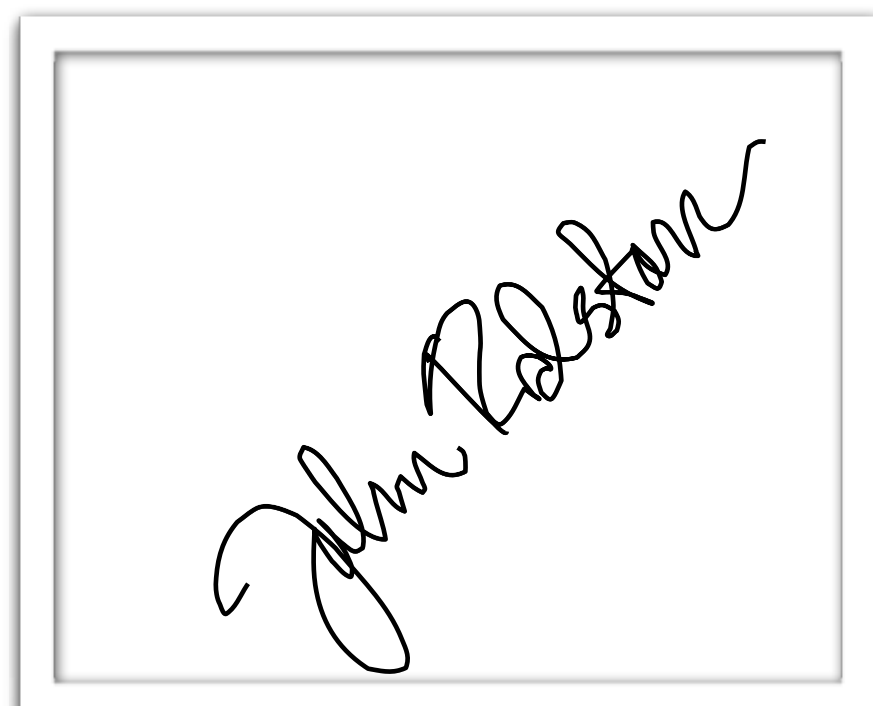
The Puzzle *Not About* the Proton Size

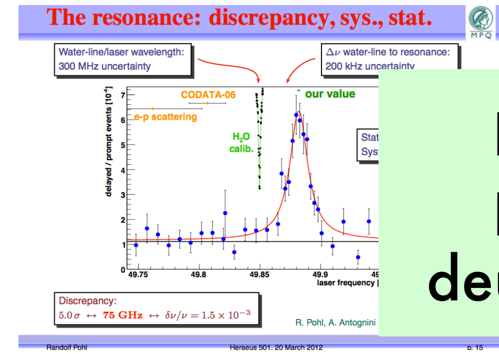


with John Martens

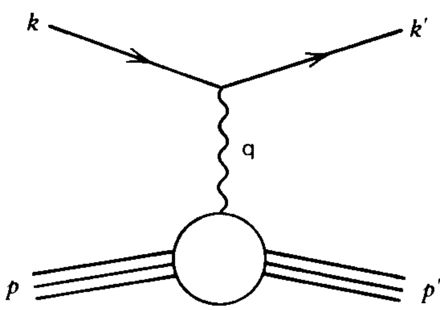
Three (3-5) not One (1) Anomalies in Muon Physics

nothing of the puzzles are actually as it seems

- The most convincing data is the *opposite of general belief*



proton size 1
proton size 2
deuteron sizes 1-3



- The most complete theory is *not the one of general belief*

sorry to disappoint !

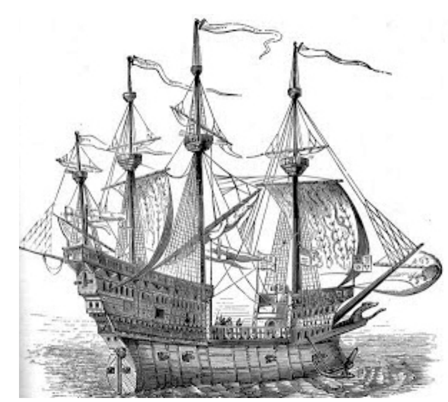
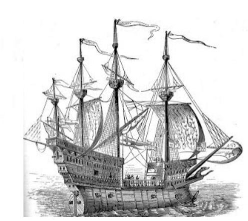
- Potentially *overturns 50 years of faith*

$$g_e - 2 \stackrel{?}{=} 2(\frac{\alpha}{2\pi} + \ldots)$$

que lastima ...

- IF NOT new physics, then *a global revision of the fundamental constants*

$$\alpha,\ R_\infty,\ m_e/h \ldots r_p$$

Our Idea: *Search for New Local Minima* of *ALL RELEVANT fundamental constants*

$$a_e = 0.00115965218073 \pm 2.8 \times 10^{-13}$$

$$a_\mu = 0.00116592091 \pm 6.3 \times 10^{-10}$$

$$\mu H : \quad \Delta E_{2S-2P} = 202.3706 \pm 0.0026\,\mathrm{meV}$$

$$m_e/h = 7.763440712 \times 10^{20} \pm 9.7 \times 10^{11}\ Hz$$

eH : 8 transitions listed

eD : 8 transitions listed

theory:
the ENTIRE BODY
of atomic QED and Standard Model
calculations

FIRST…the conventional PARTIAL PUZZLE

muonic lamb shift

antognini et al
2010, 2012

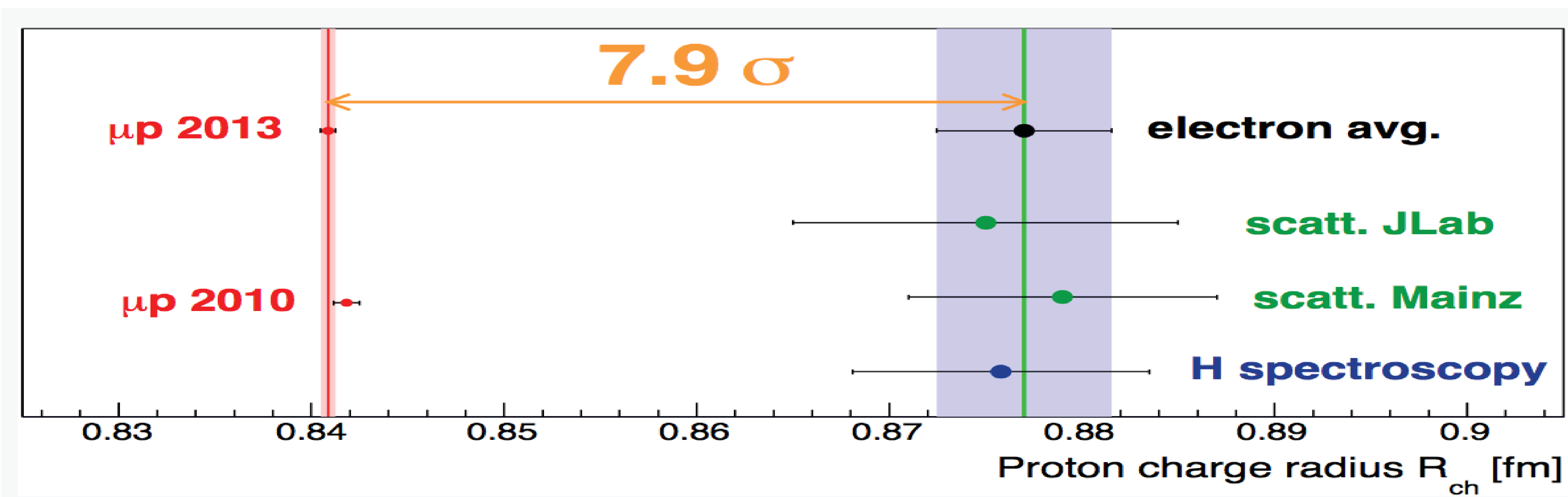
$$r_p = 0.84087 \pm (.00039)\ fm$$

CODATA

electron scattering, deuteron scattering, hydrogen and deuterium spectra

$$r_p = 0.877 \pm (.005)\ fm$$

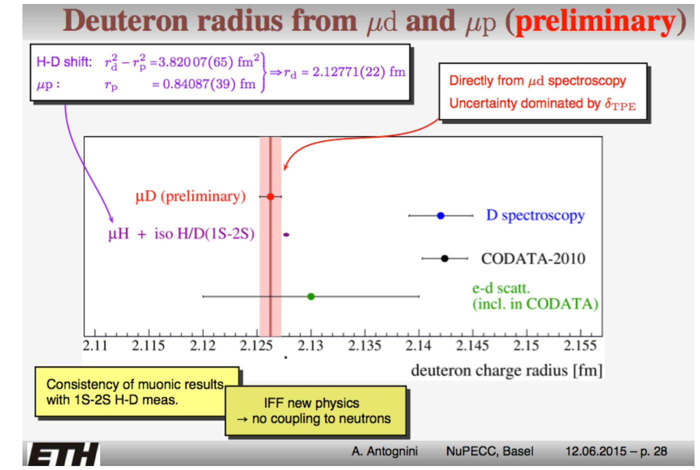
$$r_p = 0.879 \pm (.008)\ fm$$



Pohl *et al.*, Nature 466, 213 (2010) Antognini *et al.*, Science 339, 417 (2013)

Antognini ECT Trento

ACTUALLY five (5) different muonic Lamb shift discrepancies in H and D



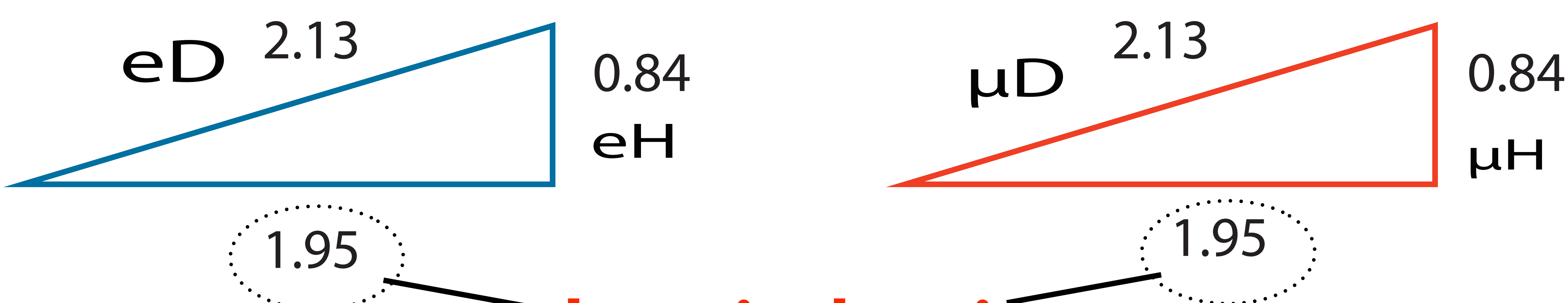
At least two (2) measured μH transitions

D=deuterium
(CREMA
preliminary)

At least three (3) measured μD transitions

...plus many ordinary eH, eD Lamb shifts...

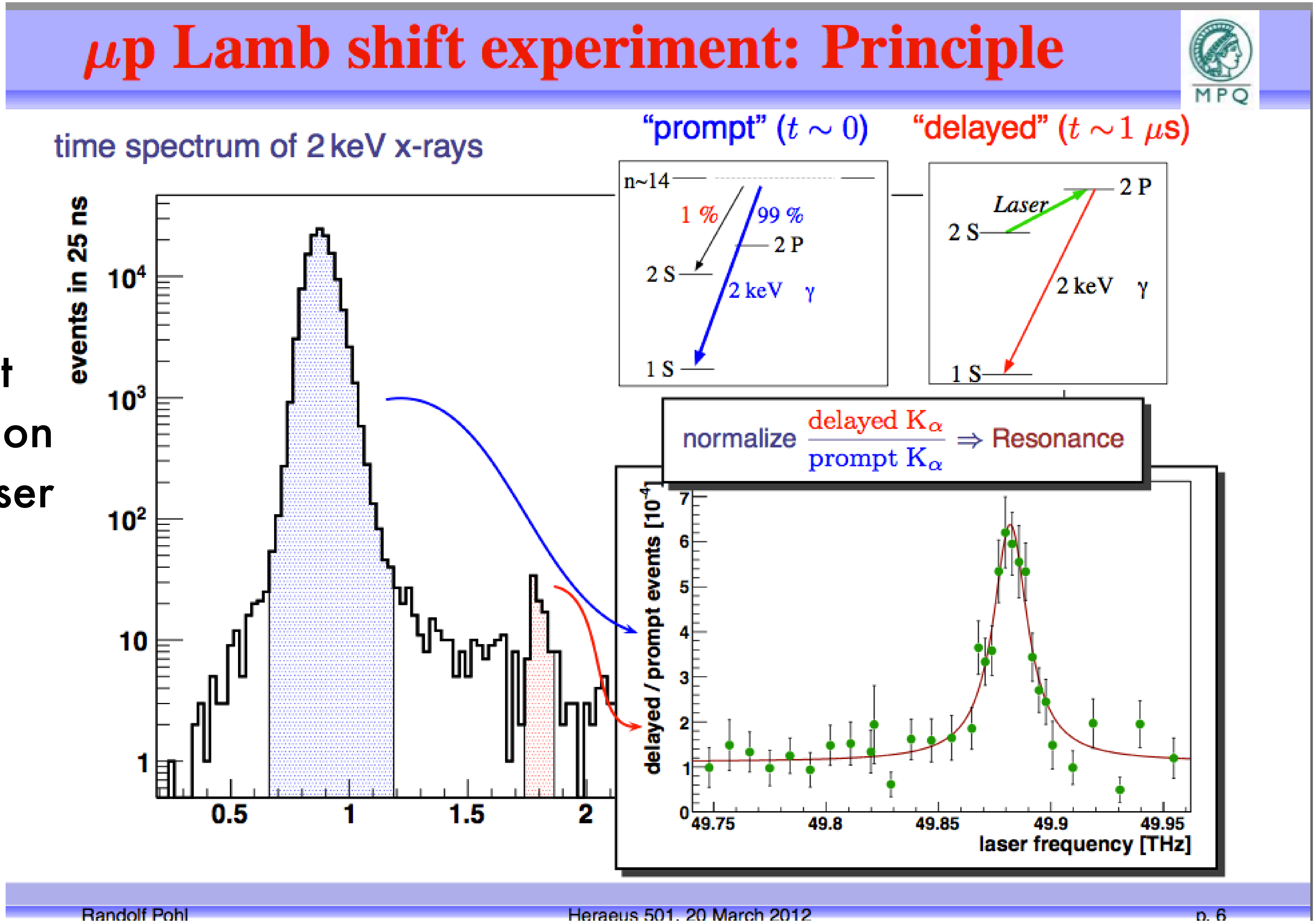
classic relation $$r_{eD}^2 = r_{eH}^2 + r_{deut}^2$$



