Proton radius puzzle

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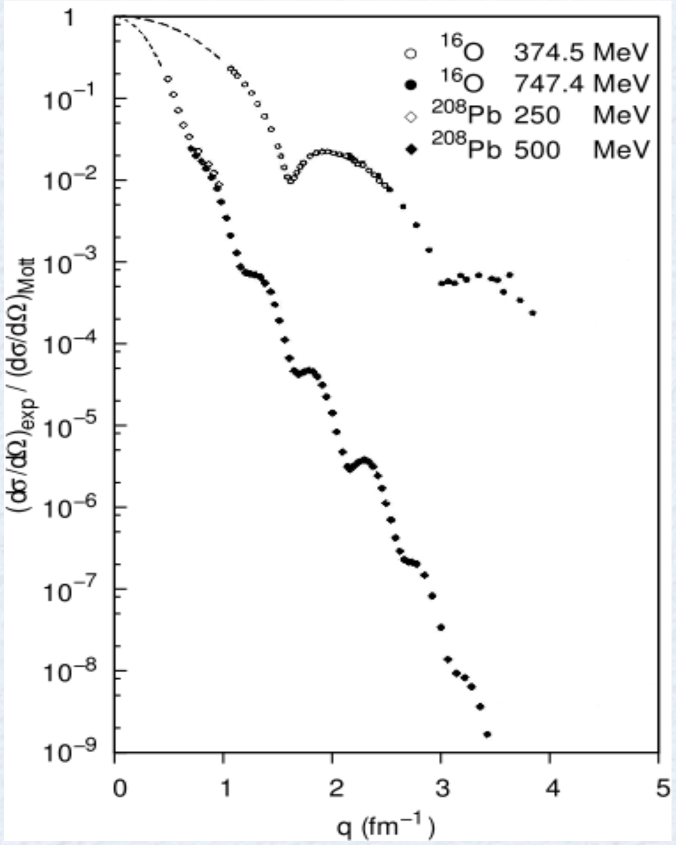
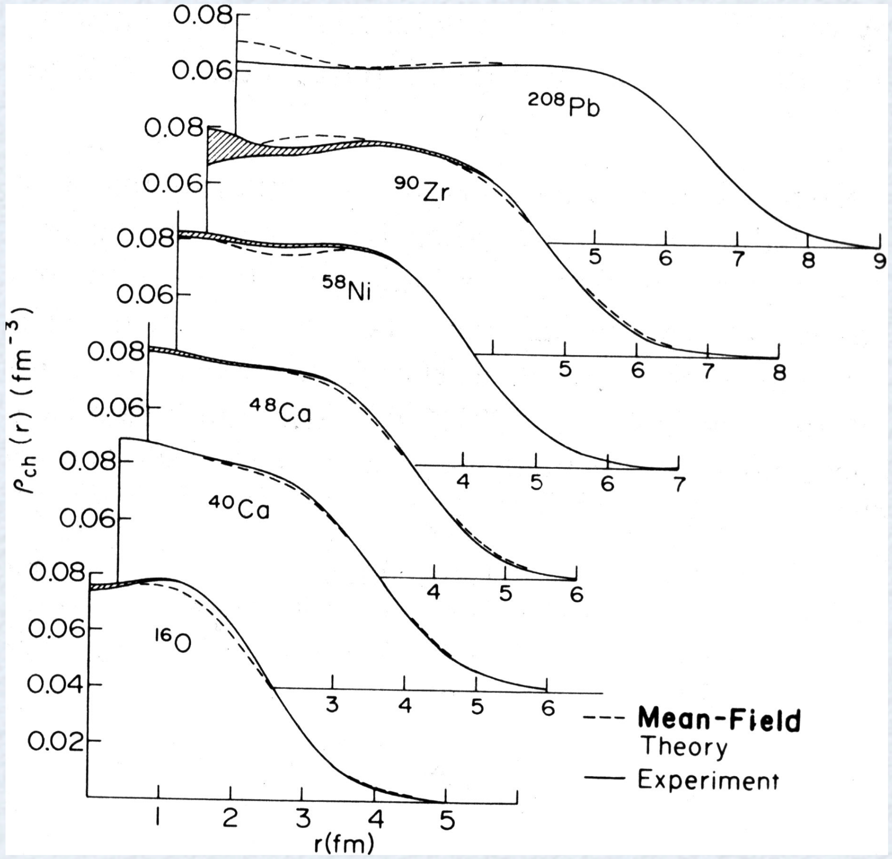
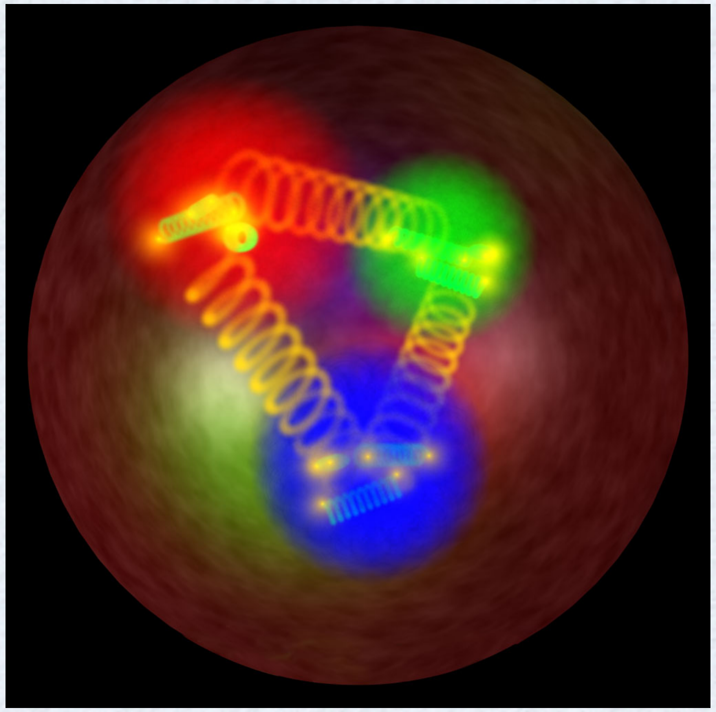
how to measure sizes of hadronic systems

time honored tool:
electroweak probe

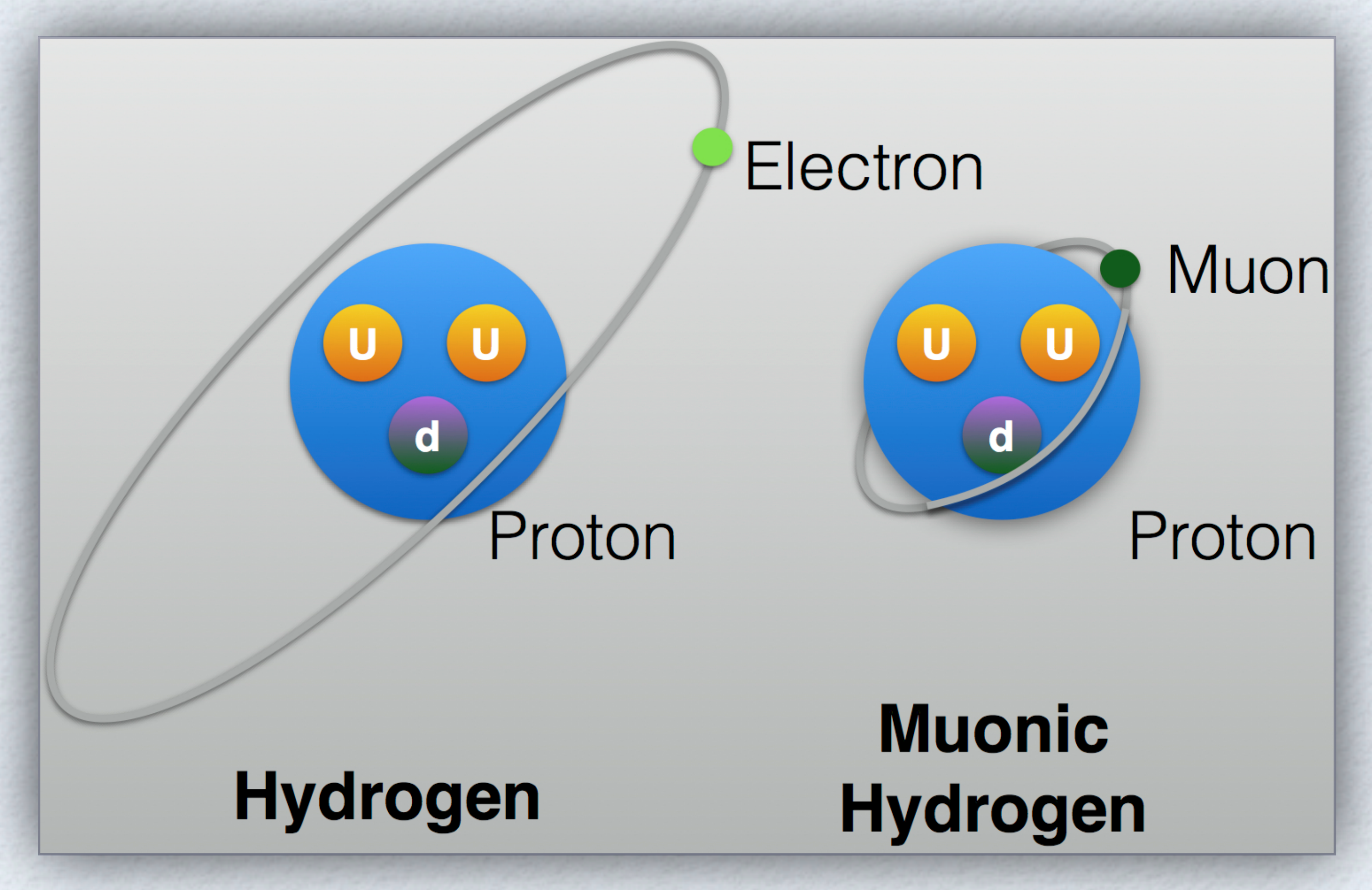


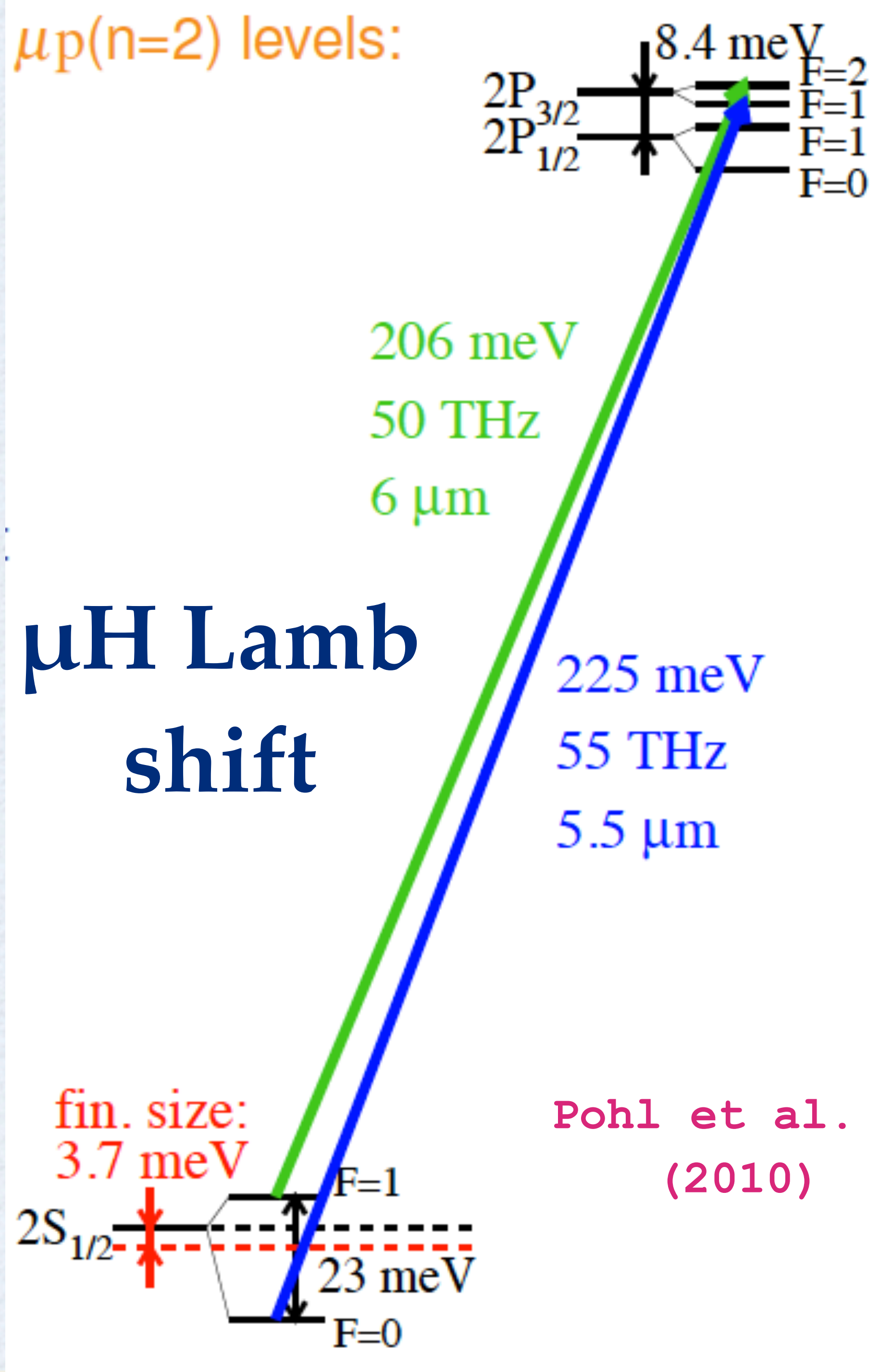


how accurate do we
know the proton size ?



