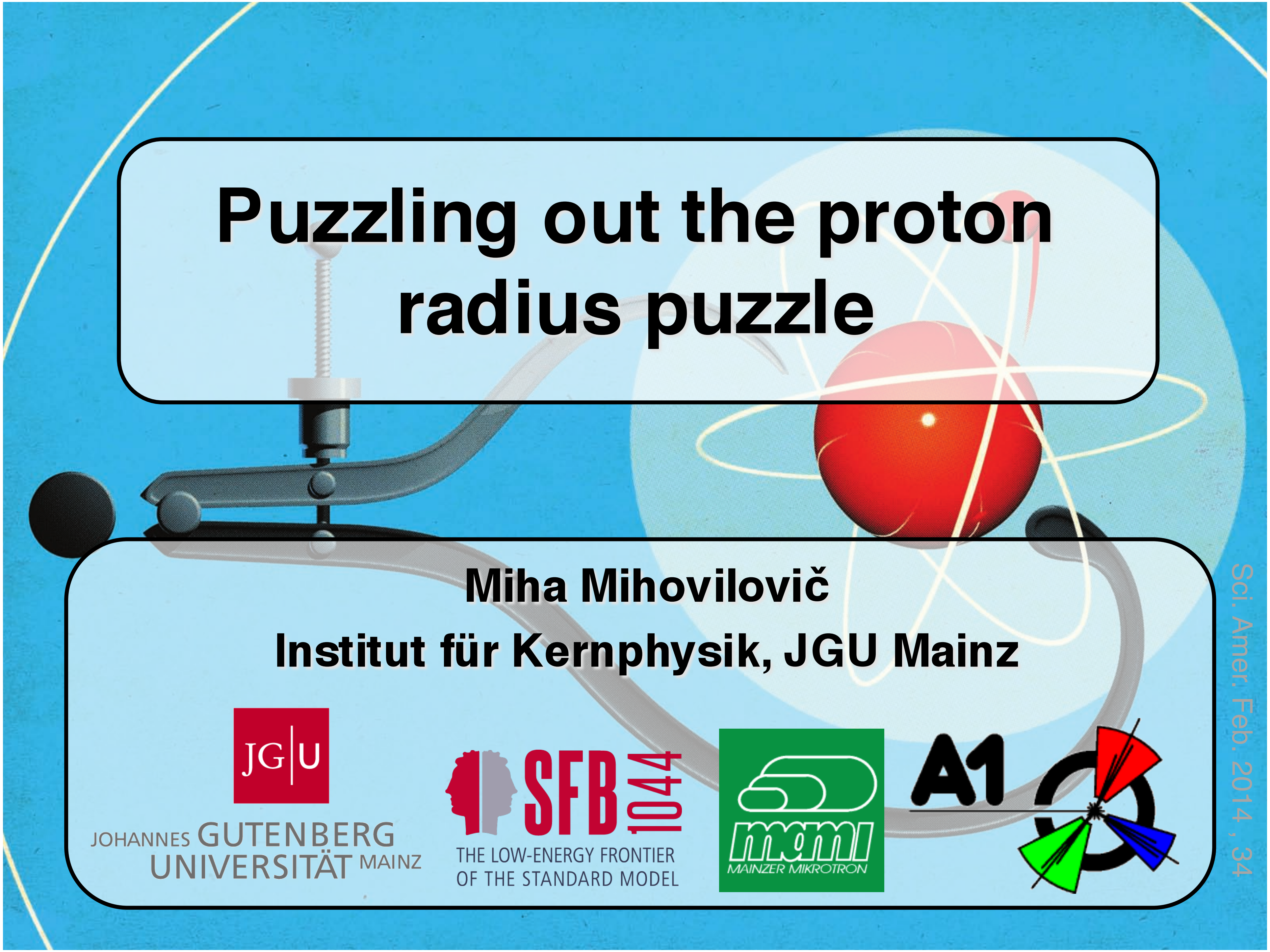


Puzzling out the proton radius puzzle

Miha Mihovilovič

Institut für Kernphysik, JGU Mainz

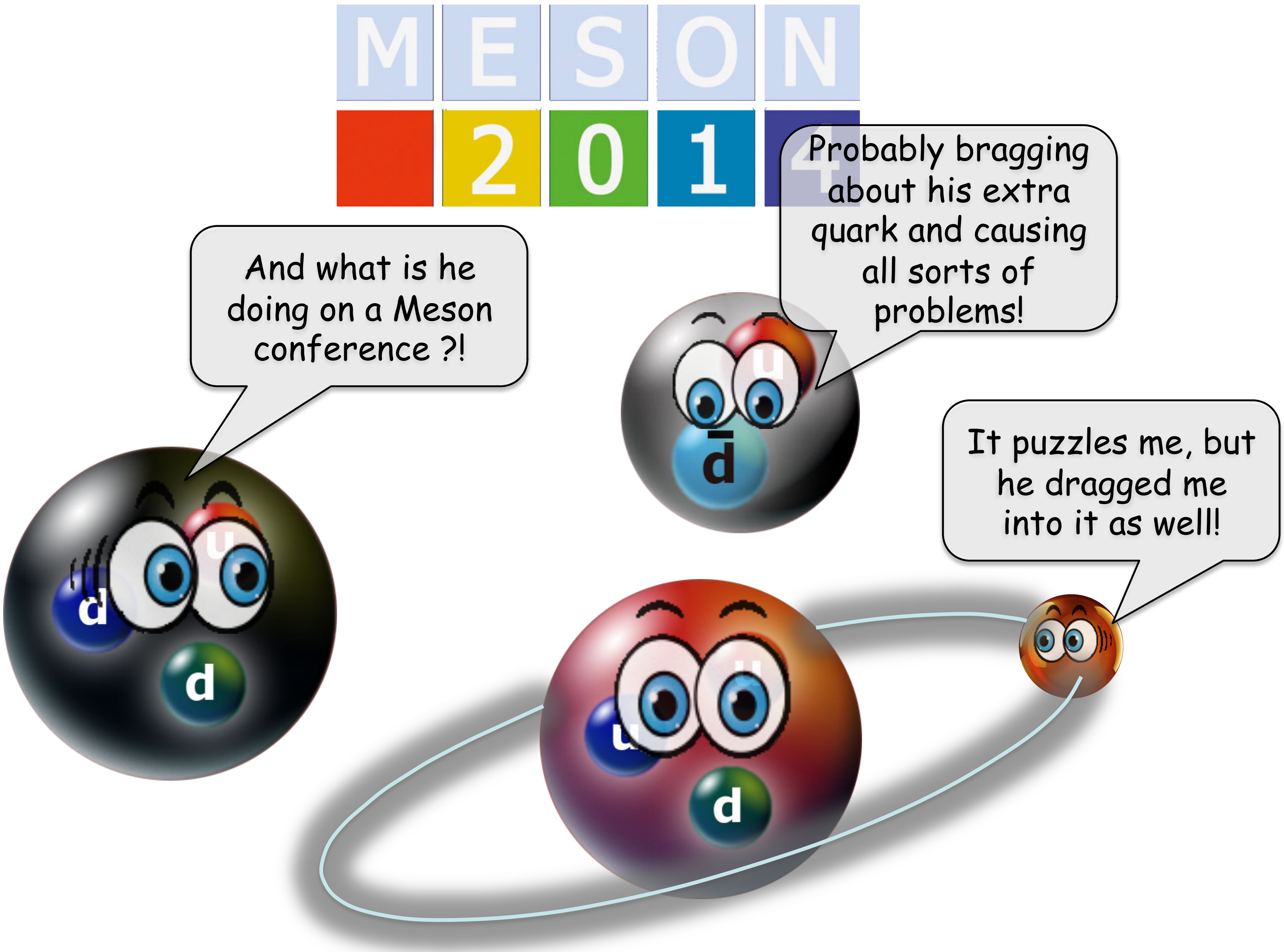
JGU
JOHANNES GUTENBERG UNIVERSITÄT MAINZ

SFB 1044
THE LOW-ENERGY FRONTIER OF THE STANDARD MODEL

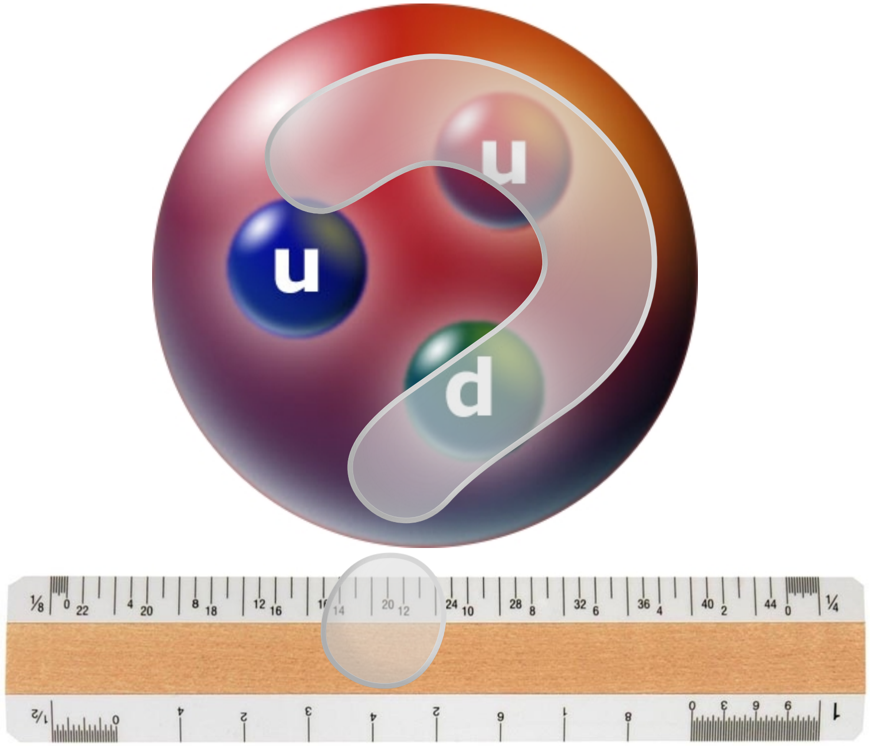
mami
MAINZER MIKROTRON

A1

Sci. Amer. Feb. 2014 , 34


MESON 2014
And what is he doing on a Meson conference ?!
Probably bragging about his extra quark and causing all sorts of problems!
It puzzles me, but he dragged me into it as well!

