Status and plans of the low Q^2 nucleon form factor program: A look at the magnetic form factor

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ECT* - June 2018

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Cross section for elastic scattering

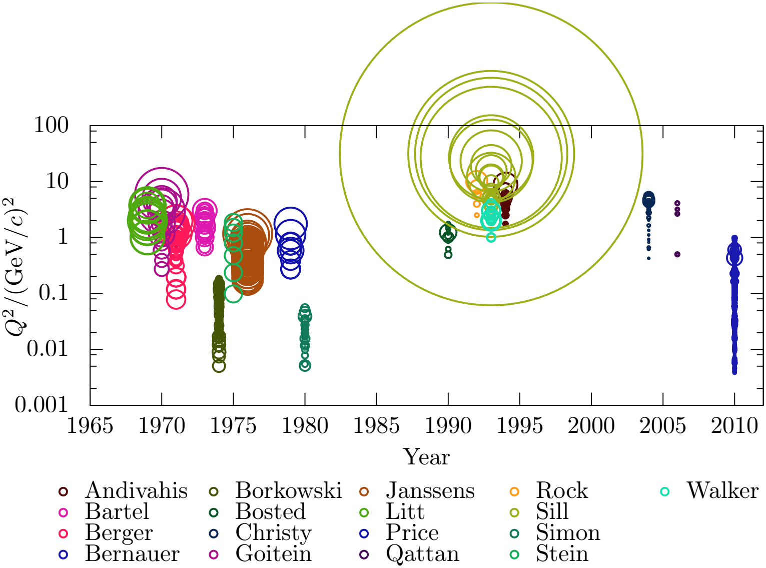
$$\frac{\left(\frac{d\sigma}{d\Omega}\right)}{\left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}}} = \frac{1}{\varepsilon\left(1+\tau\right)}\left[\varepsilon G_E^2\left(Q^2\right) + \tau G_M^2\left(Q^2\right)\right]$$

with:

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

- Rosenbluth formula
- Electric and magnetic form factor encode the shape of the proton
- Fourier transform (almost) gives the spatial distribution, in the Breit frame

History of unpolarized electron-proton scattering



High-precision p(e,e′)p measurement at MAMI

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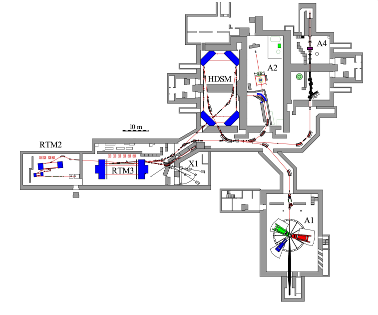
Mainz Microtron

- cw electron beam
- 10 μA polarized,
  100 μA unpolarized
- MAMI A+B: 180-855 MeV
- MAMI C: 1.6 GeV



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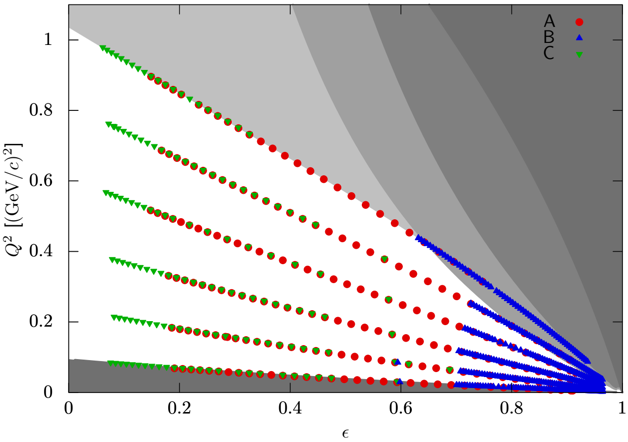
A1 3-spectrometer facility

- 28 msr acceptance
- angle resolution: 3 mrad
- momentum res.: 10^{-4}

Measured settings



1422 settings

JCB et al., Phys. Rev. Lett. 105 (2010) 242001,
M. O. Distler, JCB, Th. Walcher, Phys. Lett. B 696, 343 (2011)
JCB et al., Phys. Rev. C90 (2014) 015206

