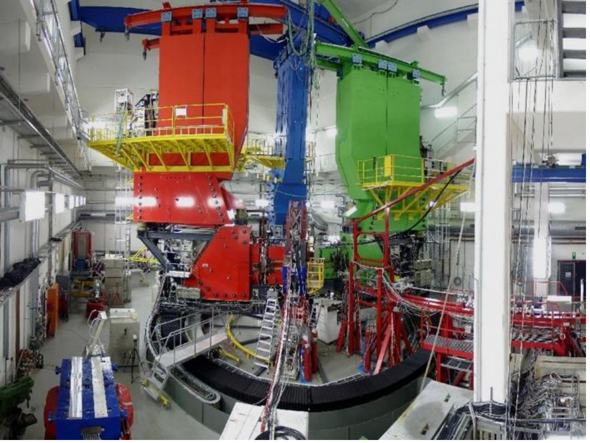
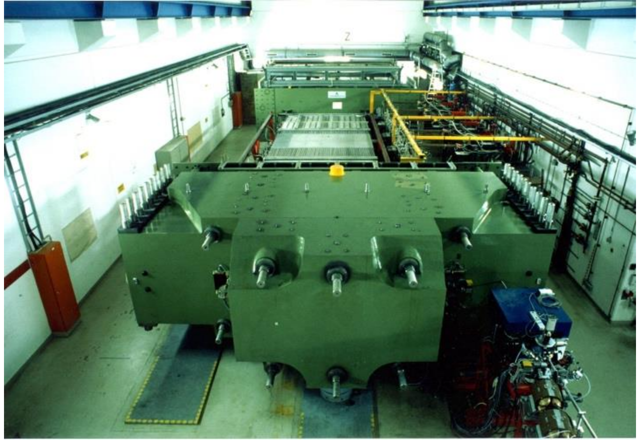
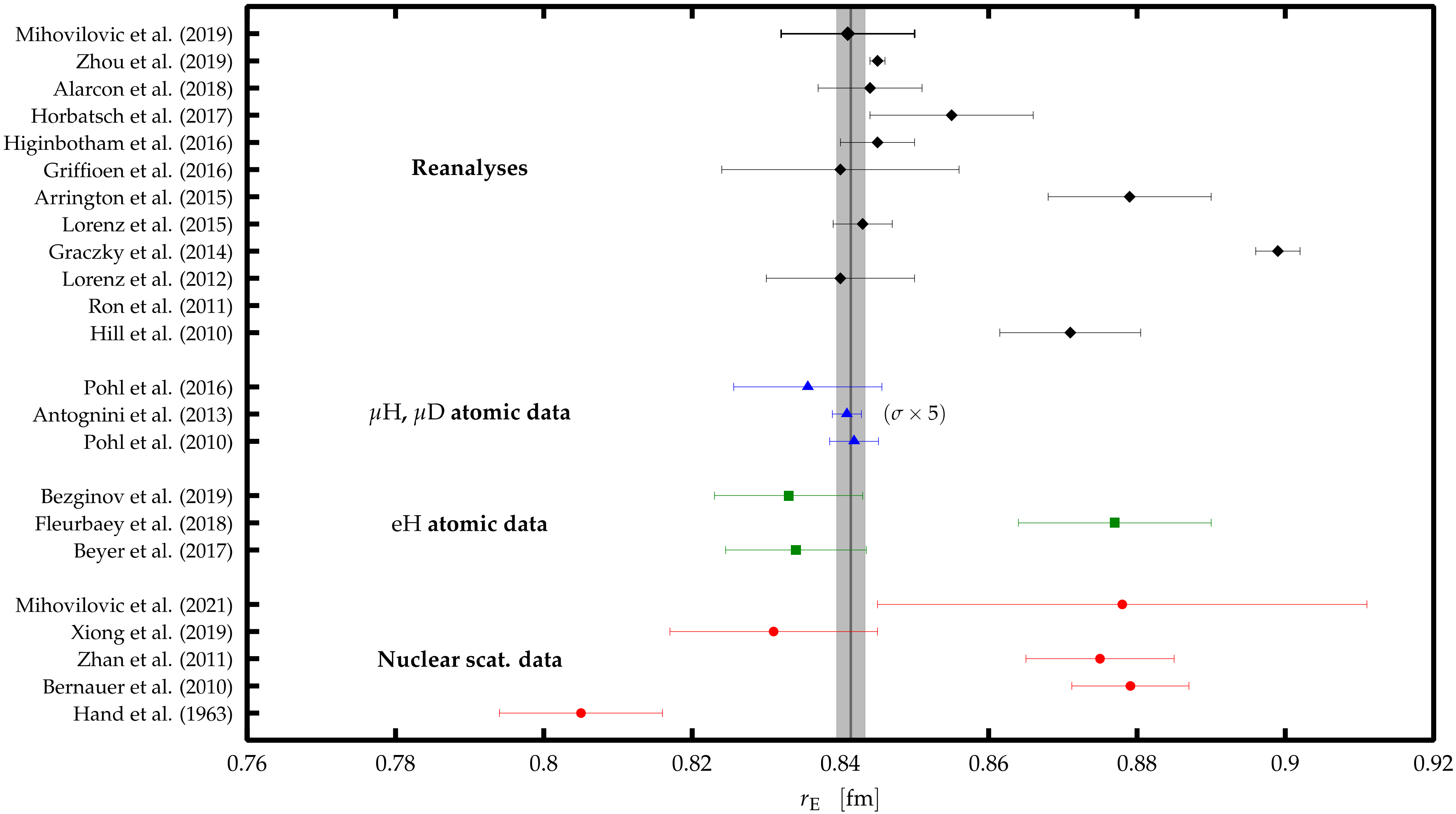




Proton Charge Radius from Electric Form Factor Measurements at Low Q^2

Miha Mihovilovic for A1 Collaboration
U Ljubljana and JSI

Motivation - The proton radius problem

- The "Proton radius puzzle" - a 6σ discrepancy in the r_p measurements.

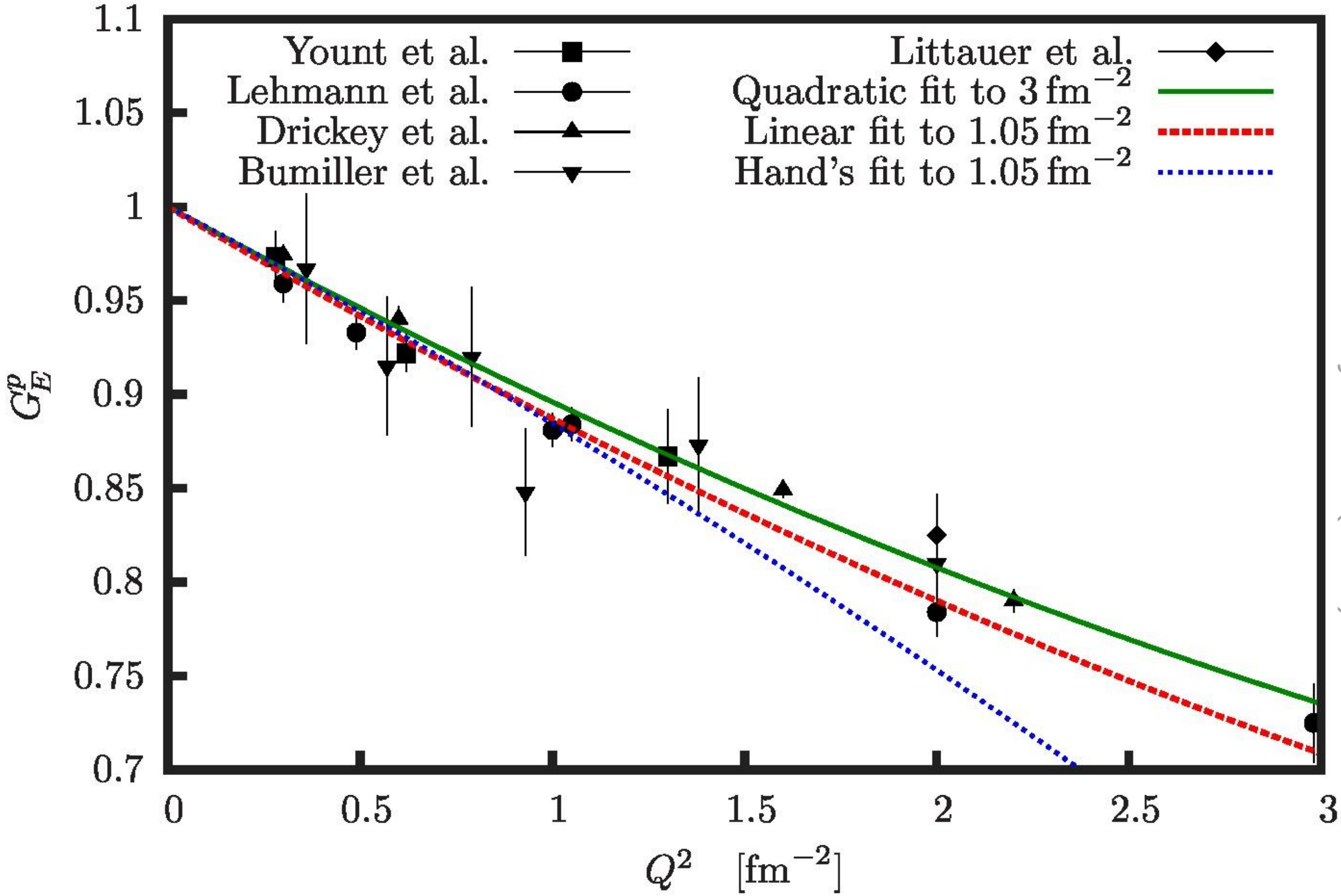


Hypotheses for competing r_p values

- Inconsistent experimental results:
  - different Q^2 ranges of data.
  - different experimental uncertainties.
  - hidden systematics (luminosity determination).
  - hidden backgrounds (cryogenic depositions).

- Differences in the interpretation of experimental results:
  - not knowing the true functional form for G_e^p.
  - use of different models (model bias) .
  - incomplete models (neglected contributions of higher-order moments).
  - inconsistent use of experimental data (different Q^2 ranges).
  - ignored model-dependent relative normalizations between data.

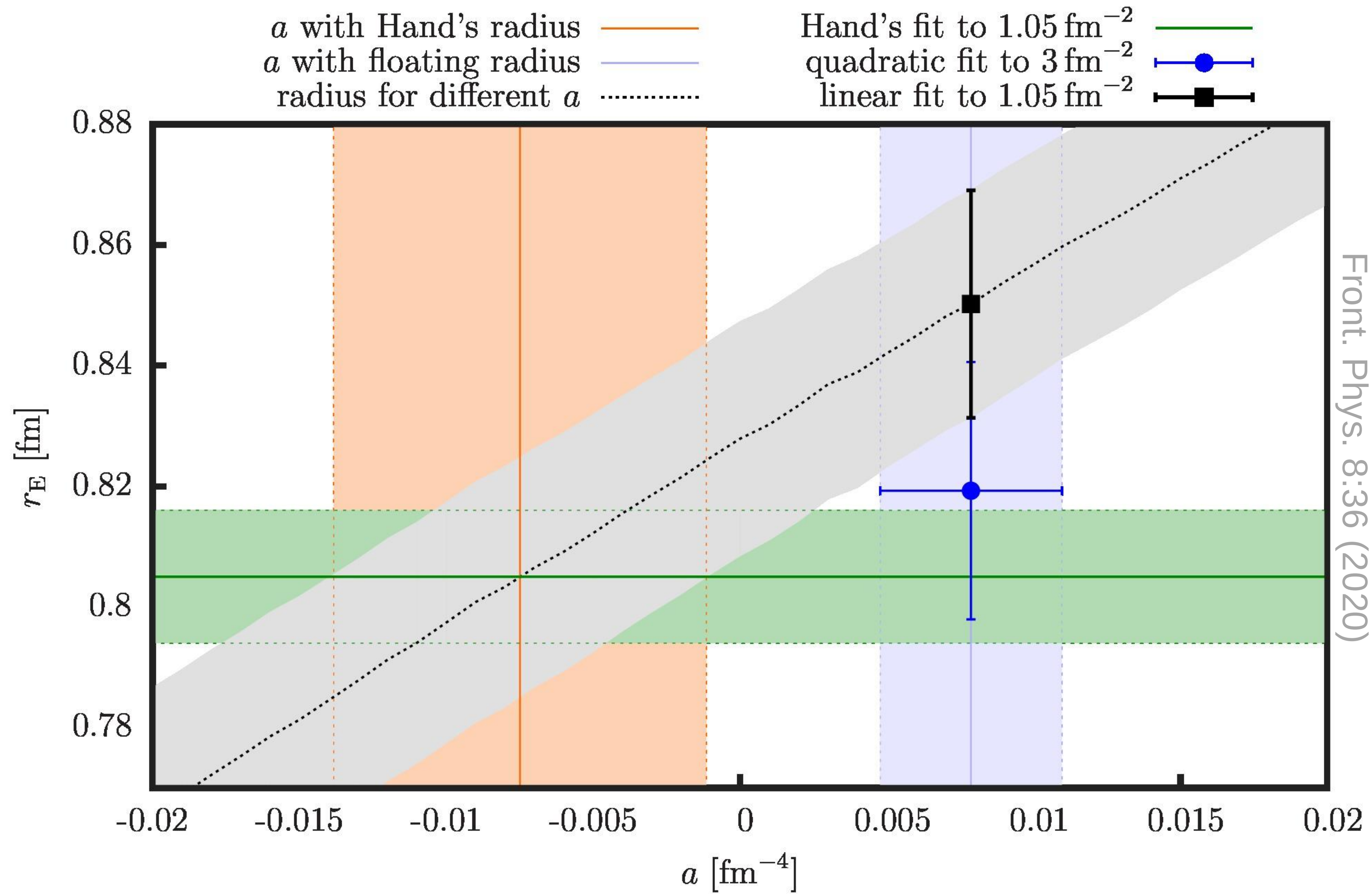
Reexamination of first extraction of r_p