Proton radius from Hydrogen spectroscopy





μH Lamb shift

Pohl et al. (2010)

$$\Delta E_{LS} = 209.9779\ (49) - 5.2262\ \ R_E^{\ 2} + 0.00913\ \ R^3_{(2)}\ \text{meV}$$

$$\downarrow \qquad\qquad \downarrow$$

3.70 meV

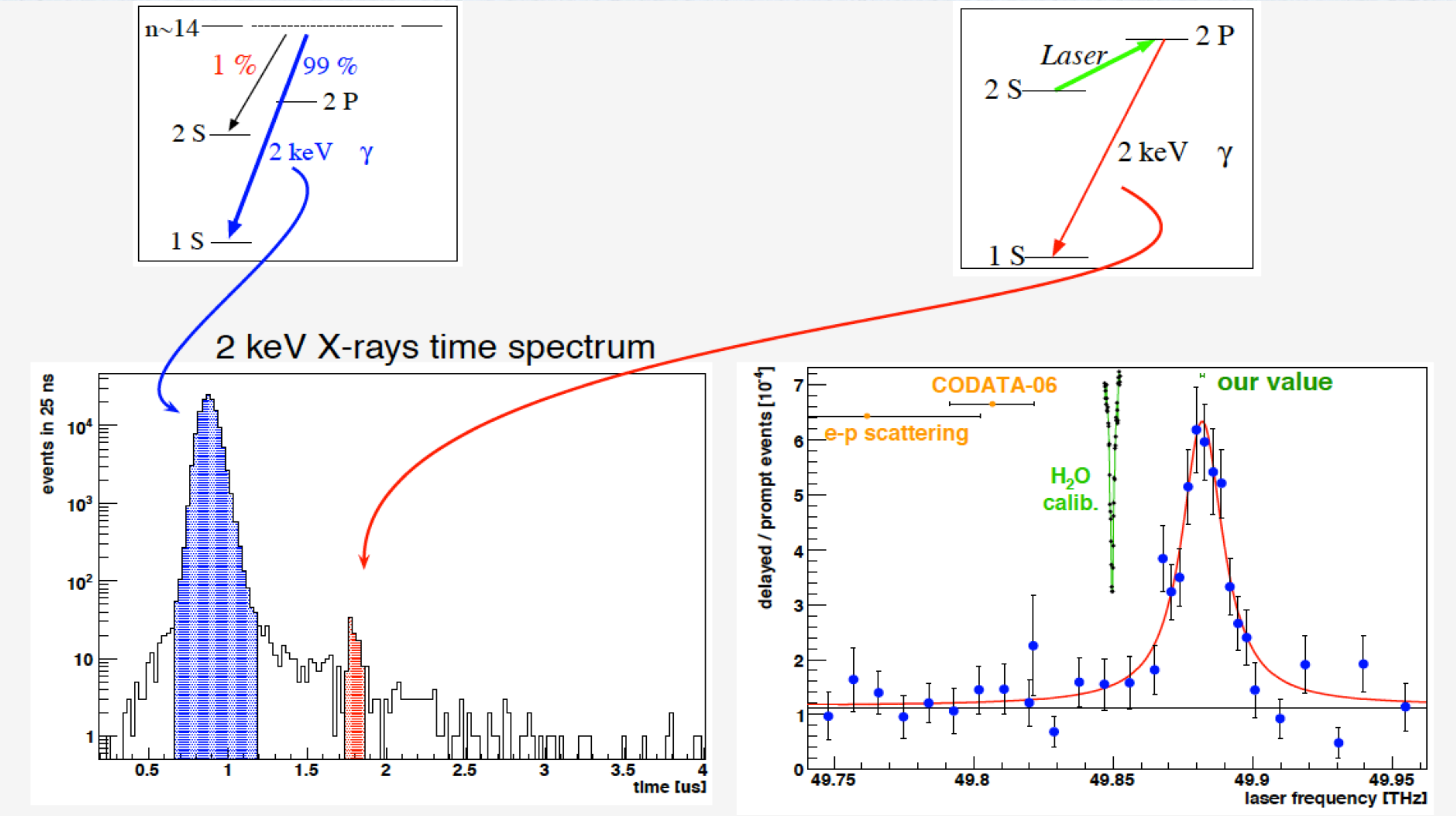
0.026 meV

O(α^5) correction

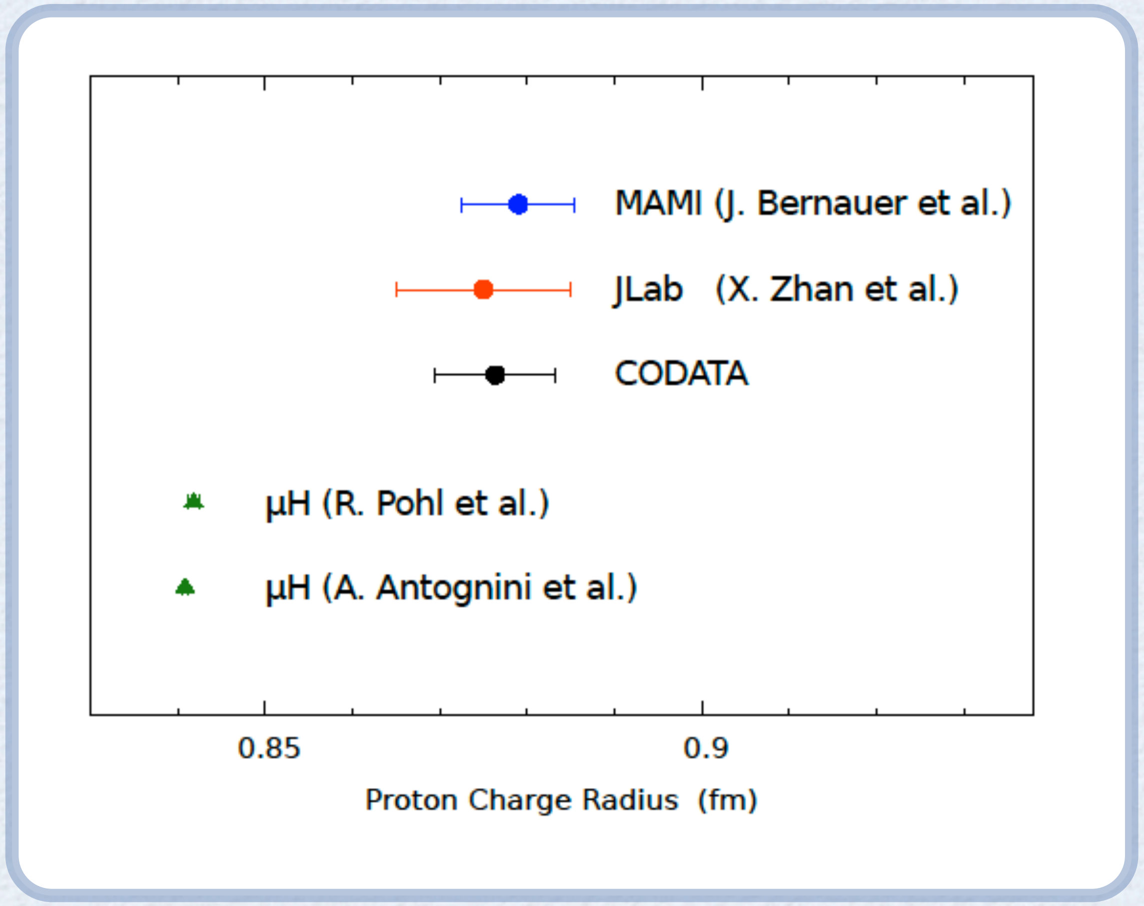
Principle of μH Lamb shift experiment

PSI experiment

Pohl et al.(2010) Antognini et al.(2013)



Proton radius puzzle



μH data: $R_E = 0.8409 \pm 0.0004$ fm

Pohl et al. (2010)

Antognini et al. (2013)

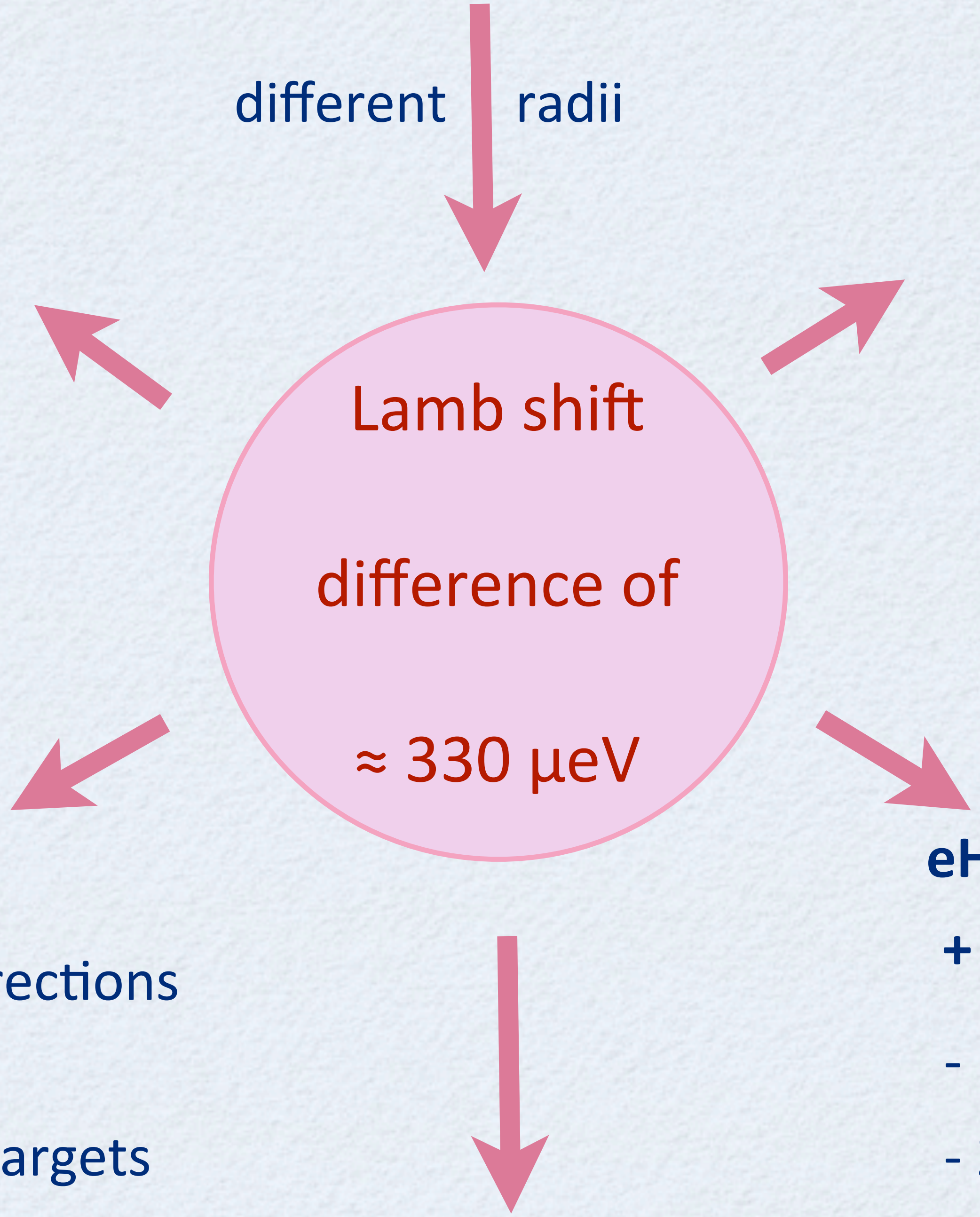
$\updownarrow$ **7 σ difference !?**

ep data: $R_E = 0.8775 \pm 0.0051$ fm

CODATA (2012)

Proton radius puzzle: what could it mean ?

$$\Delta E_{LS} = 209.9779\,(49) - 5.2262\ R_E^2 + 0.00913\ R^3_{(2)}\ \text{meV}$$



different radii

Lamb shift difference of ≈ 330 μeV

μH expt. wrong ?

eH theory wrong ?

μH theory wrong ?

- QED bound state corrections
- hadronic corrections
- check with different targets

eH expt. wrong ? -> R∞ wrong

+ ep scattering wrong ?

