The proton radius puzzle (+extras)

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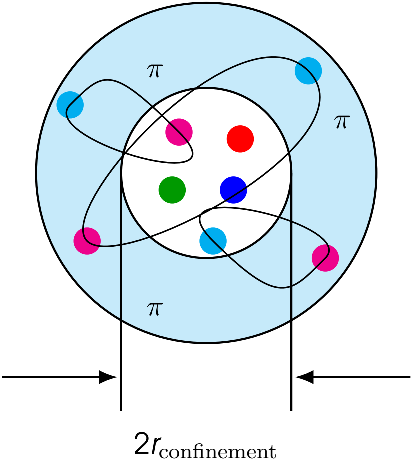
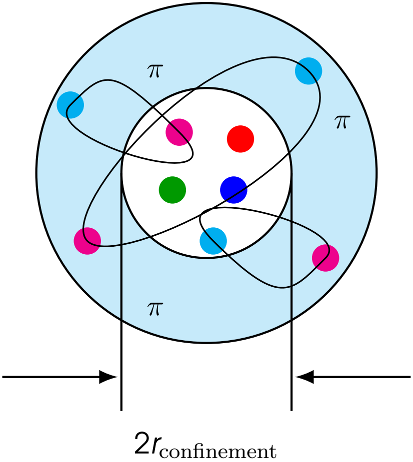
LHeC workshop, June 2015

Massachusetts Institute of Technology

What is a proton?



What is a proton?



How big is it?

All roads lead to Rome

Several methods used to determine proton radius:

1. Elastic electron-proton scattering
2. "Normal" hydrogen spectroscopy
3. Muonic hydrogen spectroscopy

Cross section and form factors for elastic e-p scattering

The cross section:

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

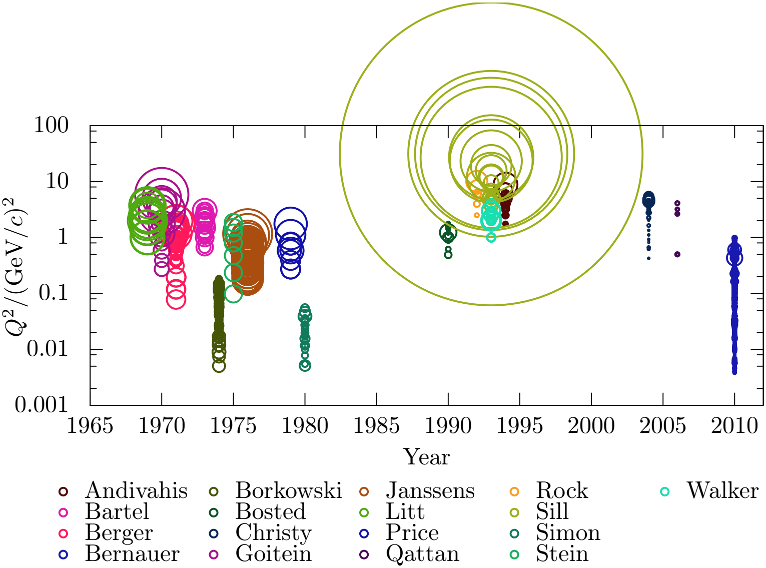
with:

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

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

$$\left\langle r_E^2\right\rangle = -6\hbar^2\left.\frac{\mathrm{d}G_E}{\mathrm{d}Q^2}\right|_{Q^2=0} \qquad \left\langle r_M^2\right\rangle = -6\hbar^2\left.\frac{\mathrm{d}\left(G_M/\mu_p\right)}{\mathrm{d}Q^2}\right|_{Q^2=0}$$

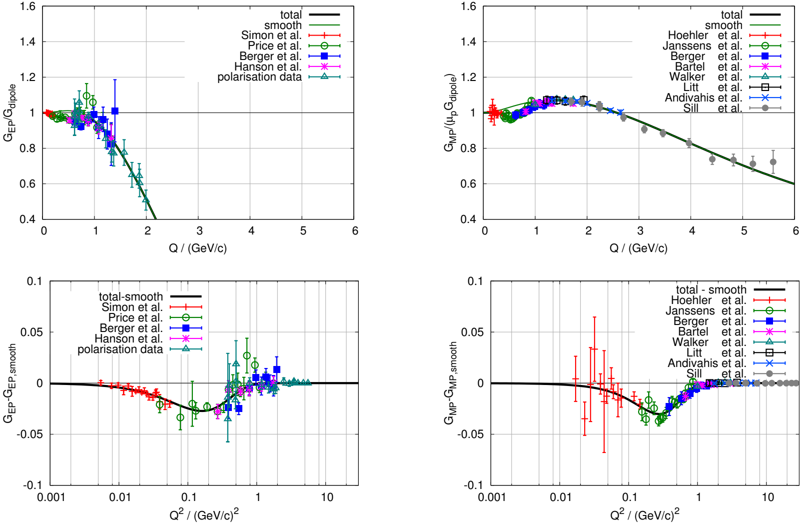
Unpolarized: Rosenbluth



High-Precision p(e,e′)p Measurement at MAMI

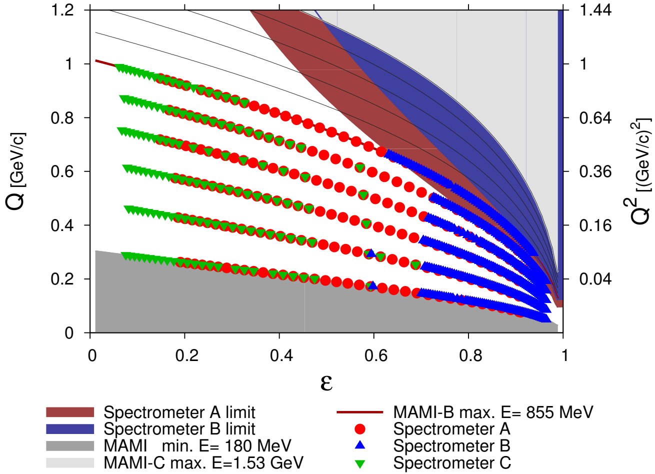
Three spectrometer facility of the A1 collaboration:

Motivation: Structure



(see J. Friedrich and Th. Walcher, Eur. Phys. J. A **17** (2003) 607)

Measured Settings



1400 settings

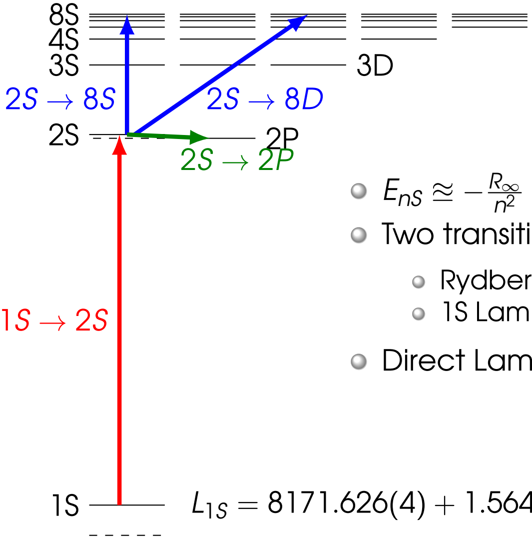
Electric and magnetic radius

Final result from flexible models

$$\left\langle r_E^2 \right\rangle^{\frac{1}{2}} = 0.879 \pm 0.005_{\mathrm{stat.}} \pm 0.004_{\mathrm{syst.}} \pm 0.002_{\mathrm{model}} \pm 0.004_{\mathrm{group}}\ \mathrm{fm},$$

$$\left\langle r_M^2 \right\rangle^{\frac{1}{2}} = 0.777 \pm 0.013_{\mathrm{stat.}} \pm 0.009_{\mathrm{syst.}} \pm 0.005_{\mathrm{model}} \pm 0.002_{\mathrm{group}}\ \mathrm{fm}.$$

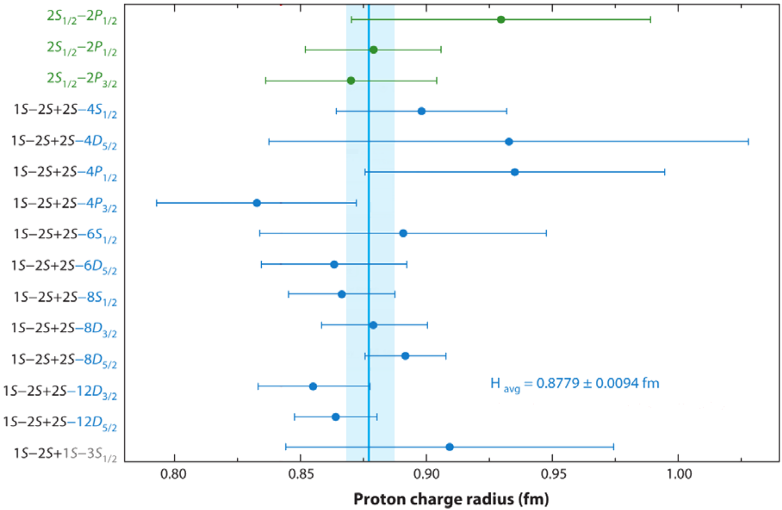
"Normal" Hydrogen Spectroscopy



- $E_{nS} \approxeq -\frac{R_\infty}{n^2} + \frac{L_{1S}}{n^3}$
- Two transitions for two unknowns:
  - Rydberg constant R_∞
  - 1S Lamb shift $\Longrightarrow$ radius
- Direct Lamb shift $2S \to 2P$

$$L_{1S} = 8171.626(4) + 1.5645 \left\langle r_p^2 \right\rangle \text{ MHz}$$

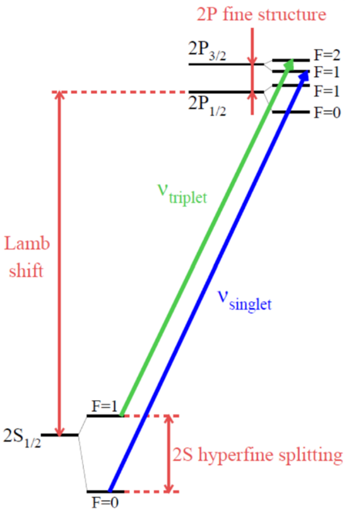
"Normal" Hydrogen Spectroscopy Results

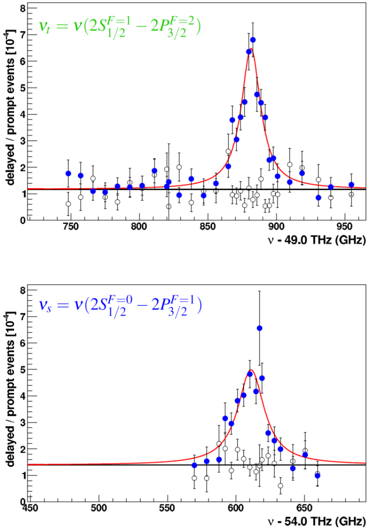


Muonic Hydrogen Spectroscopy

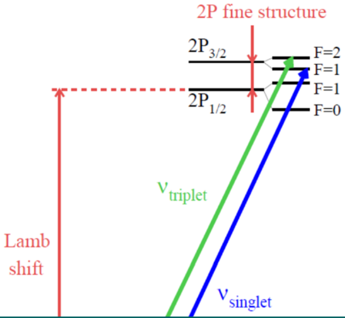
- Replace electron with muon
- 200 times heavier $\Longrightarrow$ 200 times smaller orbit
- Probability to be "inside" 200^3 higher!

