Spectroscopy of muonic atoms

and the proton radius puzzle

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CREMA collaboration

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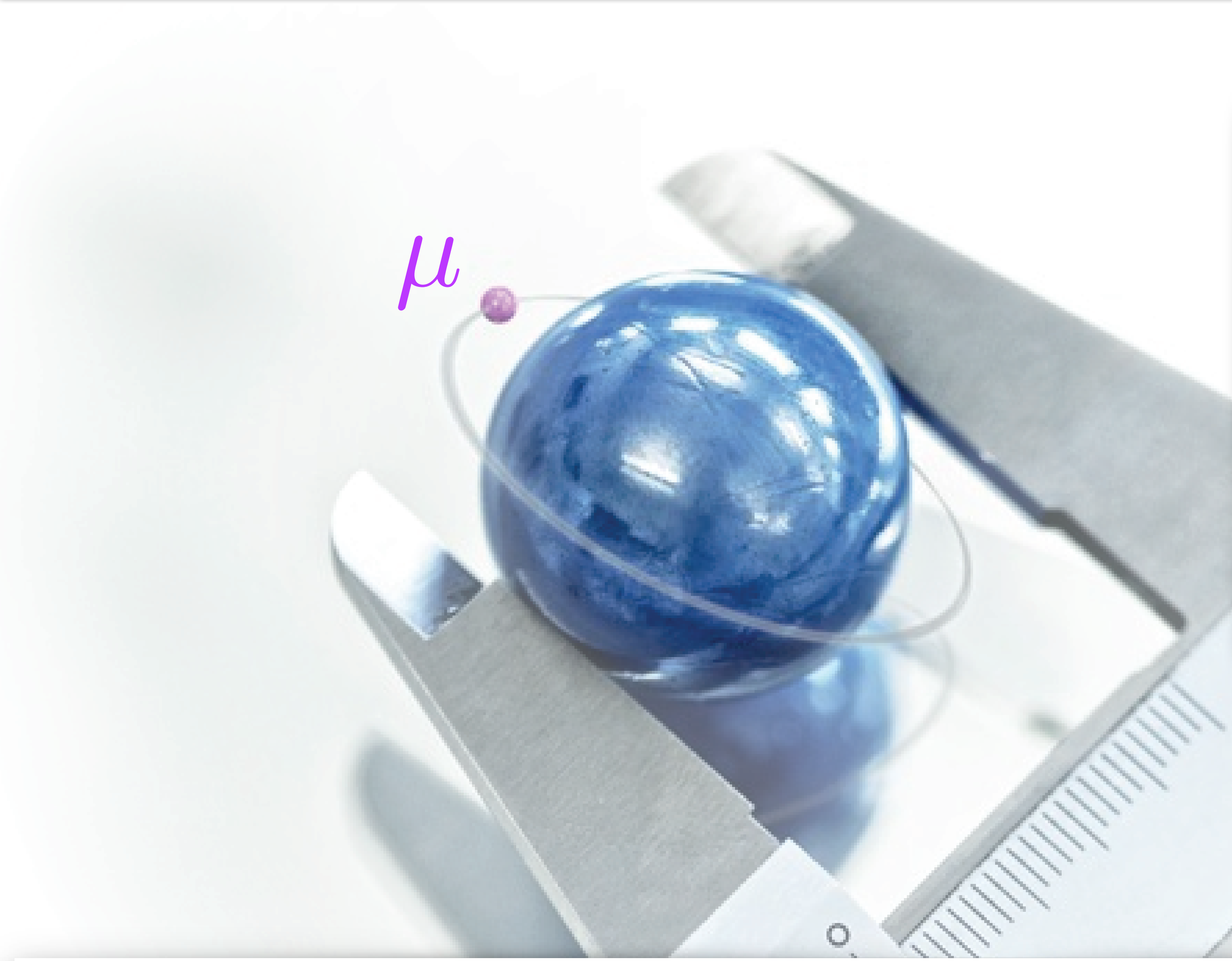
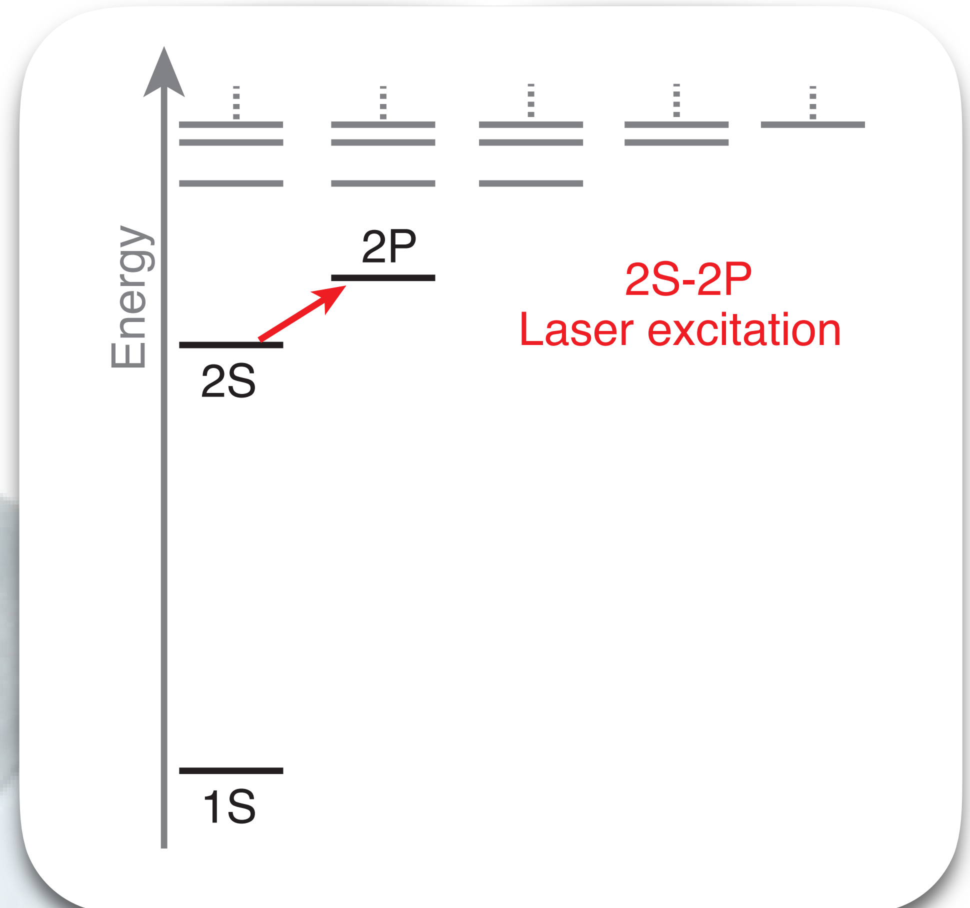
Switzerland

Laser spectroscopy of muonic atoms





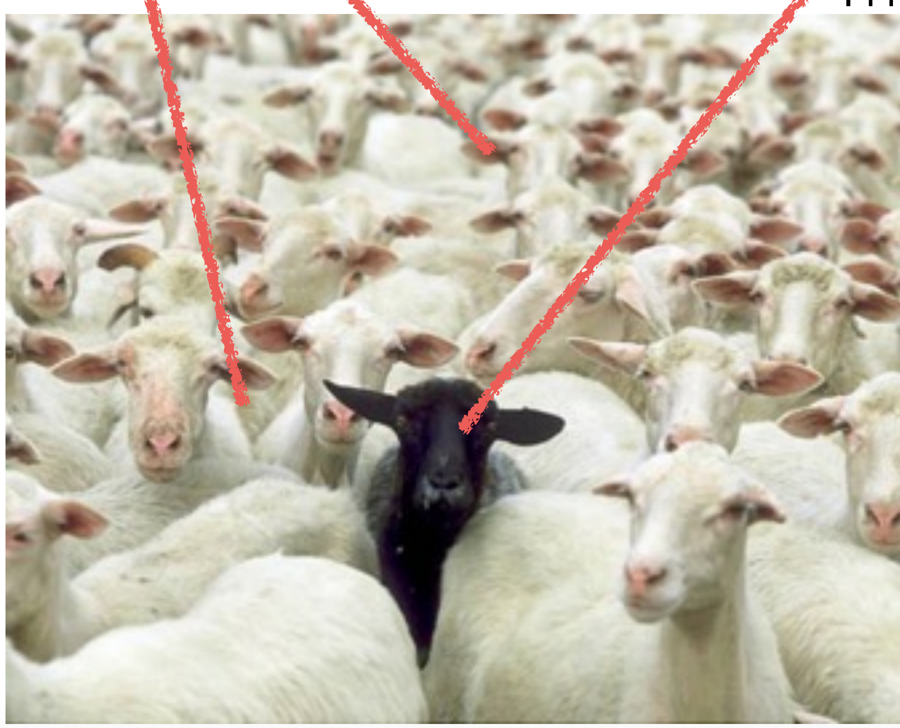
We measured 10 2S-2P transitions in μp, μd, μ^3He^+, μ^4He^+ **+** Theoretical predictions: QED + Nuclear structure ⇨ p, d, ^3He, ^4He charge radii

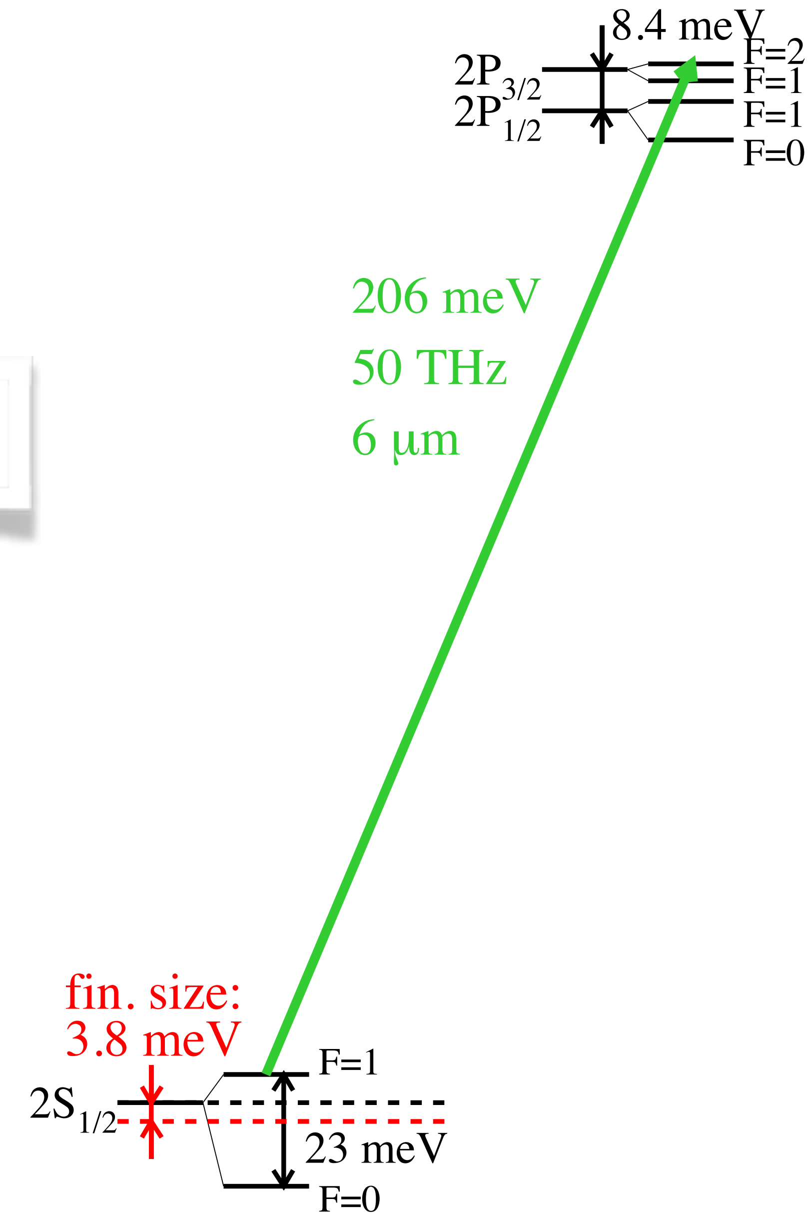
Extracting the proton radius from µp

Measure 2S-2P splitting (20 ppm)
and compare with theory
→ proton radius

$$\Delta E^{\rm th}_{2P-2S} = 206.0336(15) - 5.2275(10)\, r_{\rm p}^2 + 0.0332(20) \quad [\mathrm{meV}]$$

The most interesting





$$\Delta E_{\rm size} = \frac{2\pi(Z\alpha)}{3}\, r_{\rm p}^2\, |\Psi_{nl}(0)|^2 = \frac{2(Z\alpha)^4}{3n^3}\, m_r^3\, r_{\rm p}^2\, \delta_{l0}$$

$$m_\mu \approx 200 m_e$$

$$r_{\rm p}^2 = -6 \frac{dG_E(Q^2)}{dQ^2}\Big|_{Q^2=0}$$

Principle of the μp 2S-2P experiment

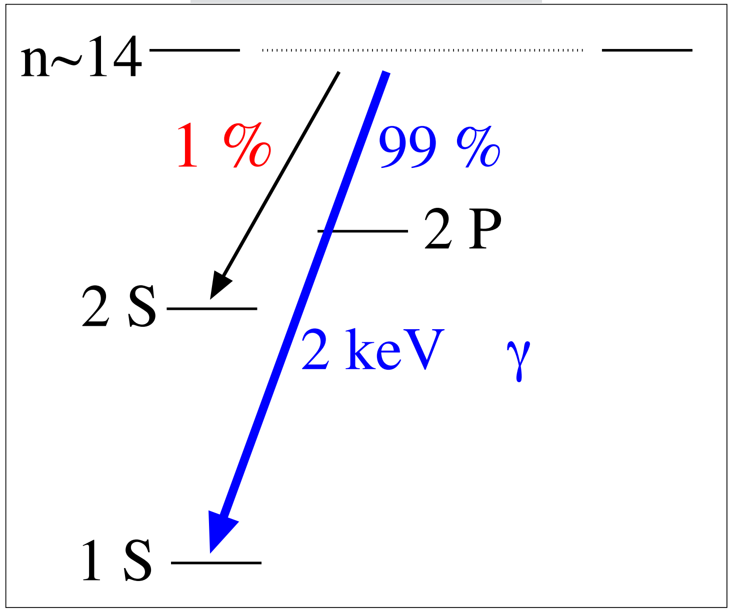
Produce many μ^- at keV energy

Form μp by stopping μ^- in 1 mbar H_2 gas

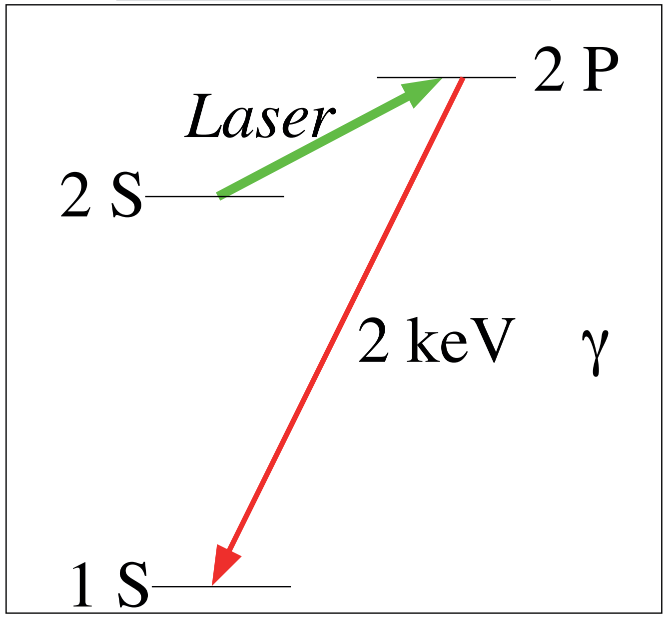
Fire laser to induce the 2S-2P transition

