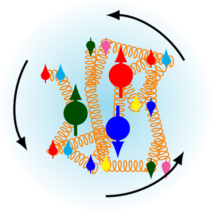
Proton radius from electron scattering: the experimental side

Jan C. Bernauer

INT 18-2a - June 2018

What is "stuff"?

The matter around us is described by non-perturbative quantum chromodynamics. npQCD is hard.
Simplest QCD system to study: Protons



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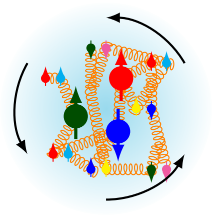

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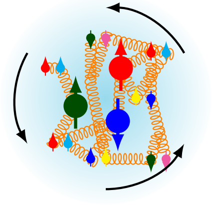
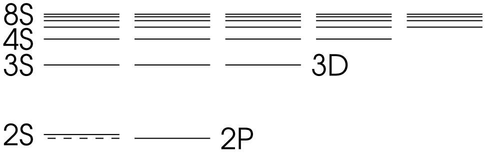


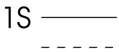
100 years of protons!
Proton is a composite system. It must have a size!

How big is it?

Motivation: "Normal" Hydrogen Spectroscopy



- $E_{nS} \approxeq -\frac{R_\infty}{n^2} + \frac{L_{1S}}{n^3}$



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

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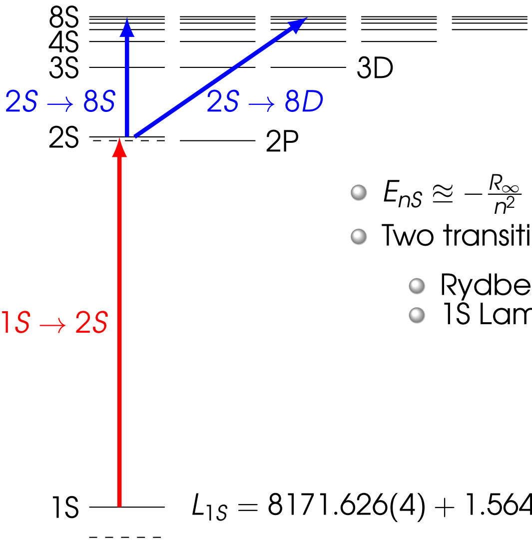

- $E_{nS} \approxeq -\frac{R_\infty}{n^2} + \frac{L_{1S}}{n^3}$
- Two transitions for two unknowns:
  - Rydberg constant R_∞
  - 1S Lamb shift $\Longrightarrow$ radius

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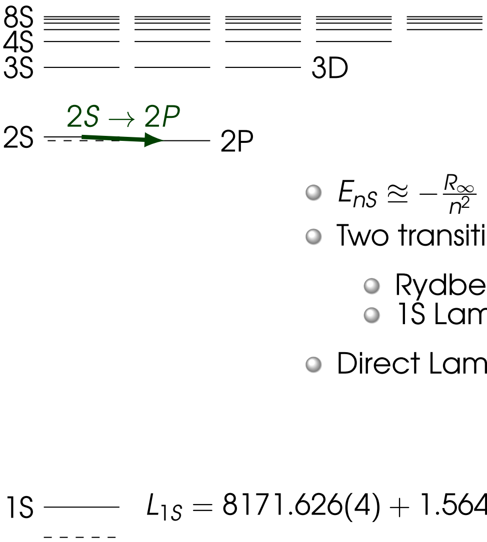

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- Direct Lamb shift $2S \to 2P$

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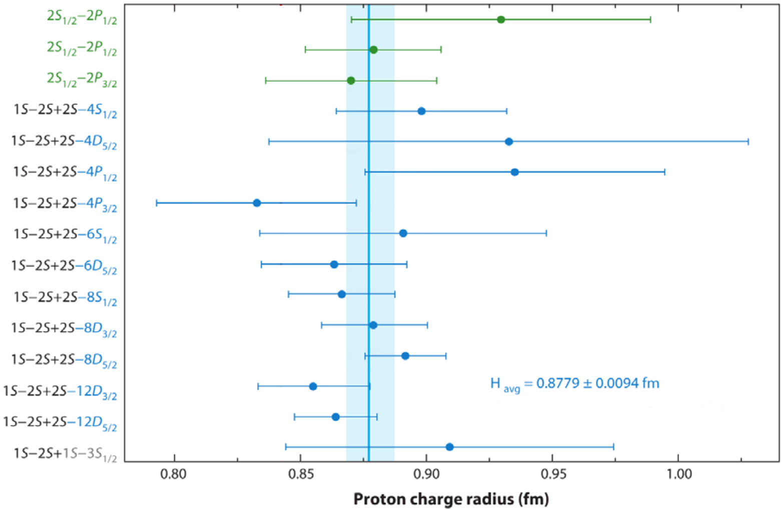
"Normal" Hydrogen Spectroscopy Results



Elastic lepton-proton scattering

Method of choice: Lepton-proton scattering

- Point-like probe
- No strong force
- Lepton interaction “straight-forward”

Measure cross sections and reconstruct form factors.

Cross section for elastic scattering

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

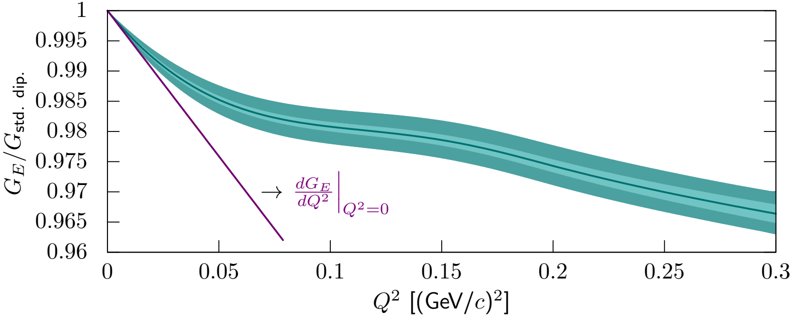
with:

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

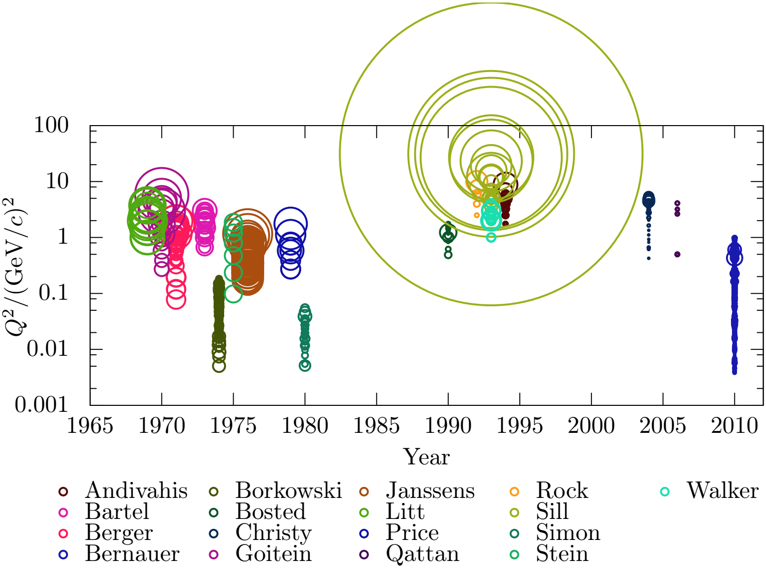
- Rosenbluth formula
- Electric and magnetic form factor encode the shape of the proton
- Fourier transform (almost) gives the spatial distribution, in the Breit frame

How to measure the proton radius

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



History of unpolarized electron-proton scattering

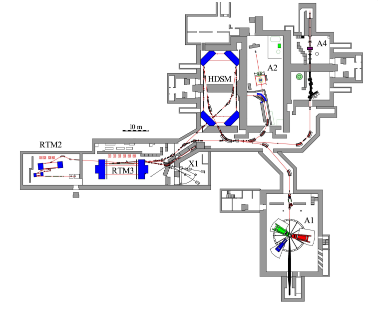


High-precision p(e,e′)p measurement at MAMI

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

Mainz Microtron

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



Johannes Gutenberg University of Mainz

3.97 mi

earth

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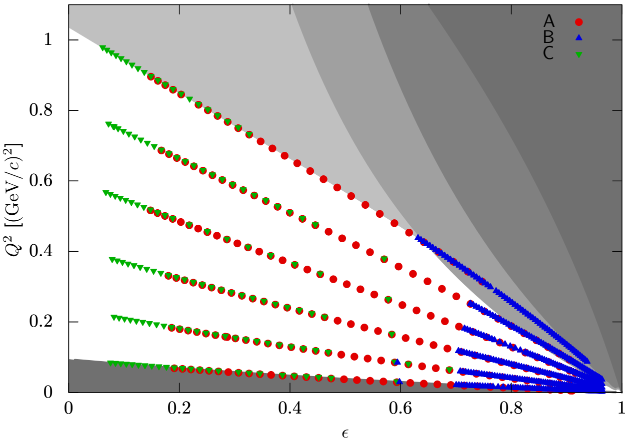
A1 3-spectrometer facility

