# Workshop Summary

# The Proton Radius Puzzle

- Introduction
- New Results
- Theory
- Future Experiments
- Summary

Summarize 28 talks in 30 minutes!
Copied (and refomatted) figures
All "statements" my personal opinion, nobody else to blame
Apologies for misrepresentations and omissions

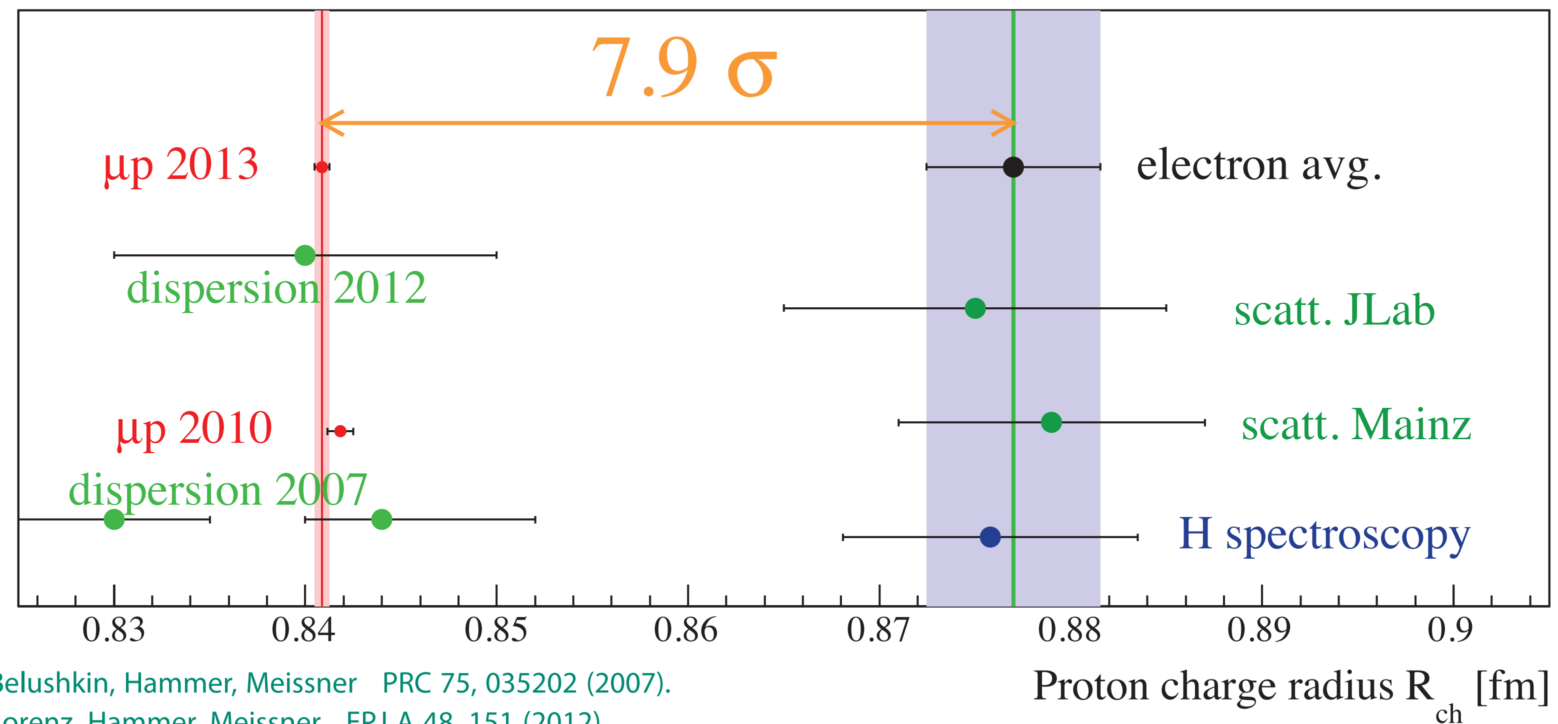
Kees de Jager (JLab (retired)/UVa)
MITP2014
Schloss Waldthausen
June 2 - 6, 2014

# The Proton Radius Puzzle

The proton rms charge radius measured with

electrons: 0.8770 ± 0.0045 fm

muons: 0.8409 ± 0.0004 fm




Belushkin, Hammer, Meissner PRC 75, 035202 (2007).
Lorenz, Hammer, Meissner EPJ A 48, 151 (2012).

- More than 20 papers in three years
- Several review papers
- Dedicated workshops

# Possible Resolutions

$$\tilde{L}^{theo}_{\mu p}(r_p^{CODATA}) - \tilde{L}^{exp.}_{\mu p} = \left\{ \begin{array}{l} 75\ \text{GHz} \\ 0.31\ \text{meV} \\ 0.15\ \% \end{array} \right.$$

$\mu$p theory wrong?

$\mu$p experiment wrong?

H theory wrong?

H experiments wrong? → $R_\infty$ wrong?

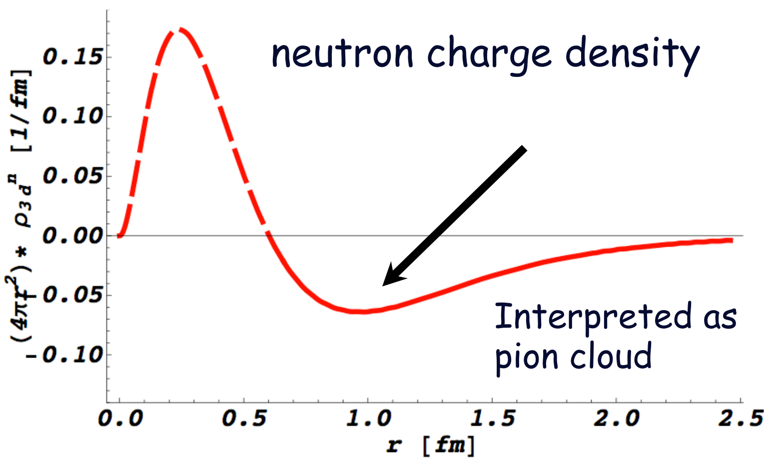
AND e-p scattering exp. wrong?

Standard Model wrong?!?

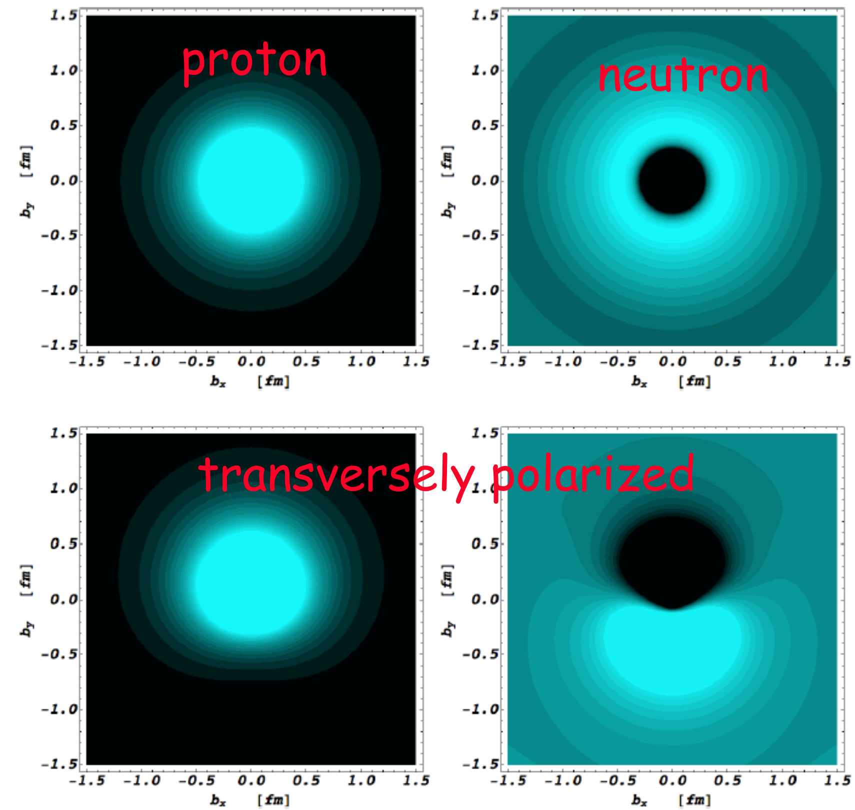
# Visualizing charge and magnetic distributions

Vanderhaeghen and Walcher, Nucl. Phys. News 21 (2011) 14

rest frame




light-front frame




Fourier transforms of nucleon FFs (the neutron pictured above) have provided important insight, but suffer in that the momentum transfers are too large to ignore relativistic effects

While referred to as "charge densities", these cannot be directly related to our usual lab-frame concept of charge density

# Workshop Presentations

→ New Results

News from muonic atoms (Pohl)

Muonic helium (Antognini)

✧ New Analysis

Latest Mainz FF fits (Bernauer)

The shape of Gep data (Griffioen)

Proton radii (Sick)

Model-independent fits (Lee)

Impact of Delta resonance (Lorenz)

Model-independent radii (Paz)

→ Theory

Lattice QCD and nucleon FF (Alexandrou)

Lattice FF activities in Mainz (Thomas Rae)

Polarizability in muonic helium (Nevo Dinur)

Higher-order QED corrections (Jentschura)

Testing exotic explanations (Rislow)

Two-photon exchange effects (Tomalak)

Two-photon exchange effects (Jerry Miller)

Proton polarizabilities contribution (Birse)

Chiral perturbation theory ( Pascalutsa)

Nuclear structure contribution (Gorshteyn)

Atomic spectroscopy (Karshenboim)

→ Future Experiments

FF ratios at low $Q^2$ (Gilman)

1S-3S spectroscopy (Nez)

Atomic Lamb shift (Hessels)

2S-4P atomic hydrogen (Beyer)

The MUSE experiment (Downie)

Electron deuteron scattering (Distler)

The ISR experiment (Mihovilovic)

The PRad experiment (Gao)

TREK (Kohl)

28 exciting talks!!

# Lamb Shifts in Muonic Hydrogen/Helium

Randolf Pohl/Aldo Antognini

# Proton Charge Radius

$$\nu(2S_{1/2}^{F=1} \rightarrow 2P_{3/2}^{F=2}) \quad = \quad 49881.88(76)\ \mathrm{GHz}$$

R. Pohl et al., Nature 466, 213 (2010)

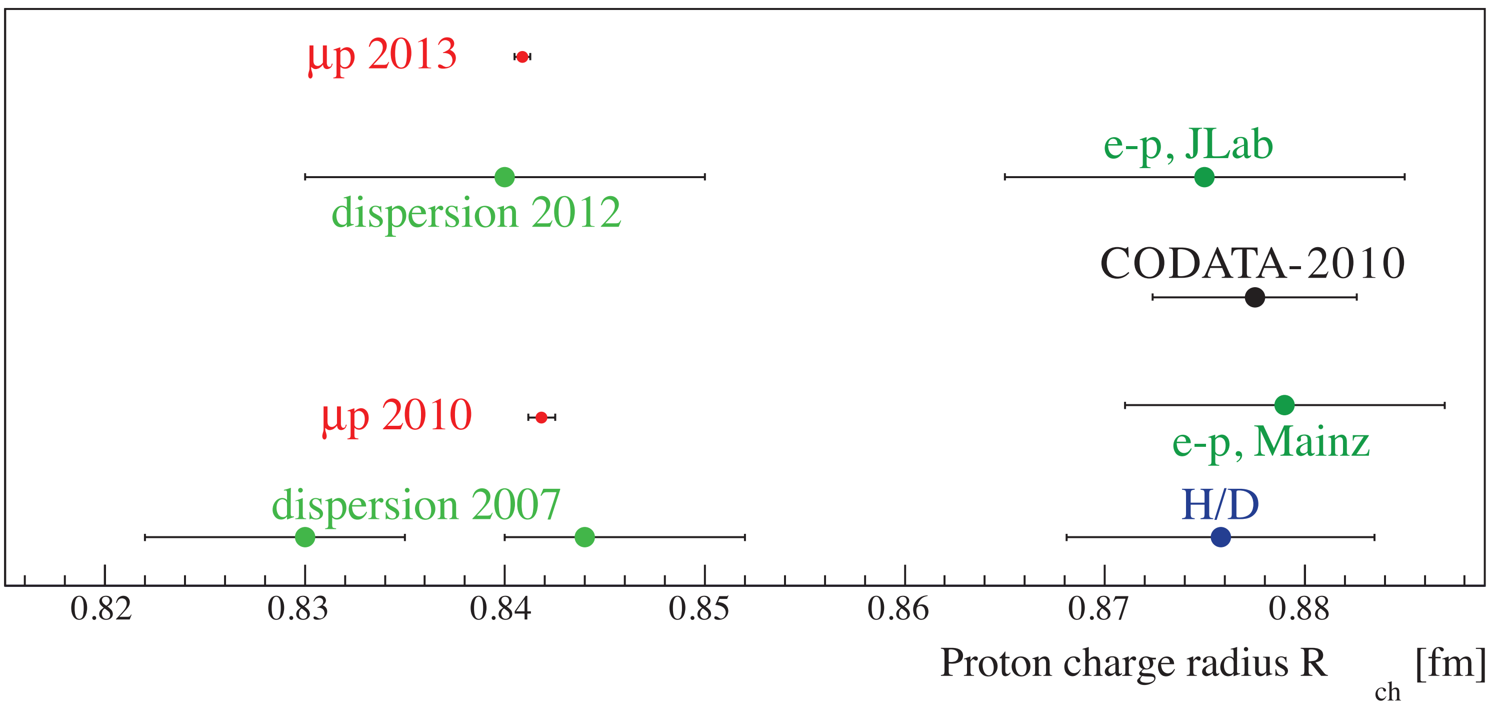
$$49881.35(65)\ \mathrm{GHz}$$

$$\nu(2S_{1/2}^{F=0} \rightarrow 2P_{3/2}^{F=1}) \quad = \quad 54611.16(1.05)\ \mathrm{GHz}$$

