Status and implications of the proton radius puzzle

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DOE cosmic frontier meeting

23 March 2017

based on the review 1702.01189

thanks especially: J. Arrington, G. Lee, G. Paz, M. Pospelov

Overview

1) description of the puzzle (circa 2010)

2) status of the puzzle (circa 2016/17)

3) some implications

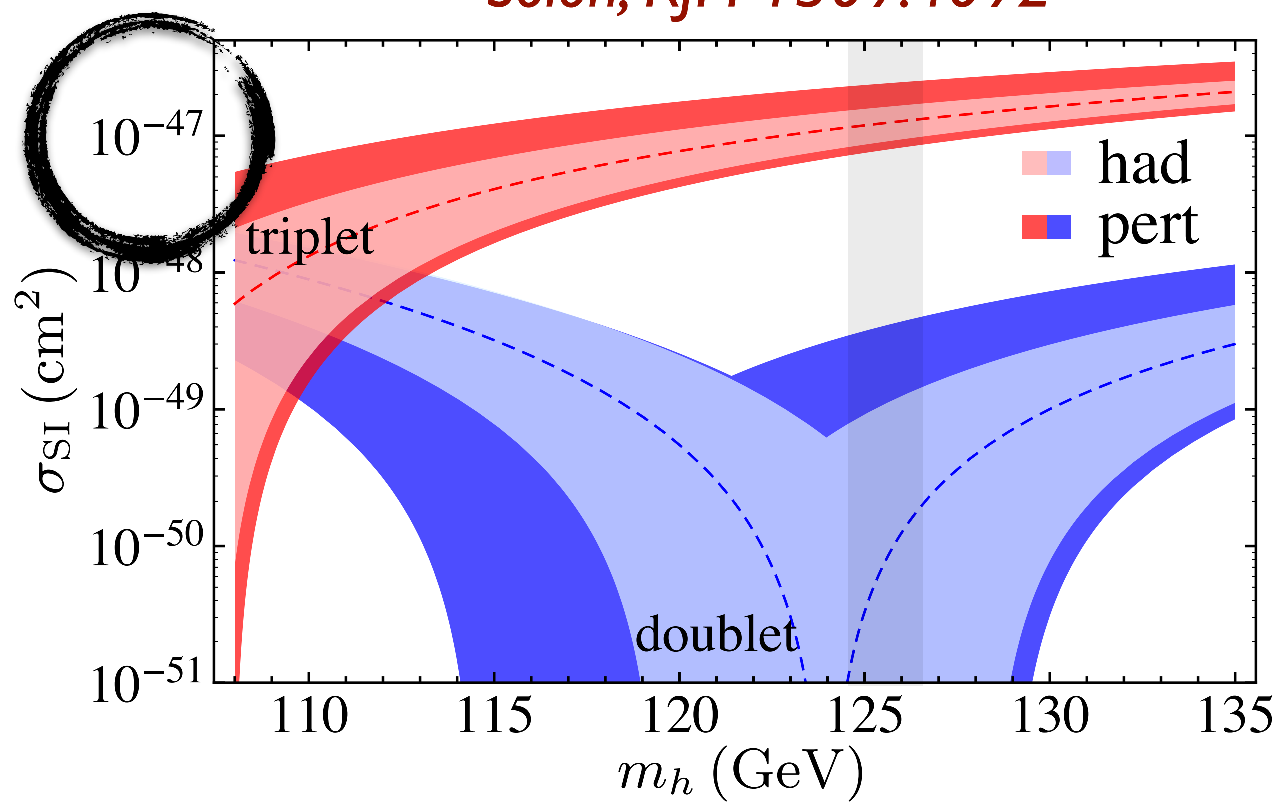
4) summary

Aside (I):

don't give up on the WIMP:

- LHC and other constraints have pushed us to higher mass
- heavy WIMP universality emerges at $M_{DM} > m_W$
- universal cross section turns out to be somewhat small, may explain why no WIMPs so far detected

Solon, RJH 1309.4092



Aside (II):

Lots of theory connections (and not just BSM)

- *QCD technology*: OPE analysis of heavy WIMP scattering, two-photon correction to μH Lamb shift

- *large log resummation*: heavy WIMP annihilation, e-p scattering, ν-N scattering

- *atomic transitions*: fundamental constants, input to ν-N, dark sector searches

- ...

Difficult to separate into particle/nuclear/atomic, or cosmic/energy/intensity

Proton radius puzzle

It's complicated, but some facts:

- 7σ anomaly from measurements in seemingly well-understood systems: hydrogen and electron scattering
- discrepancy between electron and muon measurements
- tension between low Q^2, high Q^2

Modern analysis of these issues is critical for the success of long baseline neutrino program (NOvA, DUNE, T2K, HyperK)

Interesting to consider BSM scenarios

- new physics spinoffs typically involve light bosons

Recall hydrogen spectrum:

$$E_n \sim \frac{R_\infty}{n^2} + \frac{r_E^2}{n^3}$$

$$hcR_\infty = \frac{m_e c^2 \alpha^2}{2} \approx 13.6\,\mathrm{eV}$$

proton charge radius

Disentangle 2 unknowns, R_∞ and r_E, using well-measured 1S-2S hydrogen transition *and*

electron-based measurements

muon-based measurements

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- a muonic hydrogen interval

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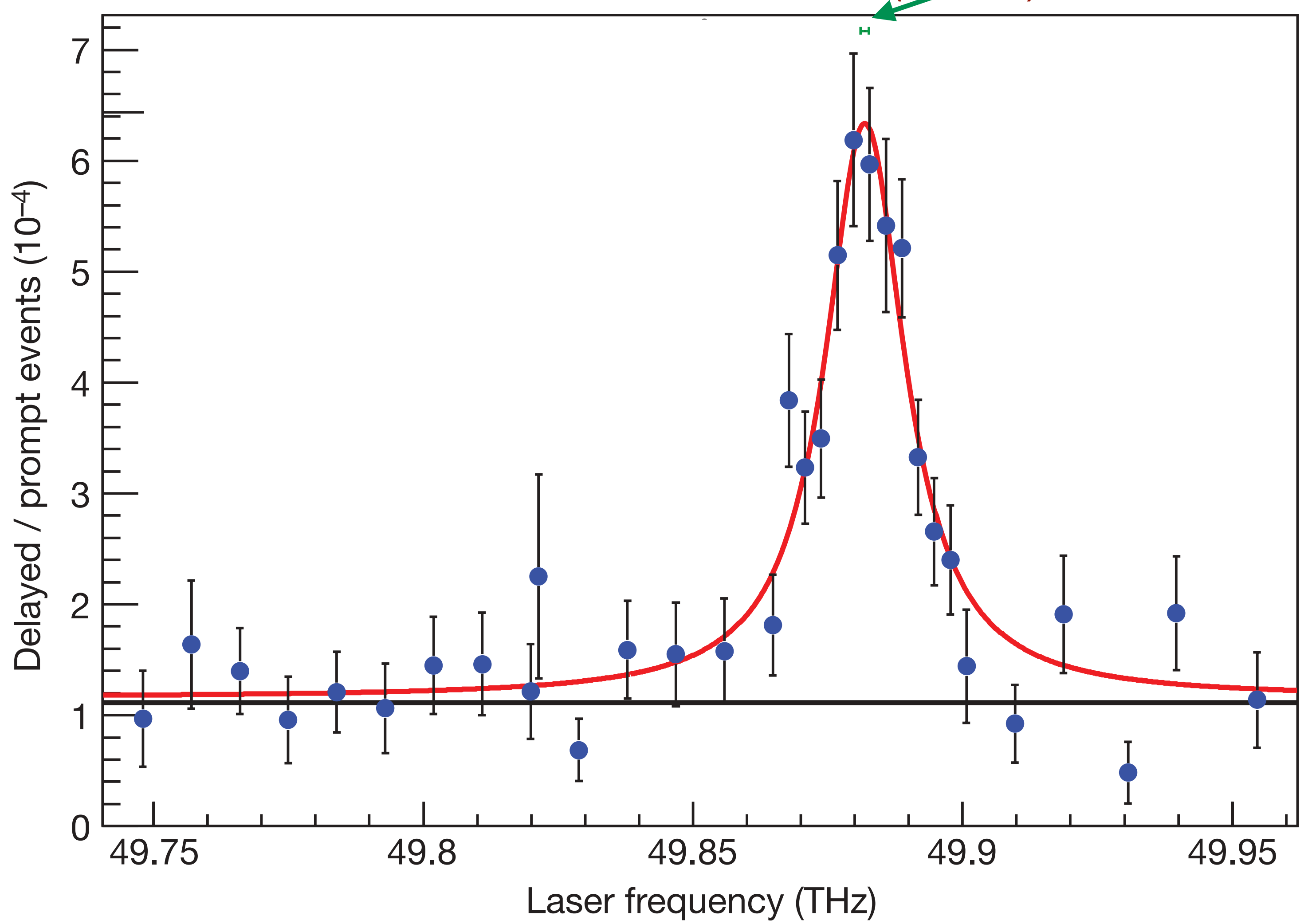
7σ discrepancy between electron-based versus muon-based measurements

muonic hydrogen Lamb shift measurement

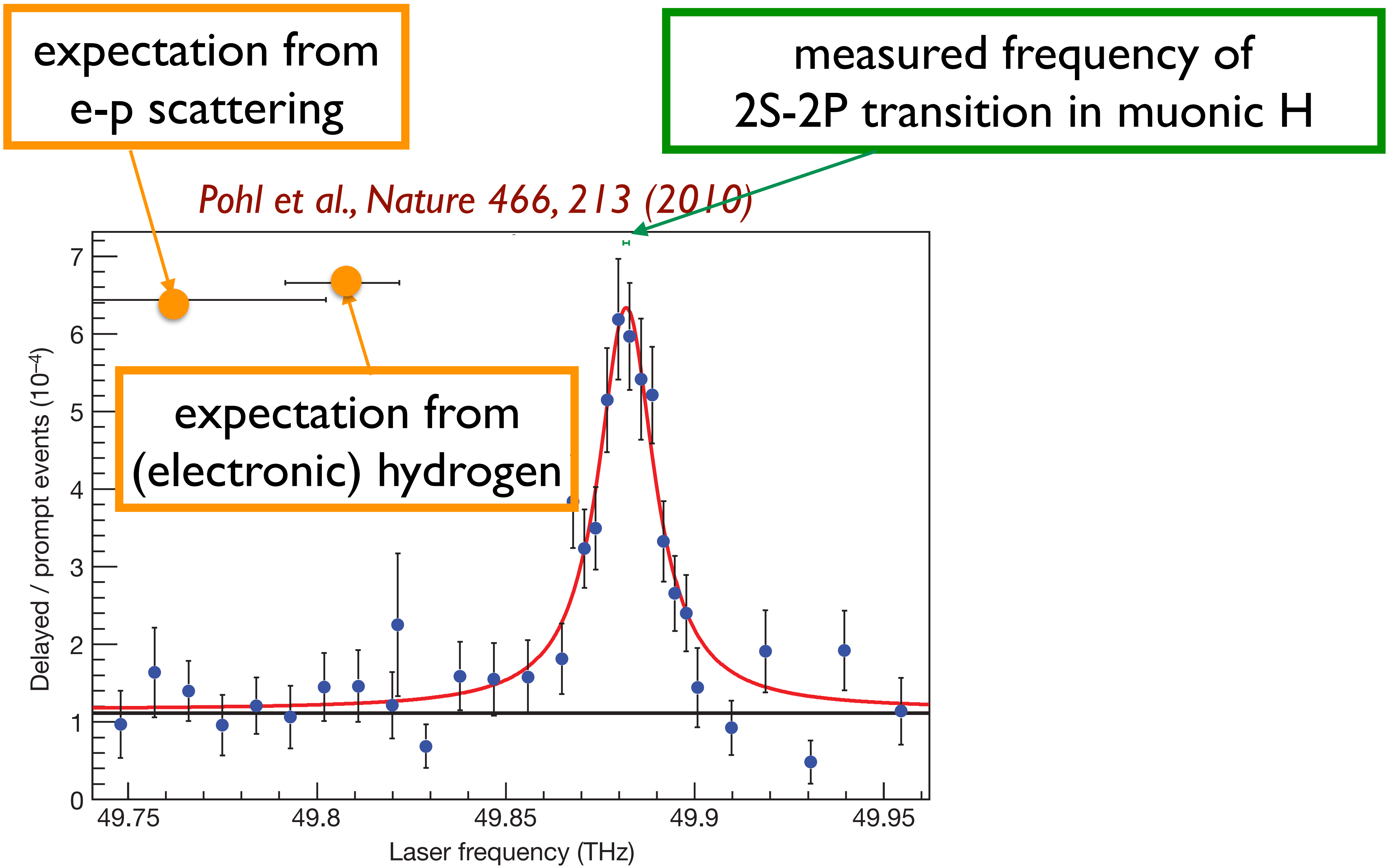
measured frequency of
2S-2P transition in muonic H