Measure the 2 keV X-rays from 2P-1S decay

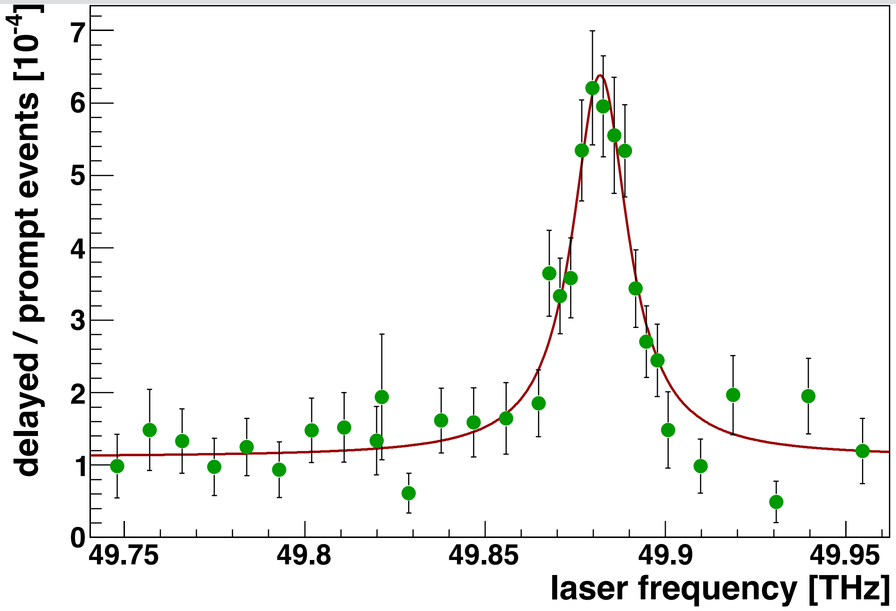
μp formation



Laser excitation

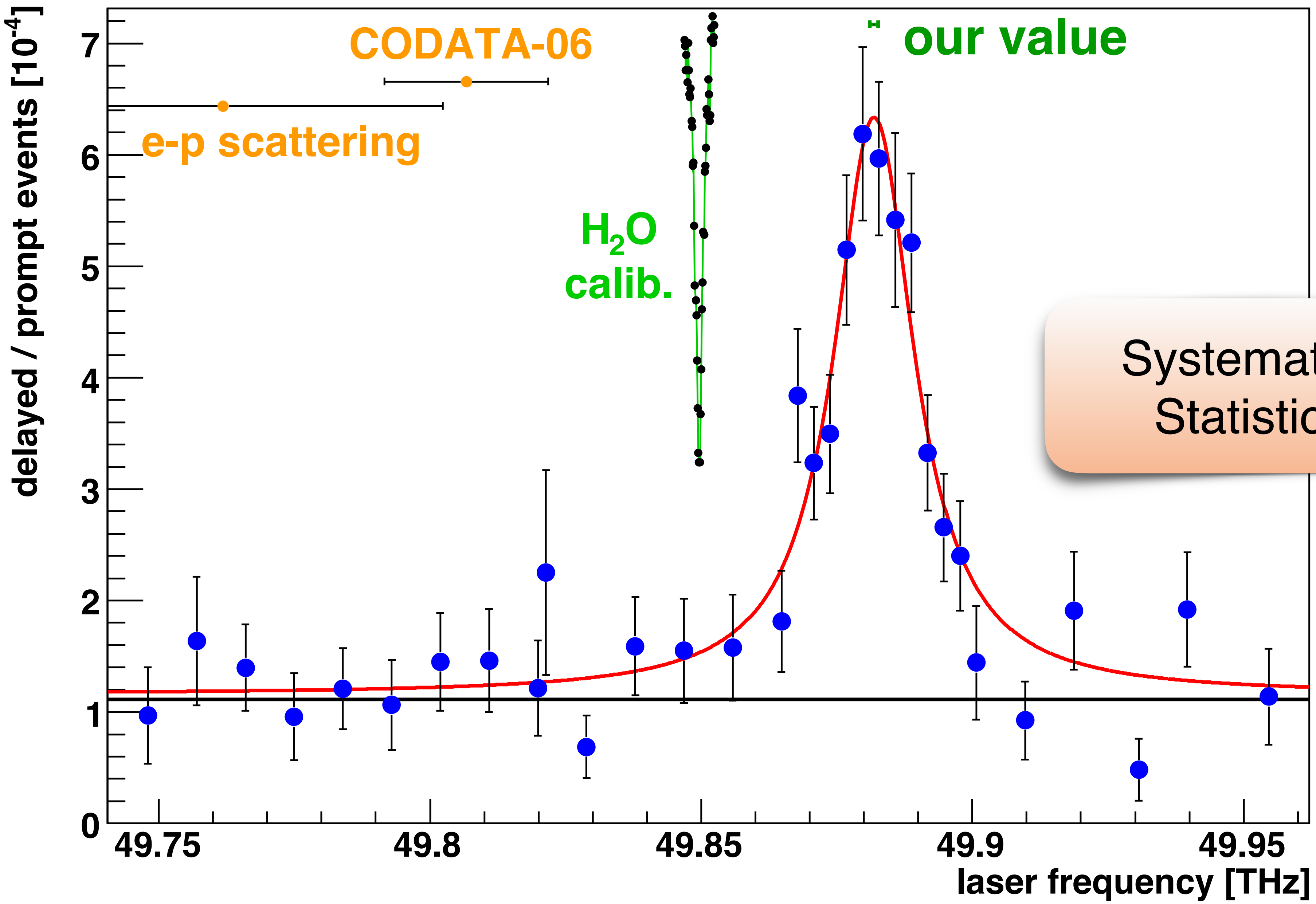


Plot number of X-rays vs laser frequency



The first μp resonance (2010)

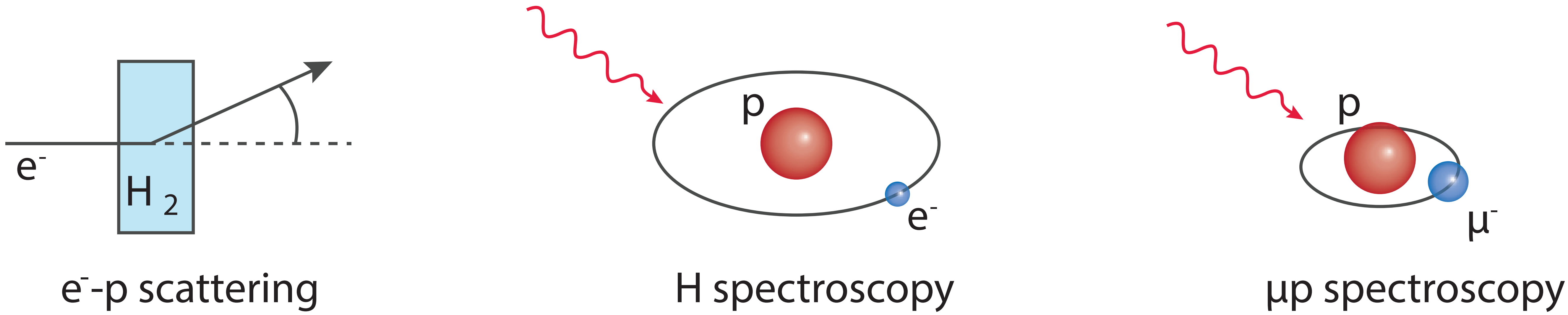
Discrepancy:
$$5.0\,\sigma \;\leftrightarrow\; 75\text{ GHz} \;\leftrightarrow\; \delta\nu/\nu = 1.5\times10^{-3}$$

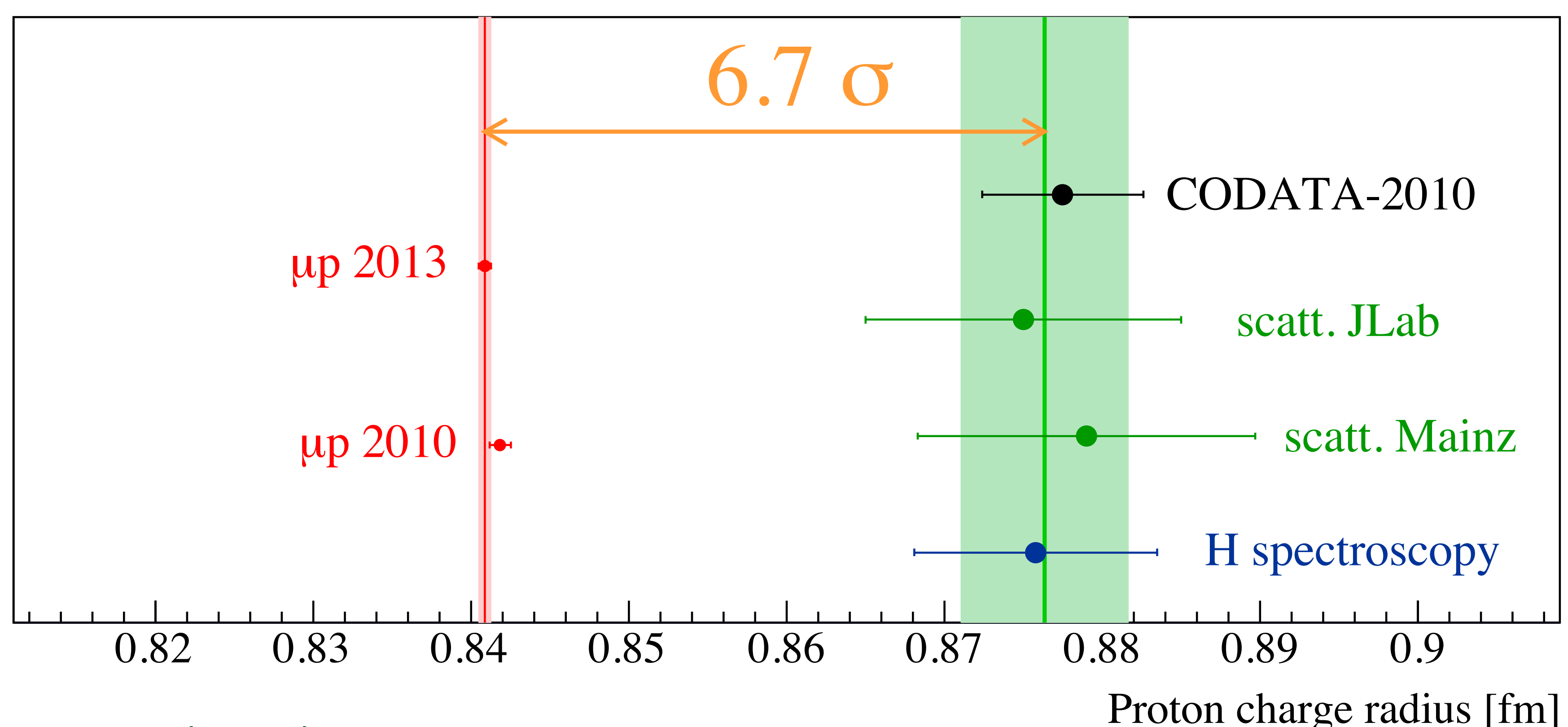


Systematics: 300 MHz
Statistics: 700 MHz

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

Three ways to the proton radius





Pohl et al., Nature 466, 213 (2010)
Antognini et al., Science 339, 417 (2013)
Pohl et al., Science 353, 669 (2016)

The proton radius puzzle

- μp experiment
- μp theory
- H experiments
- BSM physics
- e-p scattering

Rarely criticised since:

$m_\mu \approx 200 m_e$

- **sensitive** to the radius

$$\sim m^3 R_p^2 \quad ✓$$

- **insensitive** to systematical effects

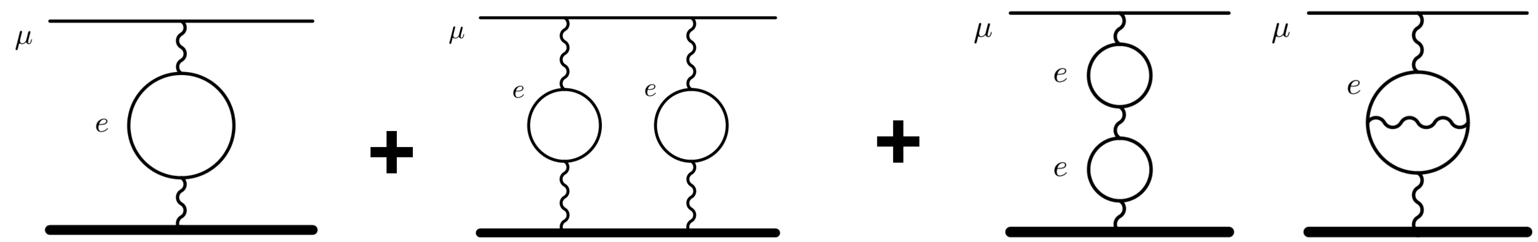
$$\sim 1/m \quad ✓$$

The proton radius puzzle

- μp experiment
- **μp theory**
- H experiments
- BSM physics
- e-p scattering

QED ✓✓✓✓

Pachucki, Borie, Eides, Karschenboim, Jentschura, Martynenko, Indelicato Pineda, Peset…

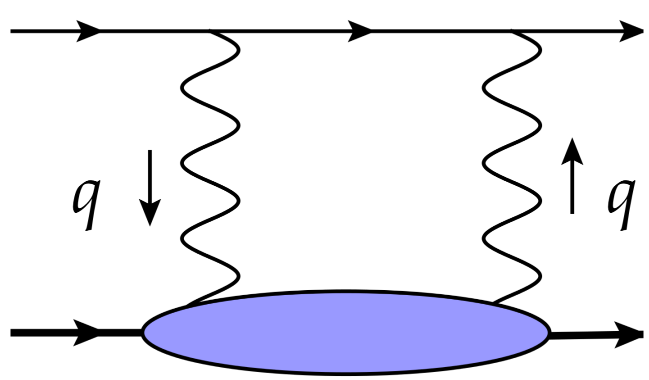


\+ many more

Finite-size contributions ✓✓✓✓

$$= -5.2275(10) r_p^2$$

Two-photon exchange ✓✓✓✓ (✗)



Pachucki, Carlson, Birse, McGovern, Pineda, Peset, Gorchtein, Pascalutsa, Vanderhaeghen, Alarcon, Miller, Paz, Hill, Hagelstein, Tomalak…

The proton radius puzzle

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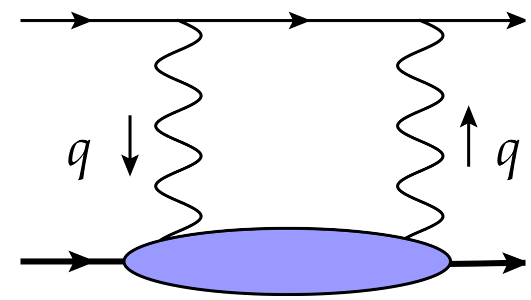
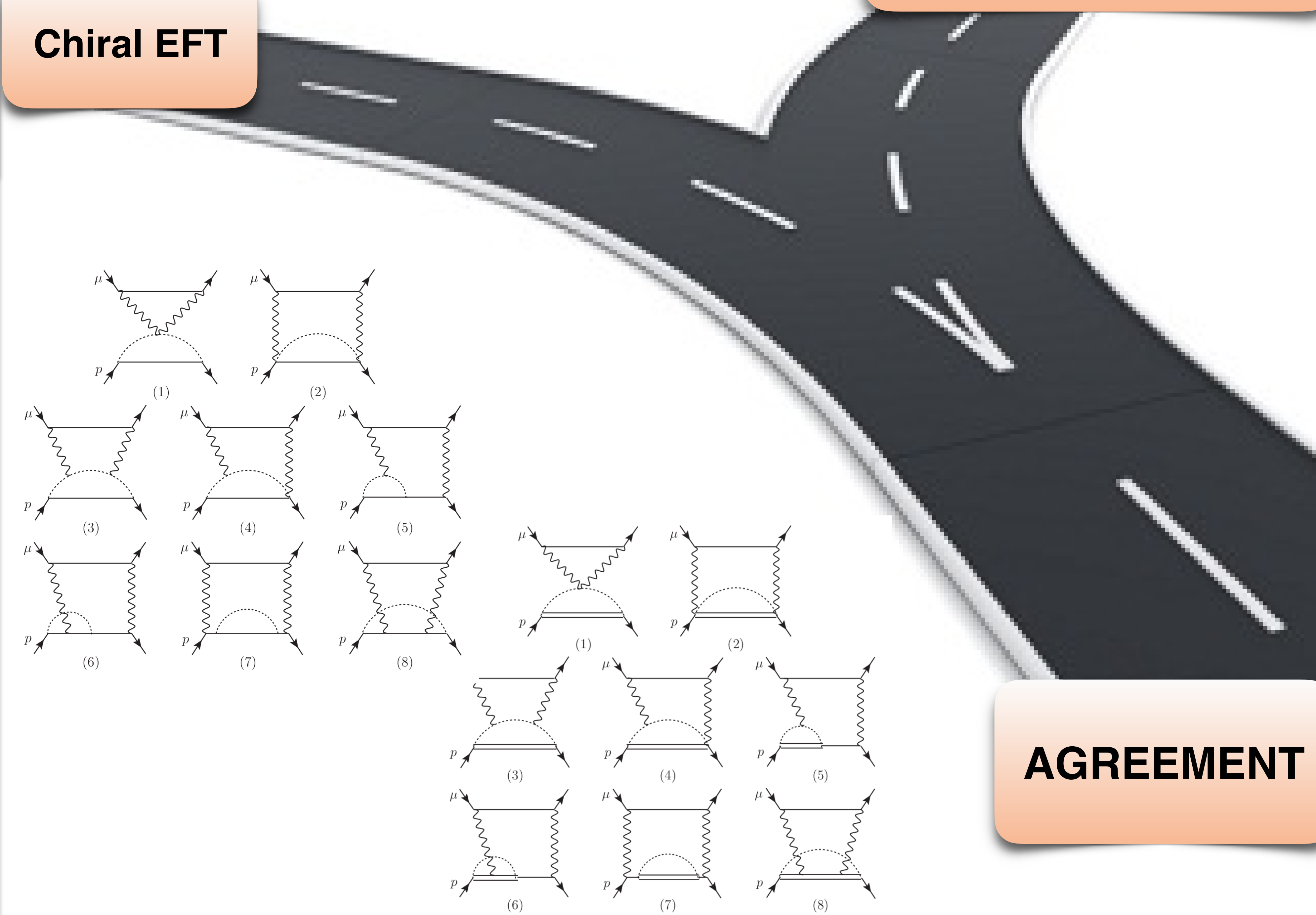