What is the size of the proton?

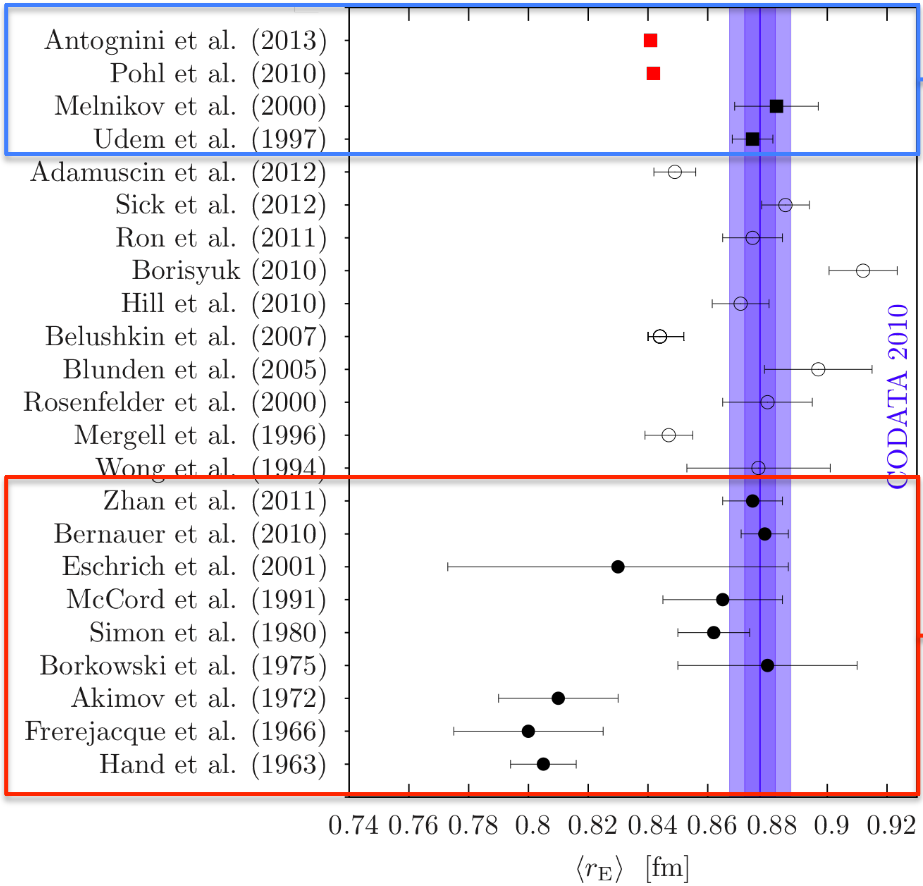


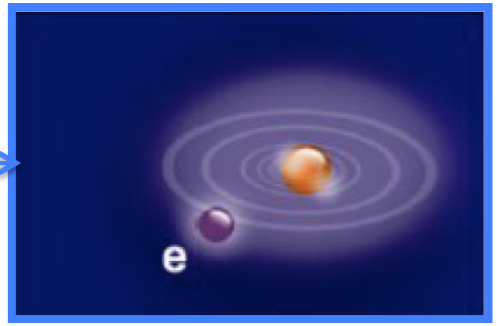
1963

2014

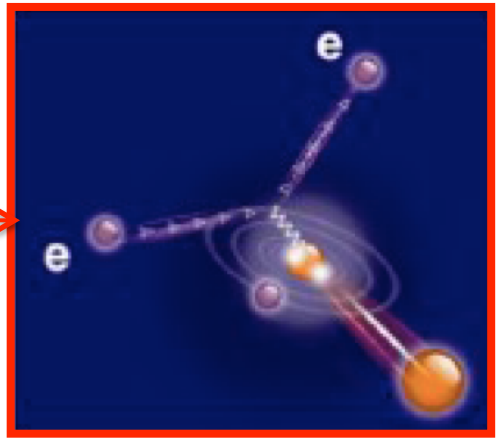
After 50 year of research is the size of the proton still
not understood to a desirable accuracy!

The proton radius puzzle





Atomic spectroscopy



V. Sulkosky

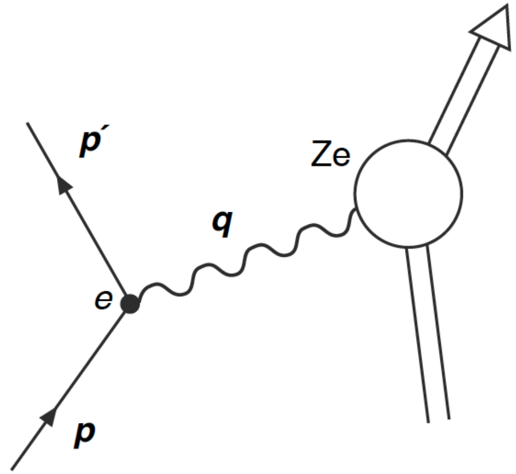
Scattering experiments

- Many different measurements done through the years.
- New μ-p Lamb shift measurement, 7σ away.
- Further investigations necessary.

Elastic Cross-Section measurement

- Radius can be obtained by measuring cross section of H(e,e')p:

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



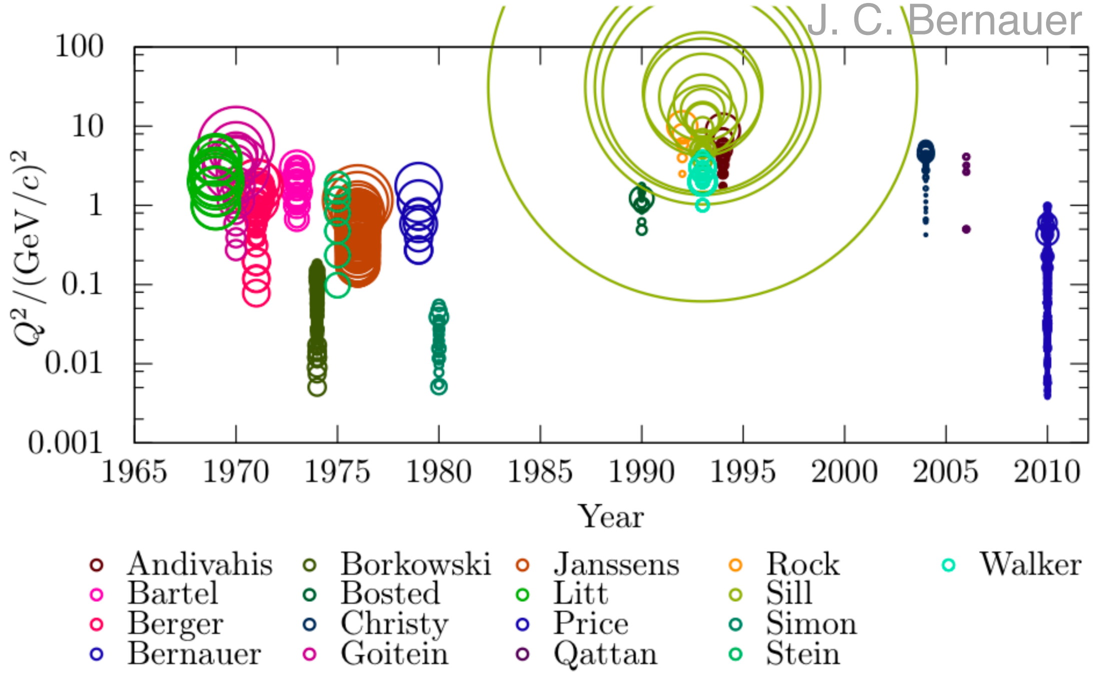
$$\varepsilon = \left[1 + 2(1+\tau)\tan^2\frac{\vartheta_e}{2}\right]^{-1} \qquad \tau = \frac{Q^2}{4m_p^2},$$