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



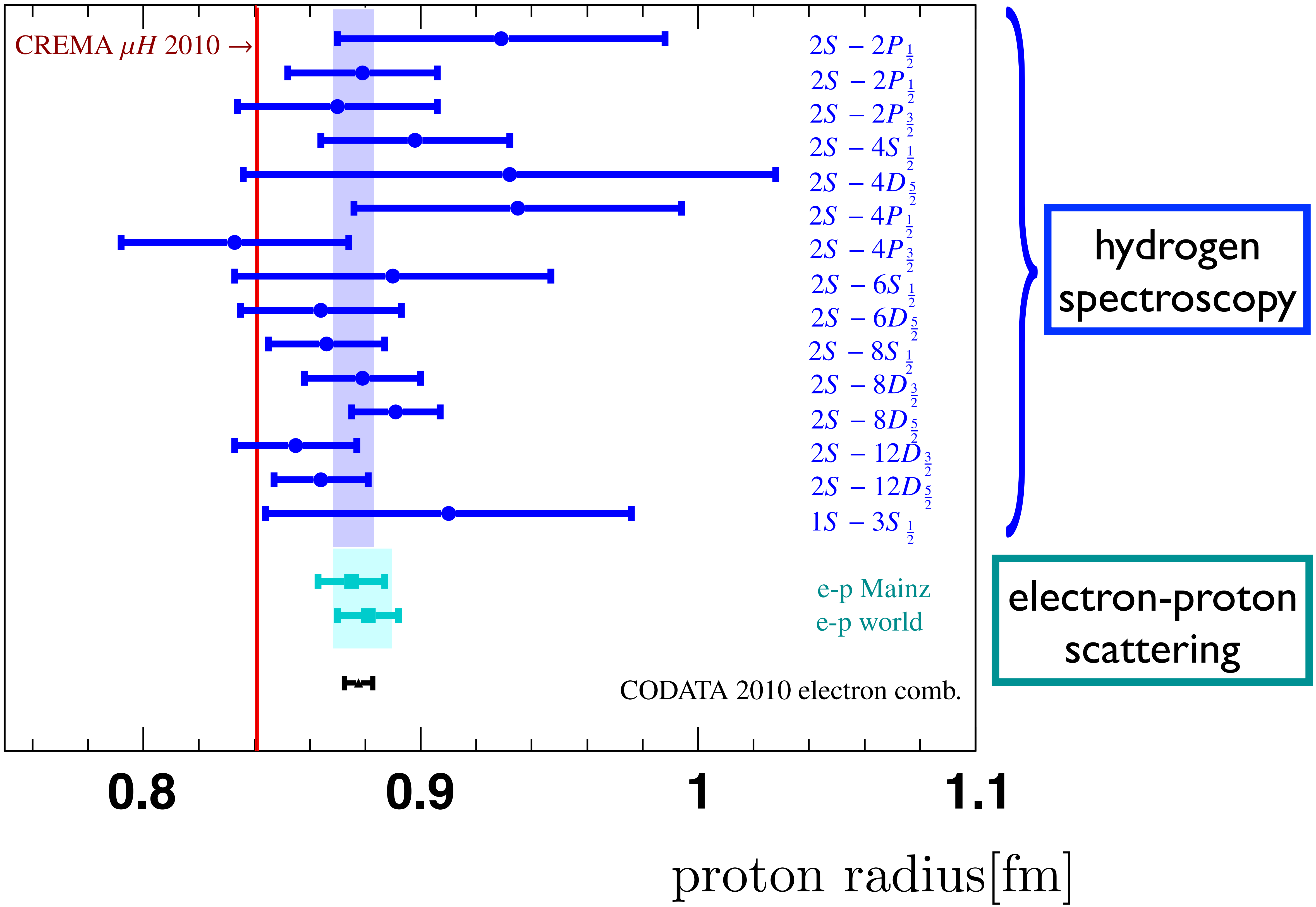
new experimental capabilities: surprises and new insight ?

muonic hydrogen Lamb shift measurement



new experimental capabilities: surprises and new insight ?

summary of electron- and muon- based measurements, circa 2010



electron-proton scattering: theory issues

radius is defined as slope of form factor

i) what are the constraints on nonlinearities?

radiative corrections impact radius extraction and can be large (~30%)

ii) are radiative corrections controlled at the sub percent level?

i) what are the constraints on nonlinearities?

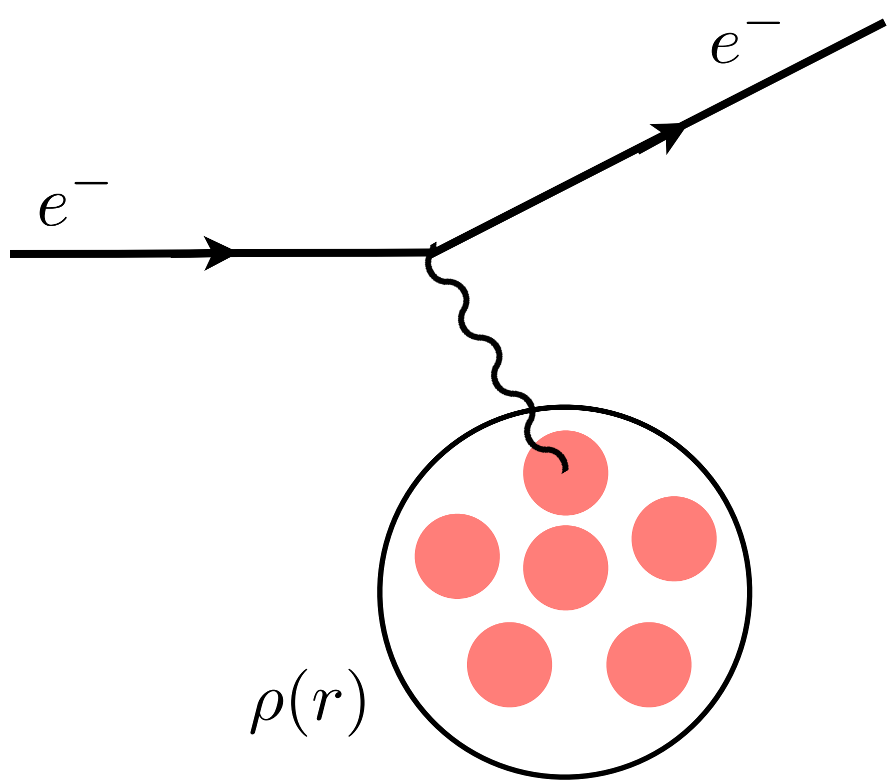
recall scattering from extended classical charge distribution:

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{\text{pointlike}} |F(q^2)|^2$$

$$F(q^2) = \int d^3r\, e^{i\boldsymbol{q}\cdot\boldsymbol{r}} \rho(\boldsymbol{r})$$

$$= \int d^3r \left[1 + i\boldsymbol{q}\cdot\boldsymbol{r} - \frac{1}{2}(\boldsymbol{q}\cdot\boldsymbol{r})^2 + \ldots\right]\rho(r)$$

$$= 1 - \frac{1}{6}\langle r^2\rangle \boldsymbol{q}^2 + \ldots$$



for the relativistic, QM, case, *define* radius as slope of form factor

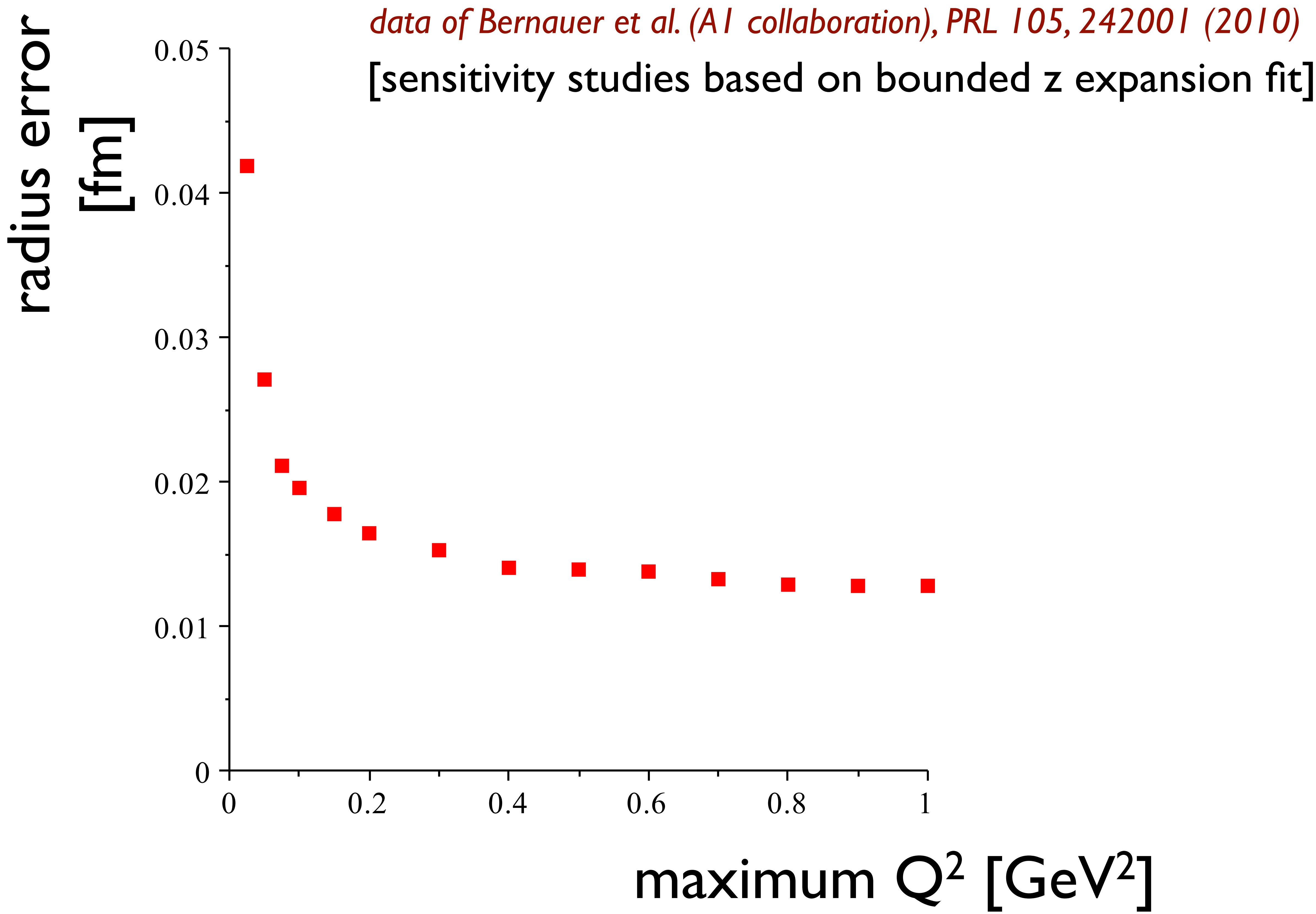
$$\langle J^\mu\rangle = \gamma^\mu F_1 + \frac{i}{2m_p}\sigma^{\mu\nu}q_\nu F_2$$

$$G_E = F_1 + \frac{q^2}{4m_p^2}F_2 \qquad G_M = F_1 + F_2$$

$$\boxed{r_E^2 \equiv 6\frac{d}{dq^2}G_E(q^2)\Big|_{q^2=0}}$$

(up to radiative corrections)

Radius extraction requires data over a Q^2 range where a simple Taylor expansion of the form factor is invalid