- radiative corrections
- 2γ corrections
- low Q^2 extrapolation

new physics ?

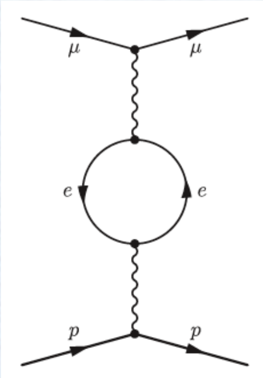
Lamb shift: QED corrections

- Calculated by several groups

Pachucki (1996, 1999)

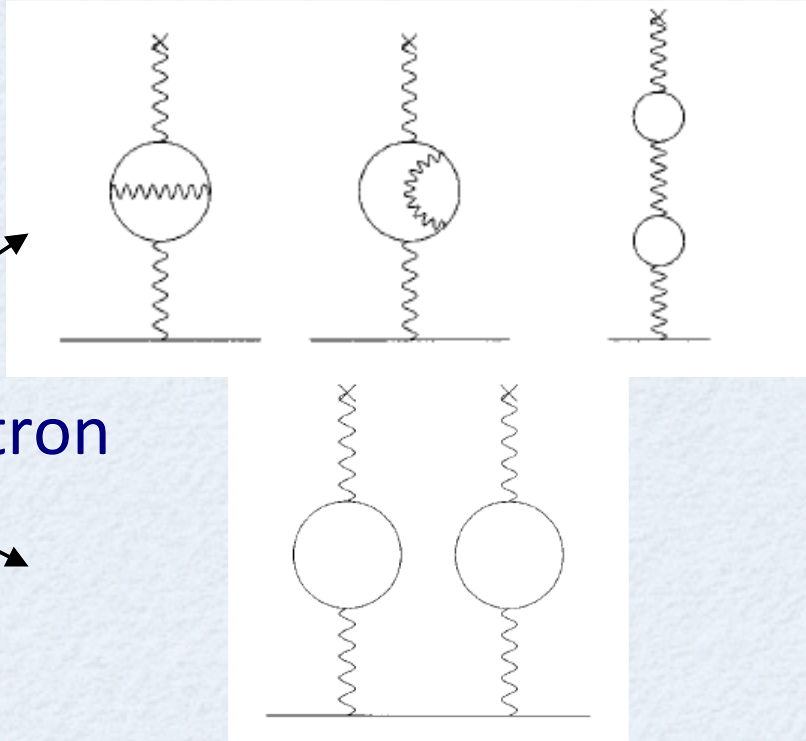
Borie (1976, 2005)

- 1 loop electron



ΔE = 205.0282 meV

- 2 loop electron



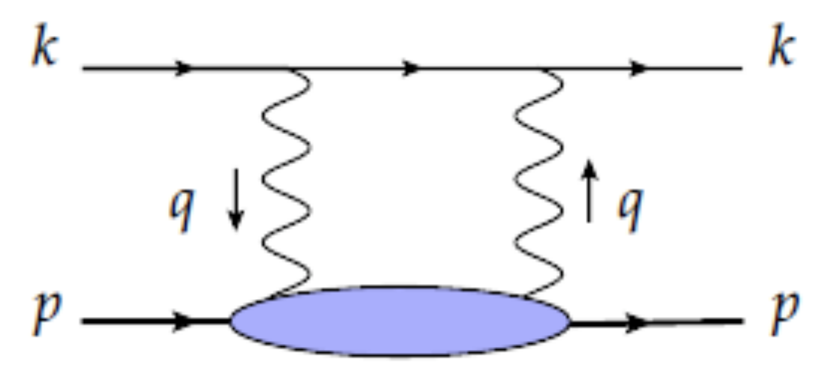
ΔE = 1.5081 meV

ΔE = 0.1509 meV

- Muon self-energy, vacuum polarization ΔE = -0.6677 meV

- other QED corrections calculated : all of size 0.005 meV or smaller << 0.3 meV

Lamb shift: hadronic corrections (I)



$$
\begin{aligned}
T^{\mu\nu}(p,q) &= \frac{i}{8\pi M}\int d^4x\, e^{iqx}\langle p|Tj^{\mu}(x)j^{\nu}(0)|p\rangle \\
&= \left(-g^{\mu\nu}+\frac{q^{\mu}q^{\nu}}{q^2}\right)T_1(\nu,Q^2) \\
&+ \frac{1}{M^2}\left(p^{\mu}-\frac{p\cdot q}{q^2}q^{\mu}\right)\left(p^{\nu}-\frac{p\cdot q}{q^2}q^{\nu}\right)T_2(\nu,Q^2)
\end{aligned}
$$

- Lower blob contains both elastic (nucleon) and in-elastic states → **Hadron physics input required**

  Information contained in **forward, double virtual Compton scattering**

  - Described by two amplitudes T1 and T2: function of energy ν and virtuality Q^2

  - Imaginary parts of T1 , T2: unpolarized structure functions of proton

$$
\begin{aligned}
\mathrm{Im}\, T_1(\nu,Q^2) &= \frac{1}{4M}F_1(\nu,Q^2) \\
\mathrm{Im}\, T_2(\nu,Q^2) &= \frac{1}{4\nu}F_2(\nu,Q^2)
\end{aligned}
$$

- ΔE evaluated through an integral over Q^2 and ν

$$
\begin{aligned}
\Delta E &= \Delta E^{el} \\
&+ \Delta E^{subtr} \\
&+ \Delta E^{inel}
\end{aligned}
$$

→ Elastic state: involves **nucleon form factors**

→ Subtraction: involves **nucleon polarizabilities**

→ Inelastic, dispersion integrals: involves **structure functions F1, F2**

Lamb shift: hadronic corrections (II)

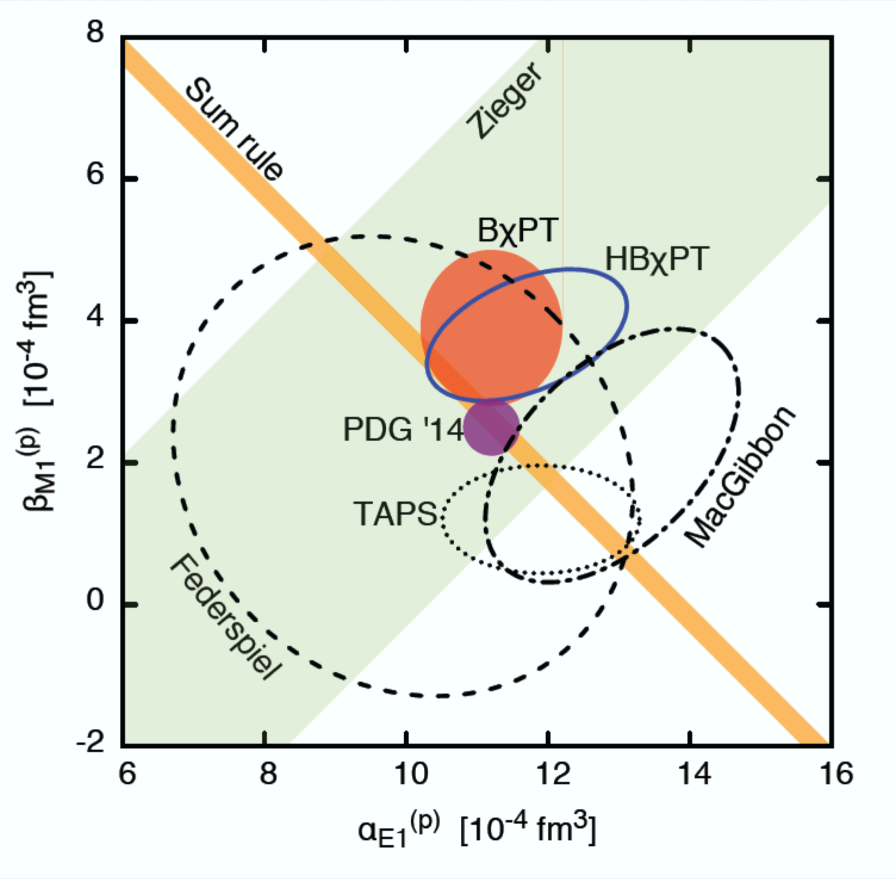
- low-energy expansion of forward, doubly virtual Compton scattering contains a subtraction term $T_1(0,Q^2)$

effective Hamiltonian:

$$\mathcal{H} = -\frac{1}{2} 4\pi \alpha_E \vec{E}^{\,2} - \frac{1}{2} 4\pi \beta_M \vec{B}^{\,2}$$

electric magnetic

polarizabilities



Theory analyses:

BChPT

Lensky, Pascalutsa(2010)

HBChPT

Griesshammer, McGovern, Phillips(2013)

PDG '14 values:

α_E = (11.2 ± 0.2) × 10^{-4} fm^3

β_M = (2.5 ± 0.4) × 10^{-4} fm^3

- subtraction term $T_1(0,Q^2)$

$$T_1^{\mathrm{non-Born}}(0,Q^2) = \frac{Q^2}{e^2}\beta_M + \mathcal{O}(Q^4)$$

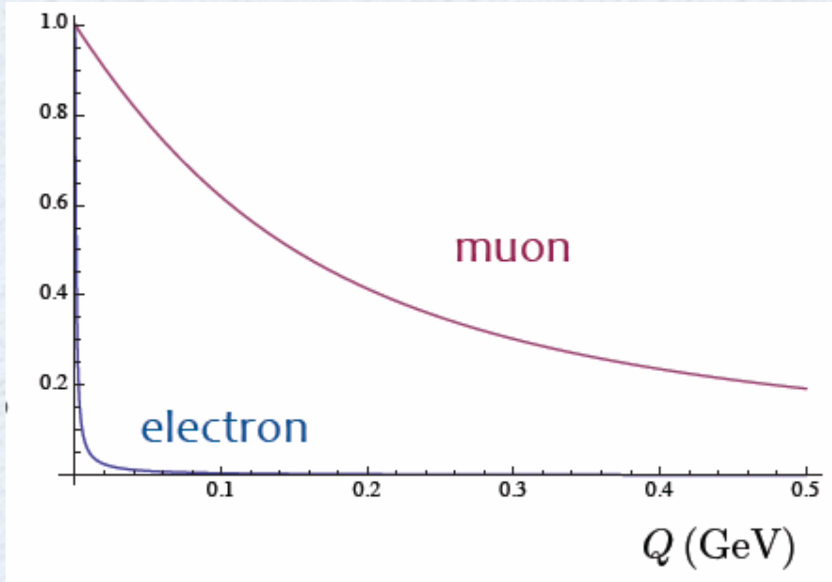
$$T_2^{\mathrm{non-Born}}(0,Q^2) = \frac{Q^2}{e^2}(\alpha_E + \beta_M) + \mathcal{O}(Q^4)$$

next order terms: calculable in chiral perturbation theory

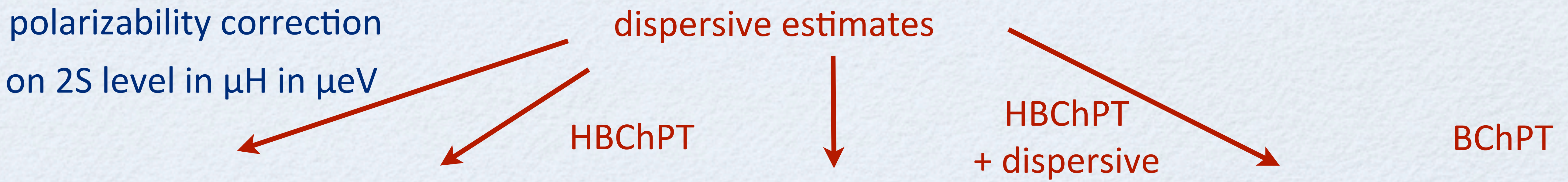
Nevado, Pineda(2008) ; Birse, McGovern(2012);

Alarcon, Lensky, Pascalutsa(2014)

weighting function in Lamb shift



Lamb shift: hadronic corrections summary



polarizability correction on 2S level in μH in μeV

dispersive estimates

HBChPT

HBChPT + dispersive

BChPT

(μeV)	Pachucki [9]	Martynenko [10]	Nevado and Pineda [11]	Carlson and Vanderhaeghen [12]	Birse and McGovern [13]	Gorchtein et al. [14]	LO-BχPT [this work]
$\Delta E_{2S}^{(\mathrm{subt})}$	1.8	2.3	–	5.3 (1.9)	4.2 (1.0)	-2.3 (4.6)[a]	-3.0
$\Delta E_{2S}^{(\mathrm{inel})}$	-13.9	-13.8	–	-12.7 (5)	-12.7 (5)[b]	-13.0 (6)	-5.2
$\Delta E_{2S}^{(\mathrm{pol})}$	-12 (2)	-11.5	-18.5	-7.4 (2.4)	-8.5 (1.1)	-15.3 (5.6)	$-8.2(^{+1.2}_{-2.5})$

[a] Adjusted value; the original value of Ref. [14], +3.3, is based on a different decomposition into the ‘elastic’ and ‘polarizability’ contributions

[b] Taken from Ref. [12]

[9] K. Pachucki, Phys. Rev. A **60**, 3593 (1999).
[10] A. P. Martynenko, Phys. Atom. Nucl. **69**, 1309 (2006).
[11] D. Nevado and A. Pineda, Phys. Rev. C **77**, 035202 (2008).
[12] C. E. Carlson and M. Vanderhaeghen, Phys. Rev. A **84**, 020102 (2011).
[13] M. C. Birse and J. A. McGovern, Eur. Phys. J. A **48**, 120 (2012).
[14] M. Gorchtein, F. J. Llanes-Estrada and A. P. Szczepaniak, Phys. Rev. A 87, **052501** (2013).