What we have

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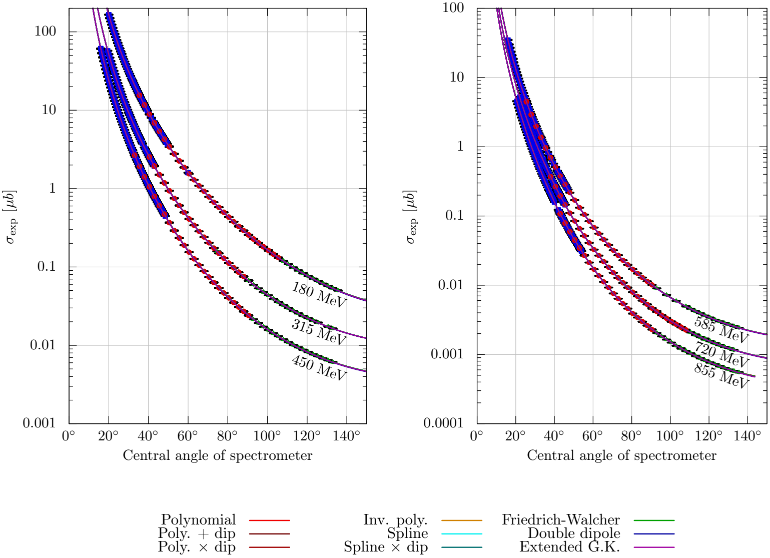
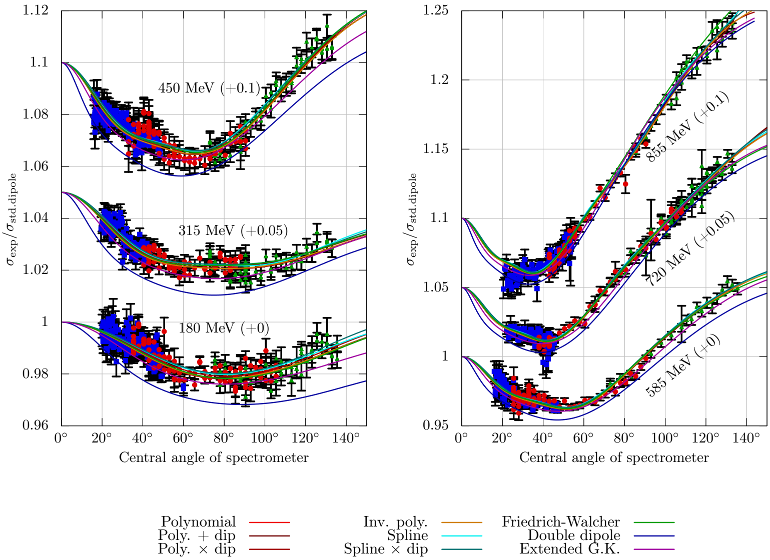
Cross sections



Cross sections (normalized)



SUMMARY

- Low-Q Form Factors and Structure Functions: Long and distinguished program with many dedicated workshops in the past
- RCS, VCS, DVCS (and in the future even VVCS): similarly vibrant community
- Many new data coming out or to be taken soon
- $\Rightarrow$ Significant reduction of the uncertainties on HFS and charge radius extraction due to nucleon/nuclear structure
- Important need: Consistent and accurate models of FFs and SFs (including TPE) using all available data
- …to be matched by new theoretical developments in χPT, effective theories, dispersion relation analysis and LQCD

What we have

- Fit to Mainz data alone
- Fit to Mainz data + world Rosenbluth data
  - consistent, good total and individual χ^2
  - extends the range to $10\,(GeV/c)^2$

Inclusion of world data

- Extend data base with world data
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  - Update / standardize radiative corrections
  - One normalization parameter per source (Andivahis: 2)

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- Two models:
  - Splines with **variable** knot spacing
    $\Longrightarrow$ Adapt knot density to data density
  - Padé-Expansion
    $\Longrightarrow$ Lower flexibility, for comparison