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

Johannes Gutenberg Uni

3.97 mi

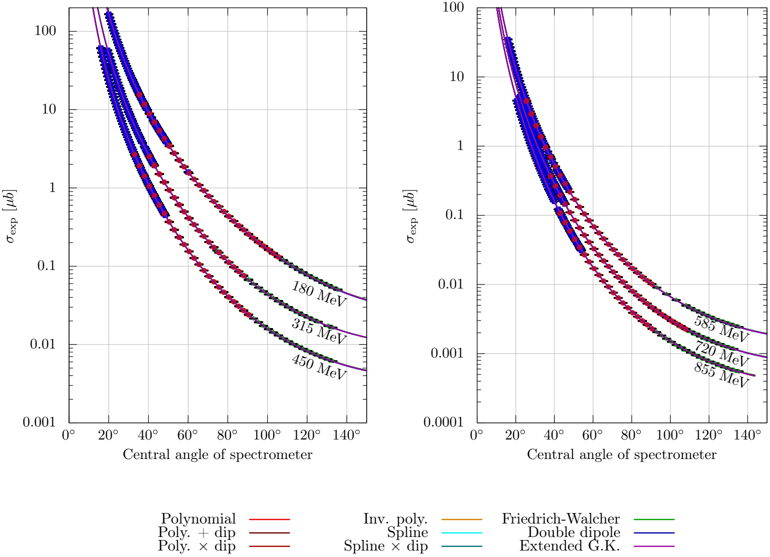
Measured settings



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

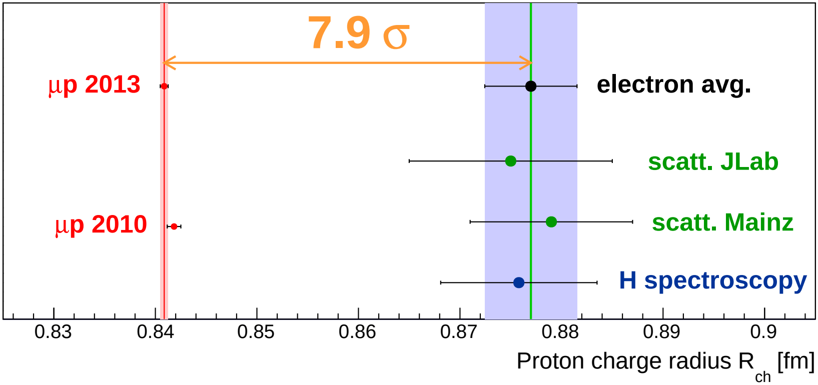
Cross sections



Muonic Hydrogen Spectroscopy

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

The proton radius puzzle



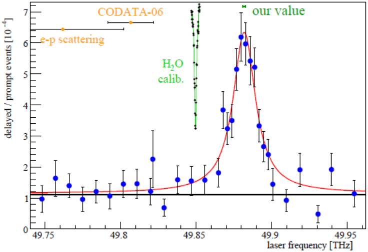
The proton radius puzzle

From the 2017 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?

- μp experiment wrong?



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- ep experiments wrong?
  - both scattering and H-spectroscopy wrong?

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- Everybody is right? New physics!
  - "Naive" dark matter models essentially excluded
  - But can play cancelation games
  - E.g.: Electrophobic force (Liu, Cloët, Miller arXiv:1805.01028)

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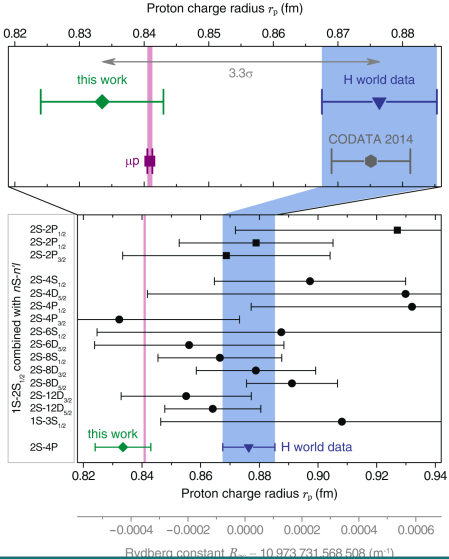
WE NEED MORE DATA

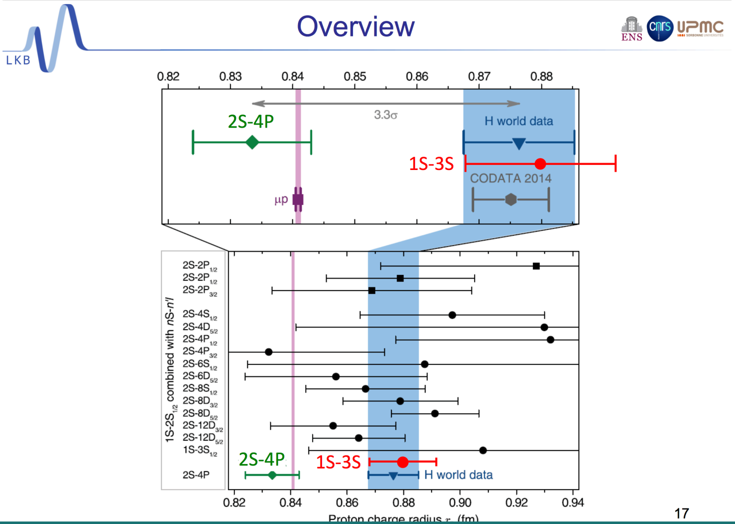
Deuteron (arxiv:1607.03165)

- In CODATA, r_d is correlated strongly to r_p because it uses "isotope shift" from 1s-2s in both systems.
- But: Can built independent value from deuteron 1s-2s and 2s-8s/8d/12d.
- This gives a difference to muonic deuterium! $\rightarrow$ another puzzle.
- Rydberg from electric Hydrogen and Deuterium in perfect agreement.
- The muonic deuterium R_∞ is in slight disagreement with the muonic hydrogen R_∞ (<3 sigma)

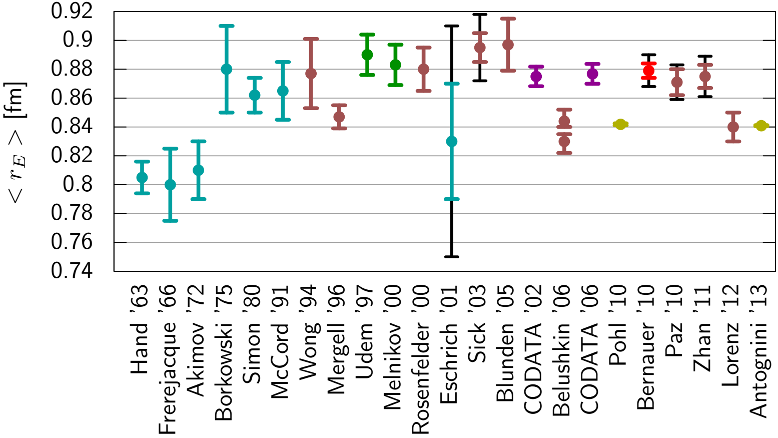
New hydrogen results: MPQ (A. Beyer et al., Science 358, 79 (2017))



New results: Paris (Fleurbaey et al., Phys. Rev. Lett. 120, 183001 (2018))



Timeline of proton radius results



Comments on some newer scattering results

2010: >0.870 Hill, Paz: old data, z expansion with disp. bounds

- Bounds on infinite exp. $\rightarrow$ bounds for truncated exp.?

2012: 0.840(10) Lorenz, Hammer, Meissner: Disp. relation fit.

- Same value but a lot more data. Probably model dominated.

2014: 0.84 Lorenz, Meissner: z expansion without bounds

- Fit did not converge. In real minimum, large radius is found.