- Extraction of FF via Rosenbluth Separation (separation at constant Q^2):

$$G_E(Q^2) \approx G^{Dipole}(Q^2) = \left(1 + \frac{Q^2}{0.71}\right)^{-2}$$

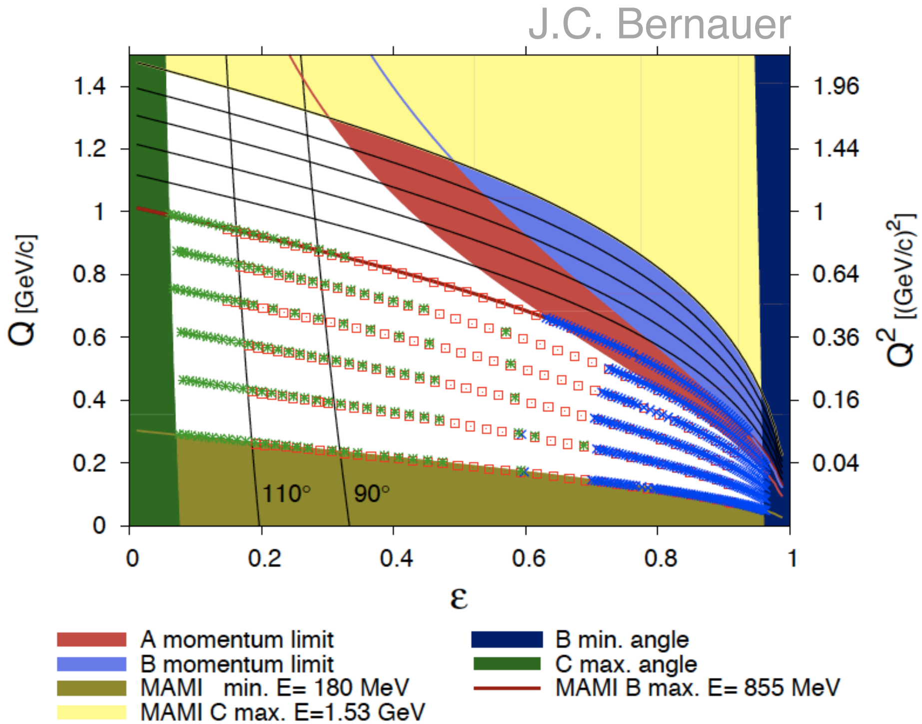
- Best estimate for radius:

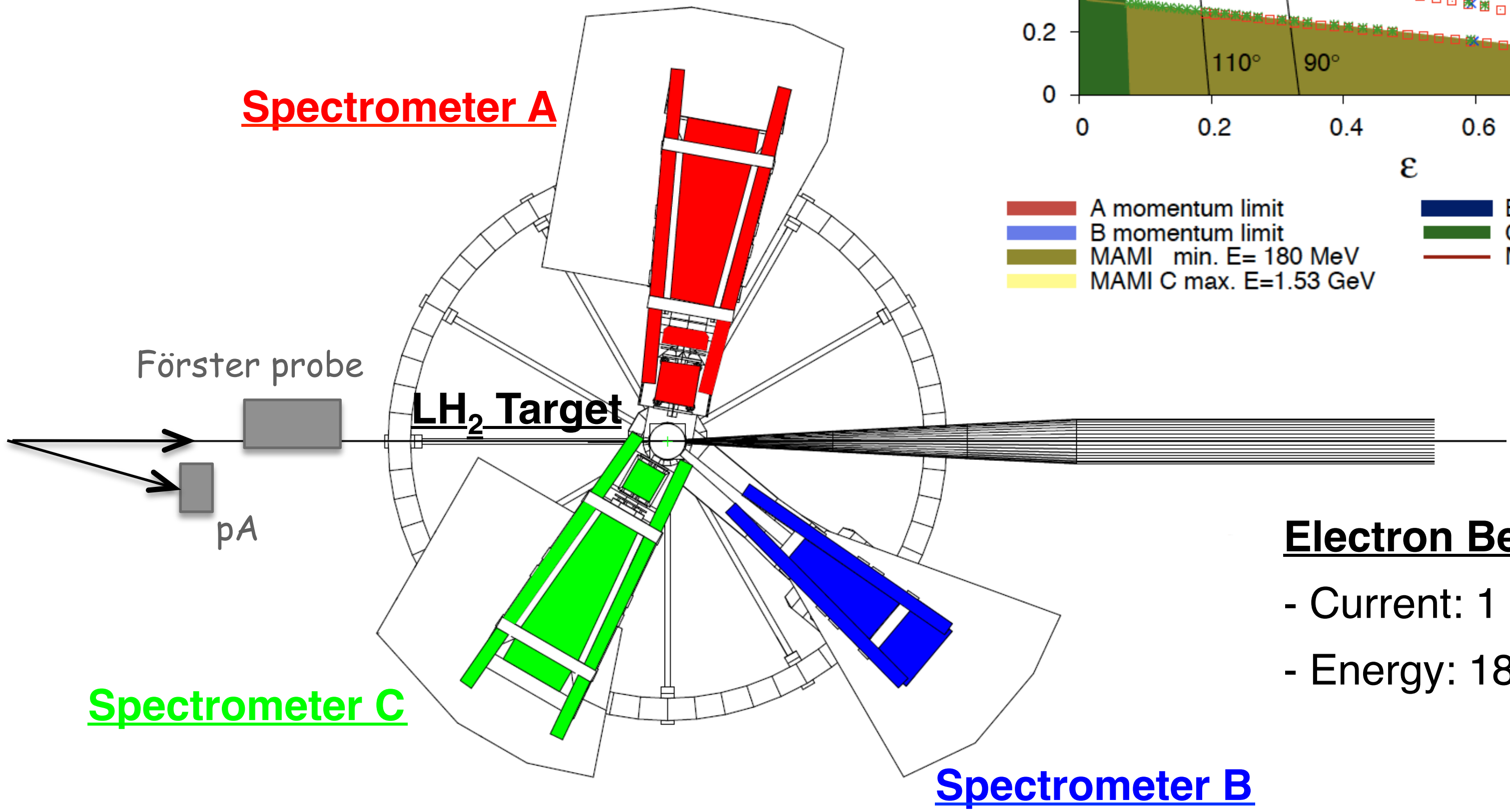
$$\langle r_E^2 \rangle = -6\hbar^2 \frac{d}{dQ^2} G_E(Q^2)\Big|_{Q^2=0}$$



The MAMI experiment

- **H(e,e')p** cross-section measurement.
- About **1400** measured cross-section points.
- Data for $\mathbf{0.004 \leq Q^2 \leq 1 (GeV/c)^2}$.
- Statistical precision better than 0.2%.





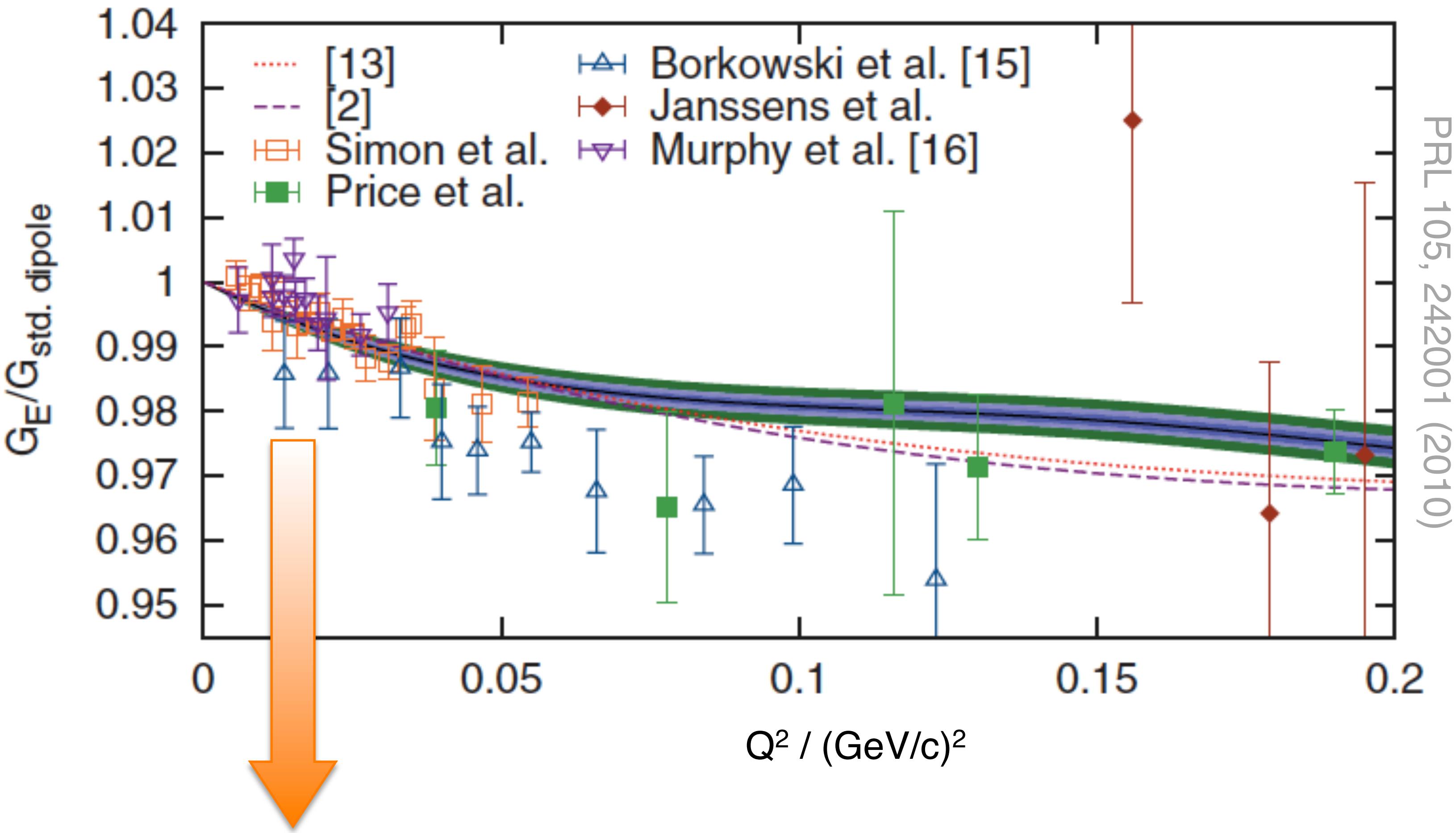
Electron Beam:

- Current: 1 nA – 10 μA
- Energy: 180 – 855 MeV

The best cross-section measurement

- Direct fit of G_E, G_M models to the data for all Q^2 and ϑ:

$$\chi^2/(1400) \approx 1.14$$



$$\sqrt{\langle r_E^2 \rangle} = 0.879 \pm 0.005_{stat} \pm 0.004_{syst} \pm 0.002_{\text{mod}} \pm 0.004_{group}\ fm$$

Hydrogen spectroscopy

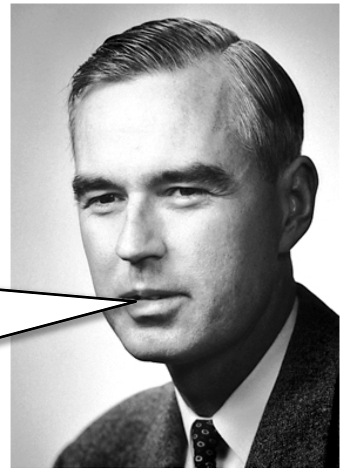
- Spectroscopy of Hydrogen states represents a stringent test of QED.
- Tests require <u>two input parameters</u>: $\mathbf{R_\infty}$ and $\mathbf{r_p}$.

