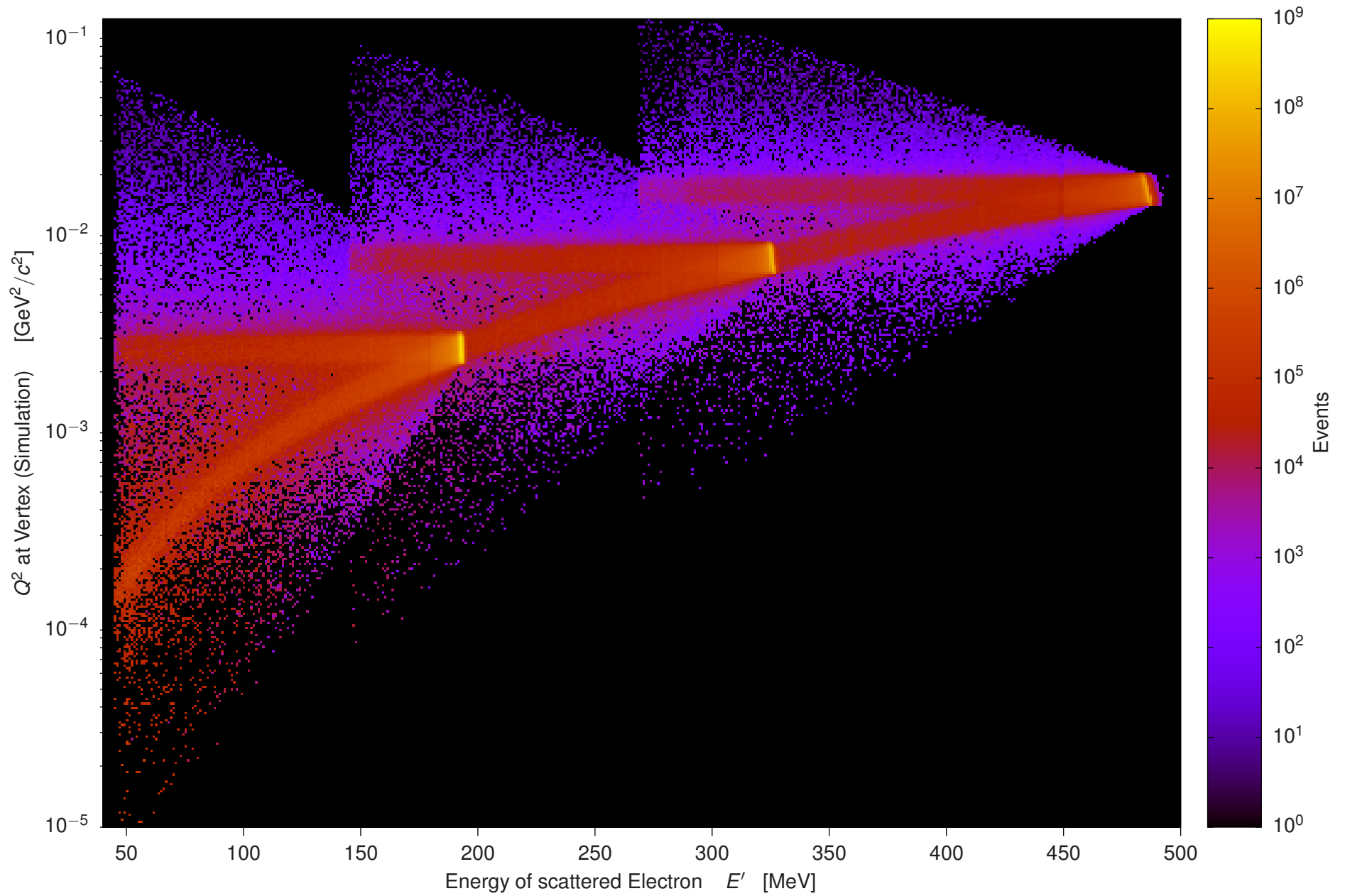
The diagram shows two Feynman diagrams for electron-proton scattering, enclosed in large vertical brackets with a superscript 2. The left diagram represents initial state radiation: an incoming electron (e) emits a photon (red wavy line) before interacting with a proton (p) via a virtual photon (gamma*). The outgoing particles are an electron (e') and a proton (p'). The right diagram represents final state radiation: an incoming electron (e) interacts with a proton (p) via a virtual photon (gamma*), and then emits a photon (red wavy line) before becoming an outgoing electron (e'). The outgoing proton is p'.

- $H(e, e')p\gamma$ Cross section dominated by Initial/Final State Radiation
- Final State Radiation: Four-Momentum-Transfer Q^2 constant
- Initial State Radiation: Continuous Q^2 range
- Experiment
 - ▶ First spectrometer for “Normalization” at elastic peak
 - ▶ Start with second spectrometer setup at elastic peak
 - ▶ Measurement of the radiative tail
by change of the magnetic field of second spectrometer
 - ▶ Keep *everything* else constant!