2014: 0.8989(1) Gracyk/Juszczak: Bayesian estimation

- Interesting technique, unbelievable? small errors

2016: 0.84? Higinbotham: F-Test to select max. order

- Misunderstood F-test. Absence of proof $\neq$ proof of absence.

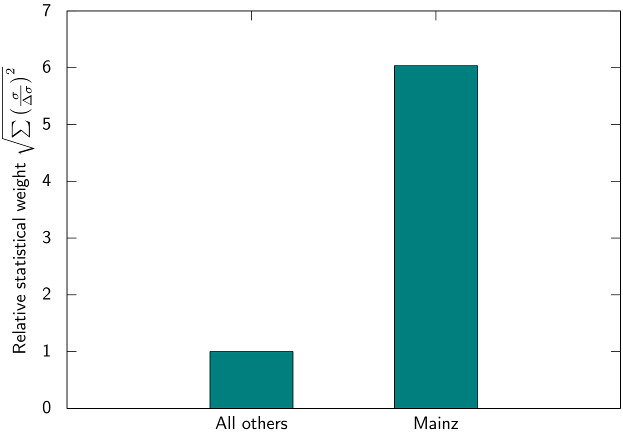
2016: 0.84? Horbatsch/Hessels/Griffioen/Carlson/Maddox... Low-Q

- Low-Q fits with low order don't work.

2018: XXX Yan/Higinbotham/...

- Small radius fraction finally does bias testing

Volume of Mainz data set



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

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?

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

(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 $6 \cdot 0.002 \cdot 0.01 = 0.012\%$. Good luck.

Why do low Q^2 then?

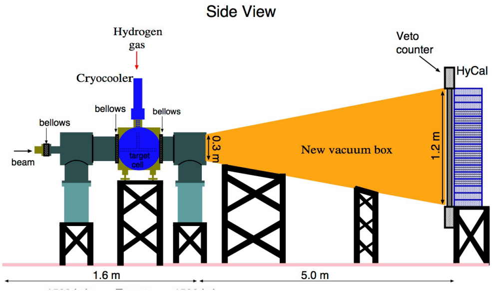
- Test / fix normalization
  Similar arguments apply, but helpful when dataset contains also higher Q^2.
- Test for new physics / ultra long range structure
  Signal can easily, but doesn't have to be undetectable small and still change the radius!
- Measure r_M
  Low Q^2 at $\epsilon = 1$ means lowish Q^2 at $\epsilon = 0$

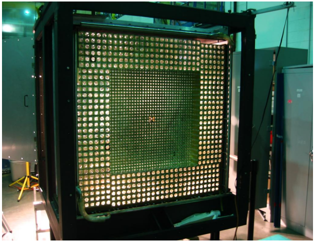
Three ways to get to lower Q^2

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

- Smaller scattering angle $\longrightarrow$ PRad
- Lower beam energy $\longrightarrow$ MESA
- Initial State Radiation

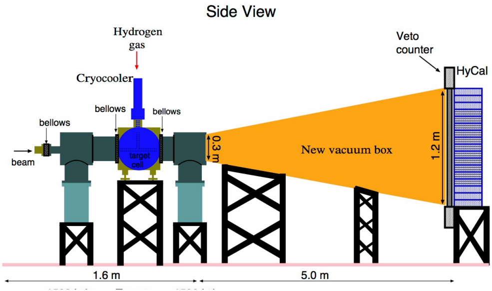
JLAB: PRoton RADius

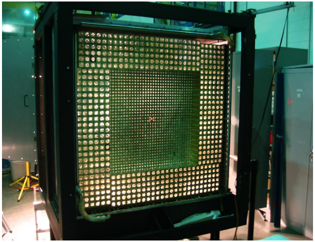




- High resolution, large acceptance hybrid calorimeter
- Windowless target
- Simultaneous measure ep $\to$ ep and Møller scattering
- Q^2 range: 2×10^{-4} to 6×10^{-2} $(\mathrm{GeV}/c)^2$

JLAB: PRoton RADius





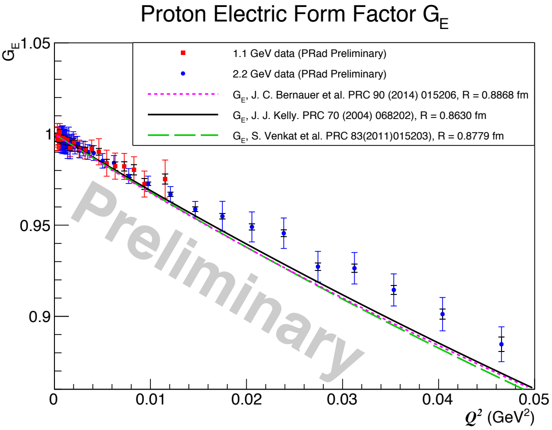
- High resolution, large acceptance hybrid calorimeter

Status

- Data taken successfully
- Analysis ongoing

Form Factor G_E (Preliminary)

- Proton electric form factor G_E v.s. Q^2, with 2.2 and 1.1 GeV data (preliminary)
- Systematic uncertainties shown as colored error bars
- Preliminary G_E slope seems to favor smaller radius



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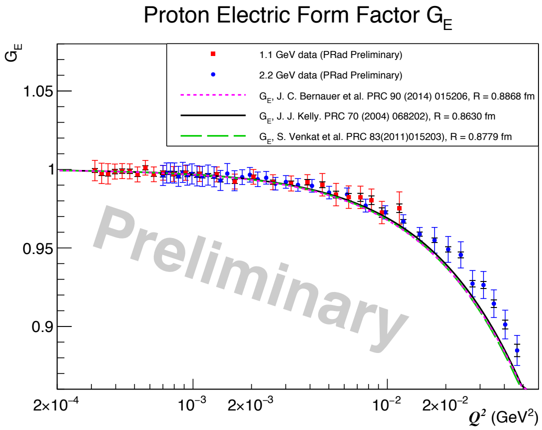

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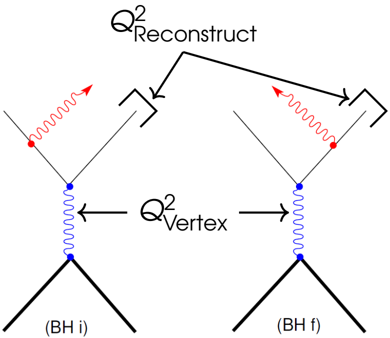
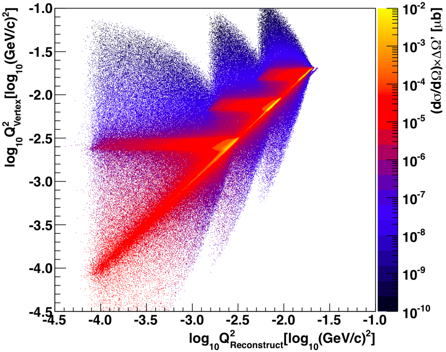
ISR method

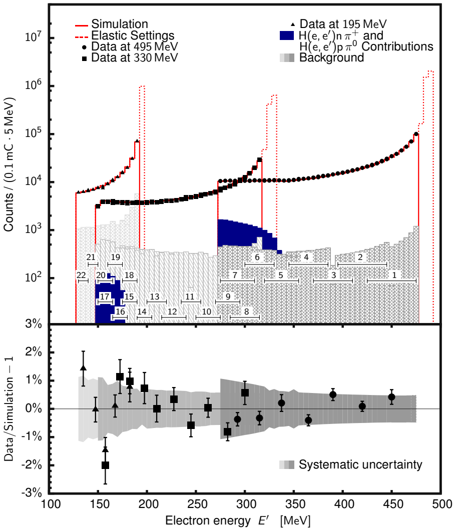




- Use initial state radiation to reduce effective beam energy
- Have to subtract FSR

ISR at MAMI

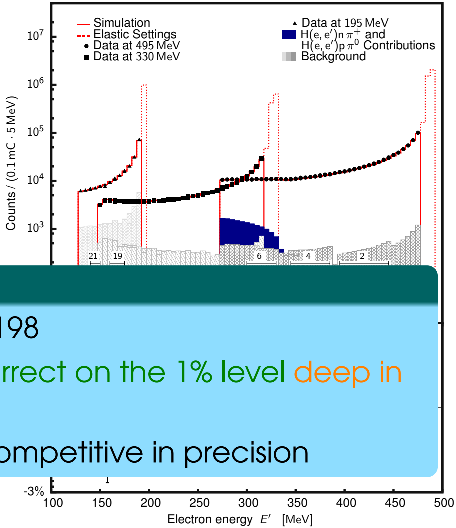
- ISR $\longrightarrow$ small E $\longrightarrow$ small Q^2
- Extract F.F. from radiative tail
- Or: test radiative tail description