Determine parameters with other measurements and use them to test QED.

Trust QED and use it to determine the values of two free parameters.

- An important success of the QED is the prediction and measurement of the **<u>Lamb shift (1947):</u>**

There is small difference in energy between energy levels $2S_{1/2}$ and $2P_{1/2}$ due to QED vacuum fluctuations.



Lamb shift in Hydrogen

- Change in level energy (approximately):

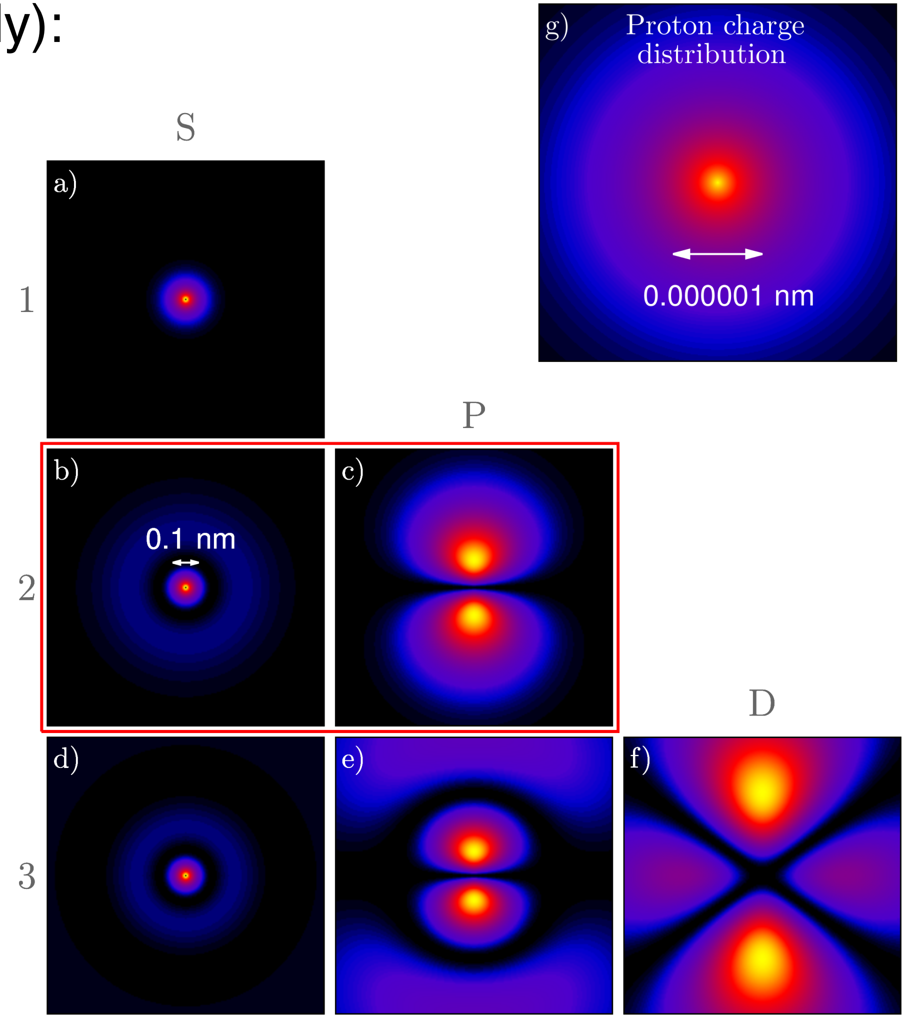
$$\Delta E^{nl}_{Lamb} \propto \left|\psi_{nl}(0)\right|^2$$

$$E(nS) \cong -\frac{R_\infty}{n^2} + \frac{\Delta E^{1S}_{Lamb}}{n^3}$$

$$\Delta E^{1S}_{Lamb} \cong \left(8.172 + 1.56\, r_p^2\right) MHz$$

- Significant effect in S-states and only tiny change in P-states.

- The center of the hydrogen atom is not empty. **Proton is here!**

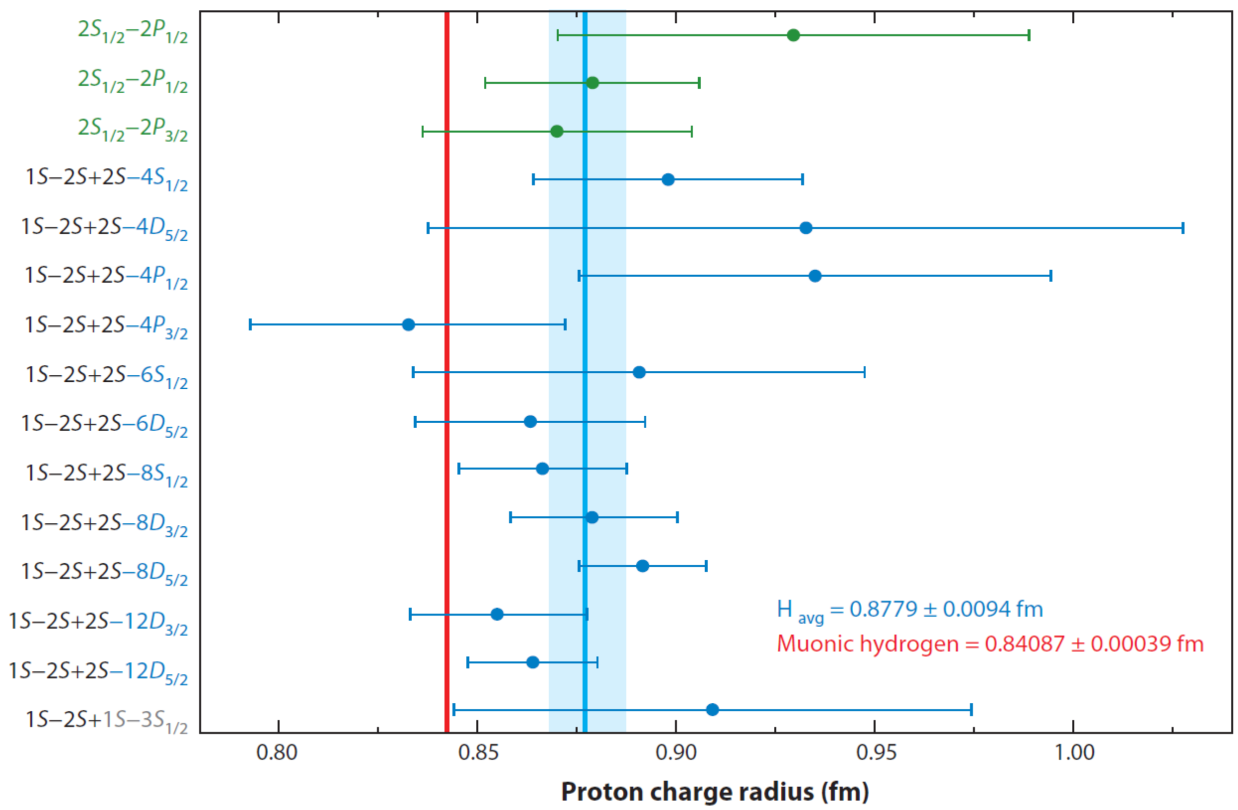


Electron probability densities for different states in eH

- Different **n-dependence** of the two terms allows the determination of R_∞ and r_p from at least two different measurements.

Hydrogen measurement

- Many different level transitions have been measured.