over-determined consistency

Is the muonic experiment convincing? Yes

direct
excitation
with laser



slide adapted from Pohl

is the muonic experiment calibrated? Yes

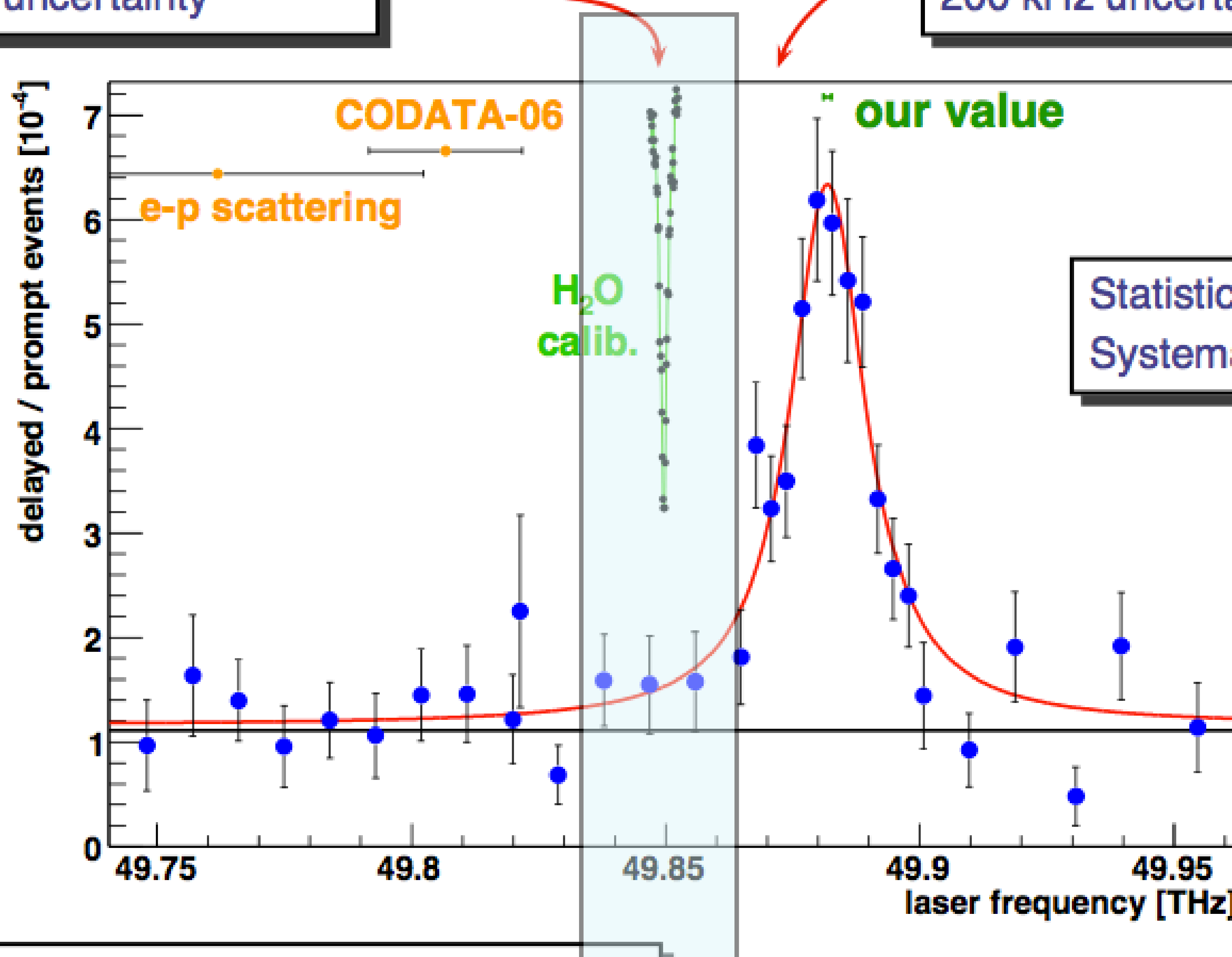
The resonance: discrepancy, sys., stat.

MPQ

Water-line/laser wavelength:
300 MHz uncertainty

$\Delta\nu$ water-line to resonance:
200 kHz uncertainty

calibrate with water line



Statistics: 700 MHz
Systematics: 300 MHz

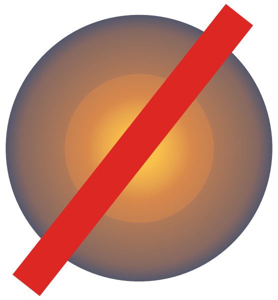
jpr added

Discrepancy:
$5.0\,\sigma \;\leftrightarrow\;$ **75 GHz** $\;\leftrightarrow\; \delta\nu/\nu = 1.5\times10^{-3}$

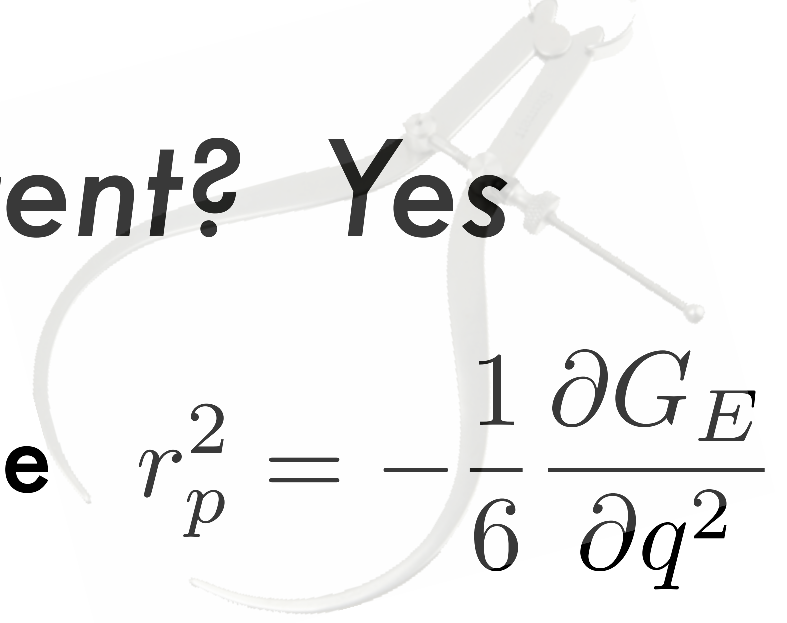
R. Pohl, A. Antognini *et al.*, Nature 466, 213 (2010).

slide adapted from Pohl

Are *all* definitions consistent? *Yes*



Please! The proton is not a little ball of classical charge



all use $r_p^2 = -\frac{1}{6}\frac{\partial G_E}{\partial q^2}\Big|_{q^2=0}$

r_p (μH)

The charge radius. The theory (*14*, *16–22*) relating the Lamb shift to r_E yields (*13*):

$$\Delta E_L^{th} = 206.0336(15) - 5.2275(10) r_E^2 + \Delta E_{TPE} \quad (7)$$

Antognini 2013

!

→ where E is in meV and r_E is the root mean square (RMS) charge radius given in fm and defined as $r_E{}^2 = \int d^3r\, r^2\, \rho_E(\boldsymbol{r})$ with ρ_E being the normalized proton charge distribution. The first

Language sloppy, but calculation is OK, straightforward, and low order

Excitement for new physics, spoiled by our actual annoying universe

Previous models artificially assume no electron interaction

PRD **82**, 125020 Jaeckel, Roy: *"Spectroscopy as a test of Coulomb's law"* *(1008.3536)* hidden photons, minicharged particles → deviations from Coulomb's law. μp transition can NOT be explained this. (Claimed contradicts Lamb shift in H)

Oops, FALSE. Assumes ATTRACTIVE interactions and inconsistent parameter limits

PRL **106**, 153001 Barger *et al.*: *"Proton size anomaly"* *(1011.3519)* decay of ϒ, J/ψ, π_0, η, neutron scattering, muon g-2, μ_{24}Mg, μ_{28}Si ⇒ It's NOT a new flavor-conserving spin-0, 1 or 2 particle

FALSE. Assumes NEUTRON interactions early, inside inconsistent parameter limits

PRD **83**, 101702 Tucker-Smith, Yavin: *"Muonic hydrogen and MeV forces"* *(1011.4922)*
MeV force carrier can explain discrepancies for r_p and $(g\text{-}2)_\mu$ **IF** coupling to e, n is suppressed relative to coupling to μ, p prediction for μHe^+, $\mu^+\mu^-$

OK as far as it goes, but explores none but ATTRACTIVE interactions, inconsistent parameter limits,abandons e-mu universality

PRL **107**, 011803 Batell *et al.*: *"New Parity-violating muonic forces"* *(1103.0721)* 10…100 MeV heavy photon ("light Higgs") can explain r_p and $(g\text{-}2)_\mu$ prediction for μHe^+, enhanced PNC in muonic systems PRL **108**, 081802 *Same as above but more model dependent*

Actually about 200 papers explore ideas

*PRA **81**, 060501 (2010) JETP Lett. **92**, 8 (2010) PRL **105**, 242001 (2010) PRD **82**, 125020 (2010) PLB **693**, 555 (2010) Nucl.Phys.News **21**, 14 (2011) Can. J. Phys. **89**, 109 (2011) PRC **83**, 012201(R) (2011) PRD **82**, 113005 (2010) PLB **697**, 26 (2011) PLB **696**, 343 (2011) EPJD **61**, 7 (2011) PRL **106**, 153001 (2011) PRA **83**, 012507 (2011) PRD **83**, 101702(R) (2011) Ann. Phys. **326**, 500 (2011) Ann. Phys. **326**, 516 (2011) Few-Body Syst. **50**, 367 (2011) PRD **83**, 035020 (2011) PRA **83**, 042509 (2011) PRL **106**, 193007 (2011) PRL **107**, 011803 (2011) PRA **84**, 012506 (2011) PRA **84**, 012505 (2011) PRA **84**, 020101(R) (2011) PRA **84**, 020102(R) (2011)Karshenboim et al.: "Nonrelativistic contributions of order $\alpha5m\mu c2$ to the Lamb shift in muonic ..." (1005.4879) Karshenboim et al.: "Contribution of light-by-light scattering to energy levels of light muonic atoms" (1005.4880) Bernauer et al: "High-precision determination of the electric and magnetic form factors of the proton" (1007.5076) Jaeckel, Roy: "Spectroscopy as a test of Coulomb's law" (1008.3536) De Rujula: "QED is not endangerec by the proton's size" (1008.3861) Vanderhaeghen, Walcher: "Long range structure of the nucleon" (1008.4225) Jentschura: "From first principles of QED to an application: hyperfine structure of P states of muonic hydrogen" Cloet, Miller: "Third Zemach moment of the proton" (1008.4345) Hill, Paz: "Model-independent extraction of the proton charge radius from electron scattering" (1008.4619) De Rujula: "QED confronts the proton's radius" (1010.3421) Distler et al: "The RMS radius of the proton and Zemach moments" (1011.1861) Jentschura: "Proton radius, Darwin-Foldy term and radiative corrections" (1012.4029) Barger, Chiang, Keung, Marfatia: "Proton size anomaly" (1011.3519) Yerokhin: "Nuclear size corrections to the Lamb shift of one-electron atoms" (1011.4272) Tucker-Smith, Yavin: "Muonic hydrogen and MeV forces" (1011.4922)Jentschura: "Lamb shift in muonic hydrogen I: Verification and update of theoretical predictions" (1011.5275 Jentschura: "Lamb shift in muonic hydrogen II: Analysis of the discrepancy of theory and experiment" (1011.5453) Sick: "Troubles with the proton rms radius" Brax, Burrage: "Atomic precision tests and light scalar couplings" (1010.5108) Carlson et al.: "Proton-structure corrections to hyperfine splitting in muonic hydrogen" (1101.3239) Pachucki: "Nuclear structure corrections in muonic deuterium" (1102.3296) Batell, McKeen, Pospelov: "New parity-violating muonic forces and the proton charge radius" (1102.3296) Carroll et al.: "Nonperturbative relativistic calculation of the muonic hydrogen spectrum" (1104.297 Jentschura: "Relativistic reduced-mass and recoil corrections to vacuum polarization in muonic hydrogen, ..." (1107.1737) Miller, Thomas, Carroll, Rafelski: "Toward a resolution of the proton size puzzle" (1101.4073) Carlson, Vaderhaeghen: "Higher-order proton structure corrections to the Lamb shift in muonic hydrogen" (1101.5965)....*

Possible possibles, unknown knowns...

If five or more μH and μD Lamb shifts are wrong...
...the muon g-2 still differs by 3.9σ from Standard Model

to protect the Rydberg, CODATA excludes rp(μH) and amu and...every inconsistency...
CODATA tables are highly model-dependent and procedure -dependent

If eH and eD calculations are wrong, r_p *might be OK,*
but ...the muon g-2 still differs by 3.9σ from Standard Model

If the muon g-2 experiment is wrong,
you have a 7σ disagreement of eH and eD with μH and μD

Supposedly no model exists with equal electron and muon interactions,....but that's precisely what is WRONG

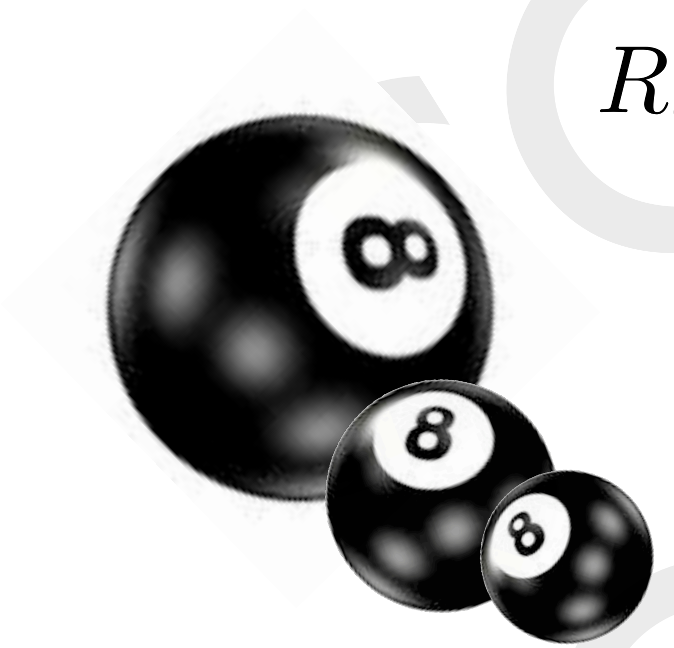
Up to now, no consistent picture

Severe limits on new interactions
from ultra-precise electron g-2, the
fine structure constant α and the Rydberg,13.6 eV