Initial State Radiation

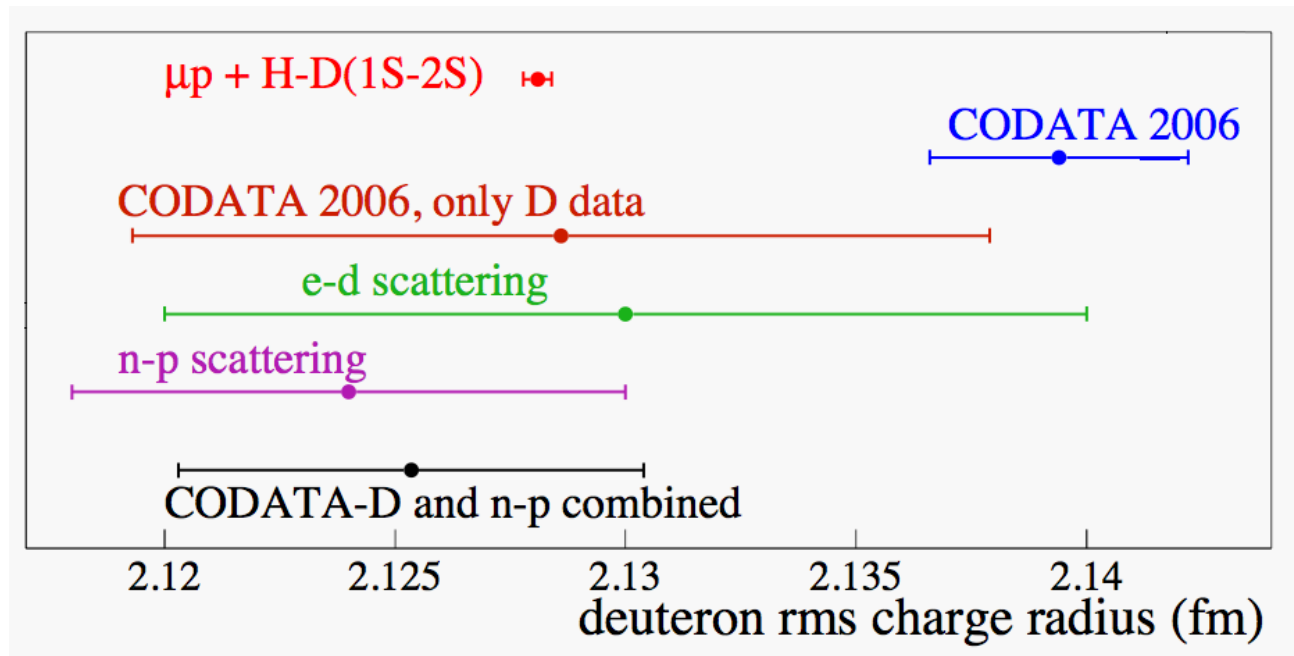


Initial State Radiation



Charge radius of Few-Body-Systems

From Hydrogen to Few-Body-Systems



- Precision Lamb-Shift/Hyperfine measurements available up to ^8He
- Muonic Deuterium Atom measured at PSI
- Deuteron
 - ▶ Isotope shift for e^- -Deuteron/Hydrogen atoms
→ reduced systematic uncertainties
 - ▶ Large contribution of the electric radius for the deuteron
 - ▶ Electron scattering data “room for improvement”

Deuteron form factor: Elastic scattering from Deuteron

- Unpolarized Cross Section for Spin-1 Target:

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

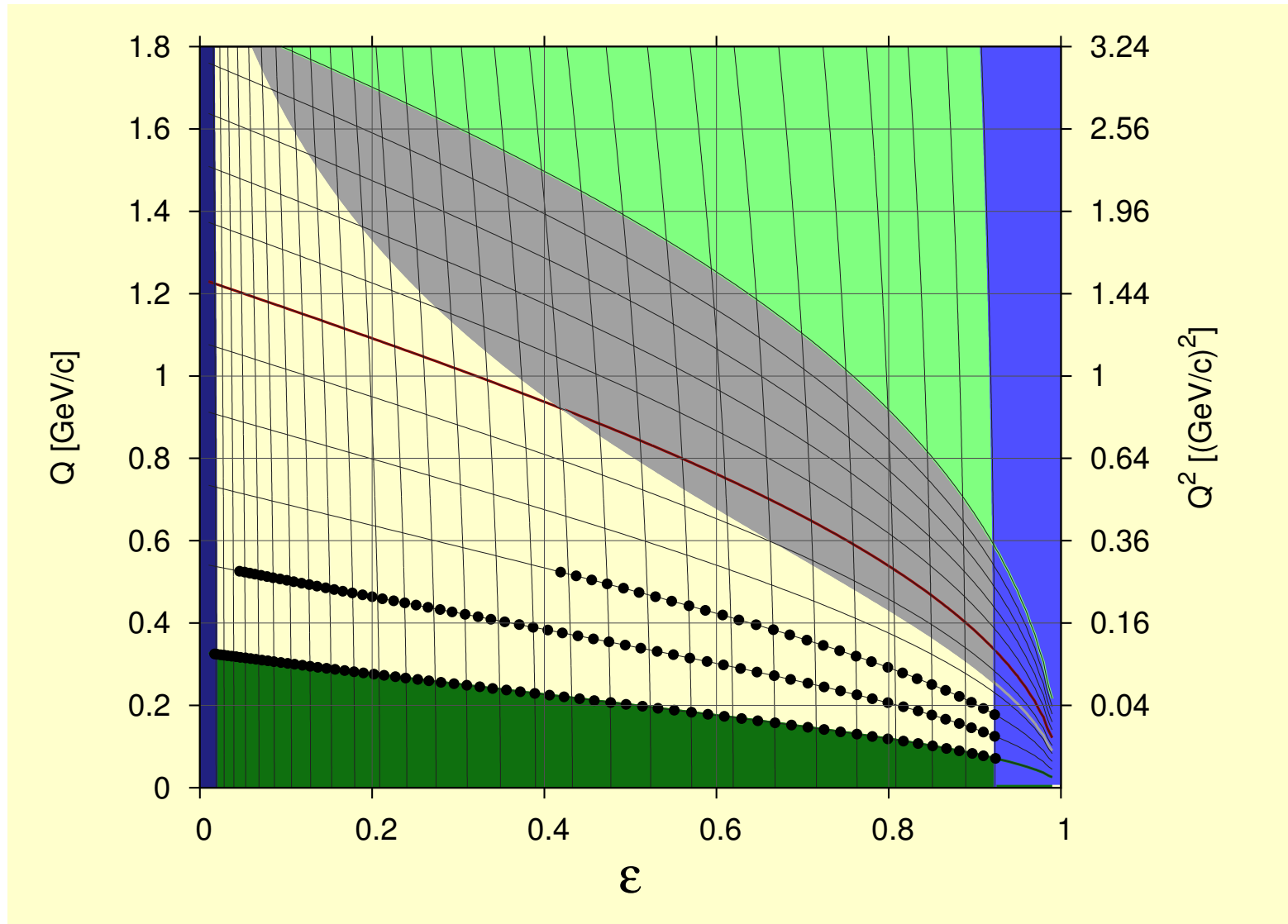
- With Form Factors:

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

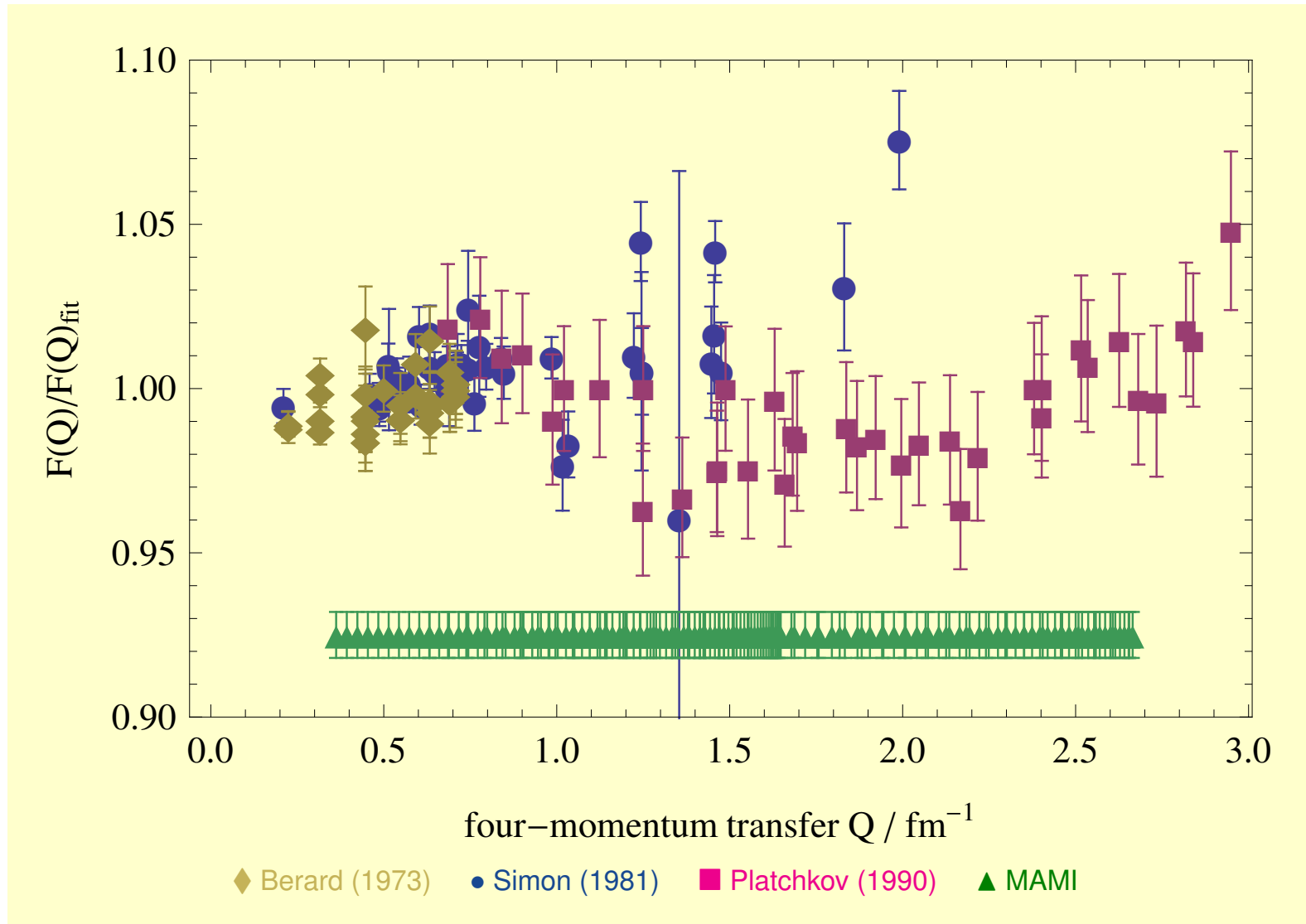
$$B(Q^2) = \left(\frac{M_d}{M} \mu_d \right)^2 \frac{4}{3} \eta(1 + \eta)^2 F_{M1}^2(Q^2)$$

- Charge Radius by $F_{C0}(Q^2)$

Deuteron form factor: Coverage



Deuteron form factor



Experimental Program

- Deuterium $d(e, e')d$

- ▶ Accepted proposal
- ▶ Experiment in preparation (beginning of 2014)

- Helium-3

- ▶ Muonic atom planned at PSI
- ▶ Target material available
- ▶ Similar technique as Hydrogen/Deuteron experiments

⇒ Proton Radius Puzzle will be tackled by several electron scattering experiments

⇒ Complementary to corresponding atomic physics experiments

⇒ Huge impact outside hadron physics community!