Front. Phys. 8:36 (2020)

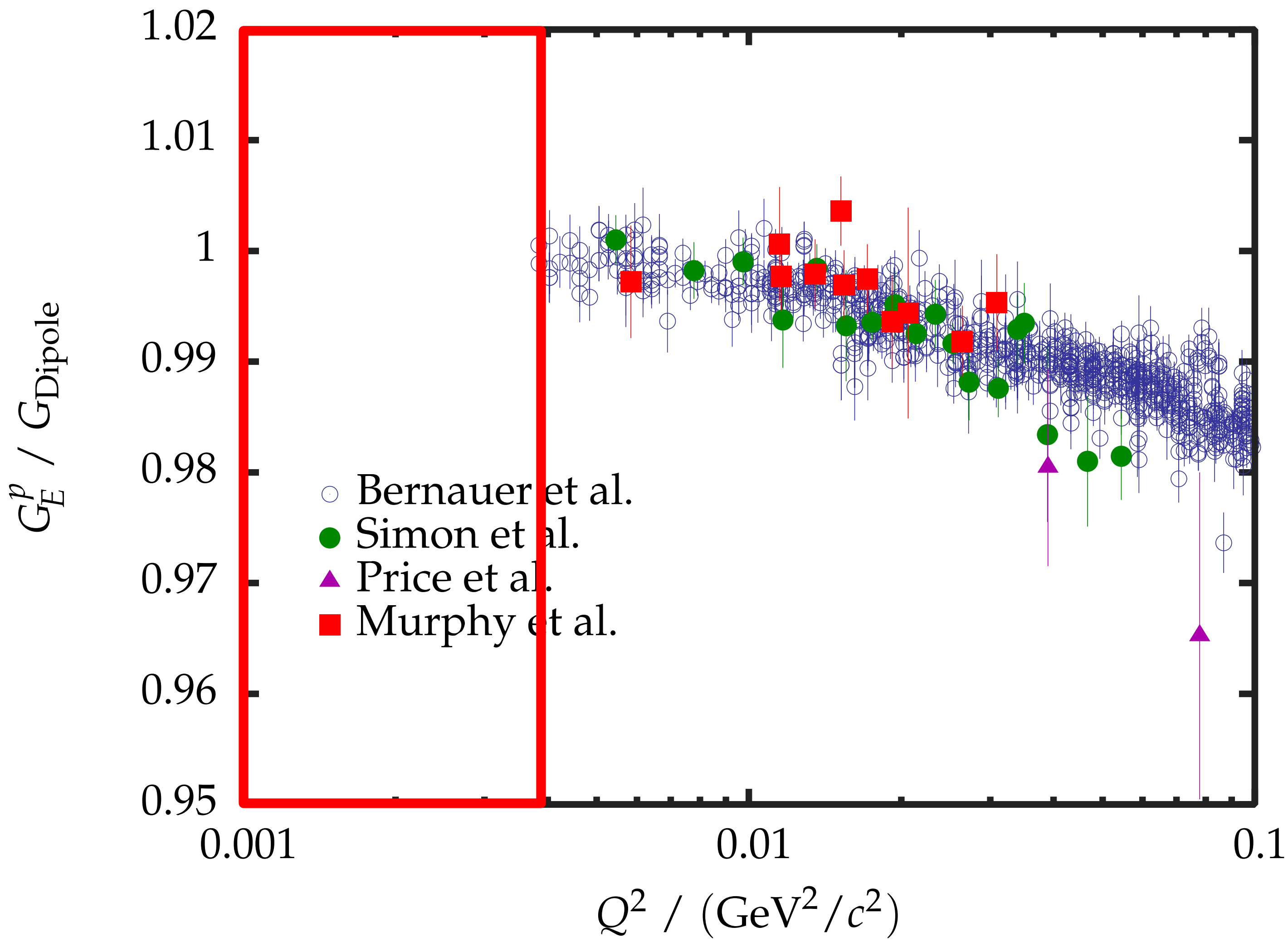
- First determination of proton charge radius done by Hand in 1963.
- Two step fitting technique was applied: quadratic fit up to 3 fm^{-2}, linear fit up to 1 fm^{-2}

Reexamination of first extraction of r_p



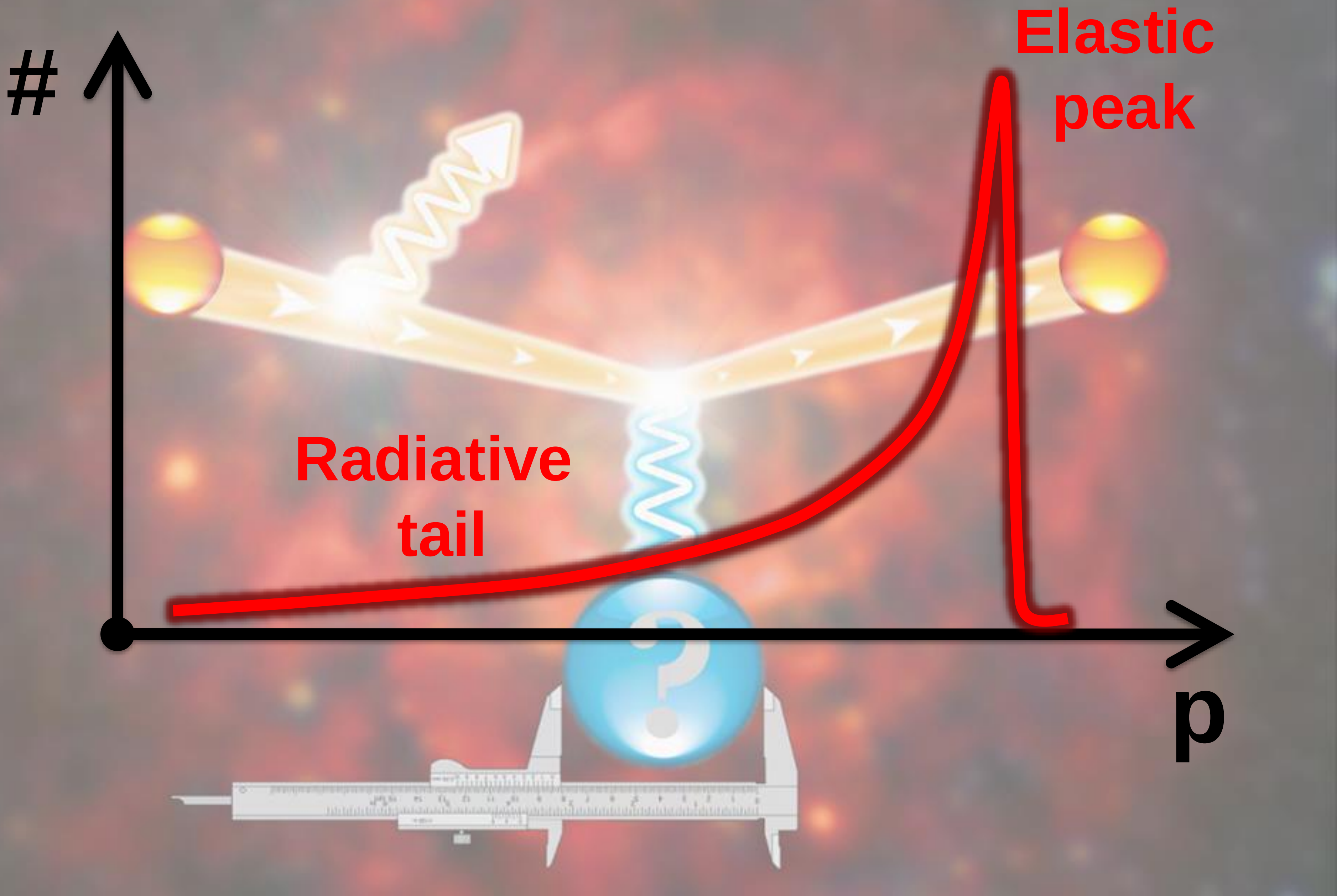
- Mistake in an analysis led to a smaller value for the radius.
- Reanalysis of original measurements gives results consistent with CODATA '18.

Proton's charge form-factor



- **In 2013 data available only for $Q^2 > 0.004$ (GeV/c)^2.**
- More data at even smaller Q^2 needed!

The idea of ISR Experiment

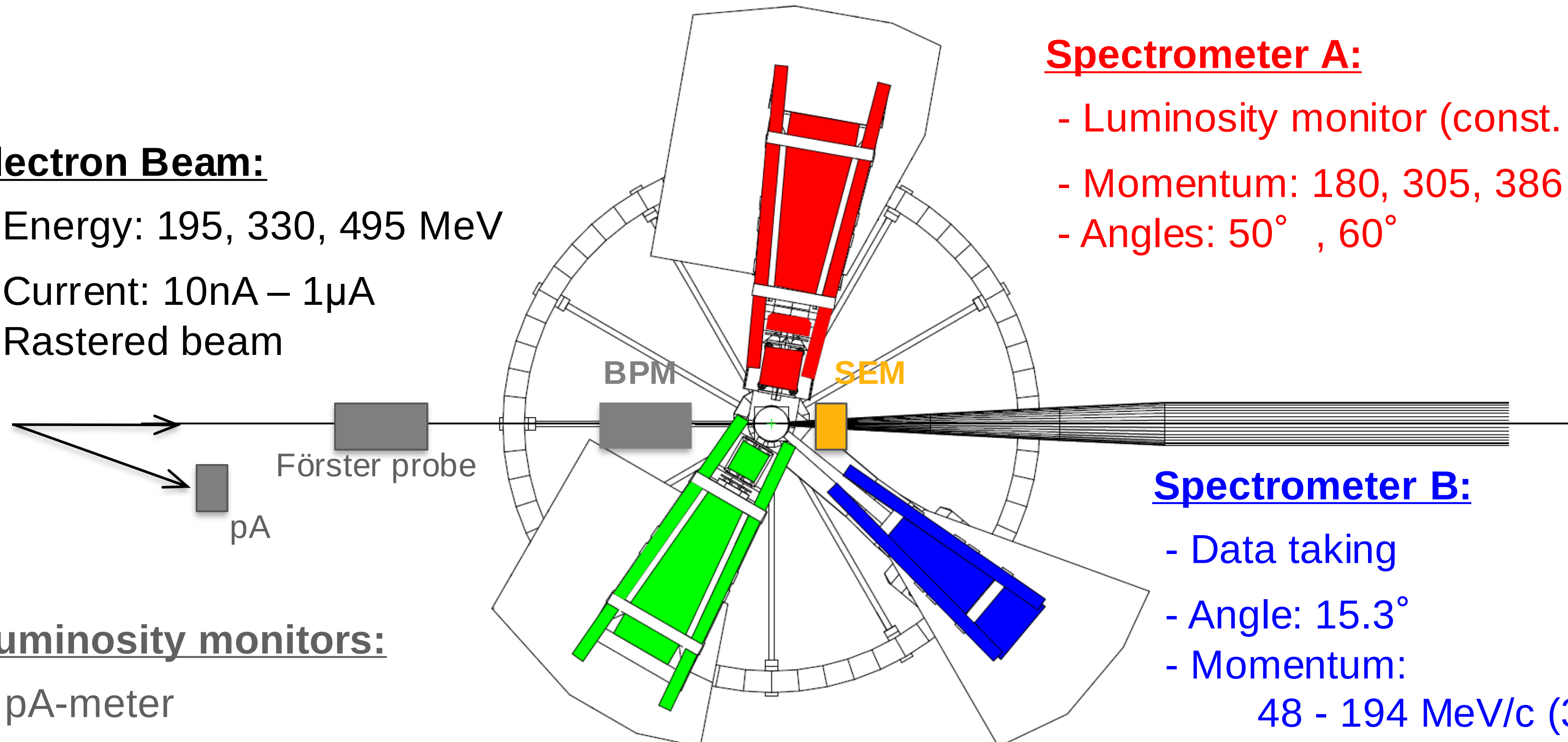


The ISR experiment

- Full experiment done in August 2013 + additional beam time in 2017.