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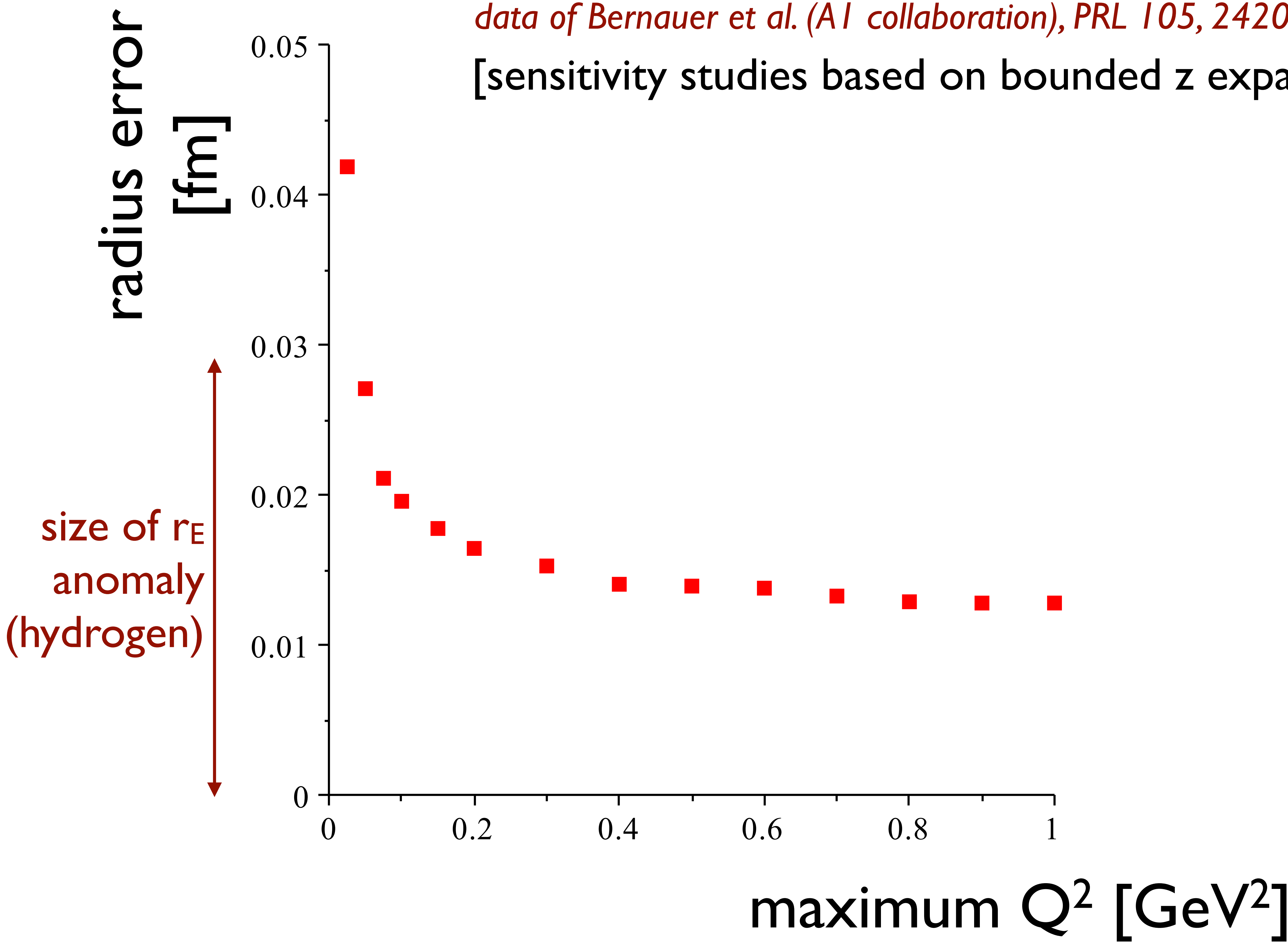
data of Bernauer et al. (A1 collaboration), PRL 105, 242001 (2010)

[sensitivity studies based on bounded z expansion fit]



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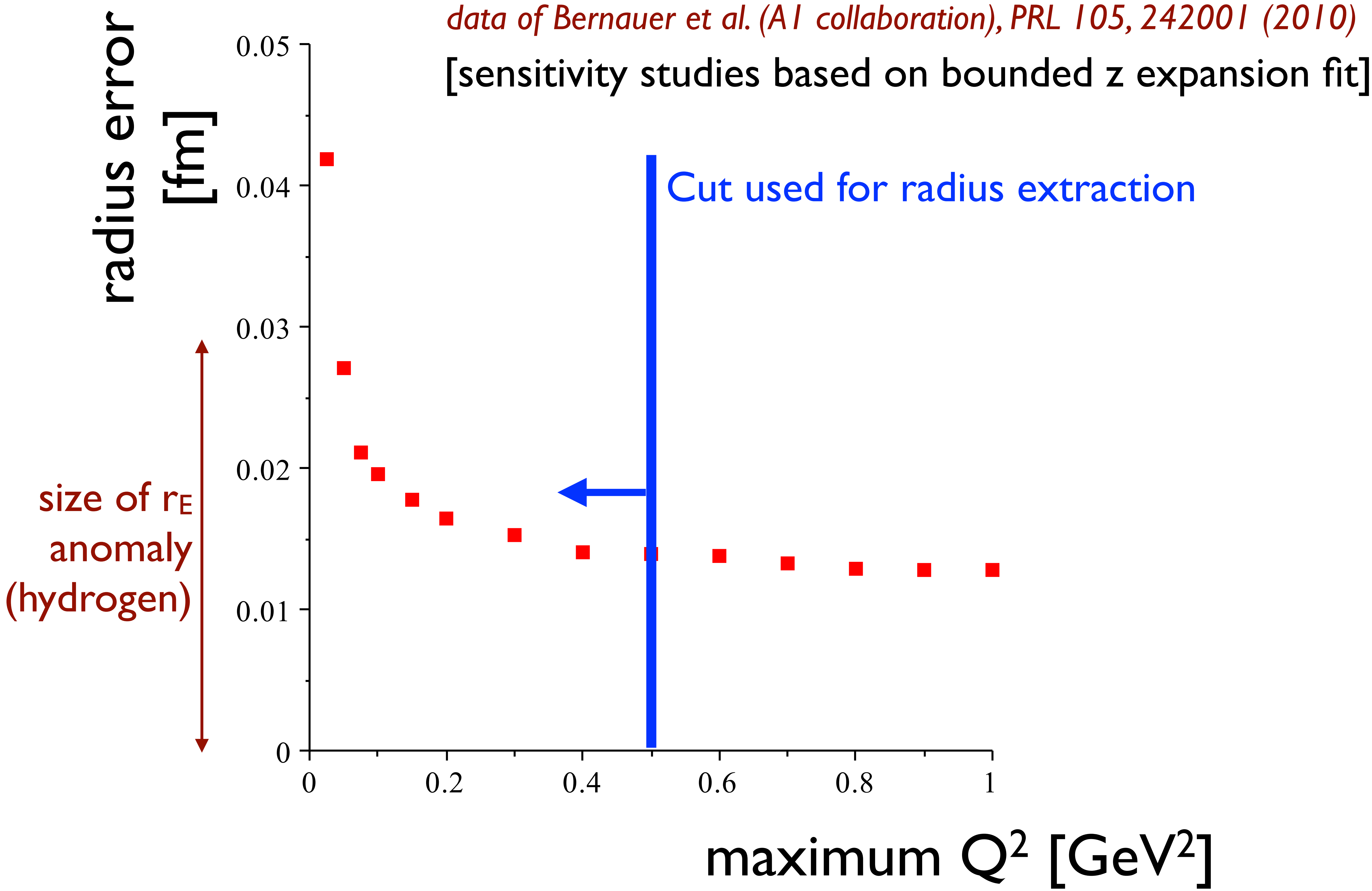

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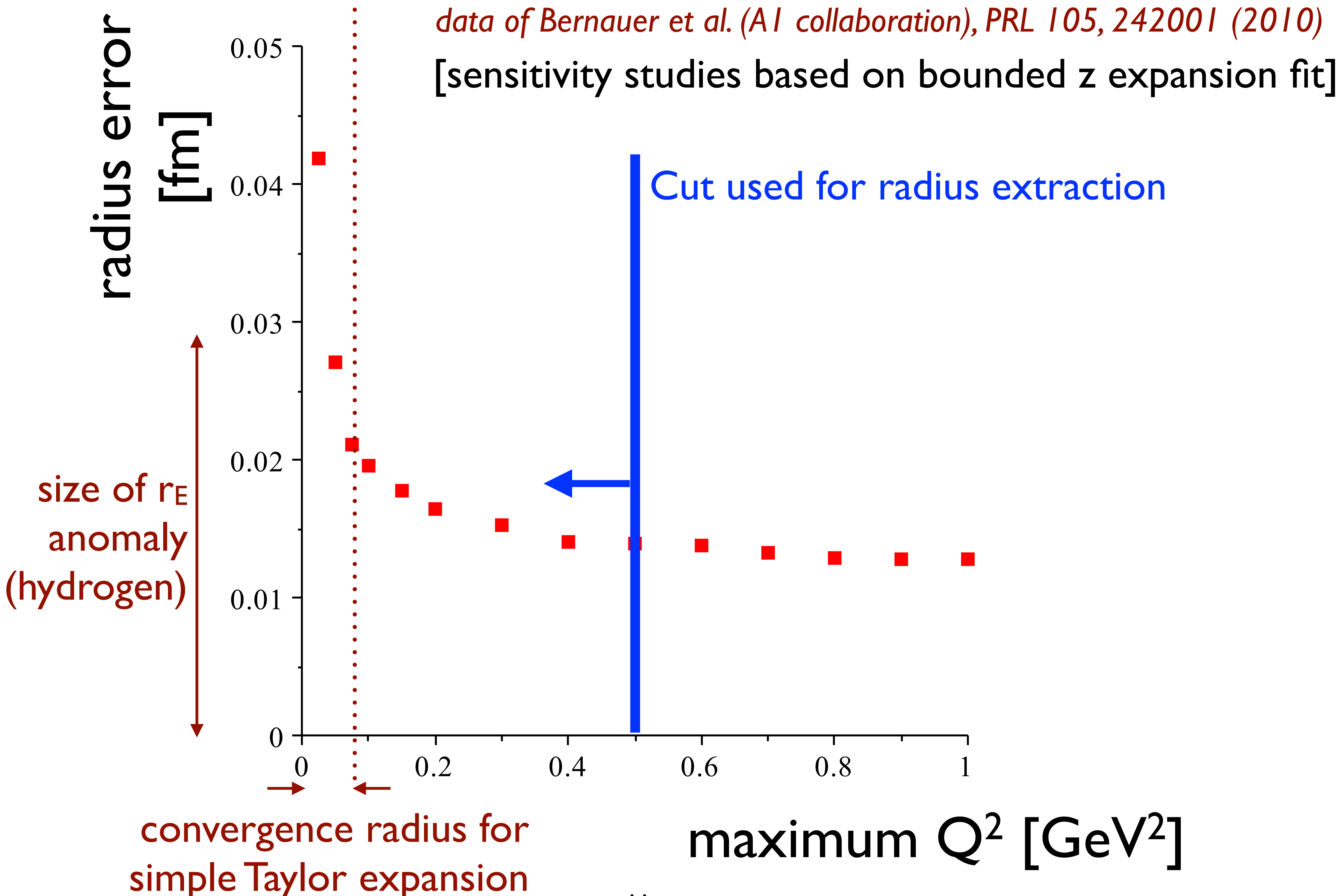
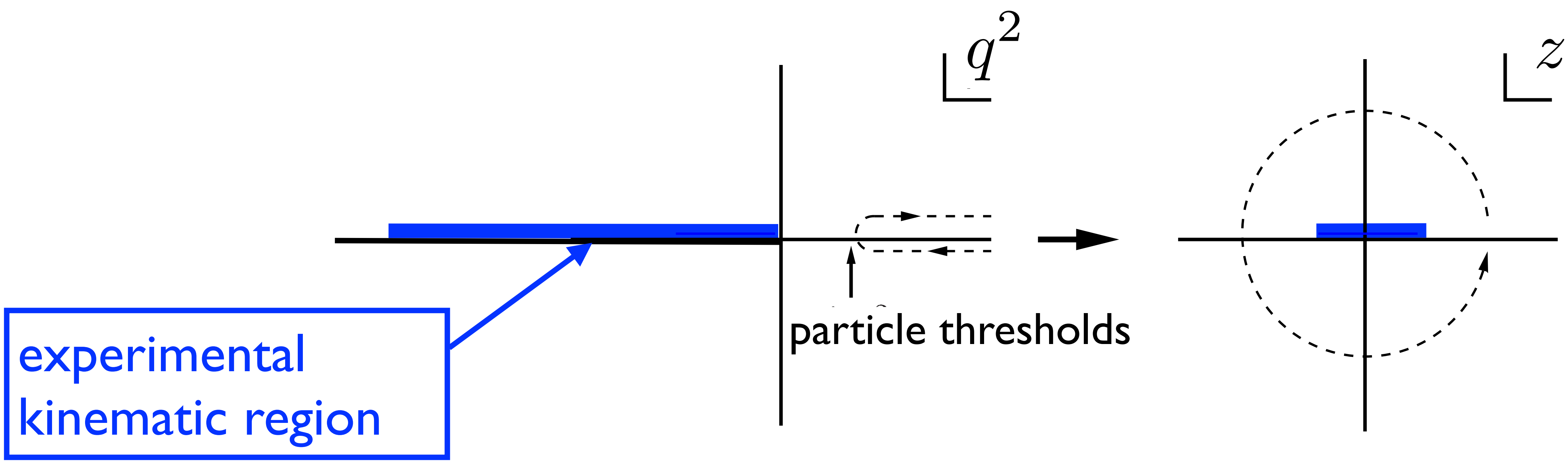


That's ok: underlying QCD tells us that Taylor expansion of form factor in appropriate variable is convergent