A. Antognini, RP et al., Science 339, 417 (2013)

Proton charge radius: $r_p = 0.84087\ (26)_{exp}\ (29)_{th} = 0.84087\ (39)\ \mathrm{fm}$

$\mu p$ theory summary: A. Antognini, RP et al., Ann. Phys. 331, 127 (2013) [arXiv :1208.2637 (atom-ph)]



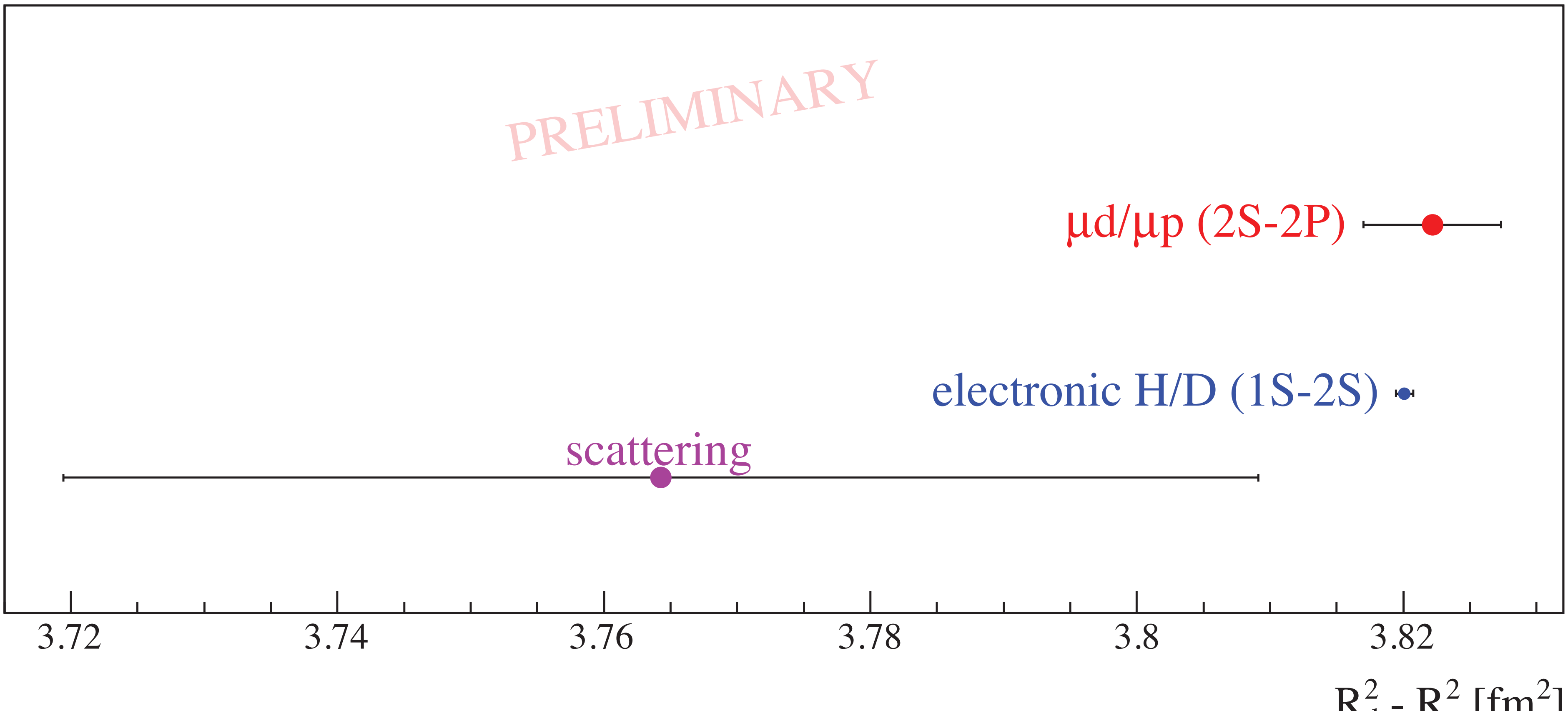
# Proton-Deuteron Isotope Shift

In other words: The muonic isotope shift agrees with the elec tronic one!

$r_d^2 - r_p^2$:

| | | |
|---|---|---|
| H/D isotope shift | $3.82007 \pm 0.00065\,\mathrm{fm}^2$ | |
| muonic Lamb shift | $3.8221 \pm 0.0052\,\mathrm{fm}^2$ | PRELIMINARY! |
| scattering | $3.764 \pm 0.045\,\mathrm{fm}^2$ | |

The muonic error is conservative (nucl. structure terms).



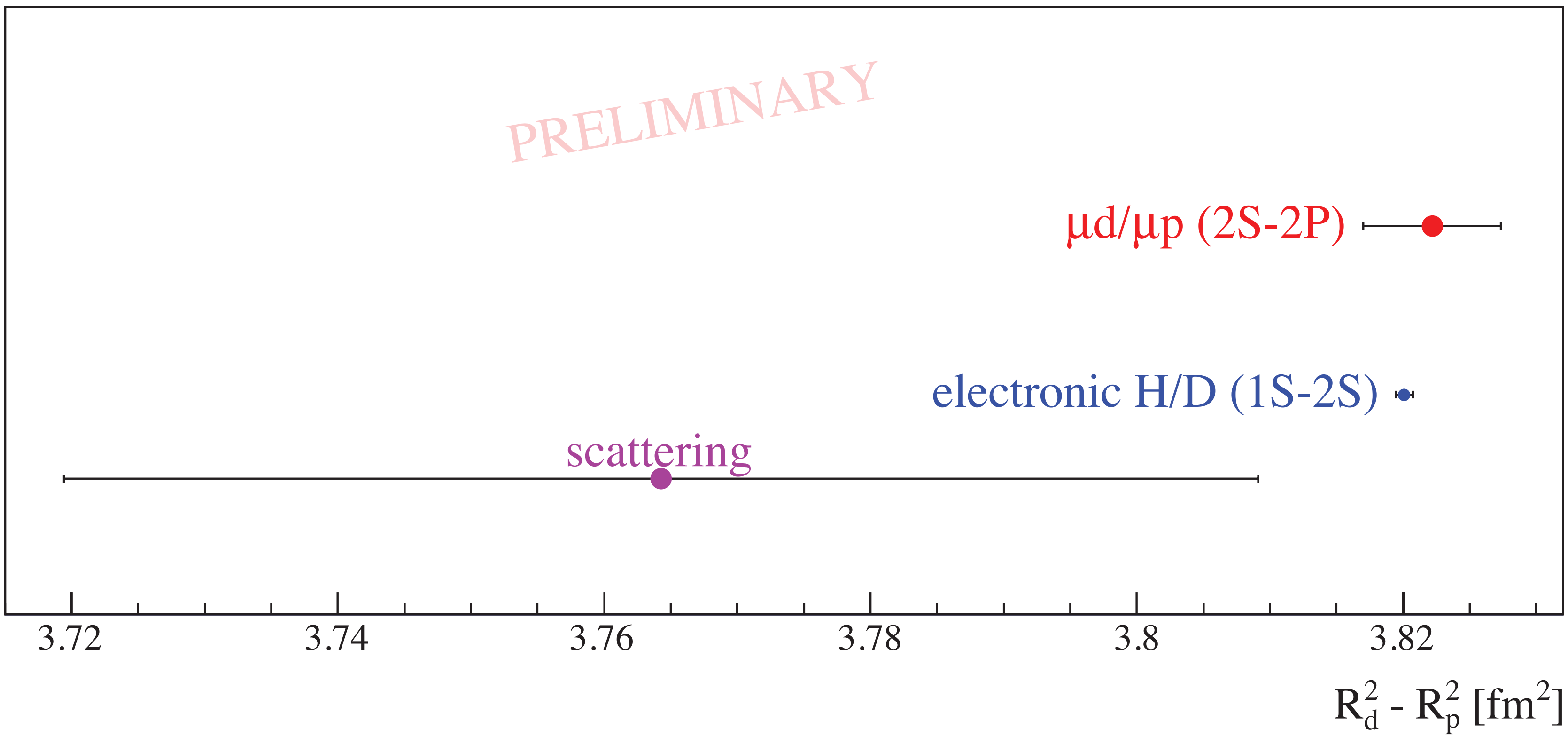
# Deuteron Charge Radius

In other words: The muonic isotope shift agrees with the elec    tronic one!

$r_d^2 - r_p^2$:

| | | |
|---|---|---|
| H/D isotope shift | $3.82007 \pm 0.00065\,fm^2$ | |
| muonic Lamb shift | $3.8221 \pm 0.0052\,fm^2$ | PRELIMINARY! |
| scattering | $3.764 \pm 0.045\,fm^2$ | |

The muonic error is conservative (nucl. structure terms).




EINN 2013

# μp, μd and μHe⁺ exp/theory (Prel !!!)

| *Measurements in muonic atoms* | | |
| --- | --- | --- |
| μp: | $\Delta E_{LS}^{exp} = 202.3706(23)$ meV | |
| μd: | $\Delta E_{LS}^{exp} = 202.8xx(34)$ meV | (preliminary !) |
| $\mu\,^4He^+$ : | $\Delta E_{LS}^{exp} = 1524.xx(8)$ meV | (preliminary !) |

Pachucki, Borie, Eides,
Karshenboim, Jentschura,
Indelicato, Miller, Martynenko,
Carlson, Birse, Gorshteyn, Paz
Hill, Pascalutsa, Pineda, Bacca
Friar, Nir, Pascalutsa...
Einstein, Schrödinger

| *Theory* | | | QED | | Finite size $[R^2]$ | | TPE $[R^3_{(2)}$ + Pol. contr.] |
| --- | --- | --- | --- | --- | --- | --- | --- |
| μp | $\Delta E_{LS}^{th}$ | = | 206.0336(15) | - | $5.2275(10)\ r_p^2$ | + | 0.0332(20) meV |
| μd | $\Delta E_{LS}^{th}$ | = | 228.7972(15) | - | $6.1094(10)\ r_d^2$ | + | 1.6910(160) meV |
| $\mu\,^4He^+$ | $\Delta E_{LS}^{th}$ | = | 1668.598(100) | - | $106.340(xx) r_{He}^2$ | + | $1.40(4) r_{He}^3$ + 2.470(150) meV |

- recoil correction to two-photon with finite size: 0.266 meV (Borie). Is this included already in the TPE?
- intrinsic polarizability of the nucleons has not been yet accounted.
- shape dependence of the finite size corrections.

$r_{He} = 1.681(4)$ fm [Sick]

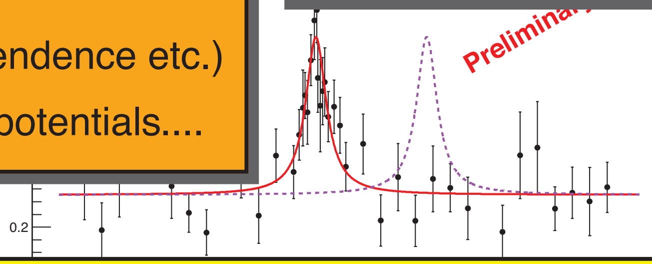
$1\sigma_r$ $\Delta E_{LS}^{th}$ changes by 1.4 meV

# Antognini's Secret(!!) Results

We have measured the $2S_{1/2} - 2P_{3/2}$ transition in $\mu\,^4He^+$ with $u_r = 5 \times 10^{-5}$.

- extract $^4He$ charge radius with $u_r = 3 \times 10^{-4}$
- agreement with the e-scattering value ($u_r = 2 \times 10^{-3}$)
- important information for the proton puzzle (spin-, isospin-dependence etc.)
- interesting information for few-nucleons theory, to disentangle potentials....

2S-2P th. is converging.




| | |
|---|---|
| Statistical accuracy of $\mu\,He^+$ meas. | 20 GHz |
| Systematics | <0.1 GHz |
| Natural linewidth | 320 GHz |
| Uncertainty third Zemach | 50 GHz |
| Uncertainty nucl. pol. | 36 GHz |

i.e., within the uncert. given by $r_{He}$ from e– He scatt

New physics model of Pospelov excluded

Missing:

- Intrinsic nucleon polarizability for $\mu\,He^+$
- Charge distribution dependence of theory?
- Polarizability contr. to Lamb shift for $\mu\,^3He^+$
- Polarizability contr. to HFS for $\mu\,^3He^+$ and $\mu d$

- Would be interesting to have a determinations of the He charge radius from few-nucleon th.
- Would be interesting to have calculations of polarizability using He breakup data
- Would be interesting to have a better $^3He$ charge radius from scattering.
- Would be advantageous/possible in e-scattering to measure cross sections ratio of H/He?