Electron Beam:

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



Spectrometer A:

- Luminosity monitor (const. setting)
- Momentum: 180, 305, 386 MeV/c
- Angles: 50°, 60°

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)

Luminosity monitors:

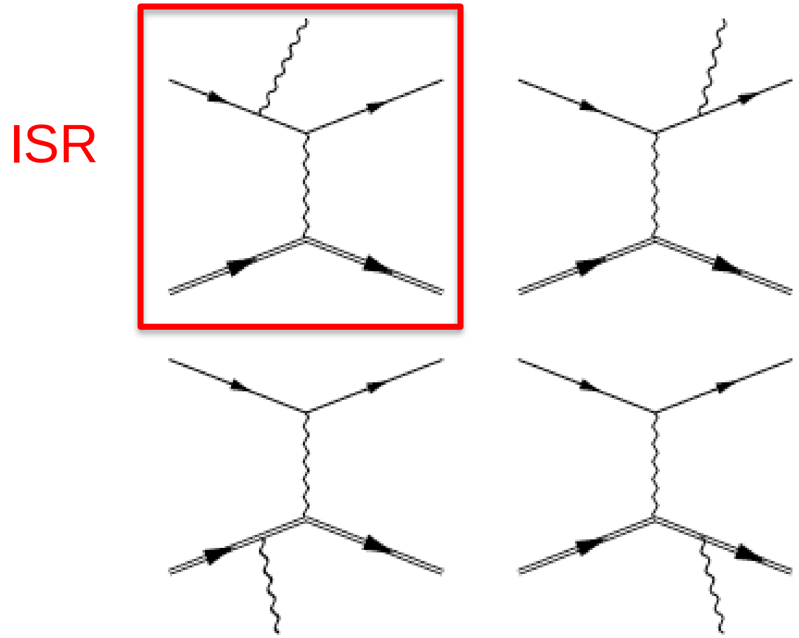
- pA-meter
- Förster probe
- SEM

Spectrometer C:

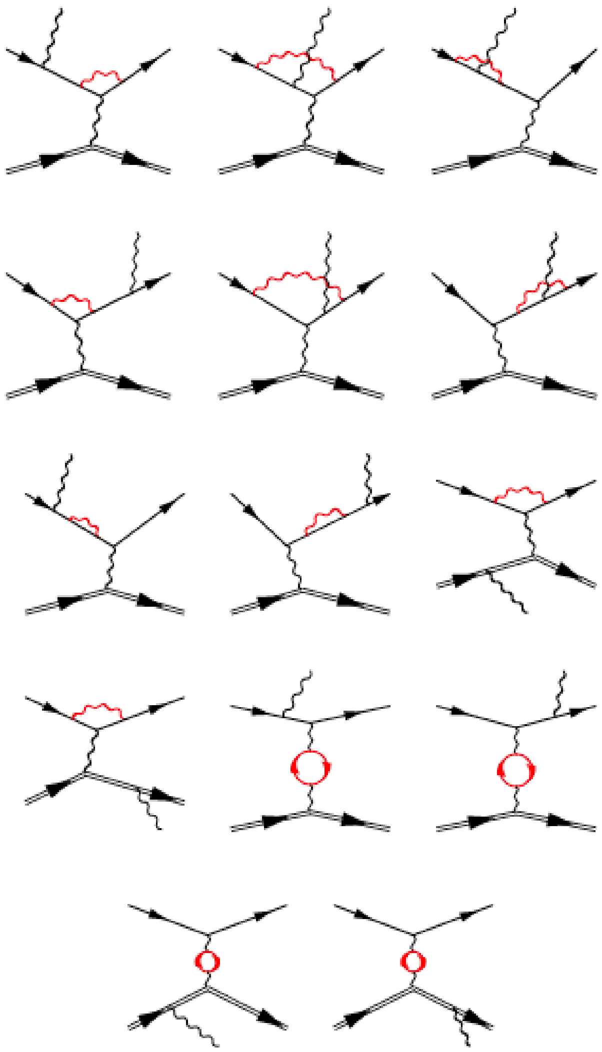
- Not used

The ISR Simulation

- Based on standard A1 framework.
- Detailed description of apparatus.
- Exact calculation of the leading order diagrams:



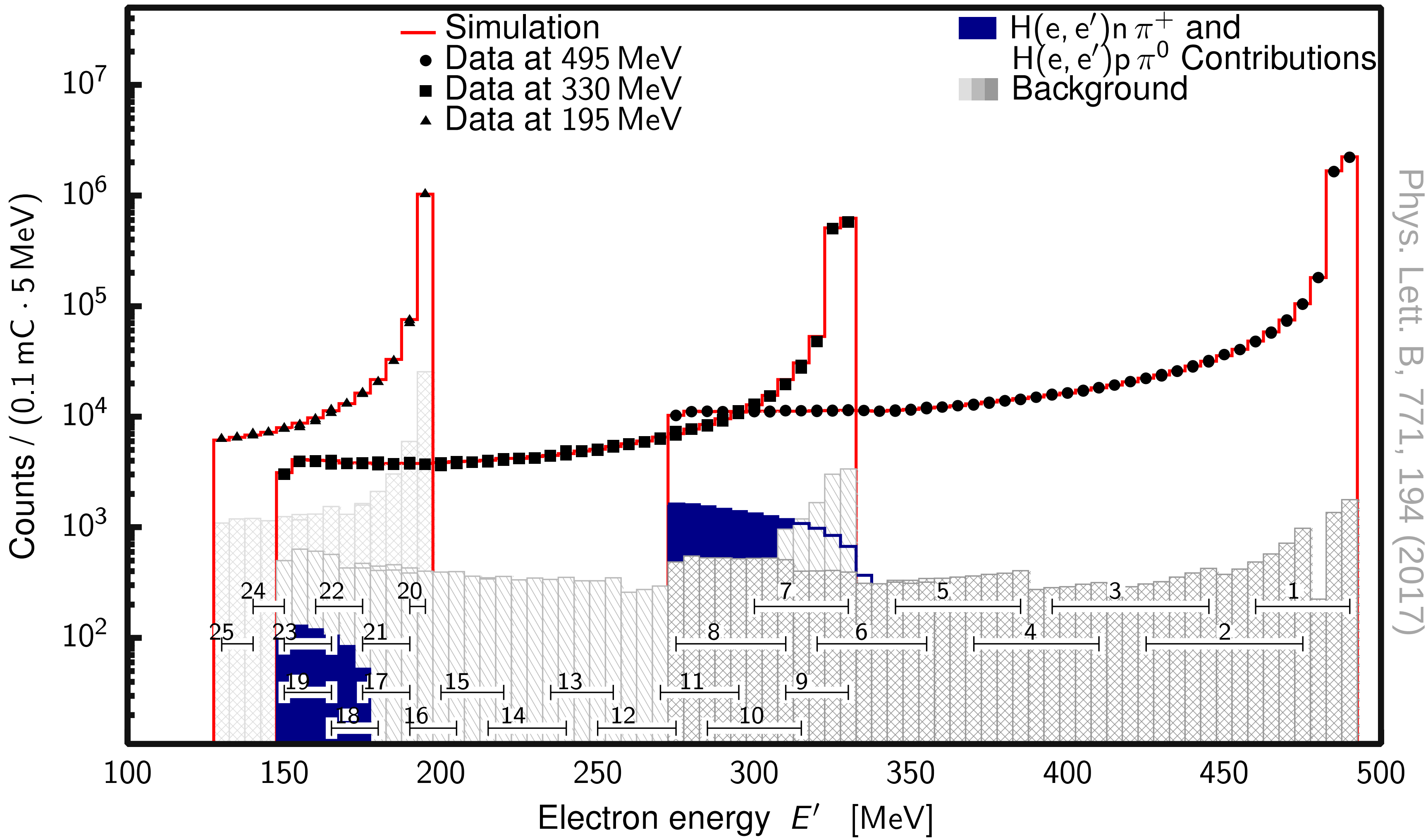
- The NL-order **virtual and real** corrections included via effective corrections to the cross-section.



…

Results

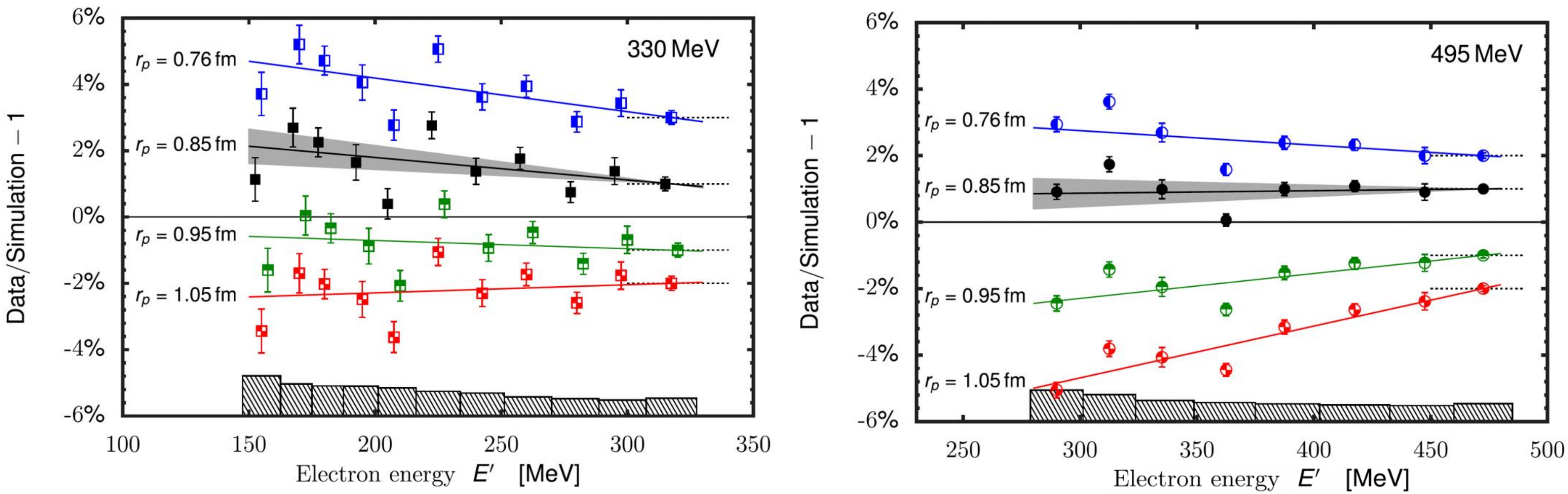
- Existing apparatus limited reach of ISR experiment to E' ~ 130 MeV.



Analysis of cross-sections

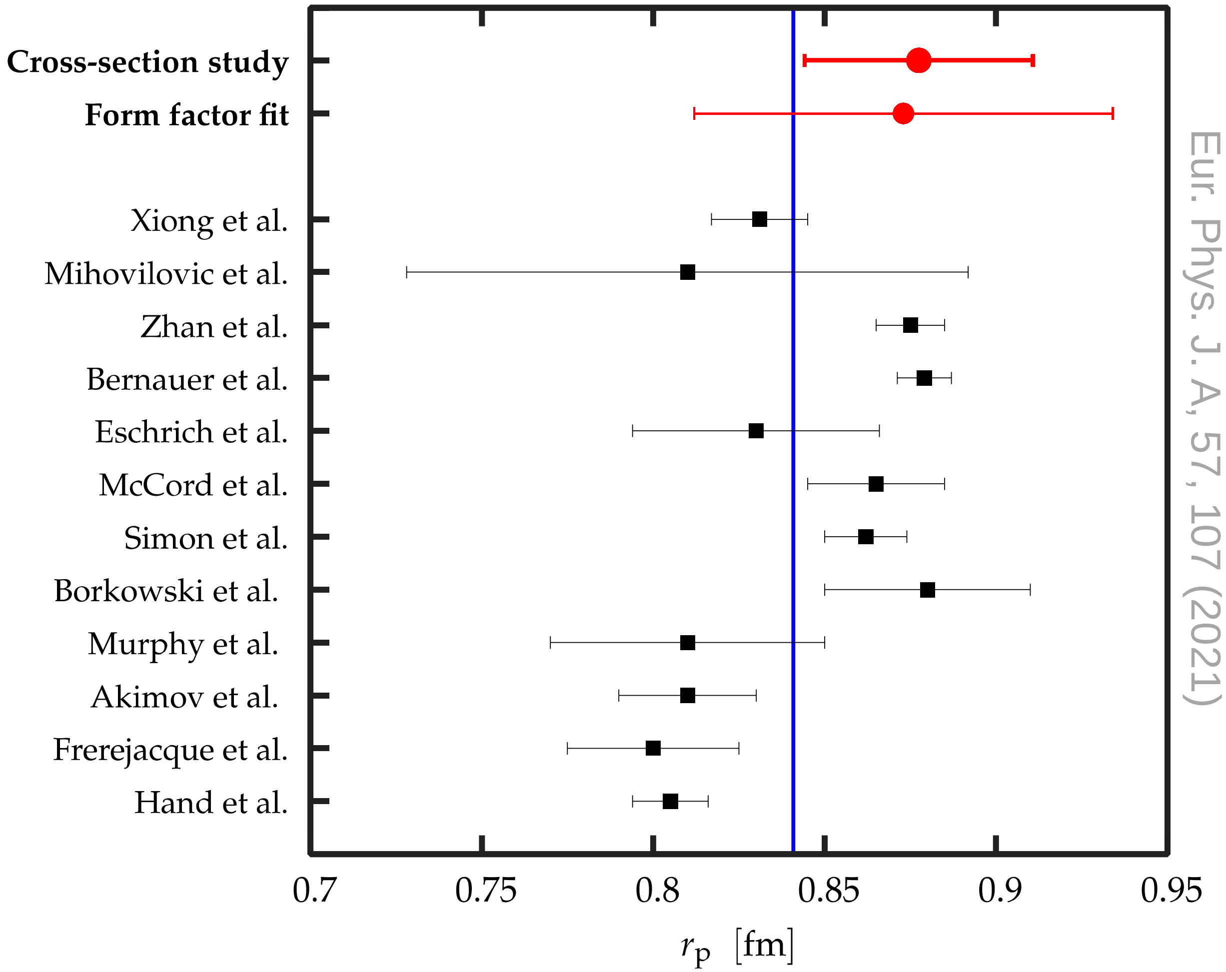
- Determination of the radius directly from the measured cross-sections.
- Small-energy data less sensitive to radius. 195 MeV data excluded.
- Analysis based on a specific form factor model.

$$G_E^p(Q^2) = n\left(1 - \frac{r_p^2}{6\,(\hbar c)^2}Q^2 + \frac{a}{120\,(\hbar c)^4}Q^4 - \frac{b}{5040\,(\hbar c)^6}Q^6\right)$$



The result of the ISR experiment

- The values from the direct analysis of cross-sections and fit of extracted form-factor.
- Uncertainty combines statistical and systematic uncertainty.