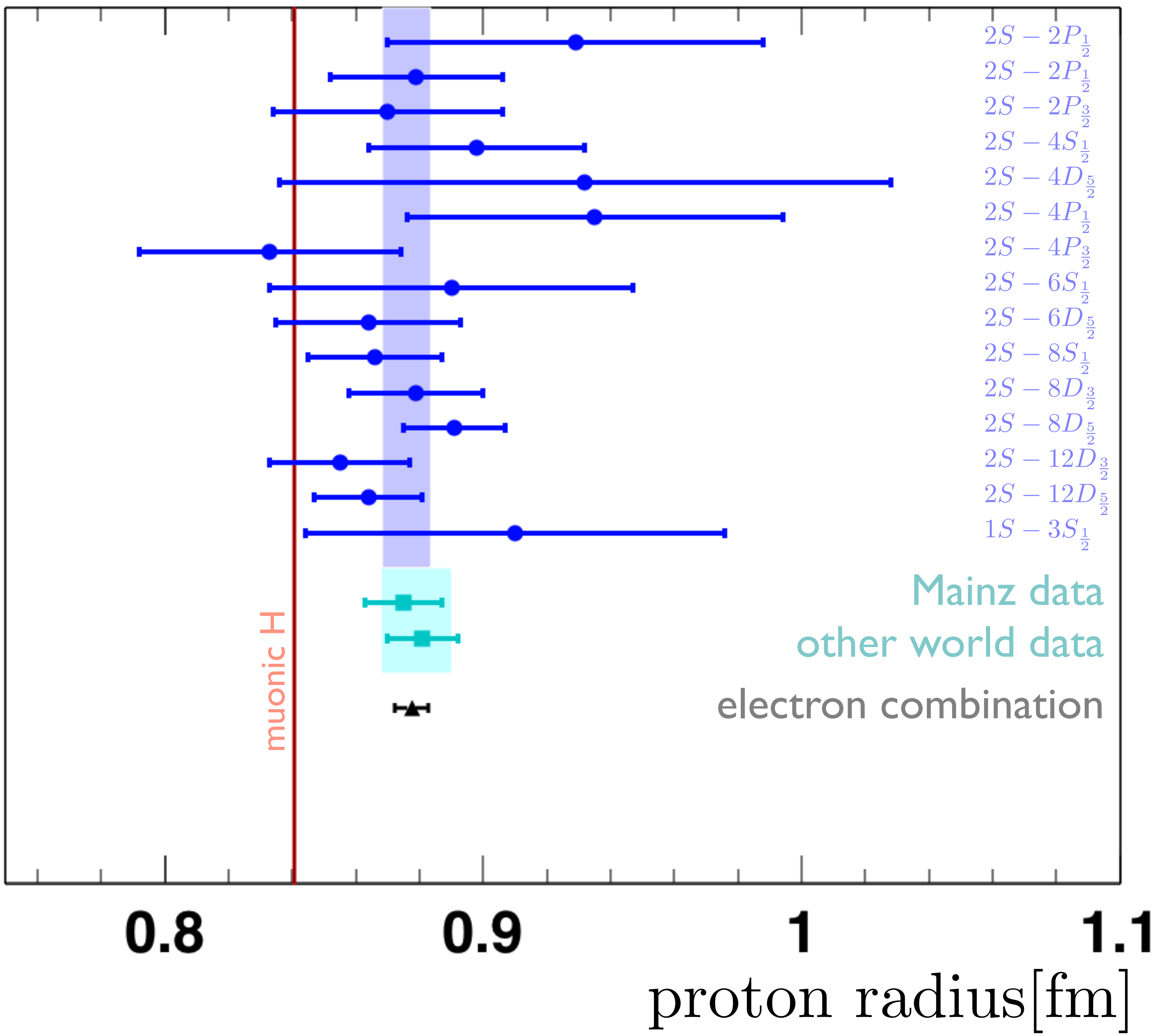


$$z(q^2, t_{\rm cut}, t_0) = \frac{\sqrt{t_{\rm cut} - q^2} - \sqrt{t_{\rm cut} - t_0}}{\sqrt{t_{\rm cut} - q^2} + \sqrt{t_{\rm cut} - t_0}}$$

$$F(q^2) = \sum_k a_k [z(q^2)]^k$$

coefficients in rapidly convergent expansion encode nonperturbative QCD

Reanalysis of scattering data reveals strong influence of shape assumptions



Errors larger, but discrepancy remains

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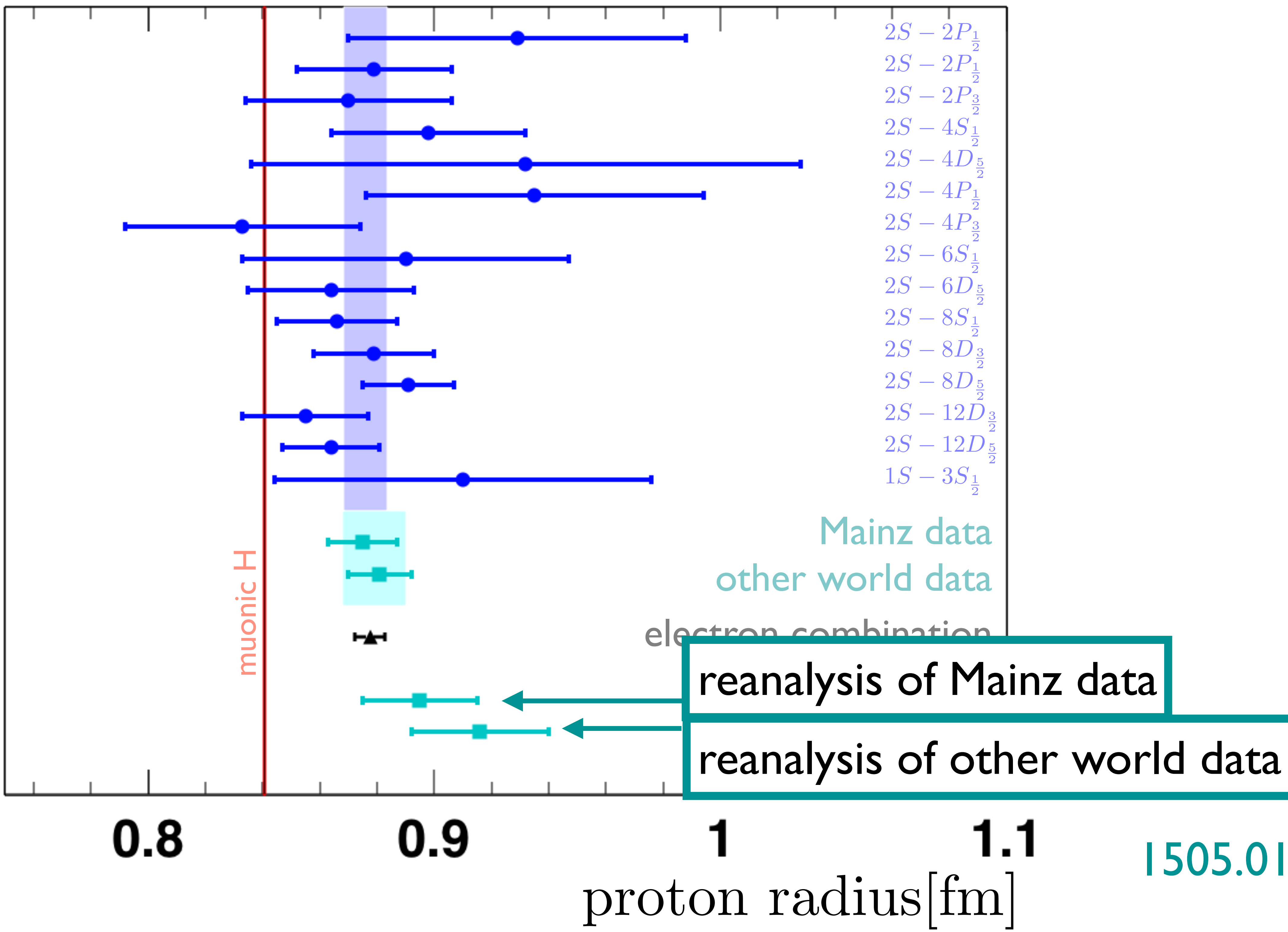

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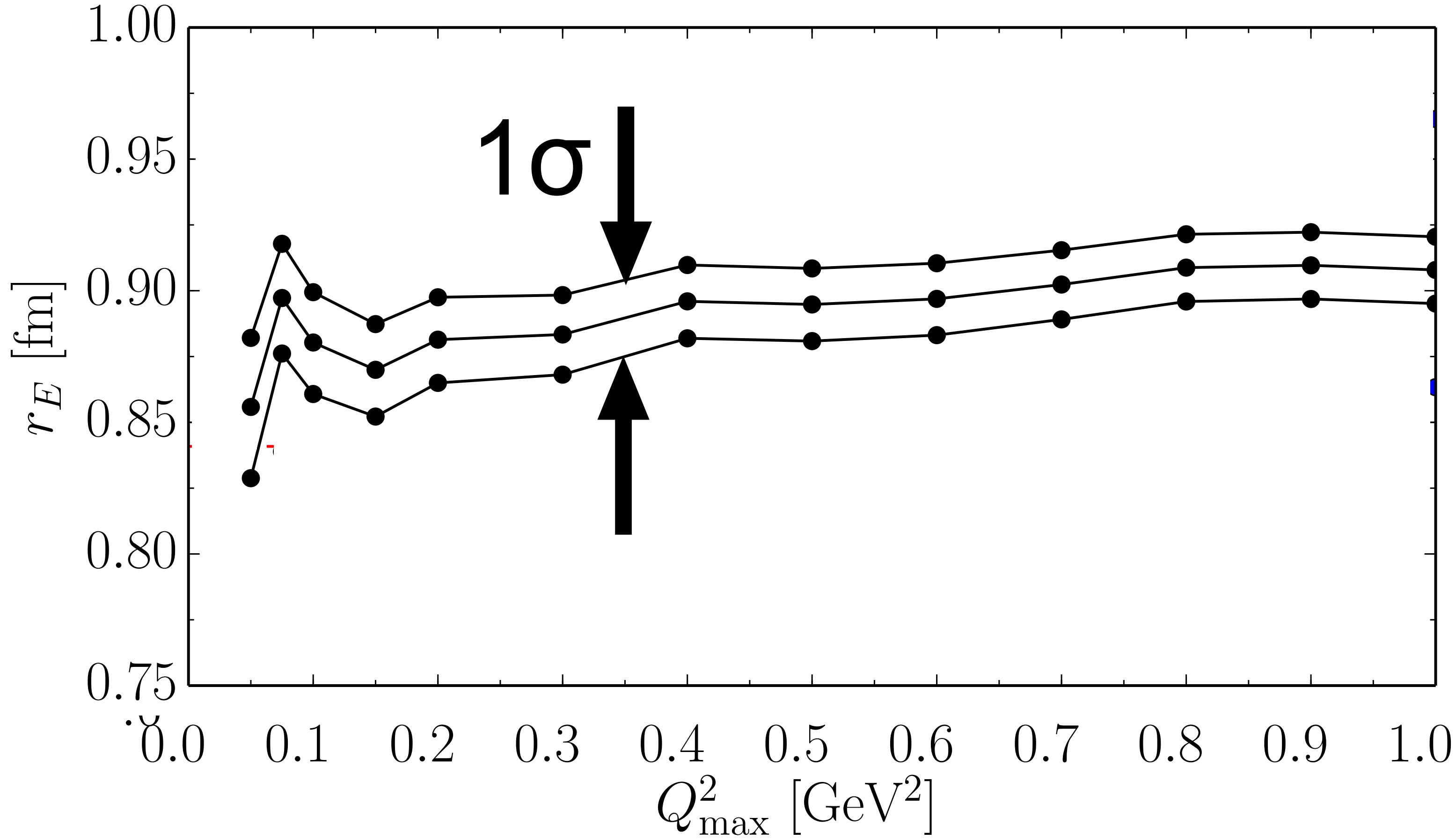
Errors larger, but discrepancy remains

Reanalysis of scattering data also reveals potential dependence of radius on chosen Q^2 range



To reconcile e-p scattering with muonic hydrogen, could:

- consider only small Q^2 data (less data ⇒ larger error)
- overrule scattering data with other data or assumptions, e.g. spectral function model

These options would avoid, but not resolve, the radius puzzle from electron scattering. Is there an unaccounted systematic effect impacting especially large Q^2 data? *(similar Q^2 dependence observed in independent datasets)*