Phenomenological
- dispersion relations
- data
- subtraction term

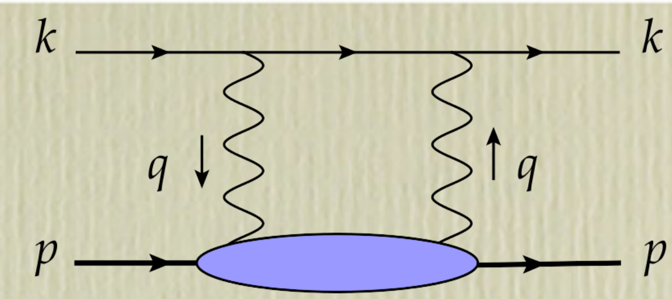
Chiral EFT



AGREEMENT

Technicalities on TPE in μp

Kinematics: 2 loop variables
q^2 and ν=(pq)/M



+ crossed

$$\mathcal{M} = e^4 \int \frac{d^4q}{(2\pi)^4} \frac{1}{q^4} \bar{u}(k) \left[\gamma^\nu \frac{1}{\not{k} - \not{q} - m_l + i\epsilon} \gamma^\mu + \gamma^\mu \frac{1}{\not{k} + \not{q} - m_l + i\epsilon} \gamma^\nu \right] u(k) T_{\mu\nu}$$

Forward virtual Compton amplitude

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

Lamb shift (nS-nP)

$$\Delta E = - \frac{\alpha^2}{2\pi m_l M_d} \phi_n^2(0) \int d^4q \frac{(q^2 + 2\nu^2) T_1(\nu, q^2) - (q^2 - \nu^2) T_2(\nu, q^2)}{q^4 [(q^2/2m_l)^2 - \nu^2]}$$

Slide stolen from Gorchtein

Technicalities on TPE in μp

T_1, T_2 - the imaginary parts known (Optical theorem)

$$\mathrm{Im}T_1(\nu, Q^2) = \frac{1}{4M} F_1(\nu, Q^2)$$

$$\mathrm{Im}T_2(\nu, Q^2) = \frac{1}{4\nu} F_2(\nu, Q^2)$$

Inelastic structure functions = data

(real and virtual photoabsorption, FF)

Real parts - from forward dispersion relation

$F_1(\nu \to \infty, q^2) \sim \nu^{1+\epsilon}$ - subtraction needed

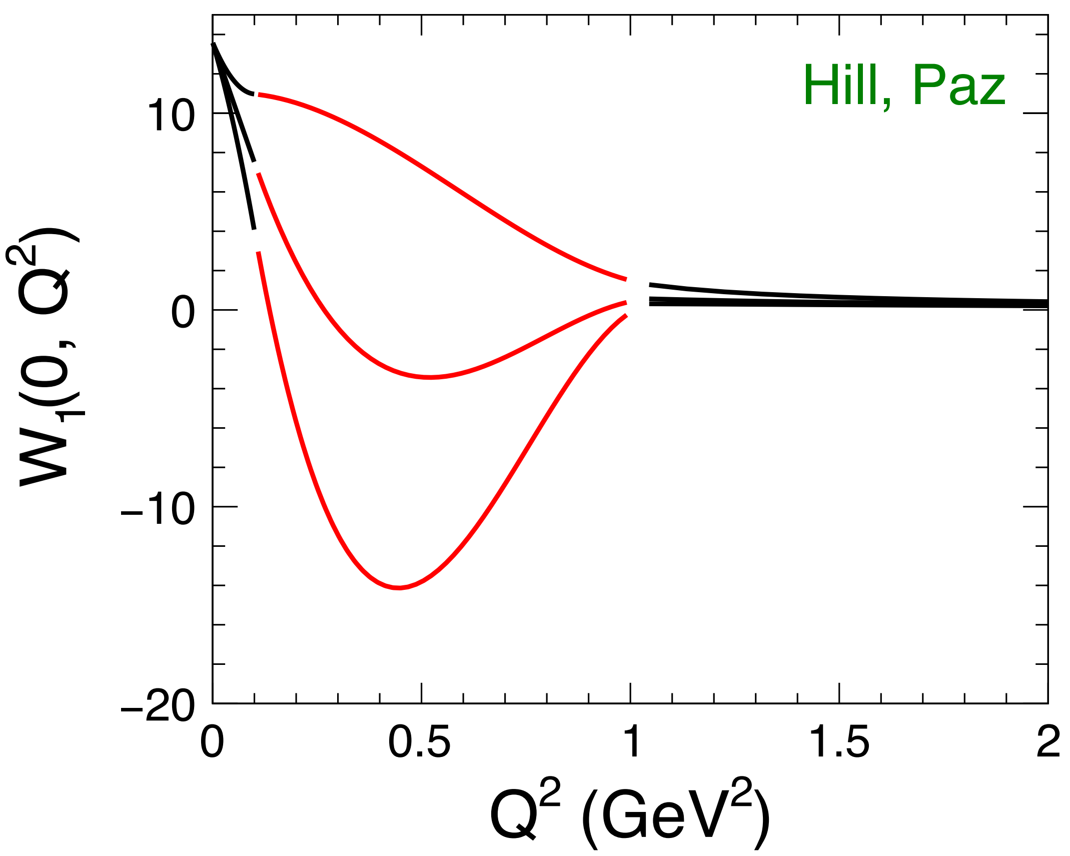
$F_2(\nu \to \infty, q^2) \sim \nu^{\epsilon}$ - no subtraction

$$\mathrm{Re}T_1(\nu, Q^2) = \bar{T}_1(0, Q^2) + T_1^{pole}(\nu, Q^2) + \frac{\nu^2}{2\pi M} \int_{\nu_0}^{\infty} \frac{d\nu'}{\nu(\nu'^2 - \nu^2)} F_1(\nu', Q^2)$$

$$\mathrm{Re}T_2(\nu, Q^2) = T_2^{pole}(\nu, Q^2) + \frac{1}{2\pi} \int_{\nu_0}^{\infty} \frac{d\nu'}{\nu'^2 - \nu^2} F_2(\nu', Q^2)$$

Slide stolen from Gorchtein

How reliable is the TPE in μp?



Pachucki, PRA 60, 3593 (1999)
Nevado, Pineda, PRC 77, 035202 (2008)
Peset, Pineda, EPJA 51, 32 (2015)
Peset, Pineda, NPB 887, 69 (2014)
Carlson, Vanderhaeghen, PRA 84, 020102 (2011)
Hill, Paz, PRL 107, 160402 (2011)
Miller, arXiv:1209.4667 (2012)
Birse, McGovern, EPJA 48, 120 (2012)
Miller, PLB 718, 1078 (2013)
Gorchtein et al., PRA 87, 052501 (2013)]
Alarcon, Lensky, Pascalutsa,EPJC 74, 2852 (2014)
Tomalak, Vanderhaeghen, PRD 90, 013006 (2014)
Tomalak, Vanderhaeghen, EPJC 76, 125 (2016)
Hill, Paz, PRD 95, 094017 (2017)
...

Subtraction term:
- low Q^2: NRQED + LEC
- medium Q^2: unknown
- high Q^2: OPE expansion

The proton radius puzzle

- μp experiment
- **μp theory**
- H experiments
- BSM physics
- e-p scattering

Uncertainties and discrepancy

0.3	meV	Discrepancy
0.01	meV:	TPE uncertainty conservatively (Hill, Pineda..)
0.0020	meV:	TPE uncertainty (McGovern, Pascalutsa…)
0.0015	meV:	QED+other uncertainties
0.00027	meV:	3ɣ uncertainty (Pachucki)
0.0023	meV:	Muonic hydrogen measurement uncertainty

Pachucki, Carlson, Birse, McGovern, Pineda, Peset, Gorchtein, Pascalutsa, Hagelstein, Vanderhaeghen, Tomalak, Martynenko, Alarcon, Miller, Paz, Hill, Llanes-Estrada, Szczepaniak…

The proton radius puzzle

- µp experiment
- µp theory
- **H experiments**
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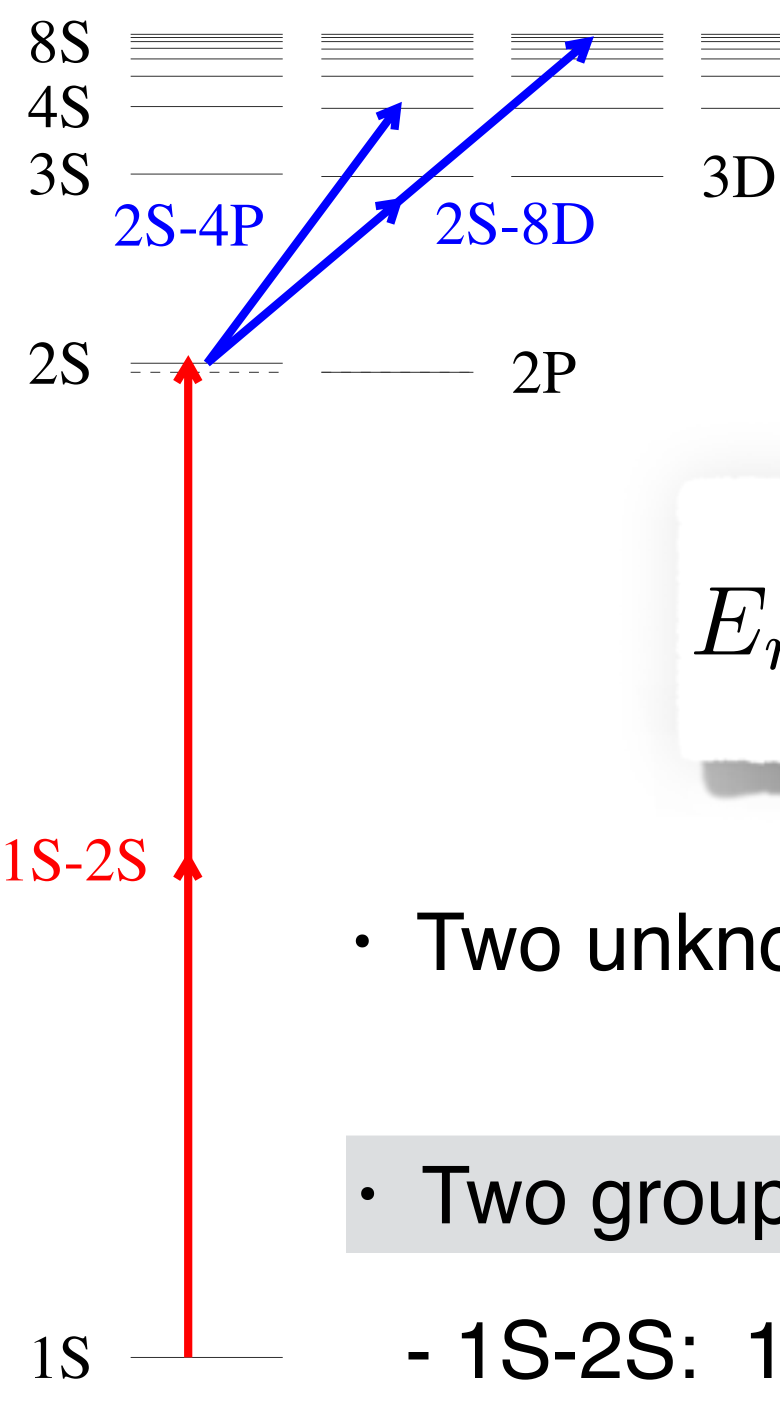


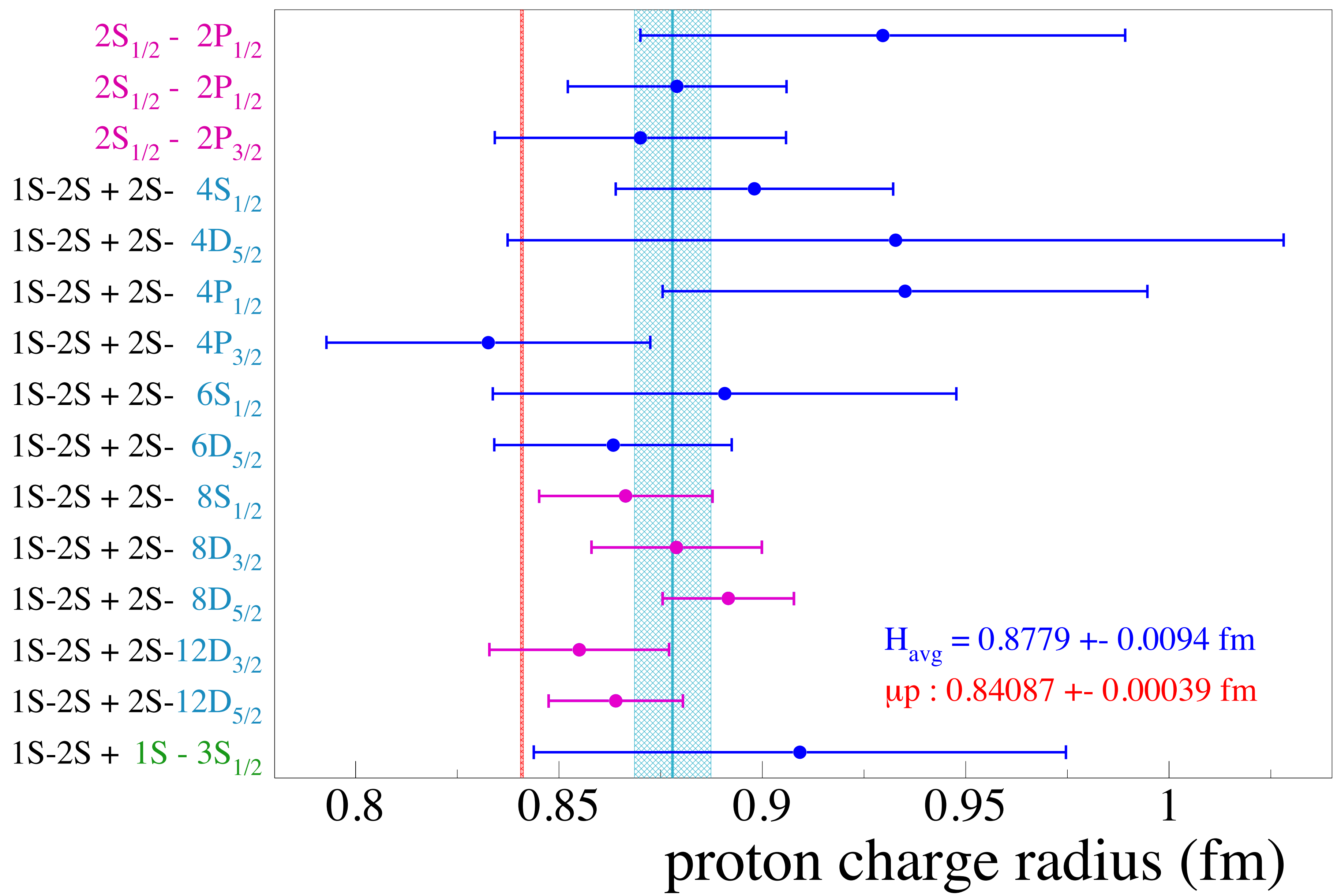
1S-3S: arXiv1801.08816
2S-4P: Science 358, 79–85 (2017)

$$E_{nS} \simeq \frac{R_\infty}{n^2} + \frac{\text{QED} + k R_p^2}{n^3}$$

- Two unknown: R_∞, R_p
- Two groups of measurements:
  - 1S-2S: 10^{-15} rel. accuracy ✓ ✓
  - others: $<10^{-13}$ rel. accuracy ✓ ✗
    broader lines, more prone to systematics

The proton radius puzzle (2010)

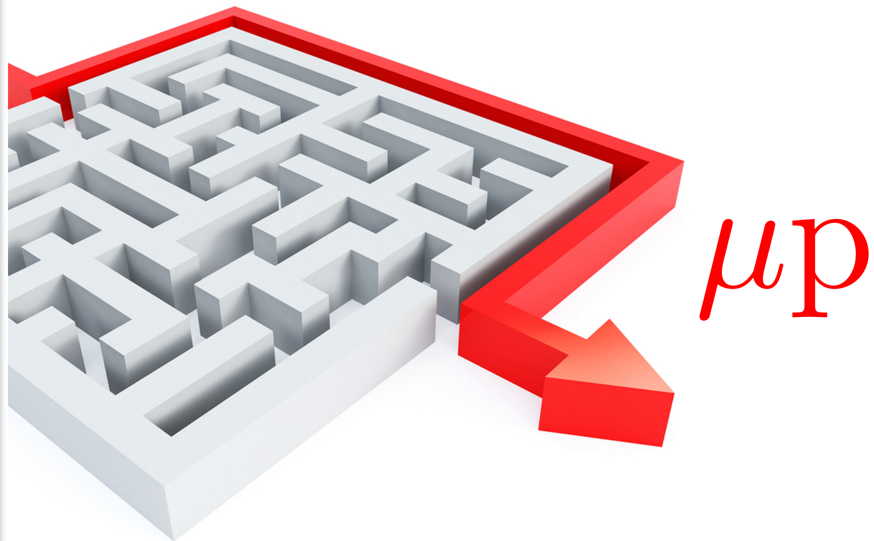
- µp experiment
- µp theory
- **H experiments**
- BSM physics
- e-p scattering