Neutron Form Factors

Neutron Form Factors

- Increasing interest in Neutron Form Factor:

- ▶ Ultimate goal: Understand the nucleon structure from fundamental interaction (QCD)
- ▶ Promising tool: Lattice-QCD
- ▶ Technical challenge: Isospin decomposition

$$\begin{array}{ll} \text{Iso-scalar:} & F_s(Q^2) = F_p(Q^2) + F_n(Q^2) & \text{Difficult: Disconnected Loop-Graphs} \\ \text{Iso-vector:} & F_v(Q^2) = F_p(Q^2) - F_n(Q^2) & \text{Increased predictive power!} \end{array}$$

⇒ Experimental tests of Lattice QCD only as good as the *Neutron Form Factors*!

- Impressive experimental progress over last decades

- ▶ No free Neutron target: Few-Body-targets D, ^3He
- ▶ $G_E^n(Q^2)$ small for neutral particle: Double polarization techniques

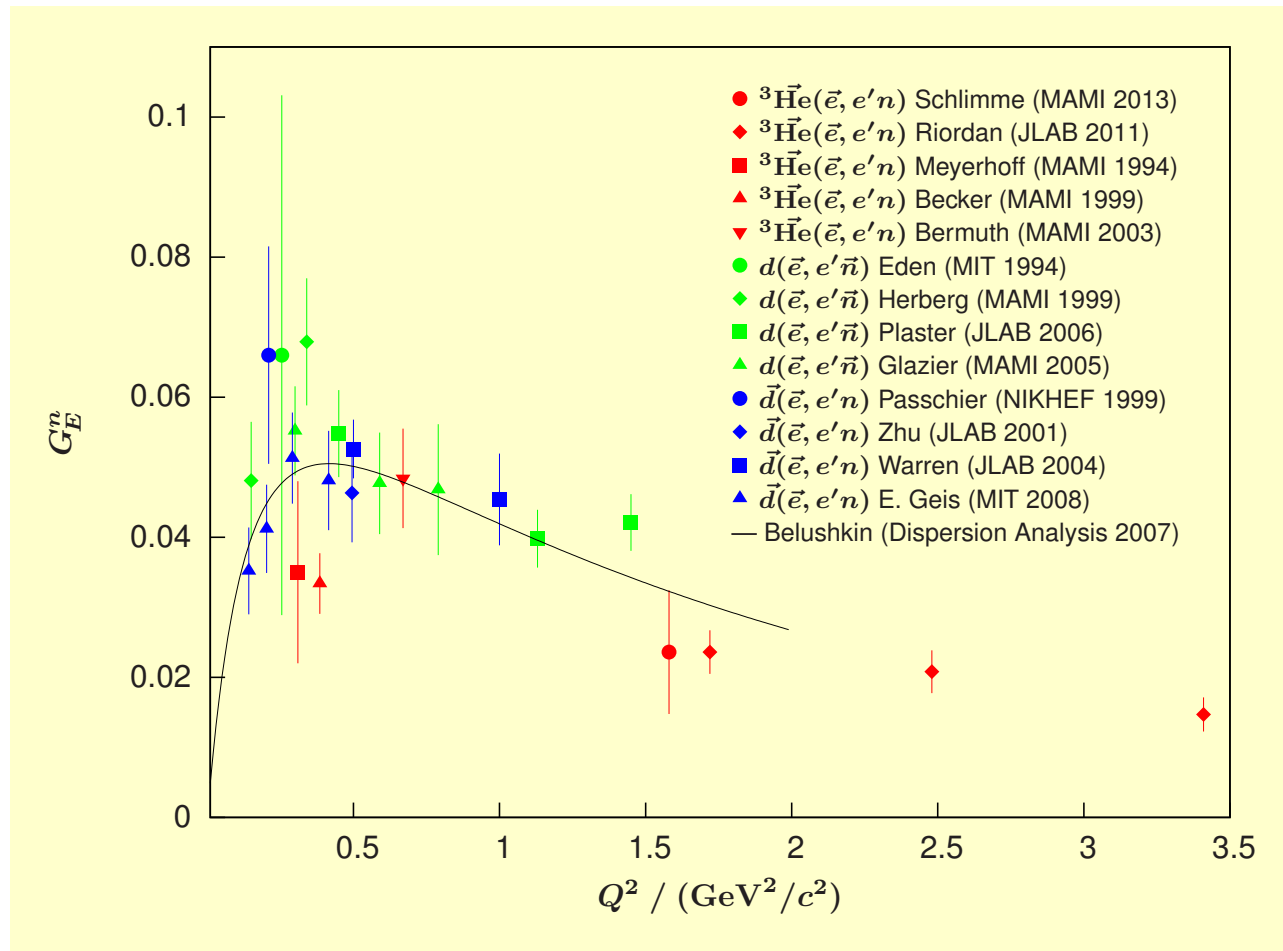
$d(\vec{e}, e'\vec{n})p$ sensitivity at low four-momentum transfer