$$a_e = 0.00115965218072 \pm 2.8 \times 10^{-13}$$

$$\alpha = 7.2973525664 \pm 1.7 \times 10^{-12}$$

$$R_\infty = 10973731.568508 \pm 6.5 \times 10^{-5}$$

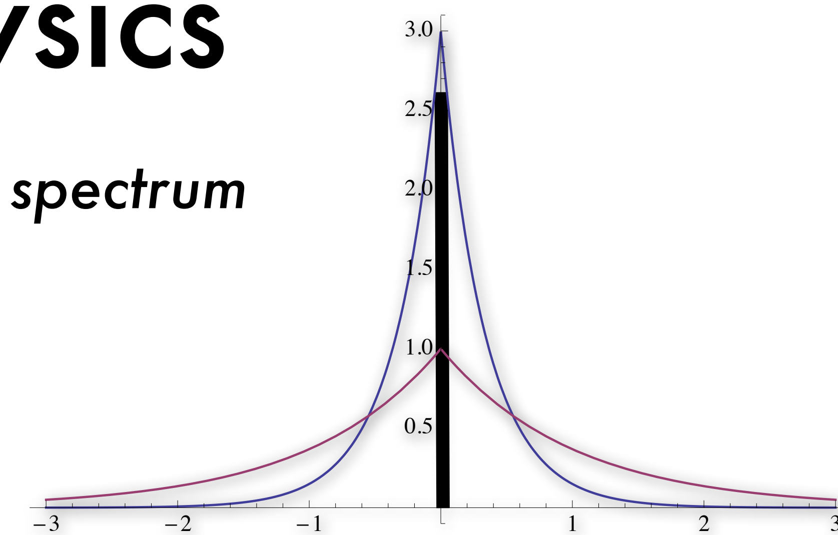


plus

A generic new interaction makes
LARGER EFFECTS in eH and eD
than in μH or μD

90 second course in atomic physics

"Lamb shift" = a certain transition OR the effects NOT in Dirac atomic spectrum



$$\Delta E_n \sim < \psi_n | e\Delta V | \psi_n >;$$

$$eV(q) \sim \frac{e^2 F(\vec{q}^2)}{\vec{q}^2} \sim \alpha \left(\frac{1}{\vec{q}^2} + \frac{< r_p^2 > \vec{q}^2}{\vec{q}^2} \right);$$

$$eV_0(r) + \Delta V(r) \sim \frac{\alpha}{r} + \alpha < r_p^2 > \delta^3(r);$$

$$\Delta E_n \sim \alpha < r_p^2 > \psi_n^*(0)\psi_n(0);$$

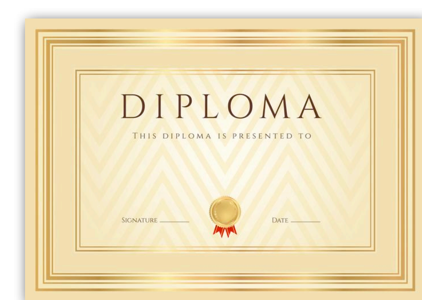
$$a_n^3 \psi_n^*(0)\psi_n(0) \sim 1; \quad \psi_n^*(0)\psi_n(0) \sim \frac{1}{a_n^3} \sim \frac{\alpha^3 m_r^3}{n^3};$$

$$\Delta E_n \sim \frac{\alpha^4 < r_p^2 > m_r^3}{n^3}$$

smaller size
wave function
bigger
proton size
effect

$$(\frac{m_\mu}{m_e})^3 = 207^3 \sim 10^7$$

$$\Delta E_{n\ell}^{size} = \frac{2(Z\alpha)^4 m_r^3 < r_p^2 > c^4}{3\hbar^2 n^3} \delta_{\ell 0}$$



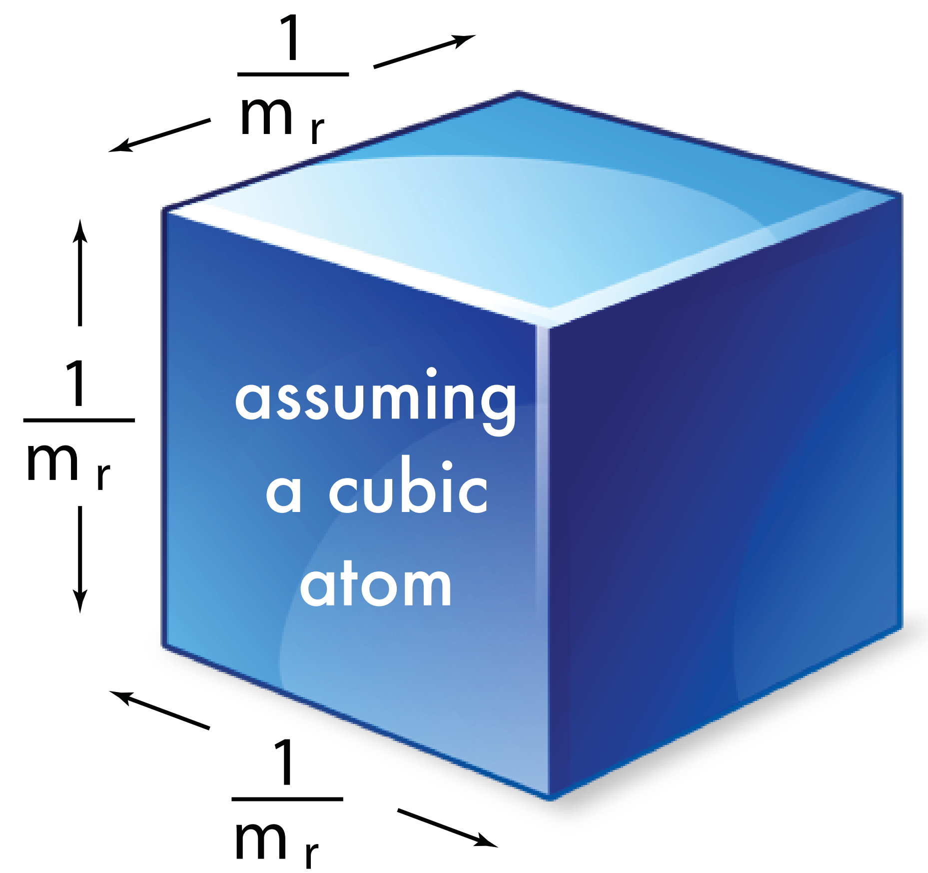
mass-cubed effect inspired muonic measurement

K. Pachucki, 1995
emphasis on Rydberg

$$\psi_n^*(0)\psi_n(0) \sim \frac{1}{a_n^3} \sim \frac{\alpha^3 m_r^3}{n^3}$$

$$\Delta E(r_p,\, \mu H) \sim 10^7\, \Delta E(r_p,\, eH)$$

muonic theory is complete;
about "one page of
calculation"
(in small font)
plus small terms



More than 200 papers on proton size puzzle

No conventional explanation. “Crisis” (G. Miller)

NOT EVEN new physics

Carlson and Carlson papers :1502.05314v1 mix axial vector + vector to FINE-TUNE cancellations of MUON-SPECIFIC model

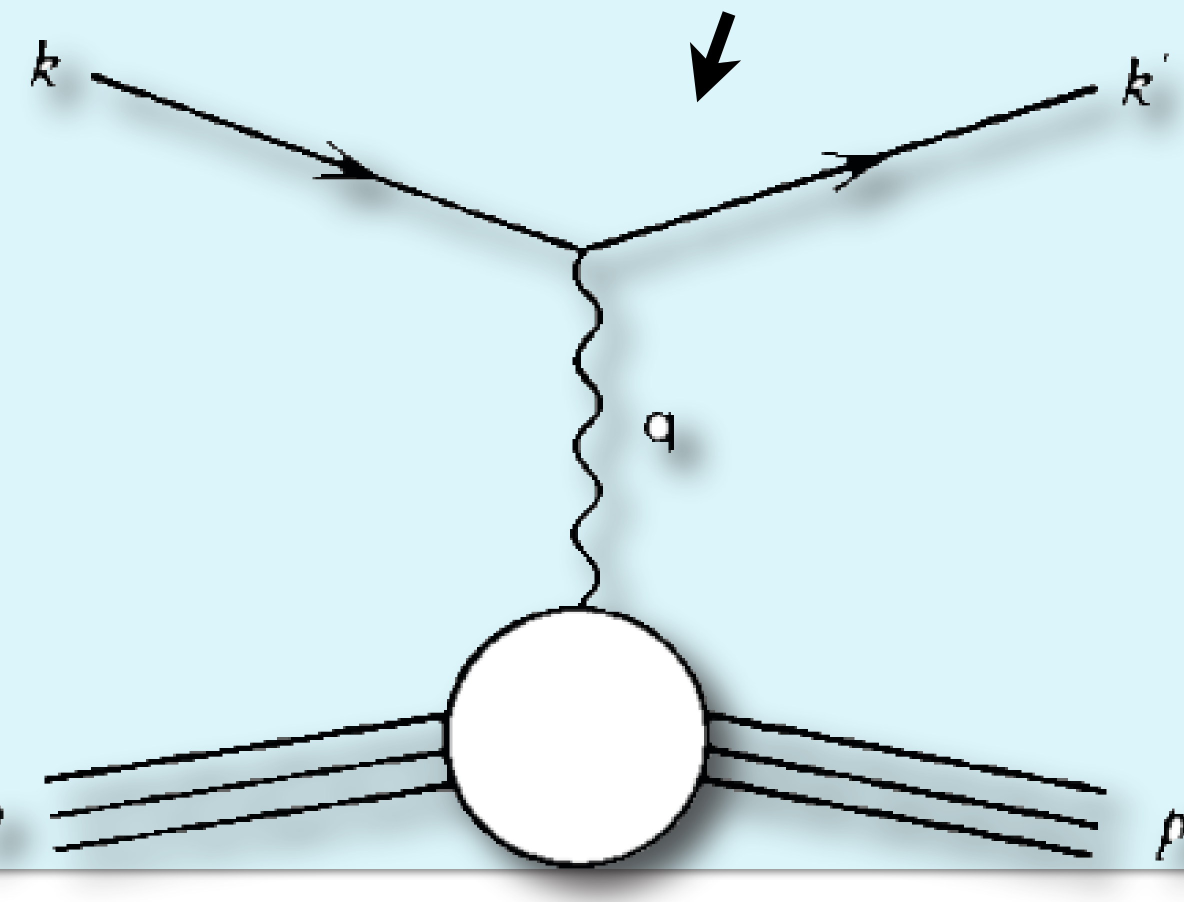
Yet a natural regime for new, low mass interactions such as “dark photon”.

Previous CENTRAL DOGMA:

Electrons OK with Standard Model.
Muons misbehave with SMALLER radius signal
Large MUON interaction should increase ELECTRON radius
Signs and strength of ELECTRON stuff all wrong with data

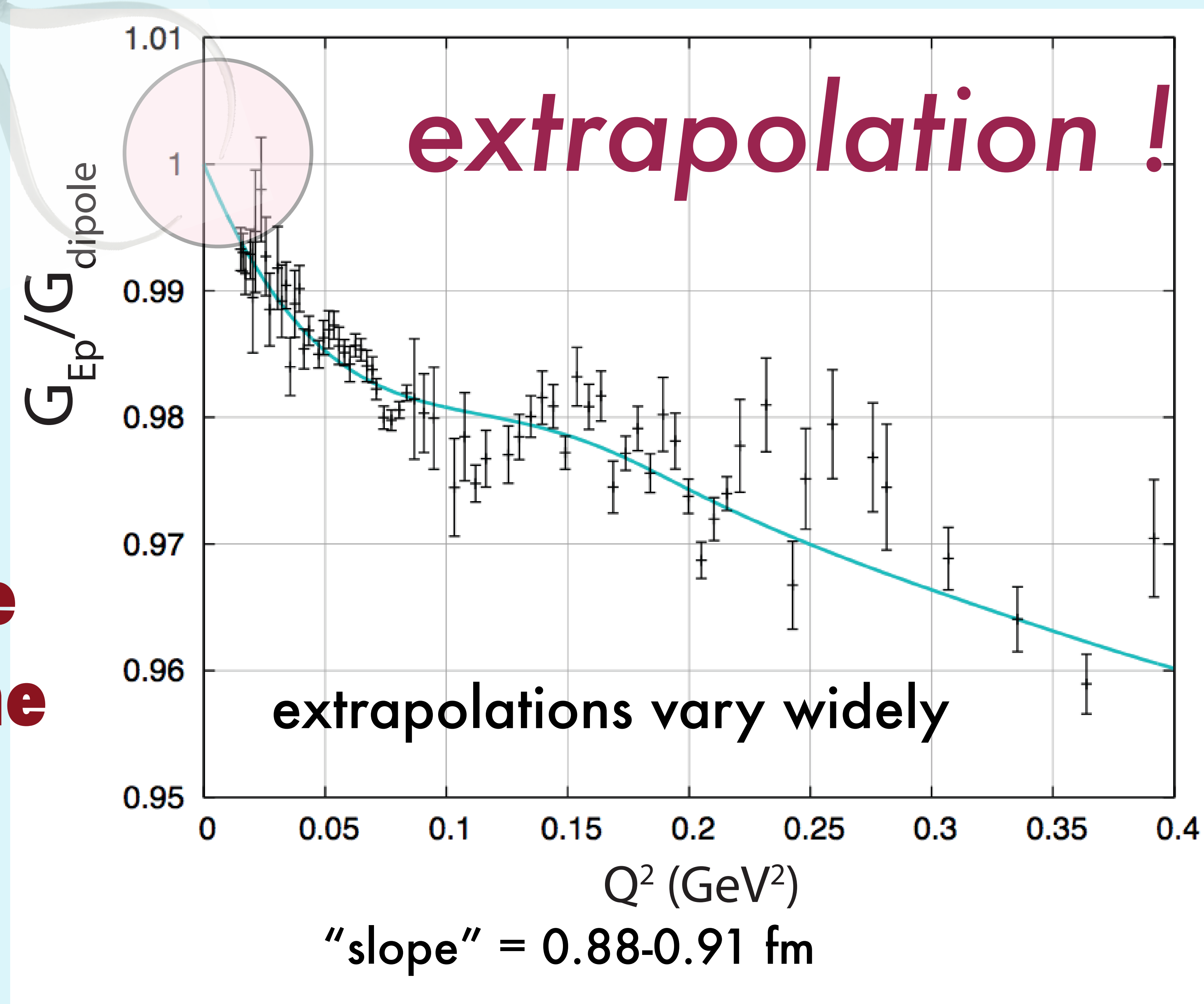
Actually the conventional blockades have some cracks

this kind of data won't resolve things



electron scattering has not measured $r_p^2 = -\frac{1}{6}\frac{\partial G_E}{\partial q^2}\Big|_0$

what if the true proton size is the muonic one?