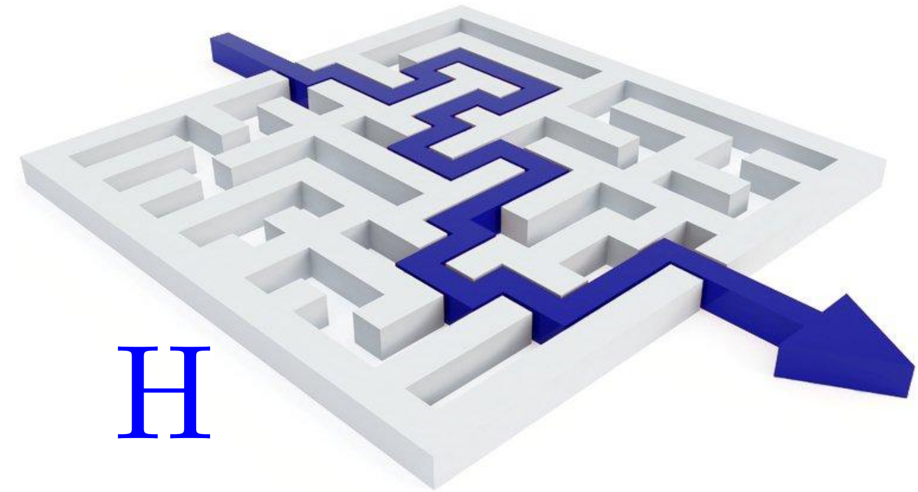


4σ only when averaging

The proton radius puzzle

- µp experiment
- µp theory
- **H experiments**
- BSM physics
- e-p scattering





Large sensitivity to r_p
⇨ requires low-precision meas.
Large **in**sensitivity to systematics
But difficult to see the signal

Low sensitivity to r_p
⇨ requires high-precision
⇨ fight with systematics
But "easy" to see the signal

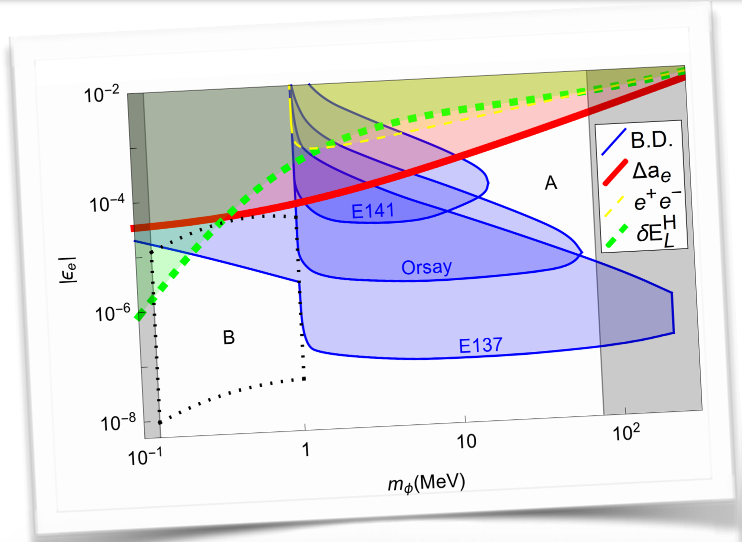
Explain the discrepancy by shifting the

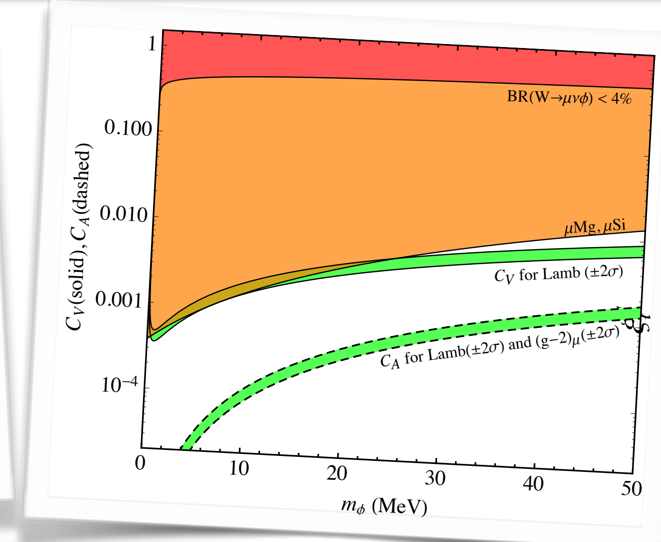
μp (2S-2P)	$100\,\sigma$	75 GHz	$4\,\Gamma$
H (1S-2S)	$4'000\,\sigma$	40 kHz	$40\,\Gamma$
H (2S-4P)	$< 1.5\,\sigma$	9 kHz	$7 \cdot 10^{-4}\,\Gamma$
H (2S-2P)	$< 1.5\,\sigma$	5 kHz	$7 \cdot 10^{-4}\,\Gamma$

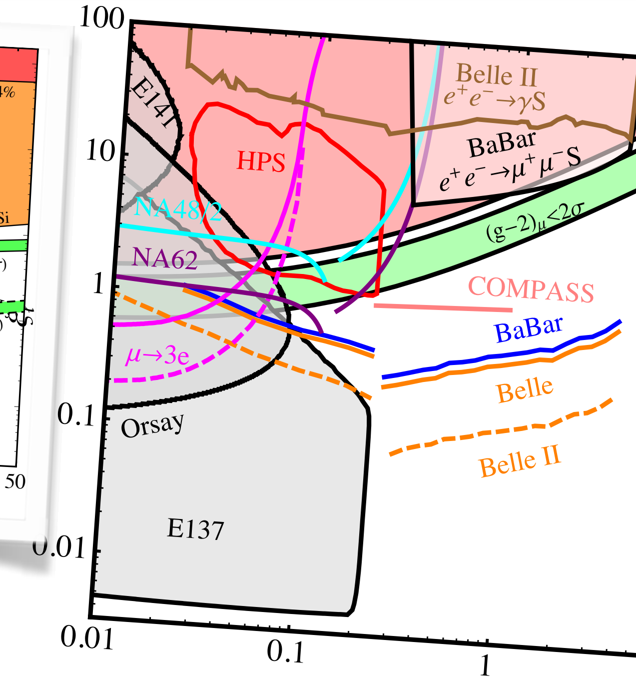
σ : exp accuracy
Γ : line width

The proton radius puzzle

- µp experiment
- µp theory
- H experiments
- **BSM physics**
- e-p scattering







Some open regions for MeV force carrier still resist

Martens & Ralston (2016), Liu, McKeen & Miller (2016), Batell et. al (2016), Carlson (2014)

- Tuning (e.g. vector vs axial-vector)
- Preferential coupling to μ and p
- No UV completion and no full SM gauge inv.

BSM explanations “unnatural” and small window!
BUT more natural extensions for

$$R_H < R_{\mu p} < R_{\mathrm{scatt}}$$

Pospelov

The proton radius puzzle

- µp experiment
- µp theory
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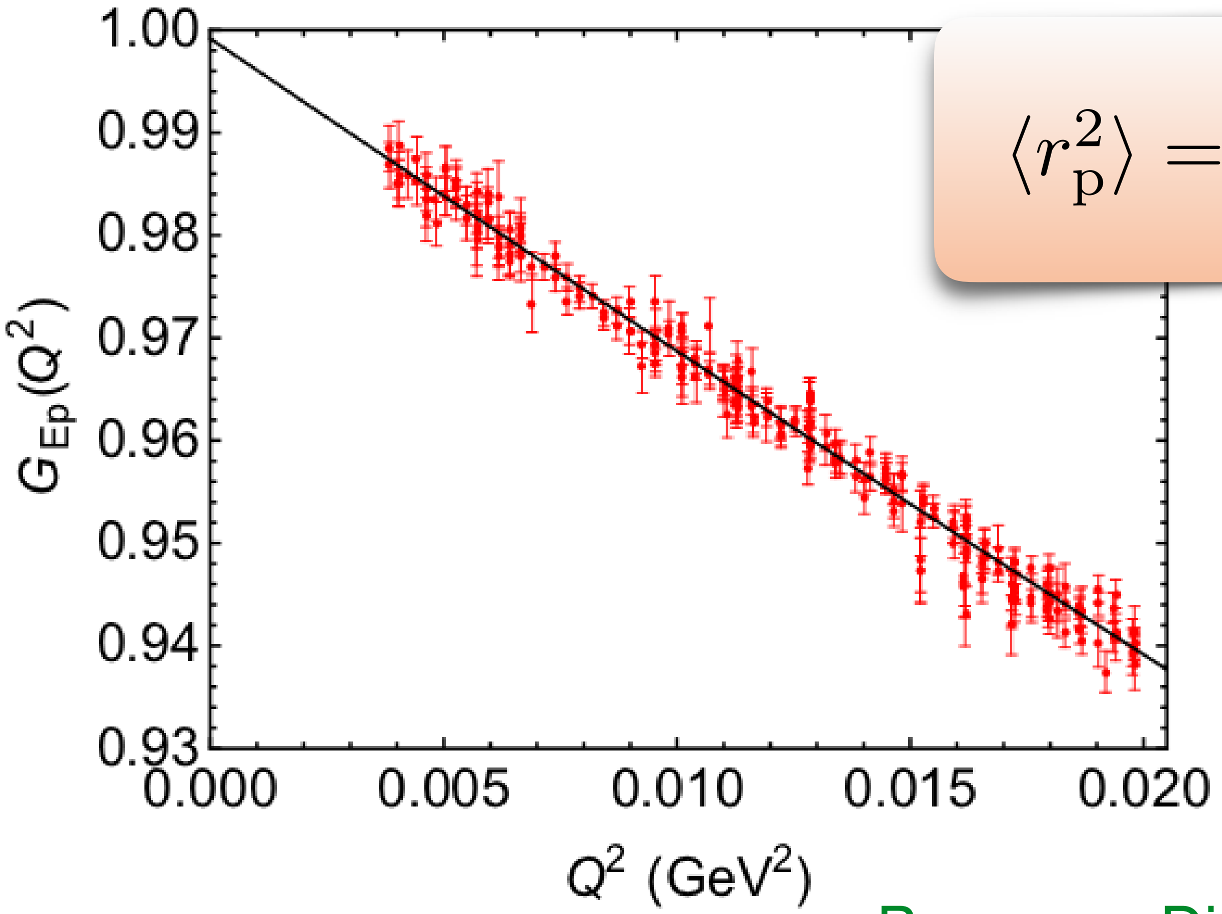
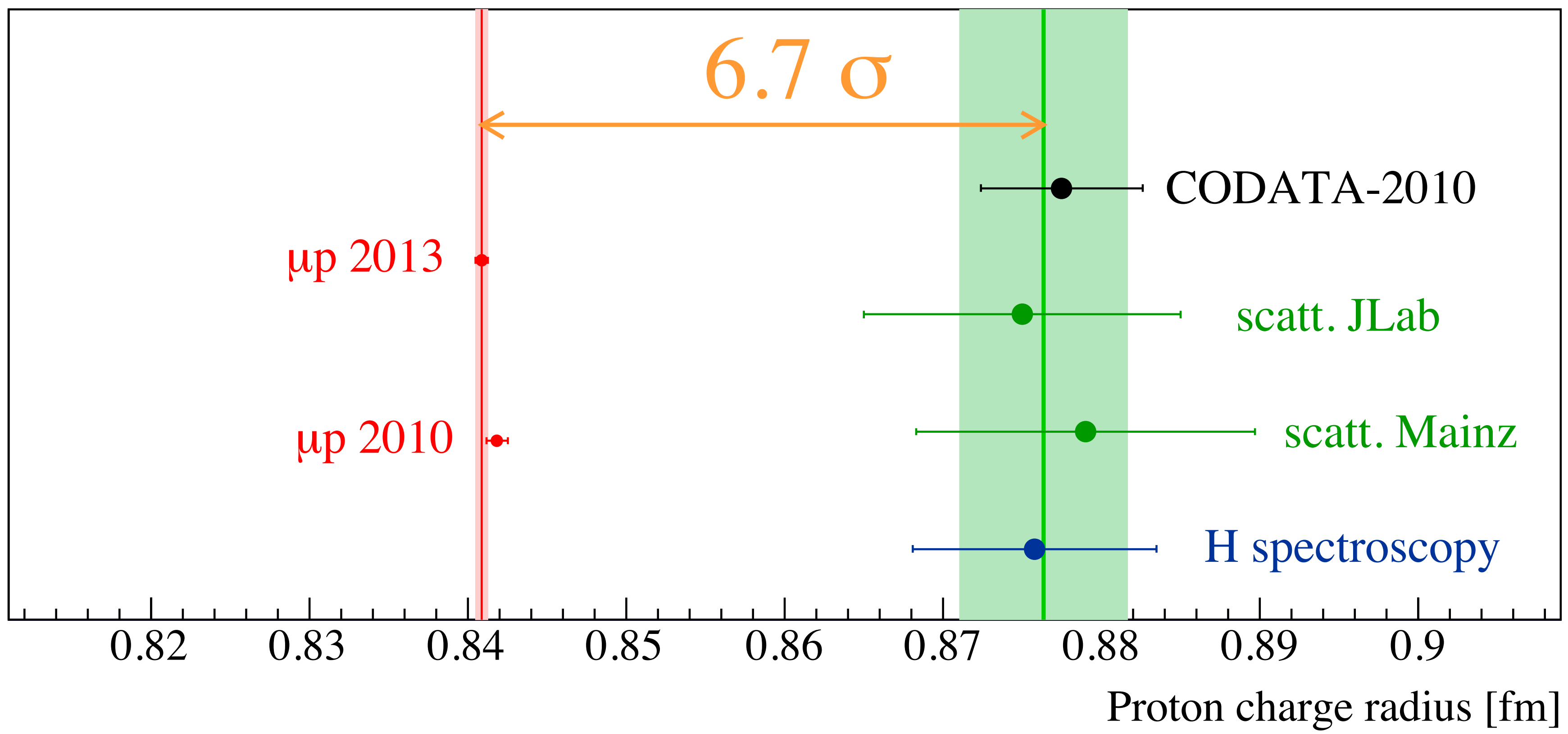


$$\langle r_{\mathrm{p}}^2 \rangle = -6\hbar^2 \frac{dG_E(Q^2)}{dQ^2}\bigg|_{Q^2=0}$$

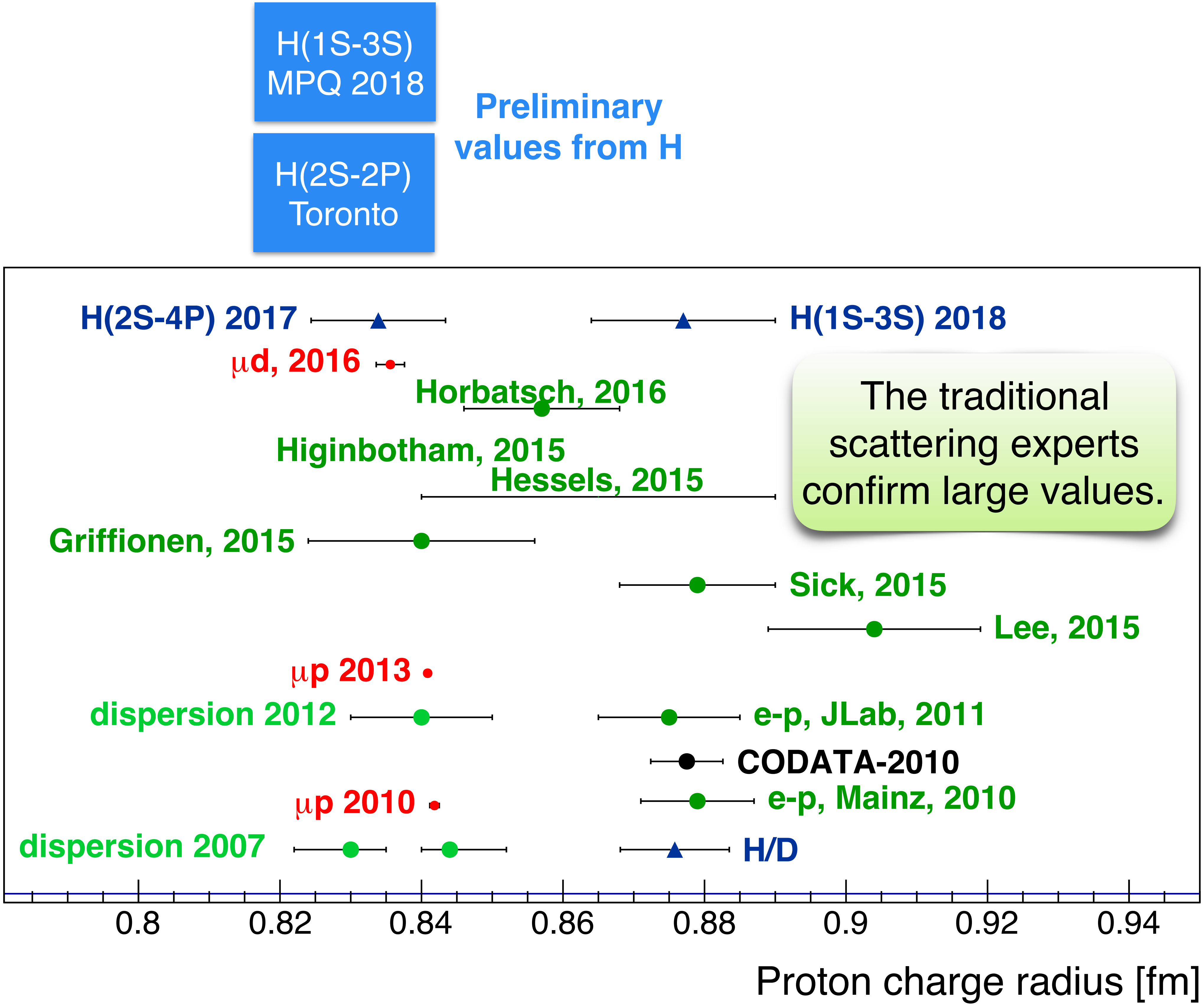
Bernauer, Distler, arXiv:1606.02159
Sick, Trautmann, arXiv:1701.01809
Lee, Arrington, Hill, arXiv:1505.01489
Hoferichter et al., EPJA 52, 331 (2016)
Alarcon, Weiss, arXiv:1710.06430
Sick, arXiv:1801.01746

