First Measurement of the Charge Form Factor of the Proton at very low Q^2 with Initial State Radiation

Harald Merkel
Johannes Gutenberg-Universität Mainz

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- The Proton Radius Puzzle
- Initial State Radiation (ISR)
  - Leading Order Effect
  - Second Order Radiative Corrections
  - How to disentangle the Cross Section
- First results

Form Factor of the Nucleon

Elastic Cross Section (Rosenbluth-Formula):

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

with $\tau = \frac{Q^2}{4m_p^2}$

$\varepsilon = \left(1 + 2(1+\tau)\tan^2\frac{\theta_e}{2}\right)^{-1}$

Structure of the Nucleon:

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

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

Normalization:

$$G_E^p(Q^2=0) = 1 \qquad G_E^n(Q^2=0) = 0$$

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

Proton Charge/Magnetic Radius:

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

Ingredients for a Precision Measurement

- Statistical error: 0.2% in less then 20 min!
- Systematic error:
  - Detector efficiency

    $\Rightarrow$ Overlap in acceptance (every angle 4$\times$)

    $\Rightarrow$ Where possible, every angle with two spectrometers

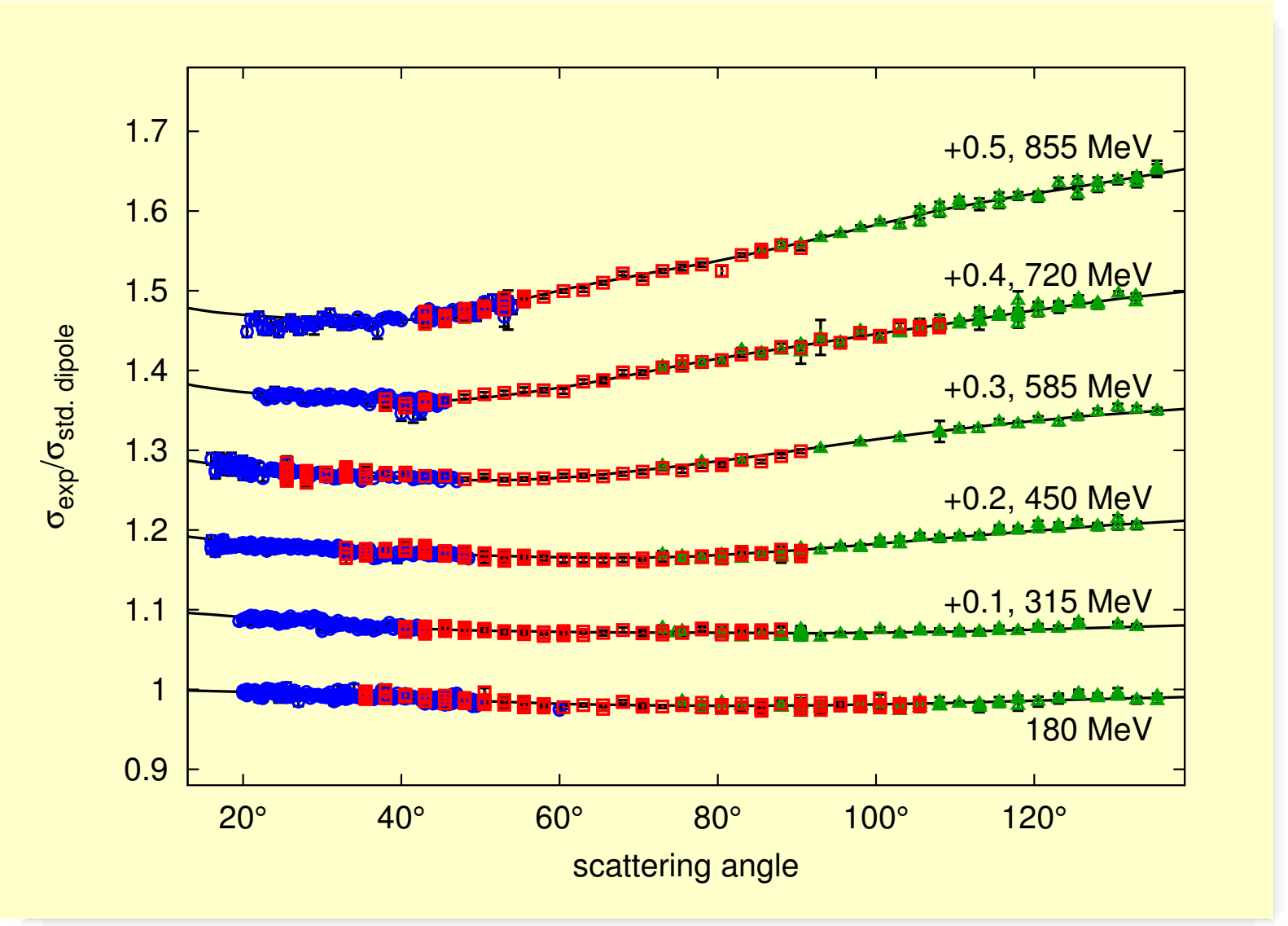
  - Luminosity over 4 orders of magnitude (I_{beam} =0.5 nA $-$ 10 μA)

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

$\Rightarrow$ Current with Foerster probe (fluxgate-magnetometer, $\times$ 90 turns)
pico-Ampere Meter (direct measurement)