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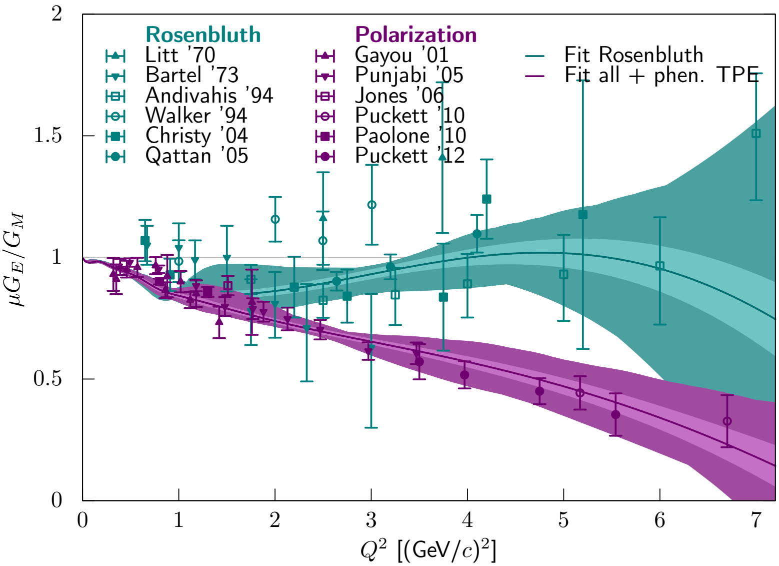
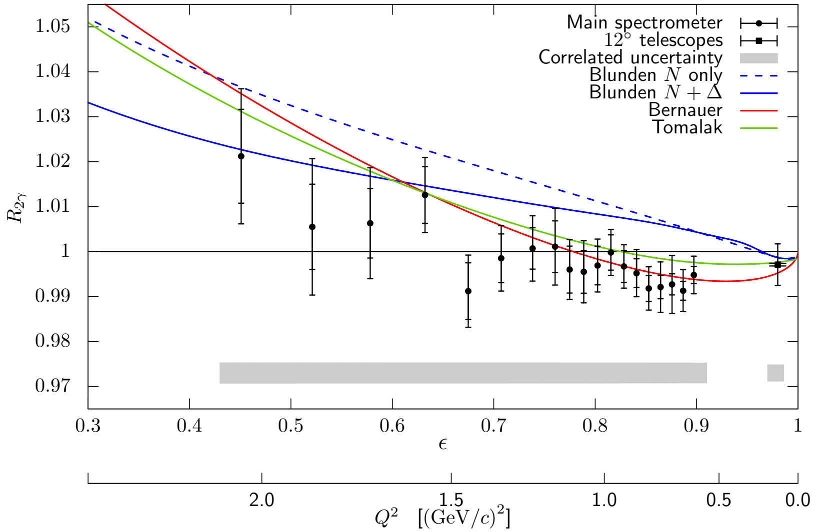
- Fit to Mainz data + world Rosenbluth data + world polarization data
  - consistent, good total and individual χ^2
  - phenomenological TPE model
  - excellent agreement with direct TPE measurements

Form factor ratio and fits



OLYMPUS results (B. Henderson et al., arXiv:1611.04685 (nucl-ex))



Soon: More "high" Q^2 data from Mainz

- Additional data (O(100) new kinematics) taken at 5 higher beam energies of MAMI-C
- Up to almost 2 $(\text{GeV}/c)^2$
- Analysis ongoing (grad student: Julian Weber)
- Ask Michael for more details

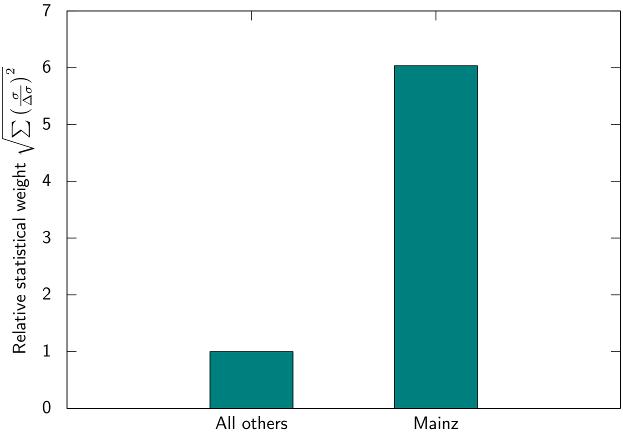
Why we want more

- .... besides the points raised in this workshop
- TPE models differ for lowest ϵ