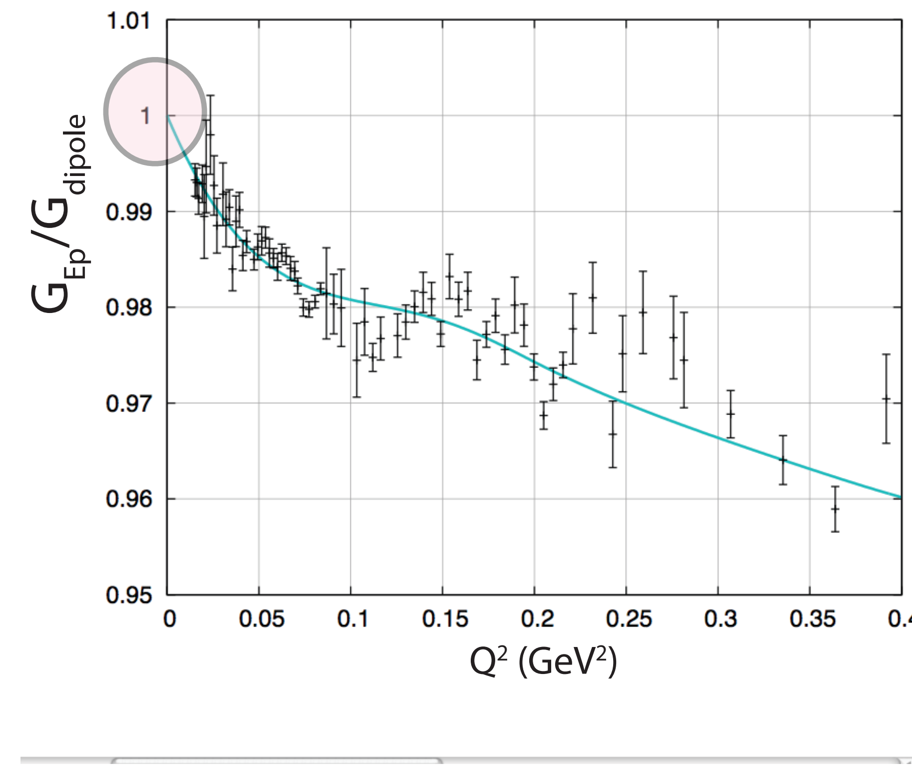


fit fromVanderhagen & Walcher

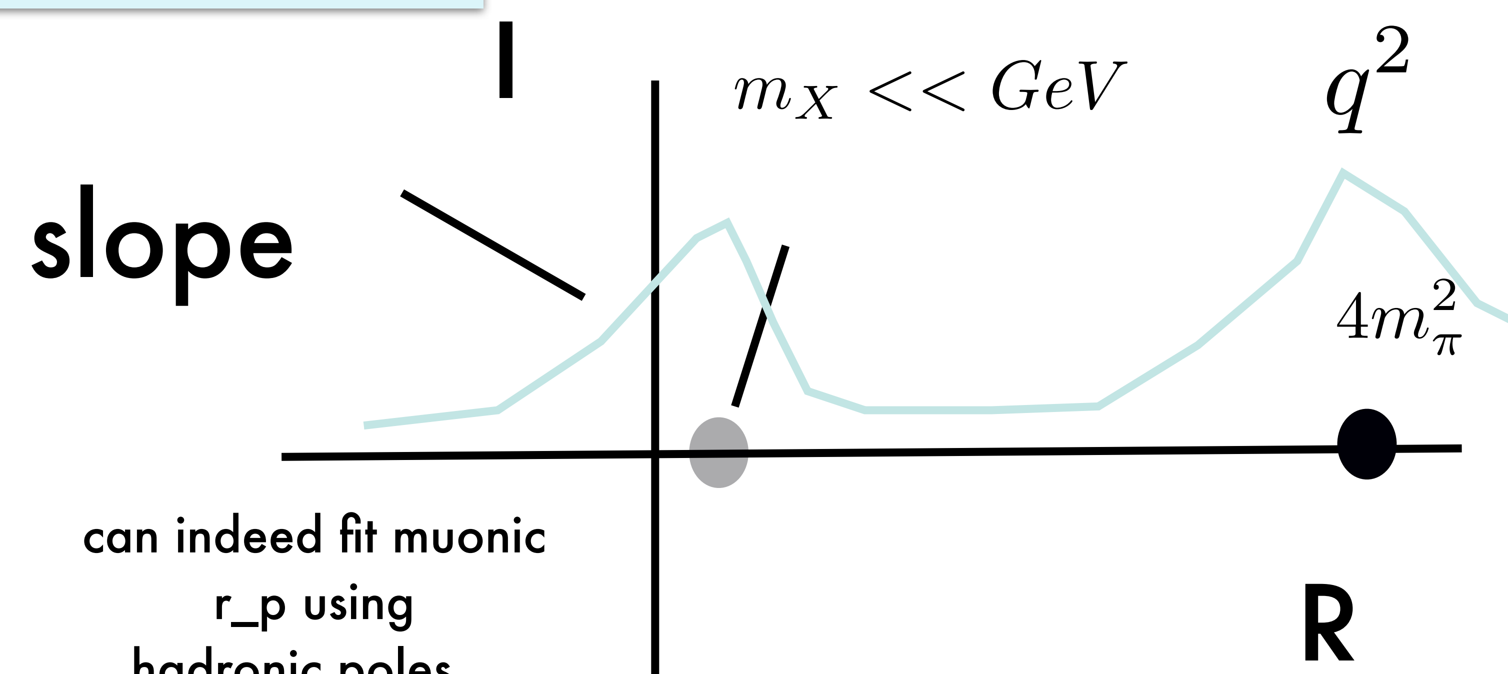
Why would extrapolation mislead?

dispersion relations
are rigorous...*if you know all the cuts, poles, and imaginary parts...*

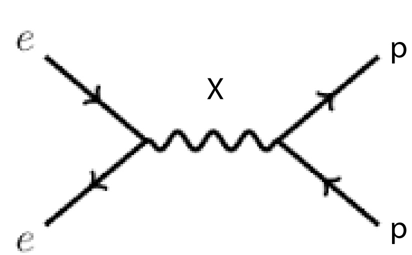
...which low mass new physics will REVISE



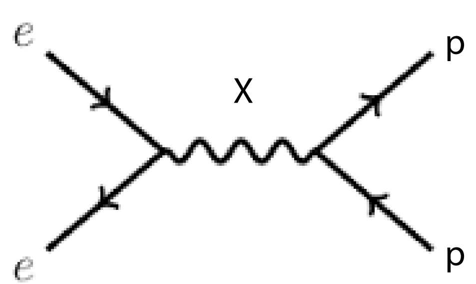
"dark photons"



can indeed fit muonic r_p using hadronic poles... (Mergell et al, Hammer et al)



What are dark photons?



$$\epsilon = \frac{\alpha_X}{\alpha}$$

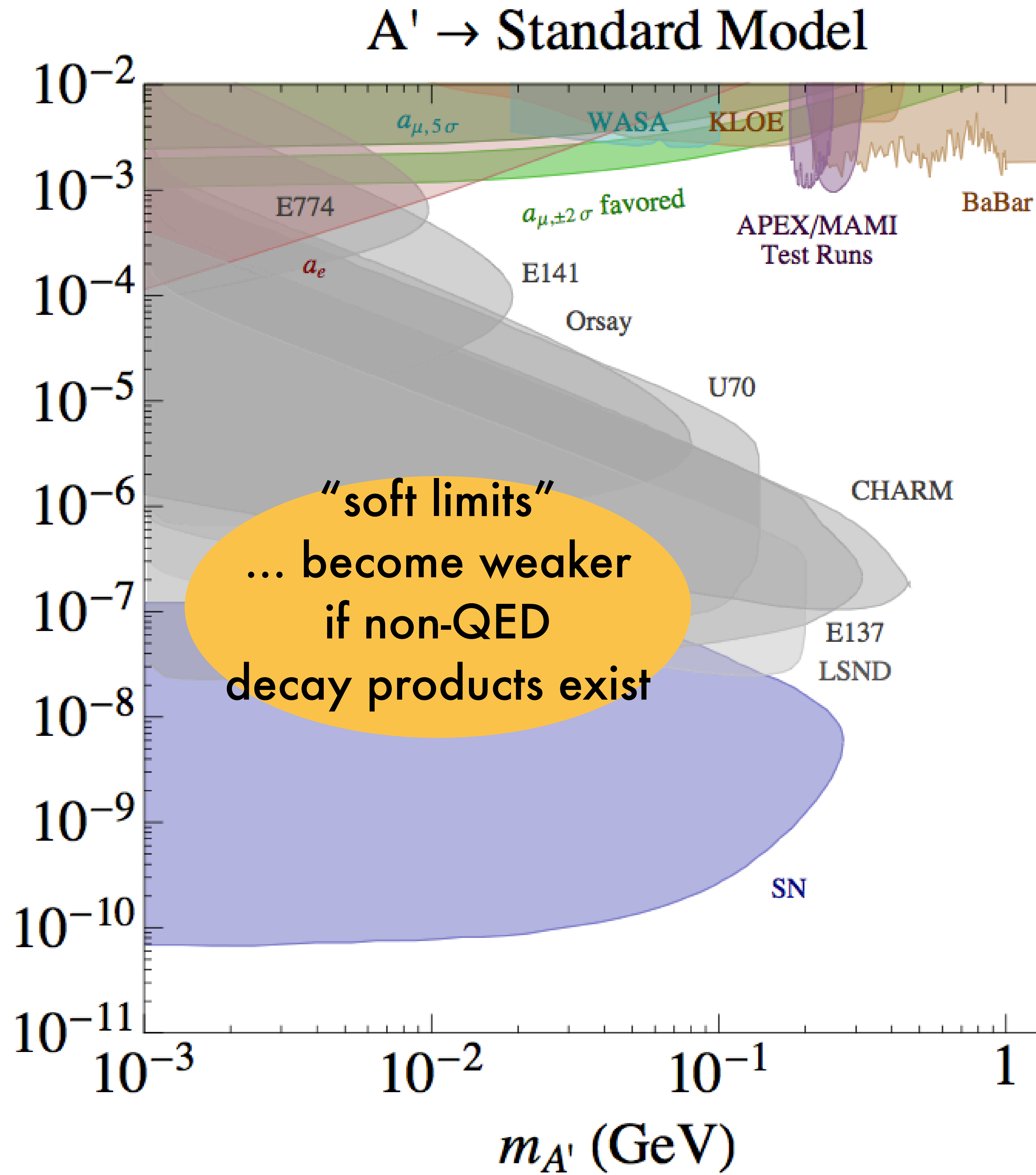
massive spin-1, coupling

$$\alpha_X = \epsilon^2 \alpha$$

no coupling to neutrons

we allow ε any sign

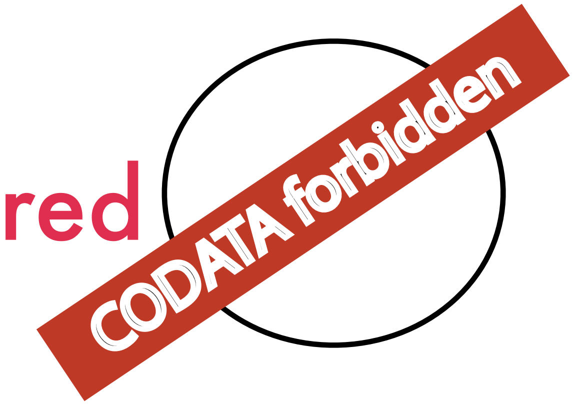
we do not determine spin



arXiv:1311.0029v1 [hep-ph]

Go , No Go, Go, No Go...

electron scattering has already measured
the charge radius for 50 years



¡ not if new physics comes
with a weak low mass singularity!

electron g-2 exactly agrees with QED.
There's no room for such an effect

¡ that agreement is *circular* in QED.
It's been used to define α.
¡New physics just shifts α!

Nobody can challenge QED
in hydrogenic spectra.

Agreement of the 1S2S is EXACT !

The RYDBERG is
the MOST PRECISE CONSTANT

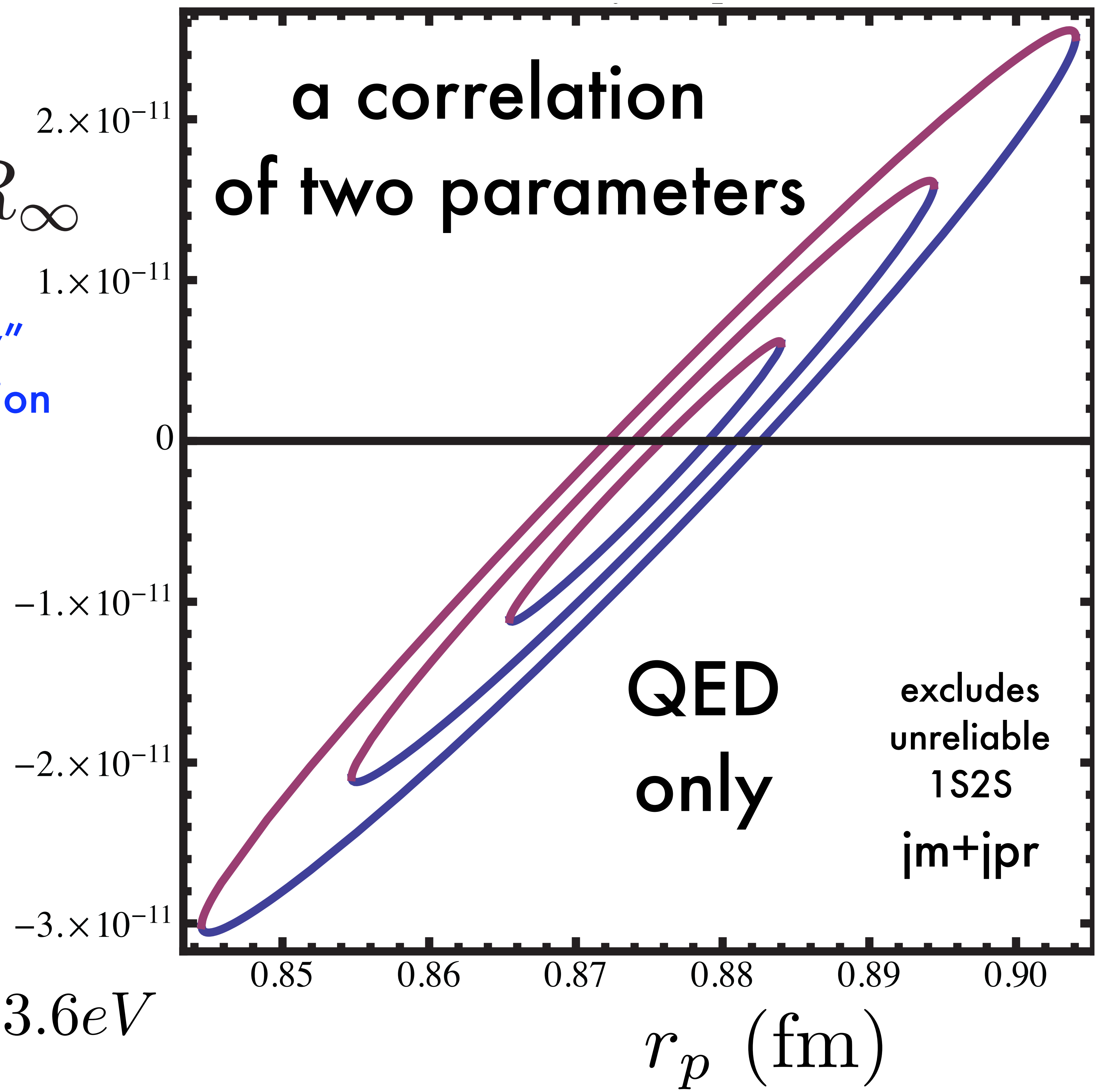
¡ Ni loca! Your famous *RYDBERG* comes
from a *COMMITTEE discarding DATA* and using
ALPHA circularly with the
PROTON RADIUS 0.99 CORRELATED !