[Sick]
[Sick]
[$\mu\,He^+$]
[$\mu\,He^+$]

# Various Analyses
# Elastic Electron Scattering

Jan Bernauer

Keith Griffioen

Ingo Sick

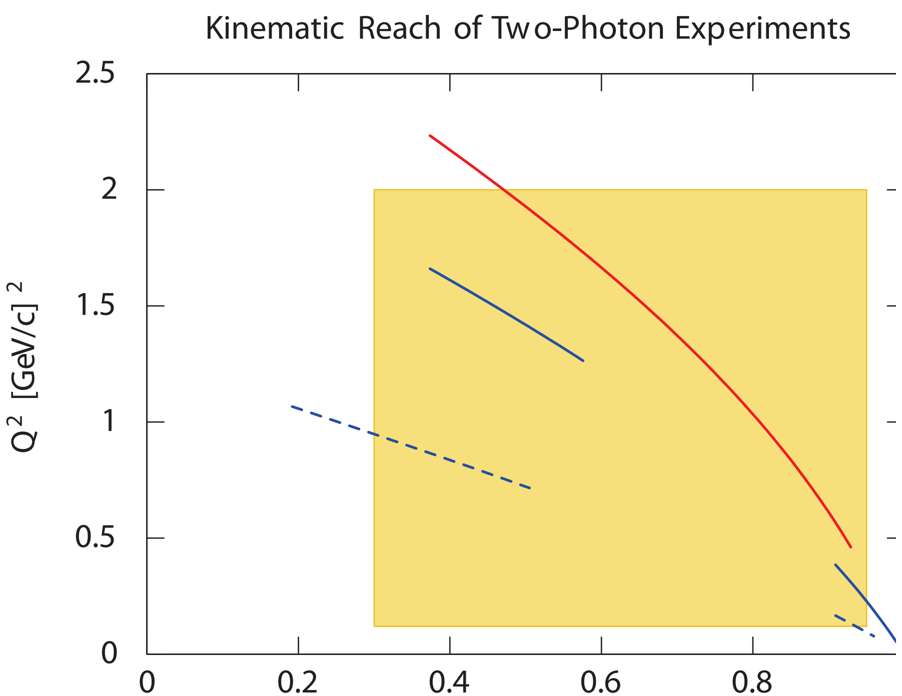
Gabriel Lee

Ina Lorenz

Gil Paz

# Comparison of TPE experiments

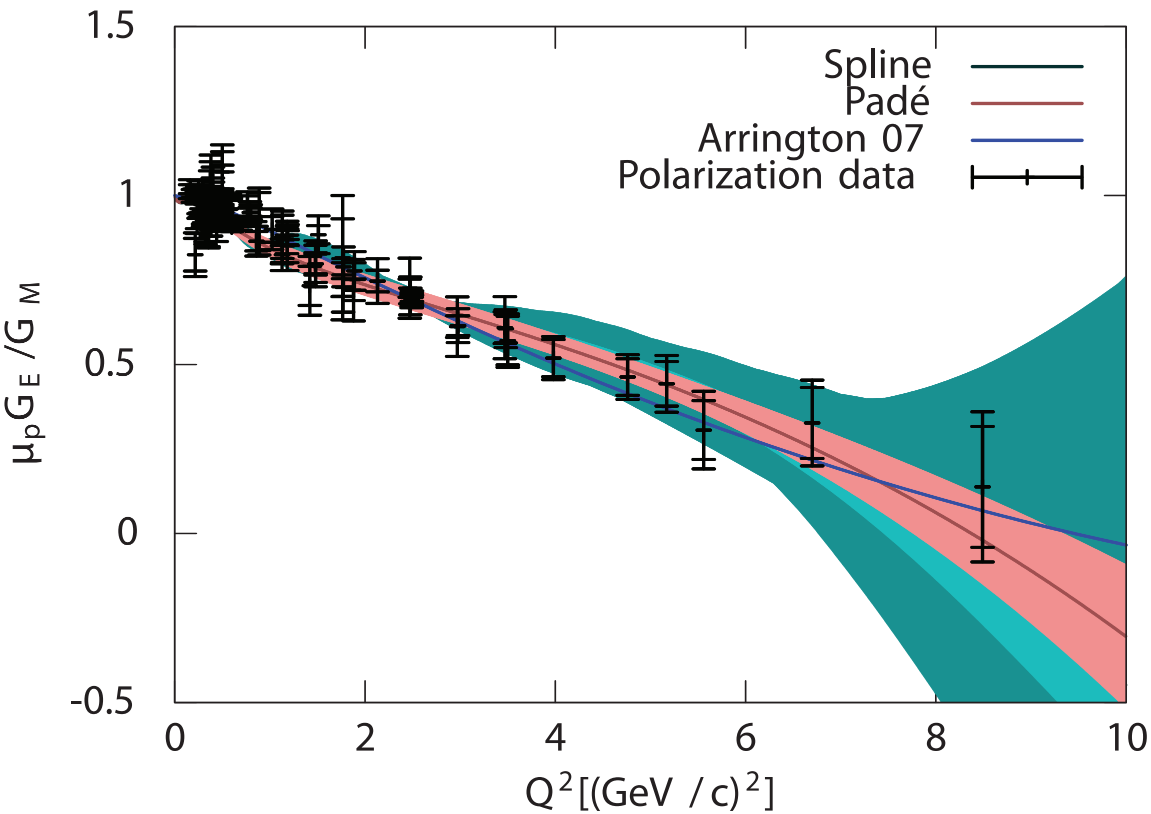
- CLAS
  - $e^-$ to γ to $e^{+/-}$ -beam
- VEPP-3
  - 1.6/1 GeV beam
  - no field
  - preliminar y results
- OLYMPUS
  - DORI S @ DESY
  - 2 GeV beam
  - data taking finished 01/2013
  - no results ye t :(




- OLYMPUS analysis ongoing, preliminary results by late 2014
- Preliminary results from VEPP-3 and JLab + Mainz fit indicate effect is of right magnitude.

# $G_E/G_M$ fit incl. polarization data

- Take cross sections from all Rosenbluth experiments
- Update / standardize radiative corrections
- One normalization parameter per source (Andivahis: 2)
- Include simple parametrization for TPE: $\delta = a \cdot (1 - \varepsilon) \cdot \log(1 + b \cdot Q^2)$




J.C. Bernauer et al., arXiv:1307.6227

# Electric and magnetic radius from both fits

## Final result from flexible models

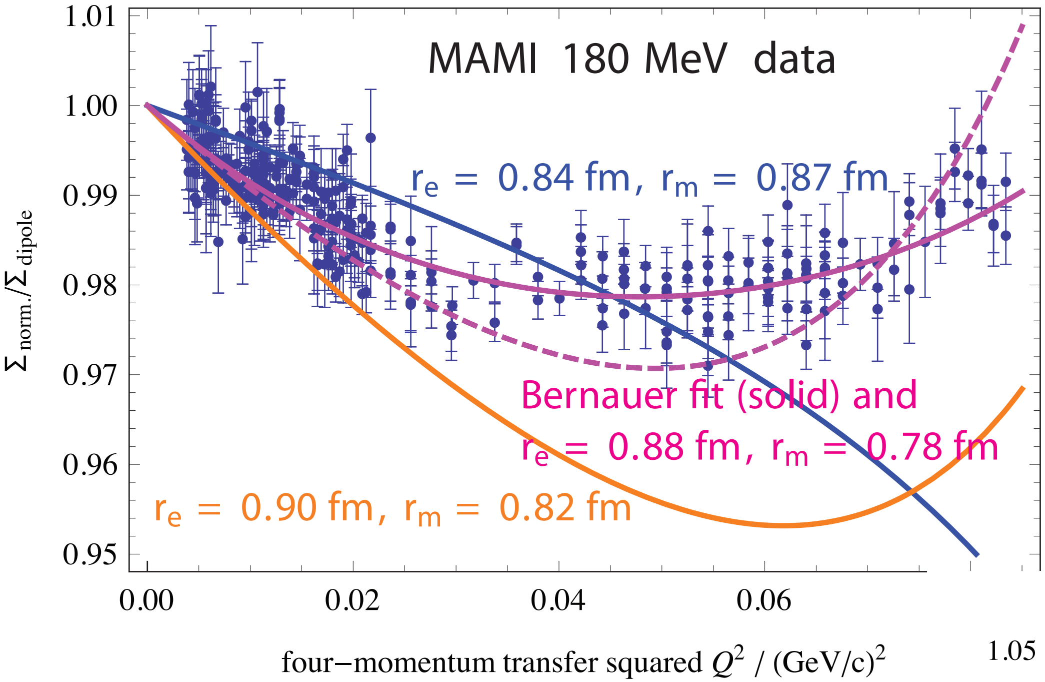
$$\langle r_E^2 \rangle^{\frac{1}{2}} = 0.879 \pm 0.005_{\text{stat.}} \pm 0.004_{\text{syst.}} \pm 0.002_{\text{model}} \pm 0.004_{\text{group}} \text{ fm},$$

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

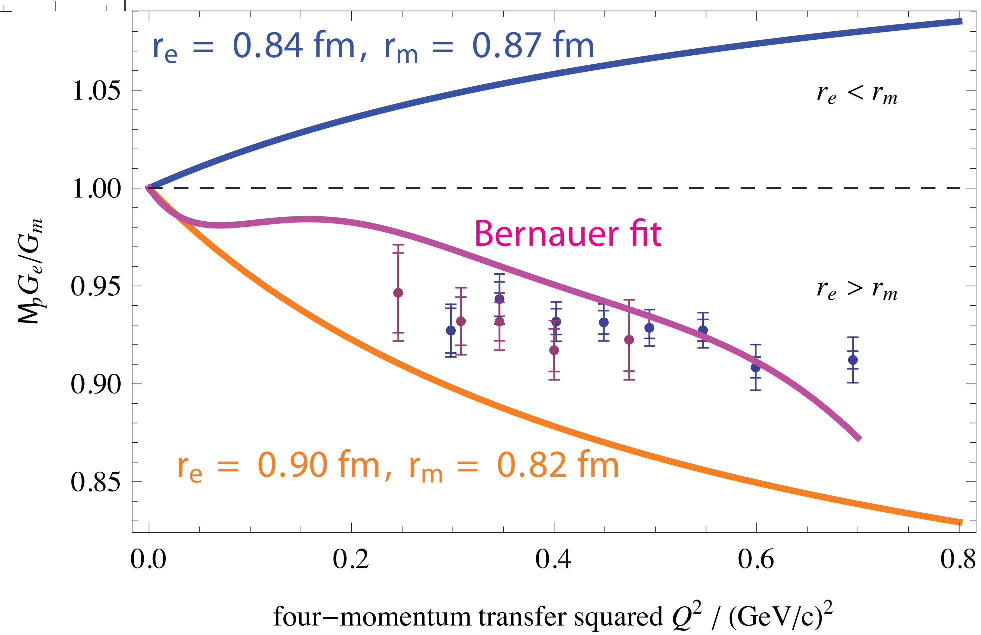
## Results with world data

| | $\langle r_E^2 \rangle^{\frac{1}{2}}$ | $\langle r_M^2 \rangle^{\frac{1}{2}}$ |
|---|---|---|
| + Rosenbluth data | 0.878 | 0.772 |
| +Rosenbluth and Polarization data | 0.878 | 0.769 |

# Effect of Proton structure from muonic hydrogen

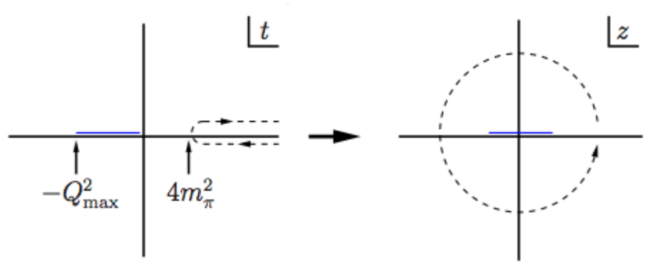



Separate dipole functions for $G_E$ and $G_M$



# Conformal Mapping

$$z(t, t_{\rm cut}, t_0) = \frac{\sqrt{t_{\rm cut} - t} - \sqrt{t_{\rm cut} - t_0}}{\sqrt{t_{\rm cut} - t} + \sqrt{t_{\rm cut} - t_0}}$$



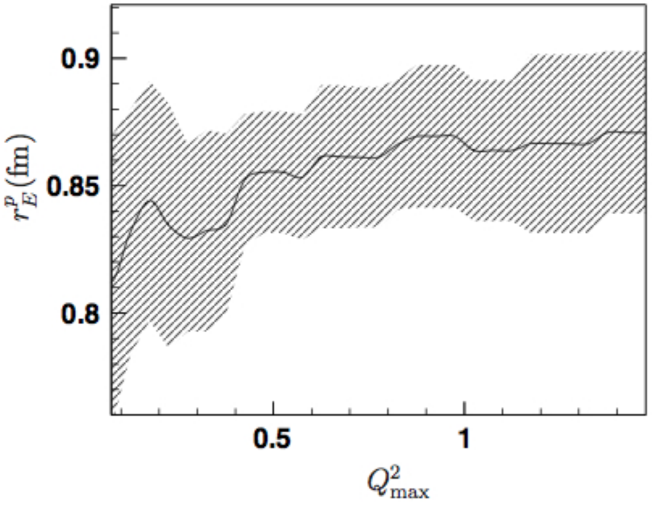

- Analytic structure implies:
  Information about $\mathrm{Im}\, G_E^p(t + i0) \Rightarrow$ information about $a_k$
- $G(t) = \sum_{k=0}^{\infty} a_k\, z(t)^k$, $z^k$ are orthogonal over $|z| = 1$

$$\begin{aligned} a_0 &= G(t_0) \\ a_k &= \frac{2}{\pi}\int_{t_{\rm cut}}^{\infty} \frac{dt}{t - t_0}\sqrt{\frac{t_{\rm cut} - t_0}{t - t_{\rm cut}}}\, \mathrm{Im}\, G(t) \sin[k\theta(t)]\,, \quad k \geq 1 \\ \sum_k a_k^2 &= \frac{1}{\pi}\int_{t_{\rm cut}}^{\infty} \frac{dt}{t - t_0}\sqrt{\frac{t_{\rm cut} - t_0}{t - t_{\rm cut}}}\, |G|^2 \end{aligned}$$

- How to constrain $\mathrm{Im}\, G(t)$?