See: arXiv:1612.06707

ISR at MAMI

- ISR $\longrightarrow$ small E $\longrightarrow$ small Q^2
- Extract FF from



See: arXiv:1612.06707

Status

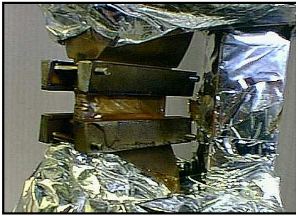
- Published: PLB 771:194-198
- Radiative correction correct on the 1% level deep in the tail!
- Radius extraction not competitive in precision

Target dominant source of uncertainty

- For Mainz data, systematic errors dominate

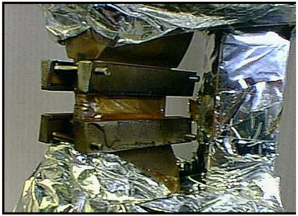
Target dominant source of uncertainty

- For Mainz data, systematic errors dominate
  - Background from target walls
  - Acceptance correction for extended target



Target dominant source of uncertainty

- 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, ...



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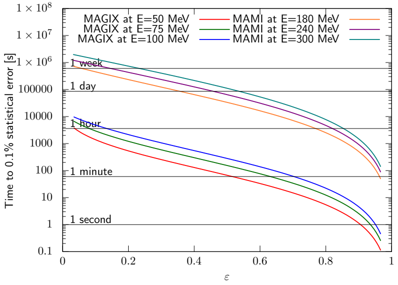
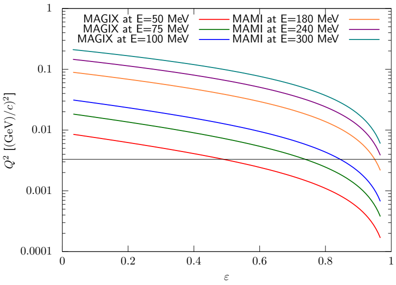
Mainz future plans

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





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

The missing piece

r_E (fm)	ep	μp
Spectroscopy	0.8758 ± 0.077	0.84087 ± 0.00039
Scattering	0.8770 ± 0.060	????

Measure radius with muon-proton scattering!

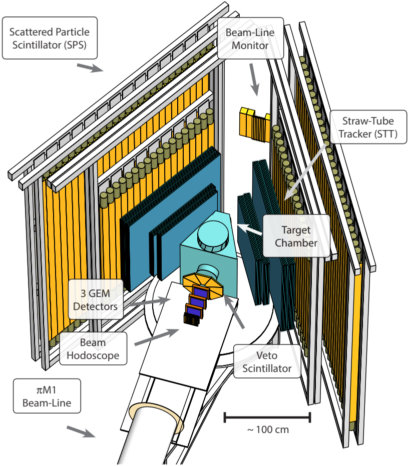
MUSE - Muon Scattering Experiment at PSI

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

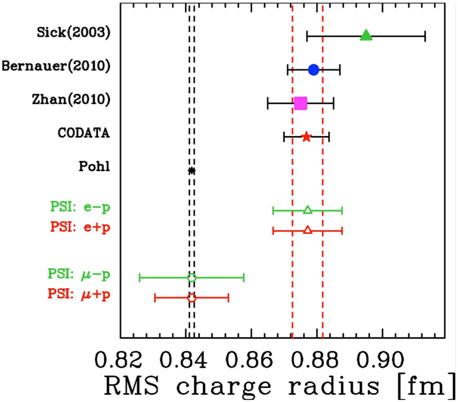


R. Gilman et al., arXiv:1303.2160 (nucl-ex)

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

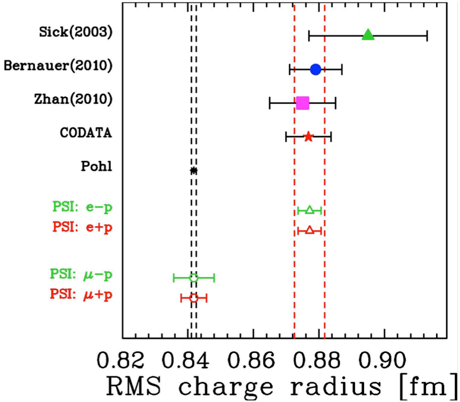
Predicted performance

- Absolute radius extraction uncertainties similar to current exp's.



Predicted performance

- Absolute radius extraction uncertainties similar to current exp's.
- Difference: Common uncertainties cancel!
- $\longrightarrow$ factor two more sensitivity



MUSE can verify 7σ effect with similar significance!

Summary

- Proton radius puzzle persists since 2010
- We need new data to resolve it
- A lot of data incoming in the next years, but pretty hard limit on achievable errors
- MUSE, with electron and muon scattering, will test
  - existing radius value
  - lepton universality
  - two photon exchange / proton polarizability

The most exciting phrase to hear in science, the one that heralds new discoveries, is not "Eureka!" but "That's funny . . . "
— Isaac Asimov

Taylor expansions and polynomial fits

It's a common theme that a polynomial fit is related to a Taylor expansion around 0, sharing important traits mainly radius of convergence.

- "We will fit ... a simple Taylor series expansion." R.J. Hill and G. Paz, Phys. Rev. D 82, 113005 (2010)
- "correct inclusion of the lowest singularity" I. Lorenz and U.G-Meißner, Phys. Lett. B 737, 57 (2014)
- "Maclaurin fits", D. W. Higinbotham et al., Phys.Rev. C93, 055207 (2016)
- "We do not advocate using polynomial fits.... since convergence ... is not assured..." K. Griffioen et al., arxiv:1509.06676

This is wrong.

Traits of Taylor, Weierstrass, Fits

Taylor expansion

- Is correct in all order (to truncated order) at x_0.
- Converges on a radius up to the next pole.
- Error is $R_k = \frac{f^{(k+1)}(\xi_c)}{k!}(x-\xi_c)^k(x-x_0)$

Weierstrass theorem

- Any function continuos over $[a, b]$ can be approximated with a polynomial in that range.
- The convergence is uniform:
  $\forall \epsilon > 0, \exists$ poly., so that $||f(x) - p(x)||_\infty < \epsilon,\ x \in [a, b]$

Polynomial fit

- Minimizes L2-norm over the points: $||f(x) - p(x)||_2$
- Will converge to the function, NOT to the Taylor expansion of the function

We have no choice

Taylor expansion

- Is correct in all order (to truncated order) at x_0.
- Converges on a radius unto the next pole.
- Error is $R_k = \frac{f^{(k+1)}(\xi_c)}{k!}(x - \xi_c)^k(x - a)$

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  $\forall \epsilon > 0, \exists$ poly. .so that $||f(x) - p(x)||_\infty < \epsilon$, $x \in [a, b]$

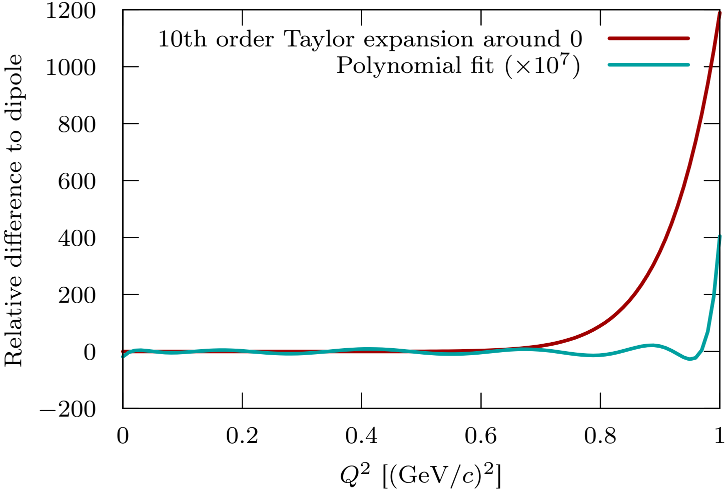
Polynomial fit

- Minimizes L2-norm over the points: $||f(x) - p(x)||_2$
- Will converge to the function, NOT to the Taylor expansion of the function

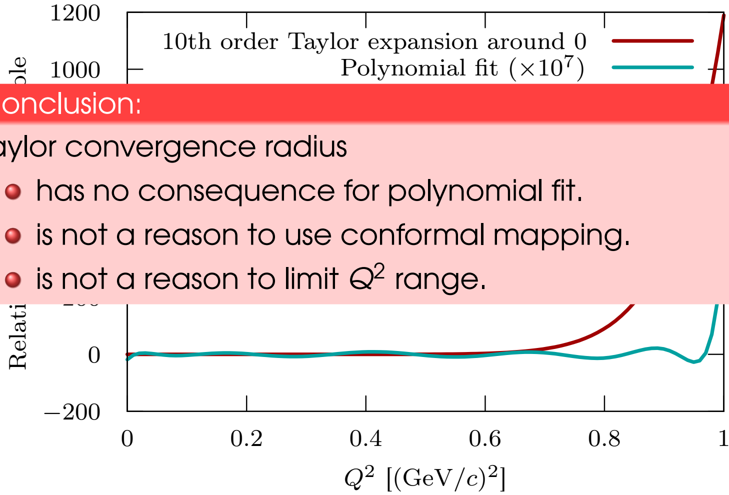
What does that mean in reality?