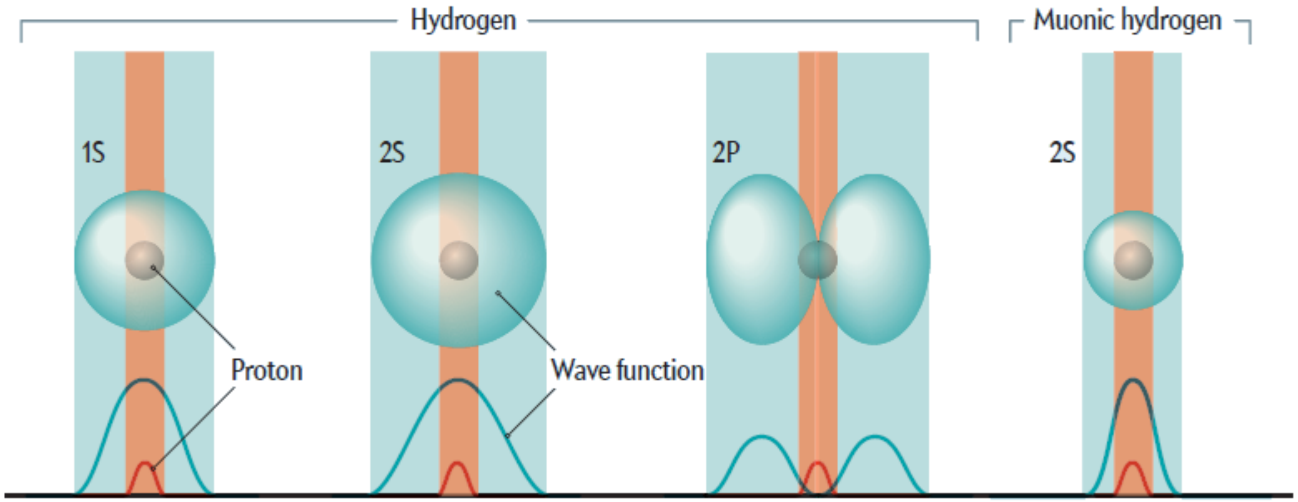
Ann. Rev. nucl. Part. Sci 2013.63:175

- These results together with scattering data form the new CODATA value.

$$\sqrt{\left\langle r_E^2 \right\rangle} = 0.8775 \pm 0.0051\, fm$$

μP-Lamb shift measurement

- Allows better determination of proton charge radius.
- Due to larger mass muon much closer to the nucleus, resulting in a more **pronounced Lamb shift effect**.



Sci. Amer. Feb. 2014 , 34

- The largest signal is given by the $2S_{1/2}^{F=1}$ and $2P_{3/2}^{F=2}$ transition.
- The QED calculation, considering relativistic, radiative, recoil, proton structure corrections, fine, hyperfine splitting, predict:

$$\Delta E = 209.9779(49) - 5.2262\, r_p^2 + 0.0347\, r_p^3 \, meV$$

- Finite size of the proton contributes 1.8% of the energy difference.

µP-Lamb shift measurement

- First such measurement done at the πE5 beam line of the PSI.

- The µs are stopped in H_2 target where the excited µH is formed.

- Majority de-excites to 1S state.

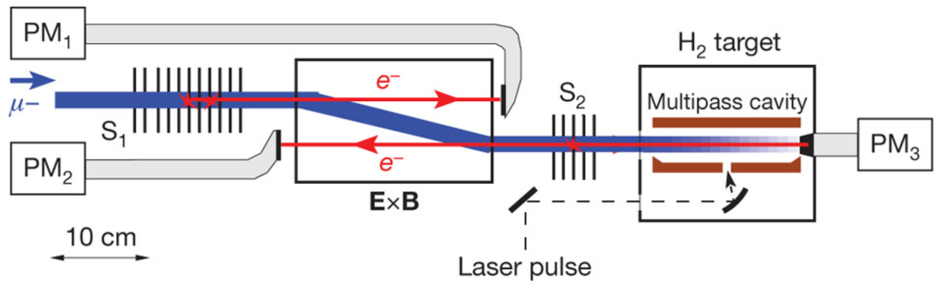
- Emitted X-ray peak used for normalization of the data to the number of µH.

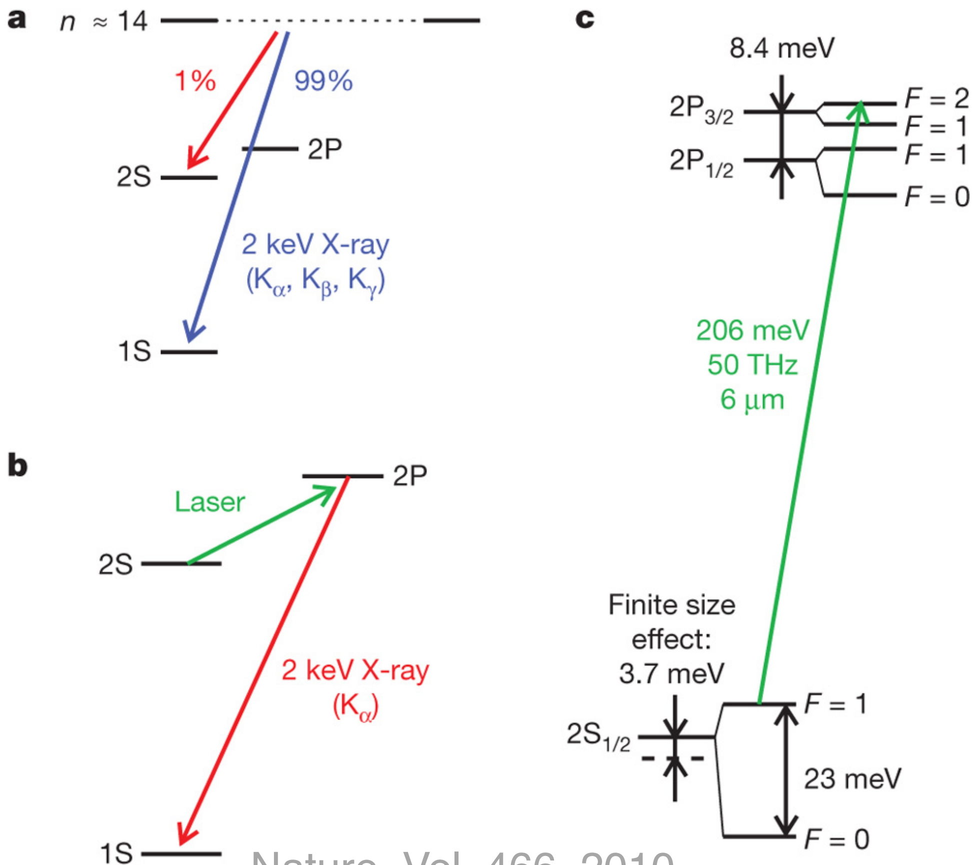
- 1% populates the 2S state.

- Tunable pulsed laser induces the 2S➔2P transitions.

- 2P states de-excite instantly to 1S, emitting 1.9 keV X-rays.

- The whole resonance peak recorded by changing the laser frequency.

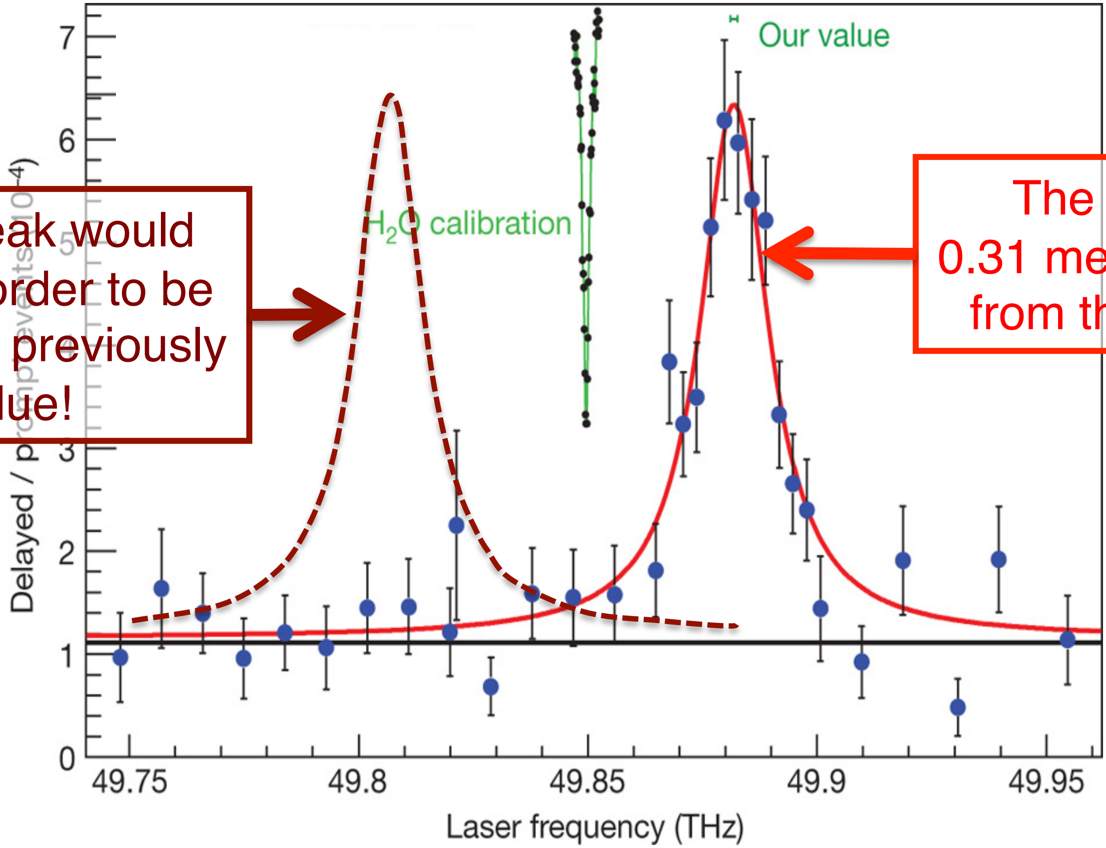




Nature, Vol. 466, 2010

μP-Lamb shift measurement #2

Nature, Vol. 466, 2010



Where the peak would have to be in order to be consistent with previously best value!

The measured peak 0.31 meV (0.15% relatively) from the expected value.