$\Rightarrow$ Two spectrometer for measurement, third at fixed position

Rosenbluth-Separation by Fit

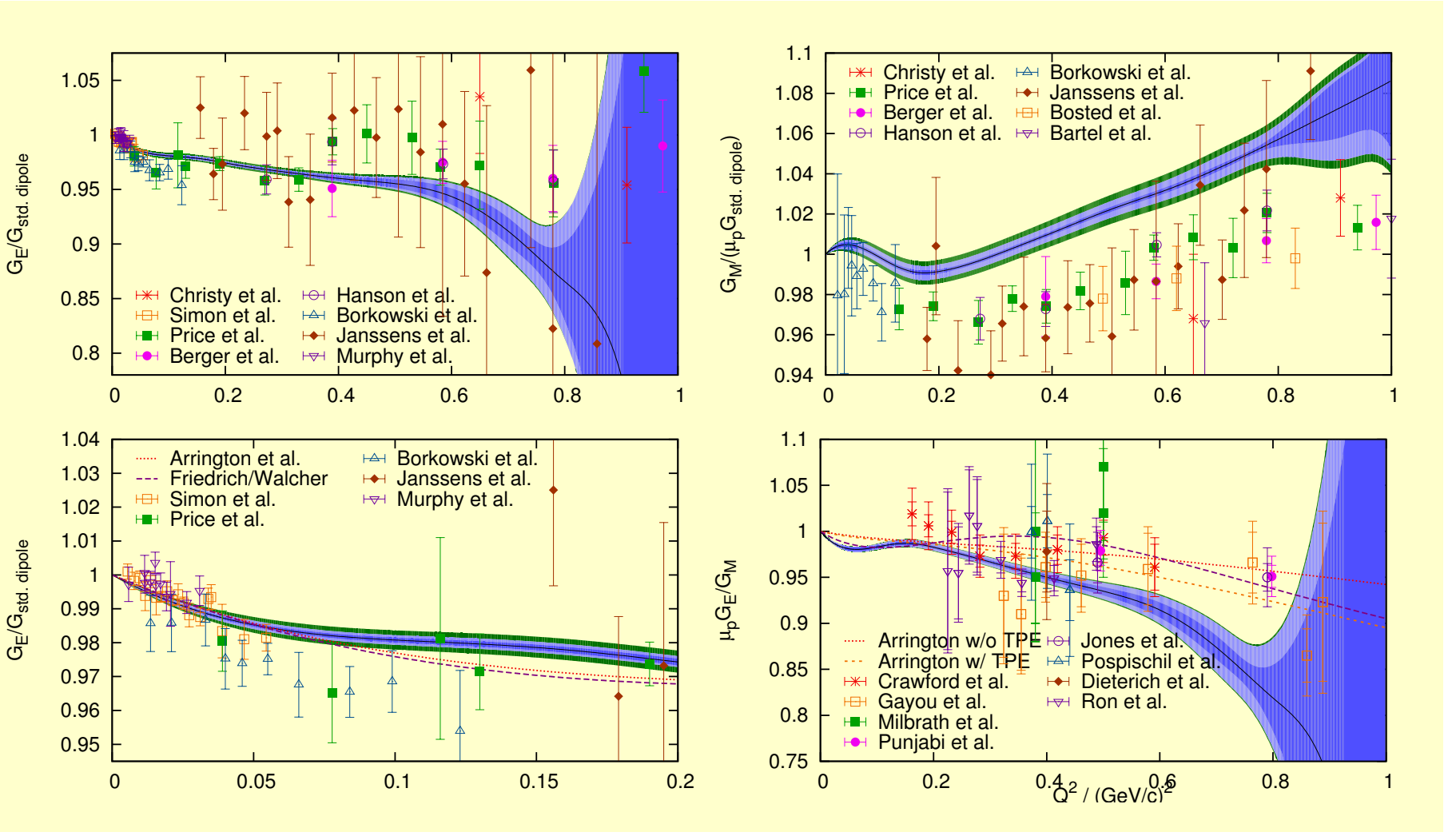


$G_{\text{std.dipole}} = \left(1 + Q^2/0.71\,\text{GeV}^2\right)^{-2}$

Data spectrometer A, B, C, error bars by spread of data $\rightarrow$ 0.2% – 0.4% (stat.: 0.1% – 0.3%)

Spline fit

Form factor results

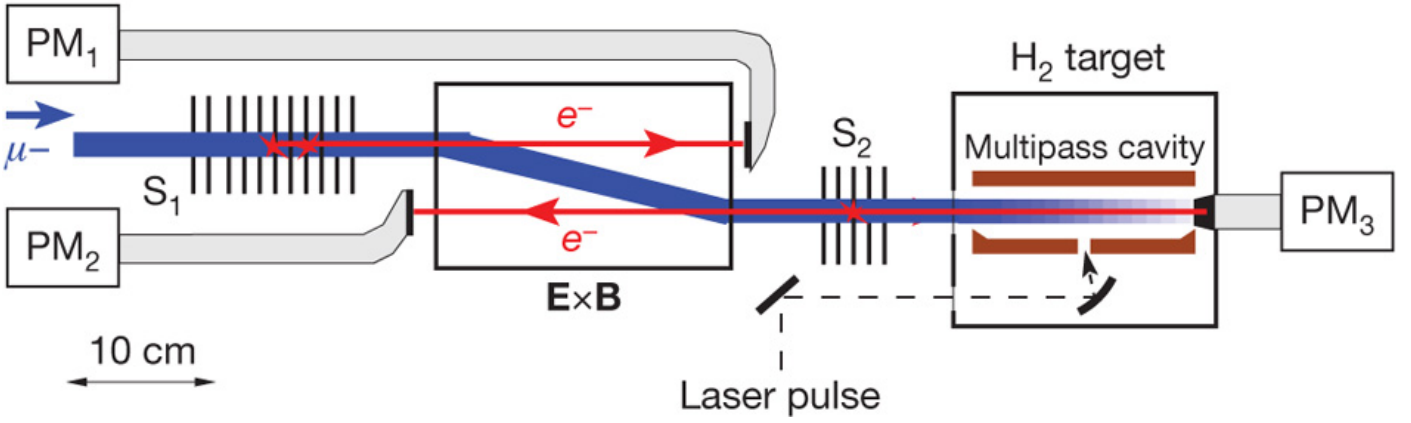


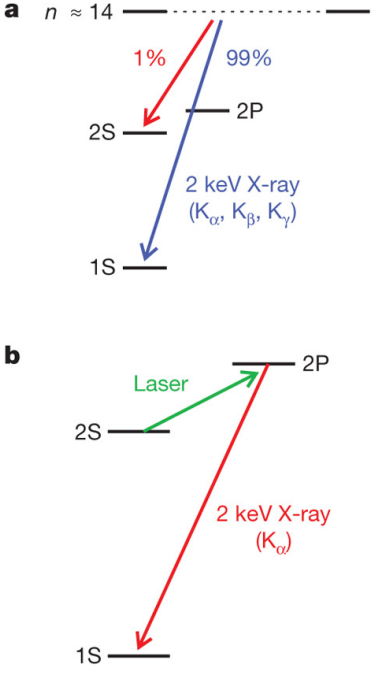
$$r_E = 0.879 \pm 0.005_{\text{stat.}} \pm 0.004_{\text{syst.}} \pm 0.002_{\text{model}} \pm 0.004_{\text{group}}\ \text{fm},$$
$$r_M = 0.777 \pm 0.013_{\text{stat.}} \pm 0.009_{\text{syst.}} \pm 0.005_{\text{model}} \pm 0.002_{\text{group}}\ \text{fm}.$$

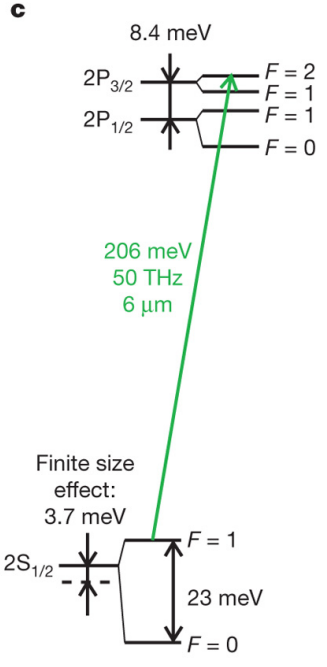
Jan C. Bernauer *et al.*, Phys. Rev. Lett. 105, 242001 (2010), Phys. Rev. C 90, 015206 (2014)