# Results from Paz

- Use data from Arrington (PRC 76, 035205 (2007))
- $k_{max}$ = 10, $t_0$ = 0, $|a_k|$ < 10
- Beyond $Q^2_{max}$ > 0.5 GeV$^2$ impact of additional data minimal
- For $Q^2_{max}$ = 0.5 GeV$^2$ $r^p_E$ = 0.870 ± 0.023 ± 0.012 fm
- Large error bars!
- If neutron data and ππ continuum included
  $r^p_E$ = 0.871 ± 0.009 ± 0.002 fm

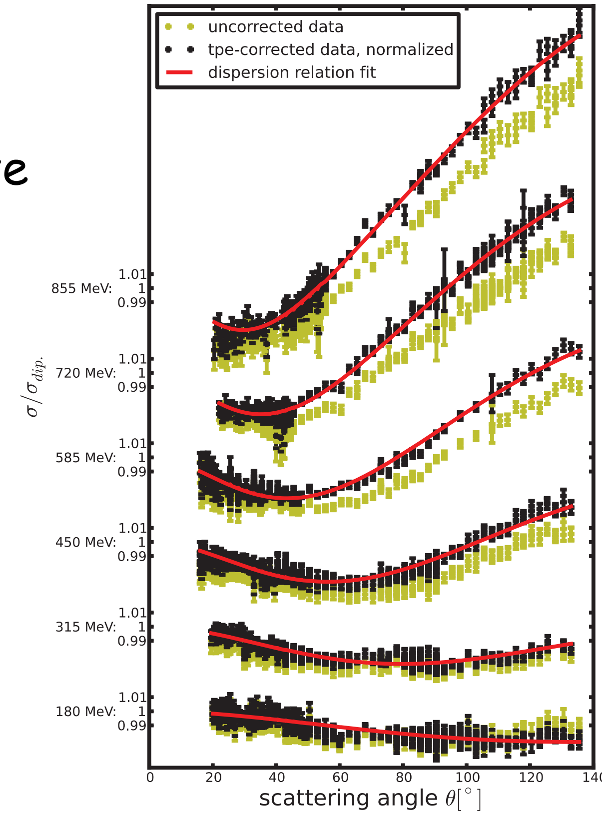



No fit to Mainz data yet!

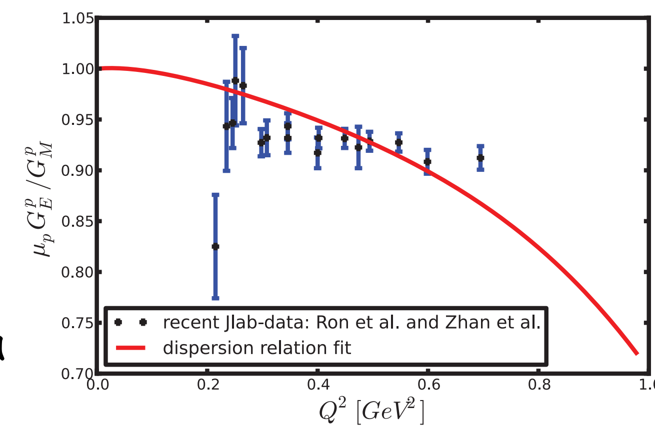
# Results from Lorenz

- Conformal-mapping fit to Mainz data
- No constraint on $a_k$
- Including own TPE corrections with Δ as intermediate
- Initial fit with just analyticity constraint:

| $k_{max}$ | $\chi^2$ | $r^P_E$ [fm] |
|---|---|---|
| 5 | 1.230 | 0.892 |
| 6 | 1.137 | 0.868 |
| 7 | 1.126 | 0.867 |
| 8 | 1.122 | 0.876 |
| 9 | 1.114 | 0.849 |
| 10 | 1.115 | 0.843 |

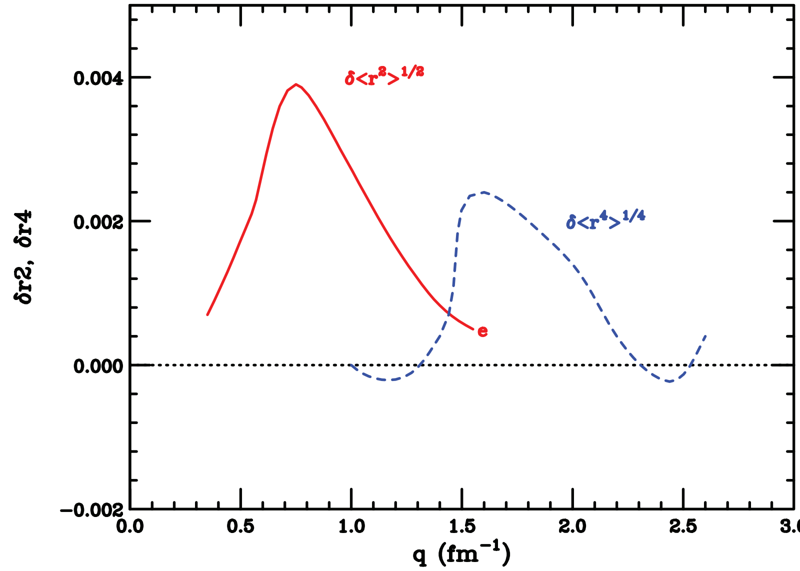



- Very strange $r^p_E$ behaviour with $\chi^2$
- Then introduce unitarity (ππ continuum +……)
- Increases impact on normalization (????)
  AND increases $\chi^2$ to 1.4 per d.o.f.
  $r^p_E = 0.840 \pm 0.013$
- Reasonable agreement with JLab polarization data

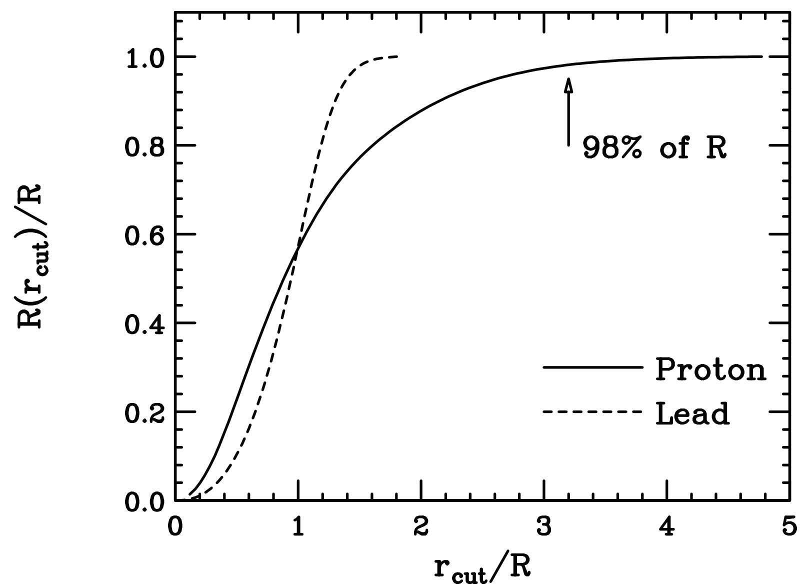


# Ingo's caveats

- Important consideration
  q-region sensitive to rms-radii
  $0.01 < Q^2 < 0.06\ GeV^2$
- Data above $Q^2 \sim 0.06$ not relevant for R!




- to get 98% of rms-radius R must integrate out to $r \sim 3.2 \times R \sim 3fm$
- $\Rightarrow$ R sensitive to very large r where $\rho(r)$ poorly determined
- large r behaviour affects G(q) at very low q, below $q_{min}$
- constrain $\rho(r \gg)$ using physical model, for r where $\rho(r) < 0.01\ \rho(0)$
- fall-off of $\rho$ given by least-bound Fock component of proton = $n + \pi+$



# Theory

## Lattice
- Lattice QCD and nucleon FF (Alexandrou)
- Lattice FF activities in Mainz (Thomas Rae)

## Electron Scattering
- Two-photon exchange effects (Tomalak)

## Muonic Lamb Shift
- Polarizability in muonic helium (Nevo Dinur)
- Proton polarizabilities contribution (Birse)
- Chiral perturbation theory (Pascalutsa)
- Nuclear structure contribution (Gorshteyn)

## Atomic Spectroscopy
- Atomic spectroscopy (Karshenboim)

## BeyondSM
- Higher-order QED corrections (Jentschura)
- Two-photon exchange effects (Jerry Miller)
- Testing exotic explanations (Rislow)

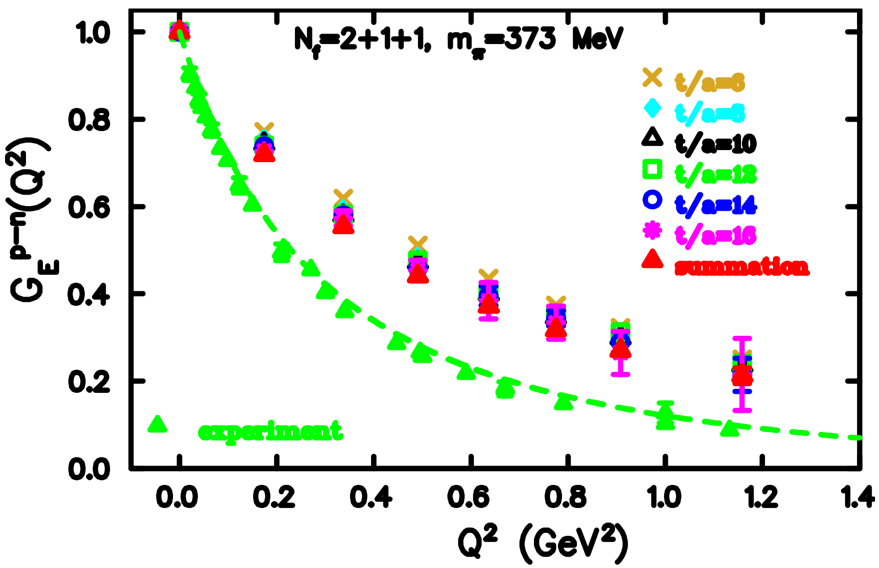
# Simplistic summary of theoretical efforts

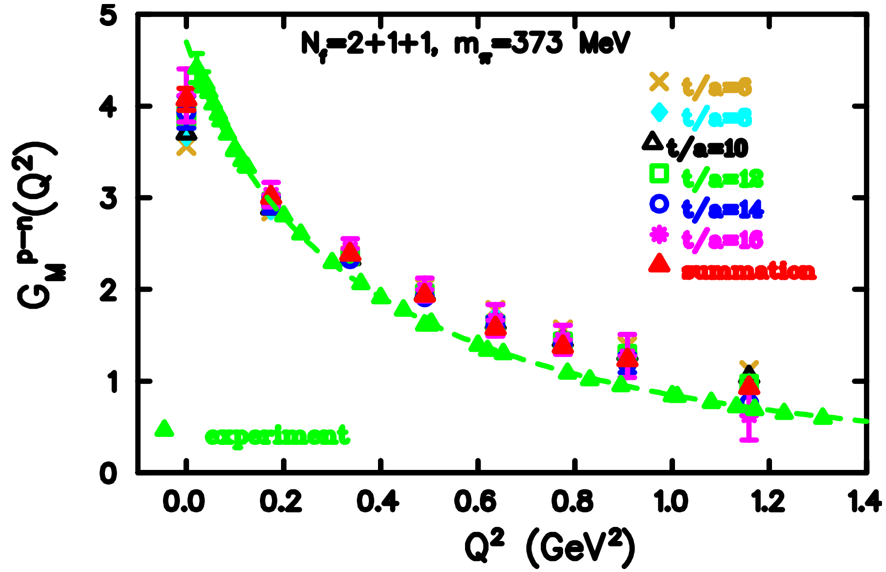
- TPE corrections starting to reach decent accuracy (Tomalak, Gorshteyn), need to be included in accurate charge radius determination
- Nuclear polarization corrections (Dinur, Birse, Pascalutsa, Gorshteyn) for muonic Lamb shift under detailed study, proton radius fully under control, deuteron needs further study AND experimental data
- Accurate determination of proton charge and magnetic radius from atomic spectroscopy (Karshenboim)
- Only very slim window left open for BSM solutions to proton radius puzzle (Rislow, Jentschura, Miller)