<u>The mean position of the peak:</u>

$$f_{2S-2P} = 49881.88(76)\ GHz$$

$$\Delta E = 206.2949(32)\ meV$$

<u>The resulting radius:</u>

$$r_p = 0.84184(36)(56)\ fm$$

Possible explanations ?!

- **Errors in the measurements:**

  Spectroscopic and scattering data reexamined.
  No problem found.

- **Coulomb and 2γ effects incomplete:**

  Effect is negligible at $Q^2 \leq 1 (GeV/c)^2$.

- **Radiative corrections in the eH Scattering:**

  Well under control. Simulation precisely describes the tail of the elastic peak tail.

- **Problems with μ-H theory:**

  * Unexplained proton structure effects.
  * Clandestine problem with one loop vacuum polarization term.
  * Fundamental problems with QED.

- **Effects of three body physics:**

  Contribution of molecuar ions? $p\mu e^-$, $pp\mu^-$ are unstable.

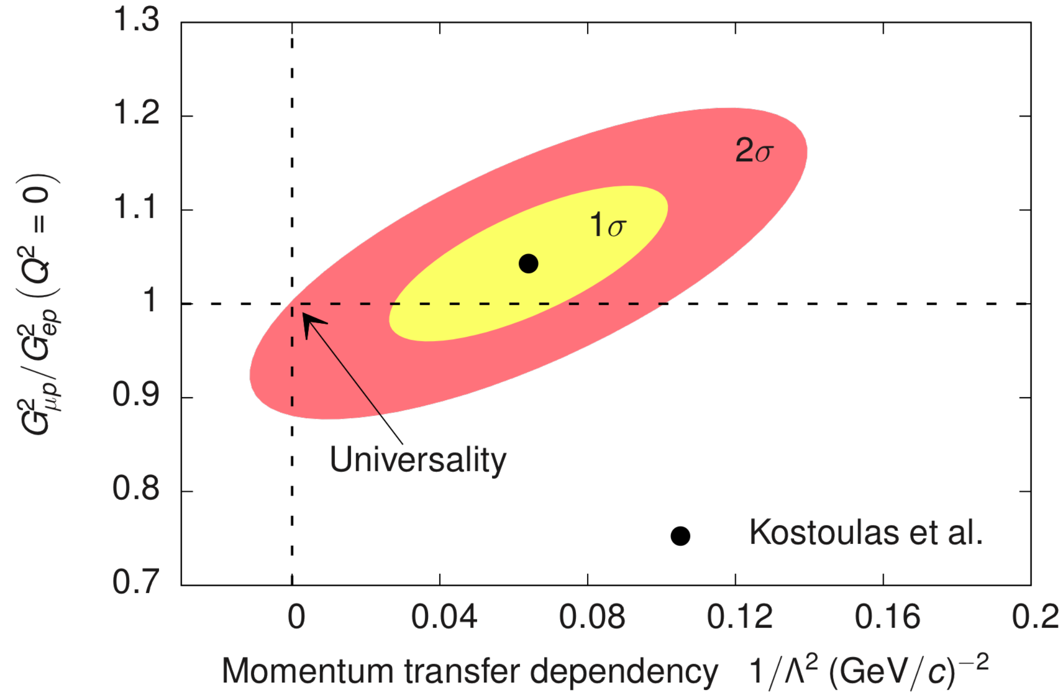
- **Physics beyond standard model?**

Physics beyond the Standard model

- Puzzle could be explained by **breaking the e-μ universality**.

- New interaction could also explain the $(g\text{-}2)_\mu$ puzzle.

- The universality tested, but constrains loose enough for such explanations.



- Various new interactions proposed. Constraints on new forces limit the possibilities.

- <u>**Most interesting candidate:**</u> A new U(1) gauge boson mediating the interaction between <u>dark matter and the Standard model particles</u>.

- See talk of Harald Merkel (Monday).

Extensive experimental efforts trying to solve the puzzle.

Upcoming measurements:

- **Scattering experiments** (ISR, MUSE, Prad)

- **μ-d Lamb shift measurement:**
  Proton radius extraction via isotope shift.

- **Spectroscopy of electronic Hydrogen:**
  Improve eH Lamb shift results. More precise measurement of R_{∞}.

- **Spectroscopy of exotic atoms:**
  Measurement of leptonic states e^+e^- and $\mu^+\mu^-$ provides strict tests of QED.

- **μ-^{3}He and μ-^{4}He Lamb shift measurement:**
  Interesting for the comparison with the scattering data.

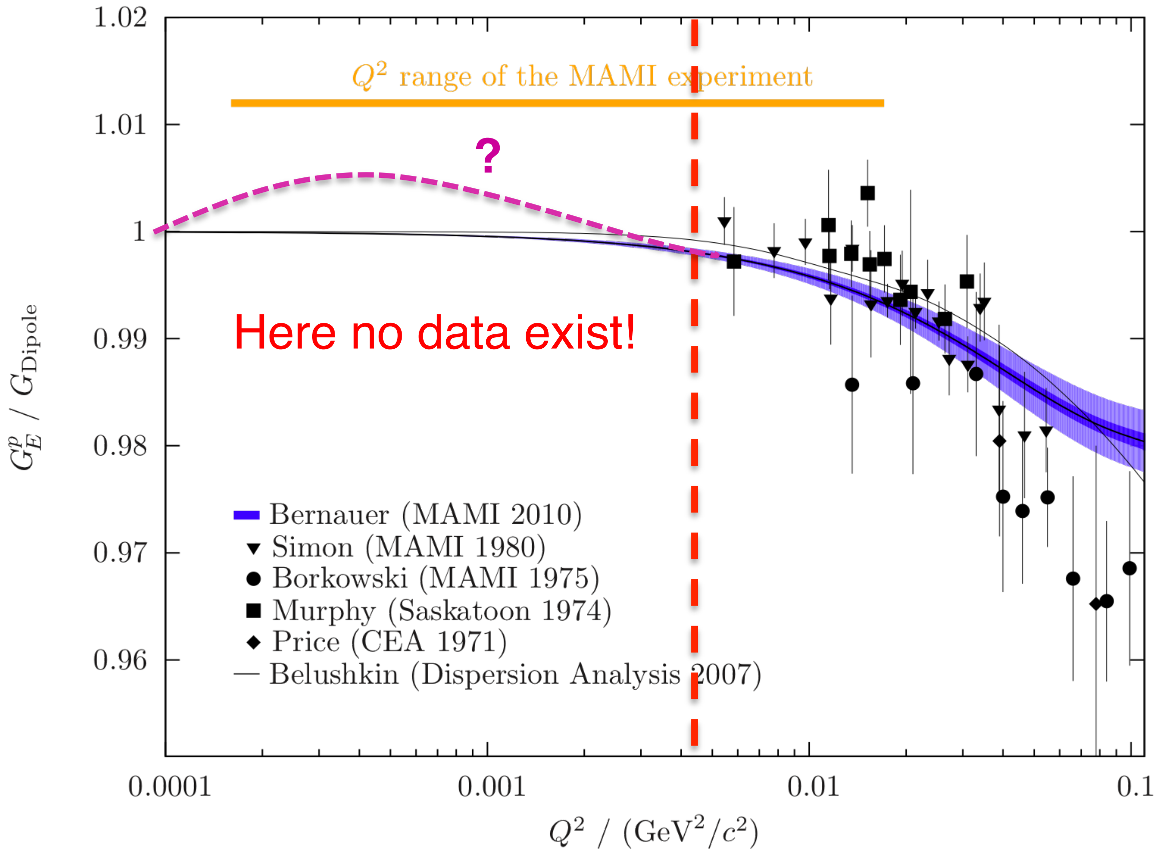
New elastic Cross-Section measurement

Elastic cross section for H(e,e')p:

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

Best estimate for radius:

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



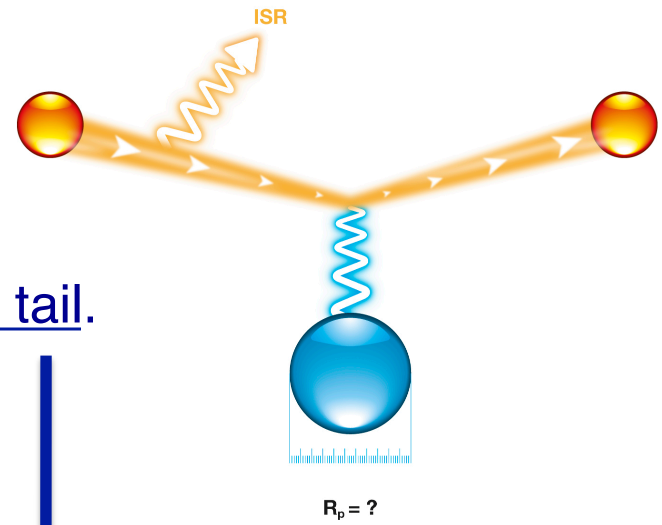
Determination of proton radius depends on the slope of FF (Q^2->0). **No data at lowest Q^2.**