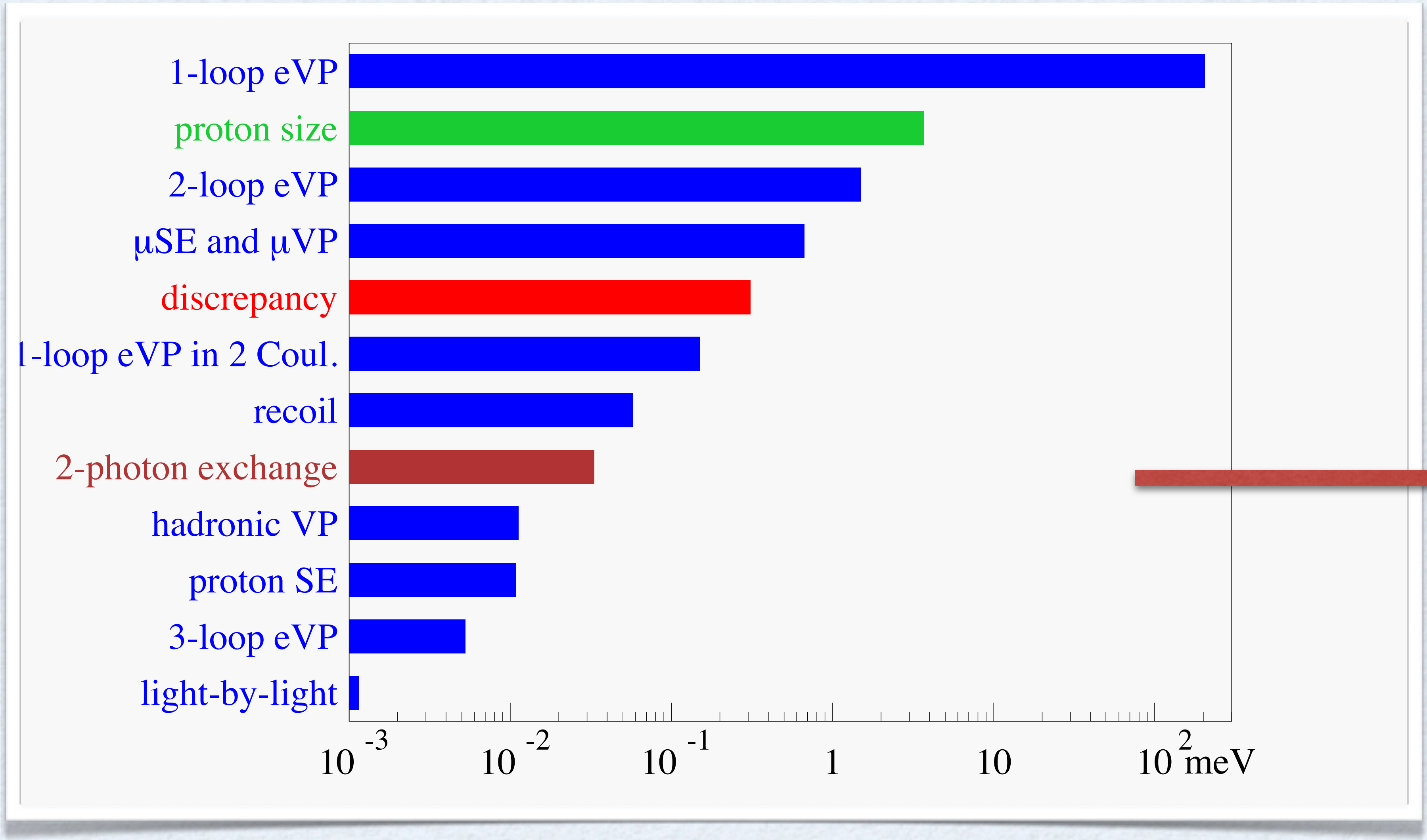
`[LO-BχPT] Alarcon, Lensky, Pascalutsa, EPJC (2014) 74:2852`

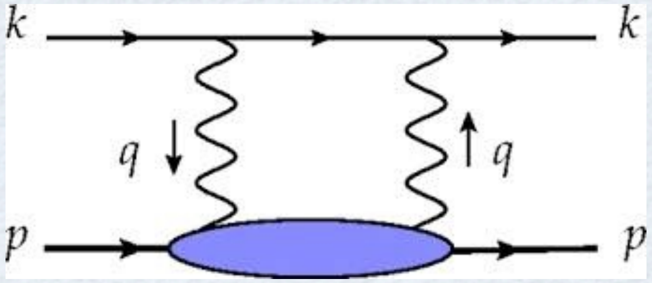
total hadronic correction on Lamb shift

$\Delta E_{(2P-2S)} = (33 \pm 2)\ \mu\mathrm{eV}$

Lamb shift: status of known corrections

μH Lamb shift: summary of corrections





largest theoretical uncertainty

- elastic contribution on 2S level: ΔE_{2S} = -23 μeV
- inelastic contribution: `Carlson, Vdh (2011) + Birse, McGovern (2012)`

total hadronic correction on Lamb shift

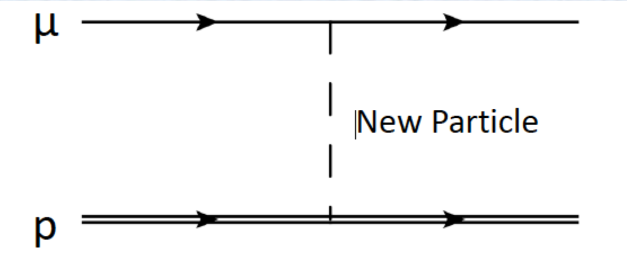
$\Delta E_{(2P-2S)}$ = (33 ± 2) μeV

...or about 10% of needed correction

Proton radius puzzle: new physics ?

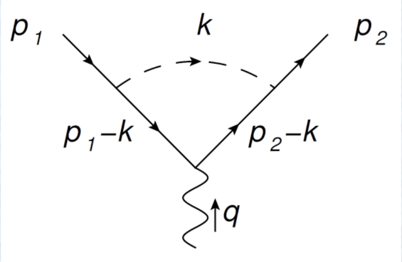
- new **muonic forces** ?

lepton universality-violating models



invoking exchange of hypothetical light boson

challenge: new physics must also respect $(g\text{-}2)_\mu$ discrepancy



simultaneously explain 1 ppm and 10^4 ppm discrepancies !!!

Tucker-Smith Yavin (2010)

Barger, Chiang, Keung, Marfiata (2011)

- parity-violating muonic forces (V and A)

fine tuning between V and A coupling to muon

$$\mathcal{L}_{\rm int} = -V_\nu[\kappa J^{\rm em}_\nu - \bar{\psi}_\mu(g_V\gamma_\nu + g_A\gamma_\nu\gamma_5)\psi_\mu]$$

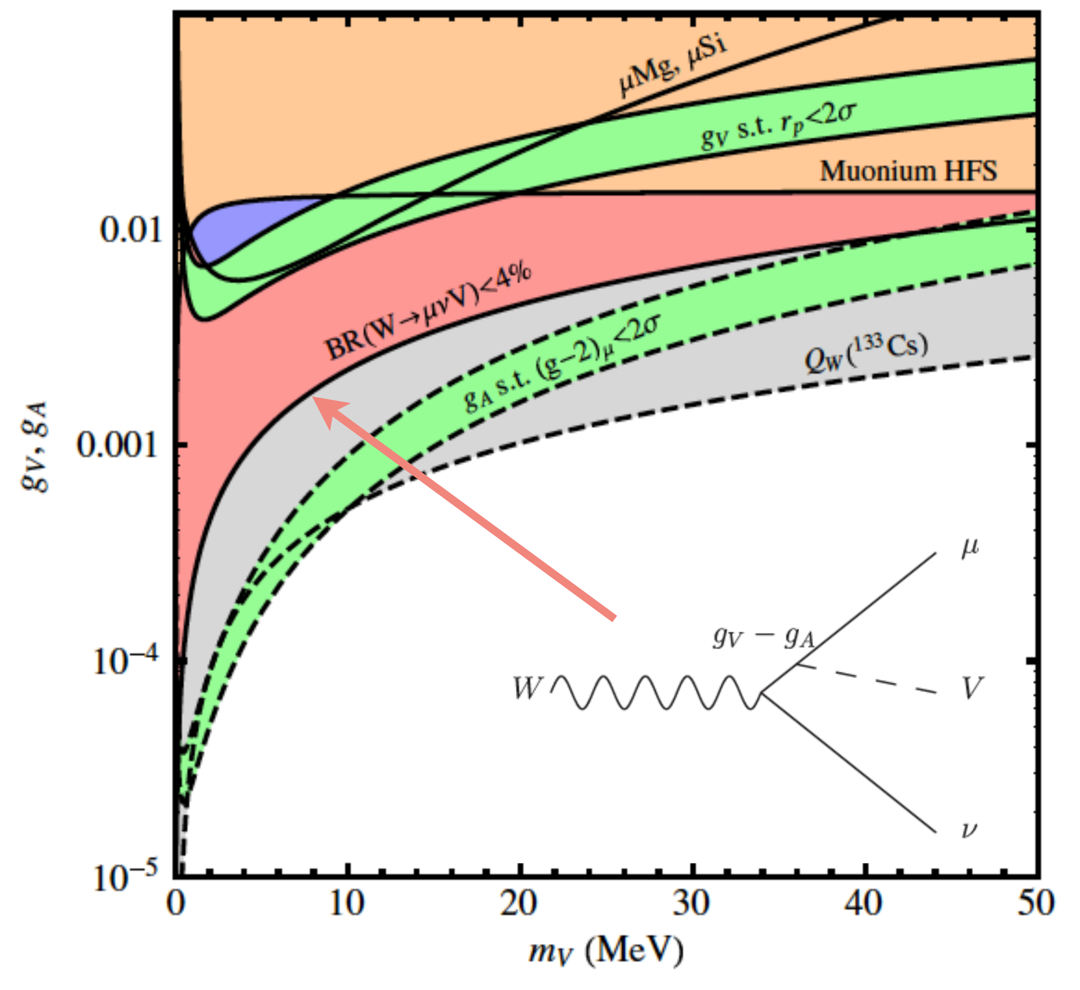
all leptons

V and A coupling to muons

Batell, McKeen, Pospelov (2011)

Carlson, Rislow (2012)

Karshenboim, McKeen, Pospelov (2014)



strong constraint from leptonic W decay

embedding in a renormalizable theory required

Carlson, Freid (2015)

Proton radius puzzle: what's next ?