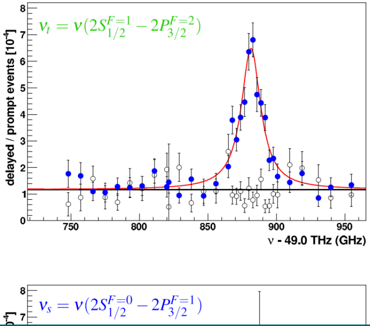
Muonic Hydrogen Spectroscopy Results





Muonic Hydrogen Spectroscopy Results

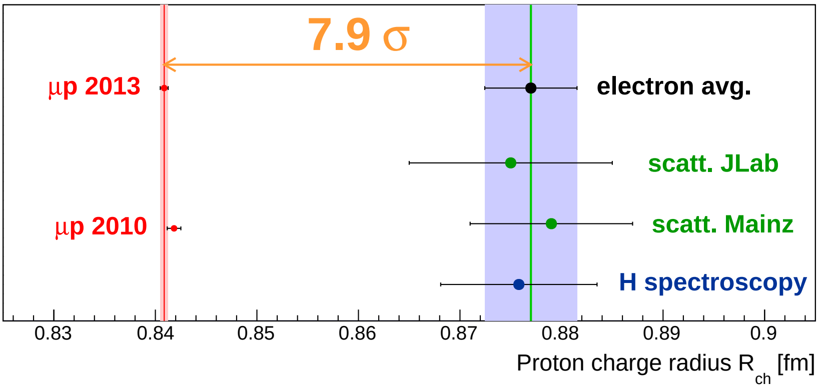


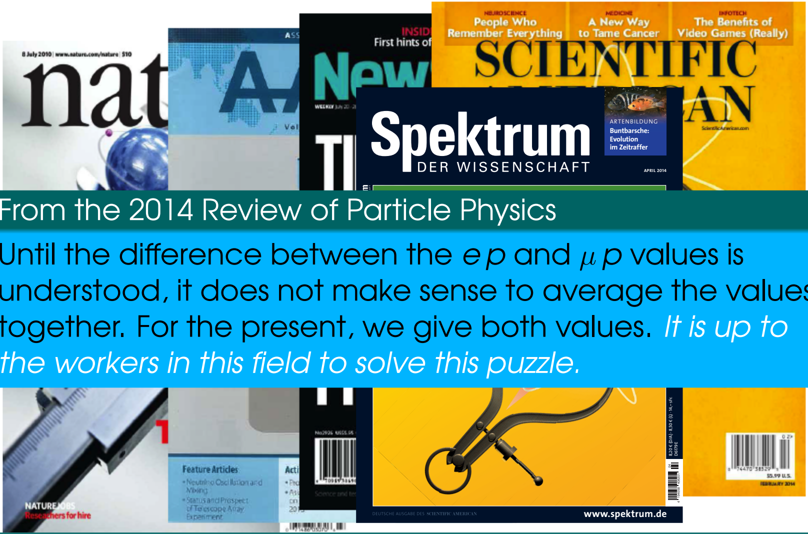


Result

- Two semi-independent measurements
- Consistent results
- $r_p = 0.84049(39)$ fm

The Puzzle


7.9 σ
μp 2013
electron avg.
scatt. JLab
μp 2010
scatt. Mainz
H spectroscopy
0.83
0.84
0.85
0.86
0.87
0.88
0.89
0.9
Proton charge radius R ch [fm]



From the 2014 Review of Particle Physics

Until the difference between the $e\,p$ and $\mu\,p$ values is understood, it does not make sense to average the values together. For the present, we give both values. *It is up to the workers in this field to solve this puzzle.*

Solutions

- There are many, many ideas.
- Too many to list, so I won't even try.
- Many seem at least unlikely.
- None accepted by community.

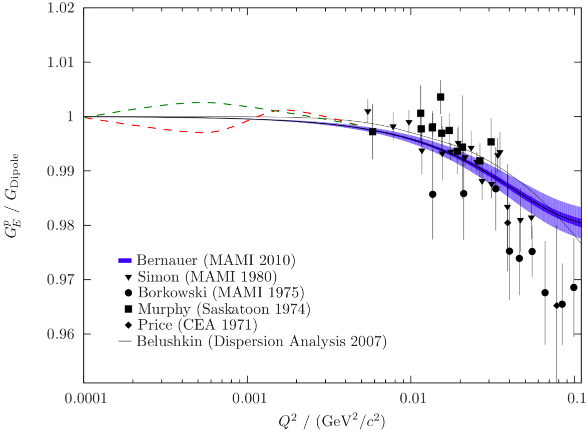
Solutions

- There are many, many ideas.
- Too many to list, so I won't even try.
- Many seem at least unlikely.
- None accepted by community.

We had a vote!

We need more data!