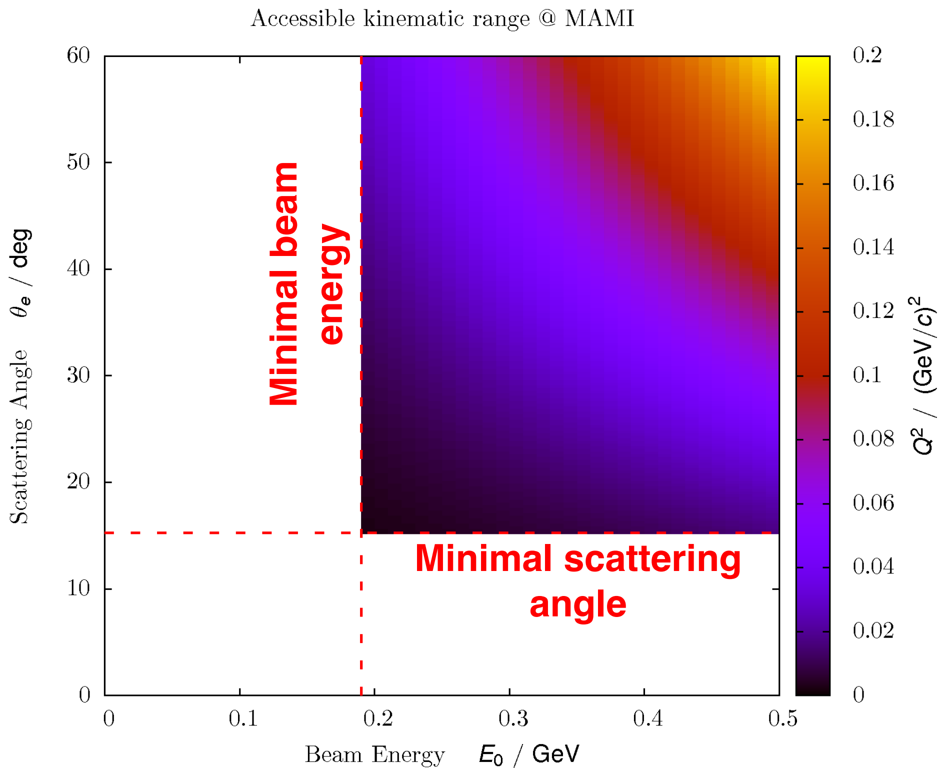
For precise radius determination new measurements at even **lower Q^2 are needed.**

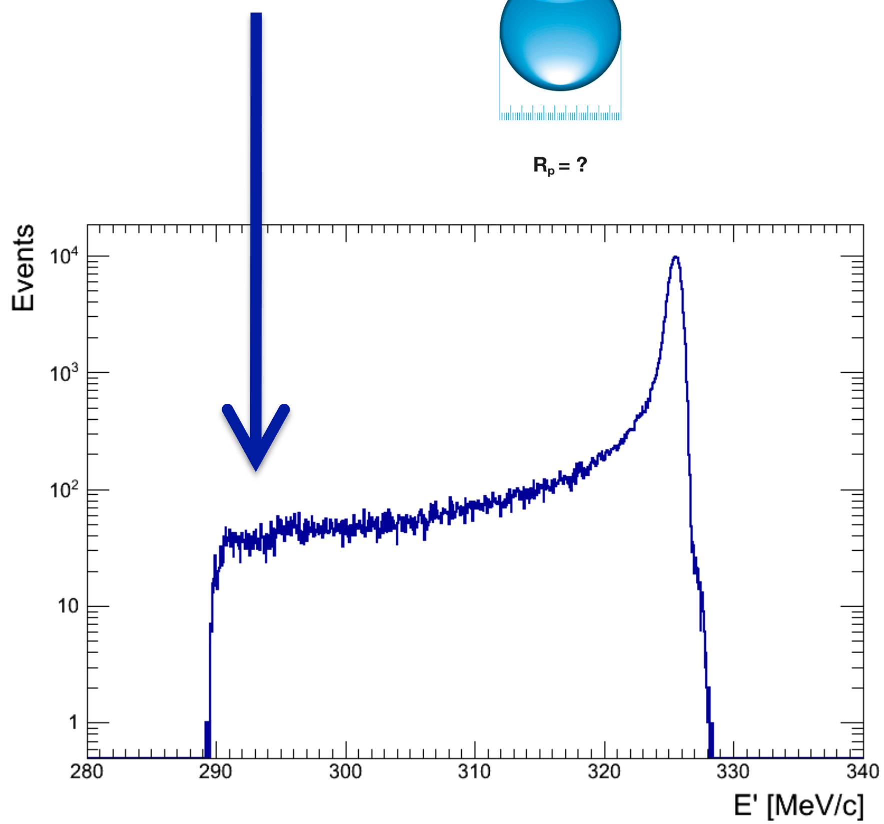
ISR Experiment at MAMI

- Lowest Q^2 where the elastic cross-section can be measured is constrained by the limitations of experimental apparatus.

- Way around: Use information from the radiative tail.