# LQCD Isovector EMFF (Alexandrou)

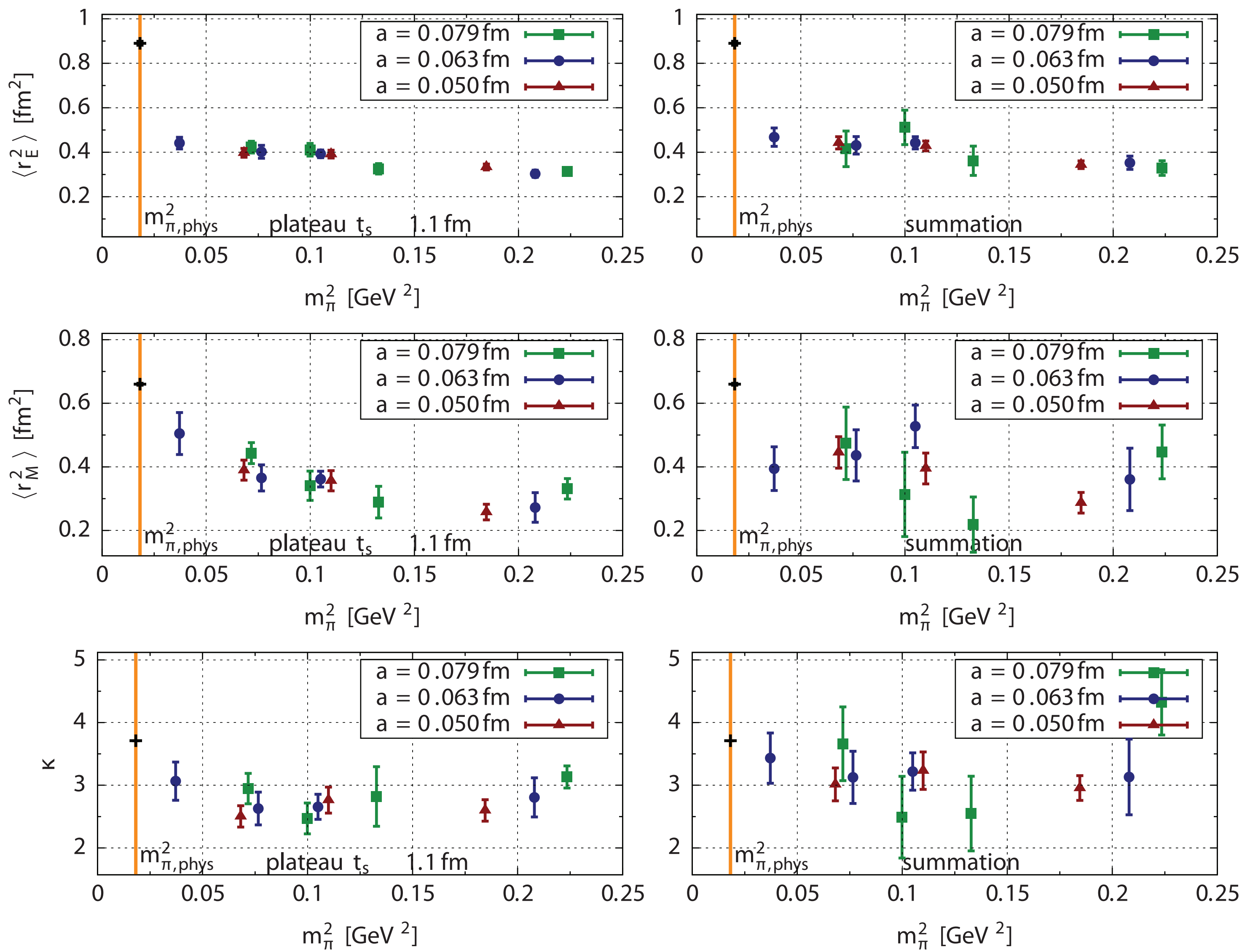
$N_f = 2 + 1 + 1$ twisted mass, $a = 0.082$ fm, $m_\pi = 373$ MeV

Connected → isovector: ~ 1200 statistics



# LQCD Chiral Extrapolations (Rae)



# New Experiments

## Atomic spectroscopy

1S-3S spectroscopy (Nez)

Atomic Lamb shift (Hessels)

2S-4P atomic hydrogen (Beyer)

## Electron scattering

Electron deuteron scattering (Distler)

The ISR experiment (Mihovilovic)

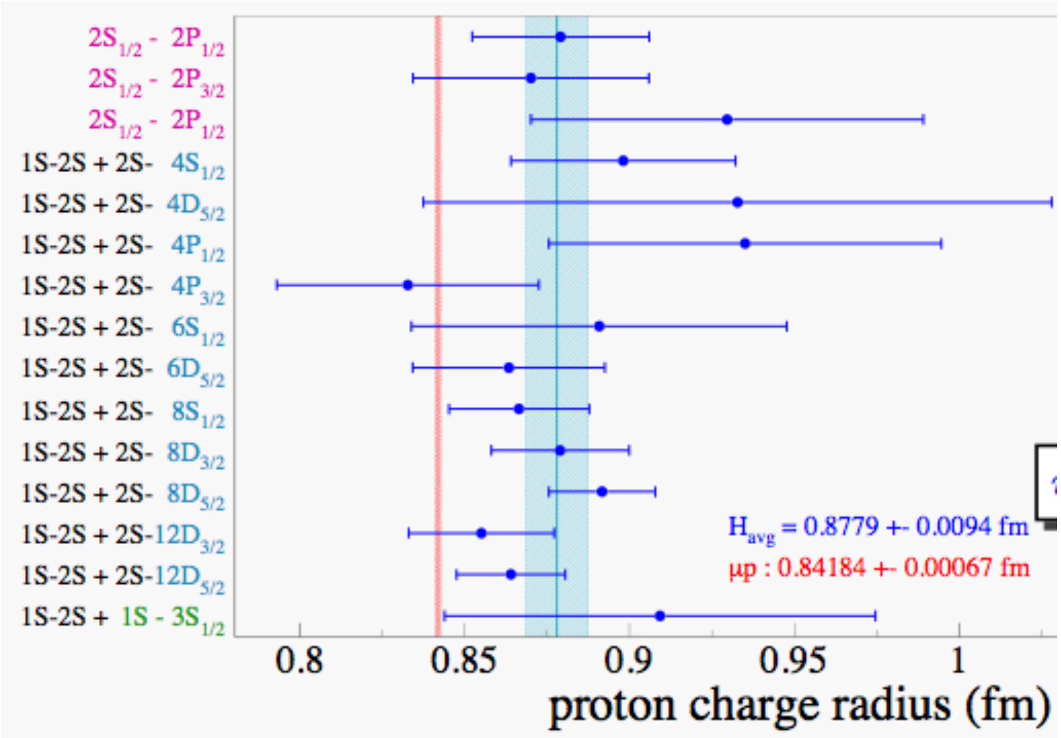
The PRad experiment (Gao)

The MUSE experiment (Downie)

## Other

TREK (Kohl)

# Radius from atomic energy splitting

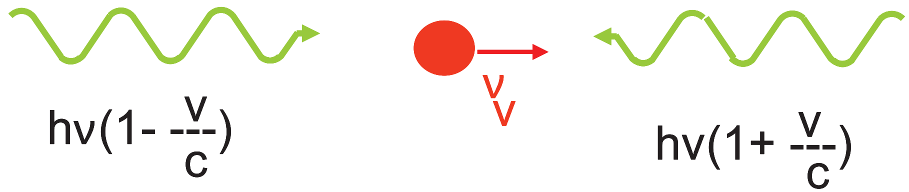


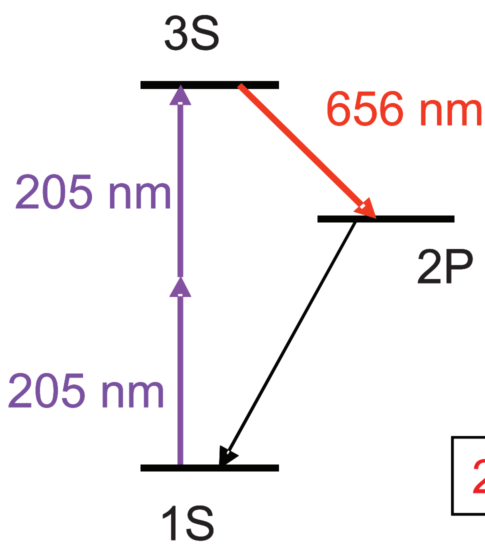

- < 1% error estimate comes from average of 15 measurements
- No specific problems known
- However, large advances in instrumentation allow new measurements with an individual error better than that of the present average
- Need to correct for QM interference from lines 100σ away!