Form factors at very small Q^2

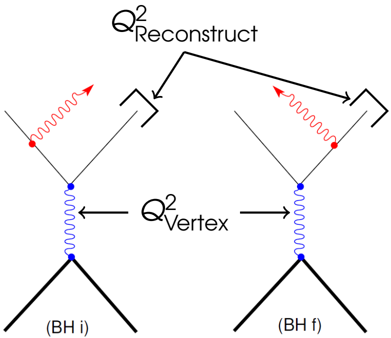


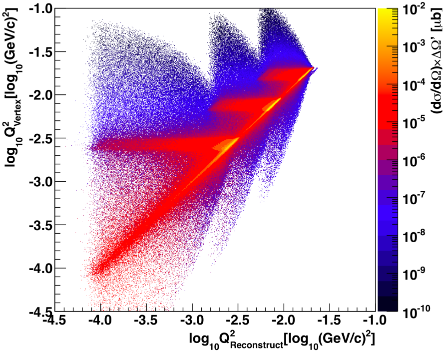
- Is extrapolation invalid?
- Structure at low Q^2?

Two experiments:

- Mainz A1: ISR
- JLab: PRAD

ISR method

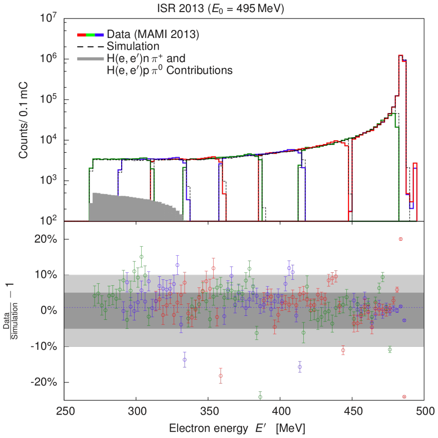




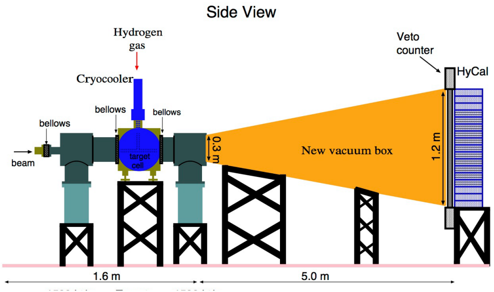
- Use initial state radiation to reduce effective beam energy
- Have to subtract FSR

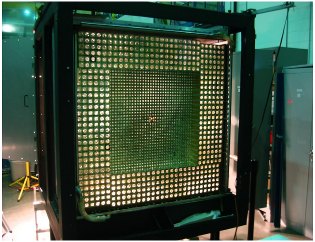
Mainz ISR measurement

- Use ISR to reach down to $10^{-4}\ (\text{GeV}/c)^2$
- Test measurement 2010
- Full experiment August 2013
- Completely different systematics!
- Data analysis ongoing



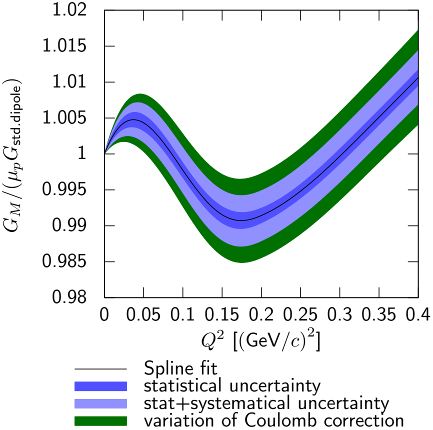
JLAB: PRoton RADius





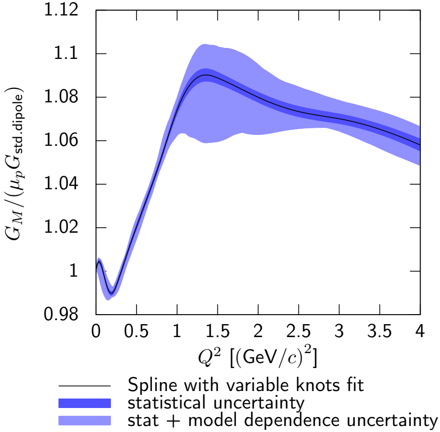
- High resolution, large acceptance hybrid calorimeter
- Windowless target
- Simultaneous measure ep $\rightarrow$ ep and Møller scattering
- Q^2 range: 2×10^{-4} to 2×10^{-2} $(\mathrm{GeV}/c)^2$

Since we are measuring anyway: low-Q G_M



- Up-Down-Up structure
- Not seen before
  - Older fits approach from below
  - Lack of data
- Gives rise to small r_m
- Calculations / physics motivated models typically can not reproduce
- Sensitive to radiative corrections

Since we are measuring anyway: high-Q G_M



- Cusp between 1 and 1.5 $(\text{GeV}/c)^2$
- Seen in older fits
- Mainz data < 1 $(\text{GeV}/c)^2$
- Should be visible in Lattice QCD

What could PERLE do?

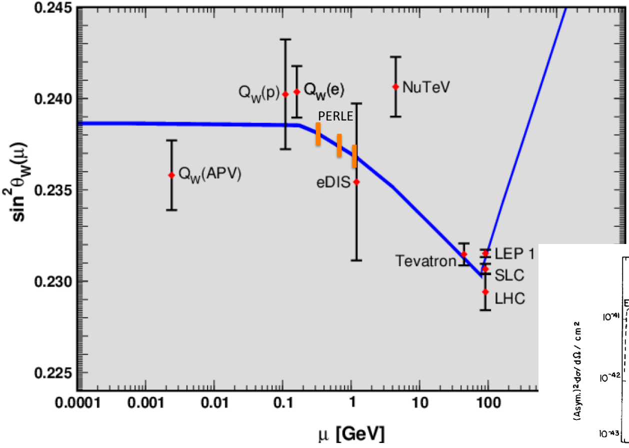
- Probe low-Q with ISR or forward scattering $\longrightarrow$ test for structure
- Just measure at one energy ~300 MeV $\longrightarrow$ cross check Mainz fit
- Measure just higher energies. Or only one, if it's the right one! $\longrightarrow$ Check cusp
- Do a "Mainz type" experiment
  - point-like target
  - no background

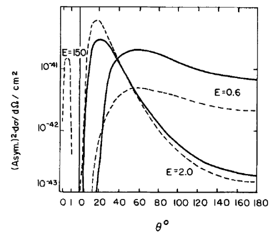
  $\longrightarrow$ better systematics
- With polarized beam+target: Measure c.s.+asymmetry $\longrightarrow$ ultimate experiment
- More, + D, ^3He, ^4He, Li, C

Proton form factors interesting on all scales. LHeC can provide crucial new data!