$^3\vec{\text{He}}(\vec{e}, e'n)$ Large corrections at low momenta, superior at high momenta

- Still inconsistent data sets

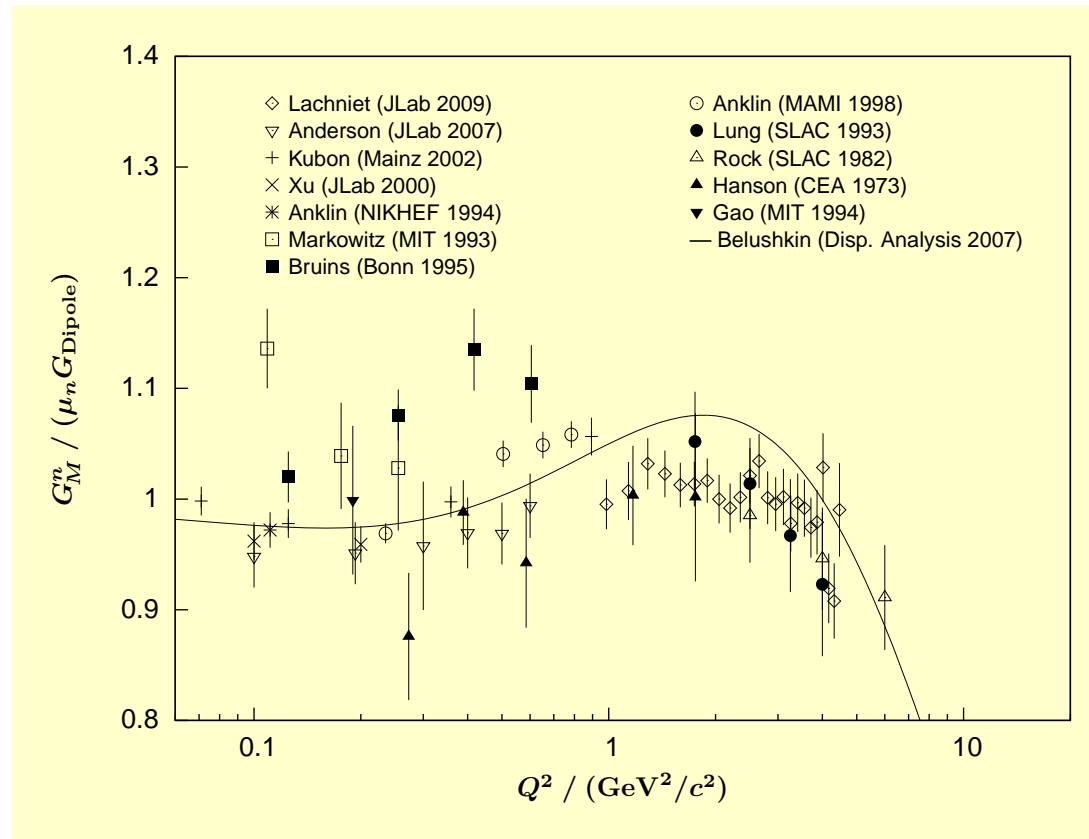
From pioneering experiments → precision coverage of whole Q^2 range

Electric form factor of the neutron: G_E^n (double Polarization)



- Single data point per experiment: Systematics
- Consistent Coverage needed
- Choice at low four-momentum-transfer Q^2 : $d(\vec{e}, e'\vec{n})$

Magnetic form factor of the neutron



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

Next generation Neutron-Detector

- Severe limits by existing neutron detectors

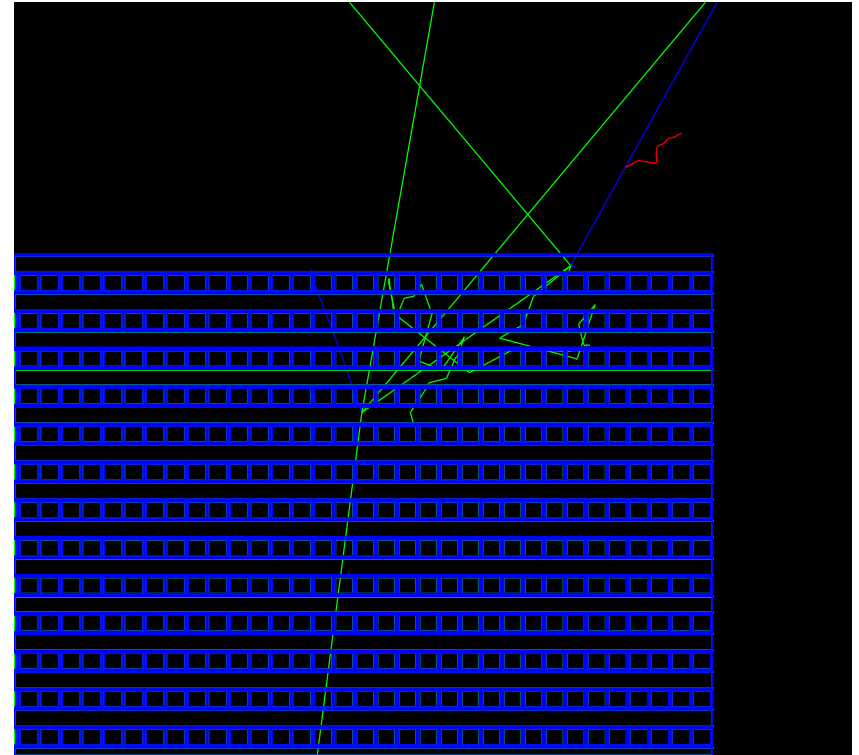
Luminosity ⇒ High segmentation
Efficiency ⇒ Large volume
Consistency ⇒ Moveable mount