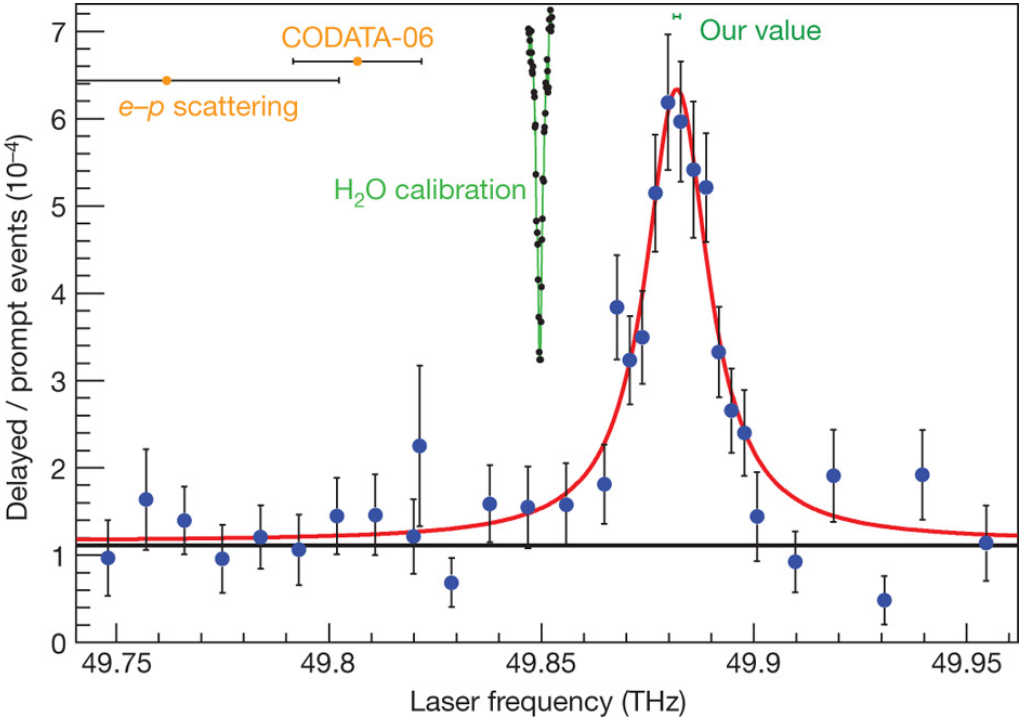
The Radius Puzzle: Lamb shift in μH-Atom