➡ μ atom Lamb shift: μ D, μ ^{3}He$^+$, μ ^{4}He$^+$ have been performed

➡ electronic H Lamb shift: higher accuracy measurements

➡ electron scattering analysis: Lorenz et al.; Hill, Lee, Paz

- radius extraction fits (use fits with correct analytical behavior: 2π cut)
- radiative corrections, two-photon exchange corrections

new fit $R_E = 0.904\ (15)$ fm (4σ from μH)

➡ electron scattering experiments:

new G_{Ep} experiments down to $Q^2 \approx 2 \times 10^{-4}$ GeV^2

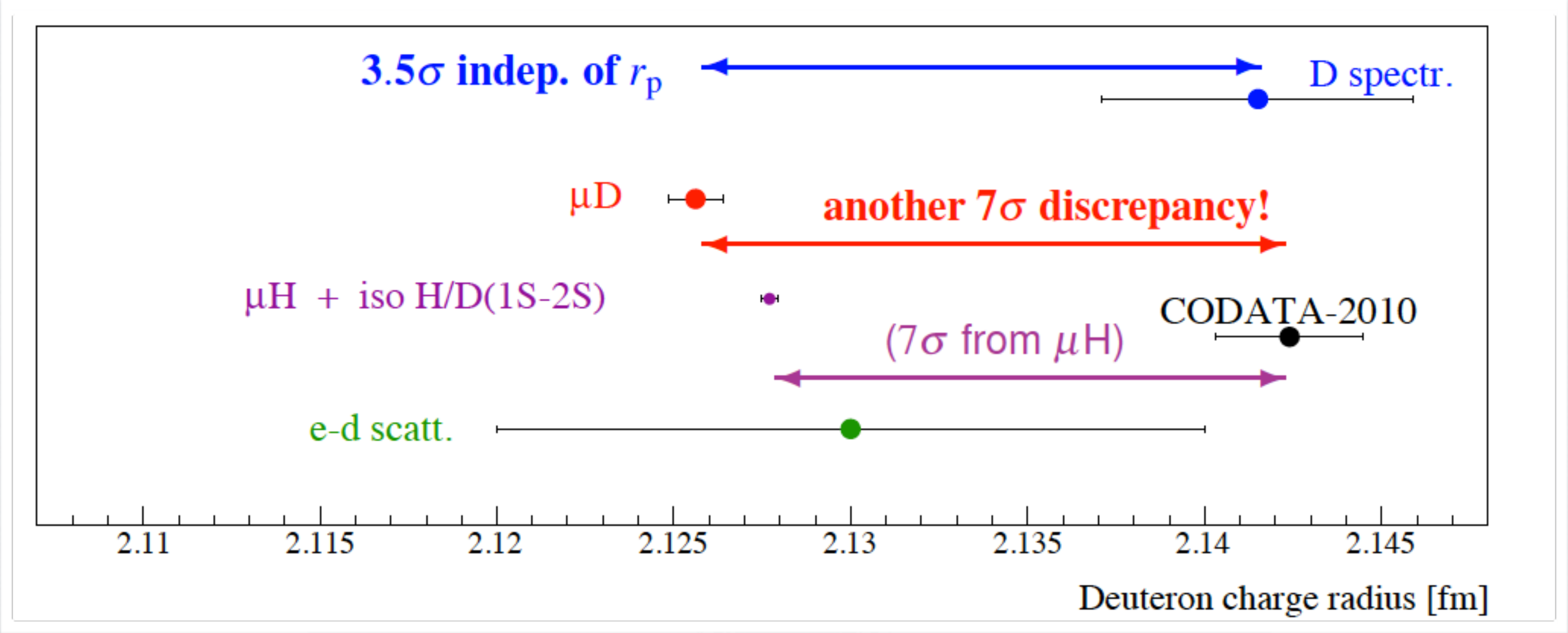
- MAMI/A1: Initial State Radiation (2013/4)
- JLab/Hall B: HyCal, magnetic spectrometer-free experiment, norm to Møller (2016/7)
- MESA: low-energy, high resolution spectrometers

➡ muon scattering experiments: MUSE@PSI (2018/9)

➡ e^-e^+ versus $\mu^-\mu^+$ photoproduction: lepton universality test

μD Lamb shift experiment

- H/D isotope shift (1S - 2S): $r_d^{\,2} - r_p^{\,2}$ = 3.82007 (65) fm^2 Parthey et al. (2010)
- CODATA 2010: r_d = 2.14240 (210) fm
- r_p from μH + isotope shift : r_d = 2.12771 (22) fm
- new μD Lamb shift @ PSI: r_d = 2.12562 (13)$_{\text{theo}}$ (77)$_{\text{theo}}$ fm Pohl et al., Science 353,417 (2016)



- electronic D (r_p indep.): r_d = 2.14150 (450) fm ← 3.5 σ Pohl et al. (2016)
- improved radius measurement from e-d scattering was performed @ MAMI (2014)

Polarization corrections for μD, μ ^{3}He$^+$, μ ^{4}He$^+$, ...

μH: ΔE^{TPE} (2P - 2S) = (33 ± 2) μeV Carlson, Vdh (2011) + Birse, McGovern (2012)

present accuracy comparable with experimental precision: $\delta_{exp}(\Delta E_{LS})$ = 2.3 μeV

μD: ΔE^{TPE} = (1727 ± 20) μeV nucleon potentials form chiral EFT Hernandez et al. (2014)

ΔE^{TPE} = (1748 ± 740) μeV dispersive analysis Carlson, Gorchtein, Vdh (2014)

ΔE^{TPE} = (1710 ± 15) μeV theory average used in exp. Krauth (2016)

present accuracy factor 5 worse than experimental precision: $\delta_{exp}(\Delta E_{LS})$ = 3.4 μeV

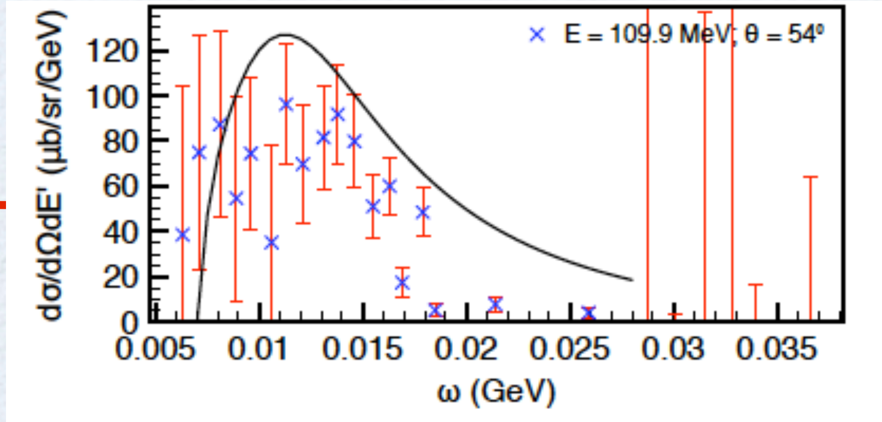
μ ^{3}He$^+$: ΔE^{TPE} = (1546 ± 39) μeV nucleon potentials form chiral EFT

Nevo Dinur, Ji, Bacca, Barnea (2016)

ΔE^{TPE} = (1514 ± 49) μeV dispersive analysis Carlson, Gorchtein, Vdh (2016)

impact of a 5% measurement at MESA

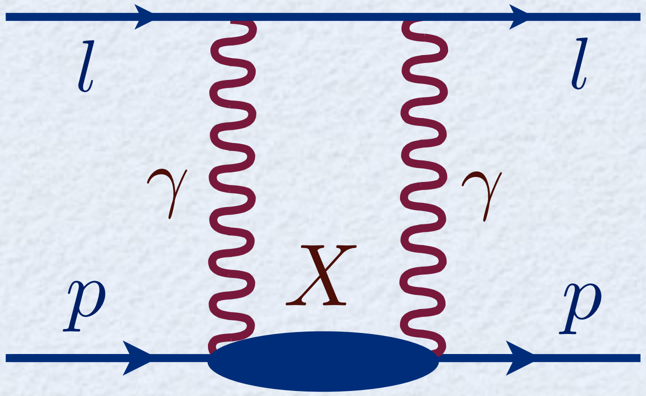
Kinematics	δa_2	$\delta(\Delta E_{2S}^{\text{nuclear}})$	$\delta(\Delta E_{2S}^{\text{TPE}})$
$E = 110$ MeV			
$\theta = 54°$	±0.014	0.40 meV	0.49 meV
$\theta = 30°$	±0.0075	0.21 meV	0.35 meV
$\theta = 25°$	±0.0055	0.16 meV	0.33 meV
$\theta = 20°$	±0.0040	0.11 meV	0.30 meV



Hyperfine splitting:
TPE for proton spin dependent amplitude

forthcoming PSI
1S-HFS measurement in μH
with 1 ppm accuracy

Antognini (2016)

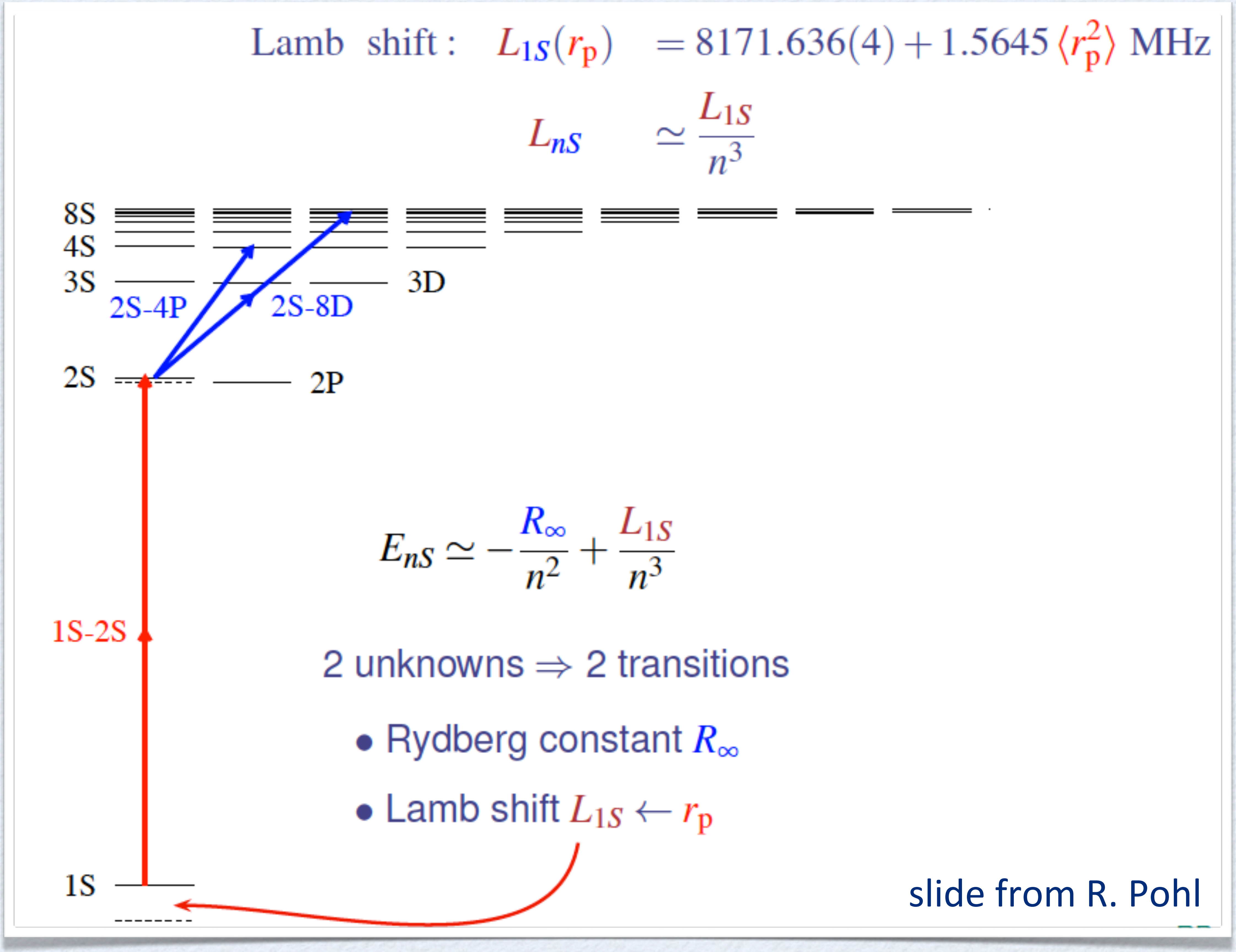


	relative contribution (×10-3)	relative uncertainty
X=p (Zemach)	-7.36	140 ppm
X=p (recoil)	0.85	0.8 ppm
X=p, πN,…(polarizability)	0.36	86 ppm
total	-6.149	164 ppm

Carlson, Nazaryan, Griffioen (2011); Tomalak et al. (2016)

Impressive 1 ppm accuracy requires improvement on 2ɣ

electronic H spectroscopy



$$\text{Lamb shift}: \quad L_{1S}(r_p) = 8171.636(4) + 1.5645\,\langle r_p^2 \rangle \text{ MHz}$$