- Improvement in detector technology

- ▶ Multi-Anode-Multipliers:
64 Channels/2000€
- ▶ 1 m³ detector volume
- ▶ Wavelength shifting fibres
- ▶ High-Voltage supply at multiplier base
- ▶ Gain-Control at multiplier base
- ▶ TDC/ADC information at multiplier base

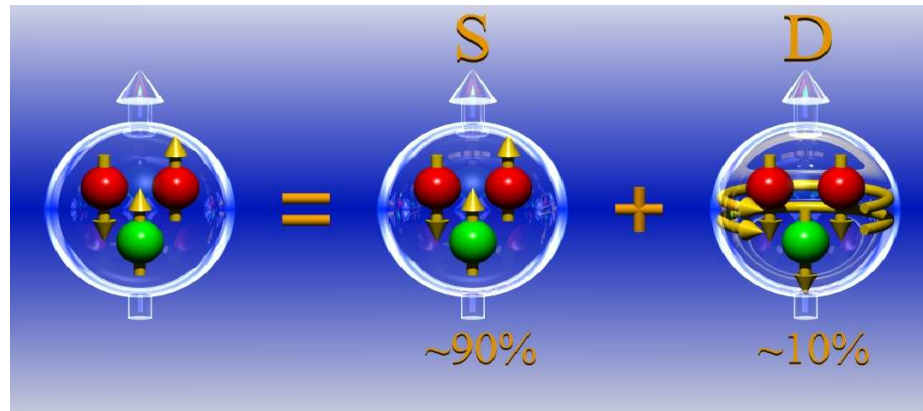
- Improvement in electronics

- ▶ FPGA readout
- ▶ Dead-time free to Gigabit network

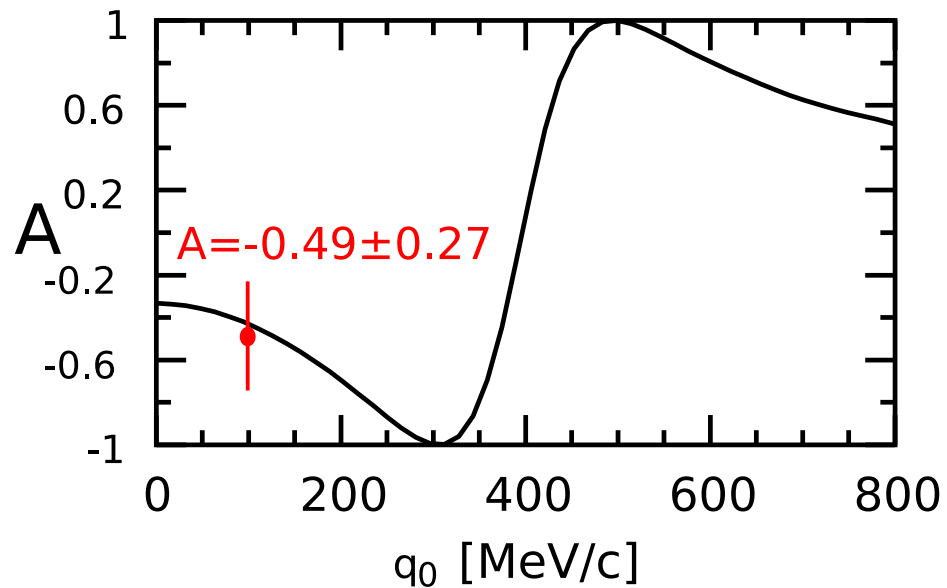


⇒ A highly segmented, high resolution, large volume neutron detector (for a still acceptable price)

Study of Few-Body-Targets



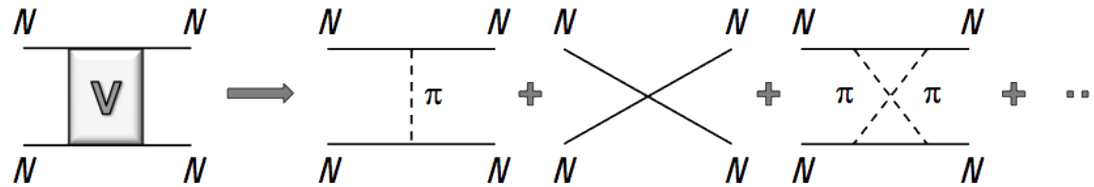
- Simple picture: Helium-3 spin is carried by neutron
- Ideal polarized neutron target
- First Triple-Polarization measurement ${}^3\vec{H}e(\vec{e}, e'\vec{p})d$