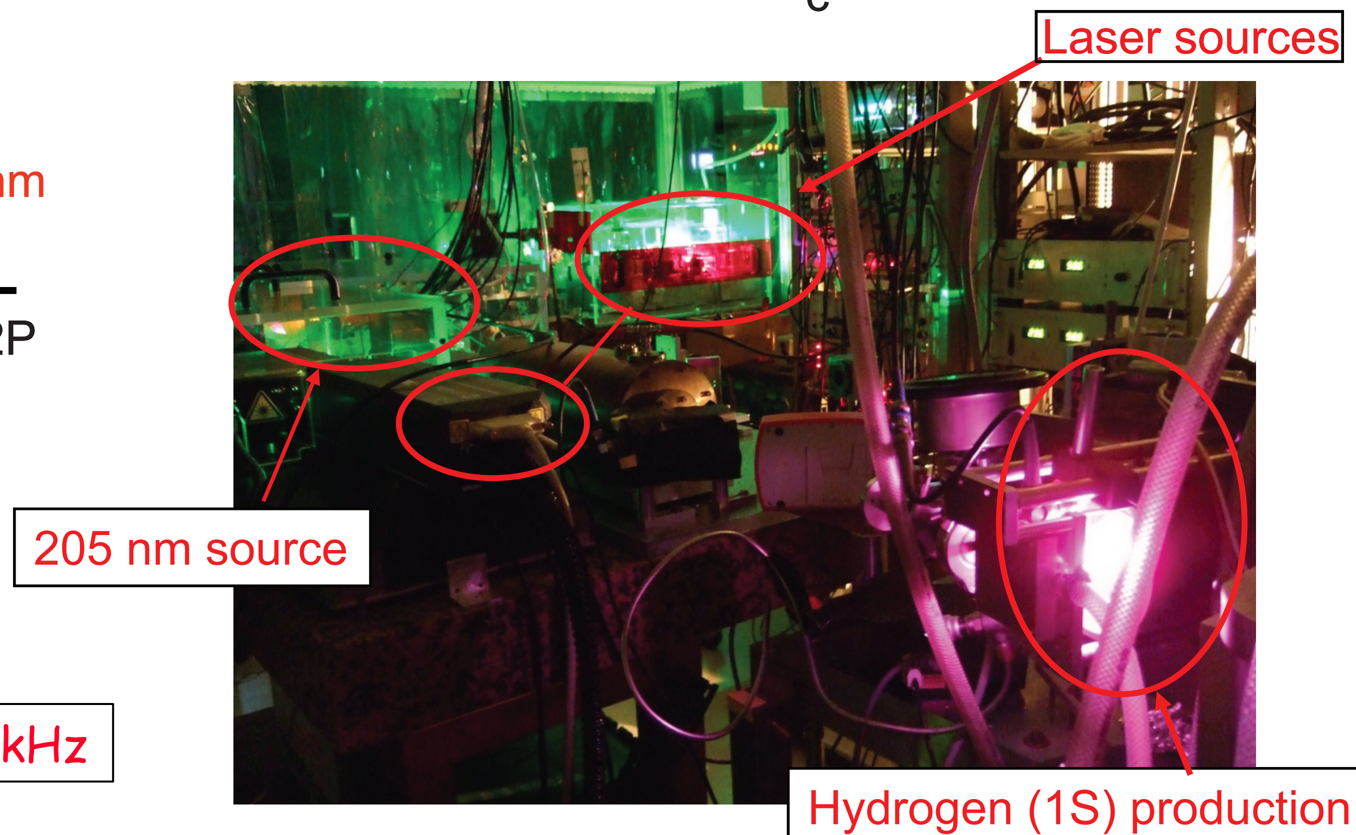
# 1S-3S spectroscopy of hydrogen

F. Nez

## Two photon spectroscopy : first order Doppler effect compensation



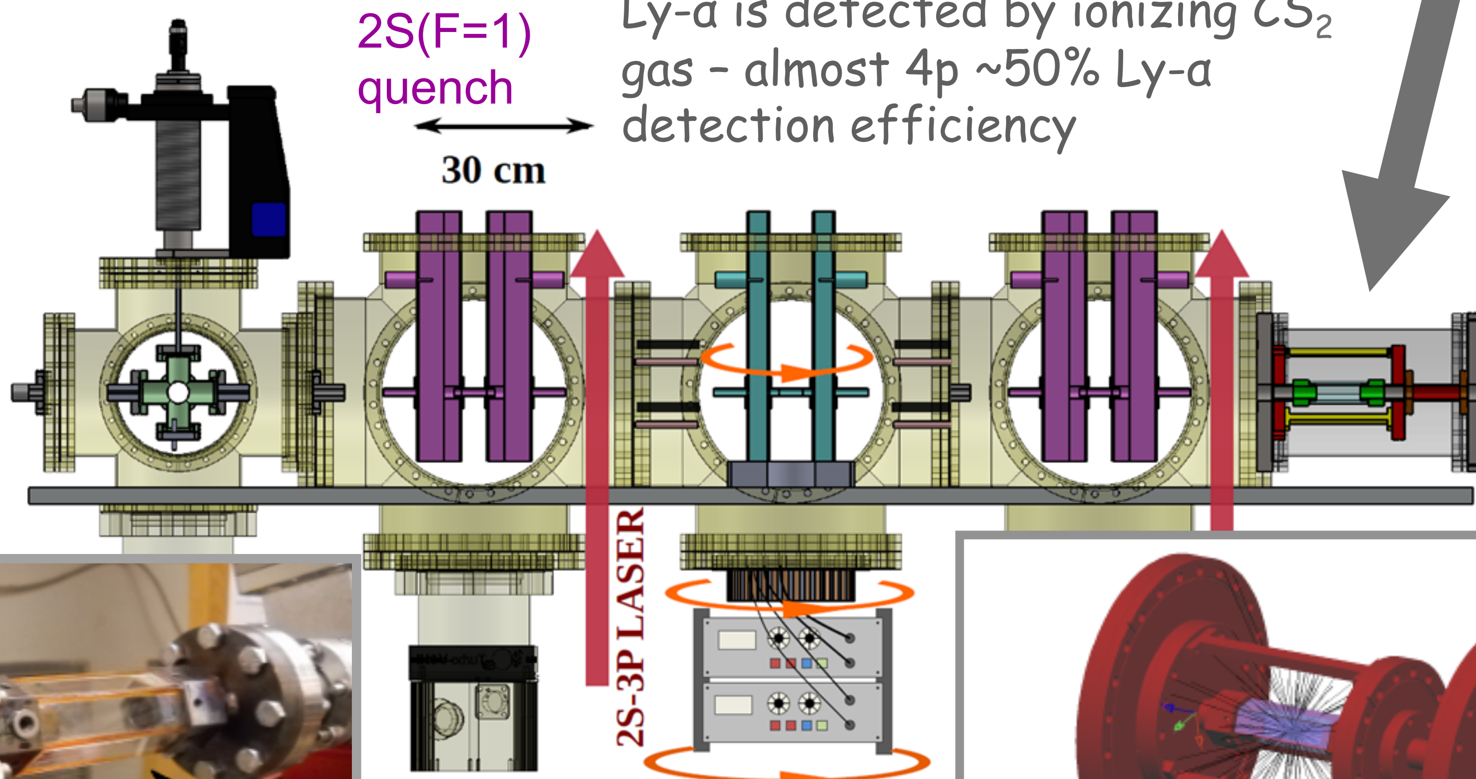



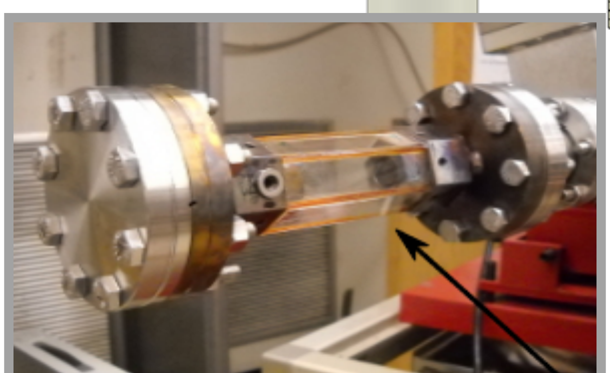

Accuracy aimed at: 7 kHz

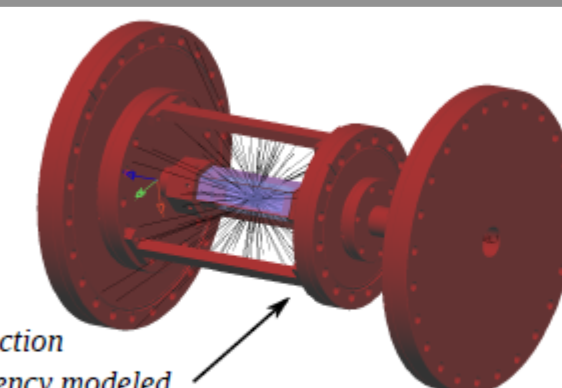

# Hessels
# Lamb shift in atomic hydrogen

We detect the 2S atoms that remain by mixing 2S with 2P with a DC electric field and resulting Ly-a is detected by ionizing $CS_2$ gas – almost 4p ~50% Ly-a detection efficiency

10 μA
50-keV to
100-keV
protons



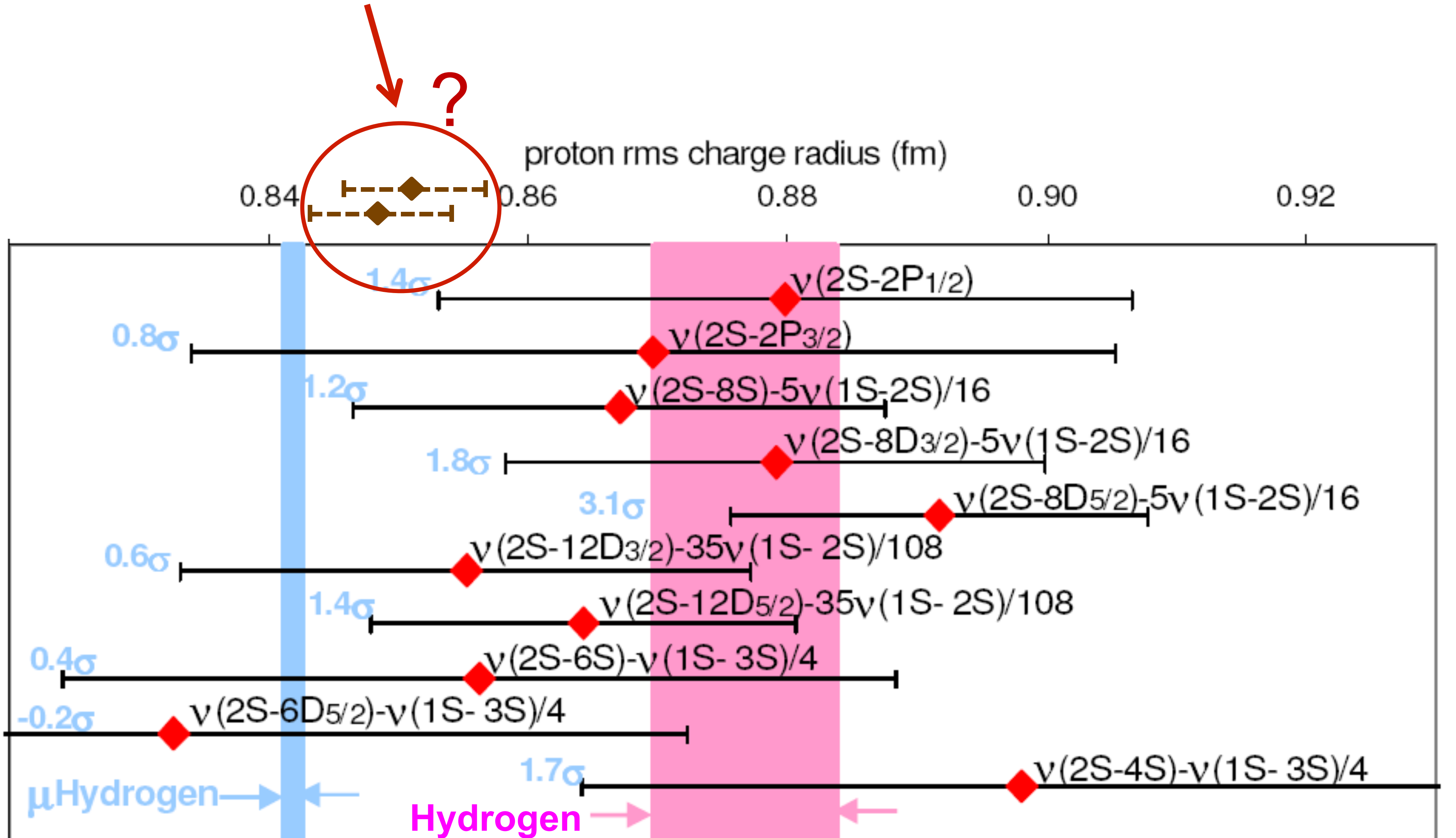


*Collection efficiency modeled with ray-tracing software (LightTools)*

# 2S-2P in atomic hydrogen

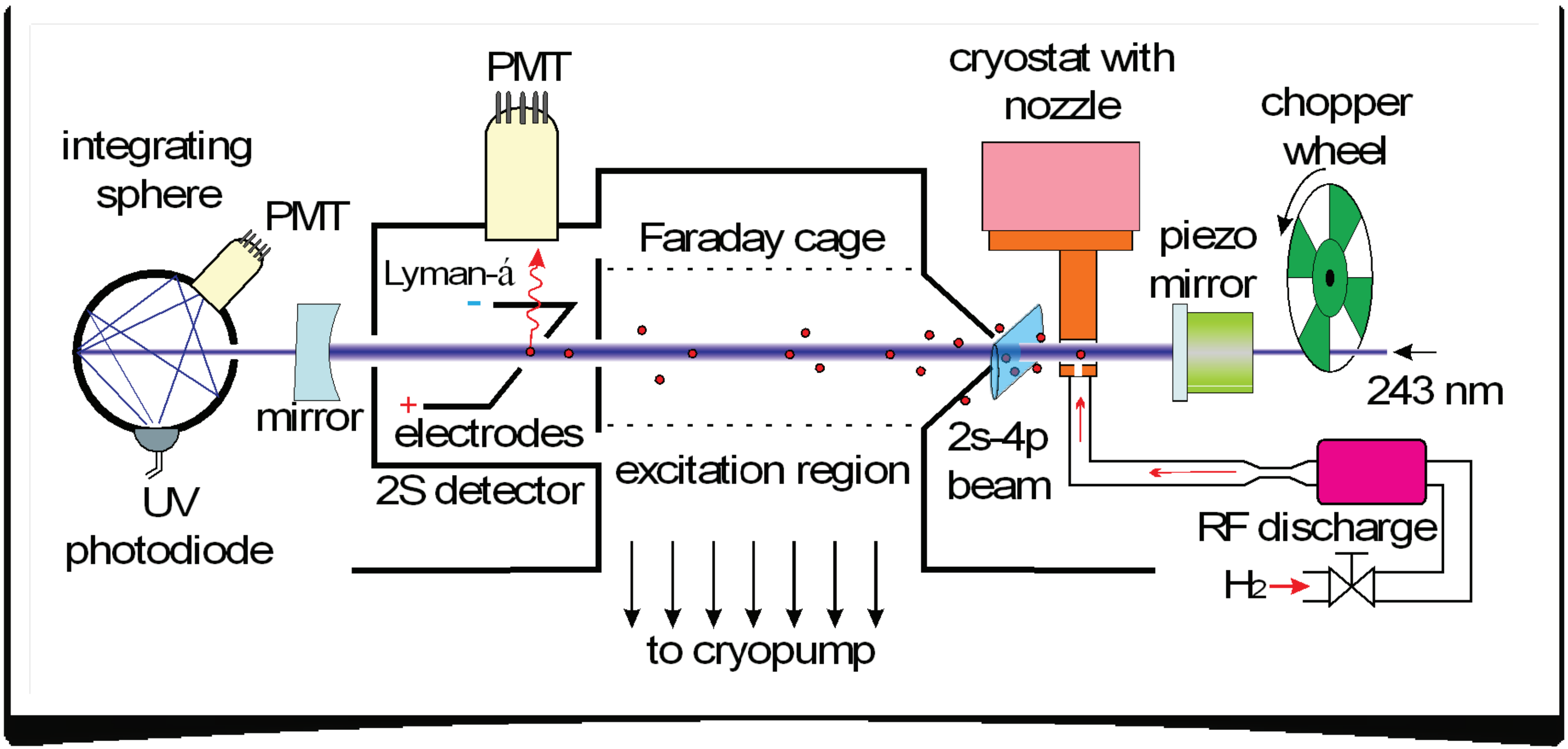
Our (eventual) aim is an accuracy of 2 kHz for each fo the 2S-2P intervals,

which would provide two new measurements of the proton radius with uncertainties indicated



# Hydrogen 2S-4P

Beyer

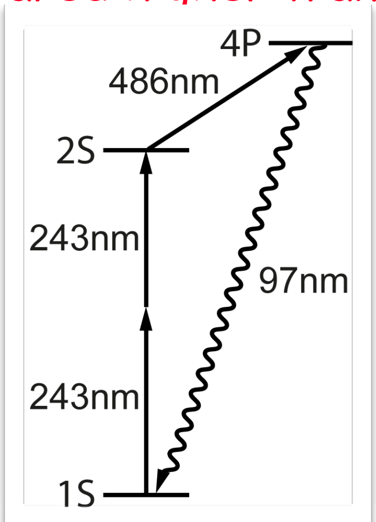


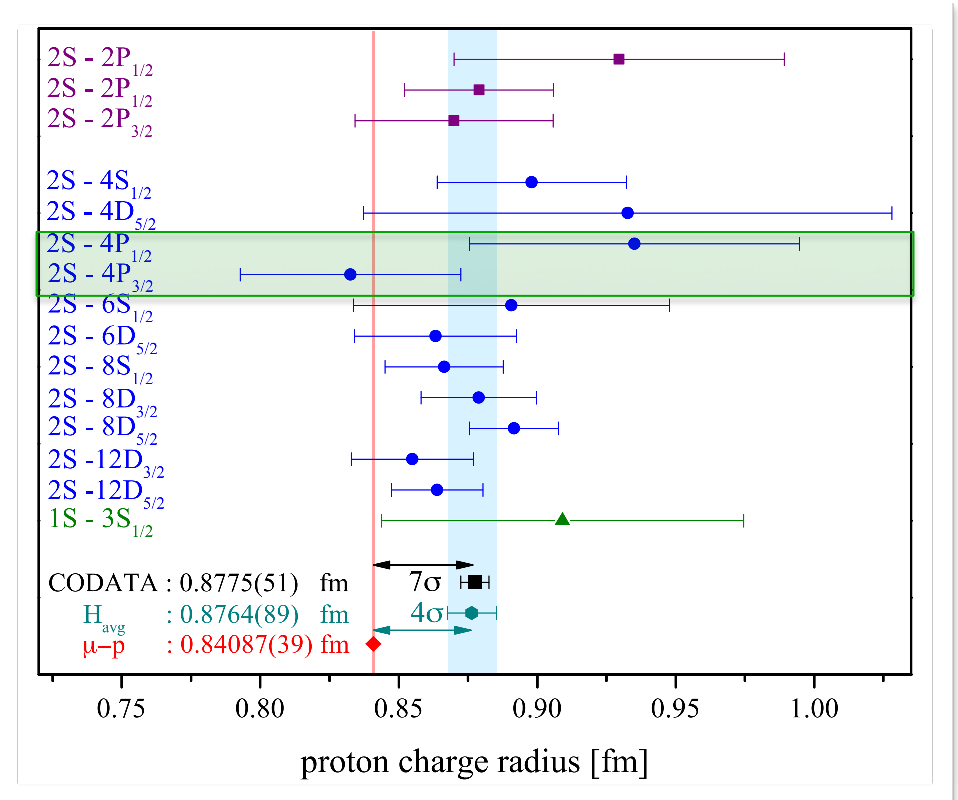

C.G. Parthey et al., Phys. Rev. Lett. **107**, 203001 (2011)