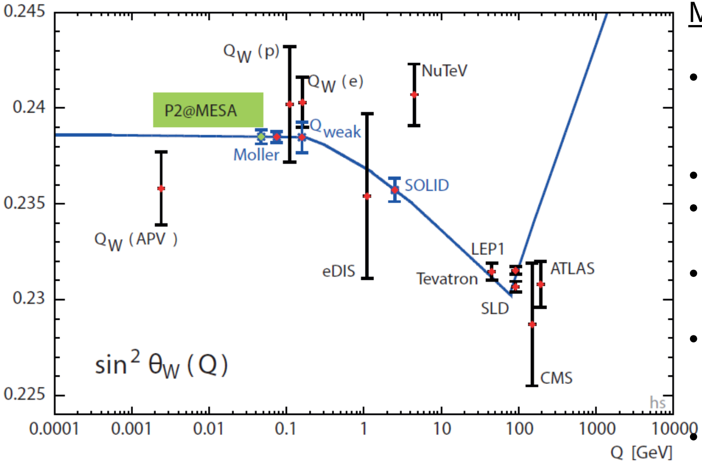
Bonus Slide: Parity Violation

$$A^{-}(P, P') = -\kappa \frac{P-P'}{2}(\nu_e A - a_e V) \Longrightarrow \sin^2\theta_W$$





The weak mixing angle $\sin^2\Theta_W(\mu)$



<u>Measurements</u>:

- Atomic parity violation
- Neutrino scattering
- LEP and SLAC
- Tevatron
- Q_{weak} (finished data taking)
- Moller (planned)
- **P2 (planned)**

Bonus Slide: More ideas

- Pion electroproduction
- DM searches ala DarkLight
- DM searches ala beamdump, BDX
- Can I Haz positron source? $\longrightarrow$ two photon physics
- Collide with other beams at 0°

Backup slides

Revamped "Classic" approach

- Modern version of Rosenbluth
- This is what we did in Mainz
- Measure angle scans at constant energy
- Fit different FF models directly to all cross section data

Hypothetical experiment

- Baseline:
  - Measure every 5° from 15 – 165°
  - At energies 100, 200, 300, 400, 500 MeV
- Assumed errors:
  - 0% systematic error
  - 0.2% statistical
  - 1% normalization

About 5 times smaller $Q^2_{\mathrm{min.}}$

Projected performance I

- Input: Spline fit from Mainz
- Analyzed with 5th order polynomial$\times$dipole
- Baseline: $\delta r_E = 0.004\,\text{fm}$, $\delta r_M = 0.006\,\text{fm}$

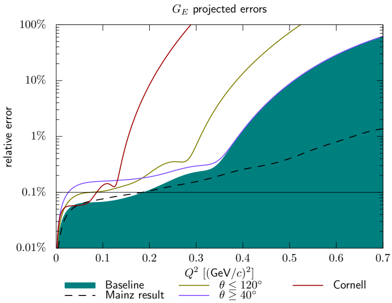
Projected performance I

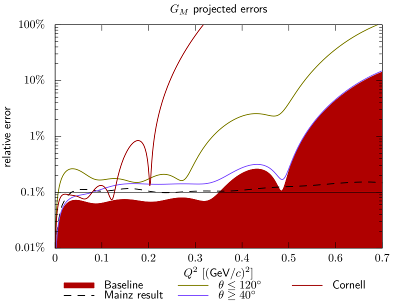
- Input: Spline fit from Mainz
- Analyzed with 5th order polynomial$\times$dipole
- Baseline: $\delta r_E = 0.004$ fm , $\delta r_M = 0.006$ fm
- Angles $15^\circ - 120^\circ$: $\delta r_E = 0.005$ fm , $\delta r_M = 0.026$ fm
- Angles $40^\circ - 165^\circ$: $\delta r_E = 0.007$ fm , $\delta r_M = 0.007$ fm

Projected performance I

- Input: Spline fit from Mainz
- Analyzed with 5th order polynomial$\times$dipole
- Baseline: $\delta r_E = 0.004\,\text{fm}$, $\delta r_M = 0.006\,\text{fm}$
- Angles $15^\circ - 120^\circ$: $\delta r_E = 0.005\,\text{fm}$, $\delta r_M = 0.026\,\text{fm}$
- Angles $40^\circ - 165^\circ$: $\delta r_E = 0.007\,\text{fm}$, $\delta r_M = 0.007\,\text{fm}$
- "Cornell": $\delta r_E = 0.008\,\text{fm}$, $\delta r_M = 0.019\,\text{fm}$