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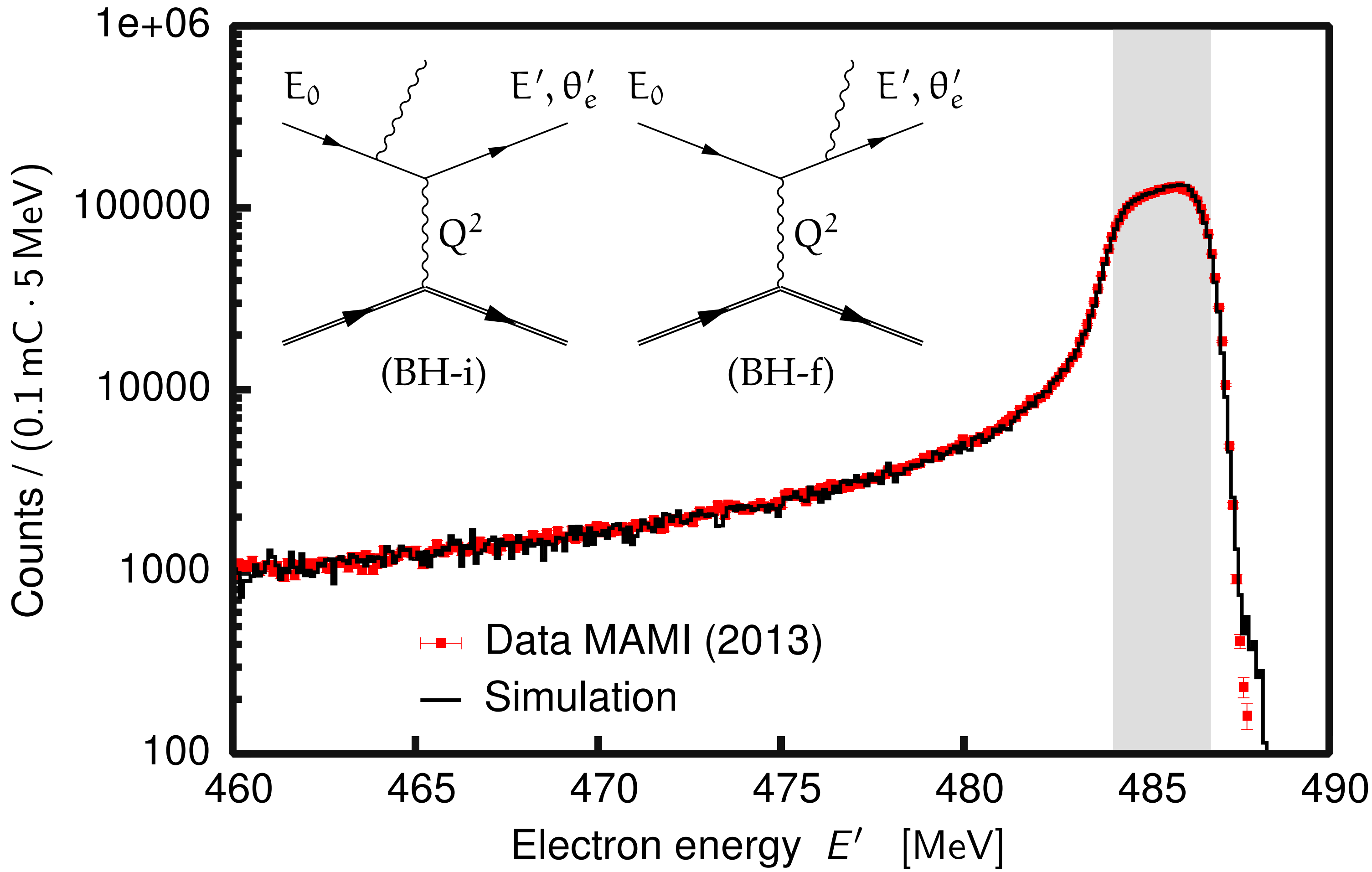
Knowing the radiative corrections



- Understanding the radiative corrections to elastic peak at the level of 1% relevant many future experiments also with other targets *(Eur. Phys. J. A, 59, 225 (2023))*.

Proton radius with Kalman Filtering (KF)

- **We are interested in proton charge radius, not so much in G_E^p .**
- KF is an alternative approach to determining the proton charge radius.
- We want to estimate r_p from many available measurements by relying on a dynamical model that dictates the Q^2 dependence of the G_e^p to get a reliable estimate for the radius that is closest to the real value.
- **The applied form-factor model does not need to be ”the correct” model, an approximate model is enough.**
- Kalman filtering is an iterative approach.
- Works with (only) linear problems and assumes normally distributed uncertainties.

Kalman filtering - Model

- The KF was run with a third-order polynomial model:

$$G_E^p(Q^2) = n\left(1 - \frac{r_p^2}{6\,(\hbar c)^2}Q^2 + \frac{a}{120\,(\hbar c)^4}Q^4 - \frac{b}{5040\,(\hbar c)^6}Q^6\right)$$

- Higher moments fixed from literature:

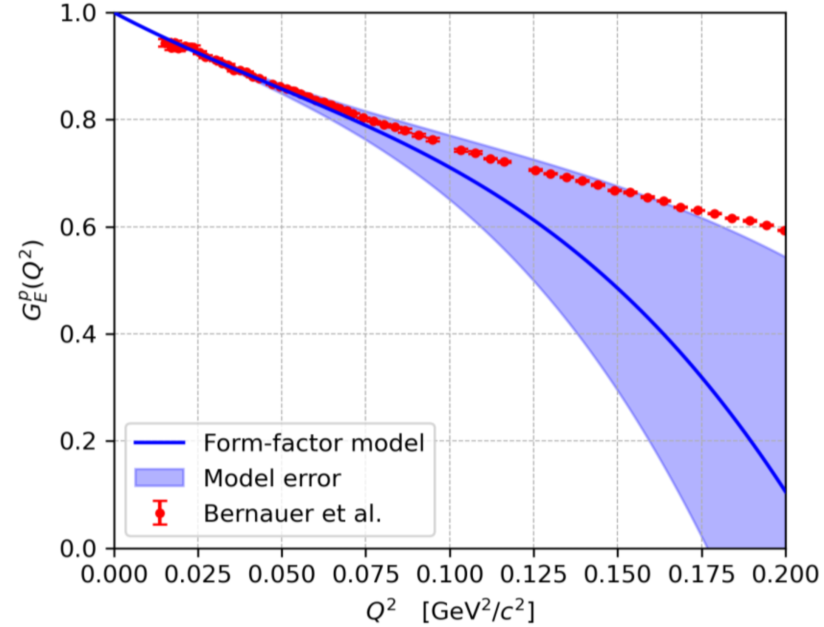
$$a = (2.59\ \pm 0.194) fm^4$$

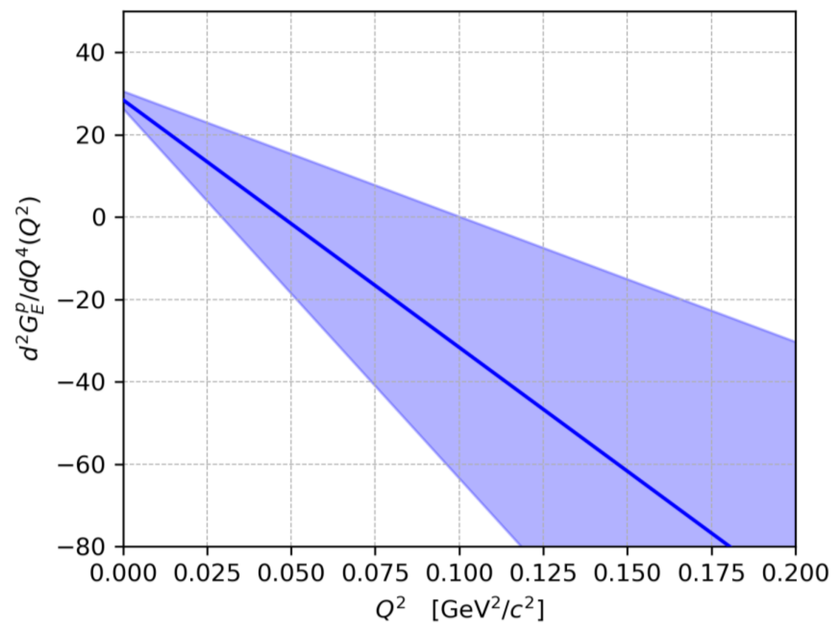
$$b = (29.8\ \pm 14.71) fm^6$$

- Model fails $Q^2 \geq 0.1\ (GeV/c)^2$.

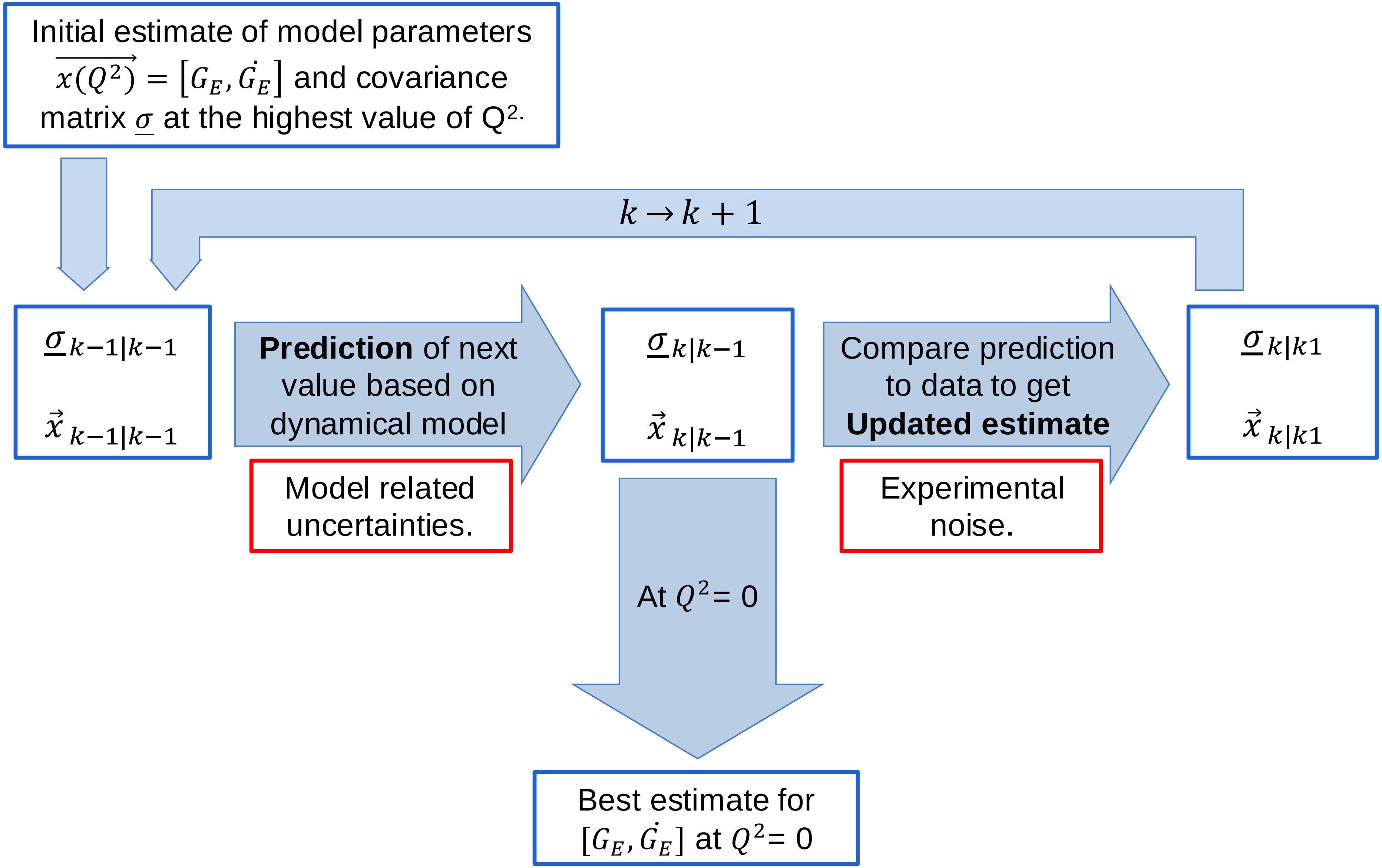
- Model enters KF in a form of a second-derivative:

$$\frac{d^2 G_E^p}{d(Q^2)^2} = \frac{a}{60\,(\hbar c)^4} - \frac{b}{840\,(\hbar c)^6}Q^2$$