- Let's fit perfect pseudo data
- Compare with Taylor expansion
- Input function: dipole, i.e. pole at $Q^2 = -0.71\,(\text{GeV}/c)^2$

Fit results



Fit within 40 ppm over data range, better than expansion for $Q^2 > 0.15\,(\text{GeV}/c)^2$



Conclusion:

Taylor convergence radius

- has no consequence for polynomial fit.
- is not a reason to use conformal mapping.
- is not a reason to limit Q^2 range.

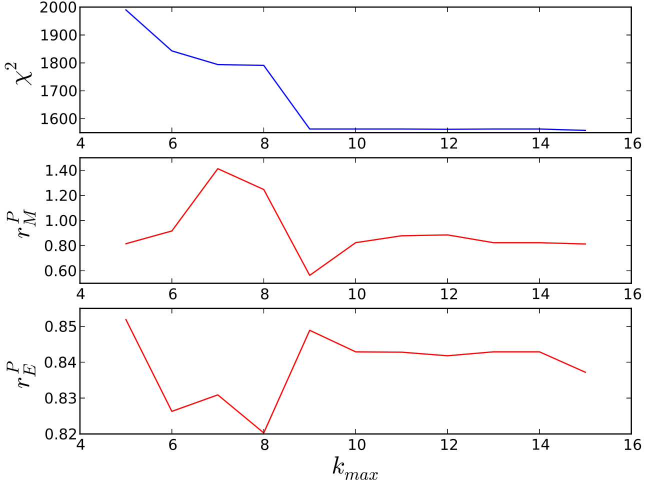
Fit within 40 ppm over data range, better than expansion for $Q^2 > 0.15\,(\text{GeV}/c)^2$

Problems of (unconstrained) conformal mapping

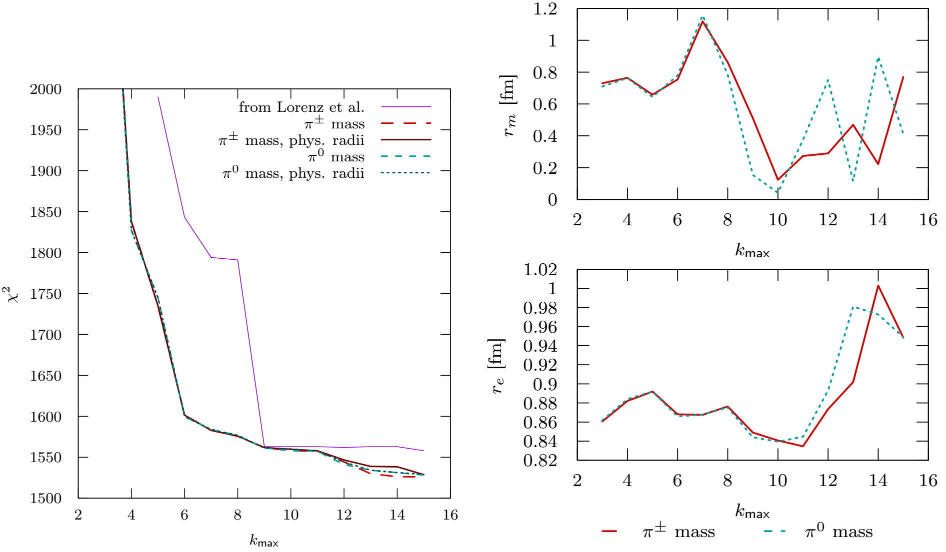
- remaps flexibility:
  - a lot of flexibility to small Q^2: Gap is 2.2% of data range instead of 0.4%
  - not enough at high Q^2
- harder to fit: many local minima

Failures to fit conformal mapping polynomials

I. Lorenz and U.G. Meißner, "Reduction of the proton radius discrepancy by 3 σ", Phys. Lett. B 737, 57 (2014)



Finding better minima via random search



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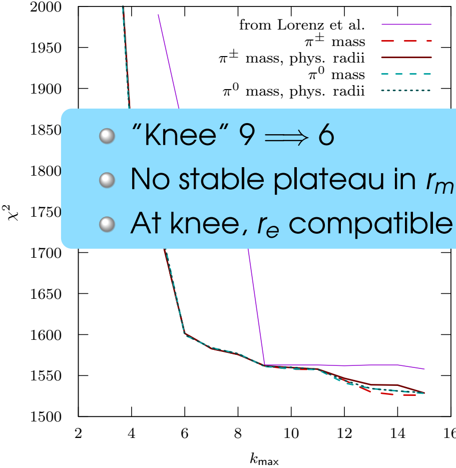

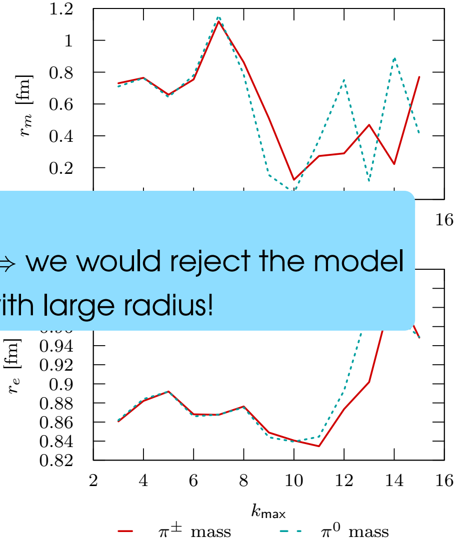

- "Knee" 9 $\Longrightarrow$ 6
- No stable plateau in $r_m \Longrightarrow$ we would reject the model
- At knee, r_e compatible with large radius!

Low-Q polynomial fits

Griffioen et al. "Are Electron Scattering Data Consistent with a Small Proton Radius?", arxiv:1509.06676 advocate a fit up to 0.02 $(\mathrm{GeV}/c)^2$.
They find:

- Linear fit: $r_e = 0.835(3)\ fm$.
- Quadratic fit: $r_e = 0.850(15)\ fm$.

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- Quadratic fit: $r_e = 0.850(15)\ fm$.

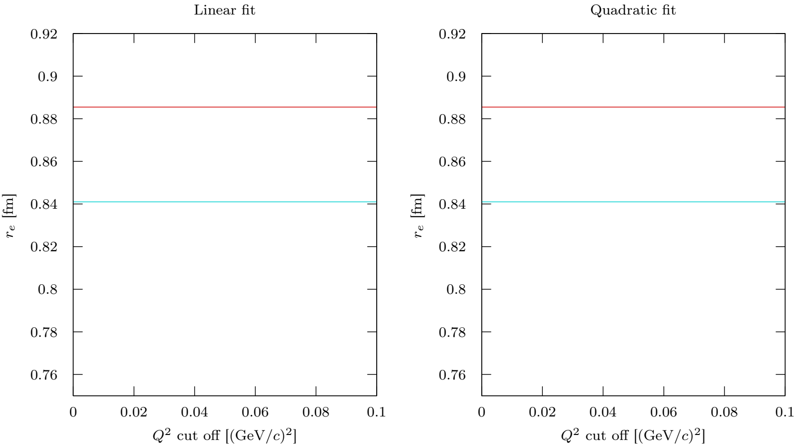
Questions

- Why 0.02? What happens at 0.01? 0.03?
- What is the bias of this method?