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

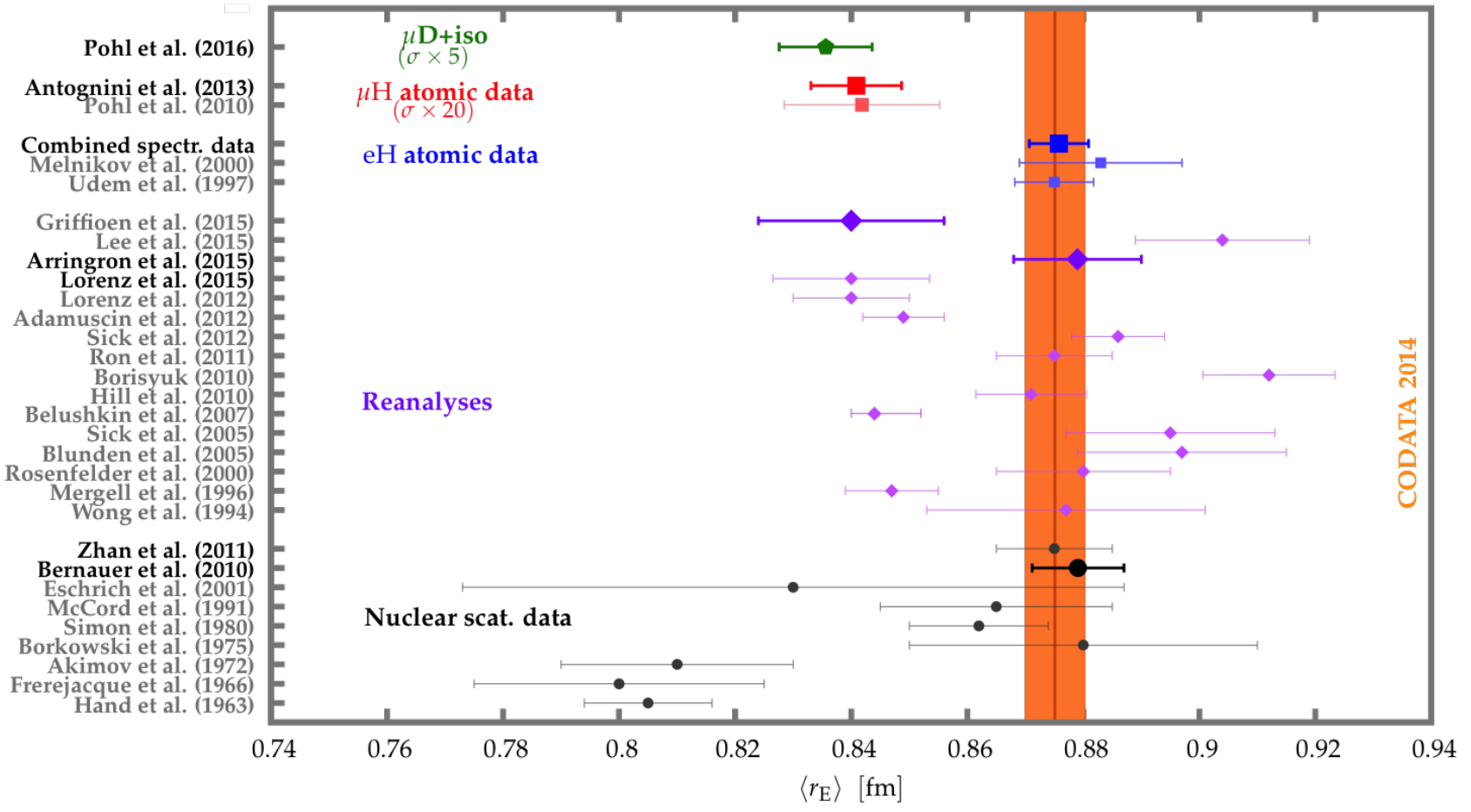






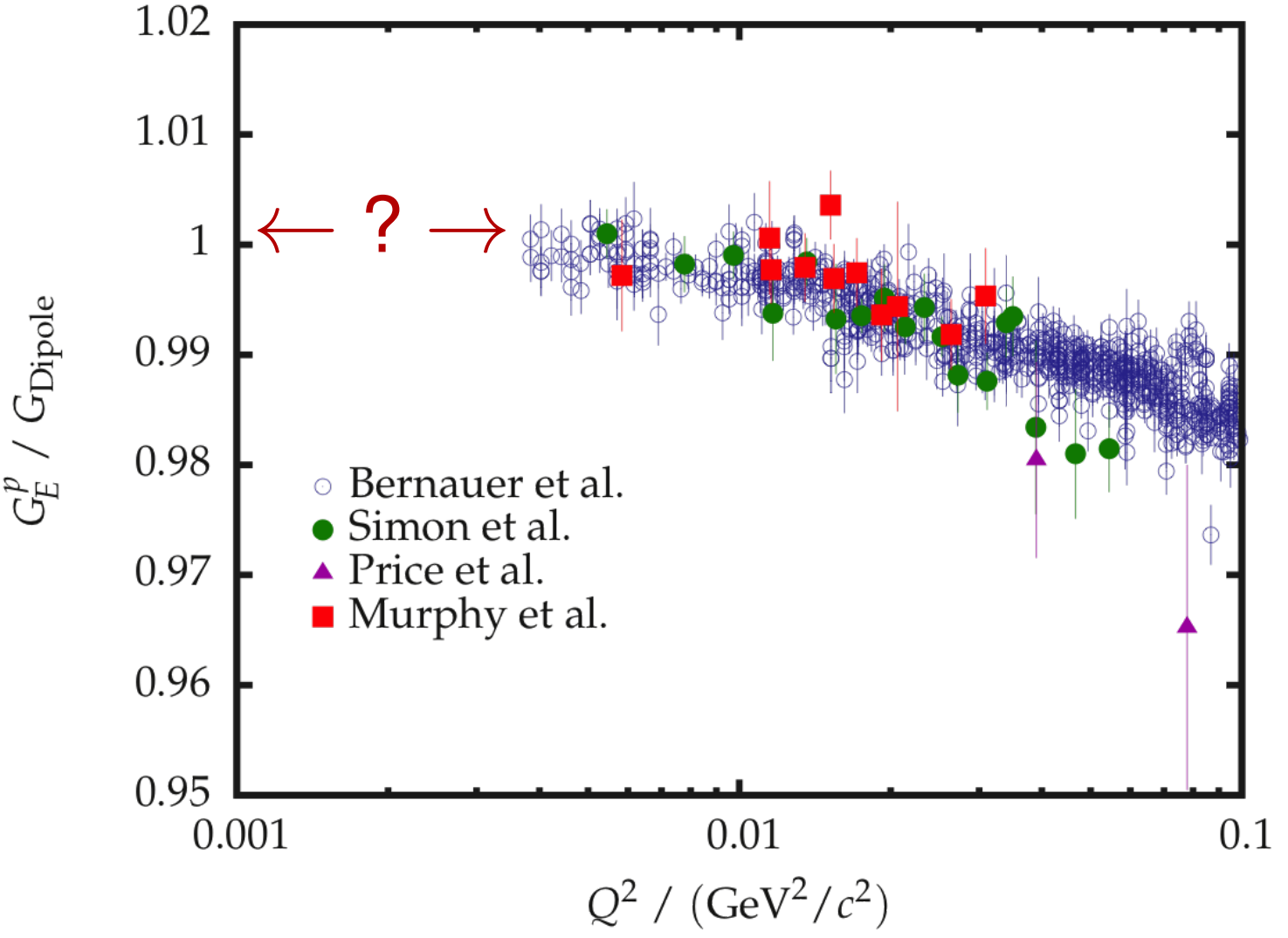


Radius of the Proton



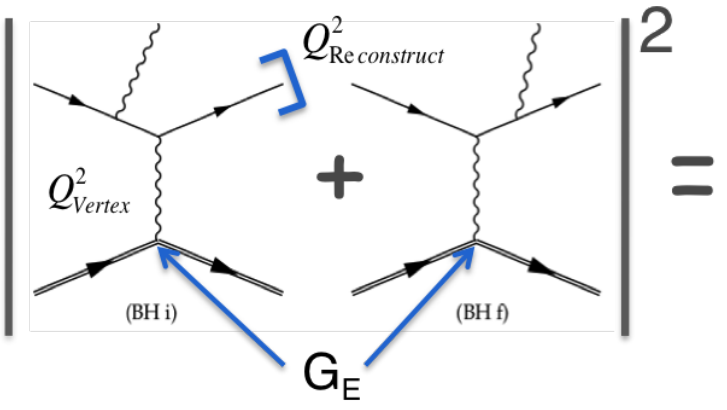
- 5σ Discrepancy between atomic physics and electron scattering
- Situation still unclear
- Serious problem far beyond nuclear science: *e.g.* Rydberg Constant, Lepton Universality,...
- Extended experimental program in atomic and nuclear physics

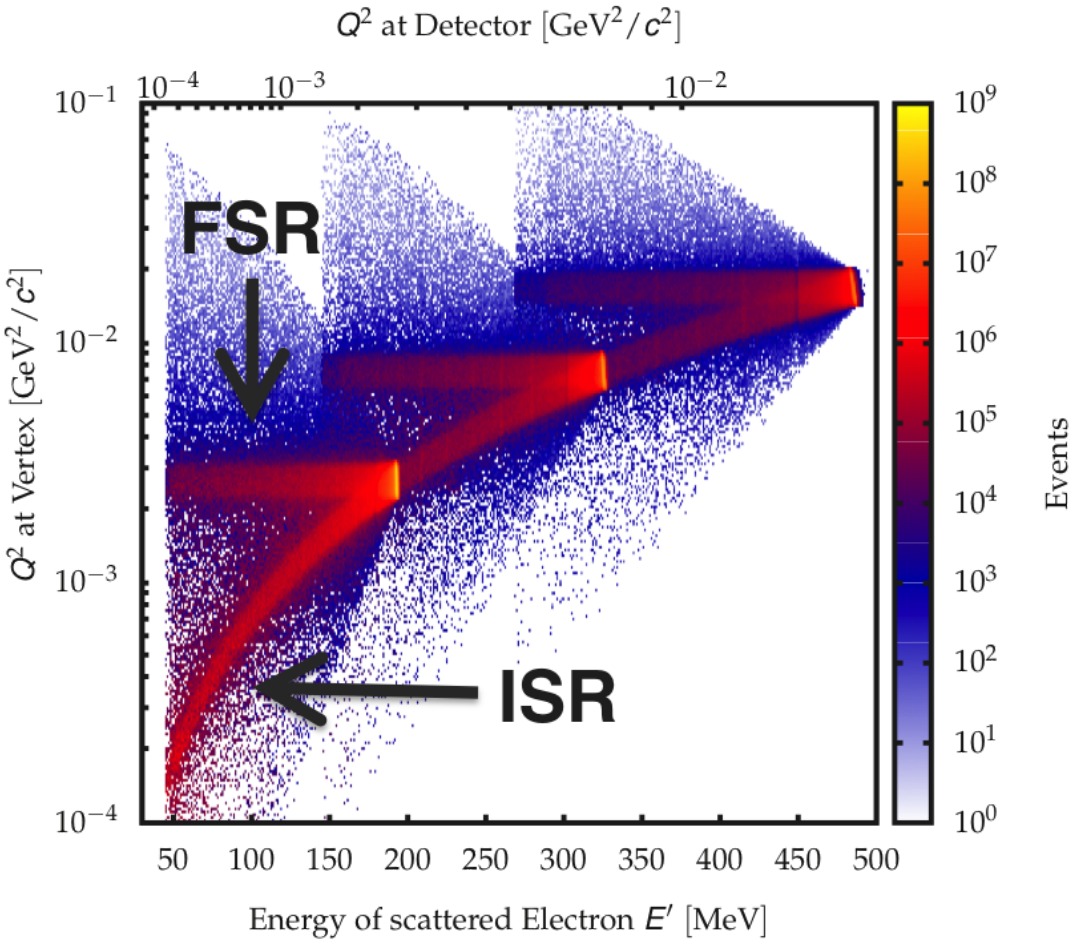
Problem: Extrapolation $Q^2 \to 0$ required for Normalization