$$L_{nS} \simeq \frac{L_{1S}}{n^3}$$

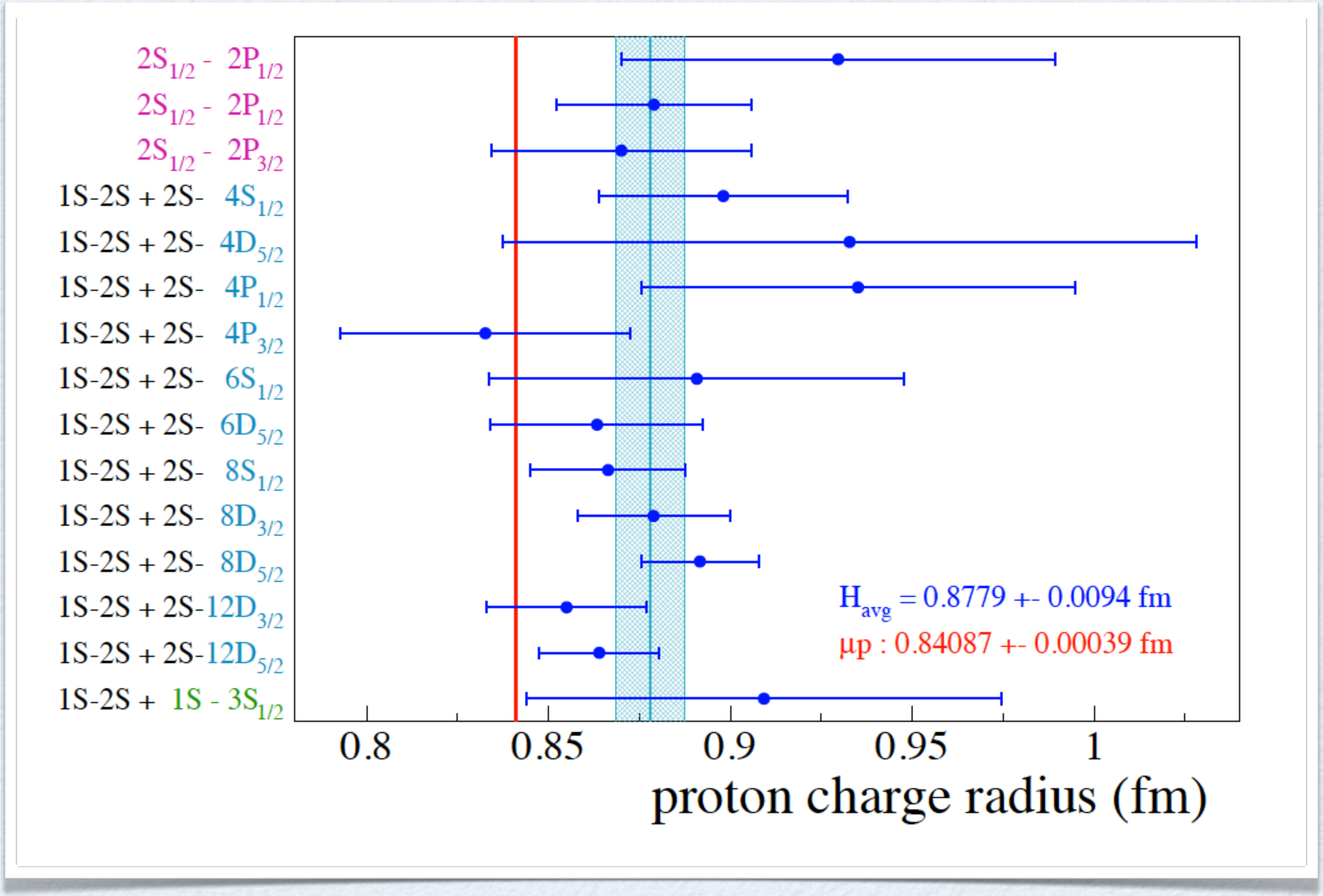
$$E_{nS} \simeq -\frac{R_\infty}{n^2} + \frac{L_{1S}}{n^3}$$

2 unknowns ⇒ 2 transitions

- Rydberg constant R_∞
- Lamb shift $L_{1S} \leftarrow r_p$

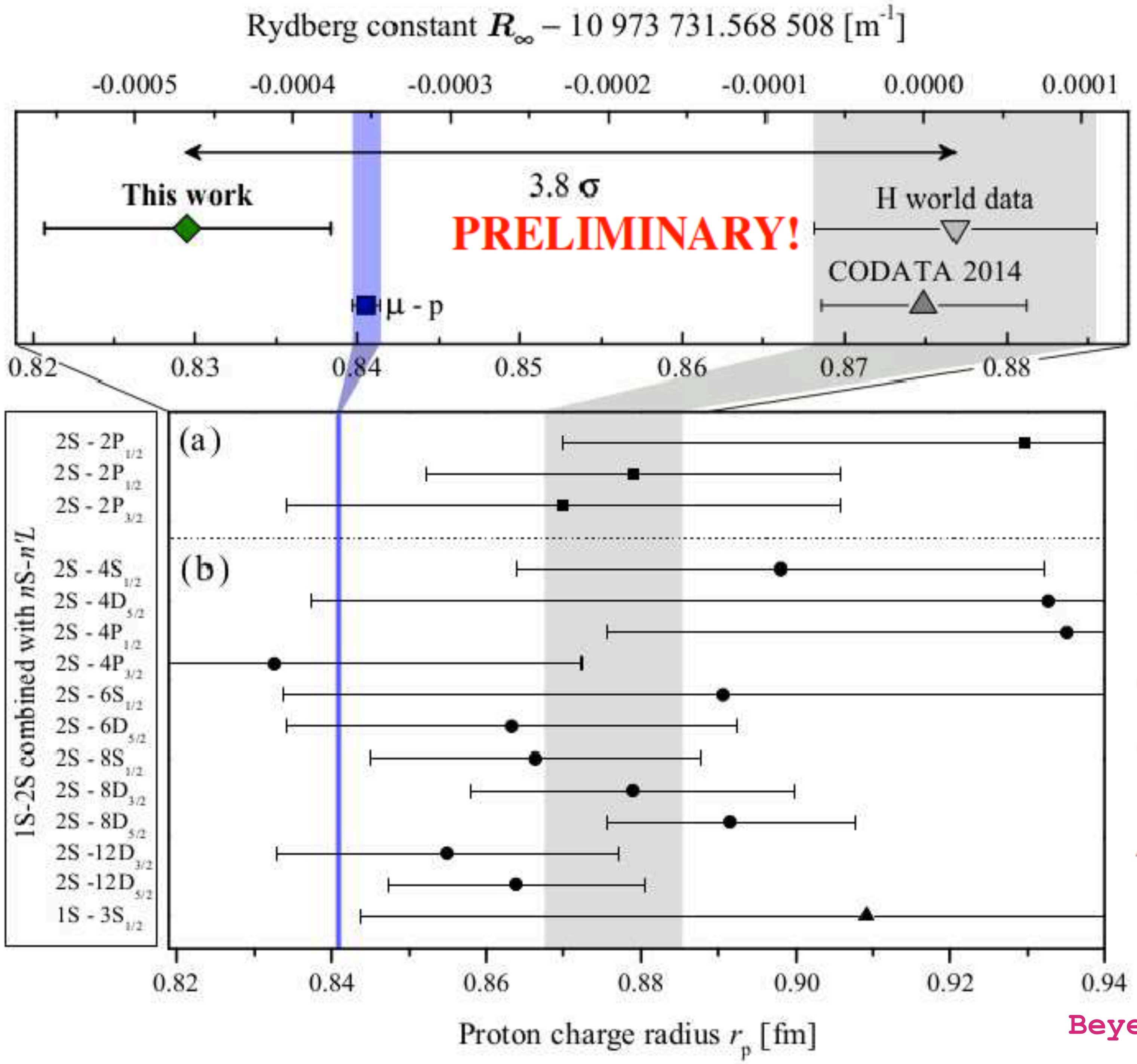
slide from R. Pohl

Proton radius from electronic H spectroscopy



- < 1% uncertainty comes from average of 15 measurements
- large advances in instrumentation allow for new measurements with individual error better than the present average

new Hydrogen 2S - 4P experiment



slide from R. Pohl

Garching H group:

Beyer, Maisenbacher, Matveev, Yost,
Kolachevsky, RP, Udem, *et al.*

$2S \to 4P_{1/2}$ and $4P_{3/2}$

cold H(2S) beam
optically excited $(1S \to 2S)$

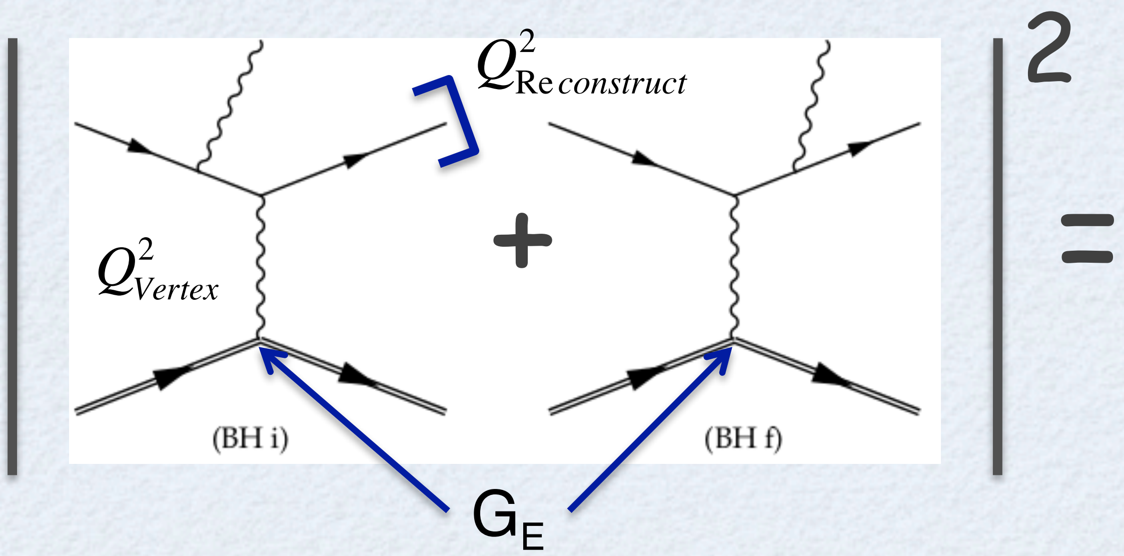
$\Delta\nu \sim 2\,\mathrm{kHz} \quad \equiv \Gamma/10'000$

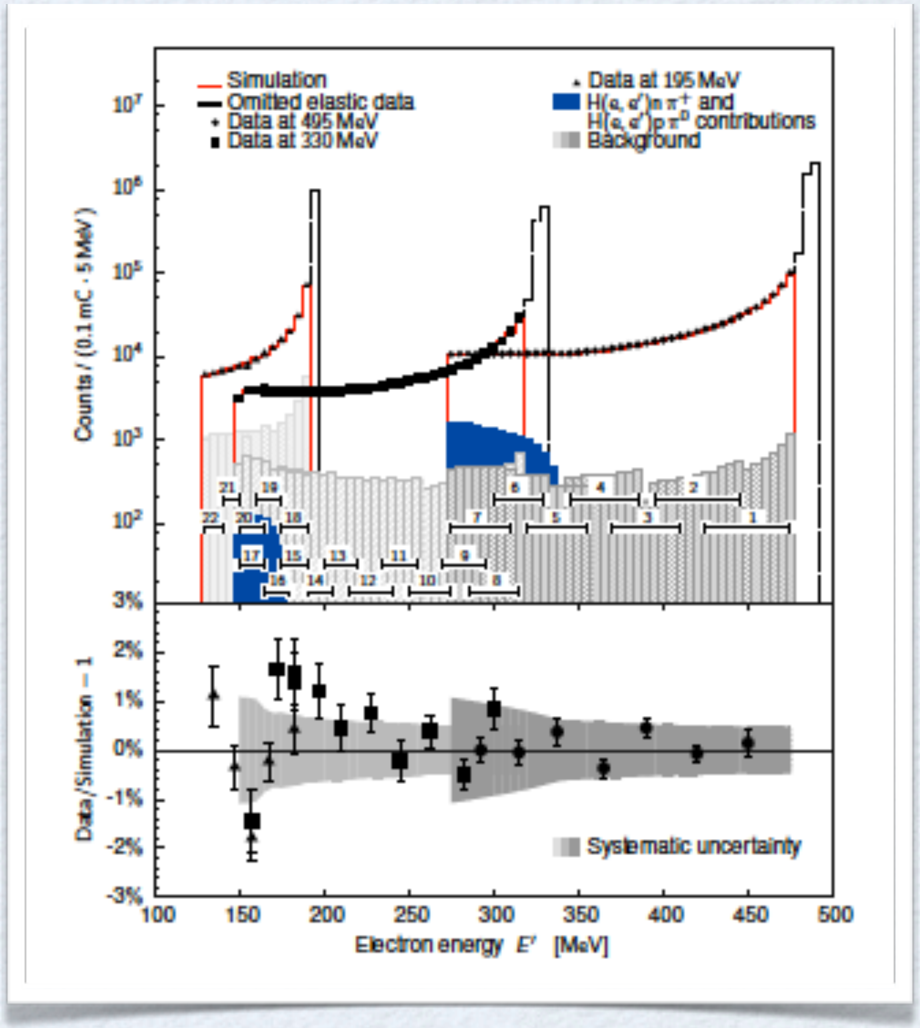
Beyer, Pohl et al. (submitted)