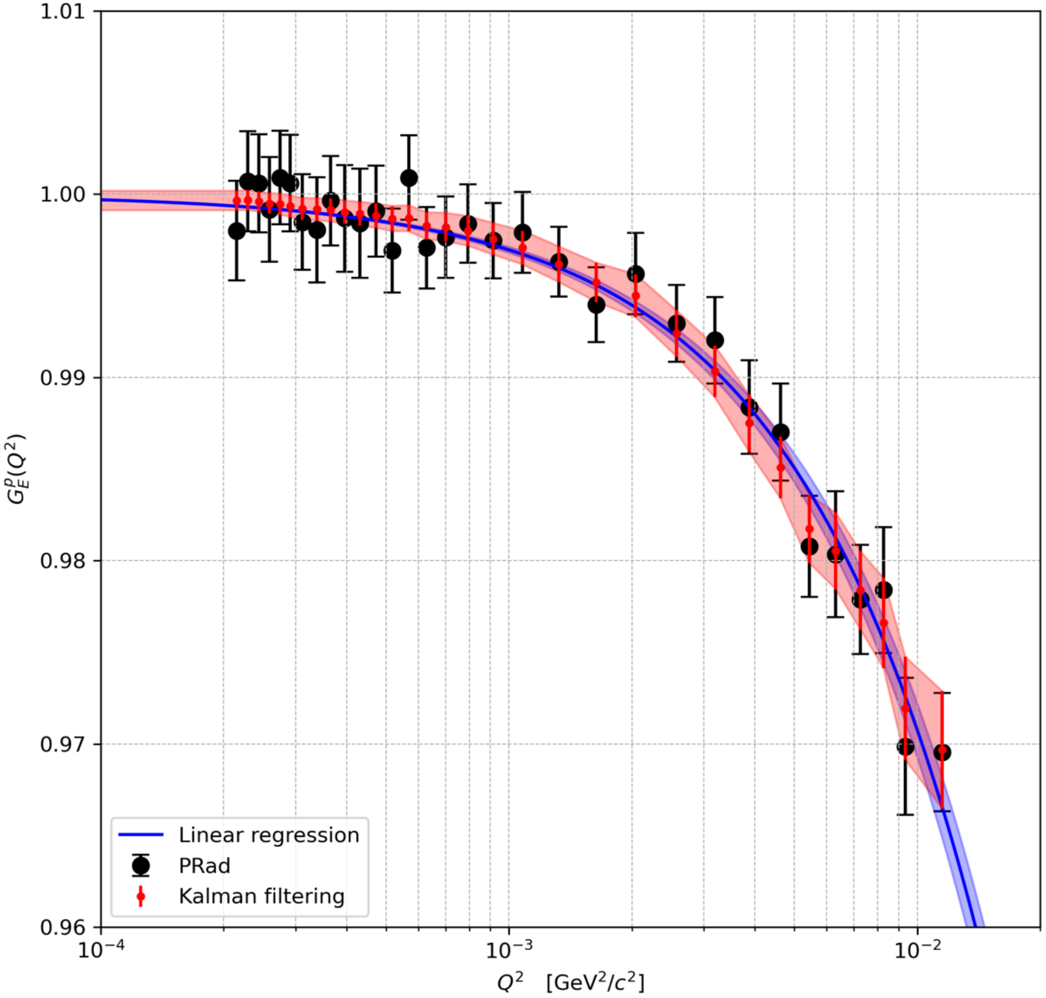




Proton radius with Kalman filtering #2

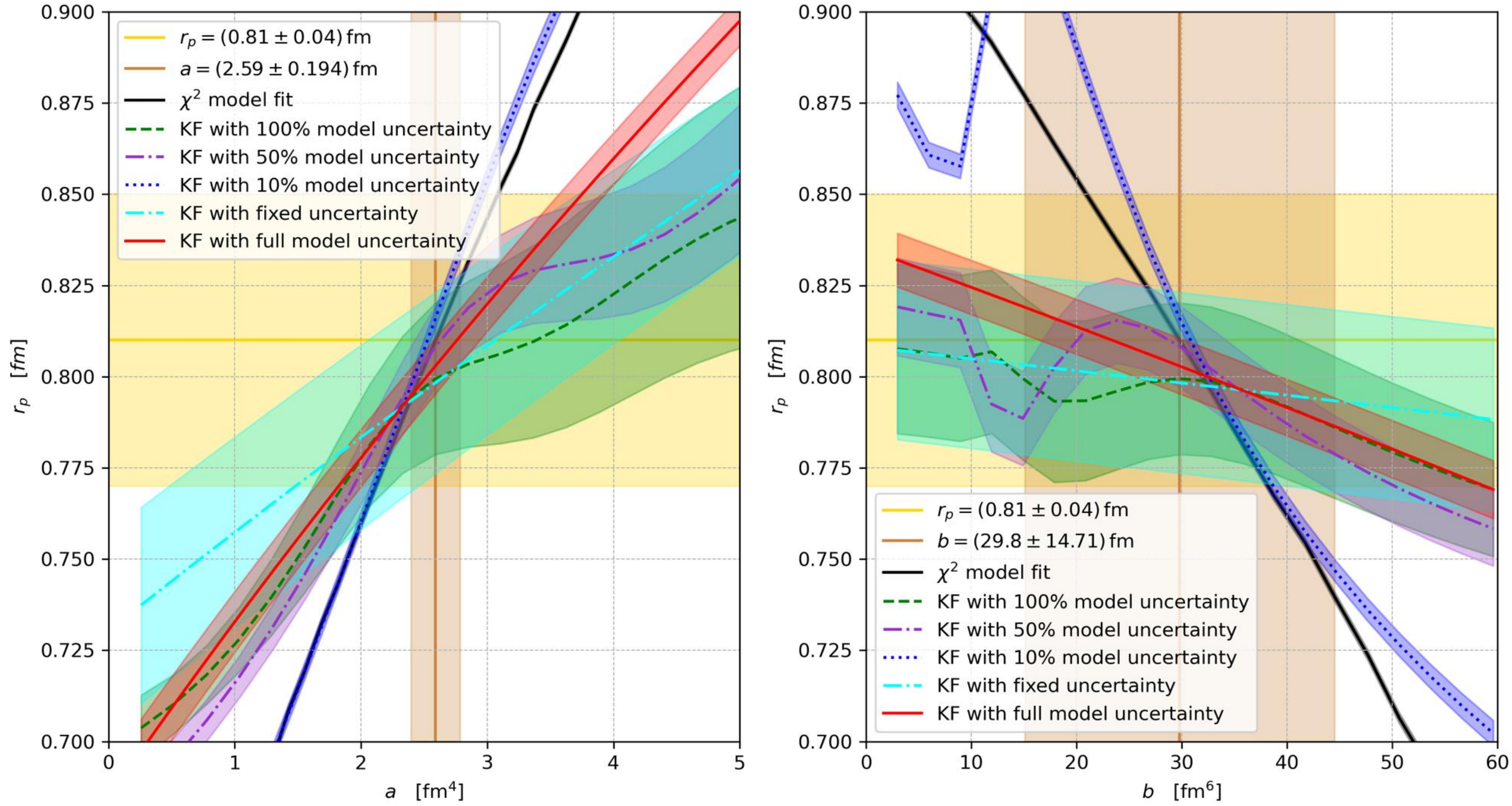


Kalman filtering - Estimates



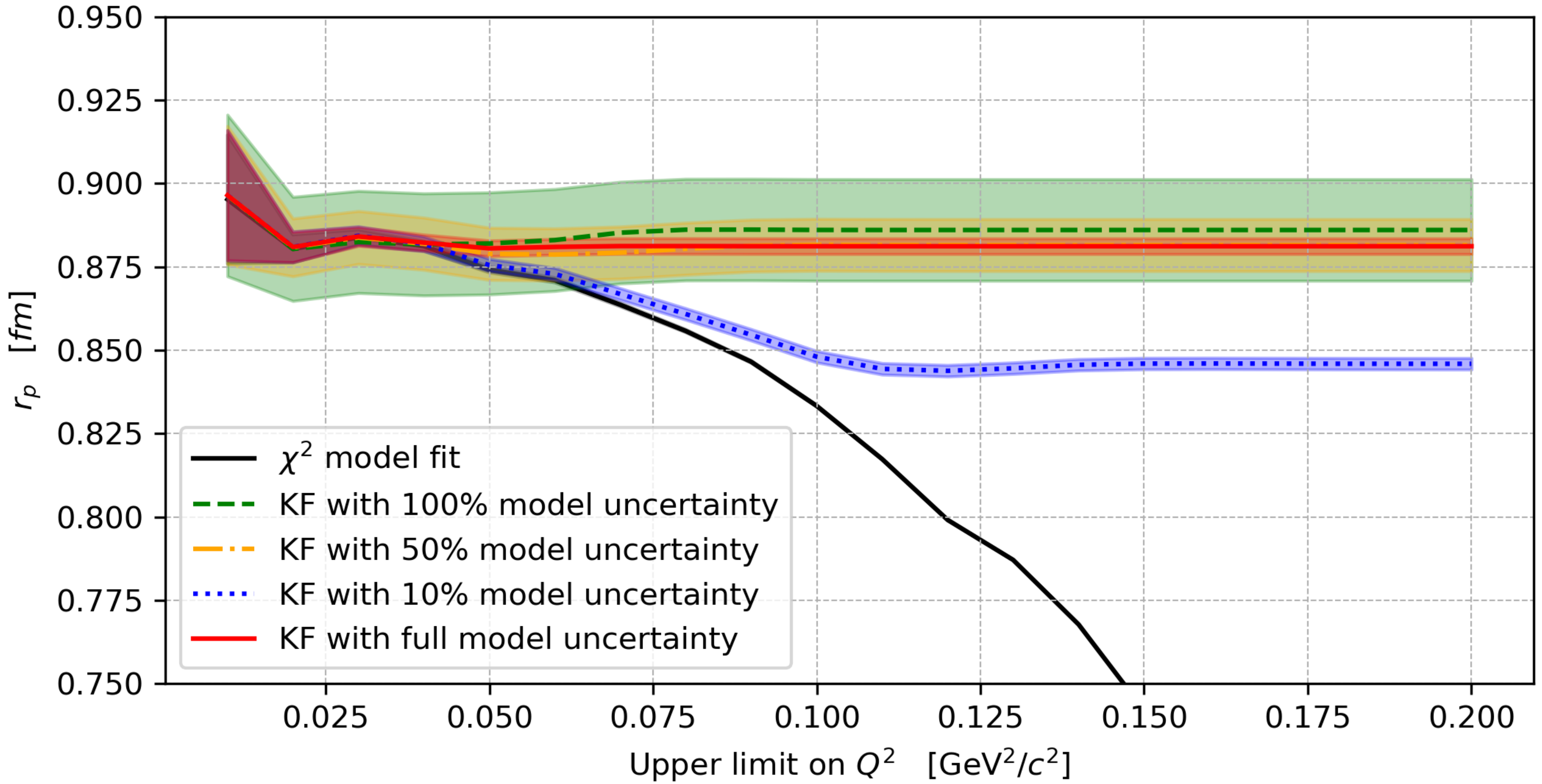
- KF operates as a MSE minimizer.
- In each step KF compares predicted values with the measurements and gives more weight to a more precise value.
- In recursive steps algorithm finds general (smooth) trend through the data to get best estimates of the two open parameters (n, r_p).