- Absolute normalization of cross section not better $\approx 1\%$
- Extrapolation $Q^2 \to 0$ where $G_p^E(0) = 1$, extraction of $r_E^2 = \frac{d}{dQ^2} G_E(Q^2)$
- Systematic error due to model assumptions

Idea: Information in radiative tail contains form factor information

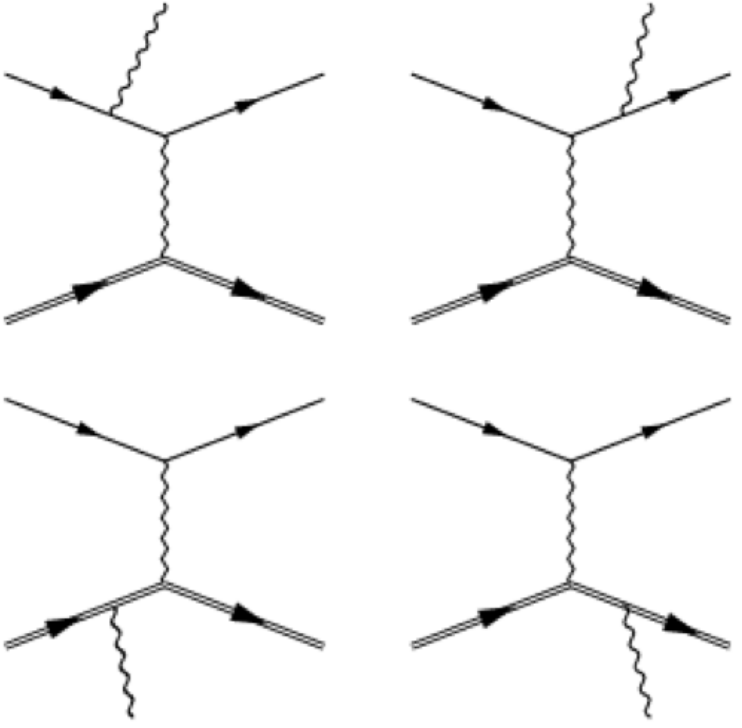




- Final State Interaction contains **known** form factor (Elastic Line)
- Initial State Interaction: Cross section changes **linear** with form factor
- Disentangle via comparison Simulation $\leftrightarrow$ Data

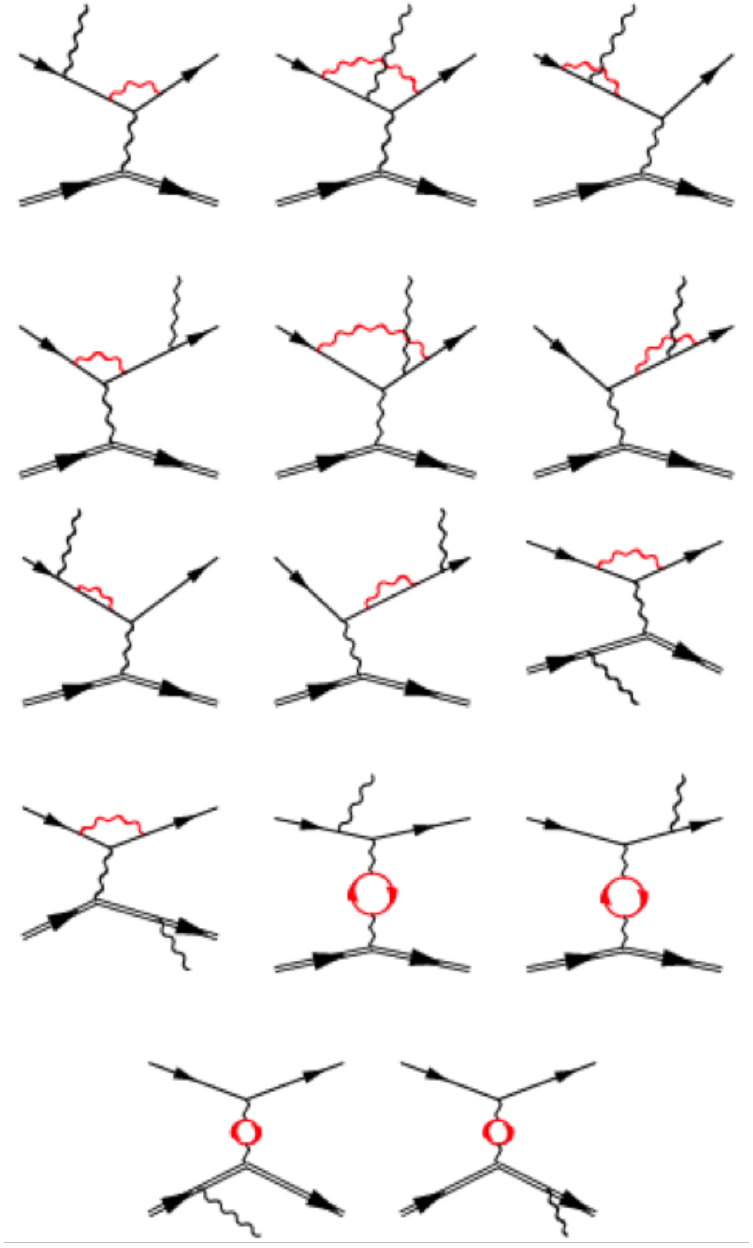
Radiative Corrections

Initial State Radiation:



- Exact calculation in Simulation
- QED part is known
- Hadronic part?
  - Born terms: Form Factors
  - Excitations: Polarizabilities

Radiative corrections at least $O(\alpha^2)$:

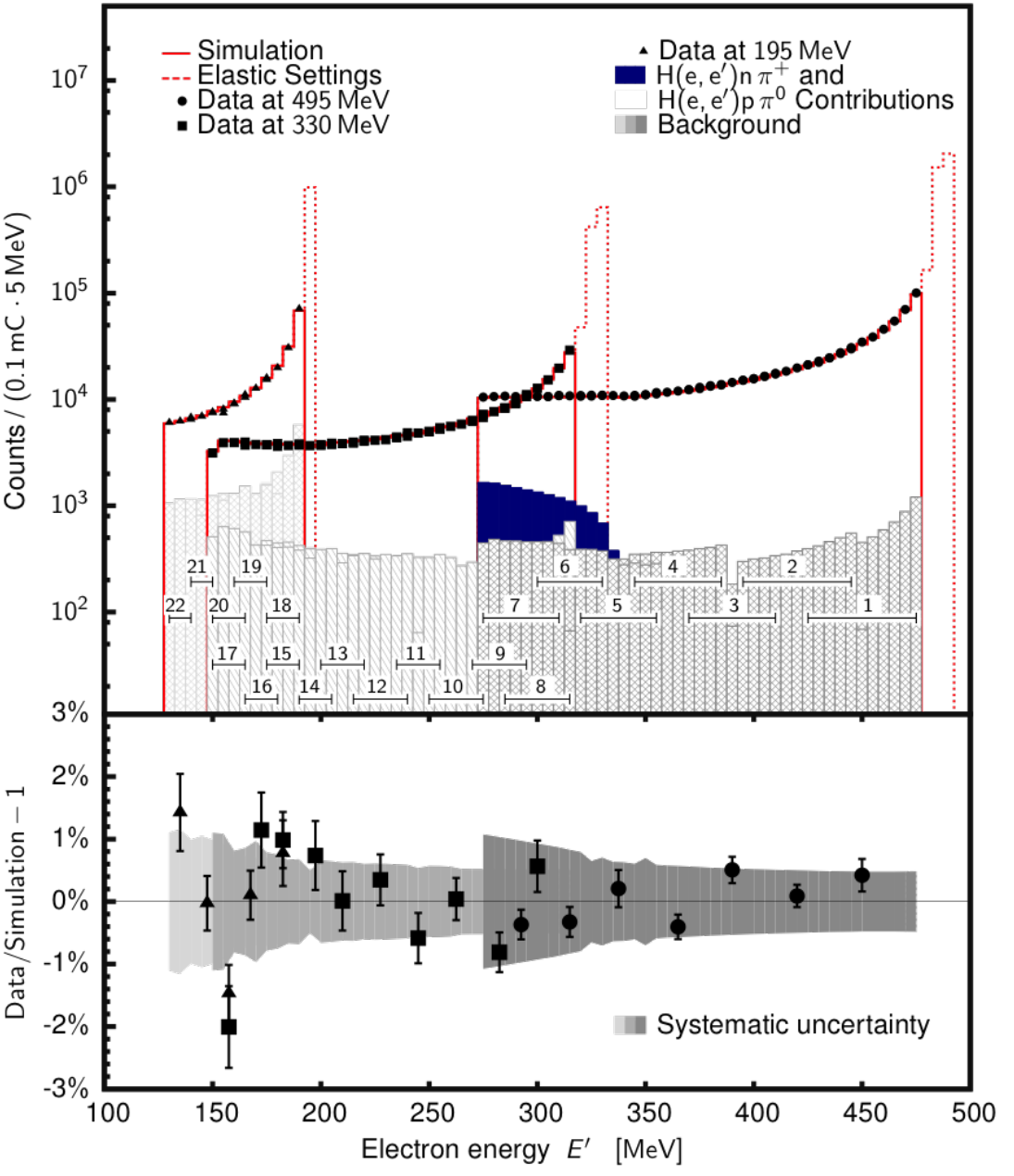


First Results

- Better than 1% achievable!
- First measurement of $G_p^E(Q^2)$ in range

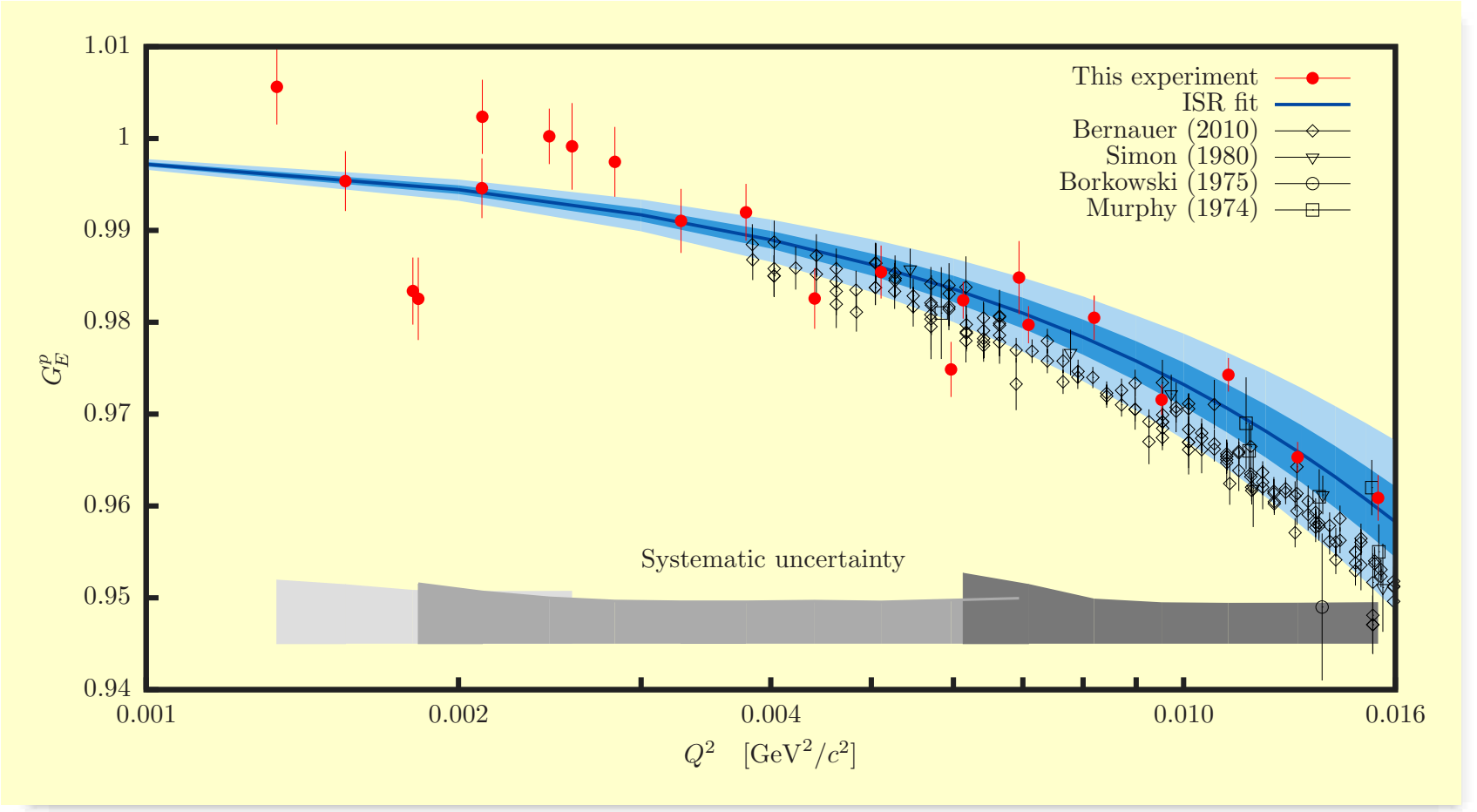
$$0.001\text{GeV}^2 < Q^2 < 0.004\text{GeV}^2$$