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

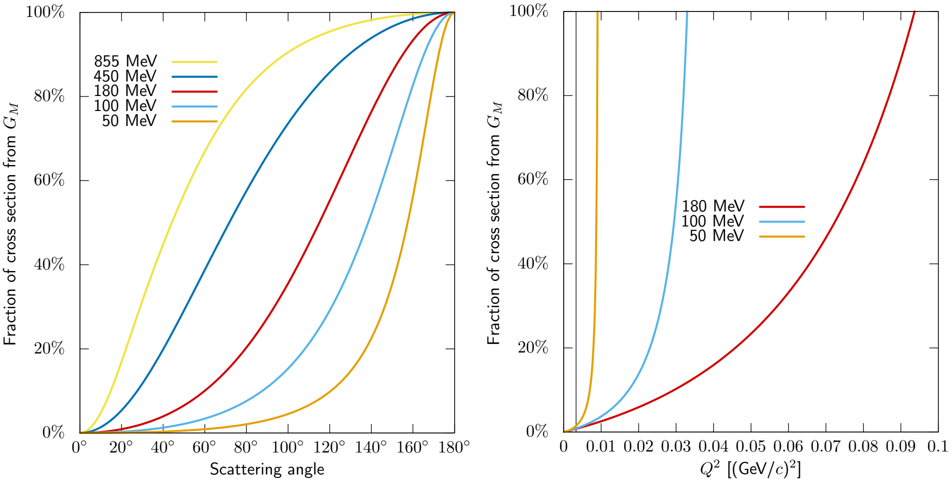
- Statistical uncertainty for magnetic radius $\sim$ 0.013 fm, about 3$\times$ the electric radius uncertainty

Volume of Mainz data set: Need validation



Mainz data will dominate any fit. Need similar data set to validate!

Low-Q G_M is hard



Extrapolation to $Q^2 = 0$

Have to extrapolate form factor to $Q^2 = 0$.
Mainz lowest $Q^2 = 0.0033\,(\mathrm{GeV/c})^2$.
We use a 10th order polynomial to fit data up to $1\,(\mathrm{GeV/c})^2$. This gets people scared.

Can we fit just a linear term?

Can a linear fit work?

$$\frac{d\sigma}{d\Omega} \propto 1 - \underbrace{A}_{\mathcal{O}(6)} \cdot Q^2 + \underbrace{B}_{\mathcal{O}(30)} \cdot Q^4 + ...$$

(Q in units of GeV/c)

We want to measure the radius (~$\sqrt{A}$) to within 0.5%, without knowing B. So:

$$B/A \cdot Q^2 \ll 0.01 \longrightarrow Q^2 \ll 0.002\,(\mathrm{GeV}/c)^2$$

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But: Need to measure A to 1%, so measure $\frac{d\sigma}{d\Omega}$ to $6 \cdot 0.002 \cdot 0.01 = 0.012\%$. Now I'm feeling depressed.

The way ahead

Question: Which planned experiments aim at low-Q^2 G_M?

The way ahead

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Answer: none

The way ahead

Question: Which planned experiments ~~aim at~~ also measure low-Q^2 G_M?

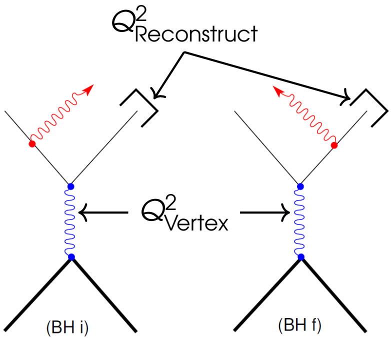
Answer: ...