Kalman filter – Model dependence



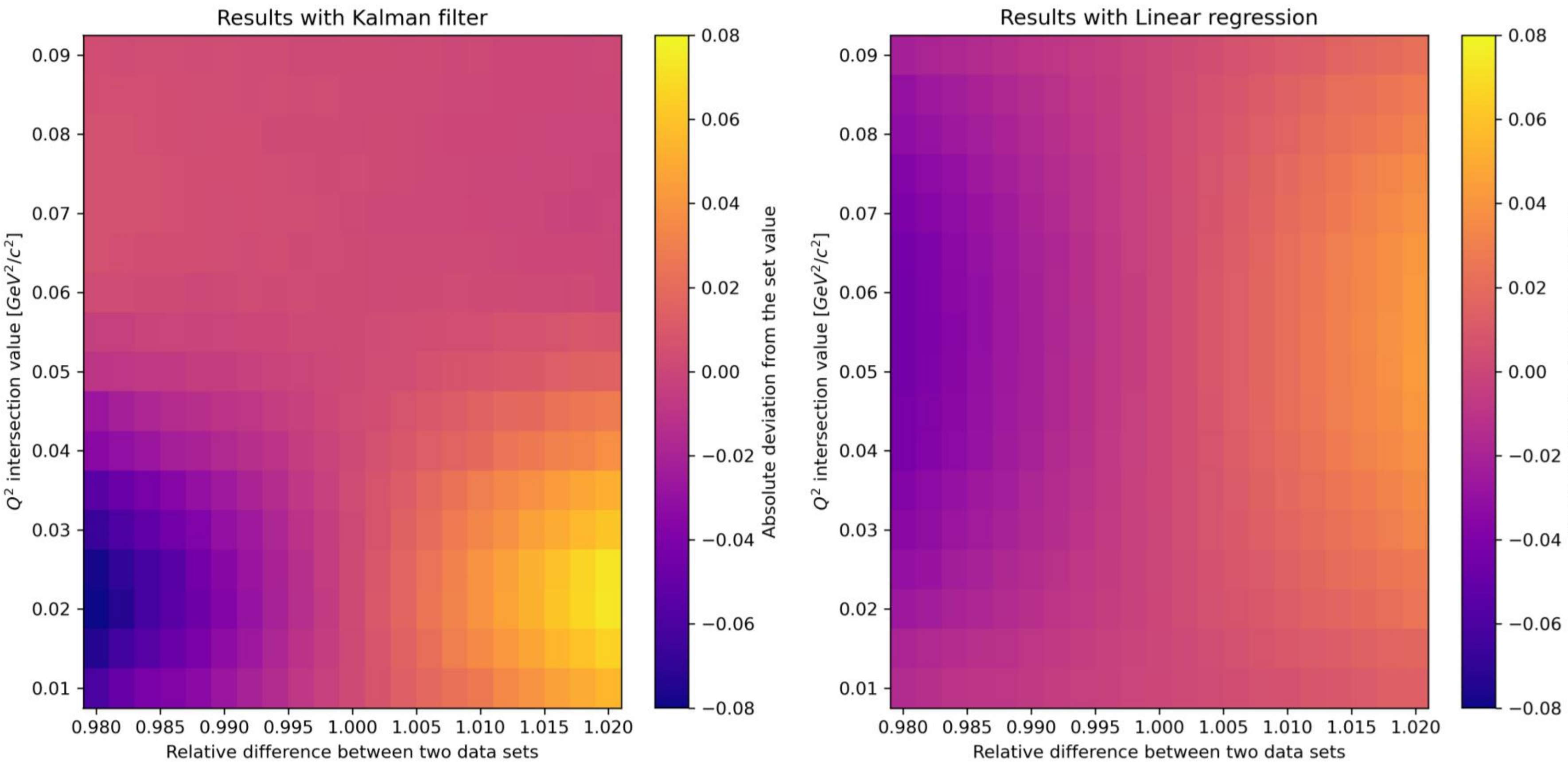
- Model dependence was tested with pseudo-data based on a Polynomial model.
- **Recursive nature of KF reduces the model bias.**
- Smaller model uncertainty brings KF results closer to the results of linear regression.

Kalman filter – Q^2 running



- Results of linear regression strongly depend on the Q^2 range considered in the fit and tend to be biased towards smaller value of r_p.
- **Results of KF avoid bias related to the upper Q^2 cut of available data.**

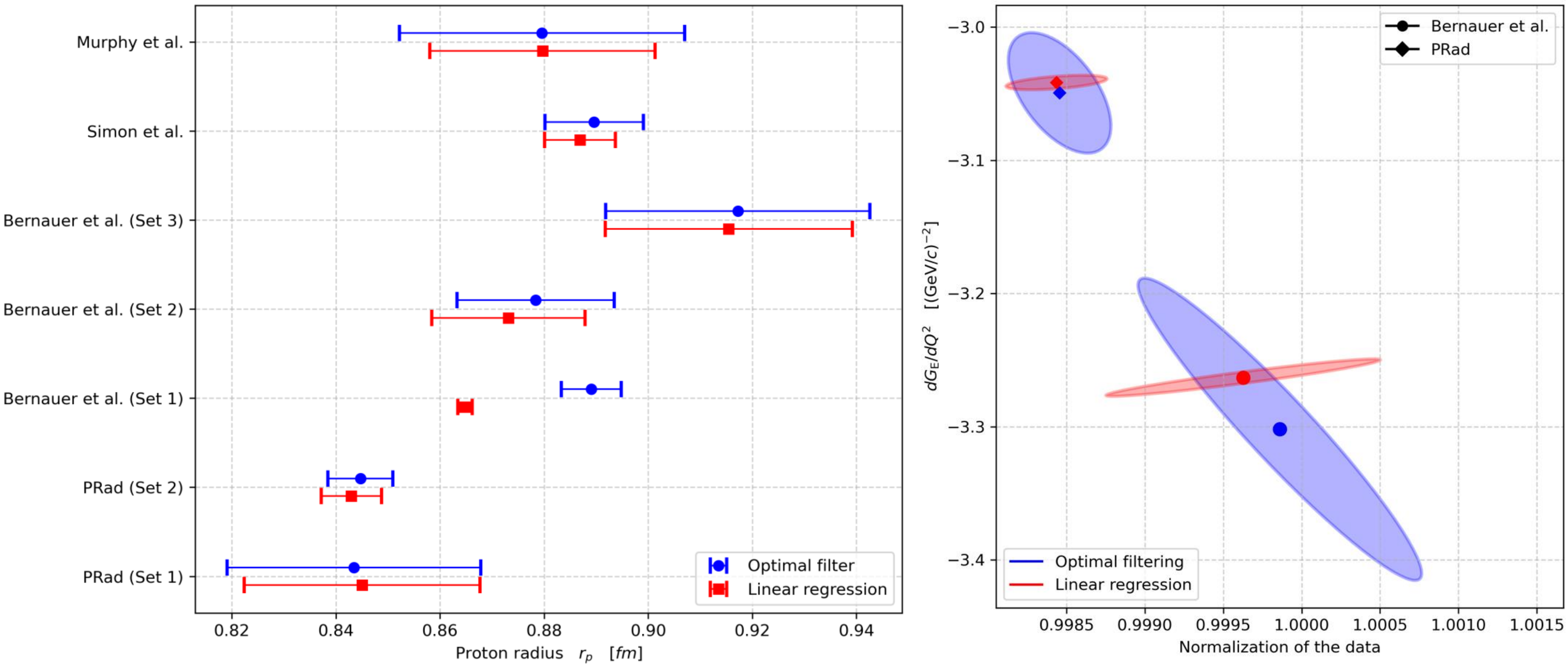
Kalman filter – Floating Normalizations



- Incorrect consideration of relative normalizations between data can significantly bias results of linear regression.

- **Results of KF avoid this bias if data quality is sufficient for algorithm to correct for the discrepancy between data sets.**

Kalman filter - Results



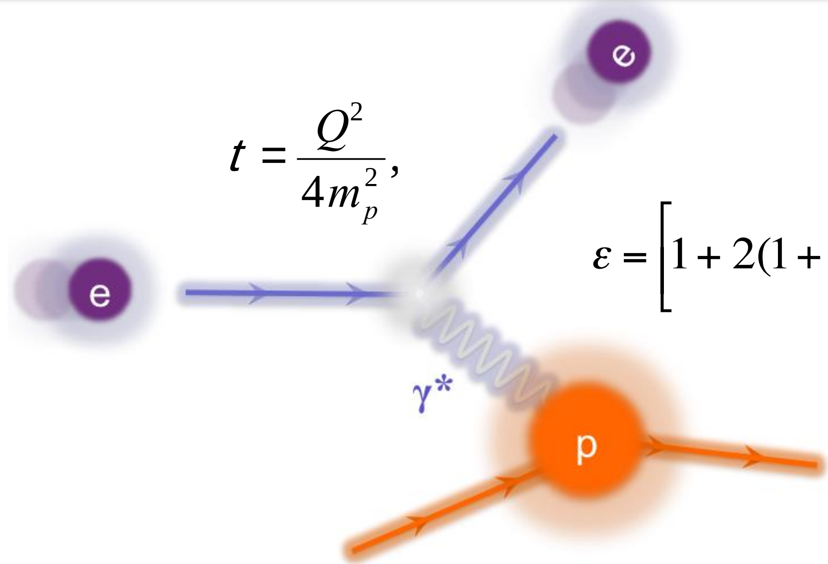
- KF of selected data-sets reproduces original results of Simon, Bernauer and PRad.
- **A self-consistent KF analysis indicates discrepancy between data-sets and motivates further experimental verification of existing FF measurements.**
- KF mostly consistent with linear regression but with different parameter correlations.

Summary

- Still facing competing values of proton charge radius.
- **Discrepancy due to inconsistent experimental results and ambiguities in the interpretation of available data.**
- The ISR experiment used a new experimental technique for determination of the proton form-factors at very small Q^2.
- ISR validated radiative corrections far away from elastic settings.
- We need to find consensus on how to fit / interpret the nuclear scattering data.
- **KF as an alternative analysis approach for more robust determination of the proton charge radius.**
- Further measurements are needed – **Magix experiment with Hypersonic gas jet (or plastic) target!**

Thank you!

Radius via Cross-section measurement



$$t = \frac{Q^2}{4m_p^2},$$

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

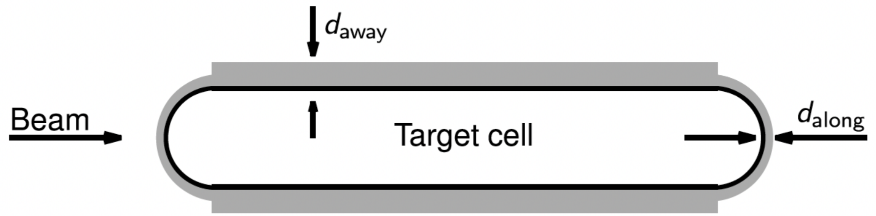
$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{Mott} \frac{1}{1+\tau}\left[G_E^2(Q^2) + \frac{\tau}{\varepsilon} G_M^2(Q^2)\right]$$

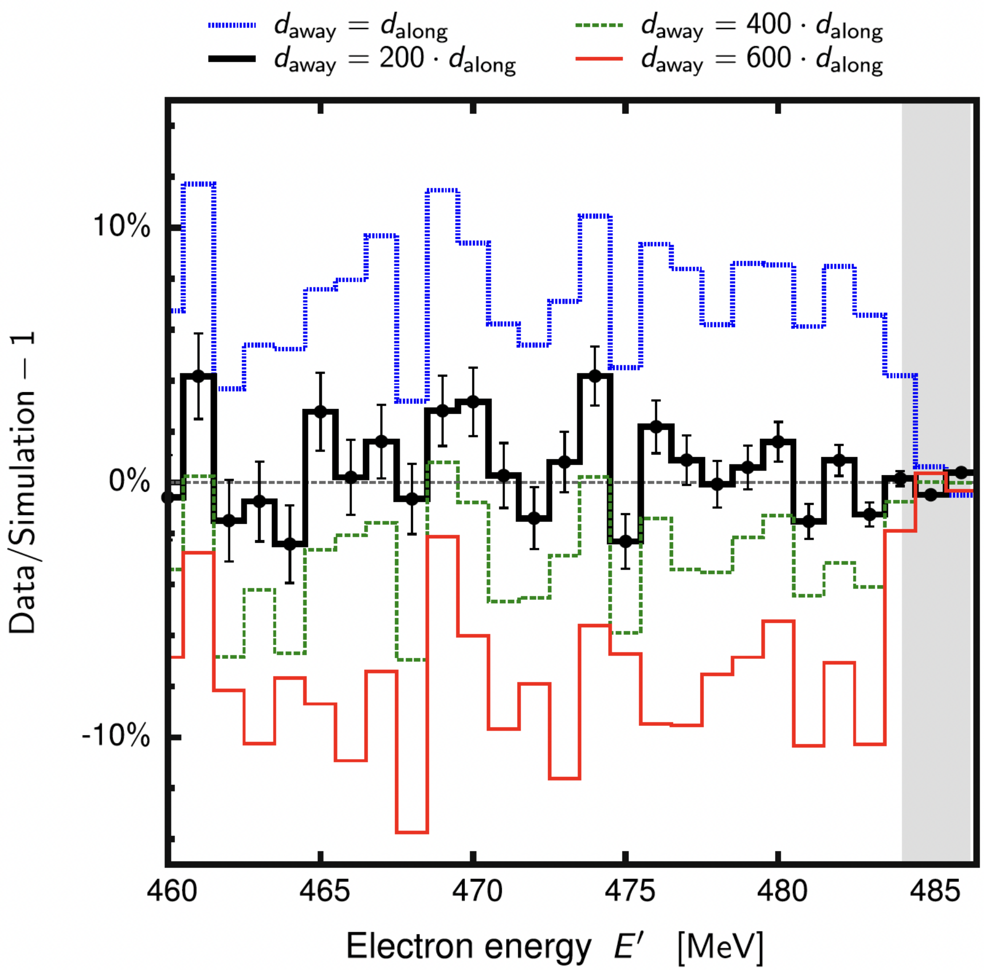
- Extraction of FF via Rosenbluth Separation.
- Best estimate for radius:

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

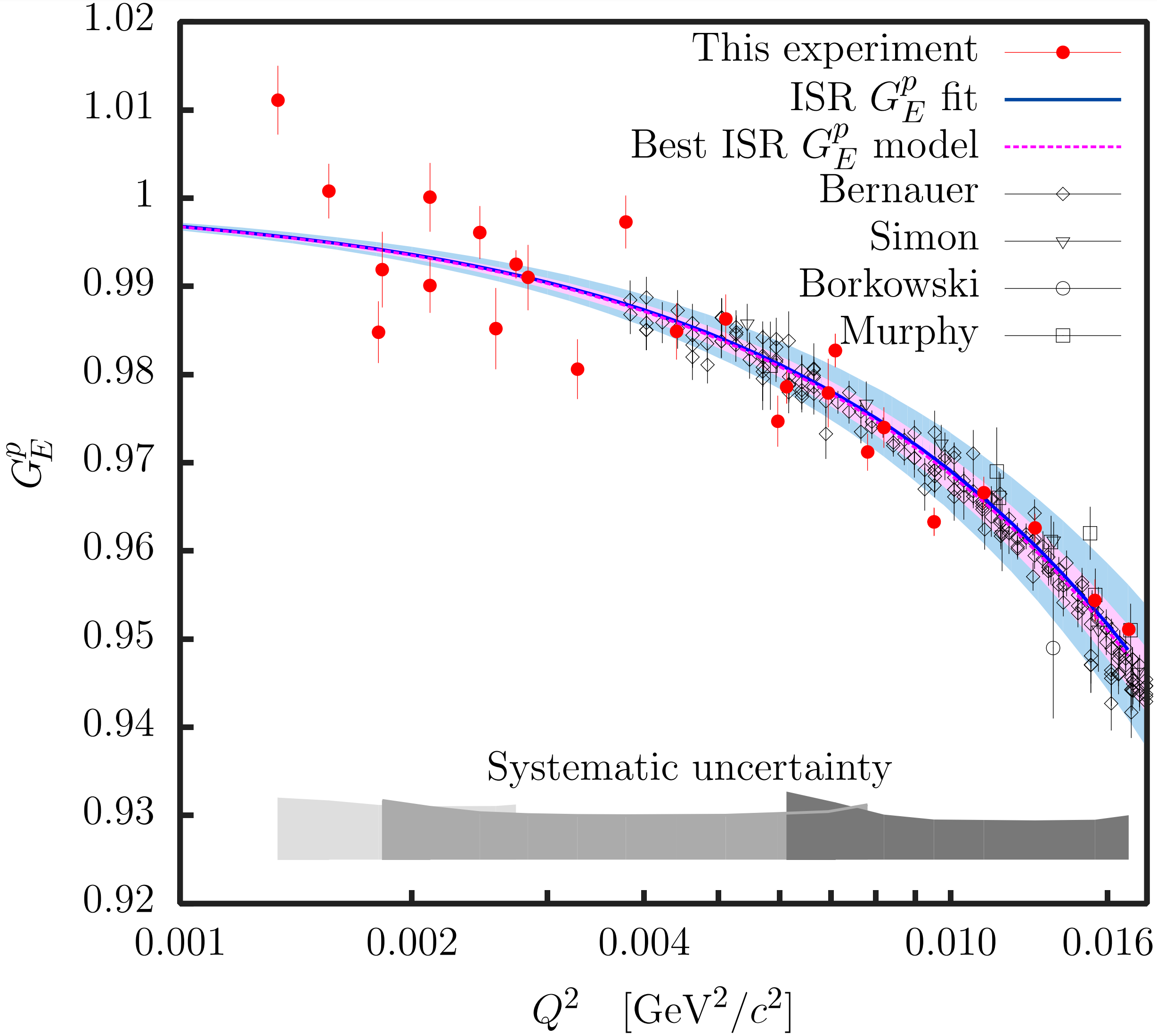
Shortcomings of Cryogenic target

- Employed an extended cryogenic target.
- Backgrounds from target walls and supporting frame.
- Spectra distorted due to cryogenic depositions on the walls.
- Cryogenic layer on the sides much thicker than in the beam direction. Huge effect on the elastic data! **<u>No control over the thickness of the layer.</u>**





ISR form-factors



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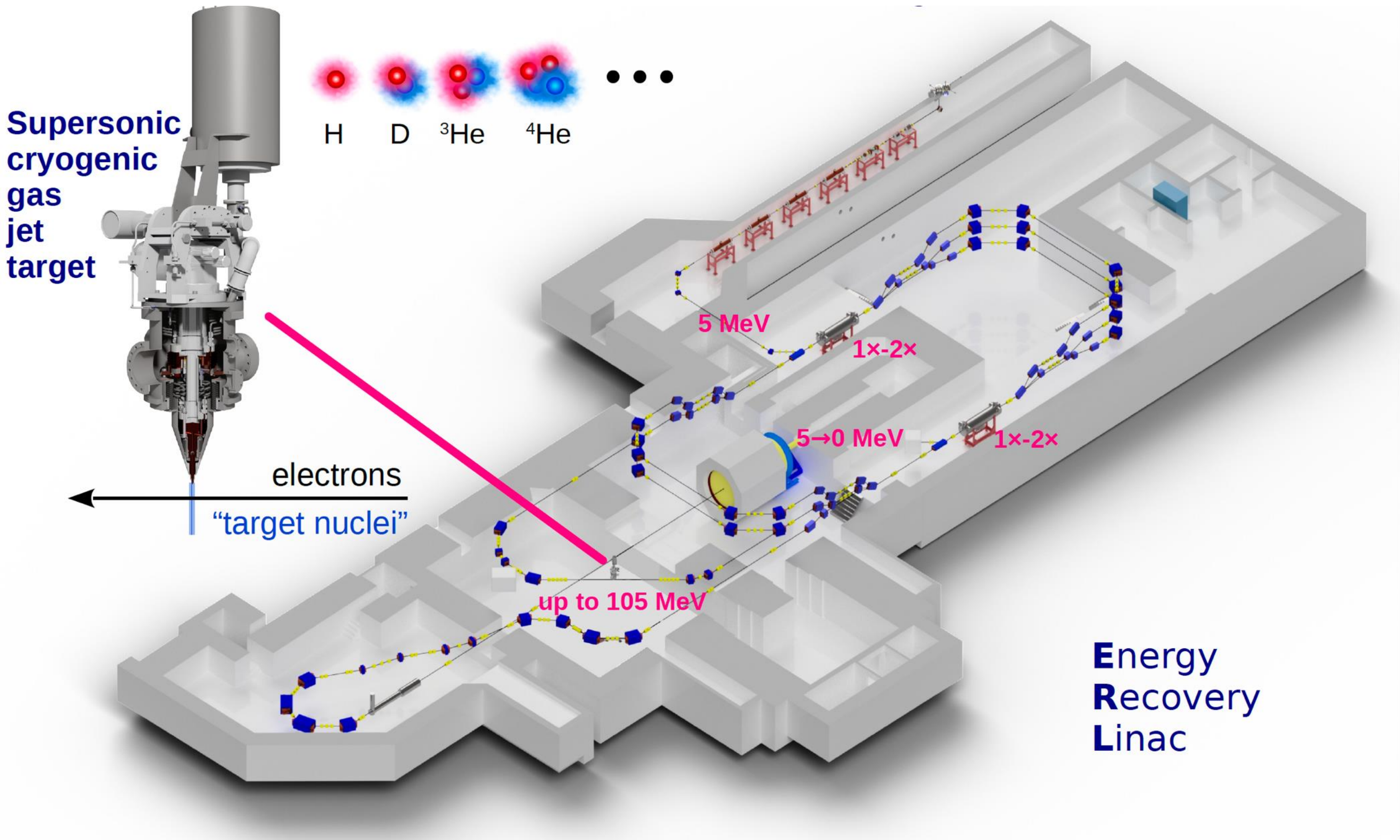
- Form-factors extracted from deviations of the measurements from the Bernauer model, assuming flawless description of radiative corrections.

Magix @ MESA



P2/DM-EB mode: ~155 MeV, 150 µA
MX-EB mode: 20-105 MeV, < 150 µA
ERL mode: 30-105 MeV, 10000 µA

B. S. Schlimme

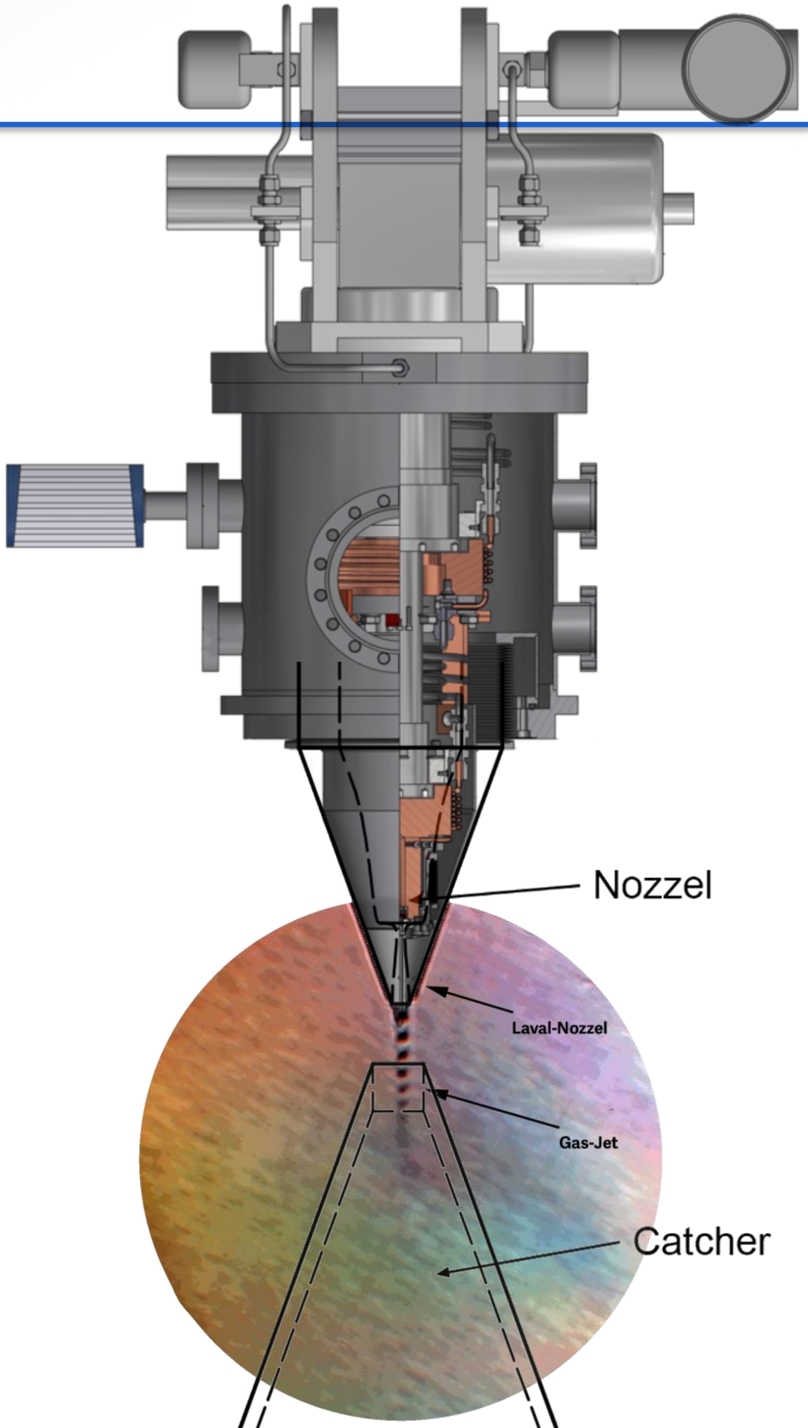
Hypersonic jet target

- Target developed for MAGIX, but could be used also in A1.

- No metal frame near the vertex.
- No target walls.
- Width of the jet 2mm (point-like target)

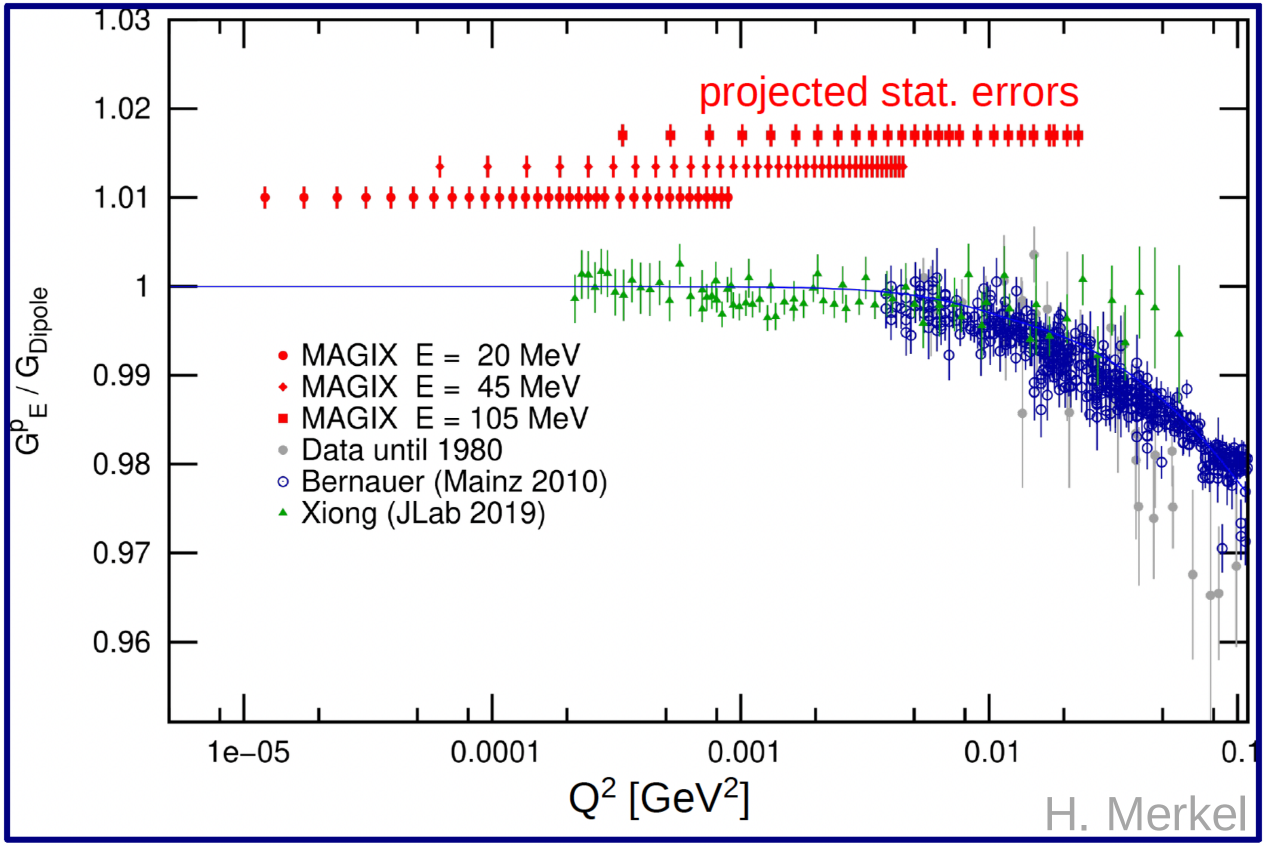
- Density of **10^{-4} g/cm^3** at 15 bar.
- Luminosity of **10^{34}/cm^{2}s** can be achieved at MAMI.