Higinbotham et al.,, arXiv: 1510.01293
Griffioen et al., arXiv:1509.06676
Lorenz et al., PRD 91, 014023 (2015)
Horbatsch, Hessels, Pineda, arXiv:1610.09760

The proton charge radii



The proton charge radii market

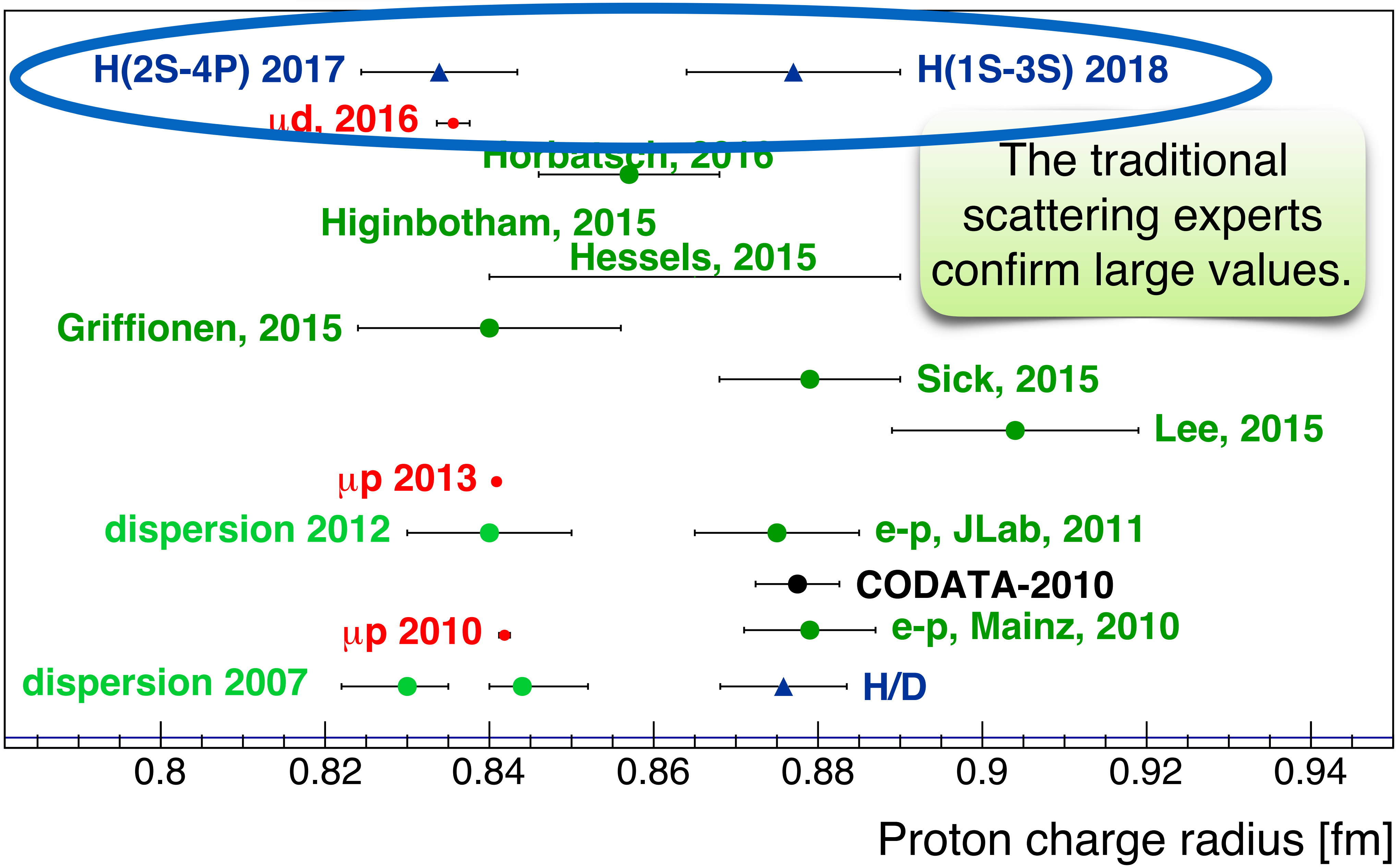


The proton charge radii market

H(1S-3S) MPQ 2018

H(2S-2P) Toronto

Preliminary values from H



The traditional scattering experts confirm large values.

The proton charge radii on the market

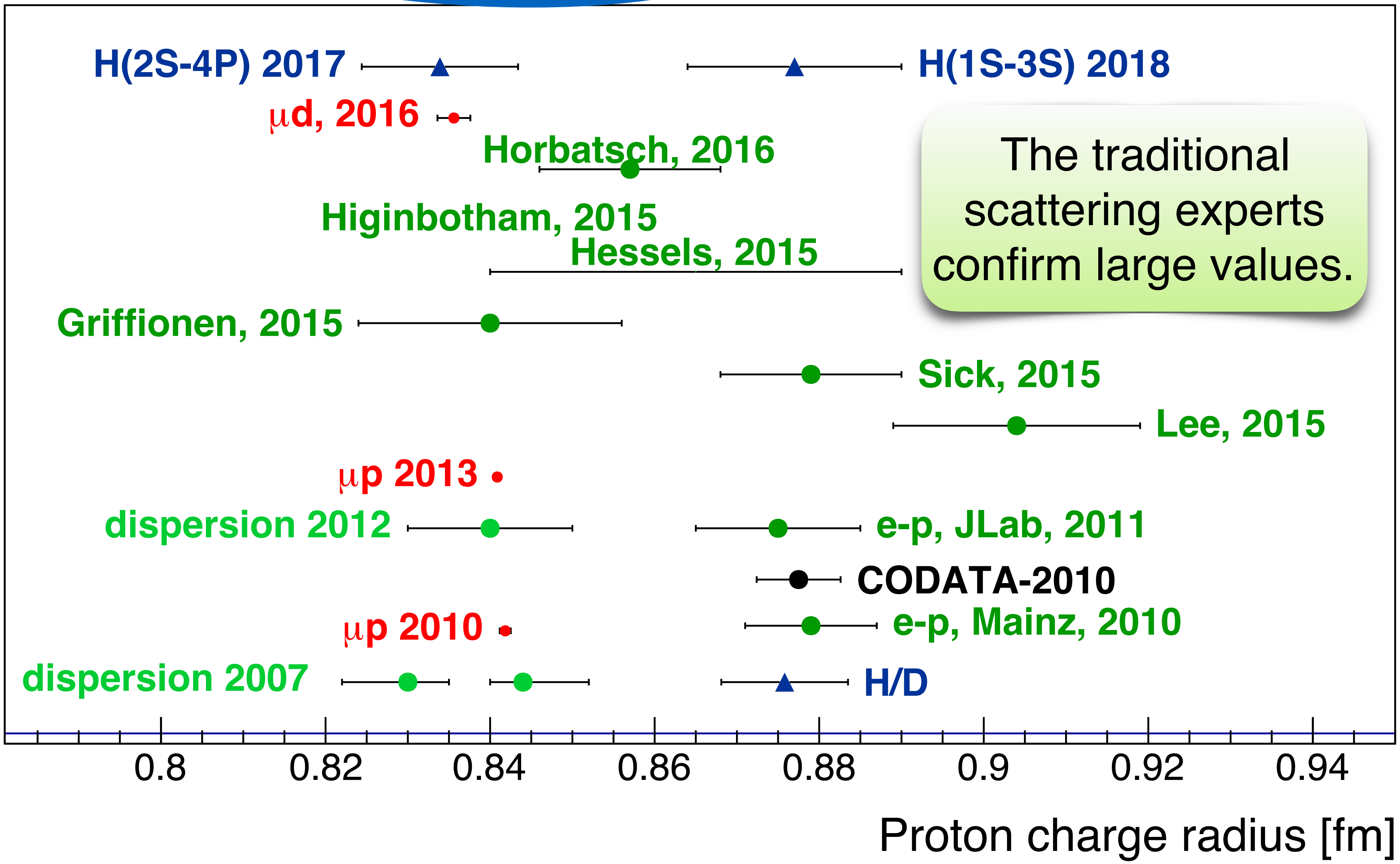
H(1S-3S) MPQ 2018

H(2S-2P) Toronto

Preliminary values from H

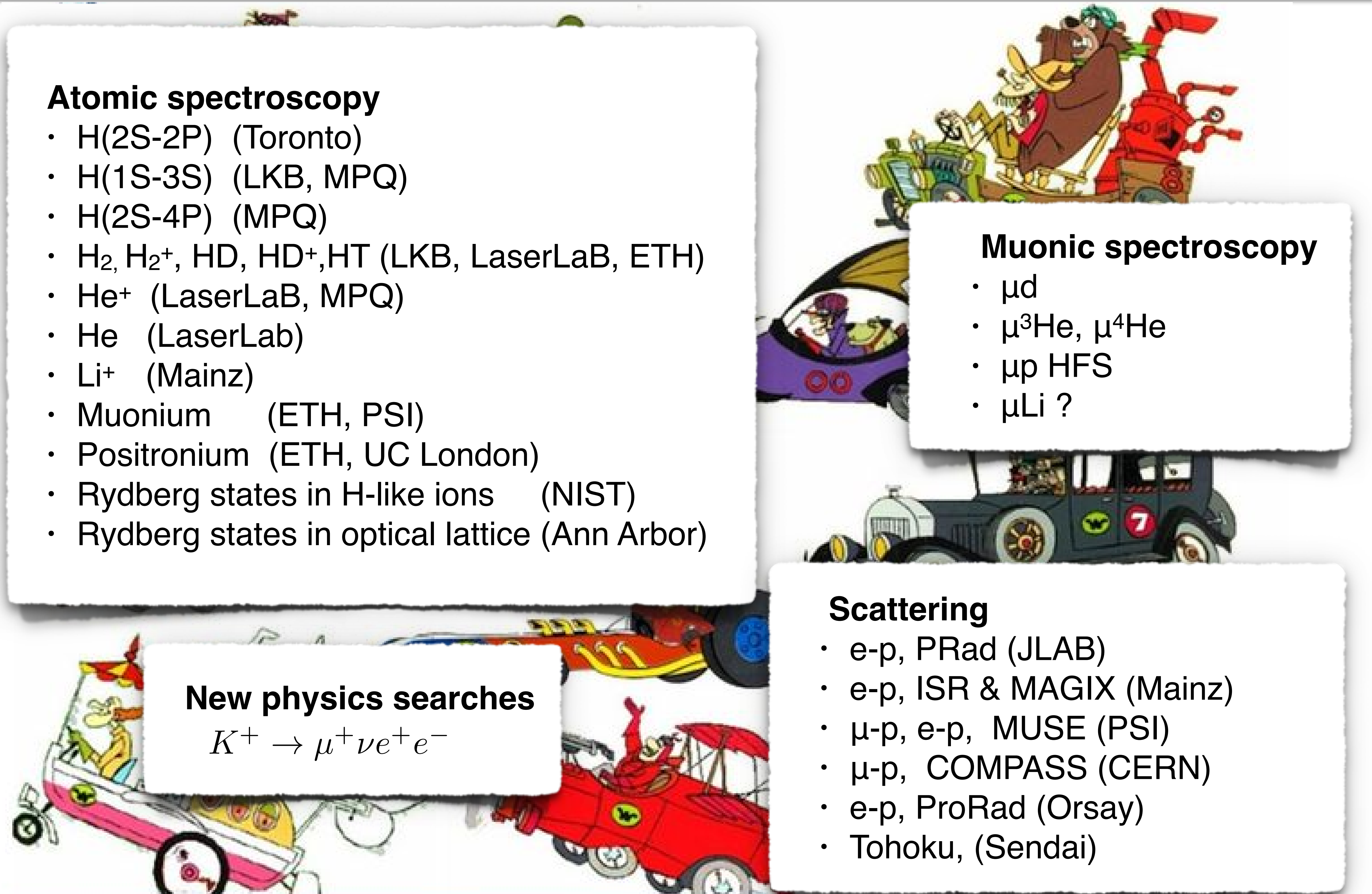
New value from e-p scattering will be soon available

Ashot et al., PRad, JLAB



The race to the proton radius solution

The race to the proton radius solution



Atomic spectroscopy

- H(2S-2P) (Toronto)
- H(1S-3S) (LKB, MPQ)
- H(2S-4P) (MPQ)
- H_2, H_2^+, HD, HD^+, HT (LKB, LaserLaB, ETH)
- He^+ (LaserLaB, MPQ)
- He (LaserLab)
- Li^+ (Mainz)
- Muonium (ETH, PSI)
- Positronium (ETH, UC London)
- Rydberg states in H-like ions (NIST)
- Rydberg states in optical lattice (Ann Arbor)

Muonic spectroscopy

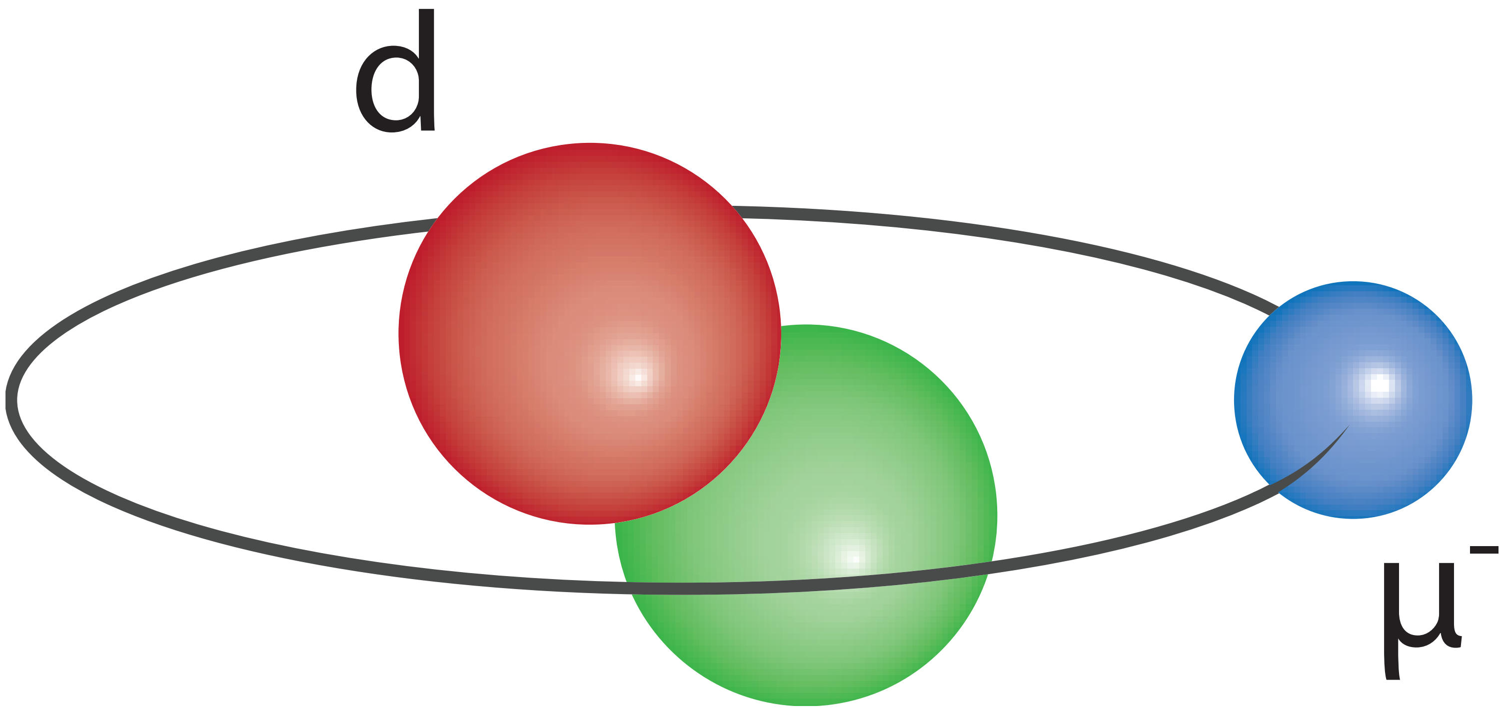
- μd
- μ^3He, μ^4He
- μp HFS
- μLi ?