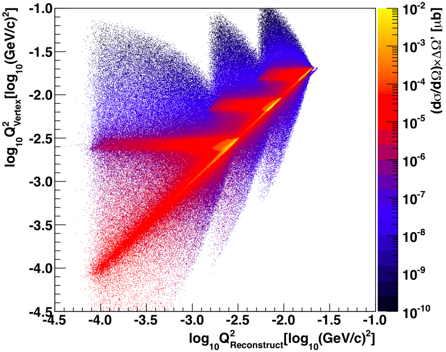
Three ways to get to lower Q^2

$$Q^2 = 4EE'\sin^2\frac{\theta}{2}$$

- Smaller scattering angle $\longrightarrow$ PRad$\longrightarrow$ no G_M
- Lower beam energy $\longrightarrow$ MESA
- Initial State Radiation

ISR method

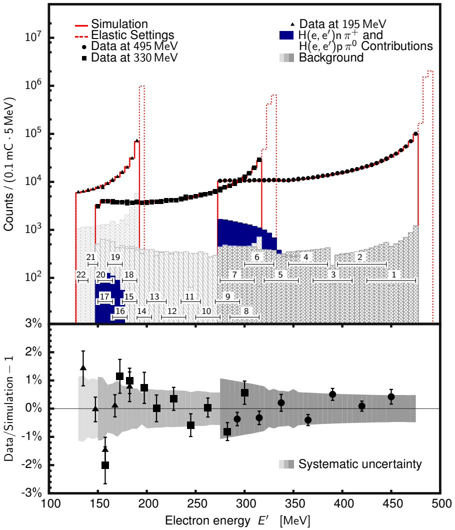




- Use initial state radiation to reduce effective beam energy
- Have to subtract FSR

ISR at MAMI

- ISR $\longrightarrow$ small E $\longrightarrow$ small Q^2
- Extract F.F. from radiative tail
- Or: test radiative tail description



See: arXiv:1612.06707

ISR at MAMI

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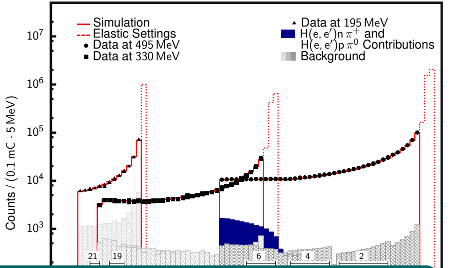

Status

- Published: PLB 771:194-198
- Radiative correction correct on the 1% level deep in the tail!
- Radius extraction not competitive in precision
- In principle: Could be redone at larger scattering angle
- But: rates small

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  - Background from target walls
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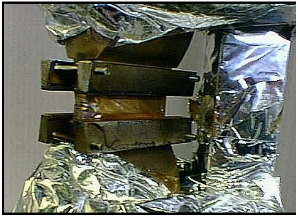

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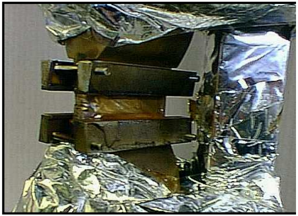
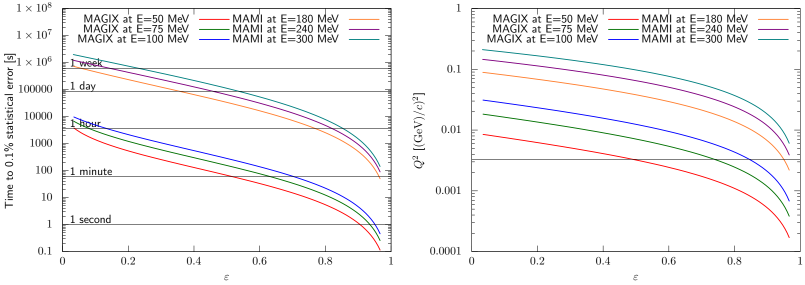


- For Mainz data, systematic errors dominate
  - Background from target walls
  - Acceptance correction for extended target
- Eliminate with jet target
  - point-like
  - no walls
  - but less density
- Rinse, repeat with D,^{3}He,^{4}He, ...

⇓

Mainz future plans

- Repeat ISR with new target
- Use new target also for classic approach



Took first data in April! Full MAMI experiment next year, MESA 2021.