# Hydrogen 2S-4P

2S-4P transition:

- one photon transition
  - ➢ low power required
  - ➢ need to deal with 1st and 2nd order Doppler Shift
- small principal quantum number *n*:
  - ➢ natural line width 13 MHz
  - ➢ DC Stark effect small compared higher transitions




difference in 2S-4P transition frequency using $r_p$ from μ-p or H: only about 8.9kHz

# Beyer Summary

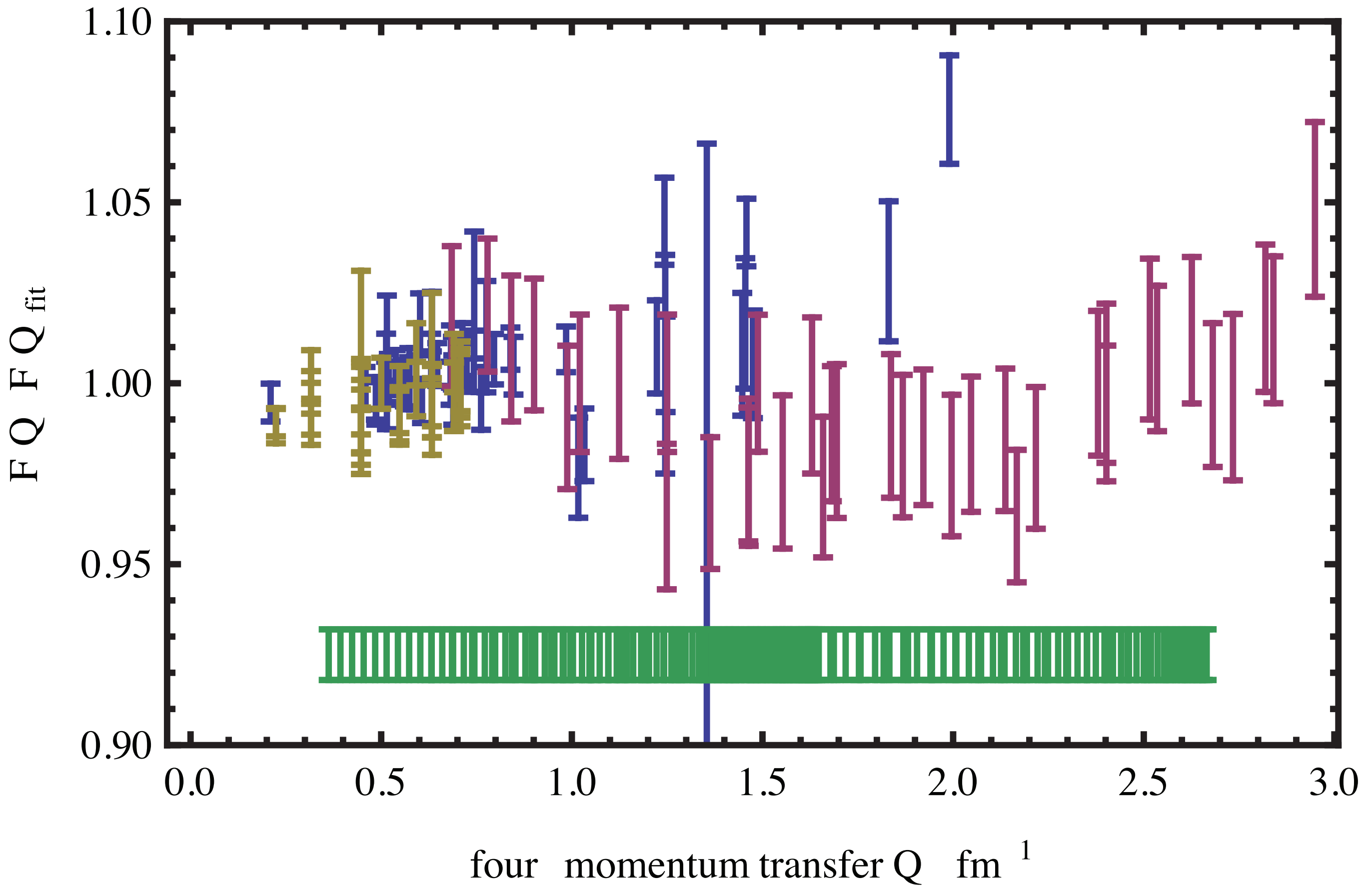
- Precision spectroscopy of the 2S-4P transition on a cryogenic beam of optically excited 2S atoms
  - $2S\text{-}4P_{1/2}$ and $2S\text{-}4P_{3/2}$
  - 1.8 kHz uncertainty for $2S\text{-}4P_{1/2}$ (statistics and FOD)
- good statistics essential to identify systematic effects on the order of the discrepancy between H and μp
- interference effect seems to be crucial for our contribution to the proton size puzzle

What's next?

- further improve statistics by direct measurement of FOD
- characterization of interference effect in new detector configuration (exp. & theo.)
- characterization of the DC Stark effect by 2S-6P spectroscopy
- new measurements of the $2S\text{-}4P_{1/2}$ and $2S\text{-}4P_{3/2}$ transition frequency with upgraded system
- apply experimental scheme to higher 2S-*n*P transitions ($n$ = 6, 8, 9,10)

# Measurement of $A(Q^2)$ at very low $Q^2$

D(e,e')D

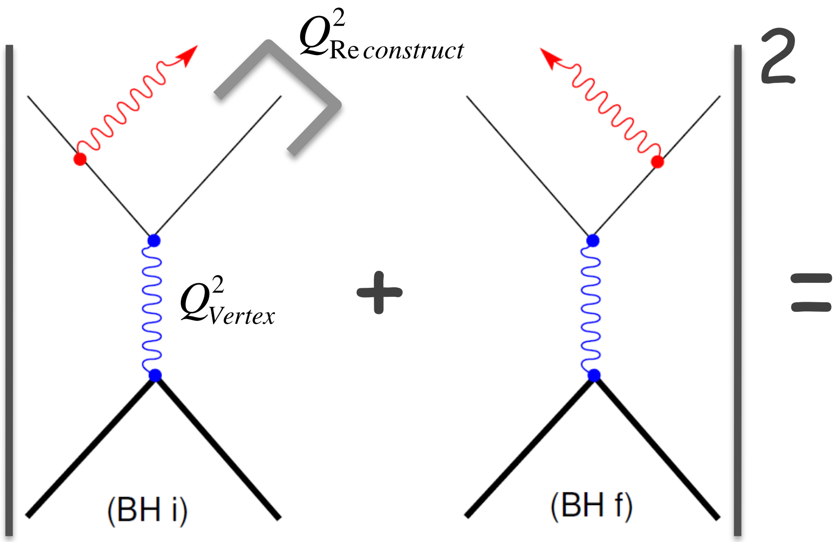


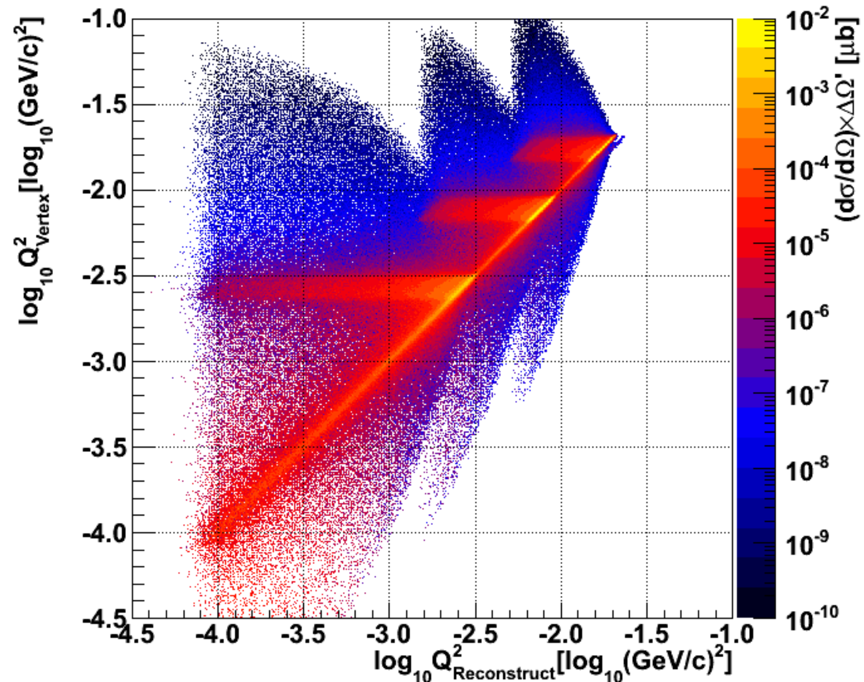

Berard (1973) , Simon (1981) , Platchkov (1990) , MAMI

Data collected (elastic and quasi-elastic)
Objective: to at least half the present error on $r^d_E$

# Initial State Radiation

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



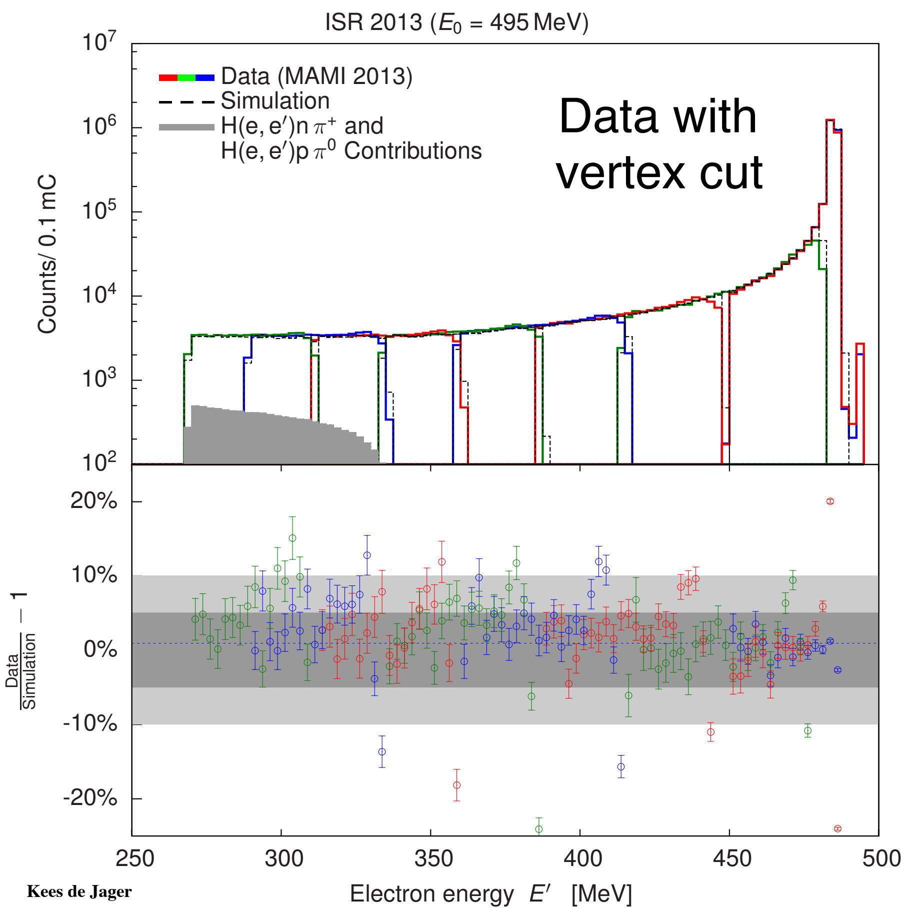

- In data ISR can not be distinguished from FSR.

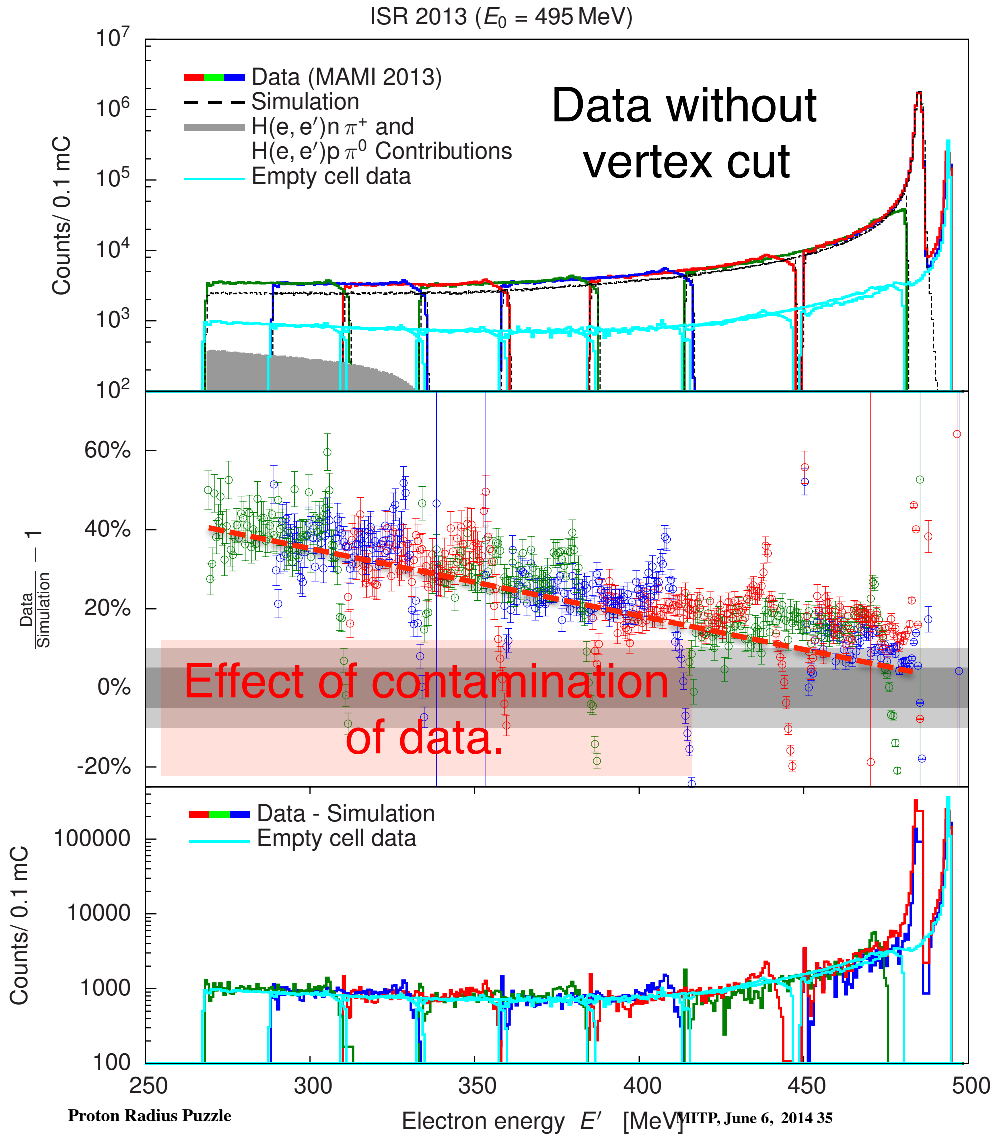
- **Combining data to the Simulation, ISR information can be reached**.