Scattering

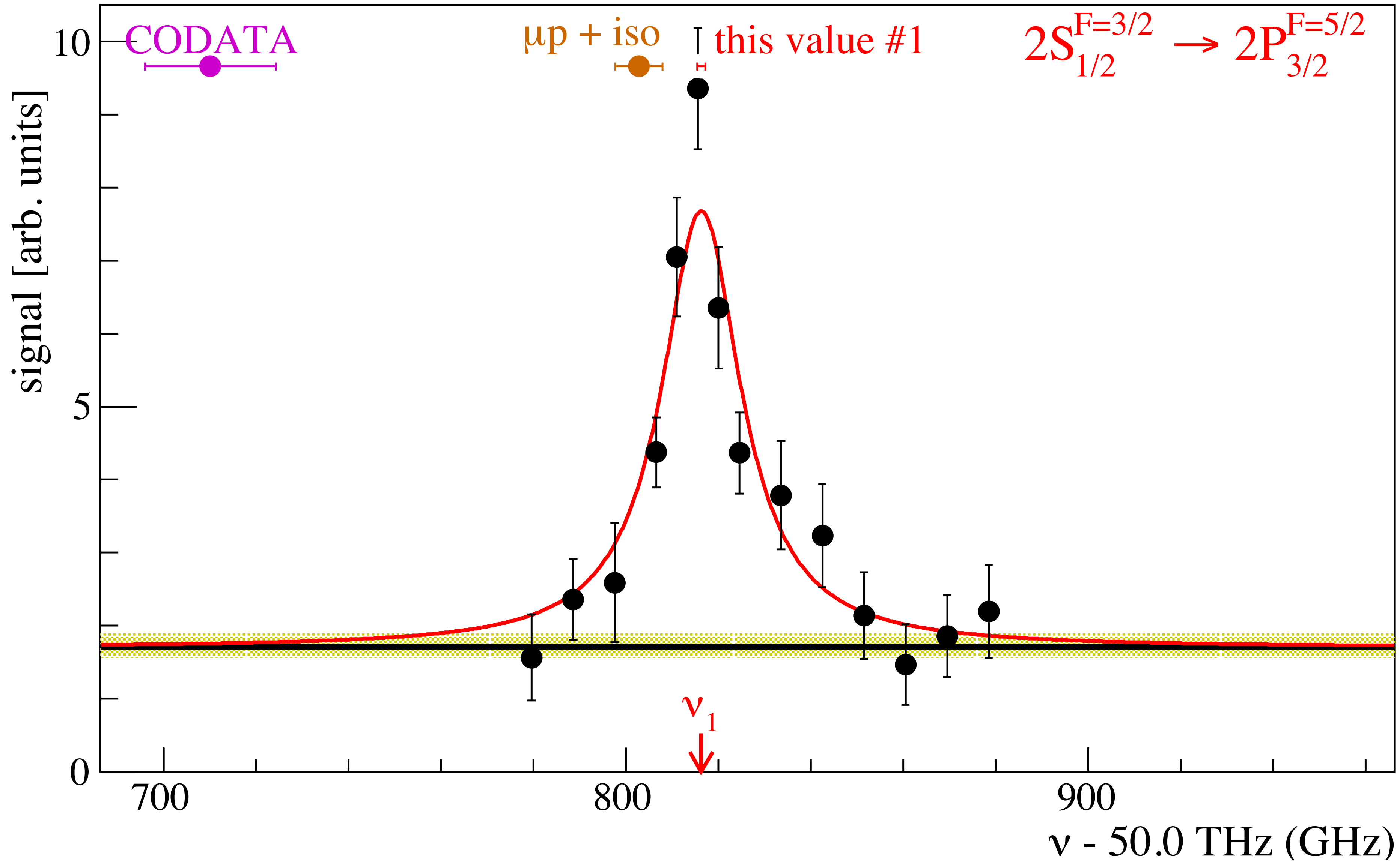
- e-p, PRad (JLAB)
- e-p, ISR & MAGIX (Mainz)
- μ-p, e-p, MUSE (PSI)
- μ-p, COMPASS (CERN)
- e-p, ProRad (Orsay)
- Tohoku, (Sendai)

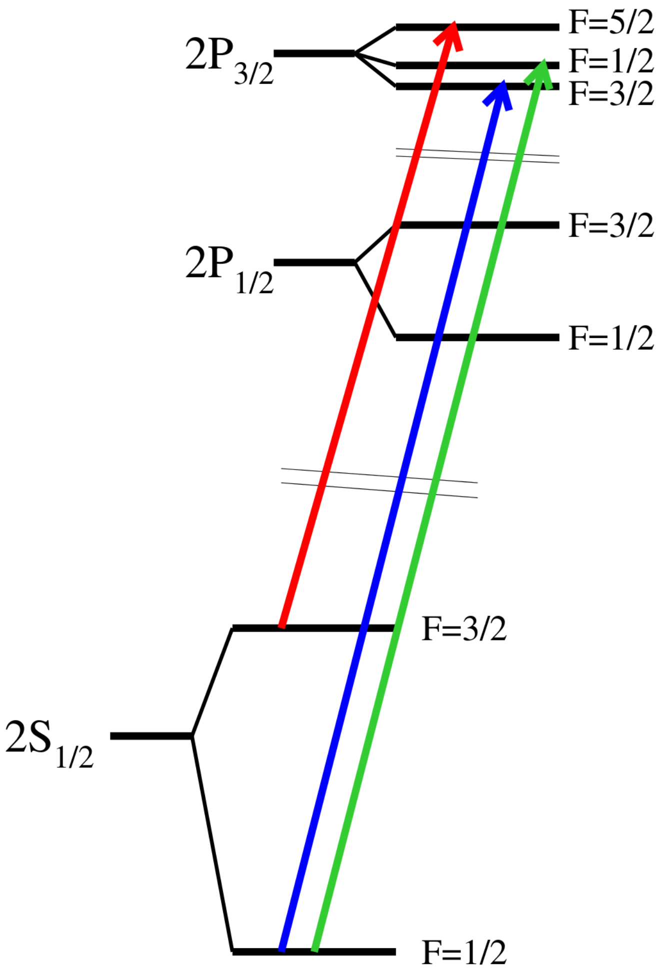
New physics searches

$$K^+ \to \mu^+ \nu e^+ e^-$$


d
μ⁻

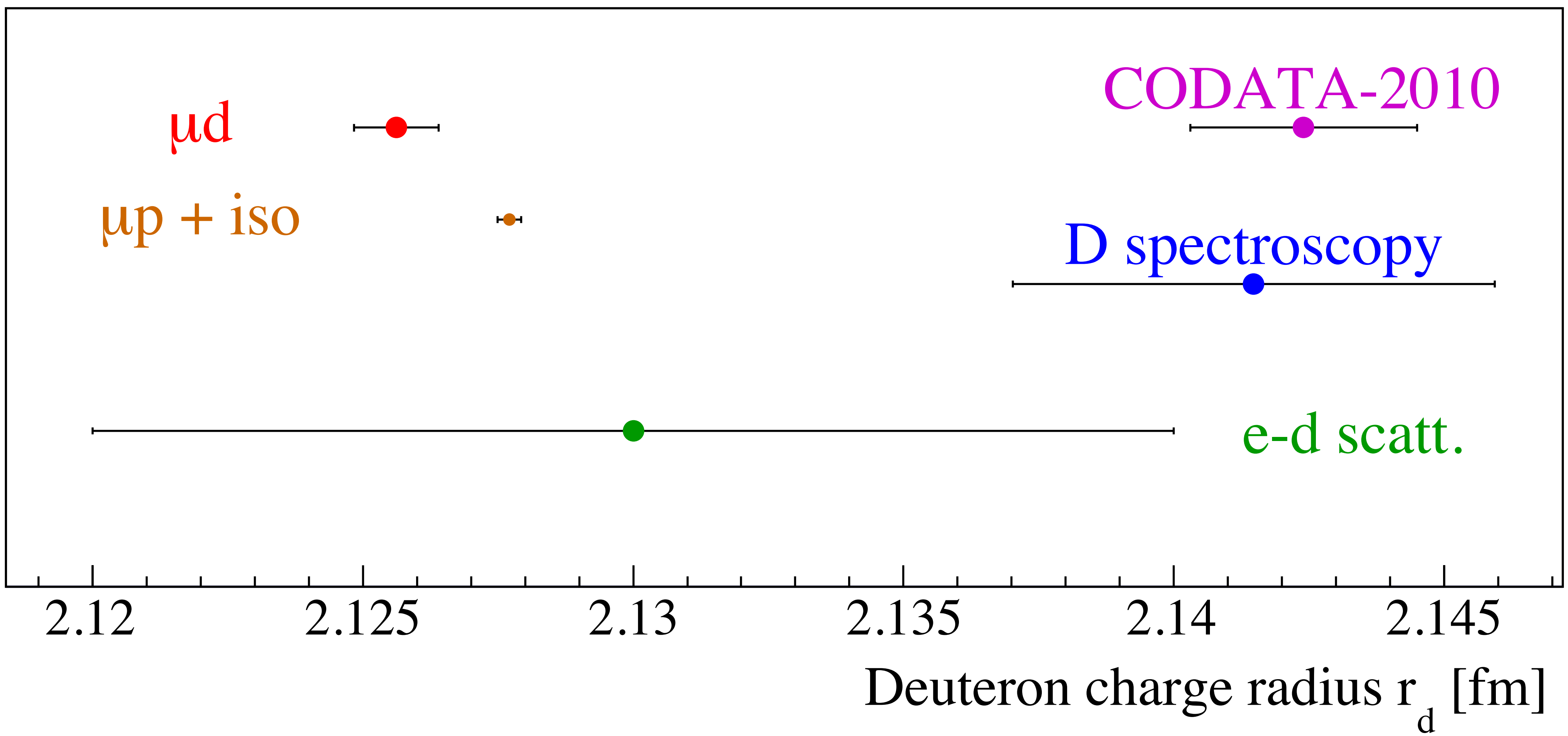
2S-2P spectroscopy of muonic deuterium (µd)





	μp [meV]	μd [meV]	
QED	206	229	$\times 1.1$
$k\langle r^2 \rangle$	4	28	$\times 7$
TPE	0.03	1.7	$\times 56$

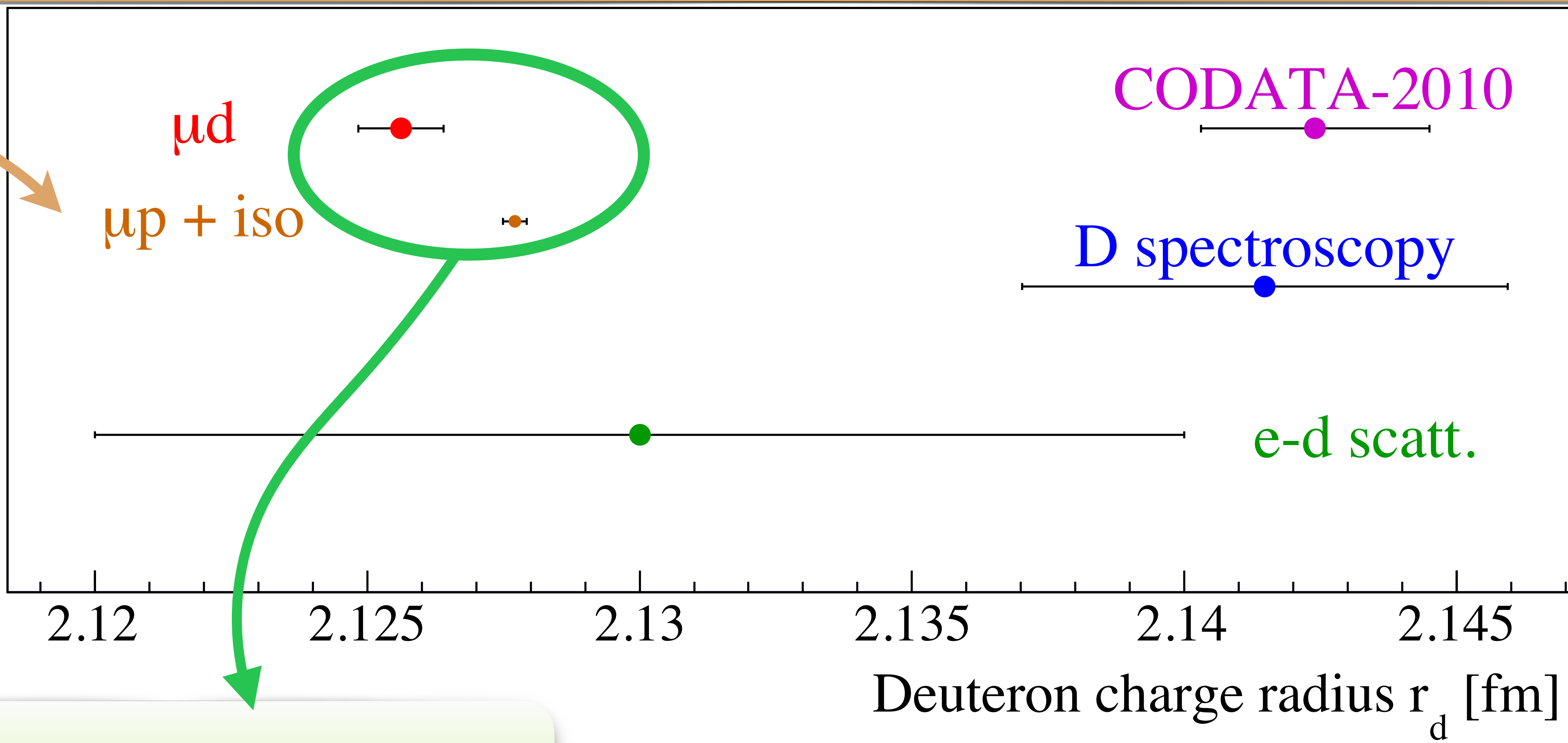
2S-2P spectroscopy of muonic deuterium (μd)



Pohl et al., Science 353, 669 (2016)
Krauth et al., Ann. Phys. 336 168 (2016)
Hernandez et. al., PLB 736, 344 (2014)
Pachucki et al., PRA 91, 040503(R) (2015)

2S-2P spectroscopy of muonic deuterium (μd)

$$\left.\begin{array}{lll} \text{H/D shift:} & r_\mathrm{d}^2 - r_\mathrm{p}^2 & = 3.820\,07(65)\ \mathrm{fm}^2 \\ \mu p: & r_\mathrm{p} & = 0.84087(39)\ \mathrm{fm} \end{array}\right\} \Rightarrow r_\mathrm{d} = 2.12771(22)\ \mathrm{fm}$$



Consistency of muonic results with 1S-2S H/D isotopic-shift

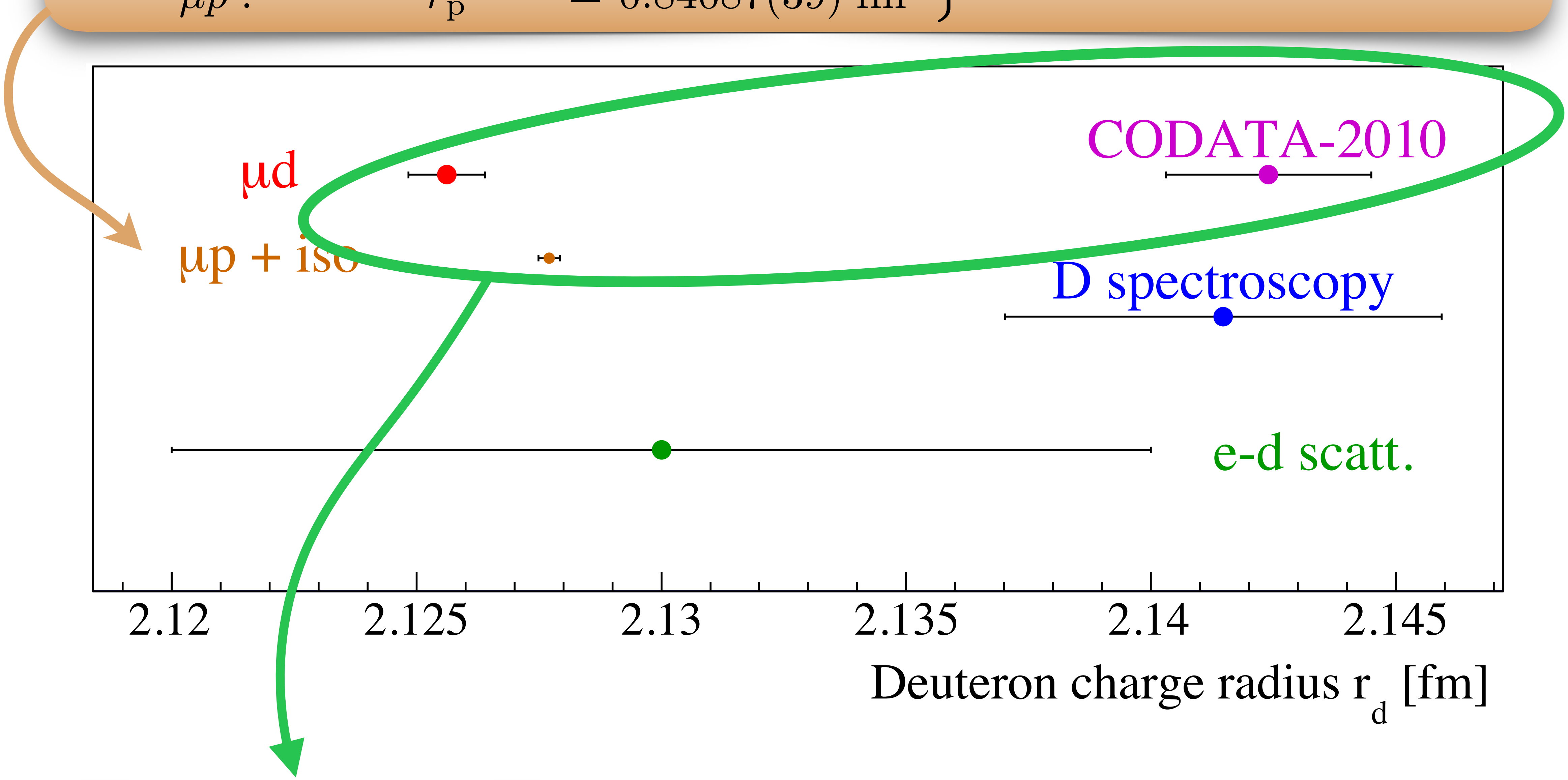
The 2.5σ difference:

- incomplete nuclear polarizabilty?
- BSM physics NOT coupling to n (reduced mass effect)?

Pachucki, Bacca, Barnea, Gorchtein, Carlson….