➡ new 2S-2P Lamb shift measurement presently under analysis Hessels

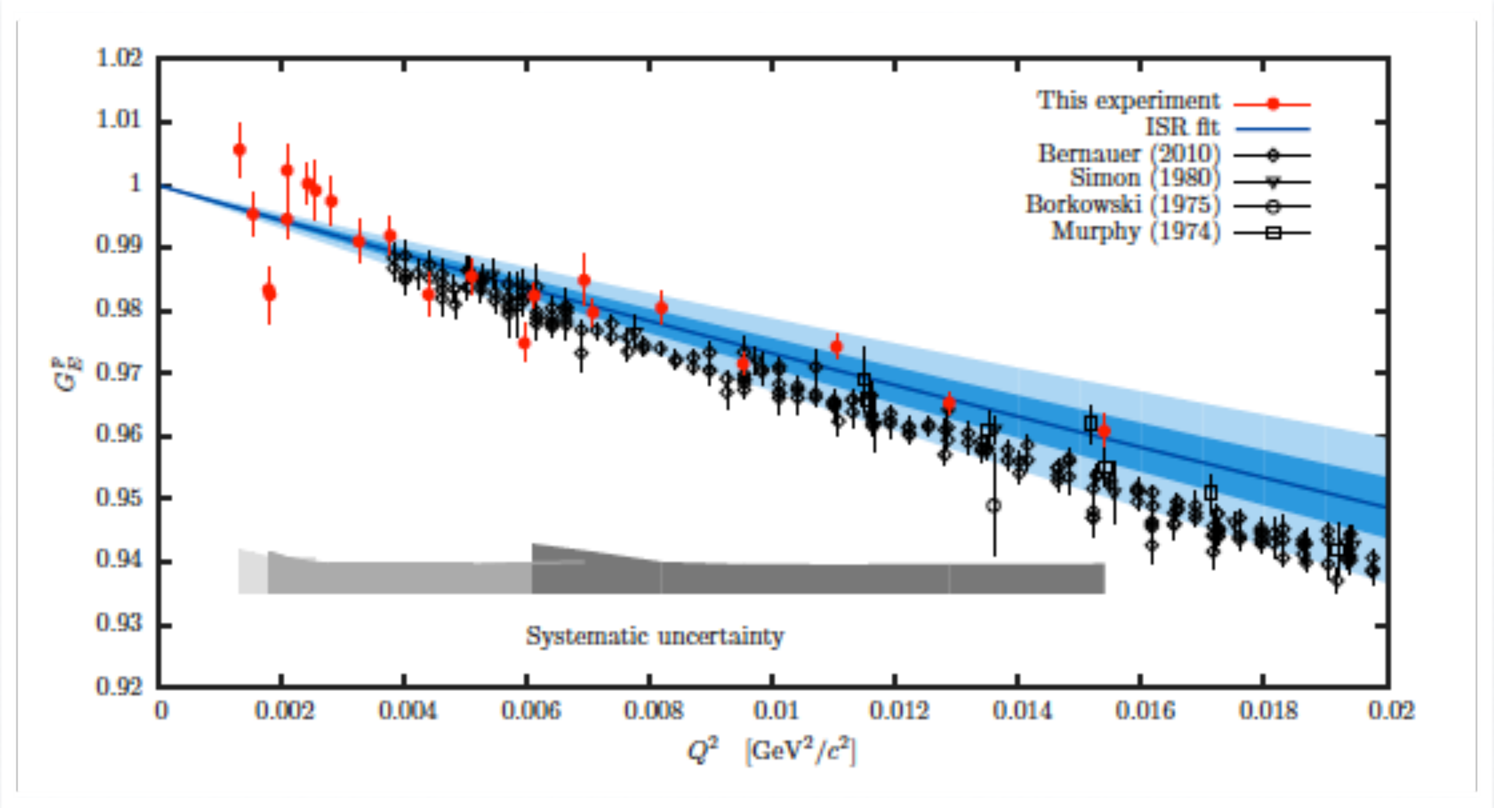
ISR@MAMI experiment

- **Extracting FFs from the radiative tail.**
- Radiative tail dominated by coherent sum of two Bethe-Heitler diagrams.





Mihovilovic et al.(2016)



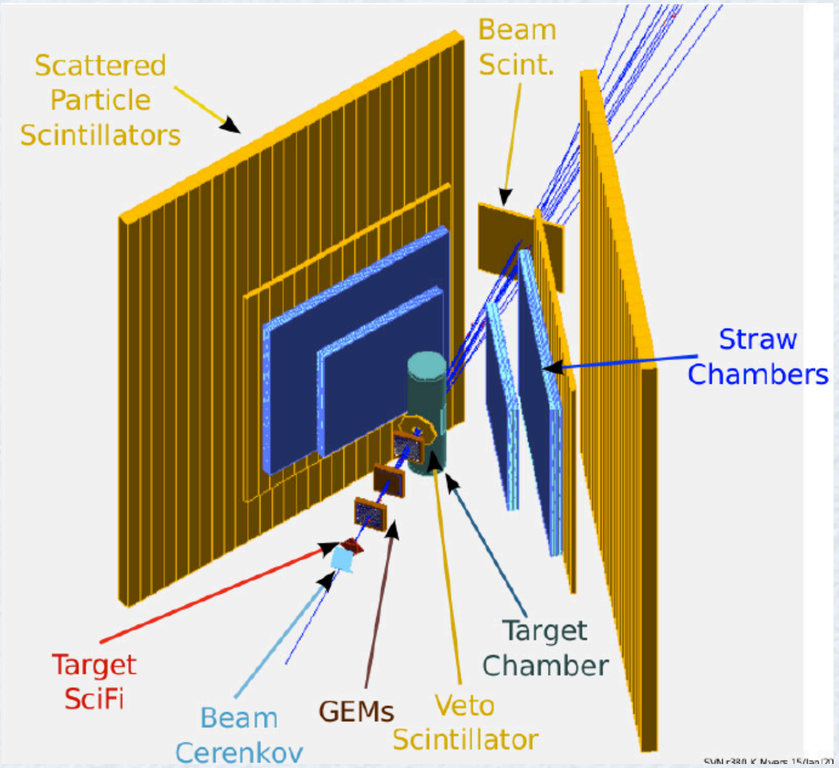
good understanding of radiative tail (~ 1%)

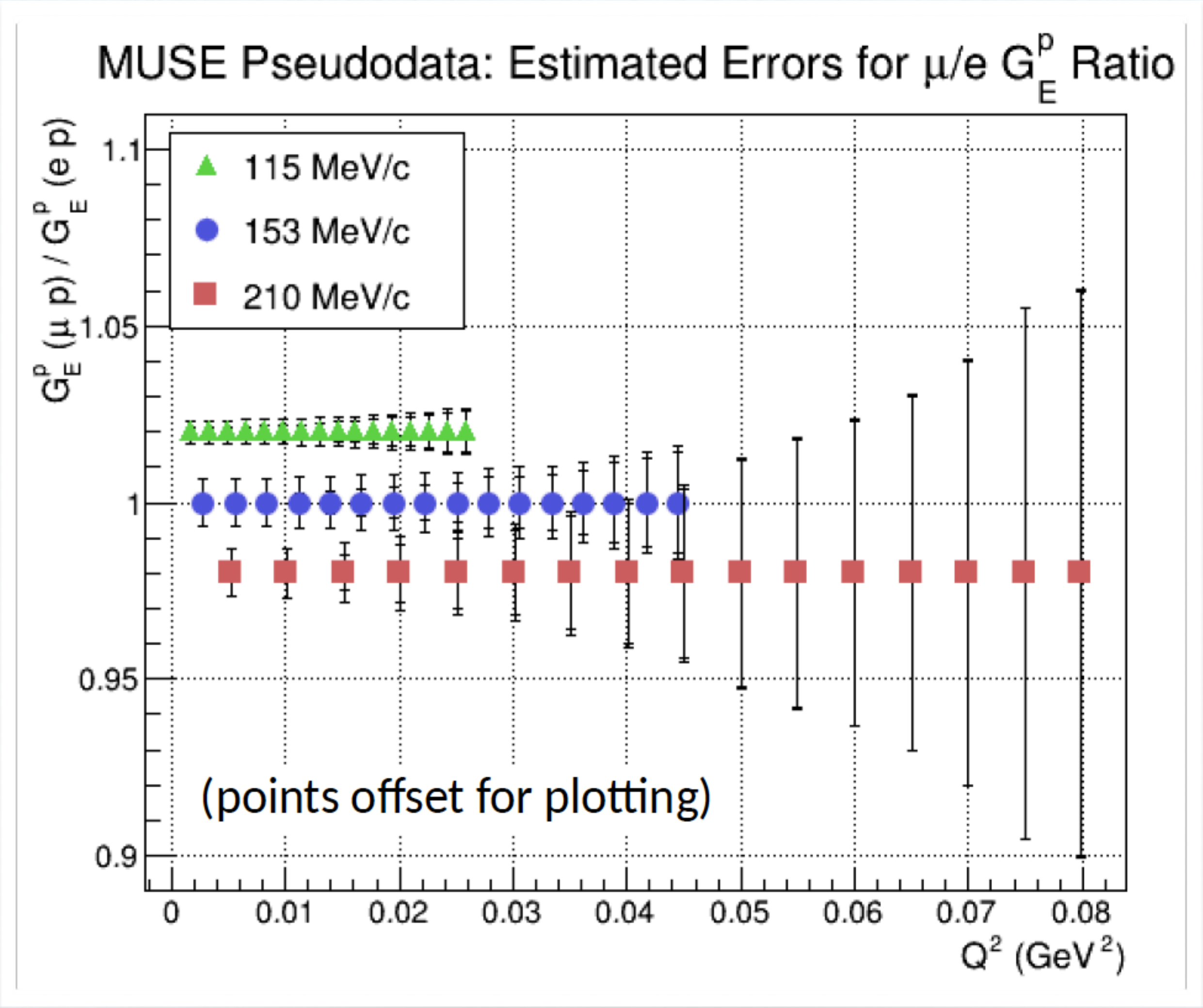
follow up experiment:
down to $Q^2 \approx 2 \times 10^{-4}$ GeV^2