read the fine print of the CODATA website and REVIEWS OF MODERN PHYSICS, VOLUME 84, 1527,, 2012

e-Hydrogen spectra measures a correlation... a correlation...

$$r_p^2 = -\frac{1}{6}\frac{\partial G_E}{\partial q^2}\bigg|_0$$

$$\delta R_\infty / R_\infty$$



"Rydberg uncertainty"
omits needed information

σ_{expt} Hz	f_{expt} Hz	$f_{our\,calc}$ Hz
35	$2.46606141319 \times 10^{15}$	$2.46606141319 \times 10^{15}$
10074	4.797338×10^{9}	$4.79733066539 \times 10^{9}$
24014	6.490144×10^{9}	$6.49012898284 \times 10^{9}$
8477	$7.70649350012 \times 10^{14}$	$7.70649350016 \times 10^{14}$
8477	$7.7064950445 \times 10^{14}$	$7.70649504449 \times 10^{14}$
6396	$7.70649561584 \times 10^{14}$	$7.70649561578 \times 10^{14}$
9590	$7.99191710473 \times 10^{14}$	$7.99191710481 \times 10^{14}$
6953	$7.99191727404 \times 10^{14}$	$7.99191727409 \times 10^{14}$
12860	$2.92274327868 \times 10^{15}$	$2.92274327867 \times 10^{15}$
20568	4.197604×10^{9}	$4.19759919778 \times 10^{9}$
10338	4.699099×10^{9}	$4.6991043085 \times 10^{9}$
14926	4.664269×10^{9}	$4.66425337748 \times 10^{9}$
10260	6.035373×10^{9}	$6.03538320383 \times 10^{9}$
11893	9.9112×10^{9}	$9.91119855042 \times 10^{9}$
8992	1.057845×10^{9}	$1.05784298986 \times 10^{9}$
20099	1.057862×10^{9}	$1.05784298986 \times 10^{9}$

$$R_\infty = \text{Rydberg} \sim 13.6eV$$

Our Idea: *Search for New Local Minima* of *ALL RELEVANT fundamental constants*

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$$a_\mu = 0.00116592091 \pm 6.3 \times 10^{-10}$$

$$\mu H : \quad \Delta E_{2S-2P} = 202.3706 \pm 0.0026\,\mathrm{meV}$$

$$m_e/h = 7.763440712 \times 10^{20} \pm 9.7 \times 10^{11}\, Hz$$

eH : 8 transitions listed

eD : 8 transitions listed

theory:
the ENTIRE BODY
of atomic QED and Standard Model
calculations

How do *inputs* affect *outputs*?

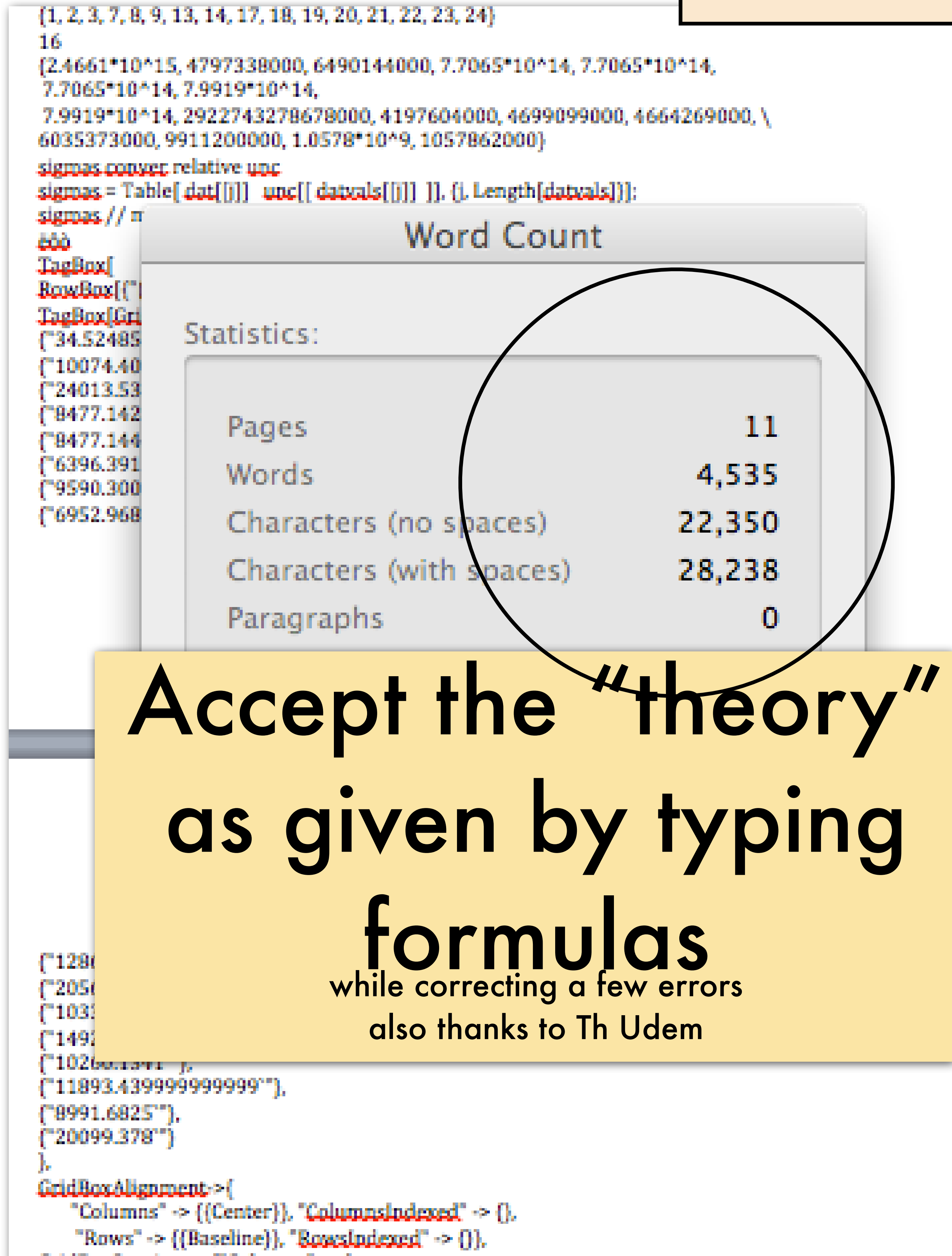
Theory: 75 years

28000 keystrokes

mathematica! In C++, estimate 260000

Breit, Dirac, Bethe...Yennie, Sapirstein, Ericson,Brodsky...Eides, Grotch, Shelyuto, Borie, Karshenboim, Mohr, Kotochigova, Pachucki, Yerokin et al, Jenstchura...

Review is over.
Our contribution



Accept the "theory" as given by typing formulas

while correcting a few errors
also thanks to Th Udem

Validating 28k keystrokes of theory implementation

this data set: 16 H transitions selected by CODATA for 20 years, 2010 includes 1S3S

meaningless exact fit →

σ_{expt} Hz	f_{expt} Hz	$f_{our\ calc}$ Hz
35	$2.46606141319 \times 10^{15}$	$2.46606141319 \times 10^{15}$
10074	4.797338×10^{9}	$4.79733066539 \times 10^{9}$
24014	6.490144×10^{9}	$6.49012898284 \times 10^{9}$
8477	$7.70649350012 \times 10^{14}$	$7.70649350016 \times 10^{14}$
8477	$7.7064950445 \times 10^{14}$	$7.70649504449 \times 10^{14}$
6396	$7.70649561584 \times 10^{14}$	$7.70649561578 \times 10^{14}$
9590	$7.99191710473 \times 10^{14}$	$7.99191710481 \times 10^{14}$
6953	$7.99191727404 \times 10^{14}$	$7.99191727409 \times 10^{14}$
12860	$2.92274327868 \times 10^{15}$	$2.92274327867 \times 10^{15}$
20568	4.197604×10^{9}	$4.19759919778 \times 10^{9}$
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JM+JPR

no theory errors listed here

two versions of theory on two machines; round off errors controlled

John Martens

We do NOT select really really special atomic data

One μH is published. *Use it, don't discard it.*

Almost all of the eH or eD data is good

We fit dozens of eH lines to fractions of uncertainty. *Including μH, we get r_p \sim 0.84*

The 1S2S is unreliable. Its *theory* uncertainty is 1000 times its *experimental* uncertainty

(Karshenboim 2005 criticism)

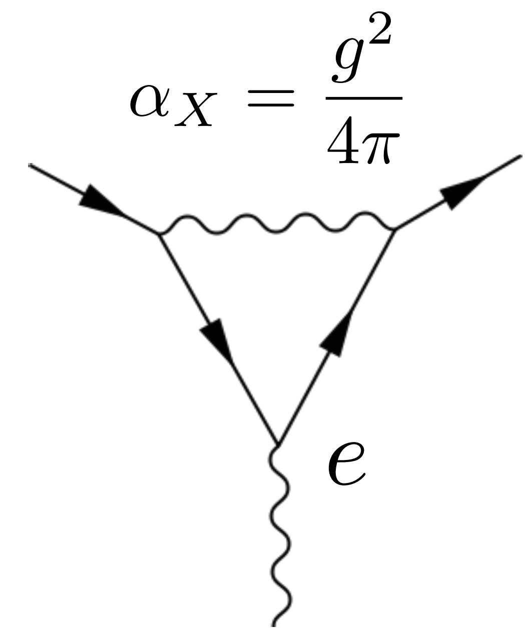
Complicated efforts ("additive corrections") have been used to cover the 1S2S theory unreliability. *We just omit it.*

That leaves 8 eH and 7+(1 repeated) eD top quality transitions free from messing with 1S2S subtractions

All the same, including the 1S2S with existing method *does not change our fits significantly* *null model:* the ENTIRE BODY of atomic QED and Standard Model calculations

test model: the null plus "universal coupling" of X, with effective potential

$$V(x) = \alpha_X \frac{e^{-m_X r}}{4\pi r}$$



which hypothesis wins?

a conventional fit to χ^2

$$\chi^2 = \frac{(a_e^{exp} - a_e^{theory})^2}{\sigma^2(a_e)} + \frac{(a_\mu^{exp} - a_\mu^{theory})^2}{\sigma^2(a_\mu)} + \sum_j^8 \frac{(\Delta f_{eH,j}^{exp} - \Delta f_{eH,j}^{theory})^2}{\sigma^2(\Delta f_{eH})} + \sum_j^8 \frac{(\Delta f_{eD,j}^{exp} - \Delta f_{eD,j}^{theory})^2}{\sigma^2(\Delta f_{eD})} + \frac{(\Delta f_{\mu H}^{exp} - \Delta f_{\mu H}^{theory})^2}{\sigma^2(\Delta f_{\mu H})} + \frac{(4\pi c R_\infty/\alpha^2 - (m_e/h)^{exp})}{\sigma^2(m_e/h)}$$

LOGICALLY INCONSISTENT
to compare CODATA procedure
biased to a_e QED, Rydberg
and excluded experimental data

our parameters:

$$\alpha,\ R_\infty,\ r_p,$$

$$(\alpha_X,\ m_X) \to \alpha_X/m_X^2$$

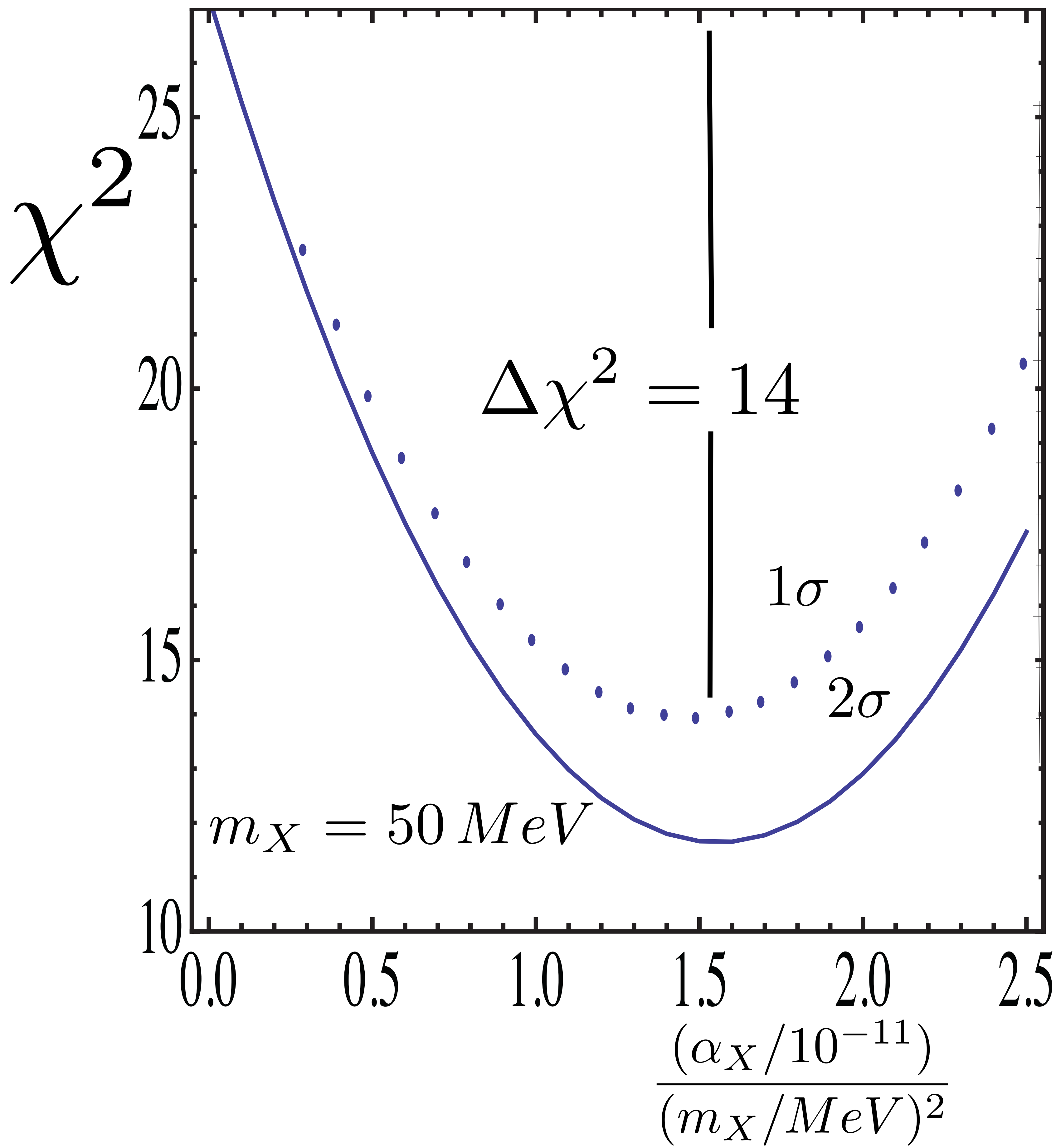
analytic degeneracy for $m_X >> m_\mu$

$r_p = 0.841 \pm .001$ across the range

Fits are sensitive
to m_e/h
uncertainty
(one Bouchendira
experiment)