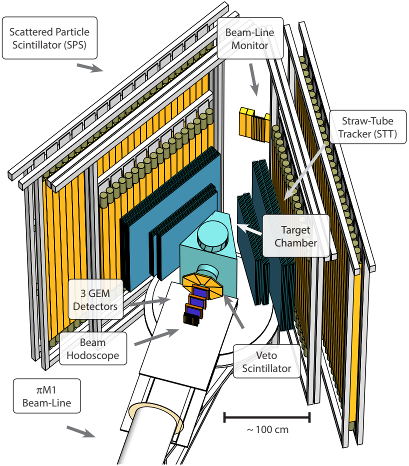
MUSE - Muon Scattering Experiment at PSI

World's most powerful low-energy $e/\pi/\mu$-beam:

Direct comparison of *ep* and μp!

- Beam of $e^+/\pi^+/\mu^+$ or $e^-/\pi^-/\mu^-$ on liquid H_2 target
  - Species separated by ToF, charge by magnet
- Absolute cross sections for *ep* and μp
- Ratio to cancel systematics
- Charge reversal: test TPE
- Momenta 115-210 MeV/c $\Rightarrow$ Rosenbluth G_E,G_M

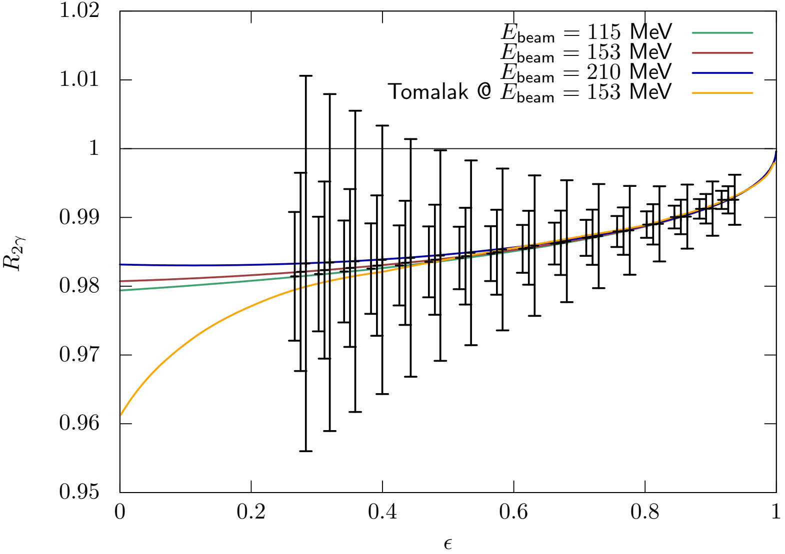
Experiment layout



R. Gilman et al., arXiv:1303.2160 (nucl-ex)

- Secondary beam $\Longrightarrow$ track beam particles
- Low flux (5 MHz)$\Longrightarrow$ large acceptance
- Mixed beam $\Longrightarrow$ PID in trigger

MUSE projected errors ($e^{\pm}$only)



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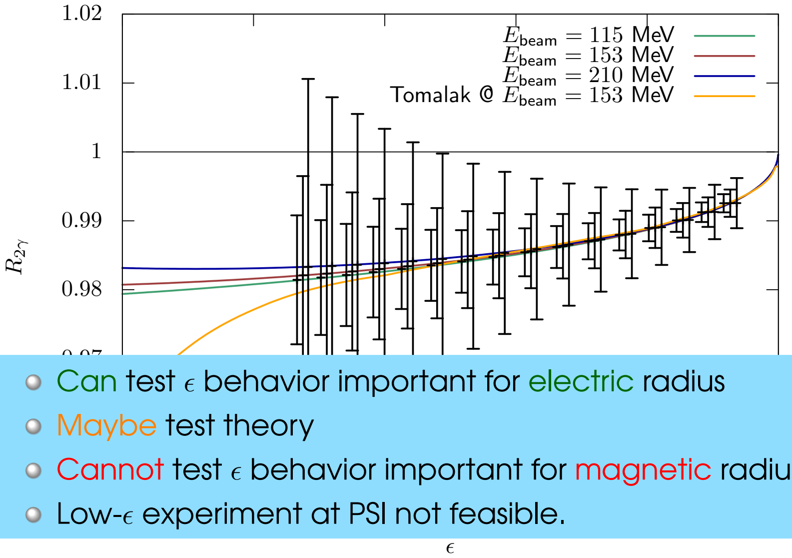

- Can test ϵ behavior important for electric radius
- Maybe test theory
- Cannot test ϵ behavior important for magnetic radius
- Low-ϵ experiment at PSI not feasible.