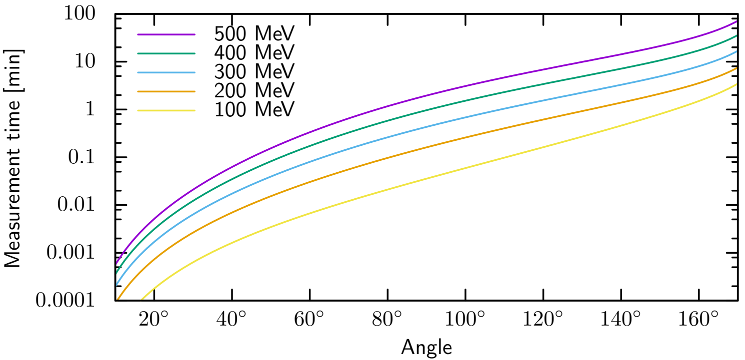
Projected perfomance II





Thoughts

- 100-300 MeV would cover interesting region in G_M, but needs more energies in between
- 50 MeV gives 10 times smaller Q^2 than Mainz
- More energies / more angles to test for systematics
- 20 msr detector, 500 MeV, 165° @ 100mA and $10^{19} cm^{-2}$ target: 50 min.



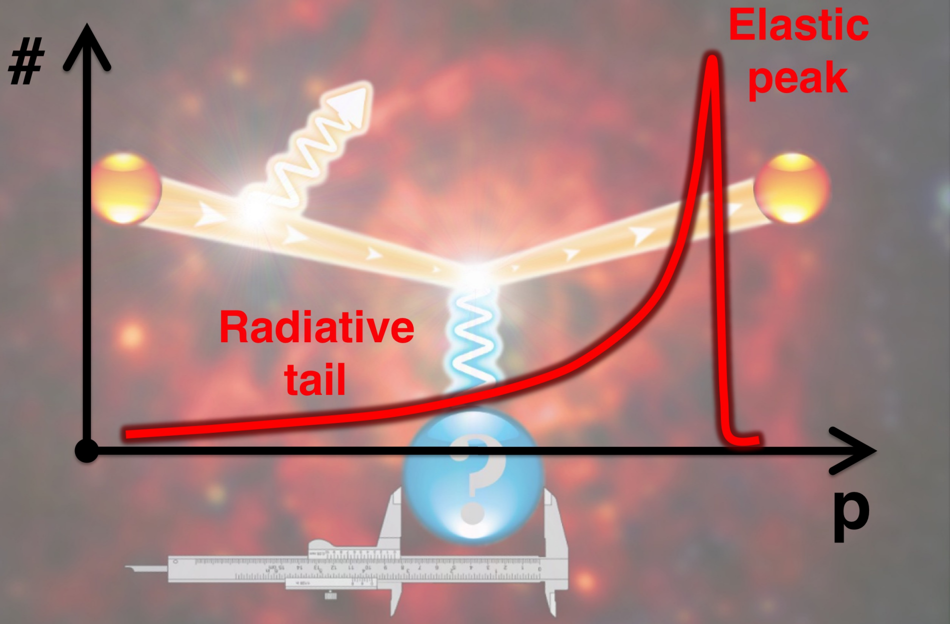
Caveats

- Same approach $\Longrightarrow$ Same systematical errors as before!
- How good do we really know the radiative corrections?
  - especially at back angles!
- How well do you know the acceptance? Better point-like target
- How well do you know the efficiency? Online monitoring!

The following slides have been provided by

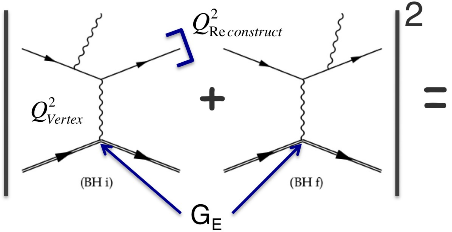
Miha Mihovilovic

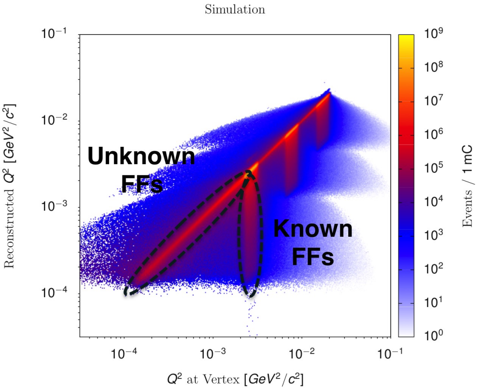
ISR Experiment at MAMI



Initial state radiation

- Radiative tail dominated by coherent sum of two Bethe-Heitler diagrams.





- In data ISR can not be distinguished from FSR.
- **Combining data with the simulation, ISR information can be reached**.
- Idea behind new MAMI experiment to extract $\mathbf{G_e^p}$ at $\mathbf{Q^2 \sim 10^{-4}\ (GeV/c)^2}$
- Redundancy measurements at higher Q^2 for testing this approach in a region, where FFs are well known.

Simul++

- In the experiment **the G_e^p will not be directly extracted** from data.

- FF are camouflaged by effects that accompany FSR and ISR diagrams (Born diagrams, vertex corrections).

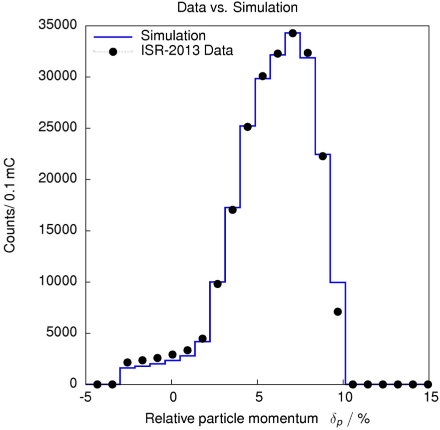
- Approach analogous to Bernauer et al. will be used, where **simulated distributions are directly compared to measured data**.