We compare
1 sigma and
2 sigma fits

Data predicts
mX > 30 MeV,
... the region where
ALL terms in χ^2
are a good fit



m_X $[MeV/c^2]$	$\delta R_\infty / R_\infty$	r_p $[fm]$	$\delta\alpha/\alpha$	ϵ^2
10	-1.14×10^{-11}	0.84175	-1.55×10^{-9}	8.28×10^{-7}
–	$\pm \left(3.3 \times 10^{-12}\right)$	± 0.00047	$\pm \left(6.3 \times 10^{-10}\right)$	$\pm \left(3.7 \times 10^{-7}\right)$
25	-1.26×10^{-11}	0.84154	-1.09×10^{-9}	3.34×10^{-6}
–	$\pm \left(3. \times 10^{-12}\right)$	± 0.00031	$\pm \left(3.2 \times 10^{-10}\right)$	$\pm \left(8.8 \times 10^{-7}\right)$
50	-1.39×10^{-11}	0.84116	-5.82×10^{-10}	5.34×10^{-6}
–	$\pm \left(2.9 \times 10^{-12}\right)$	± 0.00027	$\pm \left(2.5 \times 10^{-10}\right)$	$\pm \left(1.4 \times 10^{-6}\right)$
100	-1.44×10^{-11}	0.84101	-3.97×10^{-10}	9.69×10^{-6}
–	$\pm \left(2.9 \times 10^{-12}\right)$	± 0.00026	$\pm \left(2.3 \times 10^{-10}\right)$	$\pm \left(2.4 \times 10^{-6}\right)$
150	-1.46×10^{-11}	0.84097	-3.51×10^{-10}	1.52×10^{-5}
–	$\pm \left(2.9 \times 10^{-12}\right)$	± 0.00026	$\pm \left(2.3 \times 10^{-10}\right)$	$\pm \left(3.8 \times 10^{-6}\right)$
200	-1.46×10^{-11}	0.84096	-3.31×10^{-10}	2.21×10^{-5}
–	$\pm \left(2.9 \times 10^{-12}\right)$	± 0.00026	$\pm \left(2.3 \times 10^{-10}\right)$	$\pm \left(5.6 \times 10^{-6}\right)$
300	-1.47×10^{-11}	0.84094	-3.14×10^{-10}	3.96×10^{-5}
–	$\pm \left(2.9 \times 10^{-12}\right)$	± 0.00026	$\pm \left(2.3 \times 10^{-10}\right)$	$\pm \left(1. \times 10^{-5}\right)$

Table 1: Ejemplo numero uno.

$m_X\ [MeV/c^2]$	$m_ec^2/h\ [s^-1]$	$r_p\ [fm]$	$(\delta\alpha/\alpha)/10^{-10}$	$(\alpha_X/m_X^2)/10^{-11}\ [(MeV/c^2)^{-2}]$
10	$7.763440737 \times 10^{20}$	0.84175	-15.5	6.04
–	$\pm\left(9.8 \times 10^{11}\right)$	± 0.00047	± 6.3	± 2.7
25	$7.76344073 \times 10^{20}$	0.84154	-10.9	3.9
–	$\pm\left(4.9 \times 10^{11}\right)$	± 0.00031	± 3.2	$\pm 1.$
50	$7.763440722 \times 10^{20}$	0.84116	-5.82	1.56
–	$\pm\left(3.8 \times 10^{11}\right)$	± 0.00027	± 2.5	± 0.39
100	$7.763440719 \times 10^{20}$	0.84101	-3.97	0.707
–	$\pm\left(3.6 \times 10^{11}\right)$	± 0.00026	± 2.3	± 0.18
150	$7.763440718 \times 10^{20}$	0.84097	-3.51	0.494
–	$\pm\left(3.6 \times 10^{11}\right)$	± 0.00026	± 2.3	± 0.12
200	$7.763440718 \times 10^{20}$	0.84096	-3.31	0.402
–	$\pm\left(3.6 \times 10^{11}\right)$	± 0.00026	± 2.3	± 0.1
300	$7.763440717 \times 10^{20}$	0.84094	-3.14	0.321
–	$\pm\left(3.6 \times 10^{11}\right)$	± 0.00026	± 2.3	± 0.081

Table 2: Ejemplo numero dos.

"the small radius solution"

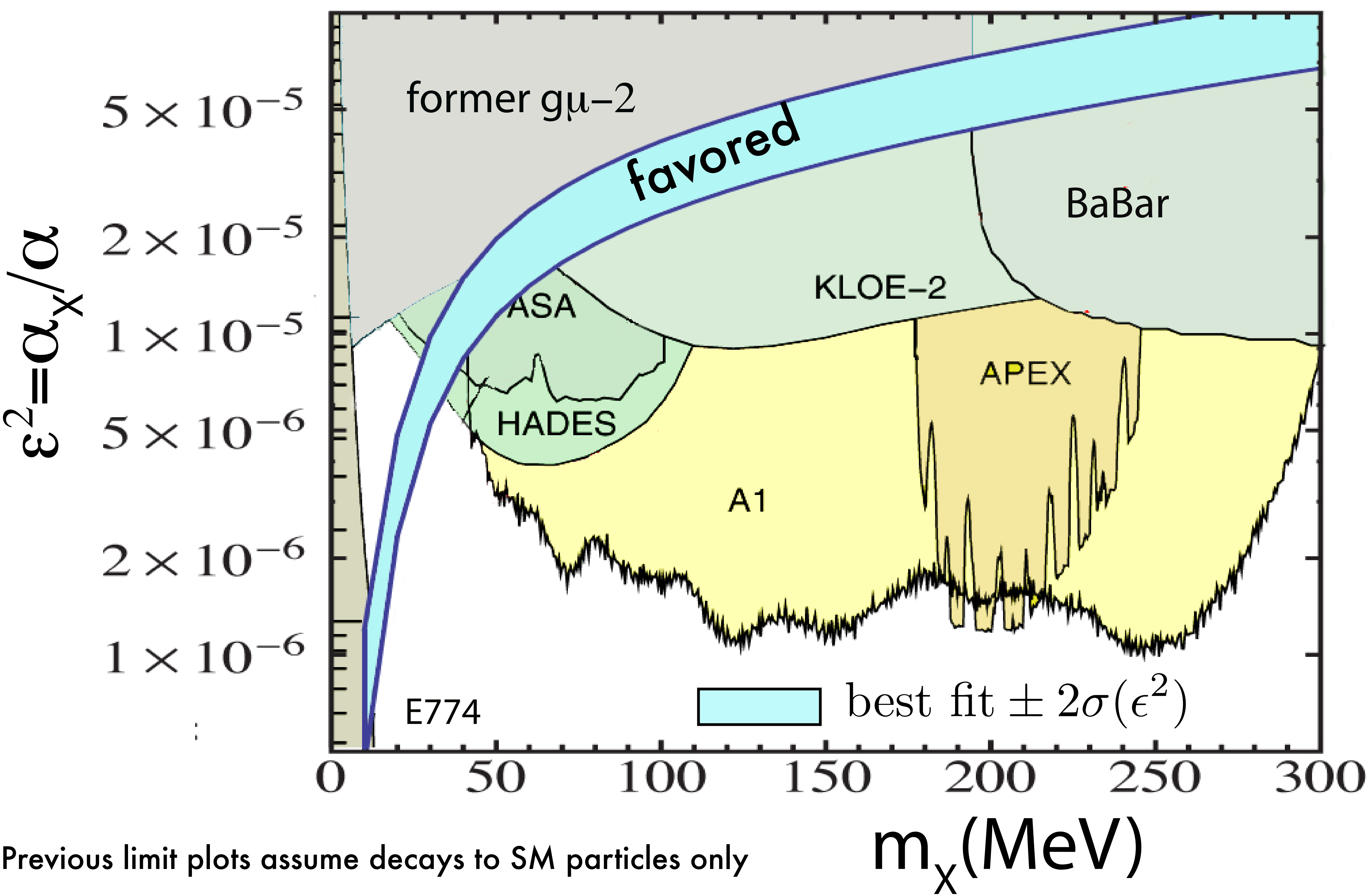
of order 10% weak effects

Fits are robust and stable under:

omit eH	$\Delta\chi^2 > 15$	$r_p = 0.84$
omit eD	$\Delta\chi^2 > 15$	$r_p = 0.84$
omit μH	$\Delta\chi^2 > 15$	$r_p \to 0.88$
omit a_e	$\Delta\chi^2 > 15$	$r_p = 0.84$
omit a_μ	$\Delta\chi^2 \to\sim 1,$	"old parameters solution"
omit m_e/h	$\Delta\chi^2 > 15$	$r_p = 0.84$

If you omit a_μ and set α_X=0 you have the previous 3.9σ discrepancy while r_p =0.84 and α changes significantly

New model beats standard model

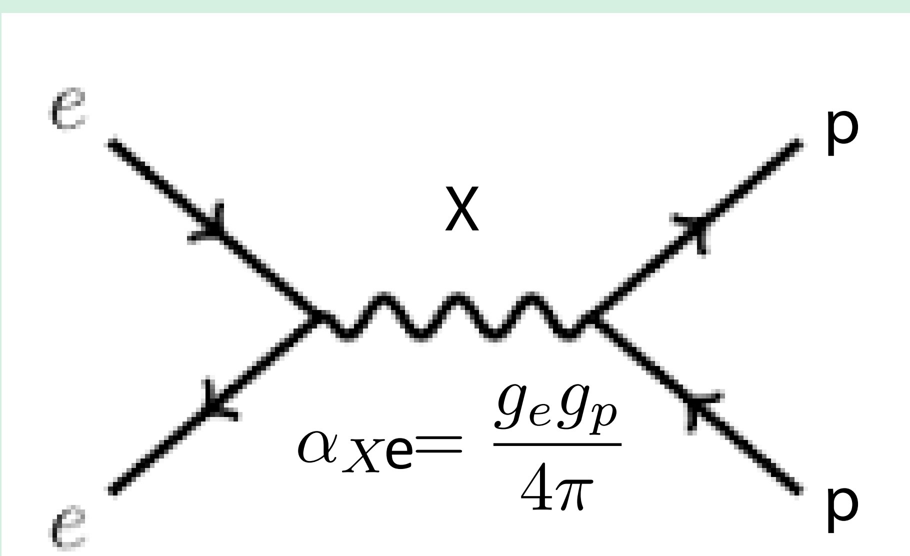


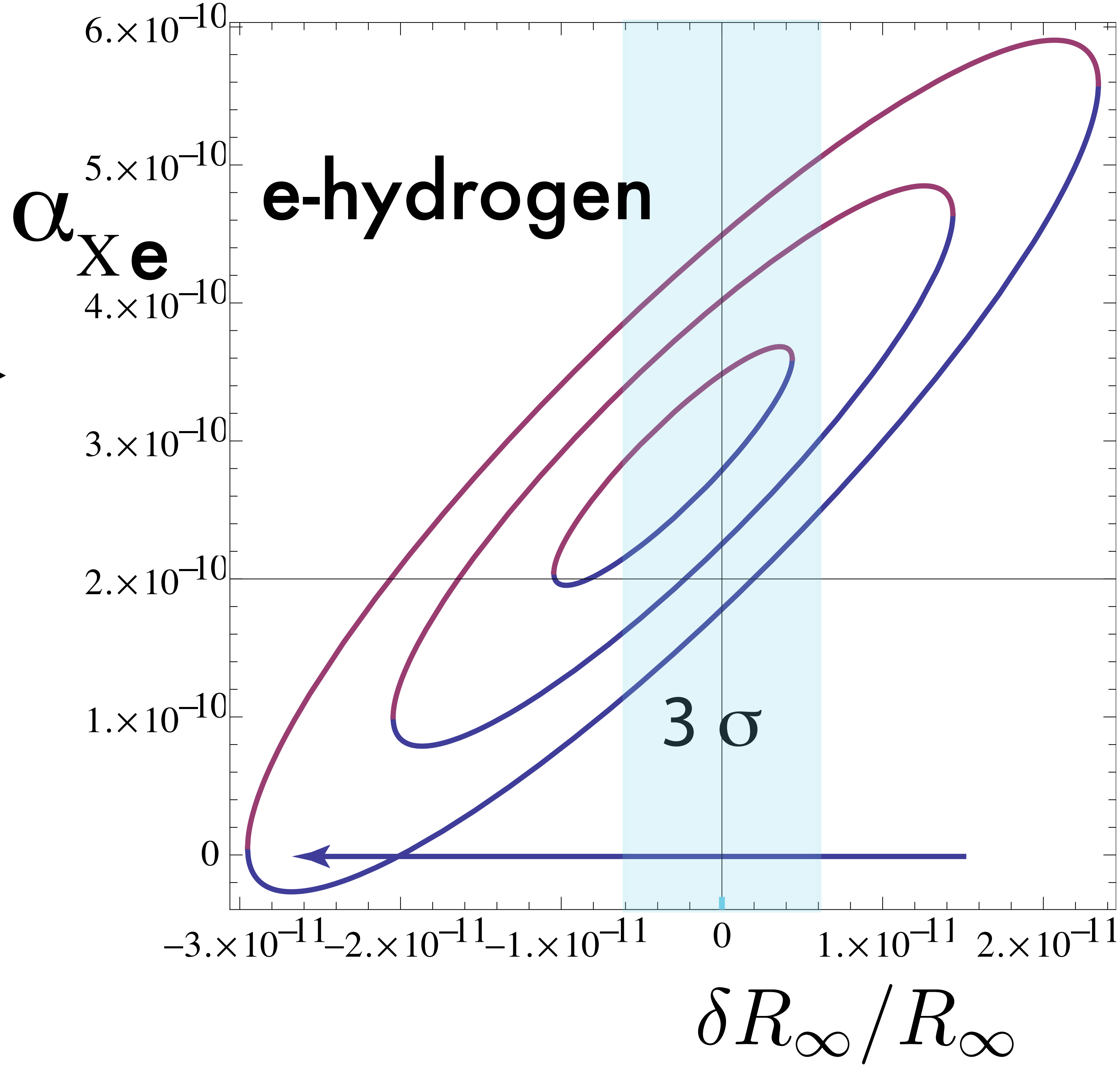
Previous limit plots assume decays to SM particles only

measuring the new coupling

uses μ-hydrogen value

$r_p = 0.841$





R_∞ = Rydberg =13.6 eV

¡TESTS! ¡PREDICTIONS! ¡TESTS!