Other experiments

- Many ultra-low-Q^2 measurements for proton radius
- Active target (Hydrogen TPC)
  - Mainz
    - might be modified to look at back angles
  - COMPASS
    - ultra-high momentum muons

What about polarization?

- Measure asymmetries $A_{\perp}$ and $A_{\parallel}$ to get ff ratio
- At high Q^2: Measure c.s.$\rightarrow$ G_M, + ratio gives G_E

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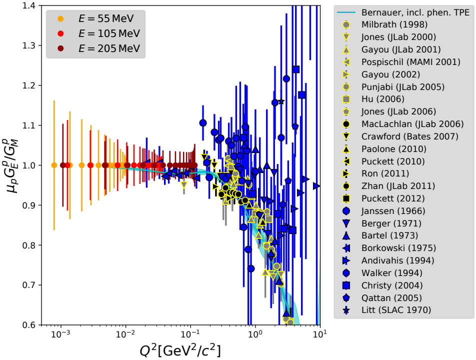
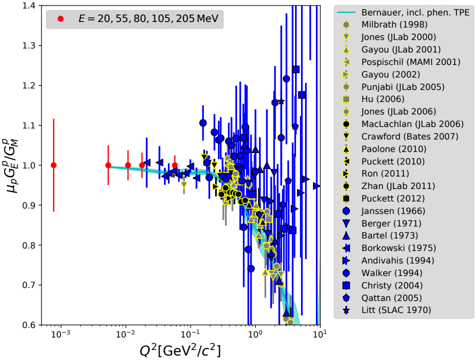
What about polarization?

- Measure asymmetries $A_\perp$ and $A_{||}$ to get ff ratio
- At high Q^2: Measure c.s.$\to$ G_M, + ratio gives G_E
- At low Q^2: Measure c.s.$\to$ G_E, + ratio gives G_M
- Two possibilities:
  - Classic: 1 spectrometer
  - Advanced: 2 spectrometer
    - measure $A_\perp$ and $A_{||}$ at the same time

Polarization at MESA





Plots and rate calculation by Sören Schlimme

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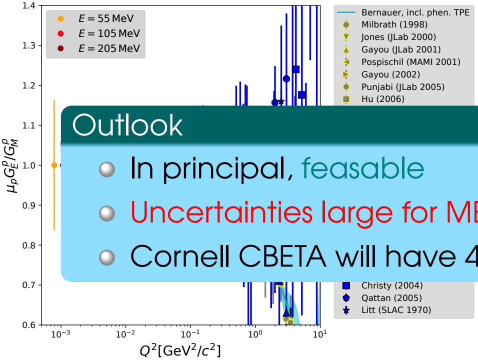

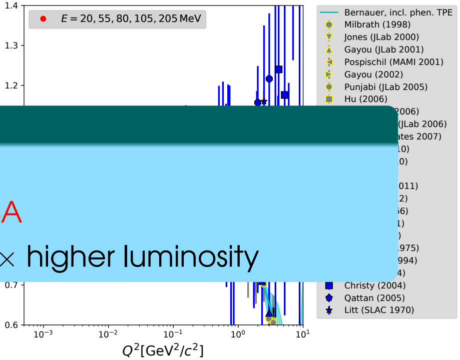

Outlook

- In principal, feasable
- Uncertainties large for MESA
- Cornell CBETA will have 40× higher luminosity

Plots and rate calculation by Sören Schlimme

Summary

- Many many many experiments
- Essentially all aim to measure proton radius
- Few will produce good G_M data, or could be extended to do so.
- Need a dedicated program. Need strong motivation to do so! Whitepaper!