New accelerator developments

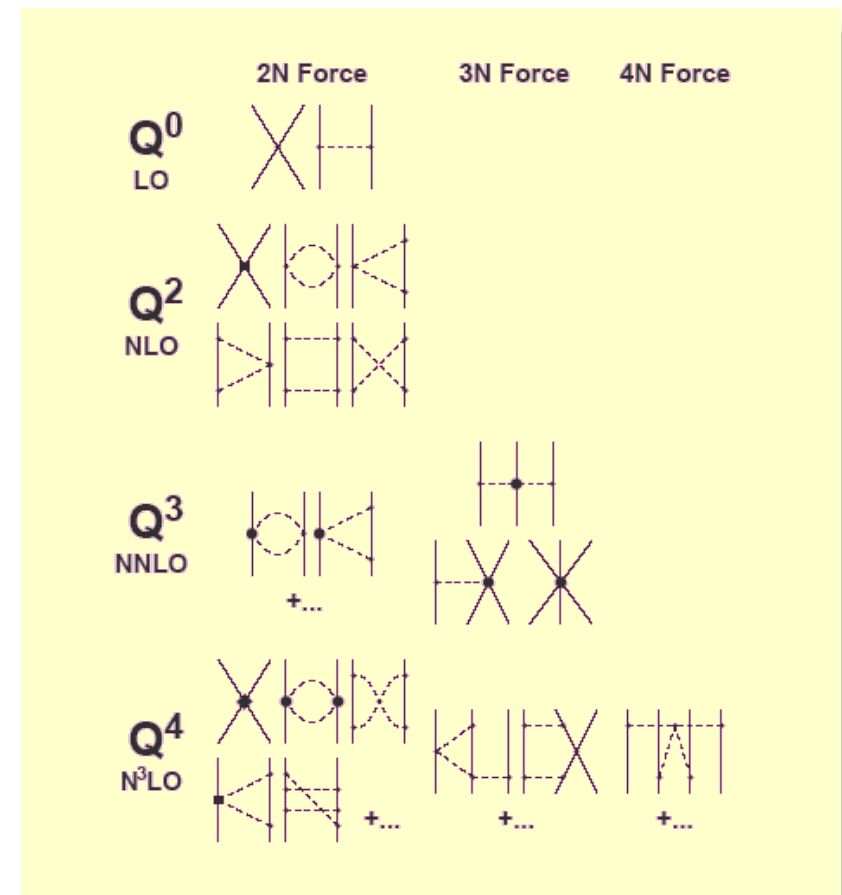
Ab Initio Calculations in Few Body Physics

- Ab initio calculations e.g. with **Effective Field Theory**
- Consistent chiral expansion of elementary NN-interaction



- Consistent expansion of Few-Body-Systems
- Next talk by E. Epelbaum after coffee

How can we test this?



How can we test Ab-Initio-Calculations?

- Challenge for theory: **Reaction dynamics**

Possible solution:

- ▶ Use EFT input for potentials
- ▶ Faddeev Calculations for dynamics (J. Golak, H. Witała, ...)
- ▶ Prediction of dynamic observables
- ▶ Promising: Polarization observables

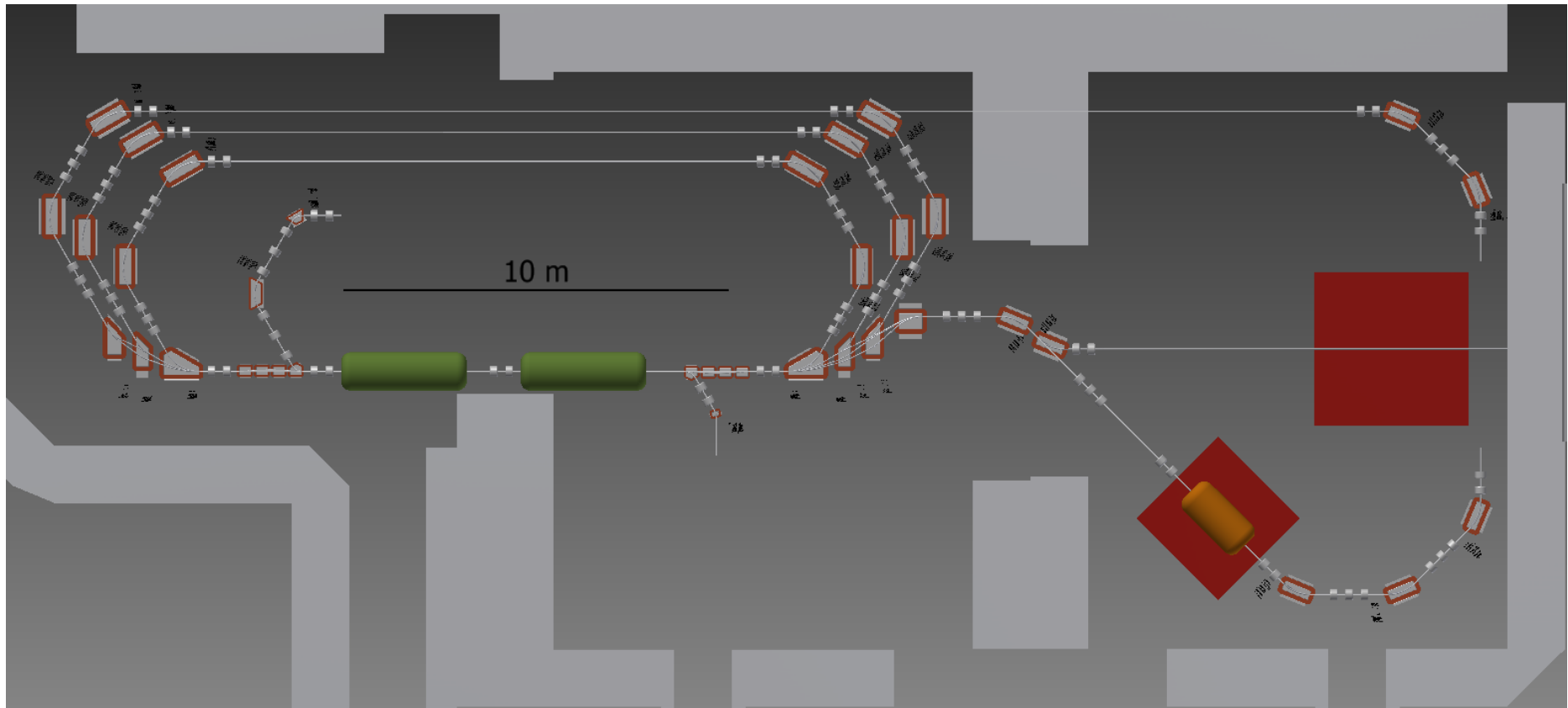
- Challenge for experiments: **Low Momentum Region**