➞ Cover $Q^2$-range 0.00015 -0.02 $GeV^2$

# Subtraction of the cell walls

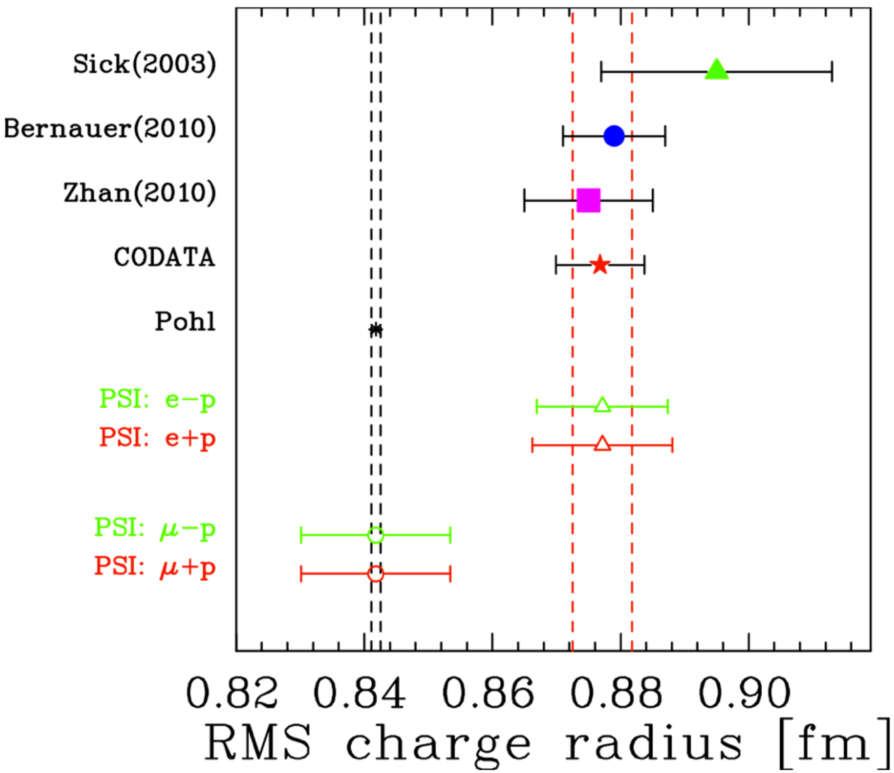
- At low momenta vertex resolution insufficient for successful vertex cuts.
- LH2 data contaminated with events  from walls.
- Empty cell data required. They need to be tuned to full data!



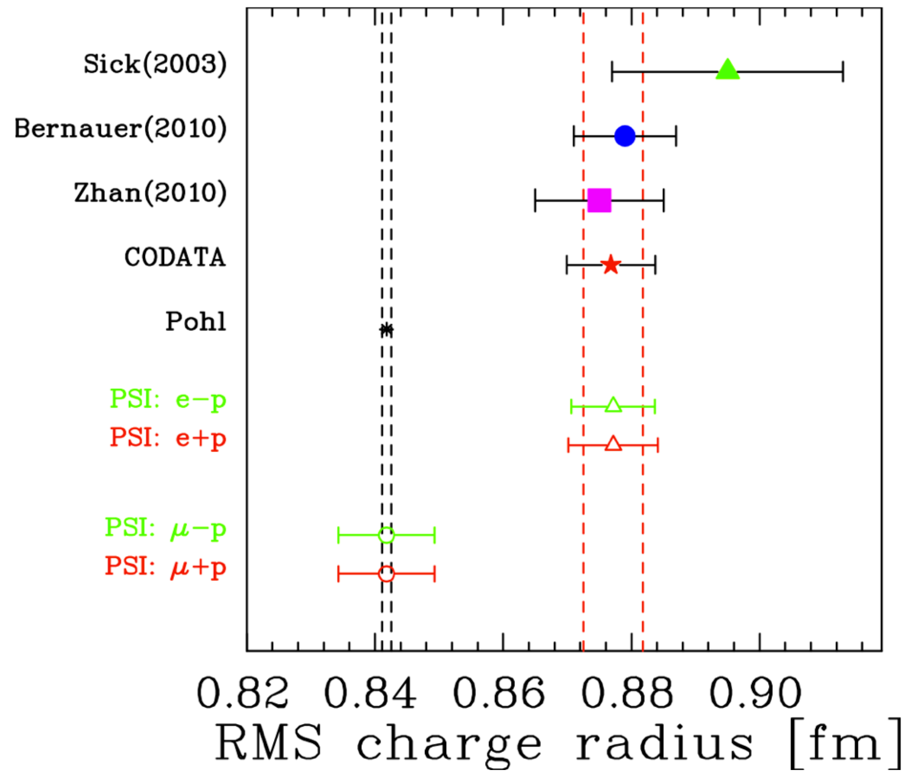



# MUSE Physics

## Radius extraction from John Arrington




independent absolute extraction




extraction with only relative uncertainties

◆ Simultaneous measurement of $e^+/\mu^+$ $e^-/\mu^-$ at beam momenta of 115, 153, 210 MeV/c allows:

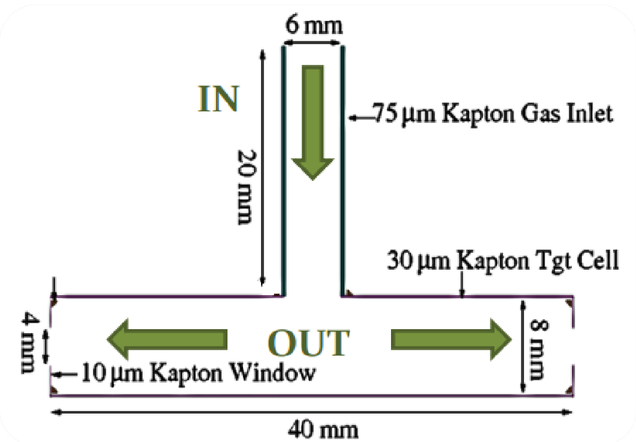
➔ Determination of two photon effects

➔ Test of Lepton Universality

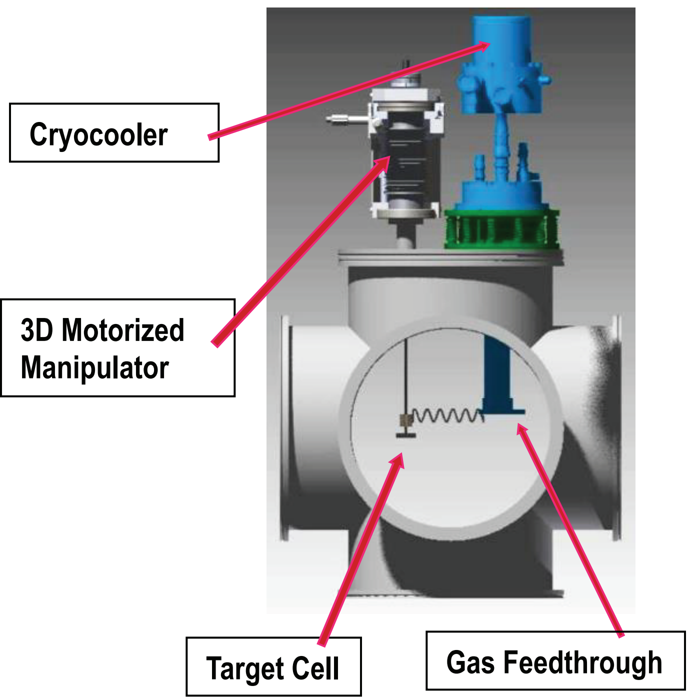
**Schedule**

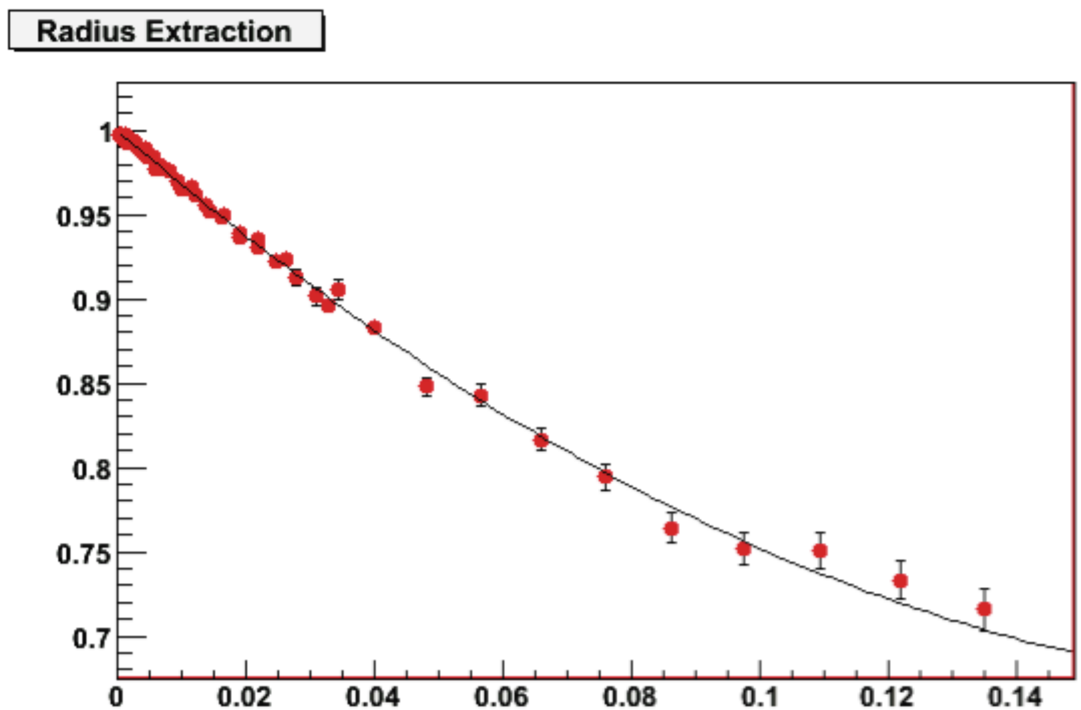
- 2014-15: construct equipment
- 2016-18: 1-month test run, then two 6-month data runs

# The PRad proton radius experiment (JLab)




First beam on target in fall of 2015



# Summary

- Results on charge radius

| | Electron scattering | Muonic spectroscopy |
|---|---|---|
| proton | 0.878 (8) | 0.84087 (39) |
| deuteron | 2.13 (1) | 2.1277 (2) |
| $^{4}He$ | 1.681 (4) | 1.677 (1) |
| $^{12}C$ | 2.478 (9) | 2.481 (9) |

Radius puzzle only for the proton!
(although present large error for the deuteron electron scattering result inhibits a significant conclusion)

# Outlook

- muonic Lamb shift
  - complete analysis of $^{4}He$
  - do experiment on $^{3}He$
  - complete nuclear polarization corrections for $^{2}H$
- electron scattering
  - complete low-$Q^2$ experiments (ISR and PRad)
  - new experiment using $CH_4$ target would yield accurate data on the proton ($^{12}C$ data extend down to 0.0006 $GeV^2$)
  - full conformal-mapping fit of Mainz data (investigate whether unitarity discrepancy is related to large-r behaviour)
  - complete MUSE experiment
  - finalize TPE calculations
  - continue large LQCD effort
- atomic hydrogen
  - complete the three running experiments

# Very Brief Personal Summary

$$\tilde{L}^{theo}_{\mu p}(r_p^{CODATA}) - \tilde{L}^{exp.}_{\mu p} = \begin{cases} 75 \text{ GHz} \\ 0.31 \text{ meV} \\ 0.15\ \% \end{cases}$$

$\mu$p theory wrong?

$\mu$p experiment wrong?

H theory wrong?

H experiments wrong? → $R_\infty$ wrong?

AND e-p scattering exp. wrong?

Standard Model wrong?!?

# Very Exciting Workshop

With many thanks to: Marc Vanderhaeghen, Carl Carlson, Richard Hill and Savely Karshenboim

# THANK YOU !

acknowledging shamelessly stealing from all workshop presenters