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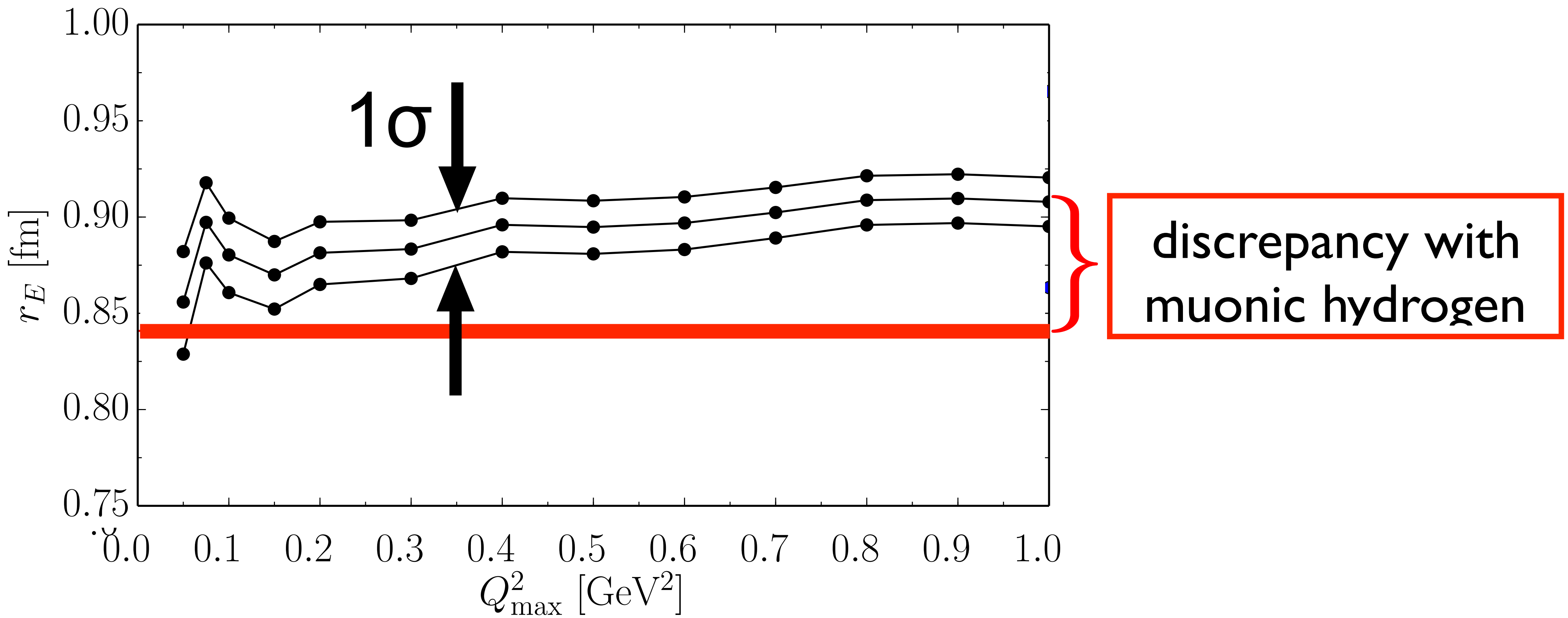

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Renormalization analysis for log-enhanced radiative corrections

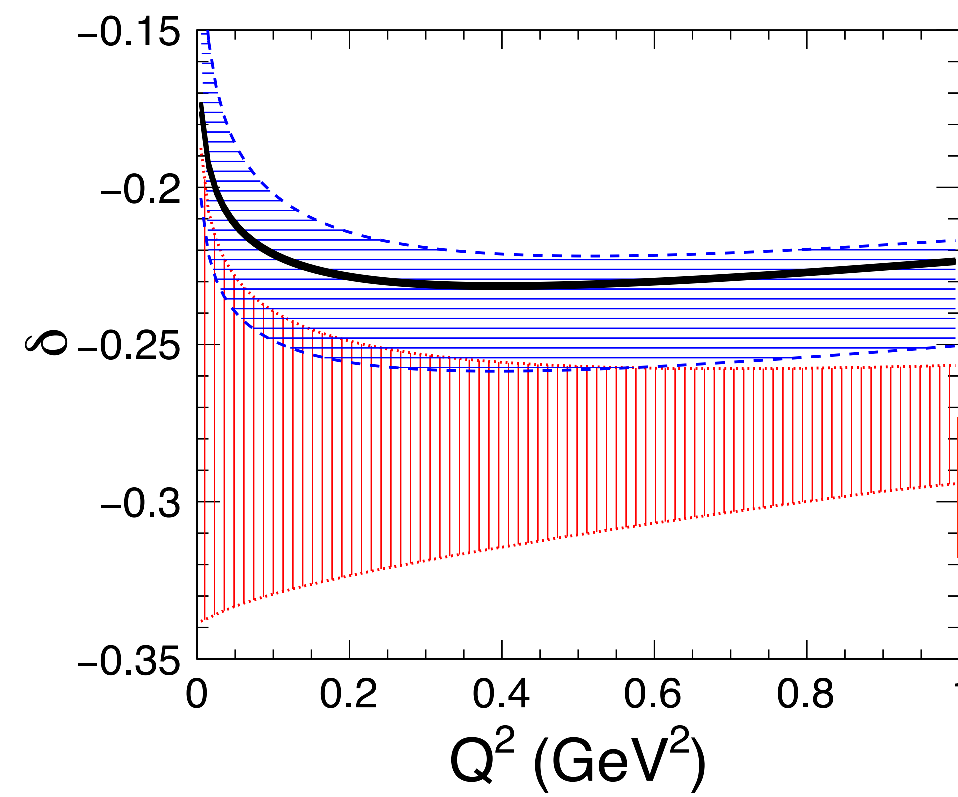
$$d\sigma = \underbrace{H(M)}_{\text{hadron structure}} \times \underbrace{\frac{H(\mu)}{H(M)} \times J(\mu) \times S(\mu)}_{\text{radiative correction}}$$

numerically: $\alpha L^2 = \alpha \log^2 \frac{Q^2}{m^2} \sim 1 \quad \Rightarrow \quad \alpha L \sim \alpha^{\frac{1}{2}}$, etc.

electron energy: $E = 1\,\mathrm{GeV}$

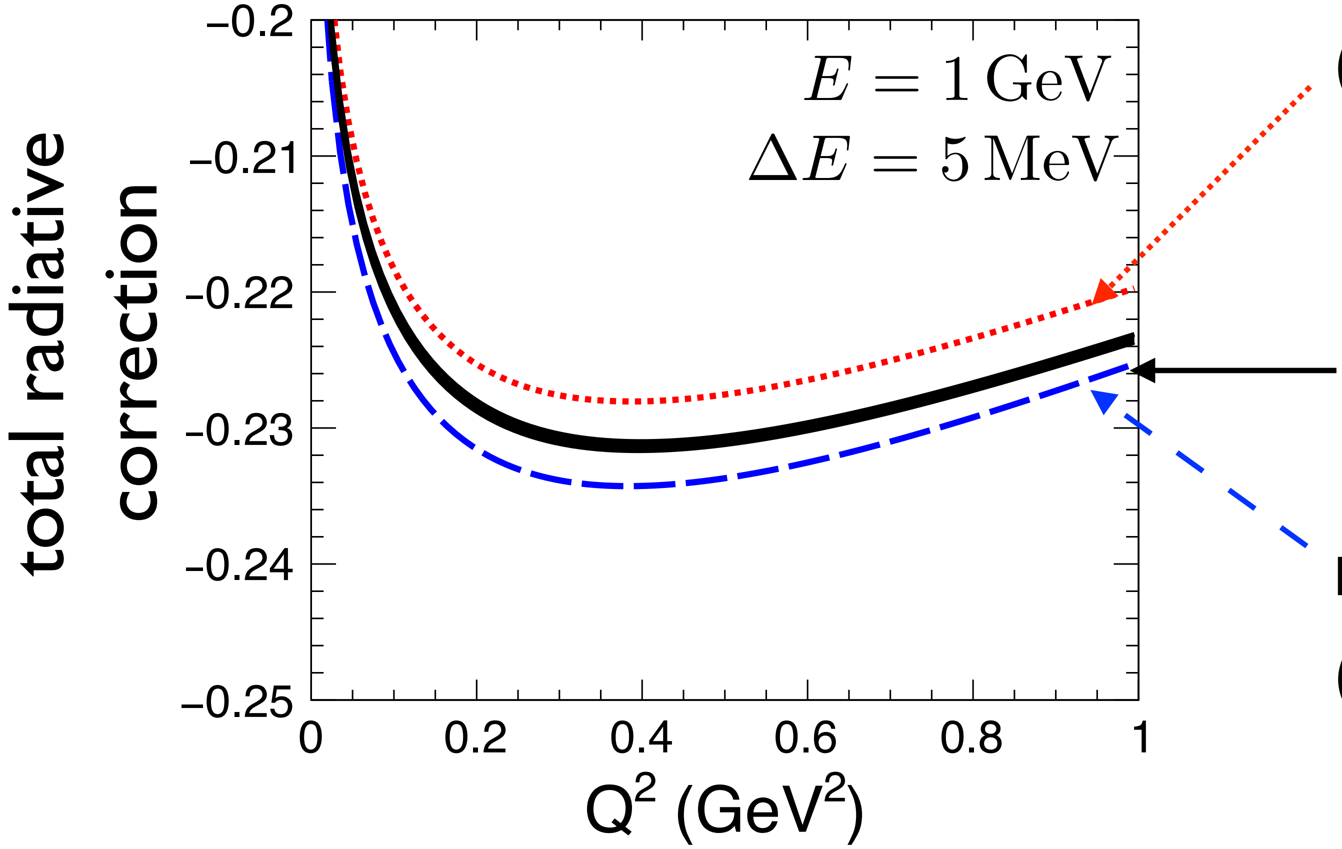
electron energy loss cut: $\Delta E = 5\,\mathrm{MeV}$

total radiative correction



	correct through:
NLO	$\mathcal{O}(\alpha)$
NLL	$\mathcal{O}(\alpha^{\frac{1}{2}})$
LL	$\mathcal{O}(1)$

Comparison to previous implementations of radiative corrections, e.g. in A1 analysis of electron-proton scattering data



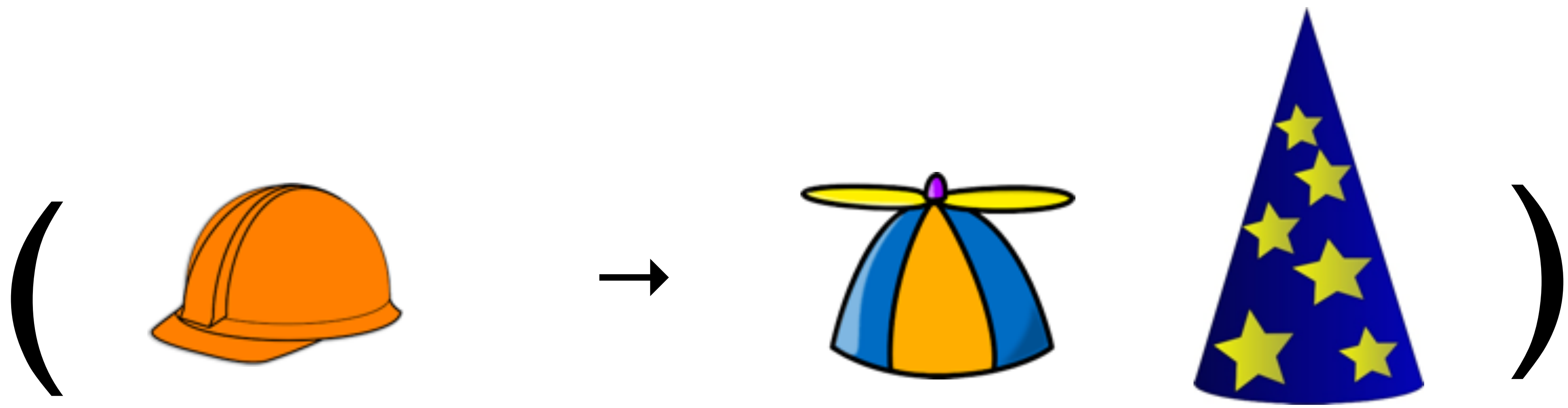
naive exponentiation of 1-loop, ($\mu^2=M^2$ in two-photon piece)

resummed EFT result

naive exponentiation of 1-loop, ($\mu^2=Q^2$ in two-photon piece)

- discrepancies at 0.5-1% compared to currently applied radiative correction models (cf. 0.2-0.5% systematic error budget of A1 experiment)
- should be implemented directly in analysis, but doesn't appear to resolve anomaly (floating normalizations)
- model dependence in hard two-photon exchange remains

Some BSM toy models



$$\mathcal{L} = \mathcal{L}_{\rm SM} + X$$

- X = vector
- X = scalar - nucleon contact interaction
  - quark contact interaction
  - light scalar mediator
- X = vector with parity violating couplings

Some BSM toy models

Haeckel, Roy (2010)

...

$$\mathcal{L} = \mathcal{L}_{\rm SM} + X$$

X = vector (maybe kinetically mixed photon)

$$\kappa V_\mu J^\mu_{\rm e.m.} \quad , \ldots$$

modification to Coulomb force

$$-\frac{e^2}{Q^2}F(Q^2) \to -\frac{e^2}{Q^2}F(Q^2) \mp \frac{g^2}{Q^2+m_V^2}$$

- depending on mass, consistent with $r_{eH} \sim r_{\mu H} < r_{e\text{-}p}$
- may (still) be an interesting scenario (await new eH results)

Some BSM toy models

$$\mathcal{L} = \mathcal{L}_{\rm SM} + X$$

X = scalar nucleon contact interactions

$$\bar{\mu}\mu\left[c_p\bar{p}p + c_n\bar{n}n\right]$$

$$c_p = -\frac{e^2}{6}\left([R_p^2]^{(\mu)} - [R_p^2]^{(e)}\right)$$

$$c_n = -\frac{e^2}{6}\left([R_n^2]^{(\mu)} - [R_n^2]^{(e)}\right) = -\frac{e^2}{6}\left([R_D^2]^{(\mu)} - [R_p^2]^{(\mu)} - \left[[R_D^2]^{(e)} - [R_p^2]^{(e)}\right]\right)$$

μD Lamb shift *μH Lamb shift* *H-D isotope shift*

- phenomenologically, $c_n \ll c_p$

Some BSM toy models

$$\mathcal{L} = \mathcal{L}_{\rm SM} + X$$

X = scalar quark contact interactions

$$\bar{\mu}\mu\left[c_u \bar{u}u + c_d \bar{d}d\right]$$

$$c_u + c_d = \frac{m_u + m_d}{2\Sigma_{\pi N}}\left(c_p + c_n\right)$$

$$c_u - c_d = \frac{m_u + m_d}{2\Sigma_{\pi N}}\frac{1}{\xi}\left(c_p - c_n\right)$$

$$\Sigma_{\pi N} = \frac{m_u + m_d}{2}\langle N|(\bar{u}u + \bar{d}d)|N\rangle \sim 40\,\mathrm{MeV}$$

$$\Sigma_{-} = (m_u - m_d)\langle N|(\bar{u}u - \bar{d}d)|N\rangle \sim 2\,\mathrm{MeV}$$

$$\xi = \frac{m_u + m_d}{m_d - m_u}\frac{\Sigma_-}{2\Sigma_{\pi N}} \ll 1$$

- $c_n \ll c_p \implies (c_u+c_d)/(c_u-c_d) \ll 1$. Large isospin violation
- contact interaction limit disfavored by existing constraints e.g.: $\Gamma(\eta\to\pi^0\mu^+\mu^-)$

Some BSM toy models

$$\mathcal{L} = \mathcal{L}_{\rm SM} + X$$

Barger, Chiang, Leung, Marfatia (2010)

Tucker-Smith, Yavin (2011)

Liu, McKeen, Miller (2016)

...