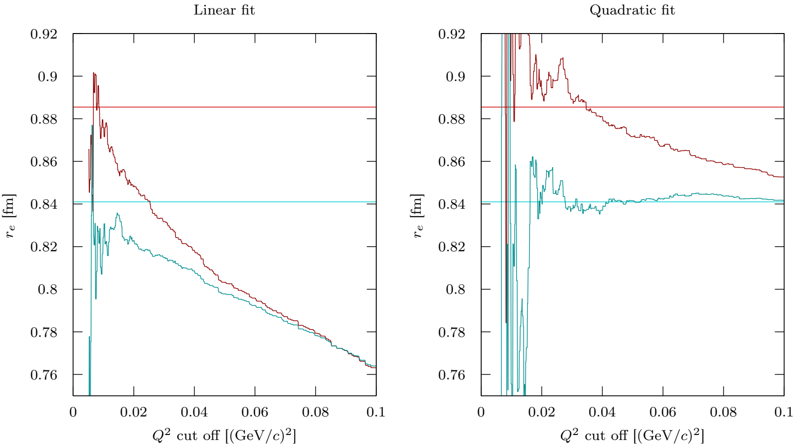
Simulate experiment with pseudo data

- Use two input parametrizations
  - Our 10th order polynomial fit
  - 10th order polynomial fit with radius forced to 0.841 fm.
- Generate 1000 pseudo data sets each
- Fit
- Look at extracted r_e as function of cut off.
- Compare with known input radius

Results on pseudo data



Results on pseudo data



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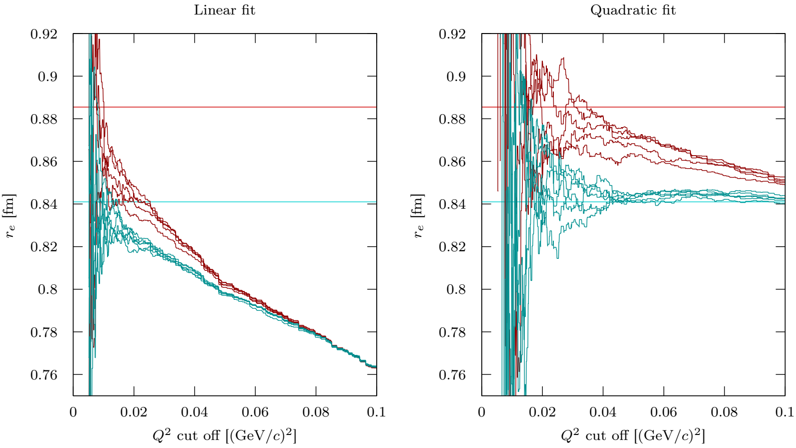
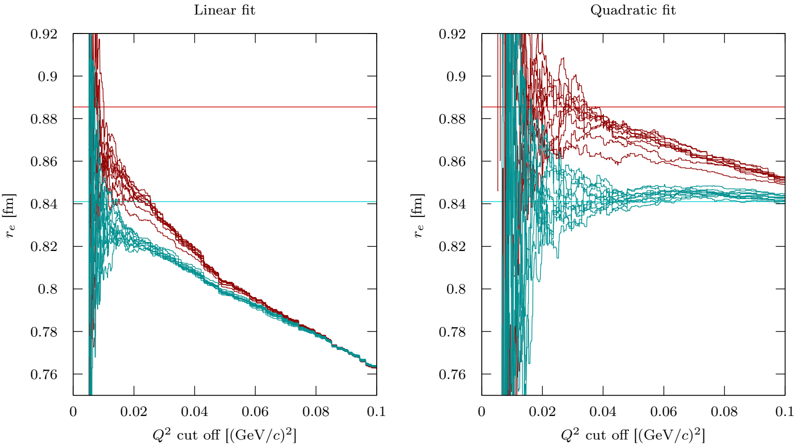
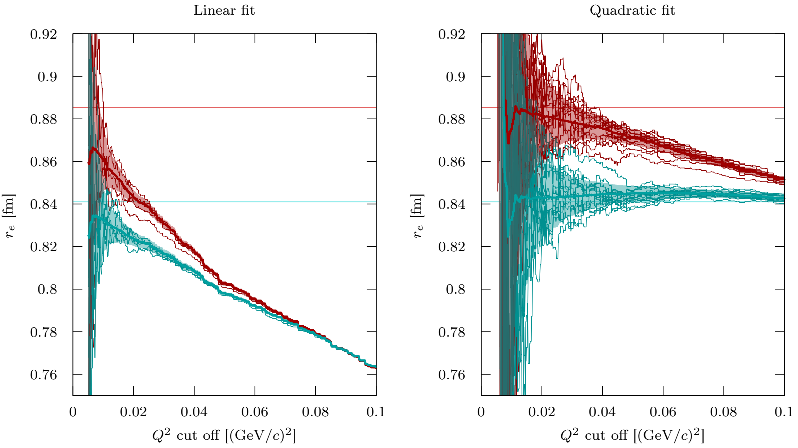


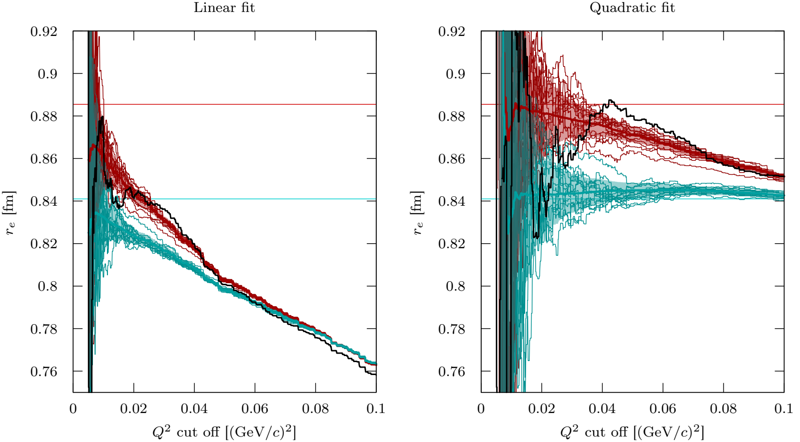
Results on pseudo data



Results on pseudo data



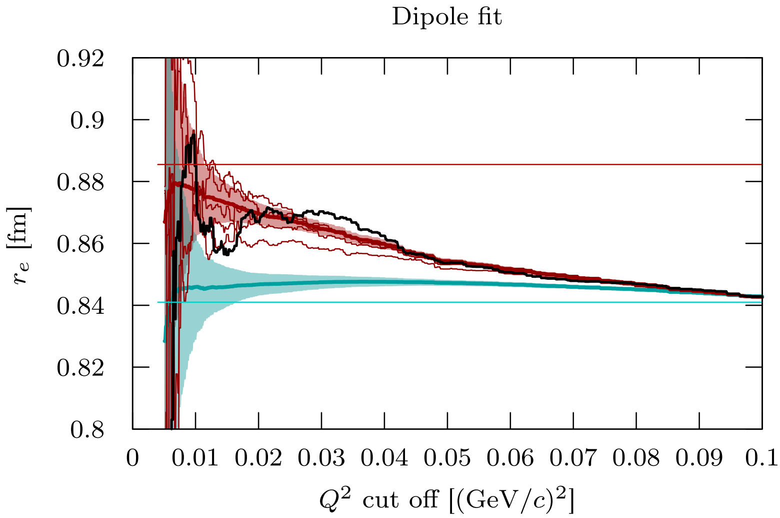
Results on data



Dipole fits

- Horbatsch and Hessels, "Evaluation of the strength of electron-proton scattering data for determining the proton charge radius", Phys. Rev. C 93 015204 compare conformal mapping fits (large radius) and dipole fits (small radius) with varying cut-off.
- We already know that dipole fit to the whole range has a large bias.
- But what about smaller range?