- Simulate **ep->epγ** with a sophisticated Monte-Carlo simulation `Simul++`.

- Simulation will be run with various values of G_E^p. Contribution of G_M^p is neglected @ Q^2~0.

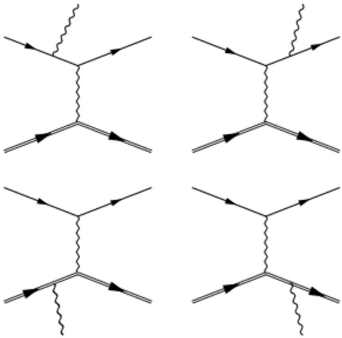
- Final values of FFs will be determined by a χ^2-minimization.

Searching for G_e^p which gives the best agreement between data and simulation



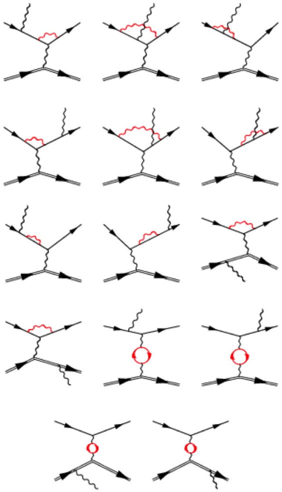
Going beyond simple approximation

- `Simul++` employs an advanced event generator, **which exactly calculates amplitudes for four leading order diagrams.**



- Precise spectrometer acceptances, particle energy-losses and rescatterings are also implemented.

- Next order terms considered via effective correction to the cross-section.



…

The Experiment

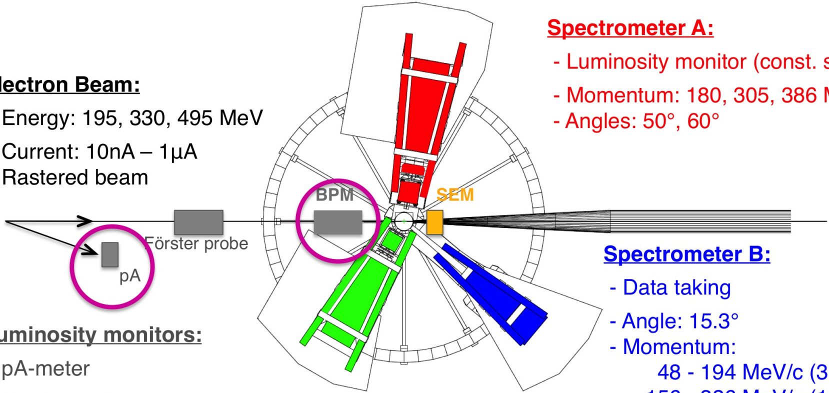
- Full experiment done in August 2013. Four weeks of data taking.

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:

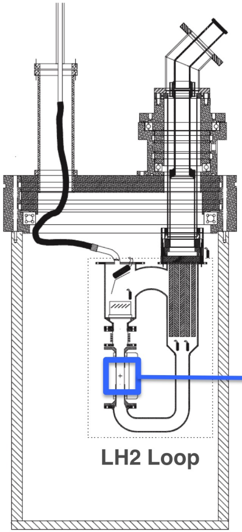
- Not used

Beam control module:

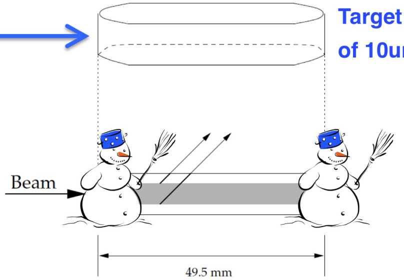
- Communicates with MAMI and ensures very stable beam.
- BPM and pA-meter measurements performed automatically every 3min.

LH_2 target and its challenges

- Experiment utilizes a standard Liquid-Hydrogen target.



Scattering chamber

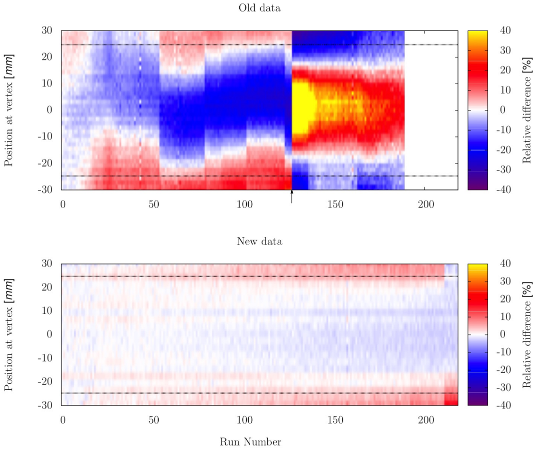


Target Cell made of 10um Havar

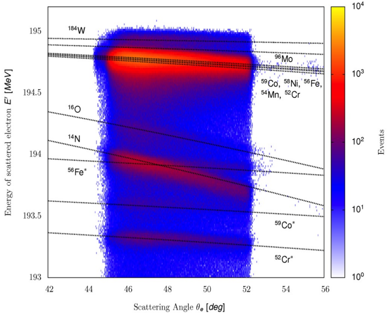
- Due to limited vacuum and low beam intensities, layer of **Cryogens covered the target cell**.
- Depositions consists mostly of residual N_2, O_2.
- Affects not only particle energy-losses but changes also the detection rates.
- Disturbs Luminosity determination.
- Amount of snow changes with time.

Minimizing cryogenic depositions

- **Solid vacuum** in target chamber (10^{-6} mbar).
- New target windows with additional layer of Aramid.
- Fixing Spectrometer A to elastic settings to see effects of snow gathering more clearly.