X = scalar mediator

$$S\left[g_\mu \bar{\mu}\mu + g_p \bar{p}p\right]$$

- might be relevant to $(g-2)_\mu$
- many interesting constraints
- interesting parameter space: $m_S \sim$ 1-10 MeV, $g_\mu, g_p \sim 10^{-4}$-10^{-3}
- can also phrase at quark level, connect to rare meson physics

Some BSM toy models

$$\mathcal{L} = \mathcal{L}_{\rm SM} + X$$

Batell, McKeen, Pospelov (2011)

McKeen, Pospelov (2012)

Karshenboim, McKeen, Pospelov (2014)

...

X = vector with parity violation

$$V_\mu \left(\kappa J^\mu_{\rm e.m.} + \bar{\mu} \left[g_V \gamma^\mu + g_A \gamma^\mu \gamma_5 \right] \mu \right)$$

- tunings for consistency with $(g\text{-}2)_\mu$, atomic PV

- may be interesting implications for new tests with spin-dependence (HFS in muonium) and parity violation (PV in muonic atoms)

Summary

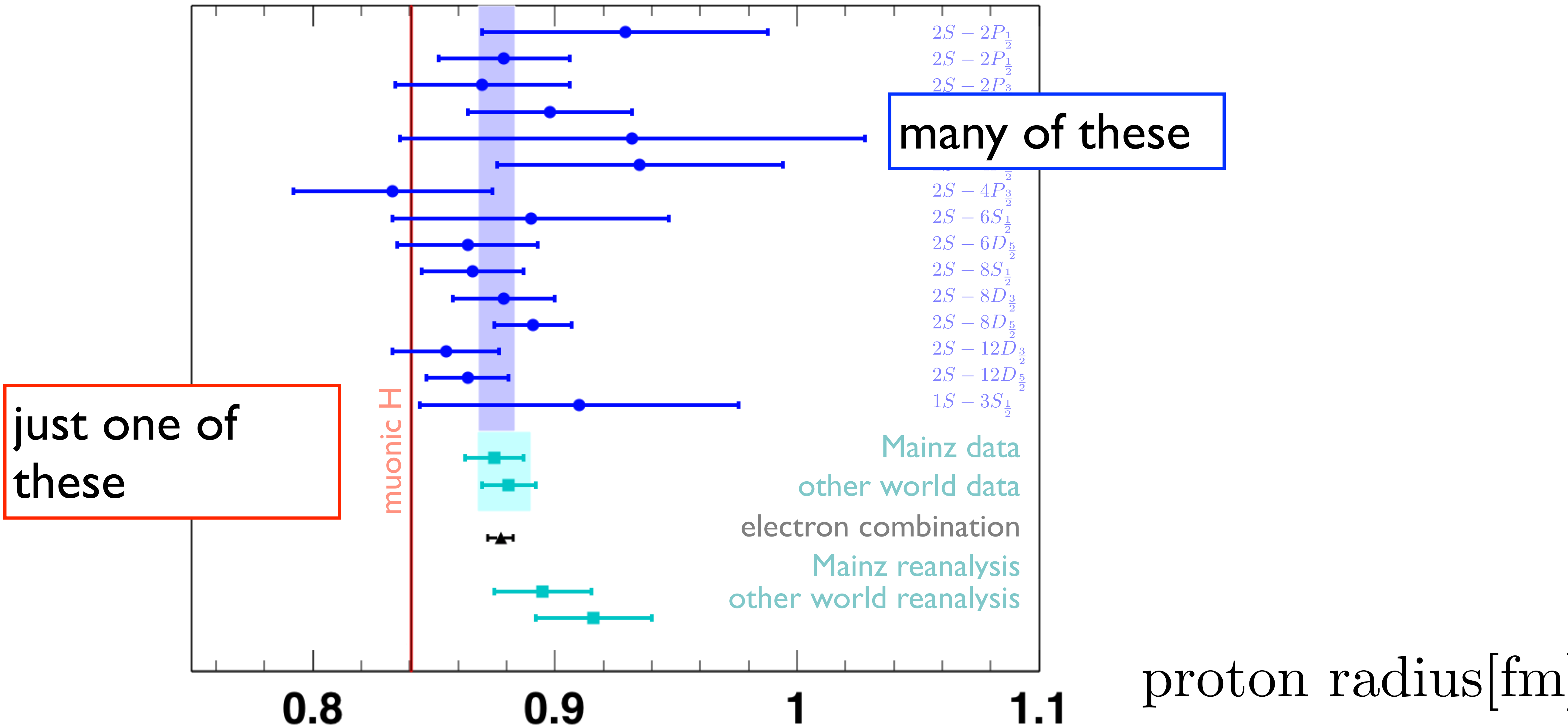
• proton radius puzzle: most mundane resolution involves ~7σ shift in Rydberg (and proton radius)

• muonic hydrogen: disruptive technology for hydrogen, e-p scattering (also muon capture, ν-N scattering)

• theory: common to e-p scattering, ν-N scattering (DUNE), heavy WIMP annihilation, …

• BSM toy models: motivation to look for light particles distinguishing e, μ

spectroscopy of other light muonic atoms: D, He



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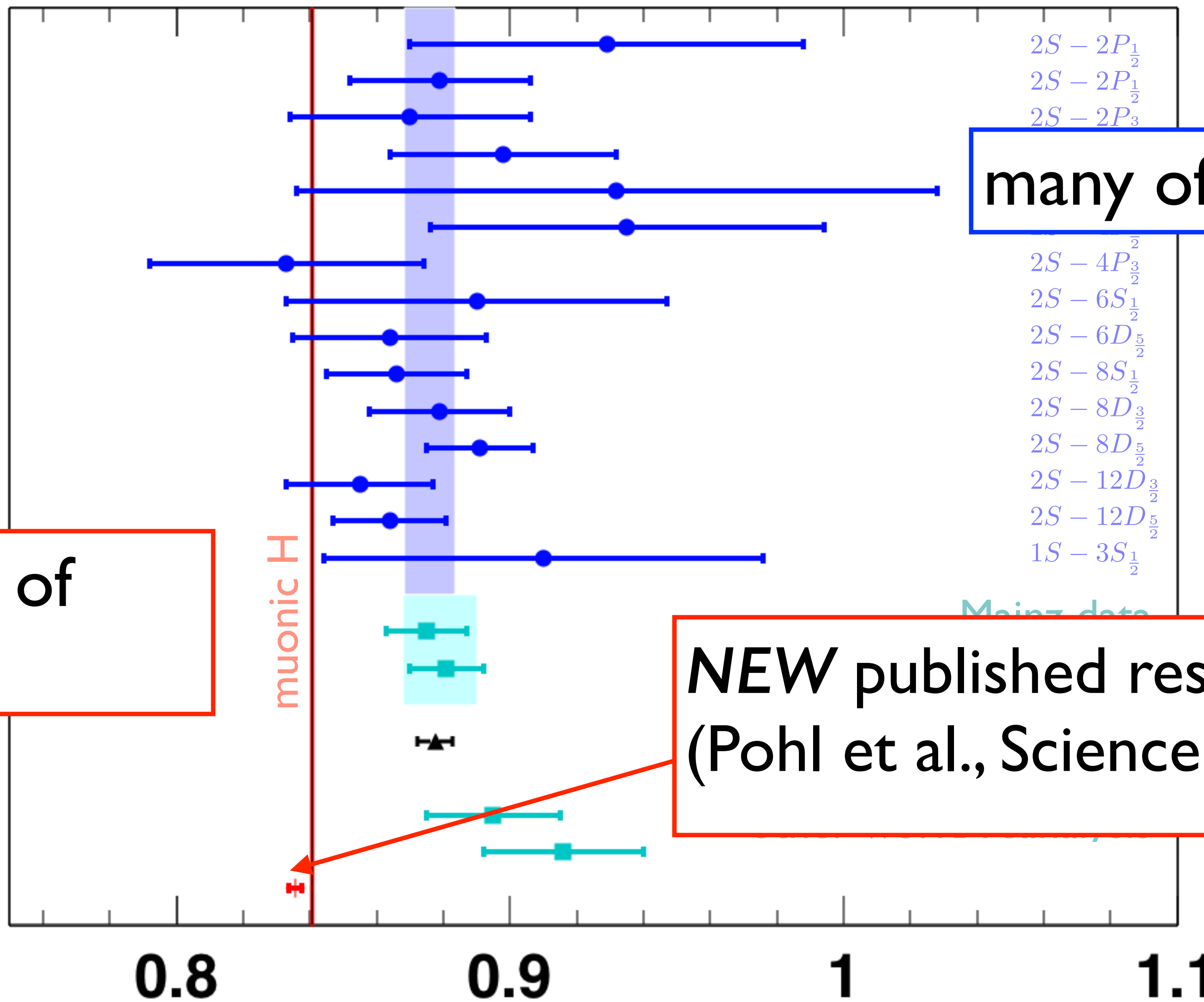


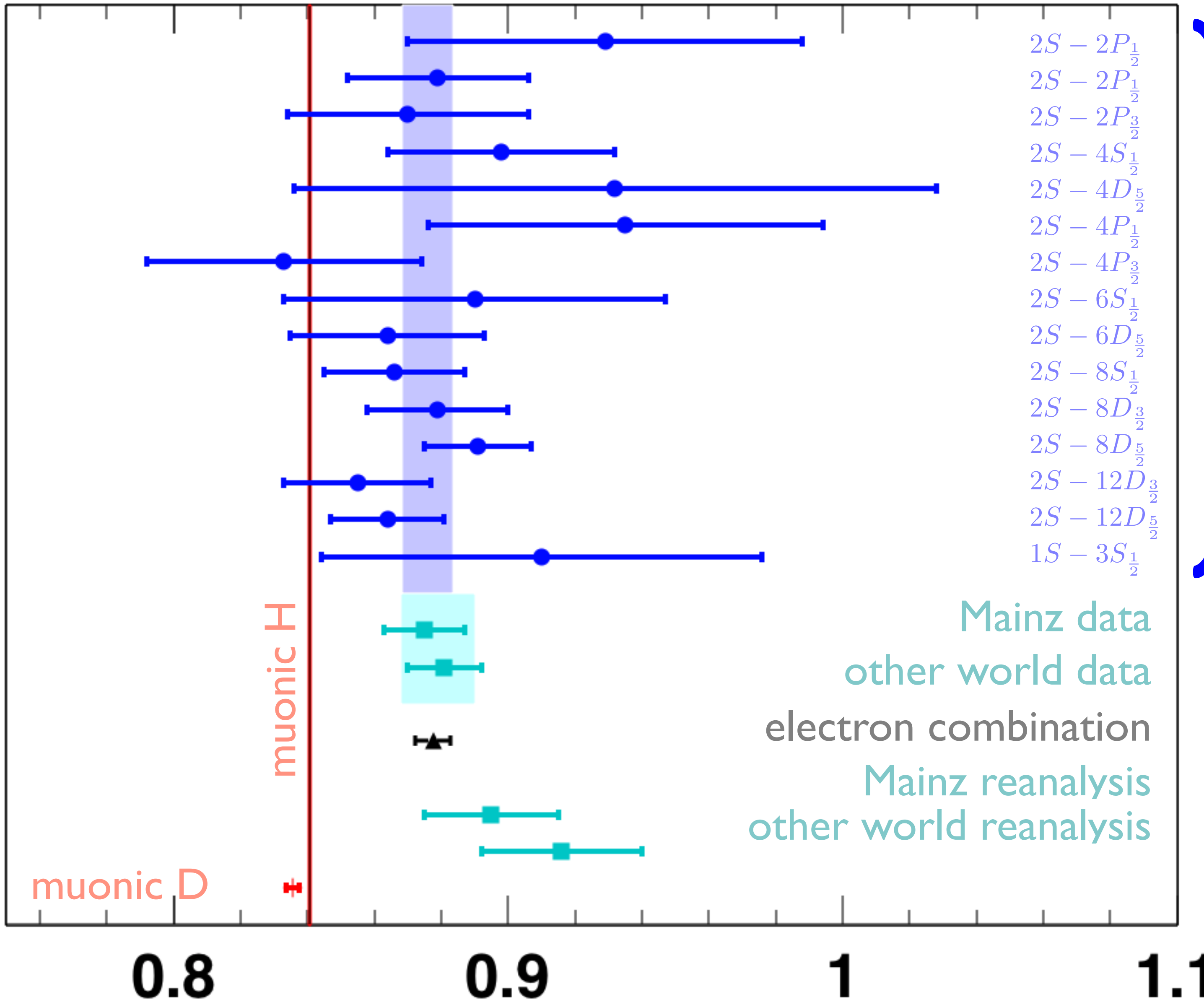
many of these

just one of these

NEW published result for muonic deuterium (Pohl et al., Science, August 2016)