- Systematic errors:
  - Target walls
  - Pion production
  - Backscattering target frame
  - Backscattering entrance flange
  - Radiative corrections



M. Mihovilovič, A. B. Weber, *et al.*, submitted, arXiv:1612.06707

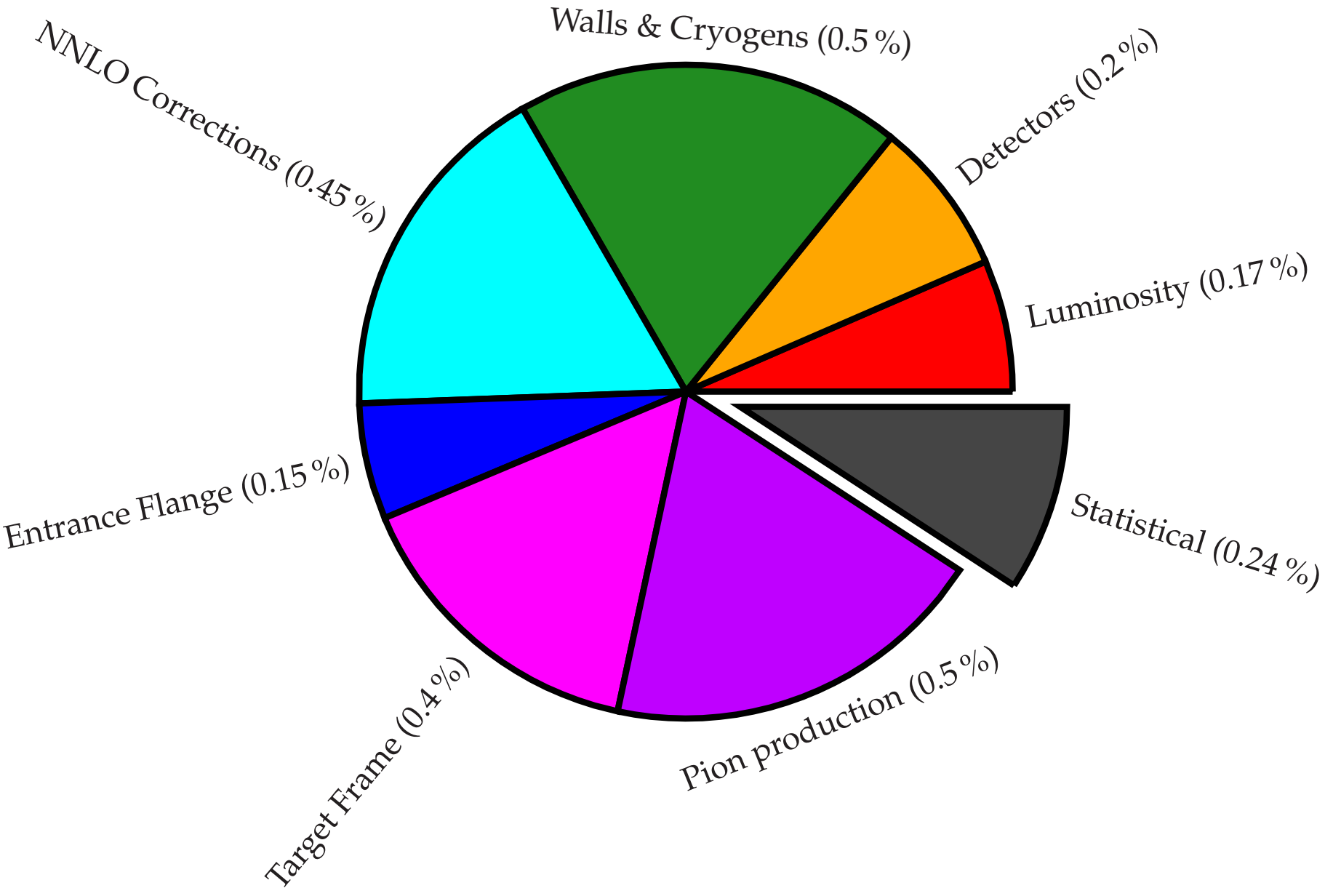
Extracted Form Factor



- Extension to low $Q^2 = 0.001$
- Statistical/systematic error not yet competitive
- First successful Initial State Radiation experiment in electron scattering