Results dipole fit to (pseudo) data



F-test to determine fit order

- Nested models!
- Compare two hypothesis:
  - H0: The true model has order j
  - H1: The true model has order j+k (or any order>j)

$$F = \frac{\chi^2_{H0} - \chi^2_{H1}}{\chi^2_{H1}} \frac{N - j}{k}$$

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Fisher-Snedecor

- F follows a Fisher-Snedecor distribution if H0 is true
- Otherwise: Non-central Fisher-Snedecor distribution (best case)

F-test

- Can rule out H0 at a given CL if $F > F_{crit}$
  - Type I error: If H0 is falsely rejected, H0 is true.
    $\Longrightarrow$ F is Fisher-Snedecor distributed
    $\Longrightarrow$ Can calculate how often $F > F_{crit}$ by random chance
- Can NOT rule out H1 at same CL if $F < F_{crit}$
  - Type II error: Have to assume H1 is correct!
    $\Longrightarrow$ F NOT Fisher-Snedecor distributed
    $\Longrightarrow$ Small F can reject BOTH H0 and H1
  - This is what D. Higinbotham et al. do wrong
  - James does it (semi) correct in explanation, but wrong in example

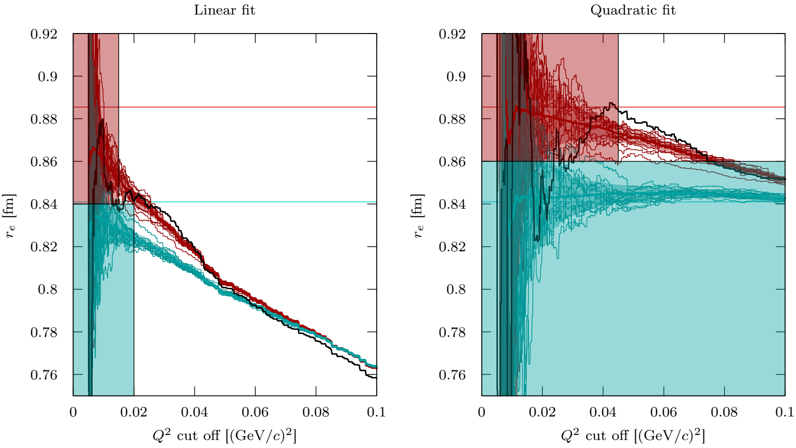
Remarks

- One can disprove H0 without assuming H1 to be right!
- Science: We can disprove a theory (because a prediction is off), we can not prove one.
- Other tests: similar story
  - Akaike Information Criterion (AIC) tells you if data can disprove that a certain model is “enough”
- This does not touch the problem of bias!

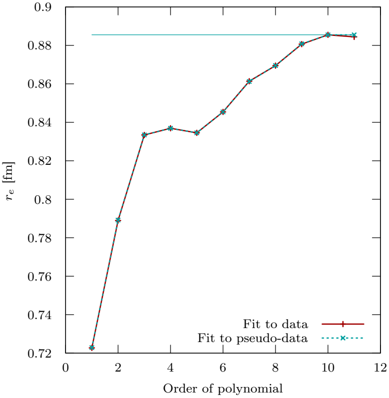
Remarks

- One can disprove H0 without assuming H1 to be right!
- Science: We can disprove a theory (because a prediction is off), we can not prove one.
- Other tests: similar story
  - Akaike Information Criterion (AIC) tells you if data can disprove that a certain model is "enough"
- This does not touch the problem of bias!
- Here:
  - We know that the form factor $\rightarrow 0$ for $Q^2 \rightarrow \infty$.
  - Any finite polynomial goes to $\pm\infty$
  - Neither H0 nor any H1 can be true
- Everything Should Be Made as Simple as Possible, But Not Simpler (Einstein, probably)
- Let's pretend we are John Snow and know nothing.

F-test results for low-order polynomials



F-test /AIC results for full data range



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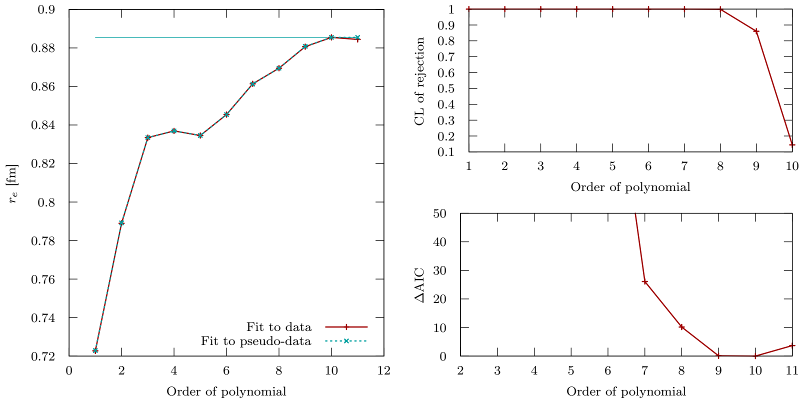

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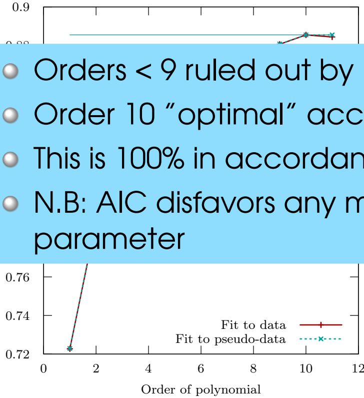
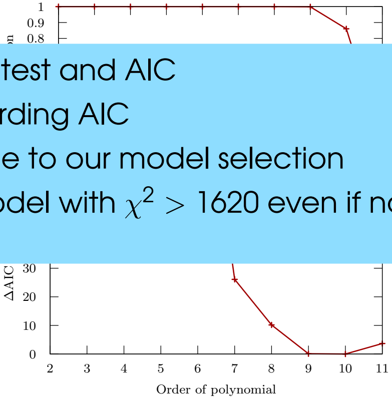


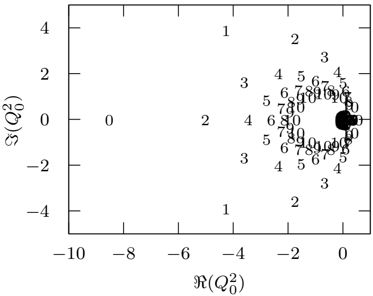


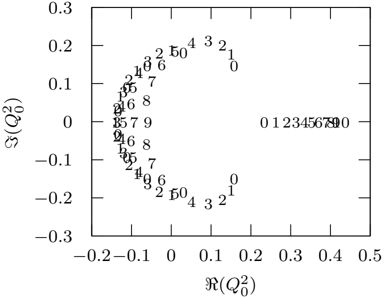
- Orders < 9 ruled out by F-test and AIC
- Order 10 "optimal" according AIC
- This is 100% in accordance to our model selection
- N.B: AIC disfavors any model with $\chi^2 > 1620$ even if no parameter

Conclusion

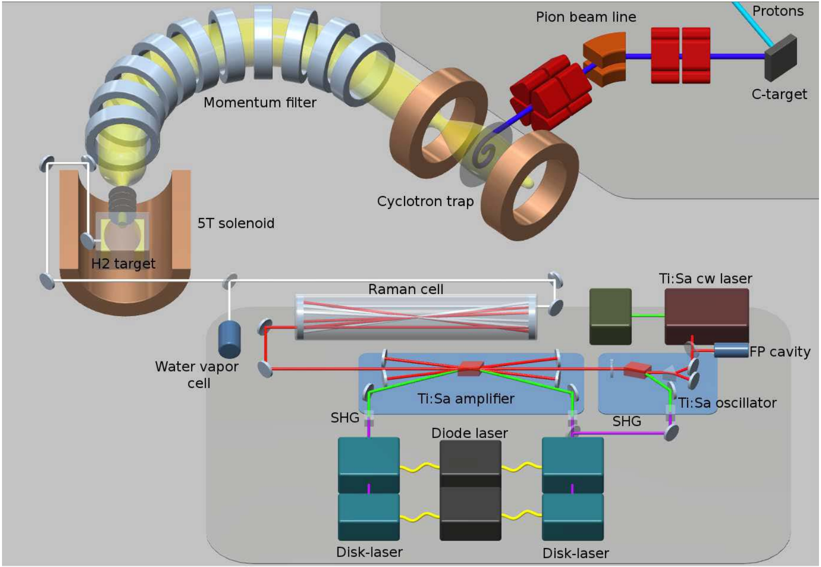
- Fitting is hard
- Taylor and polynomial fits are unrelated
- Have to balance between bias and overfitting
  - Cutting data set to small Q^2 makes balance HARDER.
- Statistical tests do not tell you about bias.
- Statistical tests, done right, support our analysis.
- Test your method on pseudo data!
  $\Longrightarrow$ If you want to disprove large radius, show that you can replicate the large radius!
- *The resolution of the puzzle can not be found in refitting of the data*
- For more info: arXiv:1606.02159