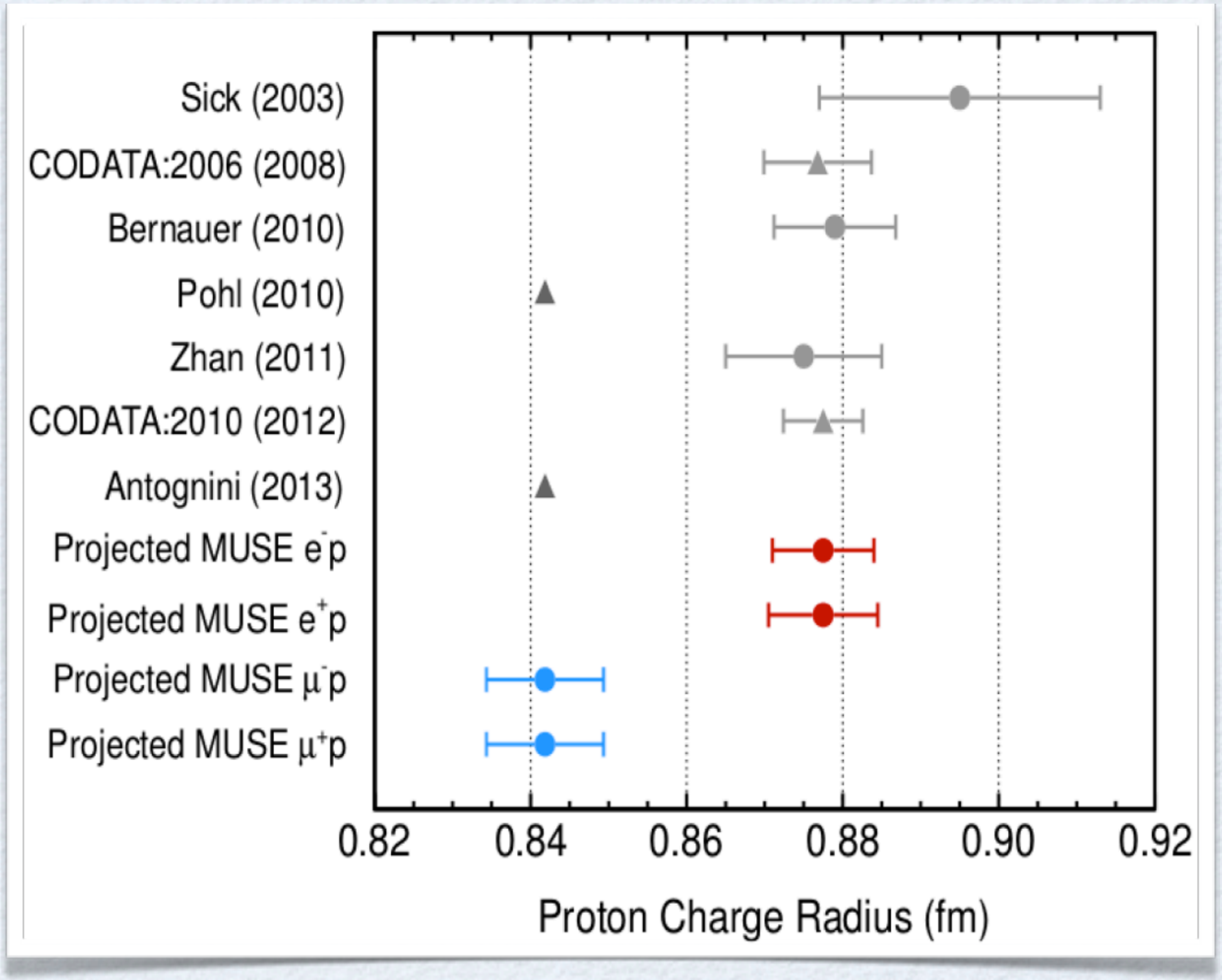
MUSE@PSI experiment

simultaneous measurement of ***e*** and **μ**

elastic scattering absolute cross sections

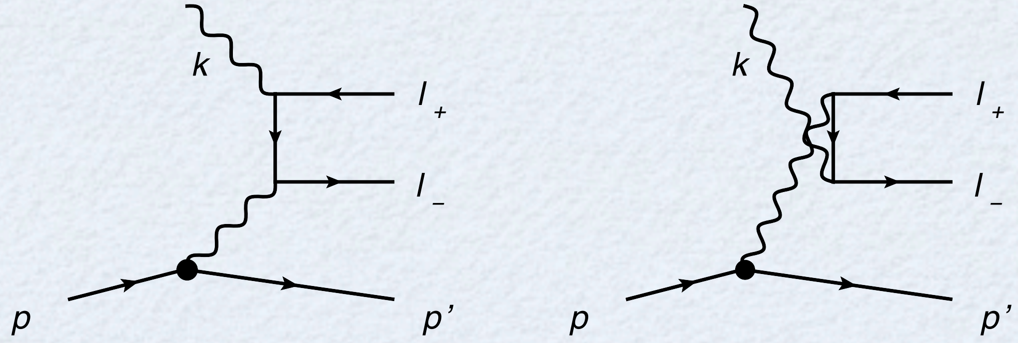






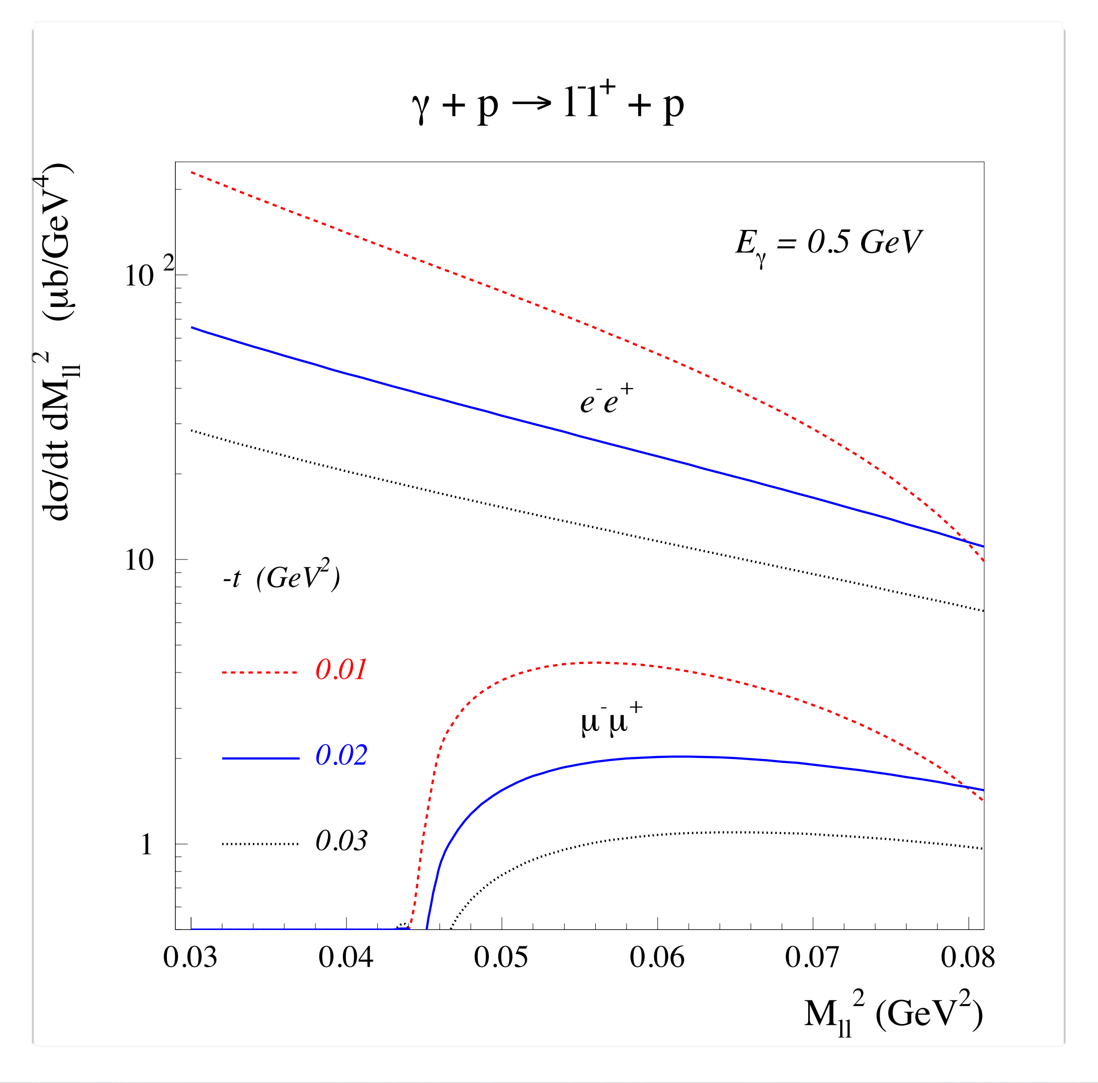
production run planned 2018 - 2019

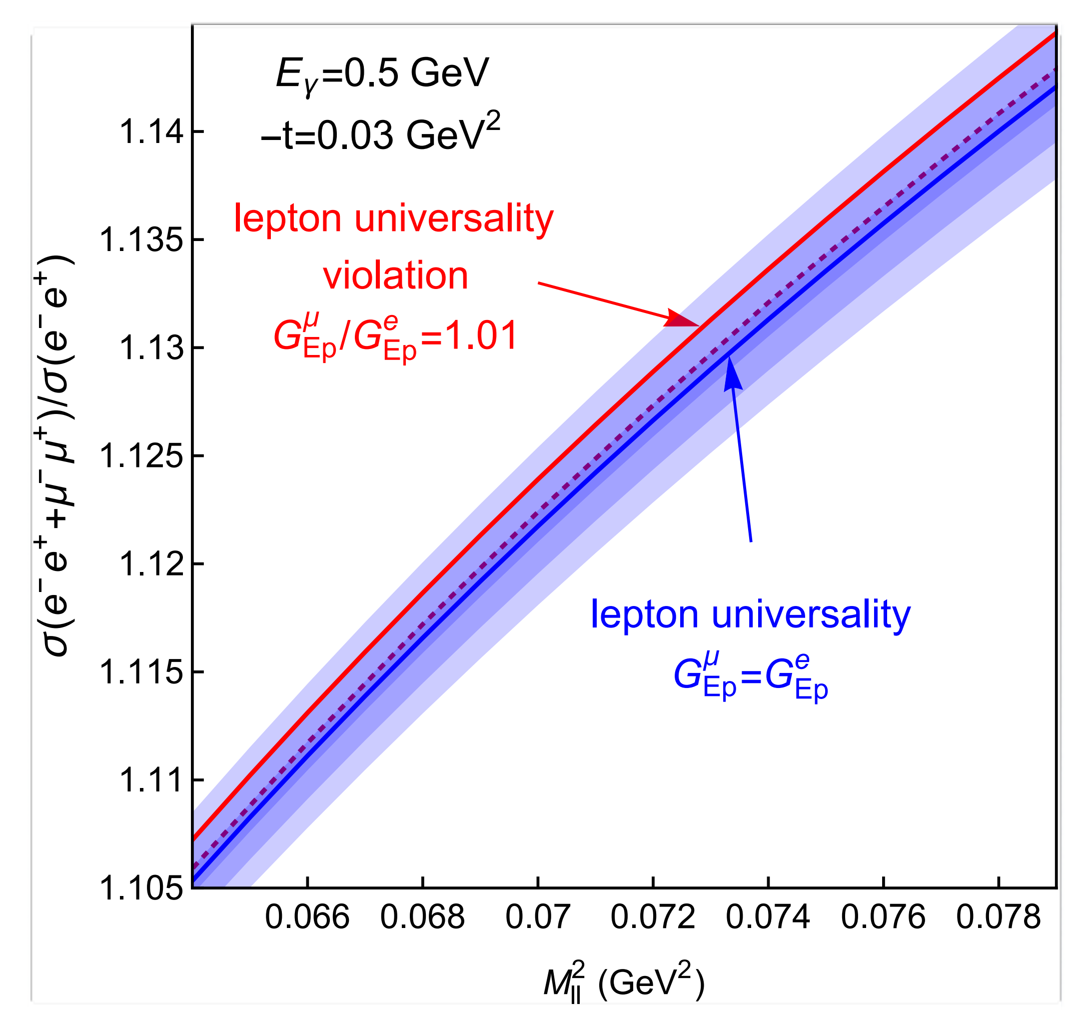
Lepton universality test in $\gamma p \to e^- e^+ p$ vs $\gamma p \to \mu^- \mu^+ p$



$$M_{ll}^2 = (l_- + l_+)^2$$

$$t = (p' - p)^2$$

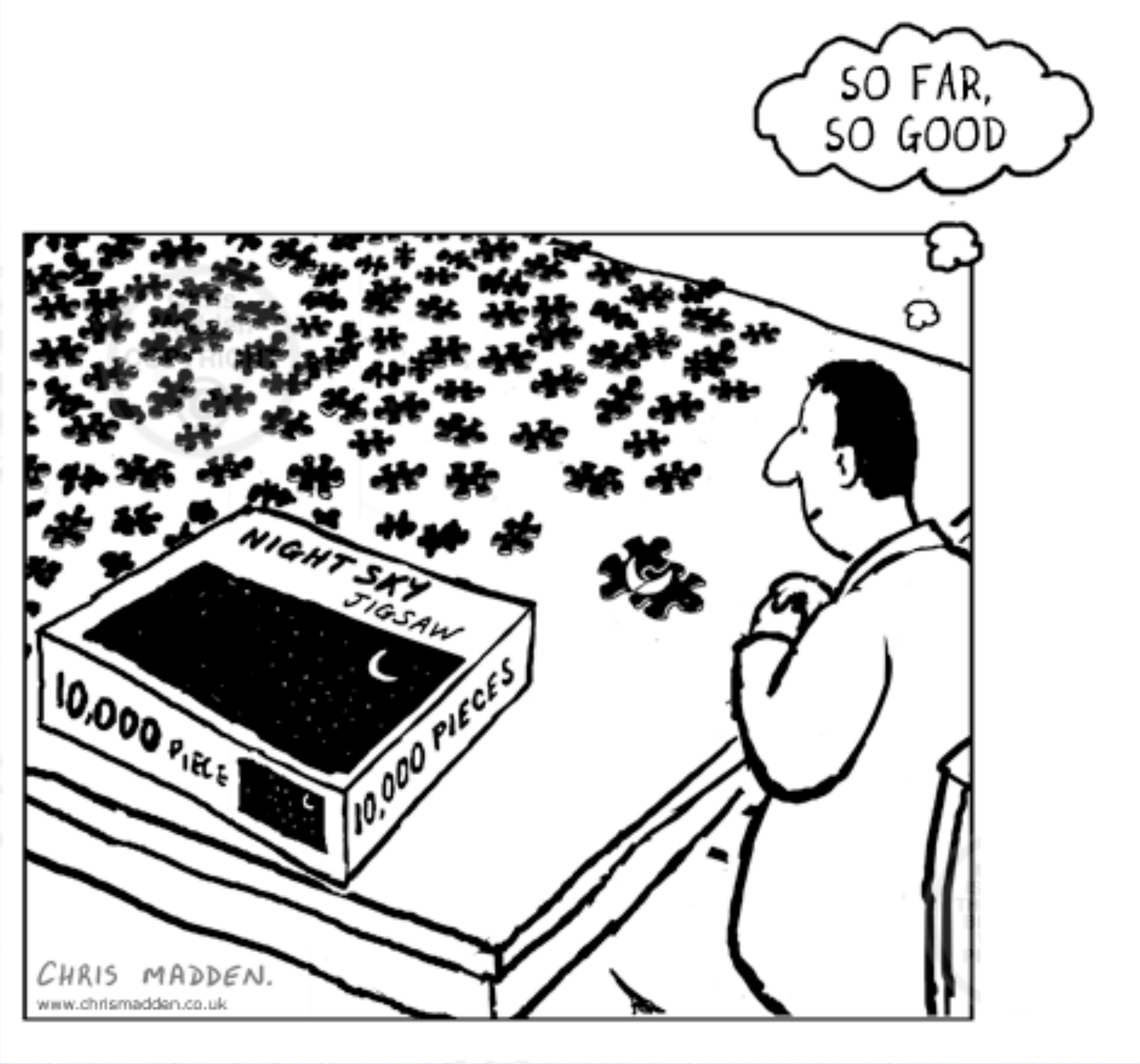




difference in measured proton charge FF
in electron vs muon observables
leads to a **0.2% absolute effect**
in $(e^-e^+ + \mu^-\mu^+)$ vs $\mu^-\mu^+$ ratio

Pauk, Vdh (2015)

Outlook: proton radius puzzle



- precision muonic atom spectroscopy has shifted precision frontier
- generated a large exp/theo activity
  - to scrutinize result
  - to improve on accuracy of hadronic corrections
- what can be expected ?

$\mu\ ^3He^+$, $\mu\ ^4He^+$ (under analysis)

eH Lamb shift (under analysis)

new e^- scattering (in progress)

μ^- scattering (~ 1-2 years)

stay tuned