Needed:

- ▶ High resolution (separate excited states!)
- ▶ Low momentum (use gas targets!)
- ▶ High luminosity (in spite of gas target!)
- ▶ High degrees of beam and target polarization (in spite of high luminosity!)

⇒ A new accelerator concept: **MESA Accelerator**

MESA: Mainz Energy recovering Superconducting Accelerator

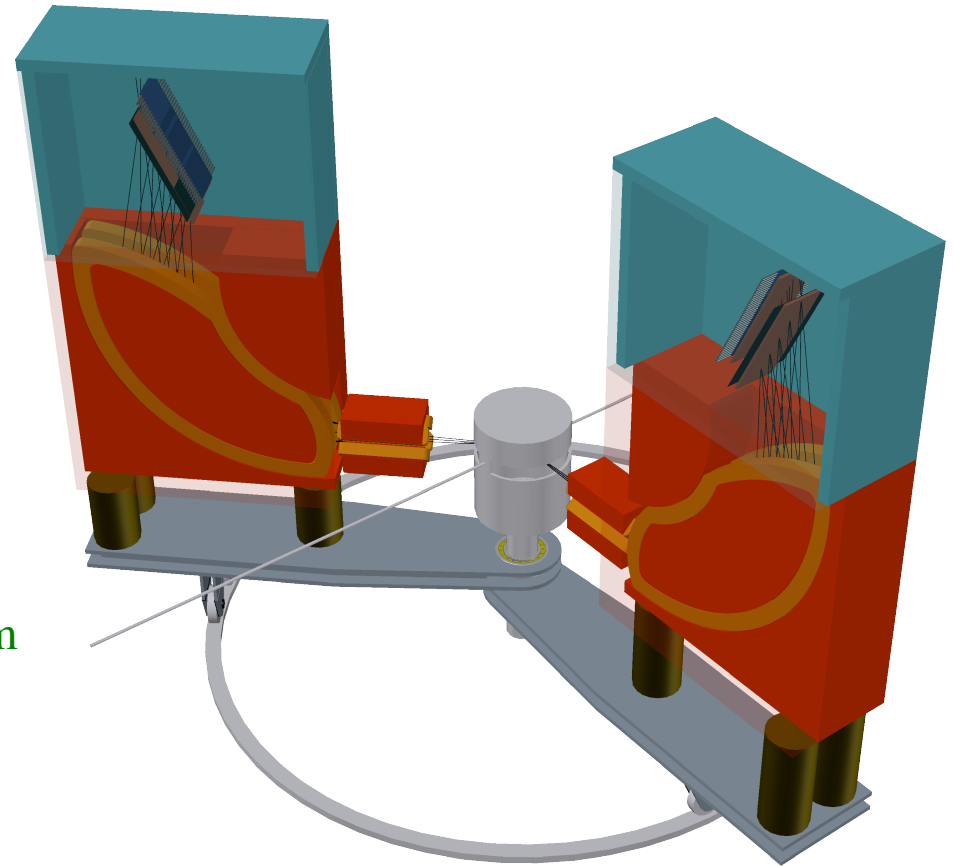


- Superconducting LINAC
- Three recirculation arcs for external beam
high external current for “next generation” parity violation experiments
- Energy recovery mode (half wave-length recirculation) for *internal target* experiments

	Current	Energy	Luminosity
External Beam Mode:	150 μA	200 MeV	$10^{39} \text{ cm}^{-2} \text{ s}^{-1}$
Energy Recovery Mode:	10 mA	150 MeV	$10^{36} \text{ cm}^{-2} \text{ s}^{-1}$

Low Momentum Spectrometers

- Target: Atomic beam source
 - ▶ High polarization possible
 - ▶ High luminosity due to beam quality
 - ▶ Window-less, low multiple scattering
- High resolution spectrometers
 - ▶ Momentum resolution $\delta p/p \approx 10^{-4}$
 - ▶ Low momentum \rightarrow modest size $r < 3$ m



Physics Book:

- Searches for dark photons
- Hadron Physics: e.g. magnetic radius of the proton via double polarization
- Polarization observables in few body physics
- ...

Summary

● Proton Form Factors

- ▶ Precision frontier of hadron physics
- ▶ The challenge of the Electric Radius
- ▶ Few-Body Physics opens additional access

● Neutron Form Factors

- ▶ Important tests for fundamental understanding of QCD
- ▶ Challenging experiments
- ▶ Few-Body Physics as important tools to understand targets

● Low Energy Nuclear Physics

- ▶ Long term perspective: Understanding nucleons from fundamental interactions
- ▶ Promising Tool: Ab-Initio Calculations
- ▶ Overcome current experimental limitations with dedicated apparatus