2S-2P spectroscopy of muonic deuterium (μd)

$$\begin{rcases} \text{H/D shift:} & r_\mathrm{d}^2 - r_\mathrm{p}^2 = 3.820\,07(65)\ \mathrm{fm}^2 \\ \mu p: & r_\mathrm{p} = 0.84087(39)\ \mathrm{fm} \end{rcases} \Rightarrow r_\mathrm{d} = 2.12771(22)\ \mathrm{fm}$$

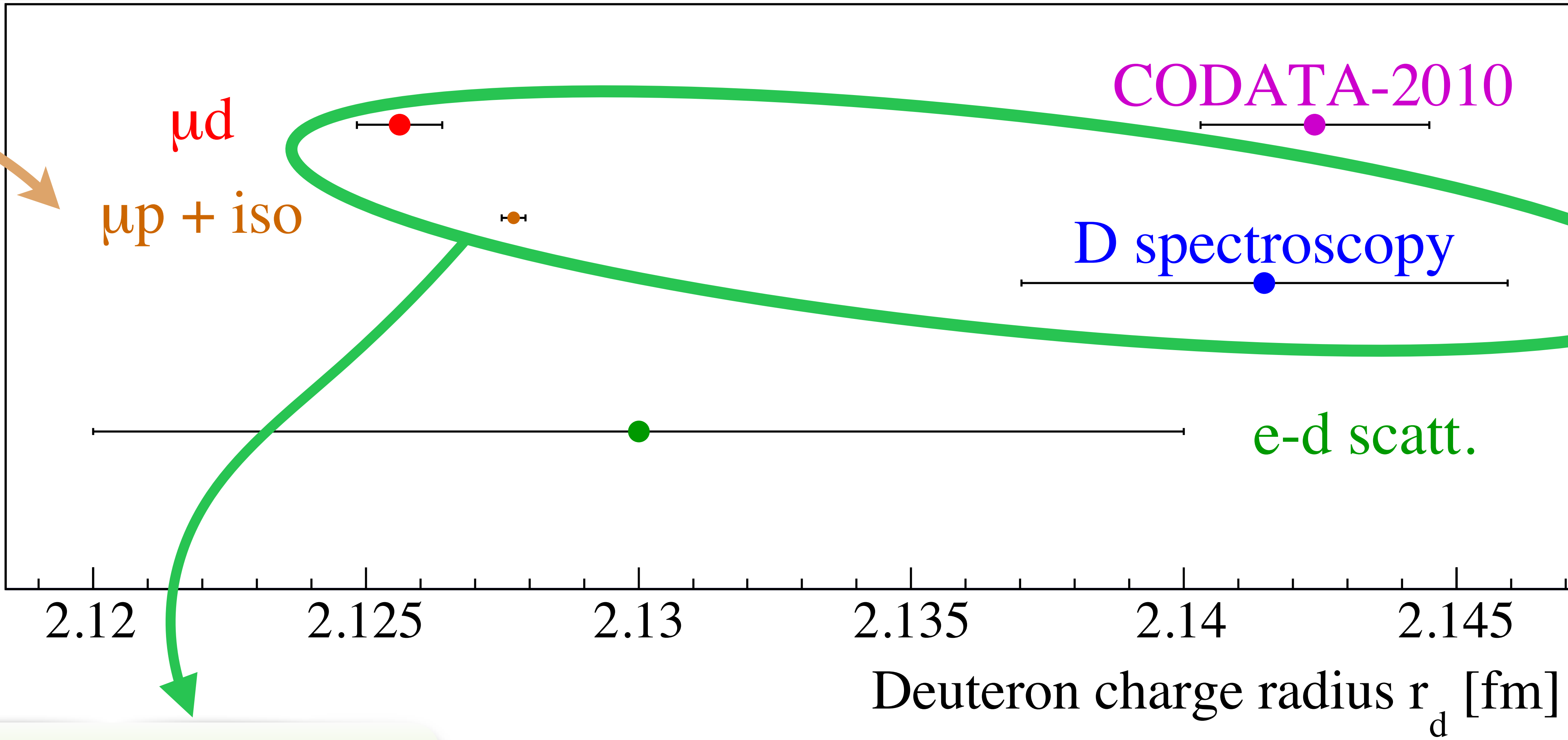


7σ from CODATA

BUT CODATA contains proton-data

2S-2P spectroscopy of muonic deuterium (μd)

$$\begin{rcases} \text{H/D shift:} & r_d^2 - r_p^2 = 3.820\,07(65)\ \text{fm}^2 \\ \mu p: & r_p = 0.84087(39)\ \text{fm} \end{rcases} \Rightarrow r_d = 2.12771(22)\ \text{fm}$$



3.5σ from ONLY D-data

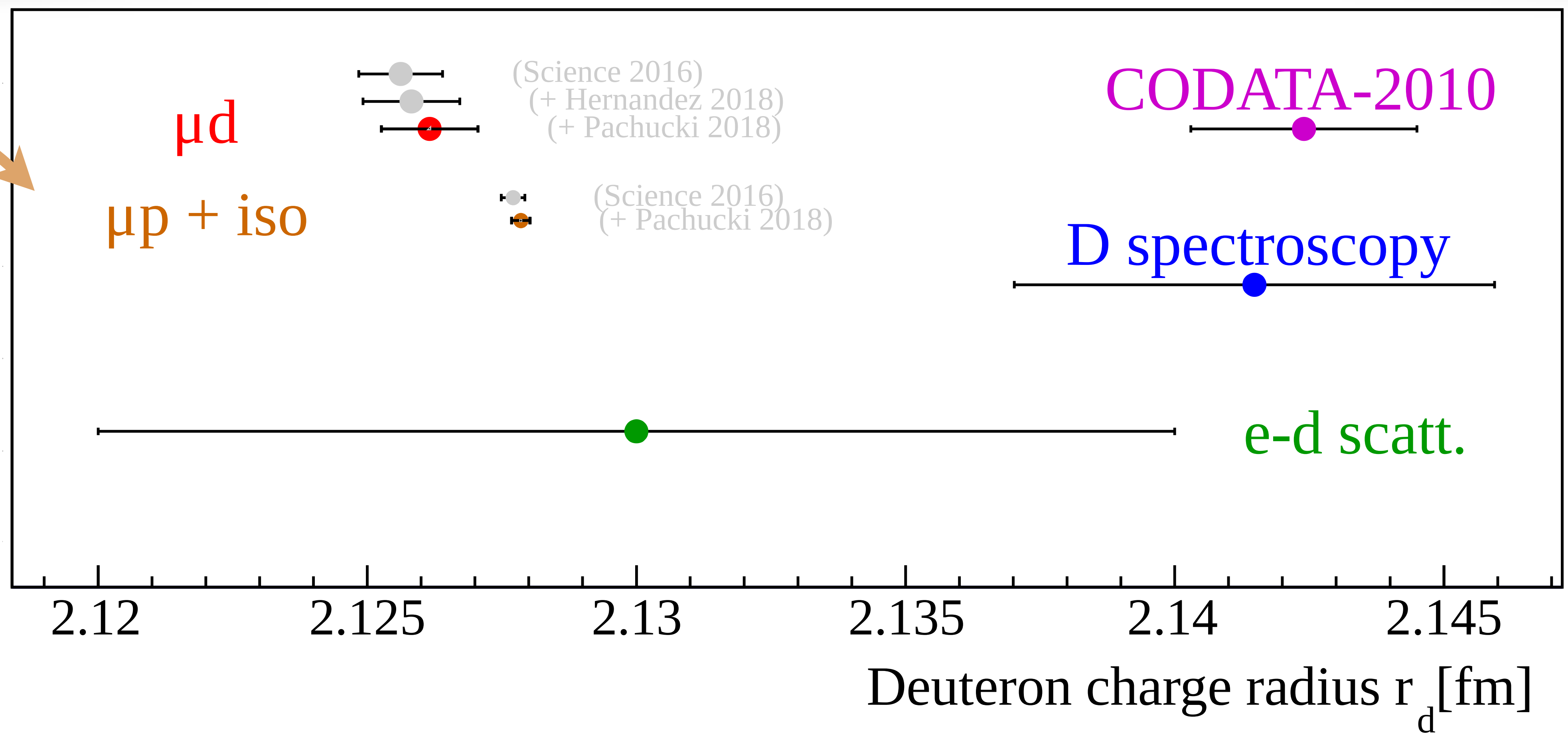
⇨ double discrepancy
- proton sector
- deuteron sector

⇨ Problem with H/D exp (R_∞)?
⇨ Problem with H/D th.?
⇨ BSM with no coupling to n?

2S-2P spectroscopy of muonic deuterium (µd)

3.820 70(31) fm²

$$\left.\begin{array}{lll} \text{H/D shift:} & r_d^2 - r_p^2 & = 3.820\,07(65)\ \text{fm}^2 \\ \mu p: & r_p & = 0.84087(39)\ \text{fm} \end{array}\right\} \Rightarrow \quad r_d = 2.12771(22)\ \text{fm}$$



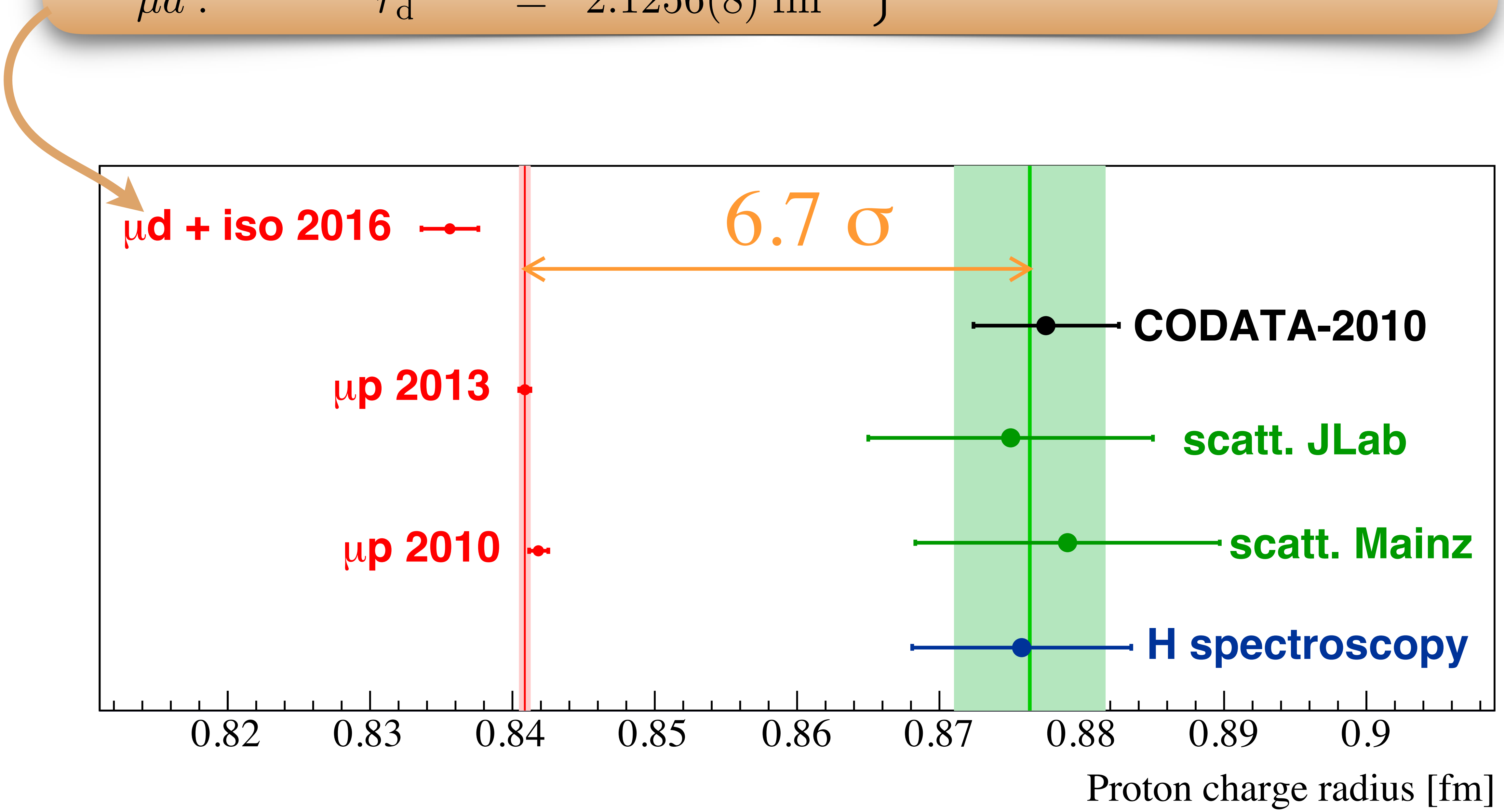
Hernandez et al, PLB (2018)
Pachucki et al., arXiv:1803.10313

Theory update

Slightly improve the consistency of the muonic results

The proton charge radius from muonic deuterium

$$\left.\begin{array}{lll} \text{H/D shift:} & r_d^2 - r_p^2 & = 3.820\,07(65)\ \text{fm}^2 \\ \mu d: & r_d & = 2.1256(8)\ \text{fm} \end{array}\right\} \Rightarrow r_p = 0.8356(20)\ \text{fm}$$



Pohl et al., Nature 466, 213 (2010)
Antognini et al., Science 339, 417 (2013)
Pohl et al., Science 353, 669 (2016)