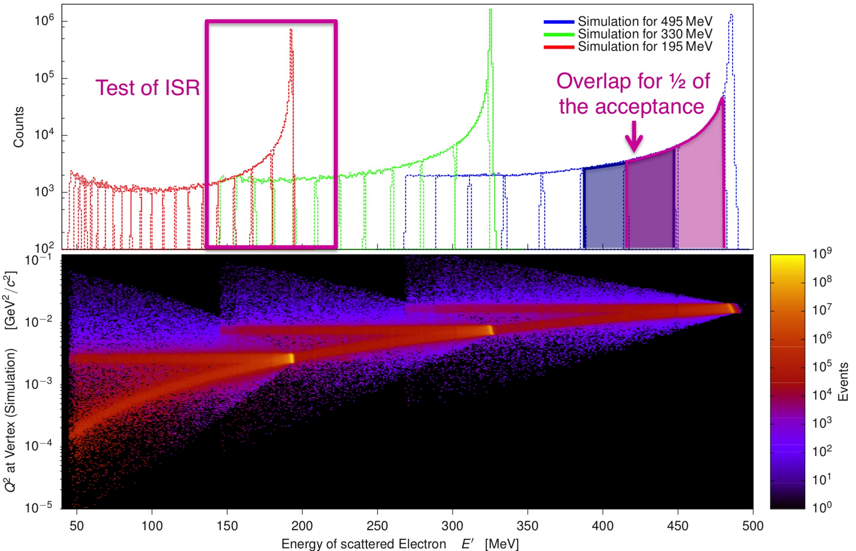


Spectrometer A has enough resolving power for clear identification of Nitrogen and Oxygen.



Kinematic settings of the full experiment

- Measured kinematic points and corresponding Q^2 at vertex.
- Three kinematic regions overlap to verify ISR approach.



The offline analysis

- **Goal:** determine the cross-sections with **accuracy of ~ 1%.**
- The analysis ongoing, so far:

Spectrometer calibrations:

- New optics calibration, absolute momentum optimization.
- Calibration of detector setup and evaluation of efficiencies.

Luminosity:

- New and improved luminosity calculator.

Background studies:

- Optimization of event selection cuts.
- Determination of thickness of the cryogenic depositions.

Simulation:

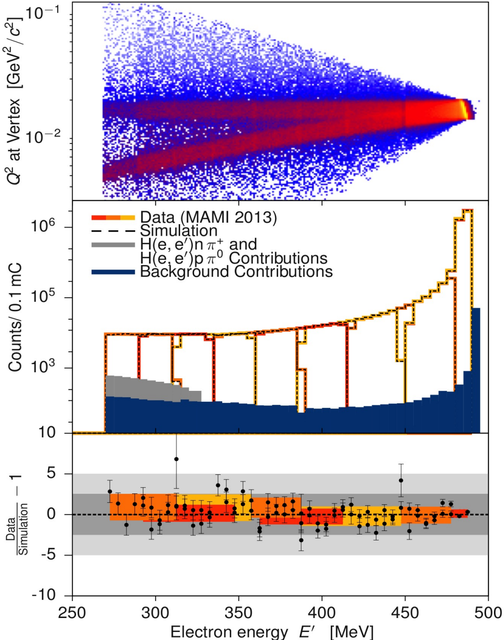
- Explicit (effective) inclusion of virtual and real 2γ corrections.
- Complete simulation of effects related to target walls and cryogenic depositions.

Data analysis:

- First analysis of the dataset at 495MeV to prove the ISR principle.

Preliminary Results

- First results for 495 MeV setting.
- Data are normalized to 0.1mC using Förster probe & Spec-A.
- Only basic kinematic cuts considered.
- Pion production processes contribute ~10% at smallest momenta.
- Contributions from target wall not negligible.
- **Agreement between data and simulation justifies use of `Simul++`.**



The upcoming challenges

- A **~ 2% agreement** between data and simulation **200 MeV** away from the elastic peak motivates further analysis:

Background studies:

- Identification and consideration of other sources of background (e.g. snout of spectrometer B).
- Full study of the Empty cell and Solid-state target data.

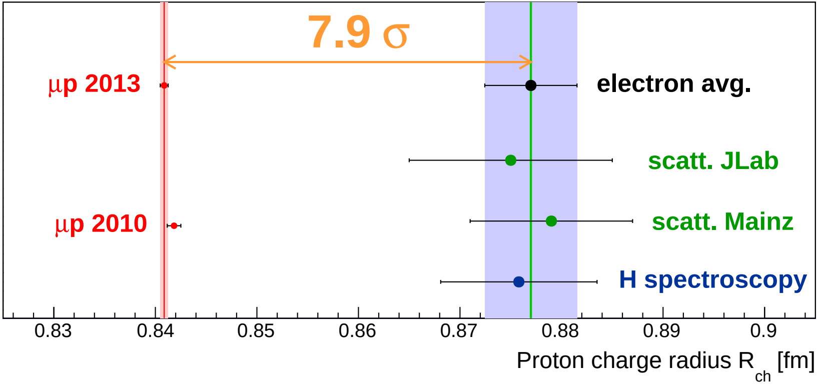
Simulation:

- Exact calculations of 2γ corrections required.
- Improvements to the simulation of background.

Data analysis:

- Analysis of the 330MeV and 195MeV settings.
- Extraction of the proton charge form-factor at $Q^2 \geq 3 \times 10^{-4}$ GeV^2.

A missing piece



	Spectroscopy	Scattering
Electron	0.876	0.877
Muon	0.841	???

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