- small discrepancy with muonic hydrogen
- large discrepancy with hydrogen-only radius
- new results also anticipated with muonic helium: *theory improvement needed for nuclear structure corrections*

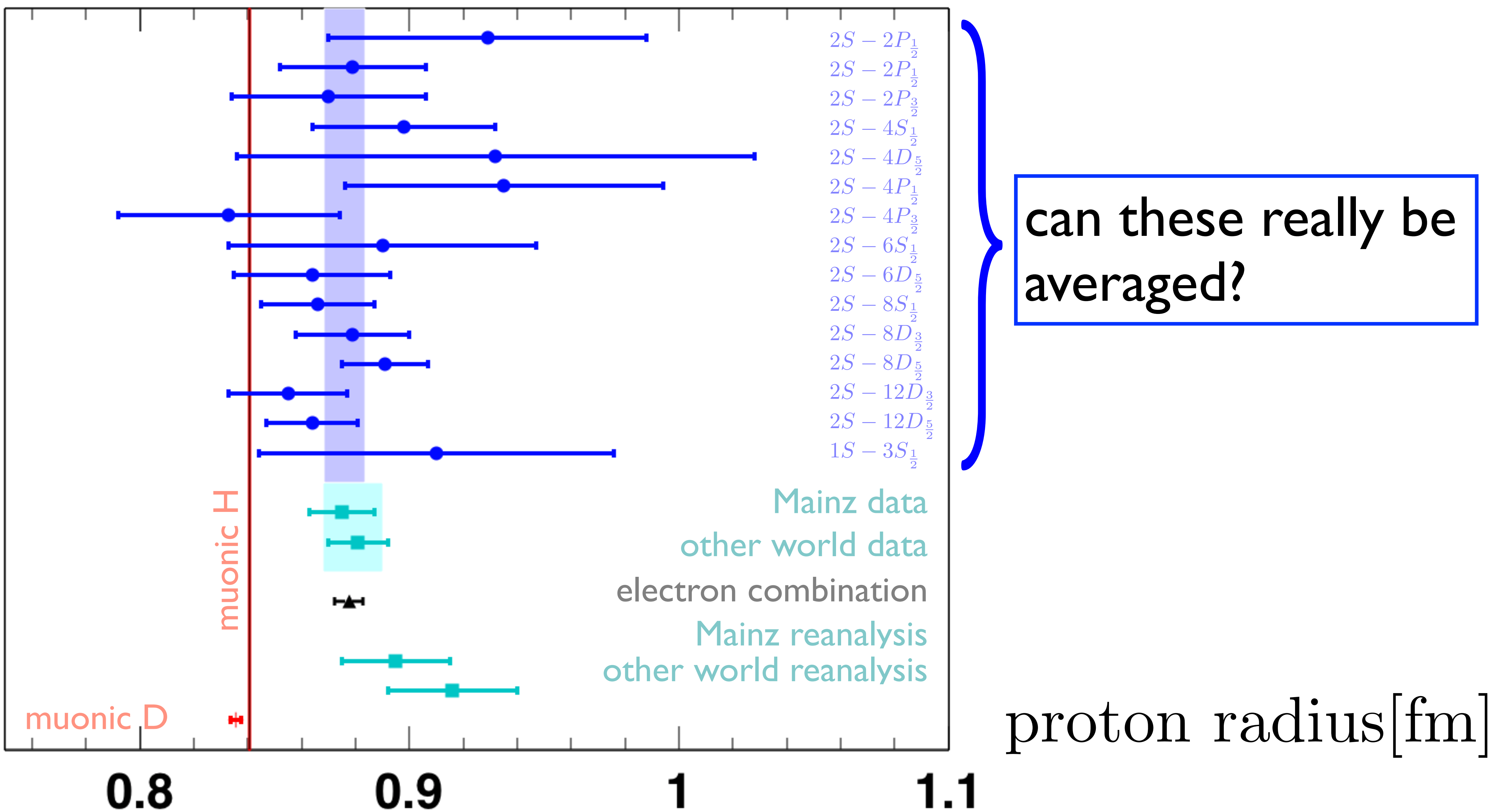
new hydrogen spectroscopy results



proton radius[fm]

can these really be averaged?

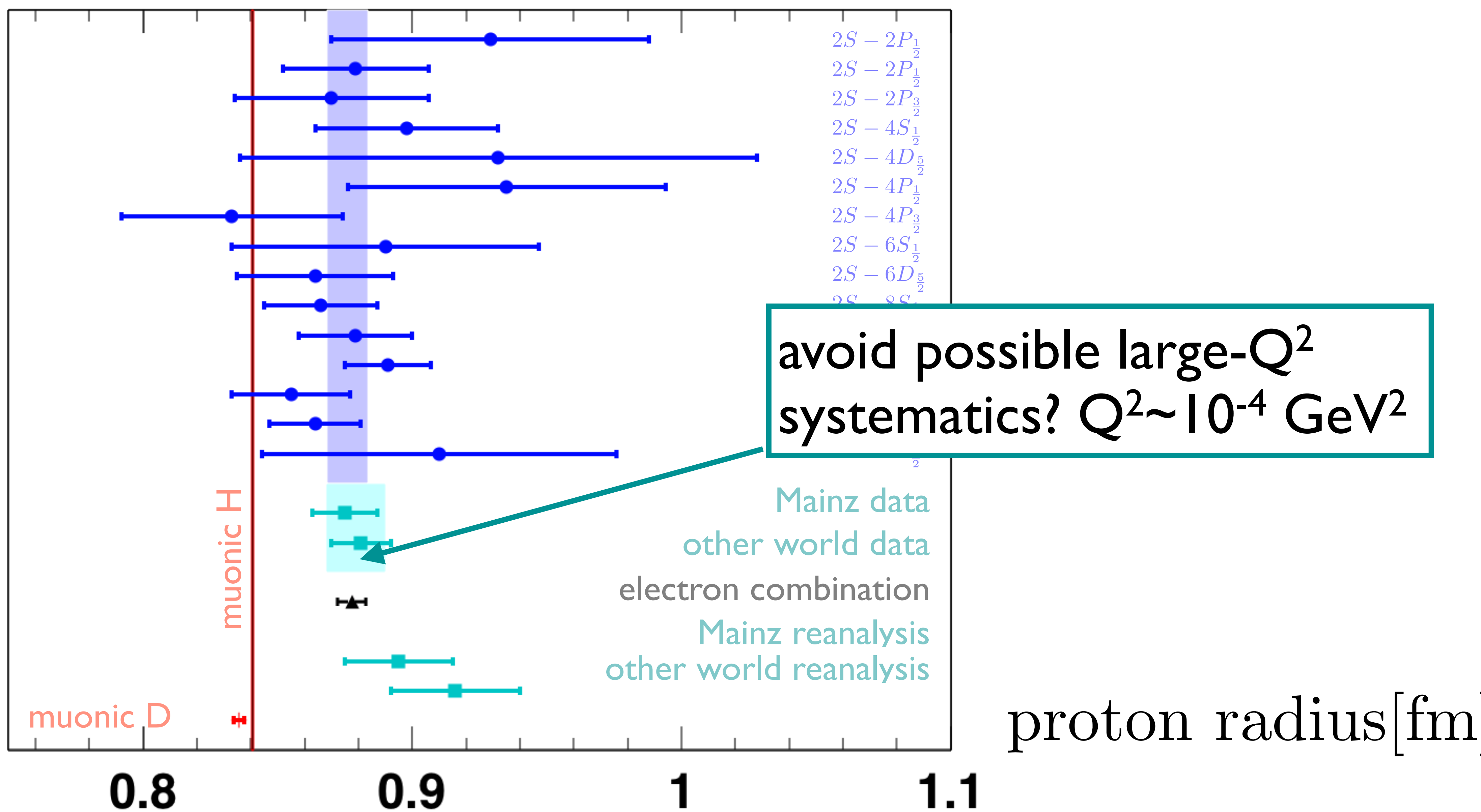
new hydrogen spectroscopy results



- Beyer, Maisenbacher, Matveev et al. (Garching): result for 2S-4P (submitted; presentation of L. Maisenbacher at Proton Radius Puzzle workshop, Trento, June 2016). *Error comparable to previous hydrogen average, central value consistent with muonic hydrogen (?)*