See talk of Yimin Wang



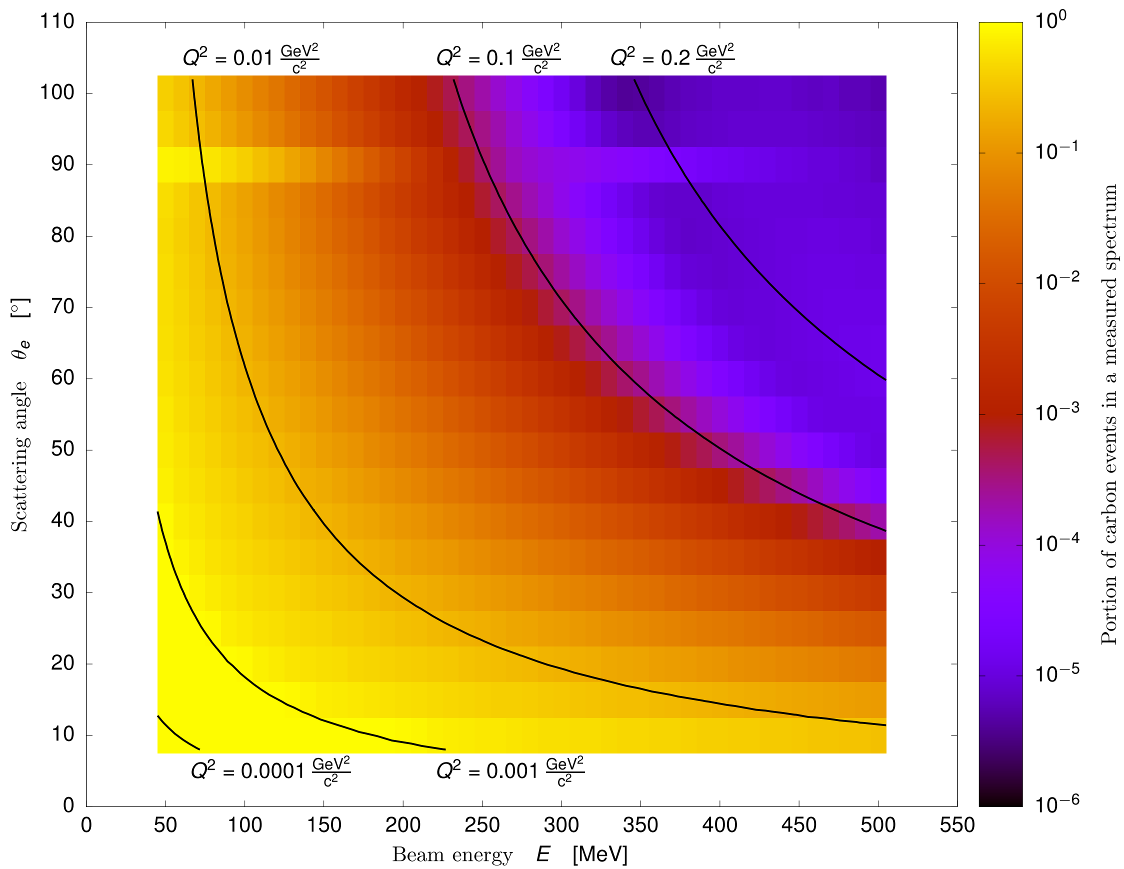
Radius measurements @ Magix

- Persistent discrepancy between different determinations of the proton radius persists demands further measurements.
- New measurement planned also at Magix @ MESA
- Measurement of G_E^p at Q^2 between $1 \cdot 10^{-5}$ and 0.03 GeV^2
- Expected statistical uncertainty ~ 0.1 %.
- Expected systematical uncertainty < 0.5 %.
- Measurement of G_M^p using double-polarized experiments.



Potential experiments with plastic targets

- Uncertainty of experiments dominated by the target-related systematics.
- Desired target is **<u>thin</u>** with **<u>known and constant density</u>** and <u>background</u>, that can be clearly <u>subtracted</u>.
- Plastic (-CH2-) target an effective hydrogen target with carbon background.



Findings of tests with plastic target

- Peaking approximations **insufficient** for describing carbon background.

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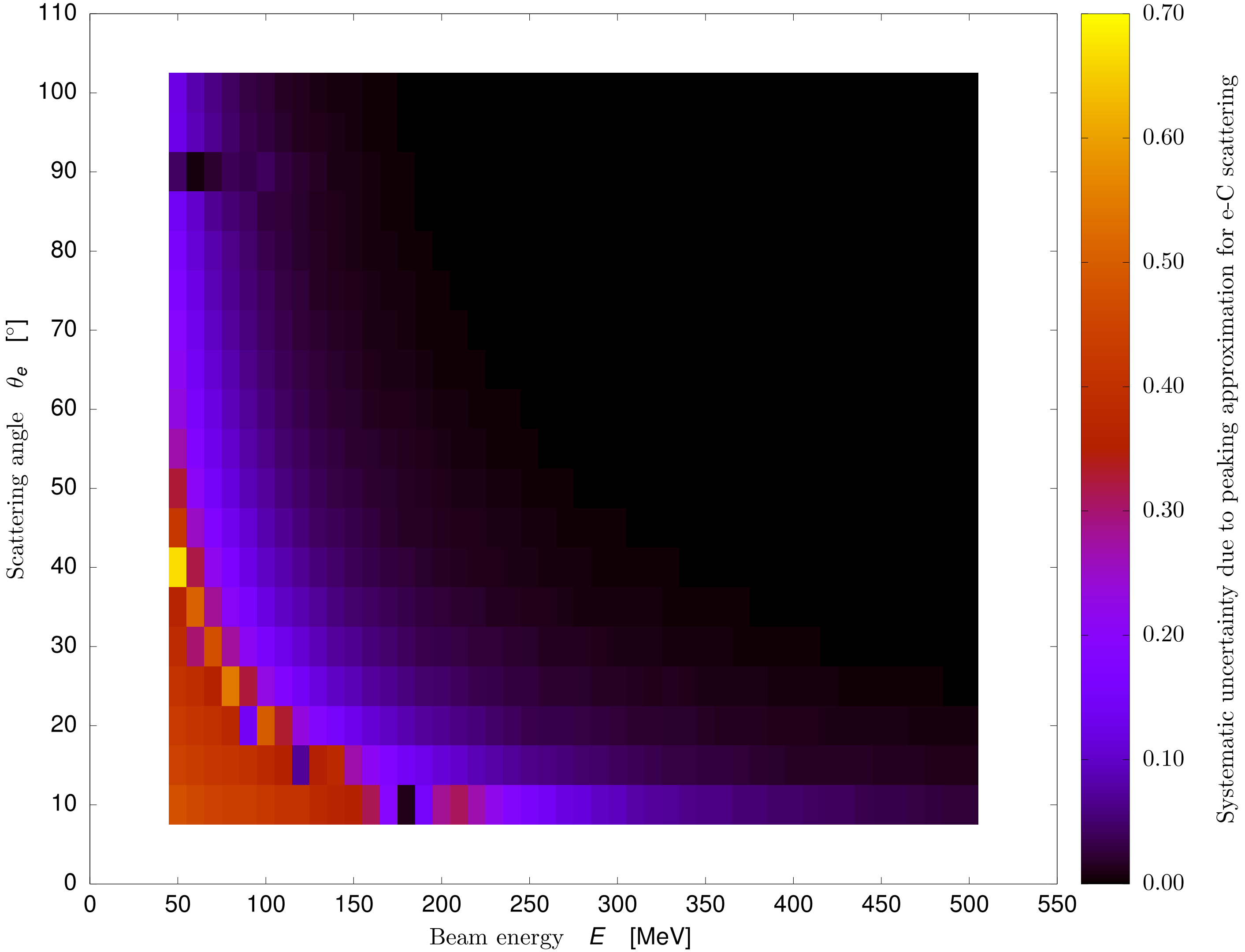
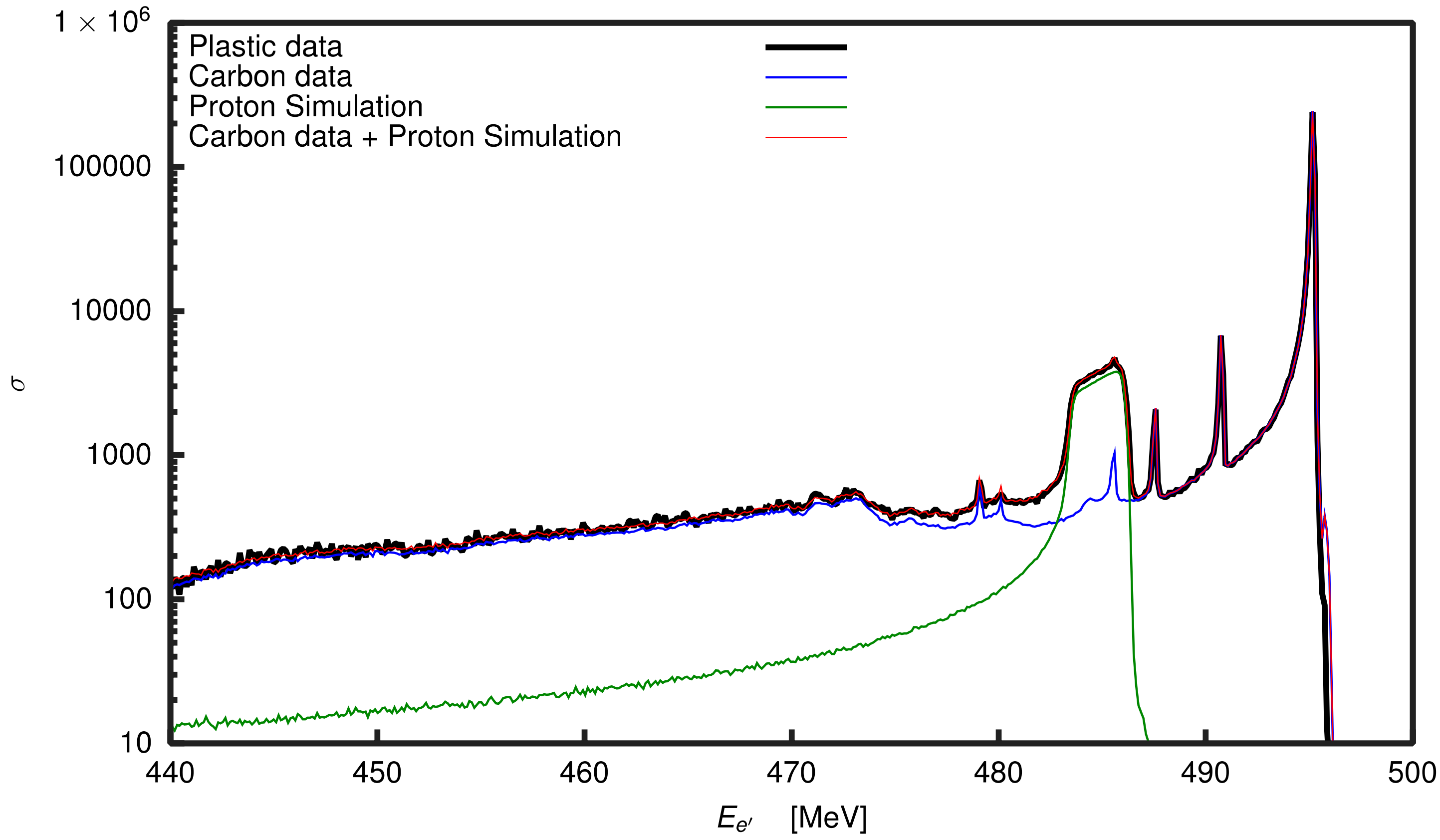


Findings of tests with plastic target



- Peaking approximations insufficient for describing carbon background.
- Measurements with thin carbon targets are necessary due to the presence of inelastic contributions for adequate background description.
- External radiative corrections need to be applied to match plastic spectra.