μD already passed... theory is

μHe_3 theory

positronium, muonium, true muonium

e^+e^- μ^+e^- $\mu^+\mu^-$

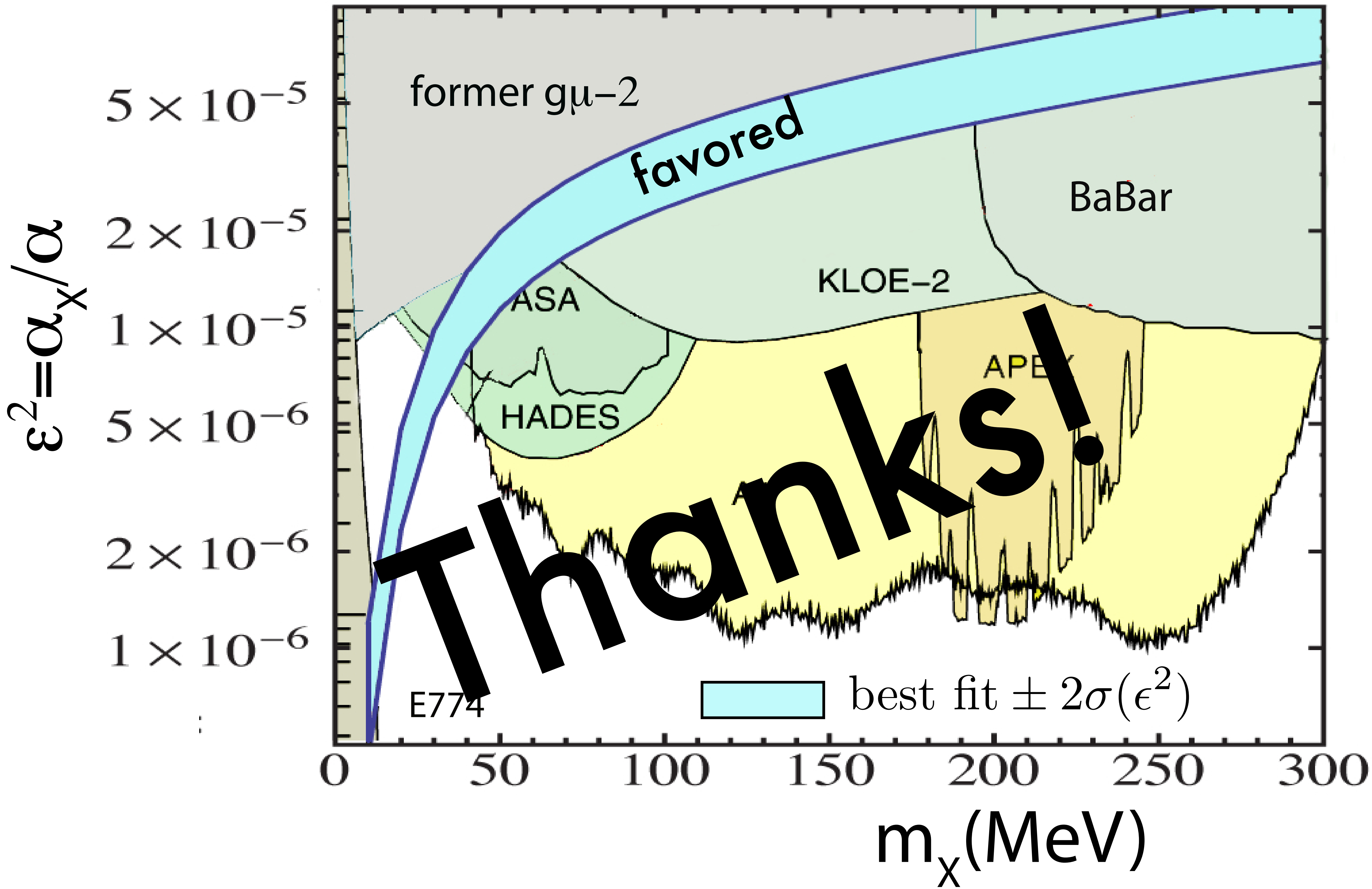
Lamb shifts and decays

Beam dump, bremms and particle decay channels

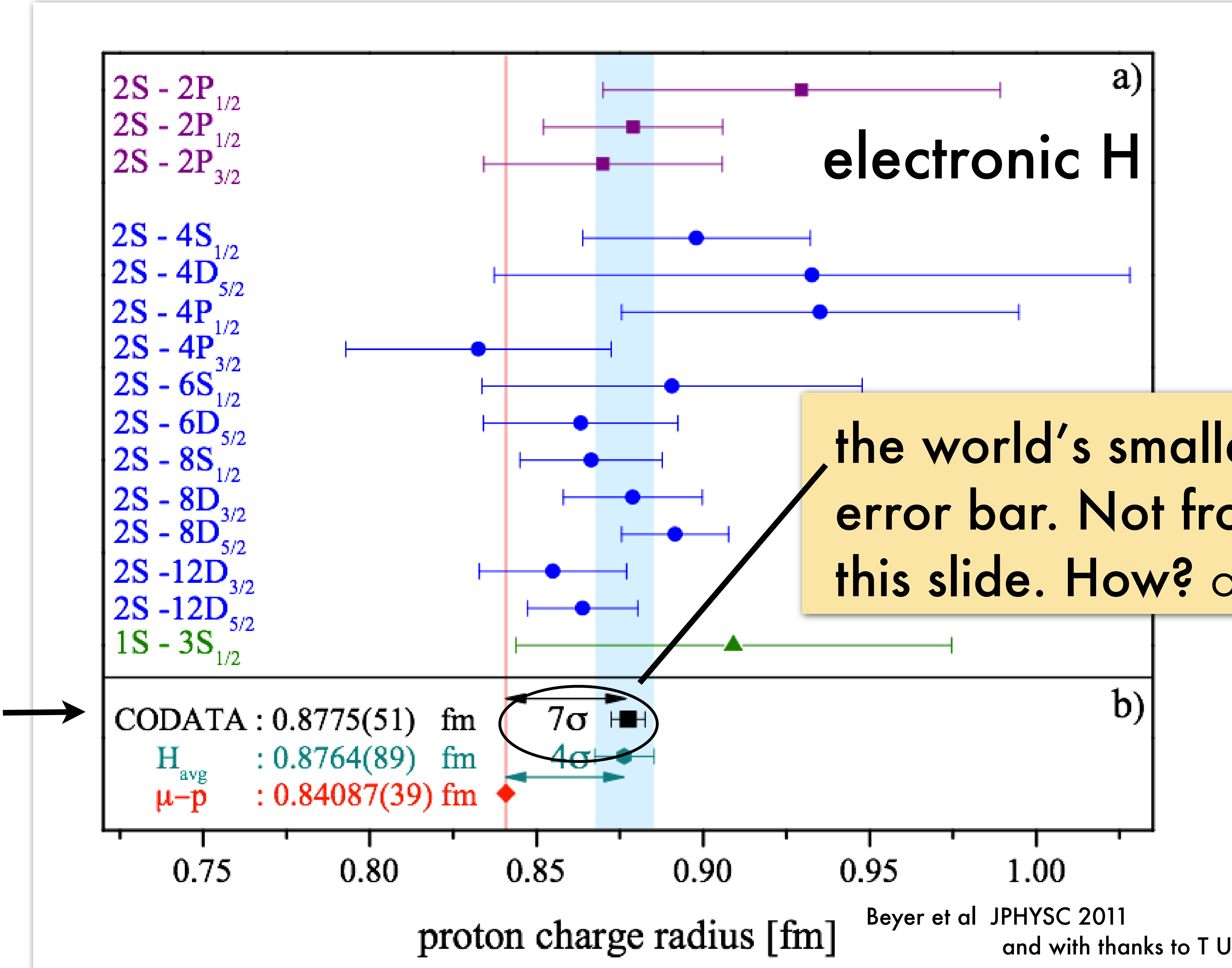
MAMI, JLAB "darklite" and other plans

APPARENT CONFLICT with finite q^2 incl.
muon scattering is a new SIGNAL

The fundamental constants are revised


Thanks!
former gμ−2
favored
BaBar
KLOE−2
ASA
HADES
APE
E774
best fit ± 2σ(ε²)
5 × 10⁻⁵
2 × 10⁻⁵
1 × 10⁻⁵
5 × 10⁻⁶
2 × 10⁻⁶
1 × 10⁻⁶
0
50
100
150
200
250
300
ε²=α_X/α
m_X(MeV)

A wide range of spectroscopic proton sizes in a simple fit



the world's smallest error bar. Not from this slide. How? Omit Data

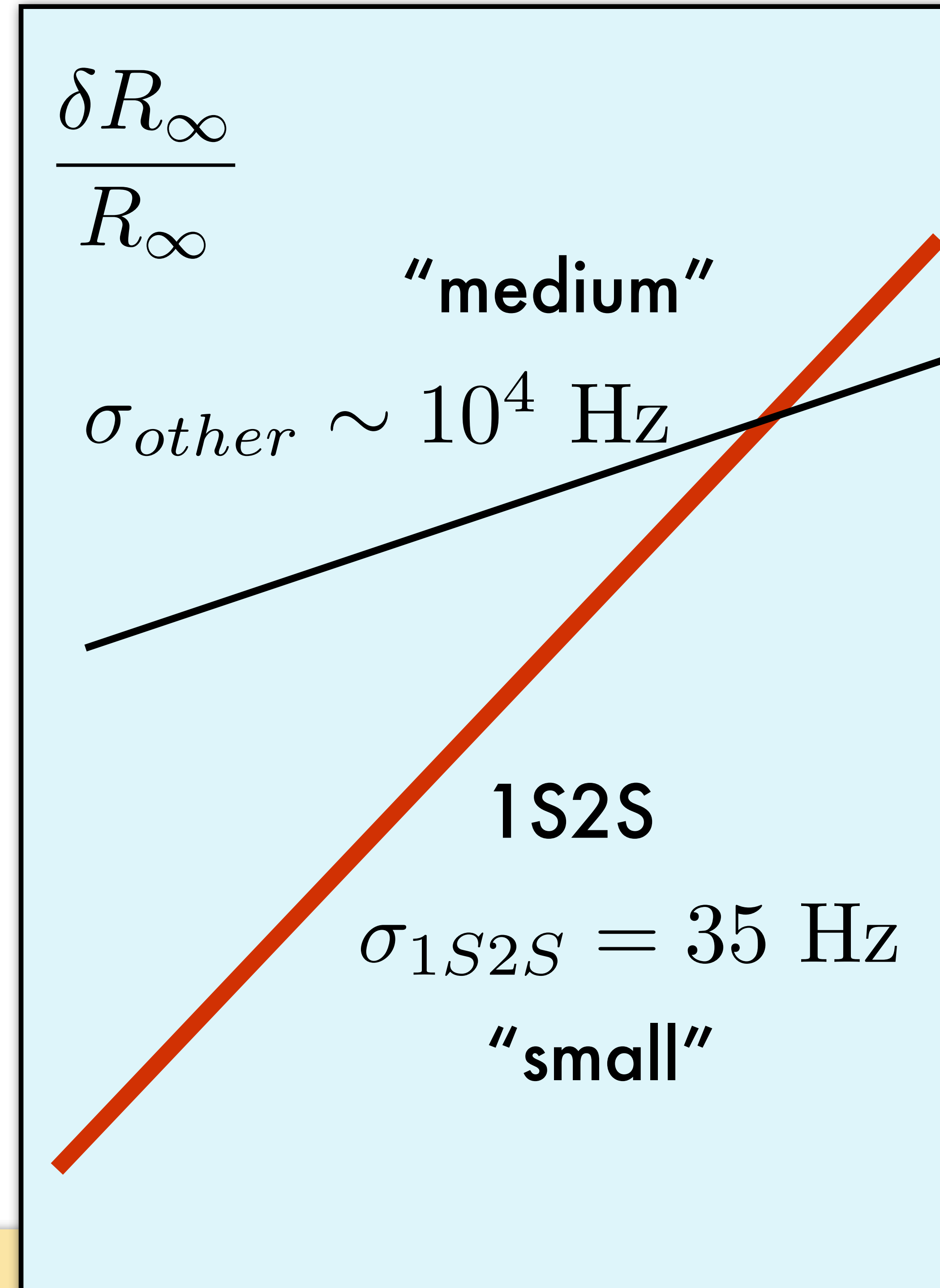
Beyer et al JPHYSC 2011
and with thanks to T Udem

“1S2S Concept Slide”

any one transition gives one datum

fit by two parameters

the result is a particular line of degeneracy for a one-point fit



So what?

ENTER, the experimental uncertainties

$$\sigma_i = (35, 6396, 6953, \ldots\ 20568, 24014)\ \text{Hz}$$

$$\chi^2 \sim 1/\sigma^2$$

The mean value of $\sigma_j^2/\sigma_{1S2S}^2 = 148,400.$

One astonishing QED prediction now explained

Jentschura, Kotochigova, LeBigot, Mohr, Taylor

PRL **95,** 163003 (2005) PHYSICAL REVIEW LETTERS week ending 14 OCTOBER 2005

TABLE I. Transition frequencies in hydrogen ν_H and in deuterium ν_D used in the 2002 CODATA least-squares adjustment of the values of the fundamental constants and the calculated values. Hyperfine effects are not included in these values.

Experiment	Frequency interval(s)	Reported value ν/kHz	Calculated value ν/kHz
Niering *et al.* [1]	$\nu_H(1S_{1/2} - 2S_{1/2})$	2 466 061 413 187.103(46)	2 466 061 413 187.103(46)
Weitz *et al.* [2]	$\nu_H(2S_{1/2} - 4S_{1/2}) - \frac{1}{4}\nu_H(1S_{1/2} - 2S_{1/2})$	4 797 338(10)	4 797 331.8(2.0)
	$\nu_H(2S_{1/2} - 4D_{5/2}) - \frac{1}{4}\nu_H(1S_{1/2} - 2S_{1/2})$	6 490 144(24)	6 490 129.9(1.7)
	$\nu_D(2S_{1/2} - 4S_{1/2}) - \frac{1}{4}\nu_D(1S_{1/2} - 2S_{1/2})$	4 801 693(20)	4 801 710.2(2.0)
	$\nu_D(2S_{1/2} - 4D_{5/2}) - \frac{1}{4}\nu_D(1S_{1/2} - 2S_{1/2})$	6 494 841(41)	6 494 831.5(1.7)

$$\sigma_{theory} << \sigma_{expt}$$

1S2S *exact agreement experiment v calculated*

`` the values of the constants... are correlated, particularly those for R_{∞} and r_{p}... The uncertainty of the calculated value for the $1s-2s$ frequency in hydrogen is increased by a factor of about 500 if such correlations are neglected."

Okay. 500 x 46 Hz = 23000 Hz theory uncertainty

"However, one thing can be stated with certainty: the exact agreement of those two ultra-precise 1S2S measurements with the QED calculations cannot be considered as a confirmation of the QED theory, because it is the result of the fitting of the fundamental constants based on these (and other) transitions."

A. Kramida, Atomic Data and Nuclear Data Tables, 96, 586 (2010)

Proton size has previous been quantified relative to *world's smallest-ever* sigma

REVIEWS OF MODERN PHYSICS, VOLUME 84, OCTOBER–DECEMBER 2012

CODATA recommended values of the fundamental physical constants: 2010*

Peter J. Mohr,† Barry N. Taylor,‡ and David B. Newell§

National Institute of Standards and Technology, Gaithersburg, Maryland 20899-8420, USA

(published 13 November 2012)

This paper gives the 2010 self-consistent set of values of the basic constants and conversion factors of physics and chemistry recommended by the Committee on Data for Science and Technology (CODATA) for international use. The 2010 adjustment takes into account the data considered in the 2006 adjustment as well as the data that became available from 1 January 2007, after the closing date of that adjustment, until 31 December 2010, the closing date of the new adjustment. Further, it describes in detail the adjustment of the values of the constants, including the selection of the final set of input data based on the results of least-squares analyses. The 2010 set replaces the previously recommended 2006 CODATA set and may also be found on the World Wide Web at physics.nist.gov/constants.