- future new results anticipated from 2S-2P (York), 1S-3S (Paris), others

low-Q^2 electron-proton scattering: PRad at JLab



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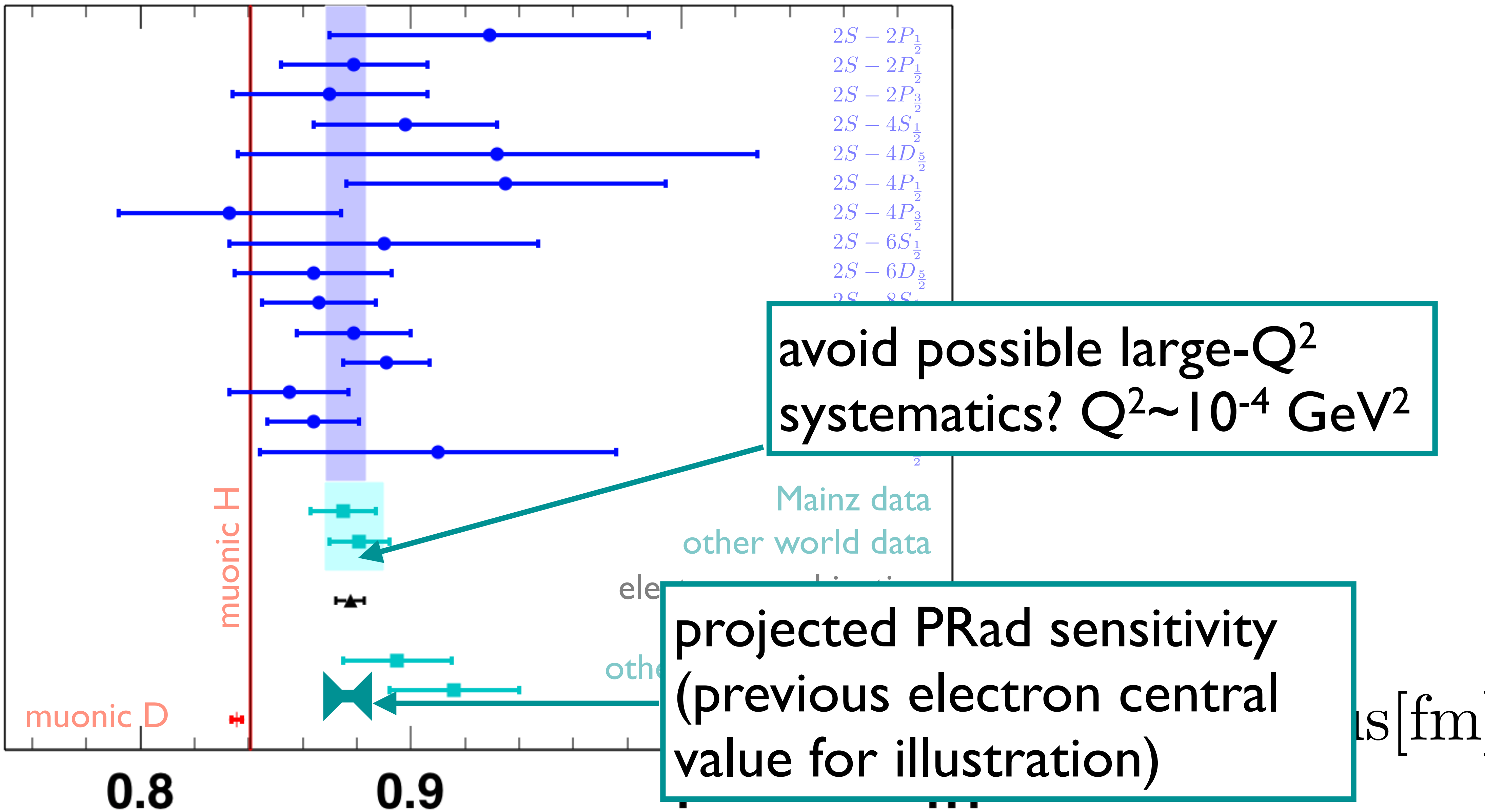
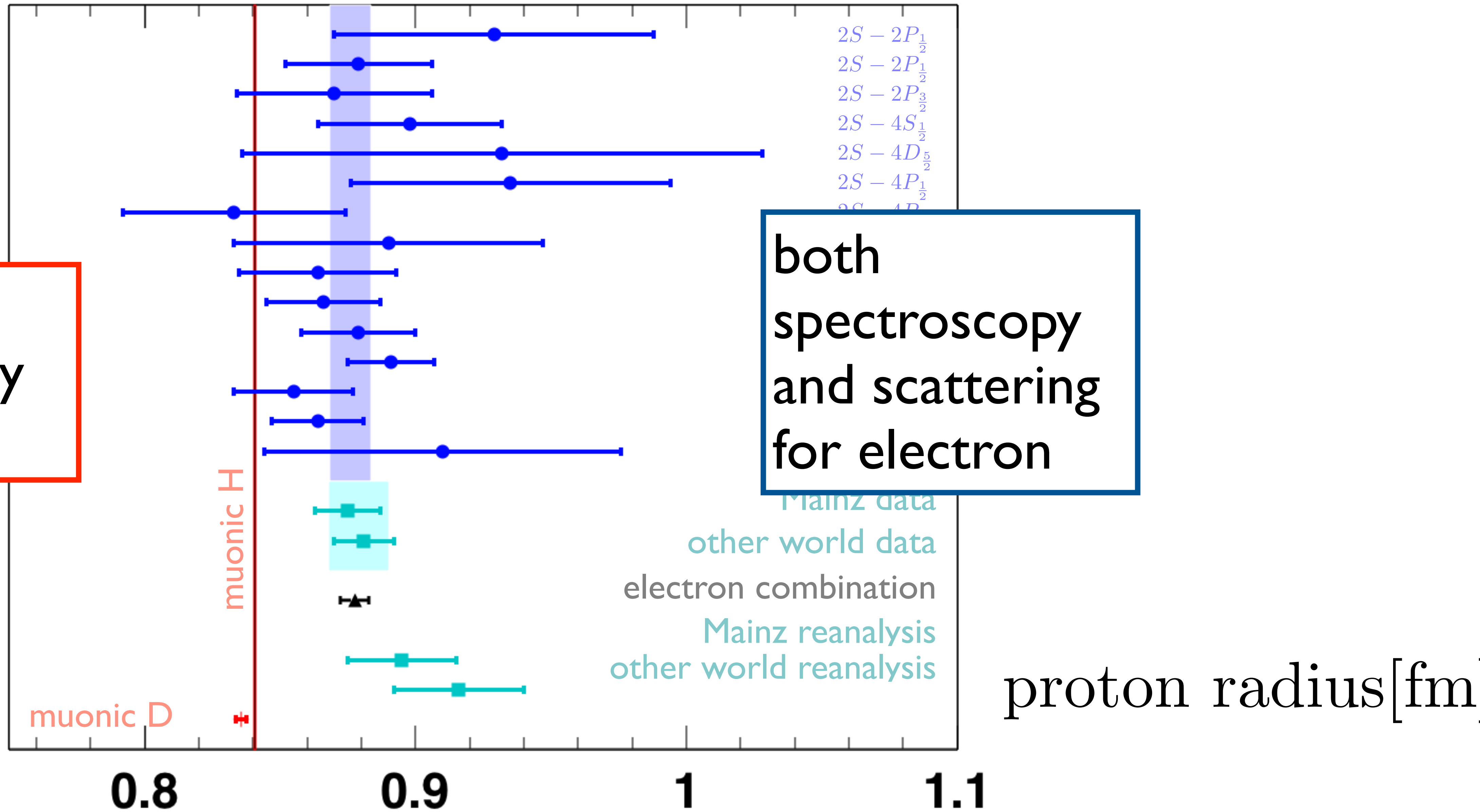


- non-magnetic spectrometer
- simultaneous calibration with e^-e^- (Moller) scattering
- windowless target

data collected in May/June 2016. first analysis 2017?

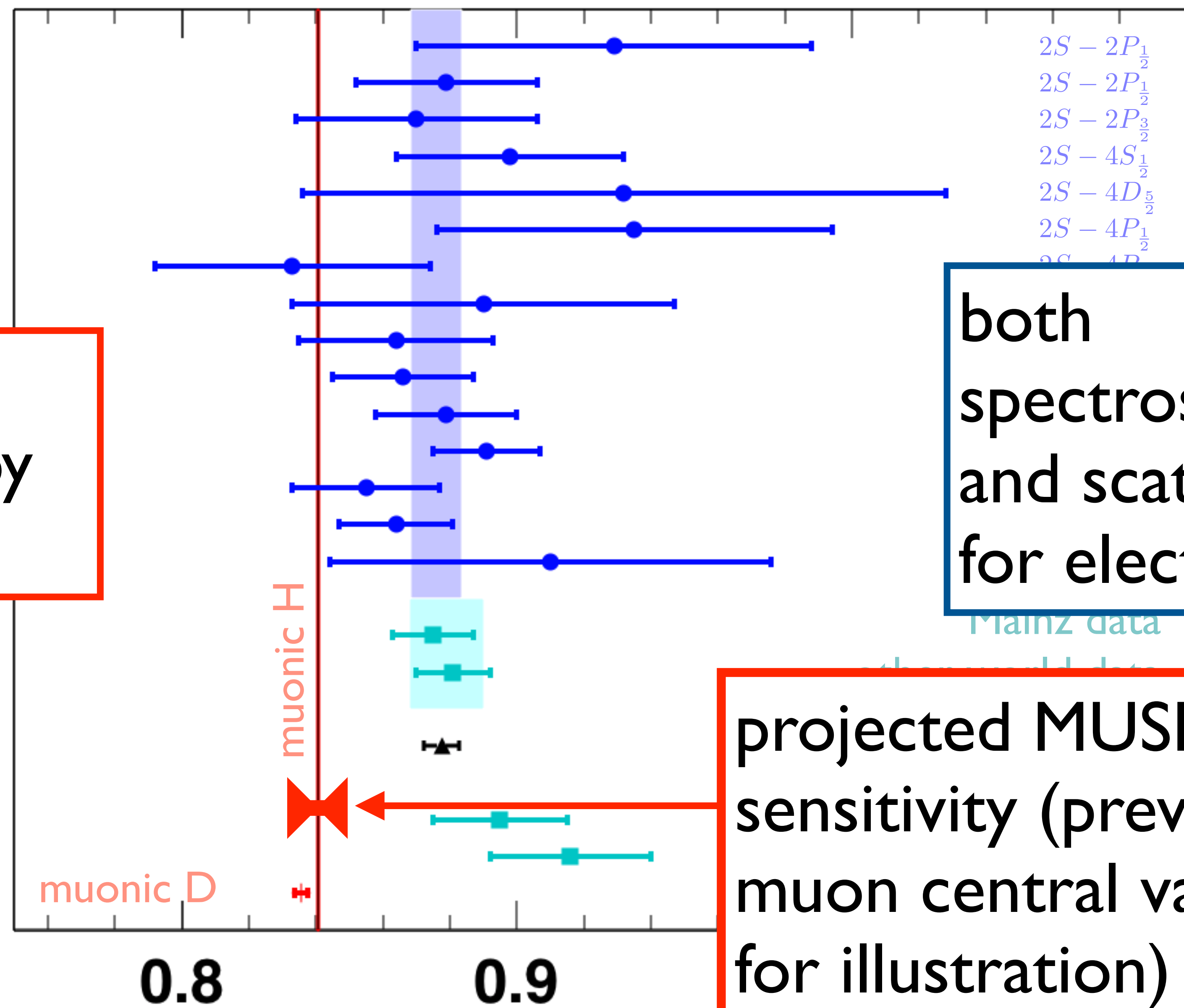
muon-proton scattering: MUSE at PSI

only spectroscopy for muon



both spectroscopy and scattering for electron

muon-proton scattering: MUSE at PSI



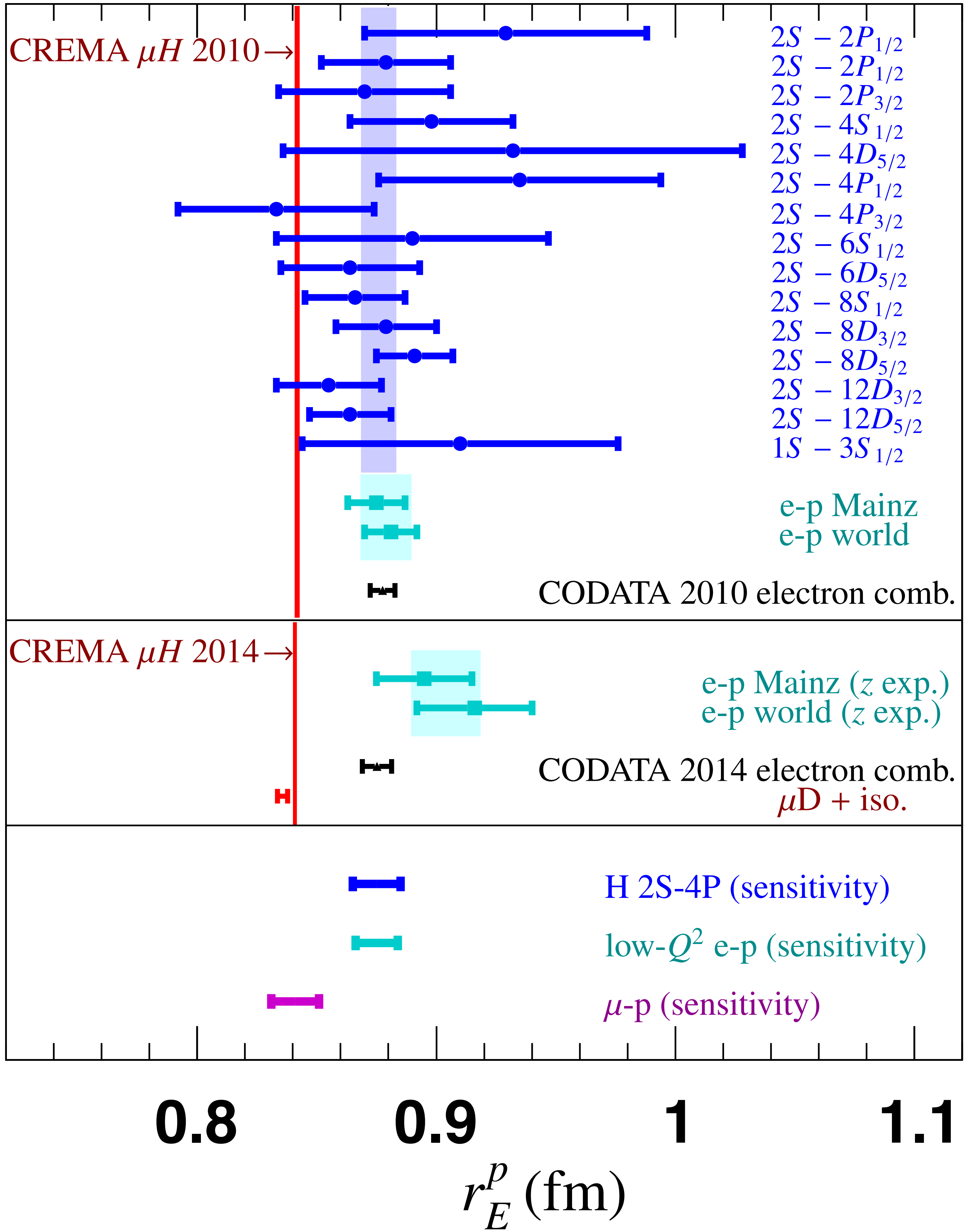
only spectroscopy for muon

both spectroscopy and scattering for electron

projected MUSE sensitivity (previous muon central value for illustration)

- measurement of e^+,e^-,μ^+,μ^-
- cancellation of systematics & direct two-photon sensitivity

production data-taking scheduled 2018-2019


CREMA μH 2010→
2S − 2P1/2
2S − 2P1/2
2S − 2P3/2
2S − 4S1/2
2S − 4D5/2
2S − 4P1/2
2S − 4P3/2
2S − 6S1/2
2S − 6D5/2
2S − 8S1/2
2S − 8D3/2
2S − 8D5/2
2S − 12D3/2
2S − 12D5/2
1S − 3S1/2
e-p Mainz
e-p world
CODATA 2010 electron comb.
CREMA μH 2014→
e-p Mainz (z exp.)
e-p world (z exp.)
CODATA 2014 electron comb.
μD + iso.
H 2S-4P (sensitivity)
low-Q2 e-p (sensitivity)
μ-p (sensitivity)
0.8
0.9
1
1.1
r_E^p (fm)