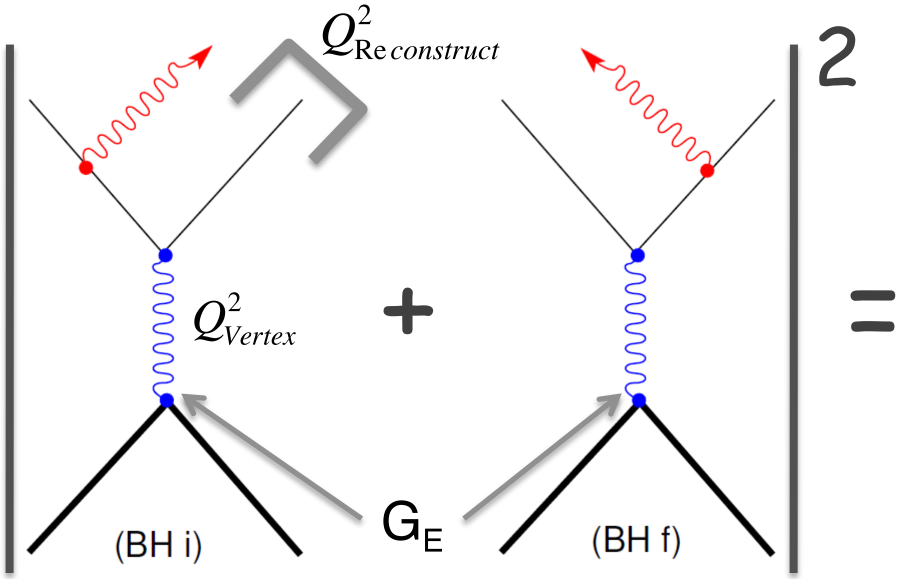


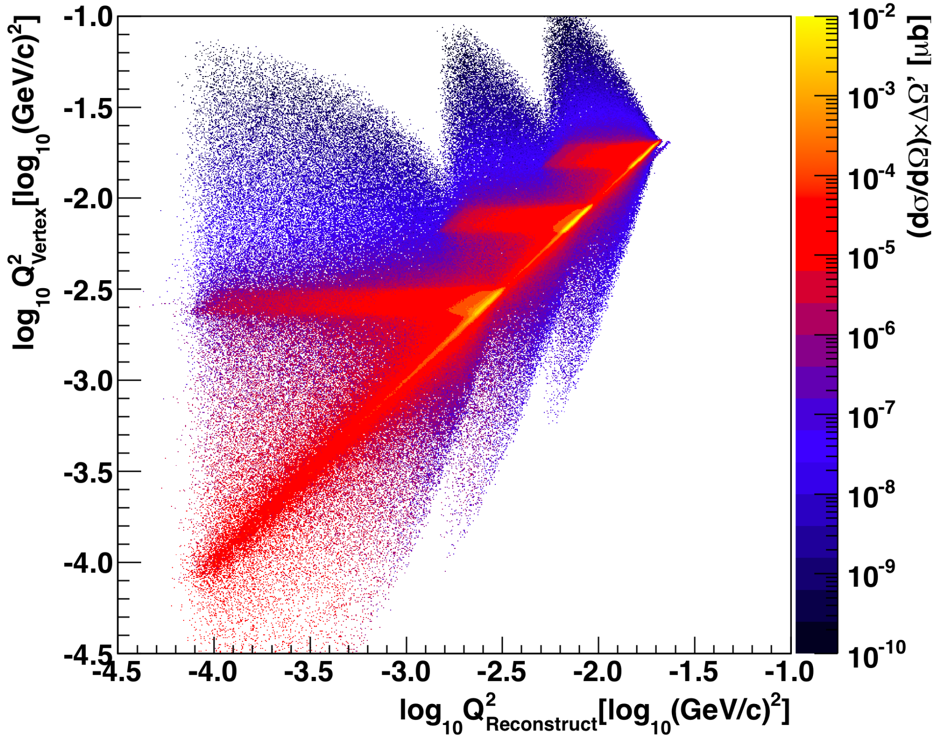




Initial state radiation

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

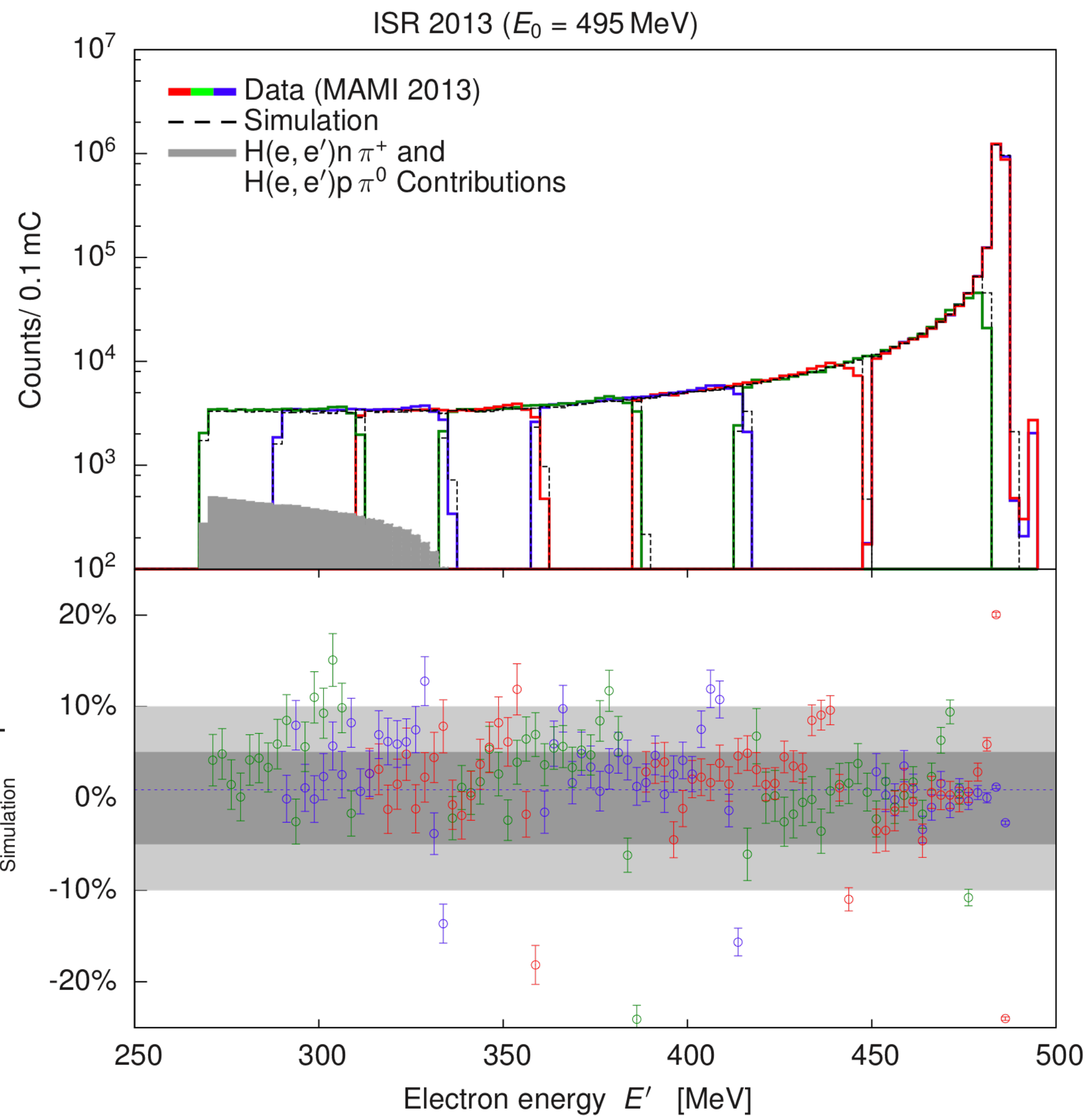




- In data ISR can not be distinguished from FSR.
- **Combining data with the simulation, ISR information can be reached**.
- Idea behind new MAMI experiment to extract $\mathbf{G_e^p}$ at **$Q^2 \sim 10^{-4}$ (GeV/c)^2**
- Redundancy measurements at higher Q^2 for testing this approach in a region, where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

First Results

- Experiment done in August 2013.
- First findings of online analysis.
- Pion production processes contribute ~10% at smallest momenta.
- Visible effects of finite resolution. (wall contributions still present)
- **Agreement between data and simulation justifies use of `Simul++`.**
- Full offline analysis underway.
- The FFs will be determined by a χ^2-minimization.



Conclusions

- **Proton radius puzzle** is a persisting open question of nuclear physics.

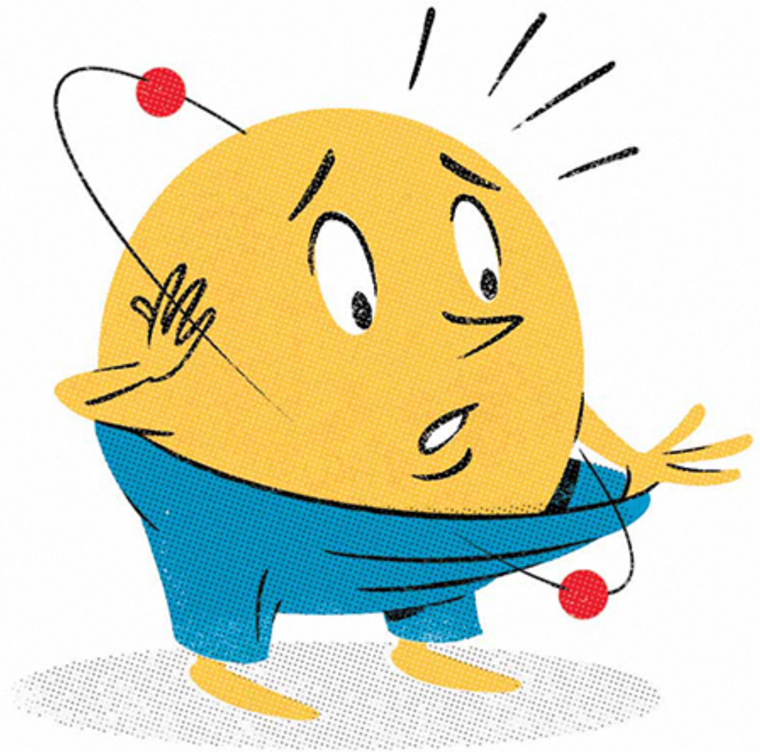
- The 4% difference in radii or 0.15% difference in the transition energy **remains unexplained**.

- Indication of a new interaction beyond standard model?

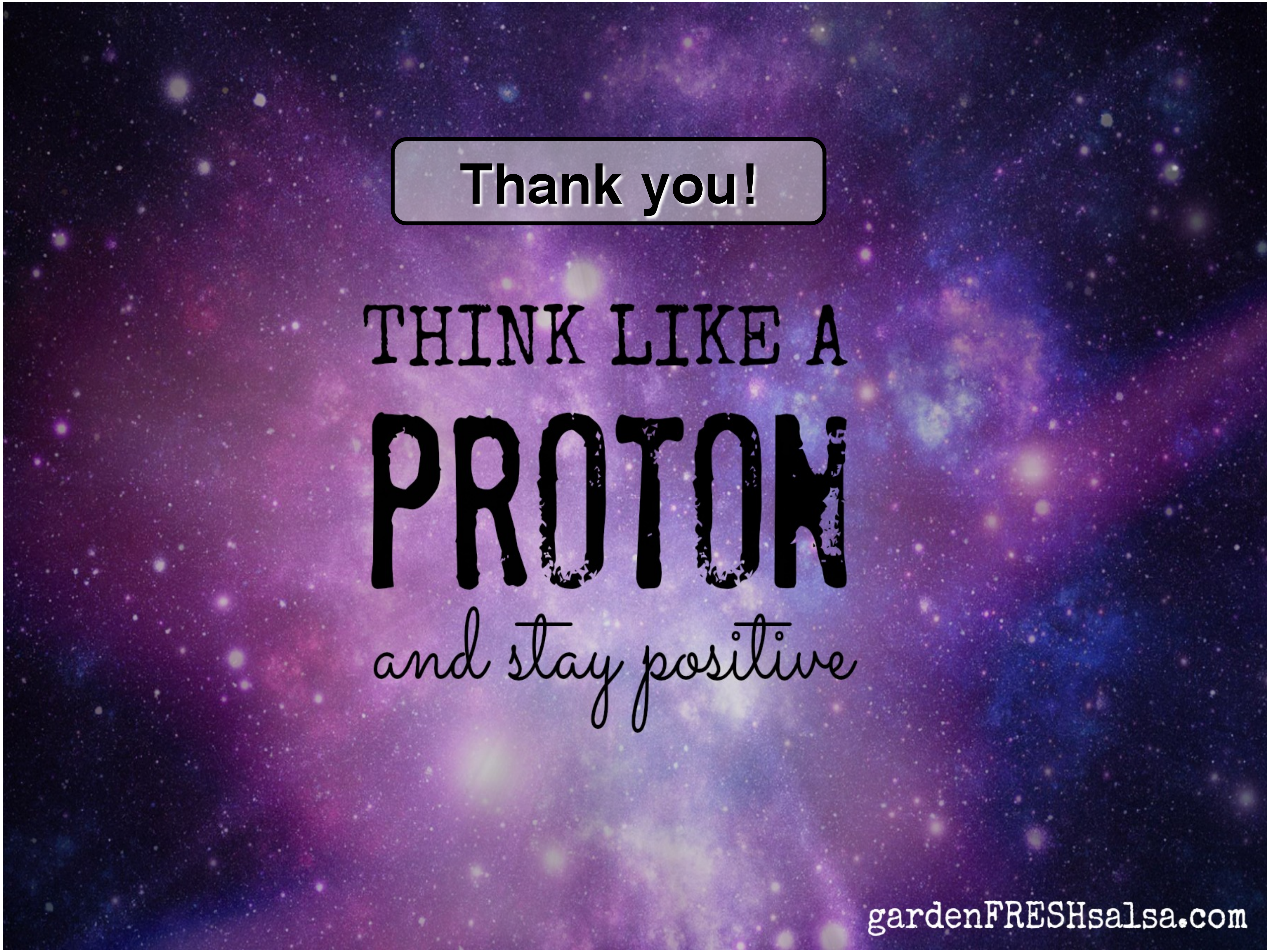
- Fundamental problem with QED?

- Continuous theoretical efforts to find the missing peace of the puzzle.

- New experiments are scheduled, examining different aspects of the problem.



Thank you!


THINK LIKE A
PROTON
and stay positive
gardenFRESHsalsa.com