DOI: 10.1103/RevModPhys.84.1527 PACS numbers: 06.20.Jr, 12.20.−m

purpose is "to periodically provide the international scientific and technological communities with an internationally accepted set of values of the fundamental physical constants and closely related conversion factors for use worldwide."

REVIEWS OF MODERN PHYSICS, VOLUME 84, OCTOBER–DECEMBER 2012

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global fit to all constants

149 input data
82 parameters

sector most relevant to proton radius:

25 experimental input data
28 adjustable constants

free parameters = # data+3

TABLE XXX. The 28 adjusted constants (variables) used in the least-squares multivariate analysis of the Rydberg-constant data given in Table XVIII. These adjusted constants appear as arguments of the functions on the right-hand side of the observational equations of Table XXXI.

Adjusted constant	Symbol
Rydberg constant	R_∞
Bound-state proton rms charge radius	r_p
Bound-state deuteron rms charge radius	r_d
Additive correction to $E_H(1S_{1/2})/h$	$\delta_H(1S_{1/2})$
Additive correction to $E_H(2S_{1/2})/h$	$\delta_H(2S_{1/2})$
Additive correction to $E_H(3S_{1/2})/h$	$\delta_H(3S_{1/2})$
Additive correction to $E_H(4S_{1/2})/h$	$\delta_H(4S_{1/2})$
Additive correction to $E_H(6S_{1/2})/h$	$\delta_H(6S_{1/2})$
Additive correction to $E_H(8S_{1/2})/h$	$\delta_H(8S_{1/2})$
Additive correction to $E_H(2P_{1/2})/h$	$\delta_H(2P_{1/2})$
Additive correction to $E_H(4P_{1/2})/h$	$\delta_H(4P_{1/2})$
Additive correction to $E_H(2P_{3/2})/h$	$\delta_H(2P_{3/2})$
Additive correction to $E_H(4P_{3/2})/h$	$\delta_H(4P_{3/2})$
Additive correction to $E_H(8D_{3/2})/h$	$\delta_H(8D_{3/2})$
Additive correction to $E_H(12D_{3/2})/h$	$\delta_H(12D_{3/2})$
Additive correction to $E_H(4D_{5/2})/h$	$\delta_H(4D_{5/2})$
Additive correction to $E_H(6D_{5/2})/h$	$\delta_H(6D_{5/2})$
Additive correction to $E_H(8D_{5/2})/h$	$\delta_H(8D_{5/2})$
Additive correction to $E_H(12D_{5/2})/h$	$\delta_H(12D_{5/2})$
Additive correction to $E_D(1S_{1/2})/h$	$\delta_D(1S_{1/2})$
Additive correction to $E_D(2S_{1/2})/h$	$\delta_D(2S_{1/2})$
Additive correction to $E_D(4S_{1/2})/h$	$\delta_D(4S_{1/2})$
Additive correction to $E_D(8S_{1/2})/h$	$\delta_D(8S_{1/2})$
Additive correction to $E_D(8D_{3/2})/h$	$\delta_D(8D_{3/2})$
Additive correction to $E_D(12D_{3/2})/h$	$\delta_D(12D_{3/2})$
Additive correction to $E_D(4D_{5/2})/h$	$\delta_D(4D_{5/2})$
Additive correction to $E_D(8D_{5/2})/h$	$\delta_D(8D_{5/2})$
Additive correction to $E_D(12D_{5/2})/h$	$\delta_D(12D_{5/2})$

adjusted in fit

Table XVIII shows 50 ``principal input data for the determination of the 2010 recommended value of the Rydberg constant R_{∞}".

However 25 of the 50 are theory parameters treated as adjustable constants
That makes one "additive correction" per energy level

Actually, more than 100 externally chosen parameters are introduced to fit three (3) physical constants

CODATA works for NIST

it's their job to assume a GIVEN theory

NIST
National Institute of Standards and Technology
U.S. Department of Commerce

Karshenboim, CODATA task committee, Can J Phys 2005:

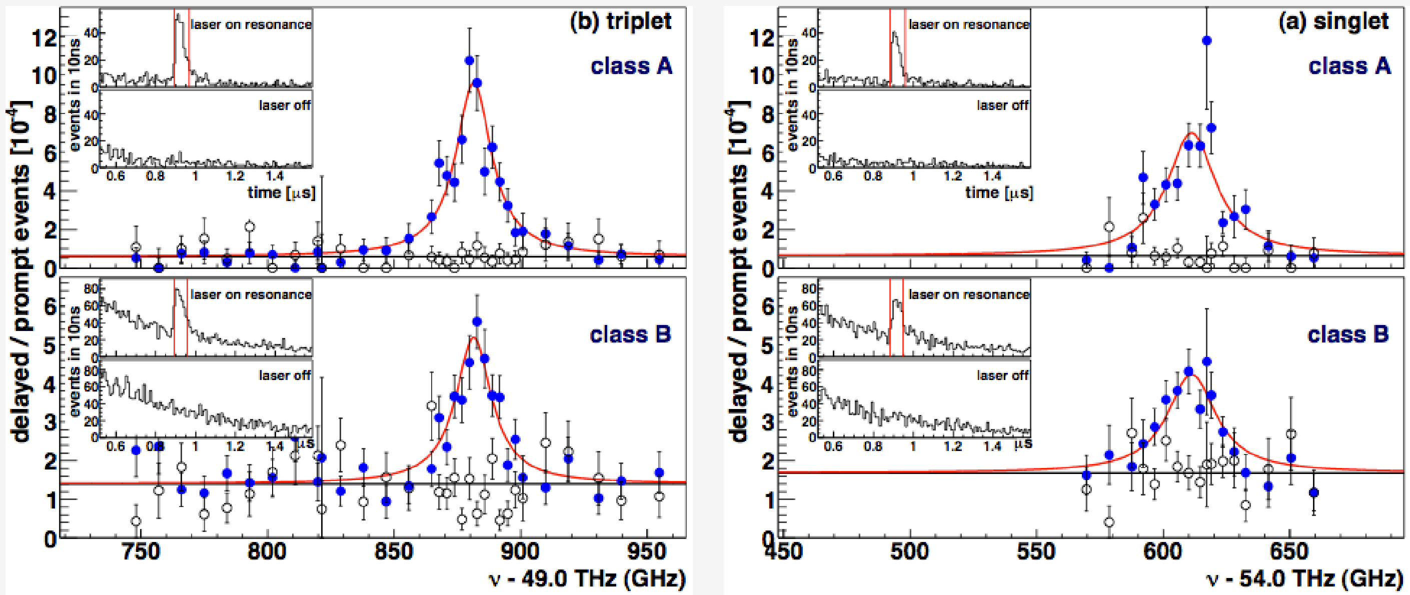
"Physicists serve as experts only while decisions are made by authorities. The SI system has been created for a legal use and trade rather than for scientific applications. "

"We (physicists) do not care about actual SI definitions partly because we do not consider seriously the legal side of SI and due to that we believe that we may ourselves interpret and correct SI definitions if necessary."

CODATA2010: *"As in all previous CODATA adjustments, as a working principle, the validity of the physical theory underlying the 2010 adjustment is assumed*

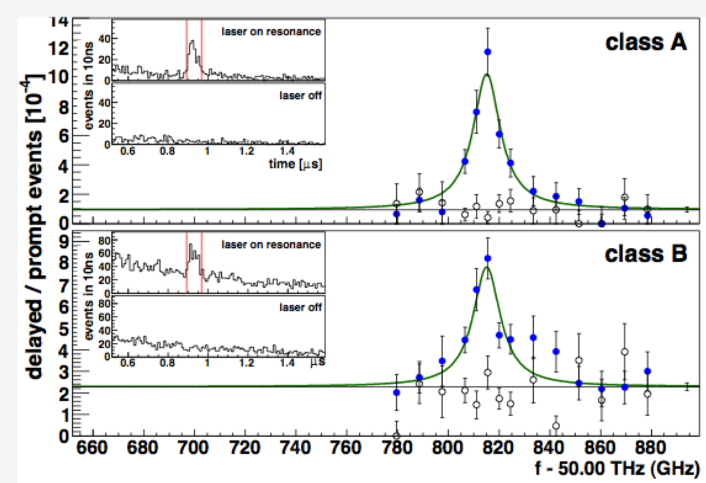
We have measured two transitions in μp!

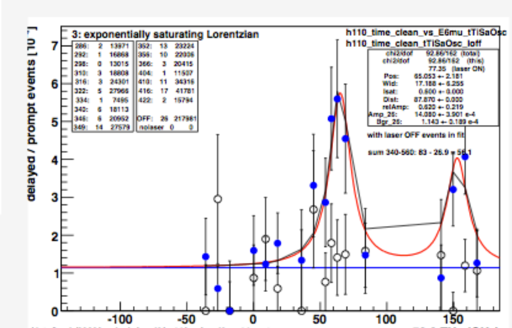
$\nu_t = \nu(2S_{1/2}^{F=1} - 2P_{3/2}^{F=2})$ at $\lambda = 6.0\ \mu m$ $\nu_s = \nu(2S_{1/2}^{F=0} - 2P_{3/2}^{F=1})$ at $\lambda = 5.5\ \mu m$



Both resonances are 0.3 meV discrepant from predictions using r_p from CODATA

The 3 measured μd transitions





The fit is done assuming the 2P splitting predicted by theory

TABLE XVIII. Summary of principal input data for the determination of the 2010 recommended value of the Rydberg constant R_∞.

Item No.	Input datum	Value	Relative standard uncertainty[a] u_r	Identification	Sec.
$A1$	$\delta_H(1S_{1/2})$	0.0(2.5) kHz	$[7.5 \times 10^{-13}]$	Theory	IV.A.1.l
$A2$	$\delta_H(2S_{1/2})$	0.00(31) kHz	$[3.8 \times 10^{-13}]$	Theory	IV.A.1.l
$A3$	$\delta_H(3S_{1/2})$	0.000(91) kHz	$[2.5 \times 10^{-13}]$	Theory	IV.A.1.l
$A4$	$\delta_H(4S_{1/2})$	0.000(39) kHz	$[1.9 \times 10^{-13}]$	Theory	IV.A.1.l
$A5$	$\delta_H(6S_{1/2})$	0.000(15) kHz	$[1.6 \times 10^{-13}]$	Theory	IV.A.1.l
$A6$	$\delta_H(8S_{1/2})$	0.0000(63) kHz	$[1.2 \times 10^{-13}]$	Theory	IV.A.1.l
$A7$	$\delta_H(2P_{1/2})$	0.000(28) kHz	$[3.5 \times 10^{-14}]$	Theory	IV.A.1.l
$A8$	$\delta_H(4P_{1/2})$	0.0000(38) kHz	$[1.9 \times 10^{-14}]$	Theory	IV.A.1.l
$A9$	$\delta_H(2P_{3/2})$	0.000(28) kHz	$[3.5 \times 10^{-14}]$	Theory	IV.A.1.l
$A10$	$\delta_H(4P_{3/2})$	0.0000(38) kHz	$[1.9 \times 10^{-14}]$	Theory	IV.A.1.l
$A11$	$\delta_H(8D_{3/2})$	0.000 00(44) kHz	$[8.5 \times 10^{-15}]$	Theory	IV.A.1.l
$A12$	$\delta_H(12D_{3/2})$	0.000 00(13) kHz	$[5.7 \times 10^{-15}]$	Theory	IV.A.1.l
$A13$	$\delta_H(4D_{5/2})$	0.0000(35) kHz	$[1.7 \times 10^{-14}]$	Theory	IV.A.1.l
$A14$	$\delta_H(6D_{5/2})$	0.0000(10) kHz	$[1.1 \times 10^{-14}]$	Theory	IV.A.1.l
$A15$	$\delta_H(8D_{5/2})$	0.000 00(44) kHz	$[8.5 \times 10^{-15}]$	Theory	IV.A.1.l
$A16$	$\delta_H(12D_{5/2})$	0.000 00(13) kHz	$[5.7 \times 10^{-15}]$	Theory	IV.A.1.l
$A17$	$\delta_D(1S_{1/2})$	0.0(2.3) kHz	$[6.9 \times 10^{-13}]$	Theory	IV.A.1.l
$A18$	$\delta_D(2S_{1/2})$	0.00(29) kHz	$[3.5 \times 10^{-13}]$	Theory	IV.A.1.l
$A19$	$\delta_D(4S_{1/2})$	0.000(36) kHz	$[1.7 \times 10^{-13}]$	Theory	IV.A.1.l
$A20$	$\delta_D(8S_{1/2})$	0.0000(60) kHz	$[1.2 \times 10^{-13}]$	Theory	IV.A.1.l
$A21$	$\delta_D(8D_{3/2})$	0.000 00(44) kHz	$[8.5 \times 10^{-15}]$	Theory	IV.A.1.l
$A22$	$\delta_D(12D_{3/2})$	0.000 00(13) kHz	$[5.6 \times 10^{-15}]$	Theory	IV.A.1.l
$A23$	$\delta_D(4D_{5/2})$	0.0000(35) kHz	$[1.7 \times 10^{-14}]$	Theory	IV.A.1.l
$A24$	$\delta_D(8D_{5/2})$	0.000 00(44) kHz	$[8.5 \times 10^{-15}]$	Theory	IV.A.1.l
$A25$	$\delta_D(12D_{5/2})$	0.000 00(13) kHz	$[5.7 \times 10^{-15}]$	Theory	IV.A.1.l
$A26$	$\nu_H(1S_{1/2} - 2S_{1/2})$	2 466 061 413 187.080(34) kHz	1.4×10^{-14}	MPQ-04	IV.A.2
$A27$	$\nu_H(1S_{1/2} - 3S_{1/2})$	2 922 743 278 678(13) kHz	4.4×10^{-12}	LKB-10	IV.A.2
$A28$	$\nu_H(2S_{1/2} - 8S_{1/2})$	770 649 350 012.0(8.6) kHz	1.1×10^{-11}	LK/SY-97	IV.A.2
$A29$	$\nu_H(2S_{1/2} - 8D_{3/2})$	770 649 504 450.0(8.3) kHz	1.1×10^{-11}	LK/SY-97	IV.A.2
$A30$	$\nu_H(2S_{1/2} - 8D_{5/2})$	770 649 561 584.2(6.4) kHz	8.3×10^{-12}	LK/SY-97	IV.A.2
$A31$	$\nu_H(2S_{1/2} - 12D_{3/2})$	799 191 710 472.7(9.4) kHz	1.2×10^{-11}	LK/SY-98	IV.A.2
$A32$	$\nu_H(2S_{1/2} - 12D_{5/2})$	799 191 727 403.7(7.0) kHz	8.7×10^{-12}	LK/SY-98	IV.A.2

here additive theory adjustments are called “principal data”