Poly/Taylor possible Q_0^2

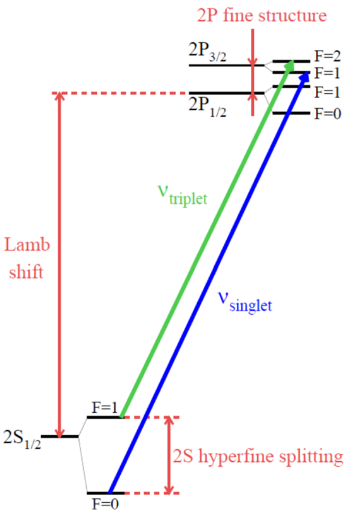


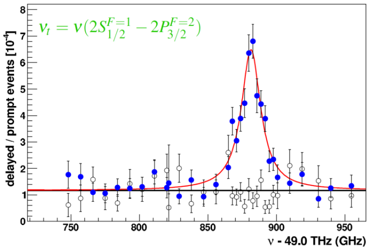


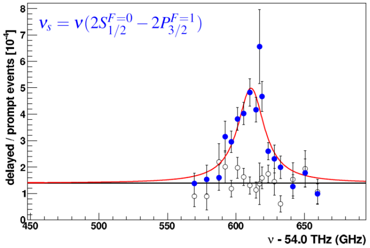
PSI setup (CREMA)

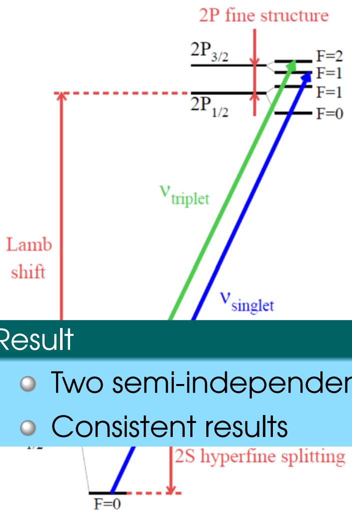


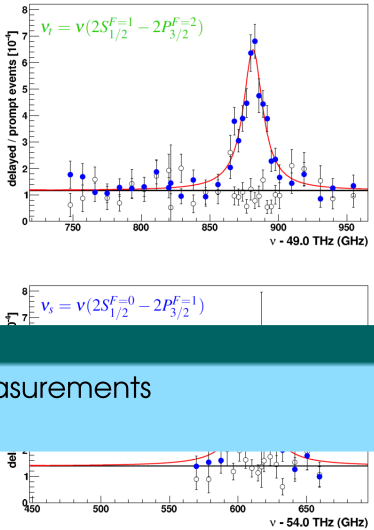
Muonic Hydrogen Spectroscopy Results











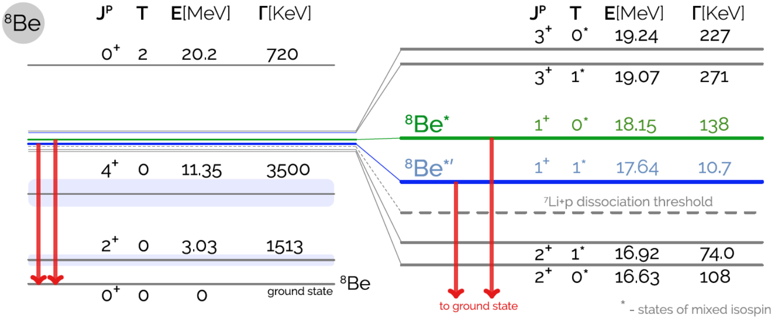
Result

- Two semi-independent measurements
- Consistent results

^{8}Be is special

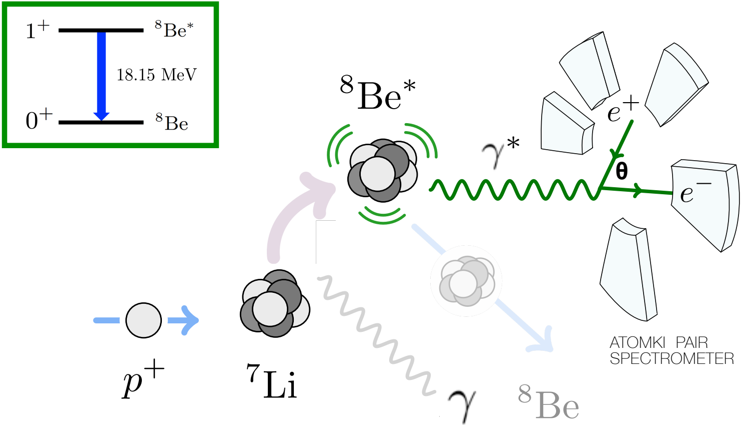
Many images from arXiv:1707.09749

^{8}Be is special: two narrow, highly energetic states which can decay to ground state via E/M



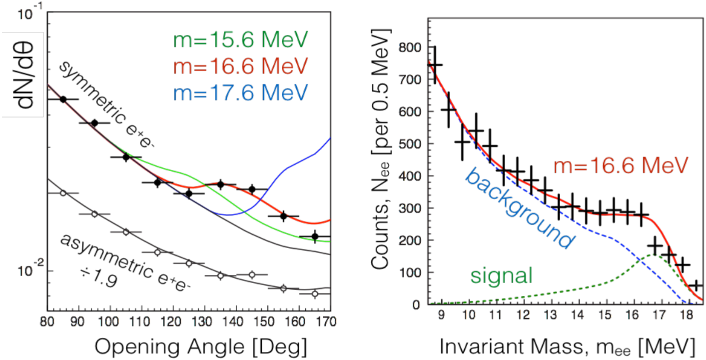
Decay modes of $^8Be(18.15)$

Hadronic, electromagnetic and through internal pair conversion



1.04 MeV proton beam on ^7Li to $^8Be(18.15) + \gamma$. Followed by decay. Looked at $e^{\pm}$ pairs from internal conversion.

The beryllium anomaly



Why believe it?

- This model has $\chi^2/d.o.f.$ of 1.07, significance of 6.8σ
- Bump, not last bin effect
- Rises/falls when scanning through proton energies around resonance
- Excess only happens for symmetric-energy pairs
- Preliminary reports of same excess in $^8Be(17.6)$ (same group)

Why not believe it?

- Group has a history of finding peaks
- IIUC, the detector acceptance has a minimum at 140°
- DM boson interpretation is proto-phobic to evade NA48/2 limits
  - Actually: $\frac{\epsilon_p}{\epsilon_n}$ coupling below $\pm 8\%$. Z^0 is $\sim 7\%$

We can measure it!

In DarkLight, production is via Bremsstrahlung, predominantly ISR off the electron.
We can look at $e^- Ta \to e^- TaX$, followed by $X \to e^- e^+$
Irreducible background: $e^- Ta \to e^- Ta\gamma^\star \to e^- Tae^+ e^-$

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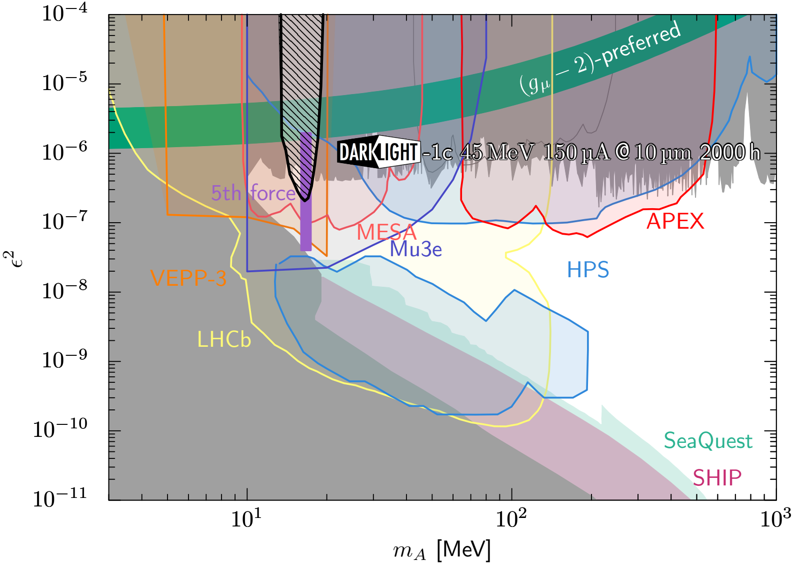
Best kinematics:

- highest production rate if X takes all electron energy. CS rise beats all
- with limited out-of-plane acceptance, symmetric angle optimal

Reach



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m_A [MeV]
$(g_\mu - 2)$-preferred
DARKLIGHT -1c 45 MeV 150 µA @ 10 µm 2000 h
5th force
MESA
Mu3e
APEX
HPS
VEPP-3
LHCb
SeaQuest
SHIP