M. Mihovilovič, A. B. Weber, *et al.*, submitted, arXiv:1612.06707

Error budget



Total systematic uncertainty of cross-section $\leq$ 1.0 %

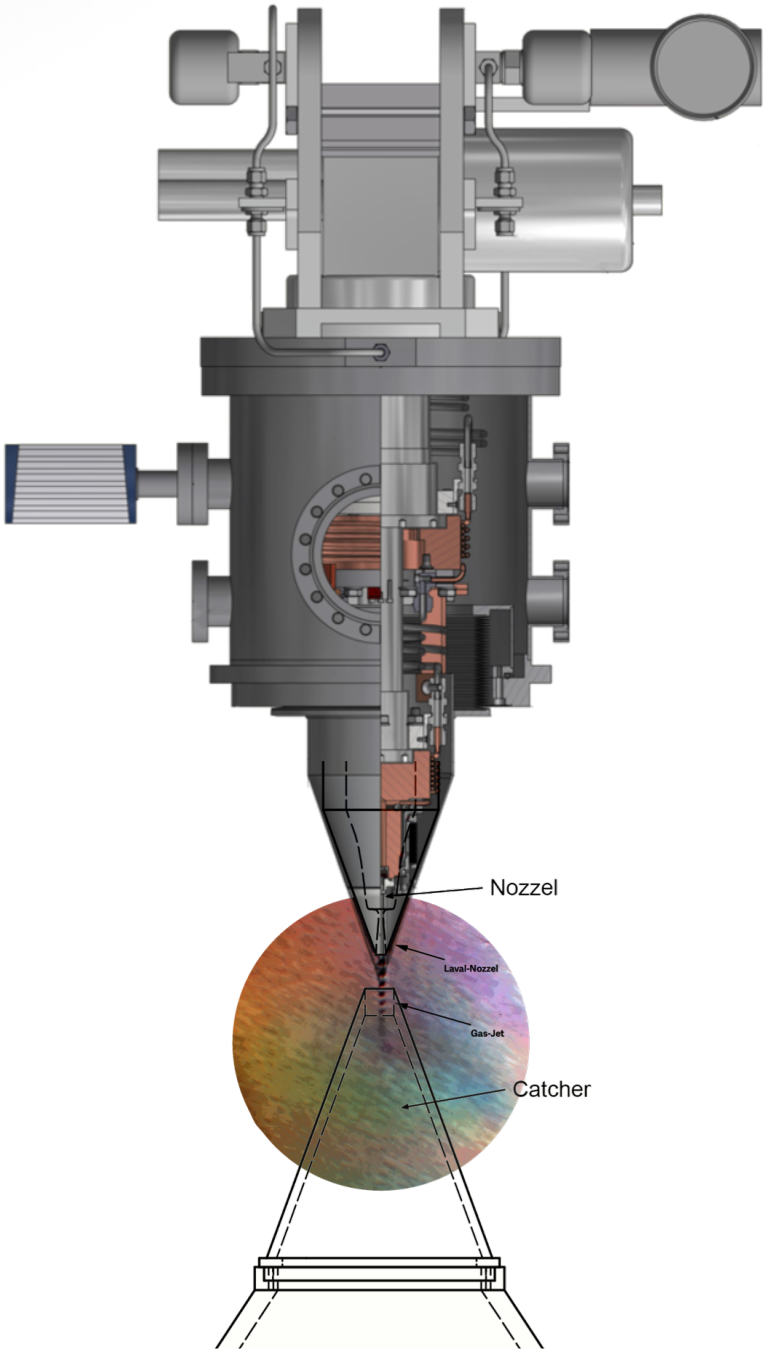
Next Generation

Internal Target designed for Magix@MESA

- Supersonic jet target
- No target walls
- Nearly pointlike target (2mm length)

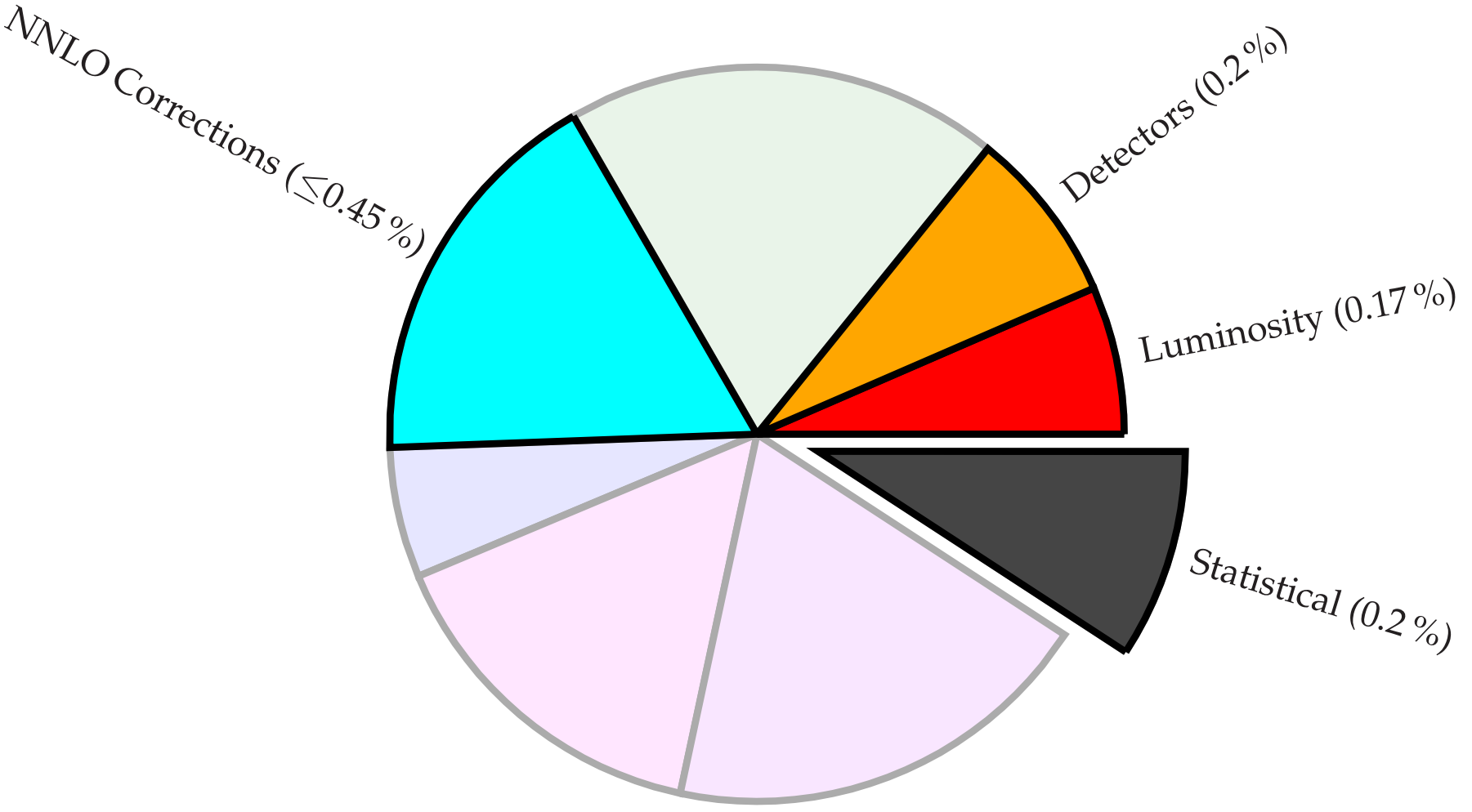
First installed at A1:

- Luminosity of up to $L = 10^{34}\,\mathrm{cm}^{-1}\mathrm{s}^{-1}$
- No Background by
  Target walls or backscattering
- $Q^2 = 0.0001\,\mathrm{GeV}^2$ achievable
- Status:
  - Core with cold head tested
  - Vacuum pumps delivered (9800 m^3/h)
  - Experiment scheduled for June 2017



In collaboration with A. Khoukaz *et al.* (Münster University)

Error budget with Jet-Target



Total systematic uncertainty of cross-section $\leq$ 0.5 %

Summary

- Proton Radius Puzzle
  - Still unresolved
  - Huge impact beyond nuclear physics
- Initial State Radiation
  - Information in radiative tail can be used
  - Access to very low Q^2 now possible
  - First successfull experiment
- Future Experiment
  - Reduced systematic errors
  - Key ingredient: Gas Jet Target
  - Not discussed today: Other experiments (PRAD, MUSE, ...)