Small value of the proton radius is confirmed from *μd*

The proton charge radii on the market

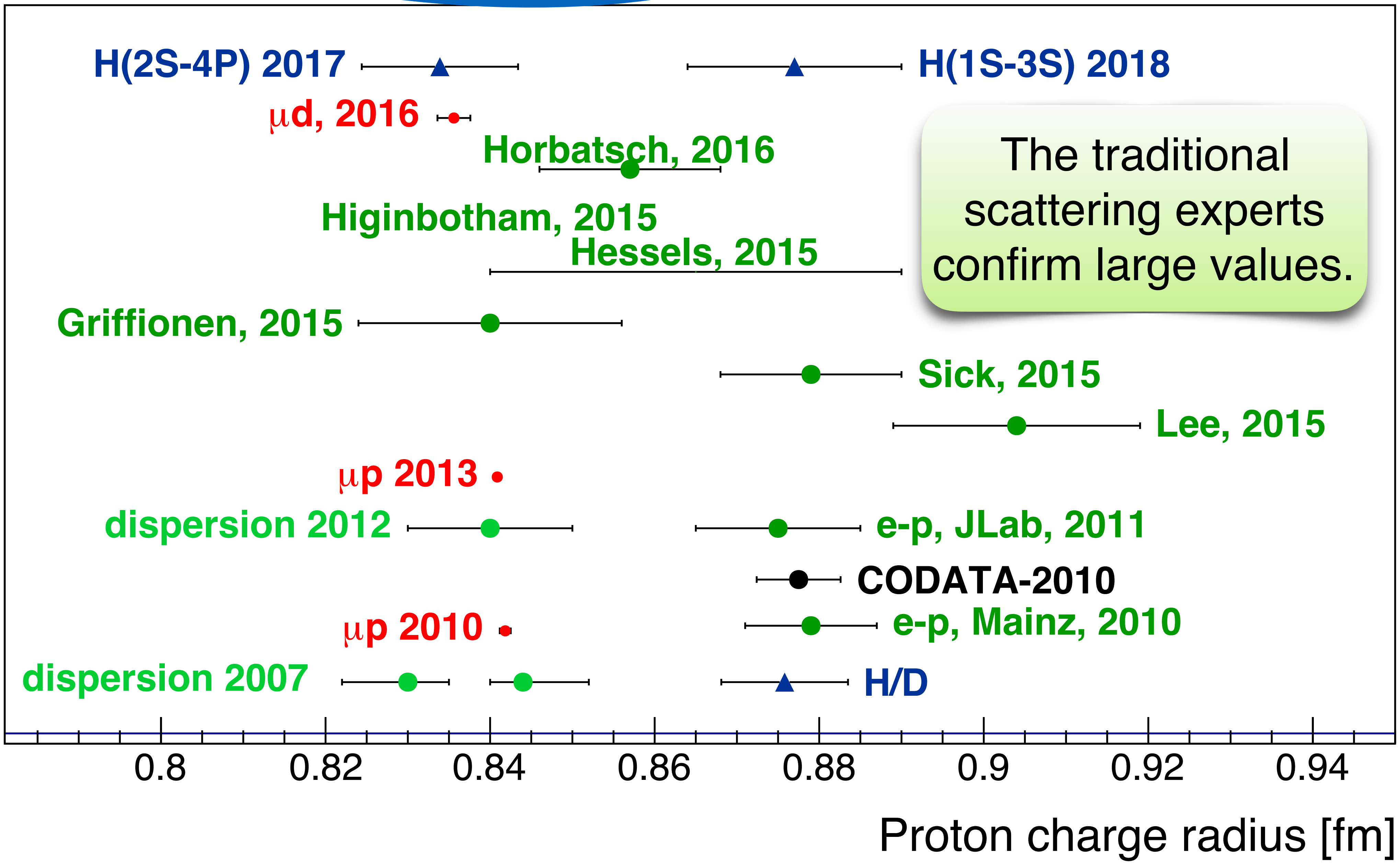
H(1S-3S) MPQ 2018

H(2S-2P) Toronto

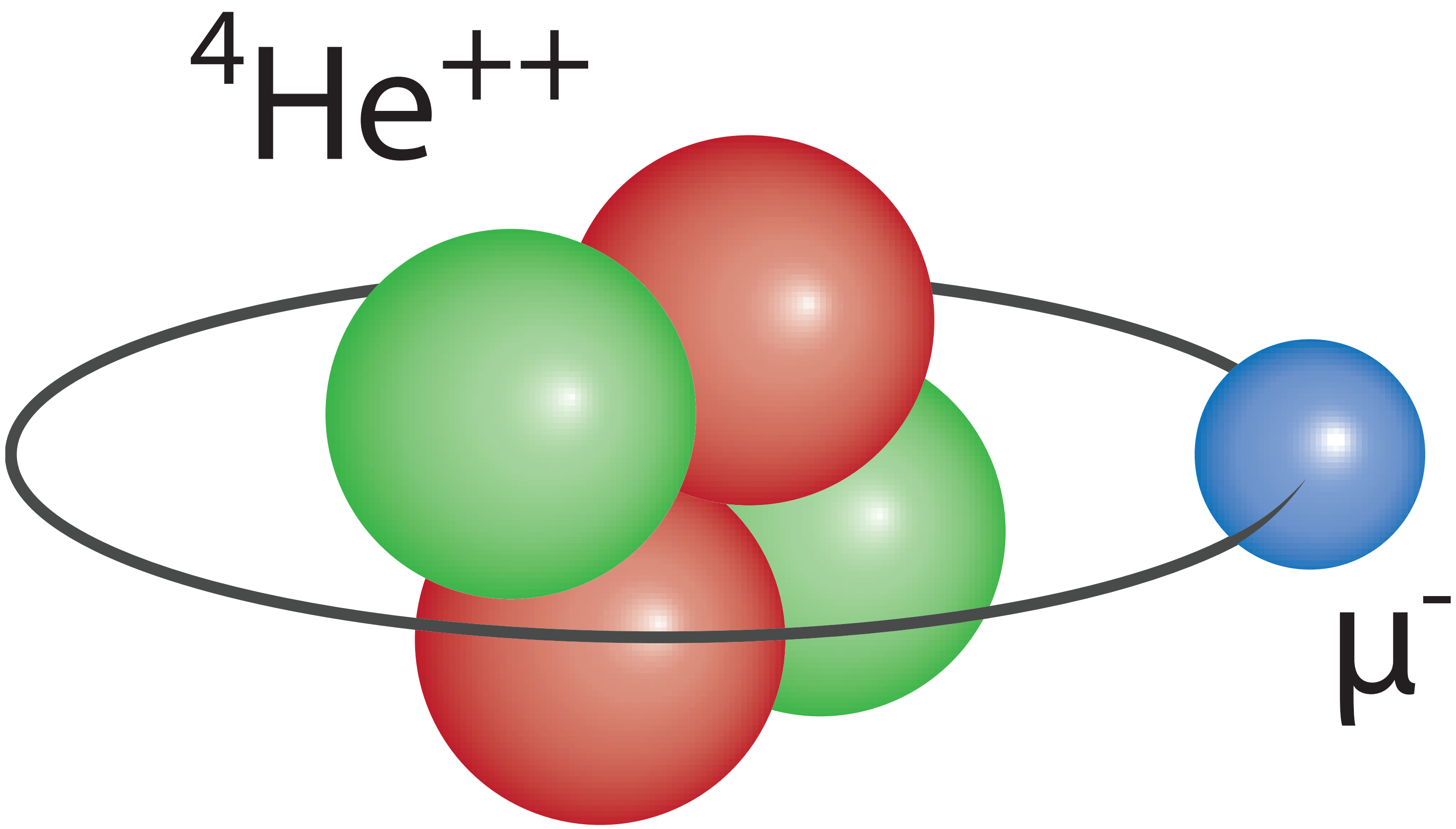
Preliminary values from H

New value from e-p scattering will be soon available

Ashot et al., PRad, JLAB

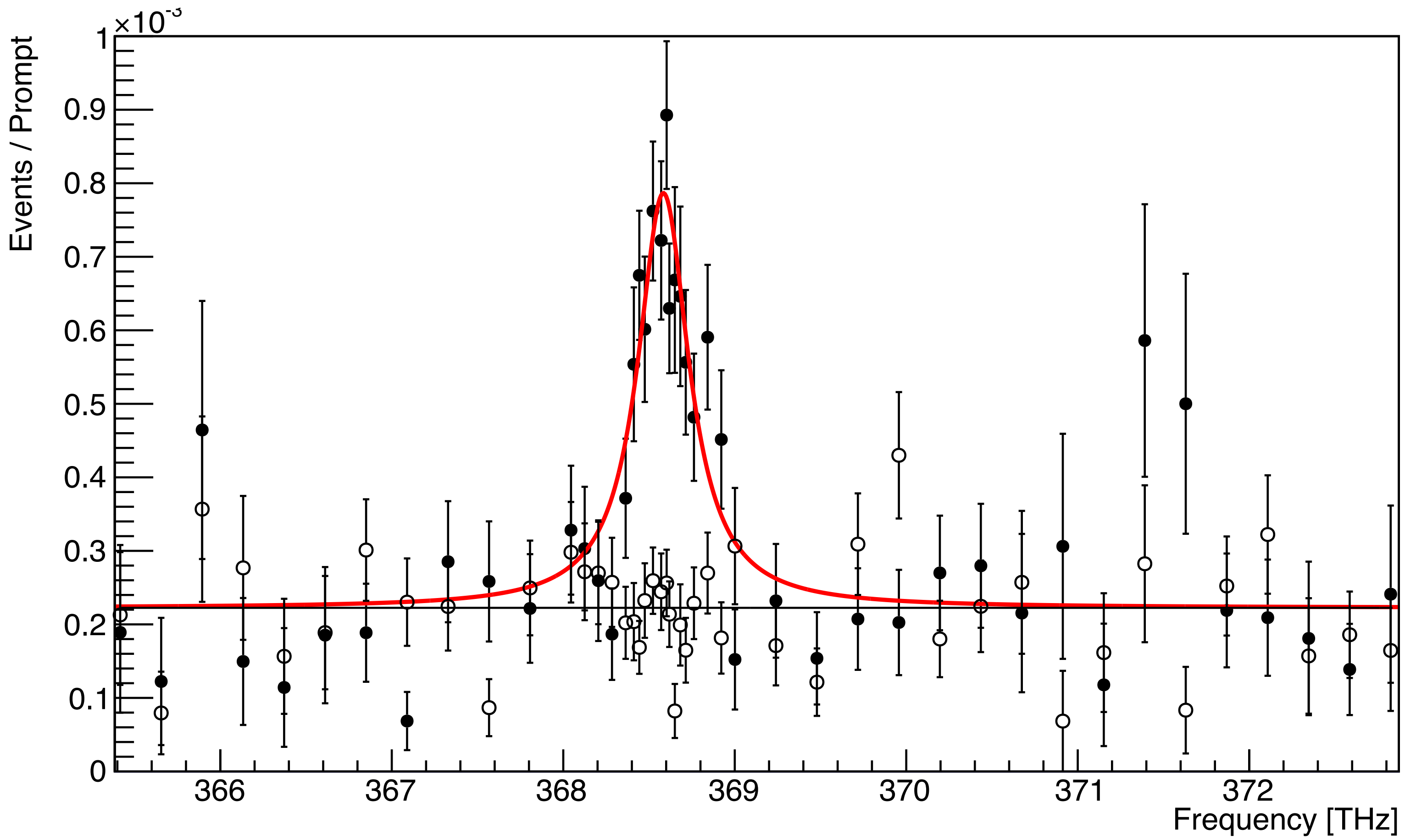


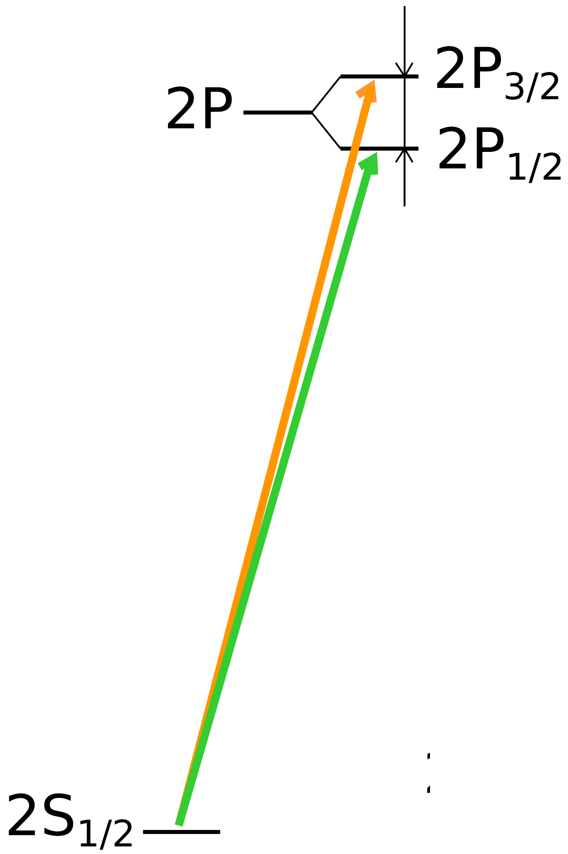
The traditional scattering experts confirm large values.



$^4He^{++}$
μ^-

Spectroscopy of muonic Helium (μ^4He^+)

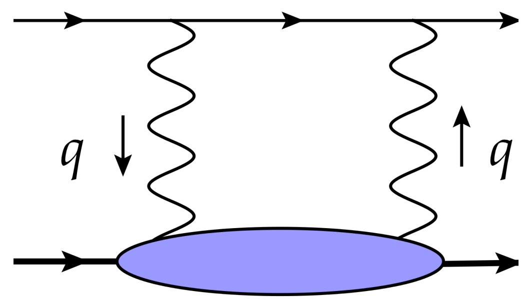




Experimental accuracy:	17 GHz (0.066 meV)
Statistics / Laser freq. / systematics unc.:	17 GHz / 100 MHz / 10 MHz
Theory uncertainty:	0.205 meV

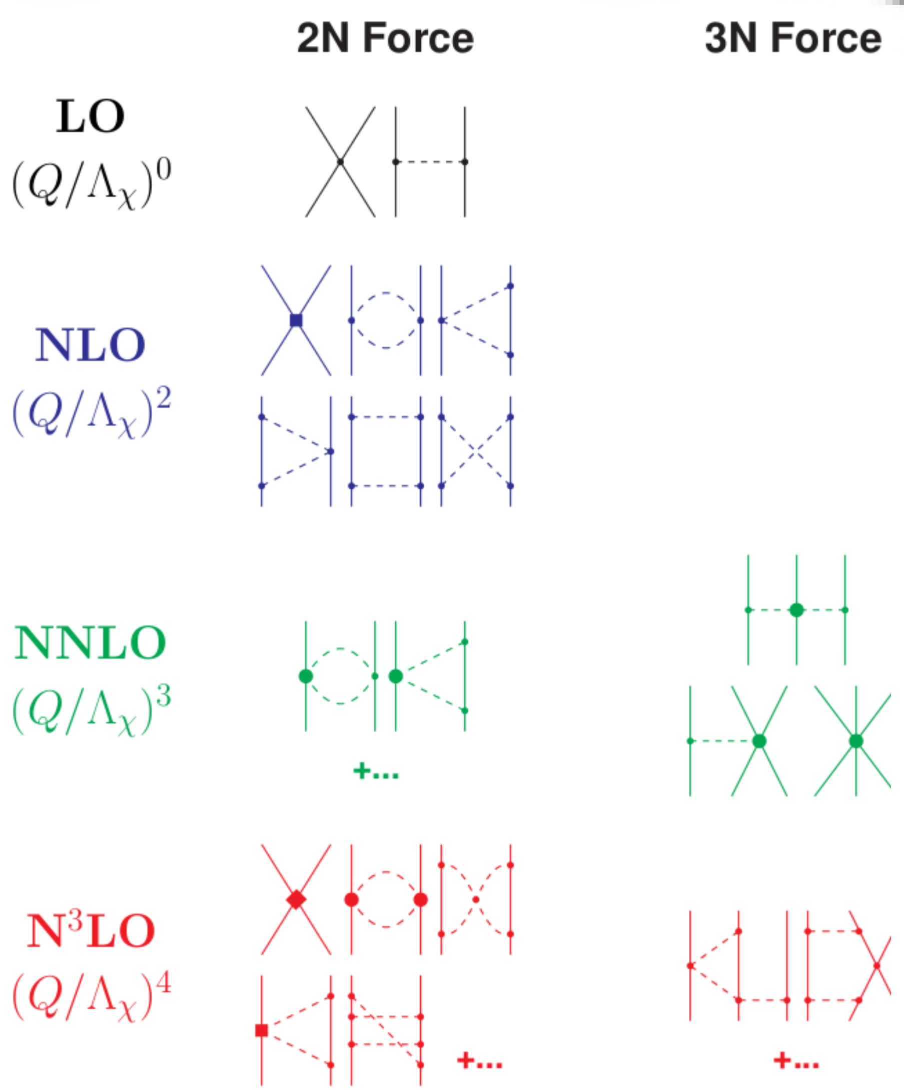
$$\Delta E(2S{-}2P_{3/2}) = \underbrace{1668.487(14)}_{\text{QED}} - \underbrace{106.358(7) R_E^2}_{\text{finite size}} + \underbrace{6.761(77) + 3.296(189)}_{\text{TPE}} + \underbrace{146.197(12)}_{\text{fine splitting}} \ [\text{meV}]$$

TPE: the key to extract precise charge radii



Dinur, Ji, Barnea,
Bacca, Hernandez

chiral EFT
few-necleoun th.



Phenomenological:
- dispersion relations
- data
- sum rules

Carlson, Gorchtein,
Vanderhaeghen

Impressive improvement in last years

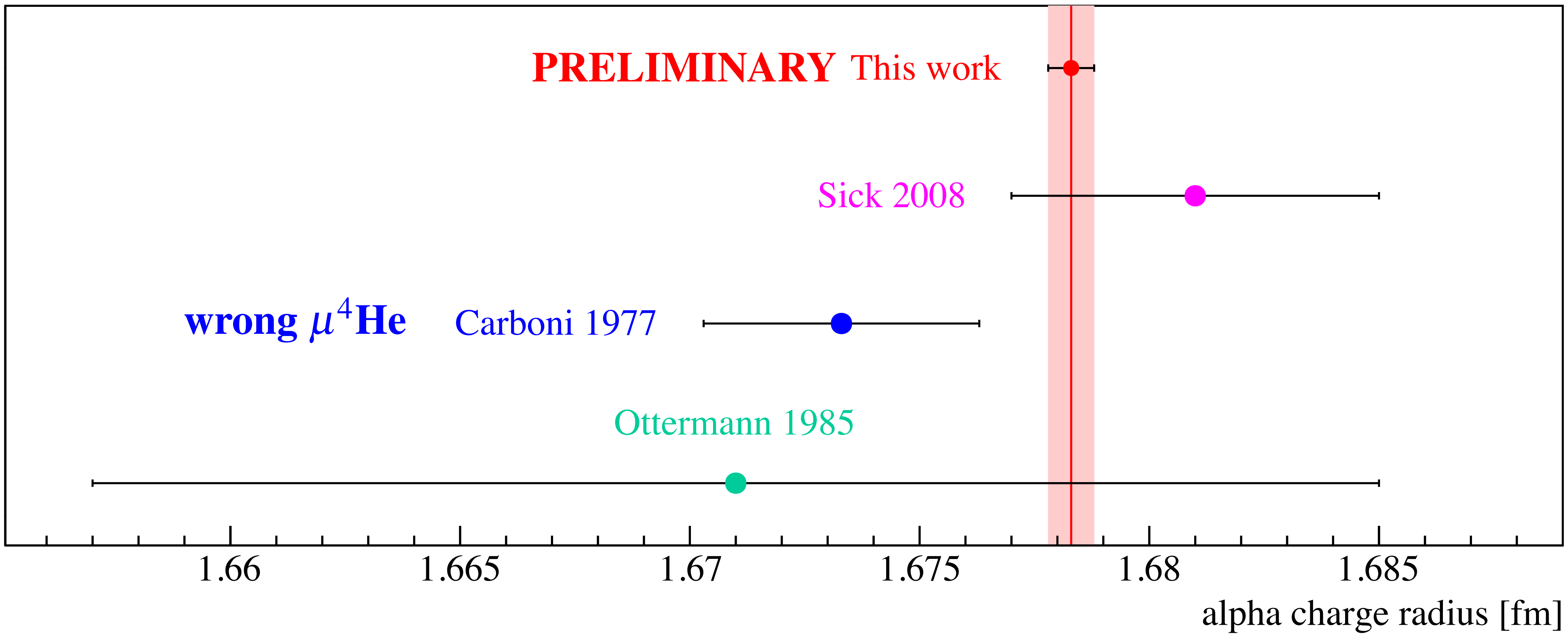
For μ^3He

Dispersion:	15.14 (49) meV
Few-nucleon th.:	15.46 (39) meV

Alpha-particle radius from μ^4He^+ spectroscopy

$$R_E(^4\text{He}) = 1.67xxx(19)_{\text{exp}}(58)_{\text{theo}} \text{ fm} \quad \text{(muonic helium)}$$
$$R_E(^4\text{He}) = 1.68100(400) \text{ fm} \quad \text{(scattering)}$$

Sick, arXiv1505.06924



Excellent agreement between scattering and muonic results

BSM contribution does not have to exceed 3 meV

(1σ R_E (Sick, 2015) ⇨ 1.4 meV shift in muonic helium)

Impact of muonic helium (μHe) measurements

Antognini et al., Can. J. Phys. 89, 47 (2011)

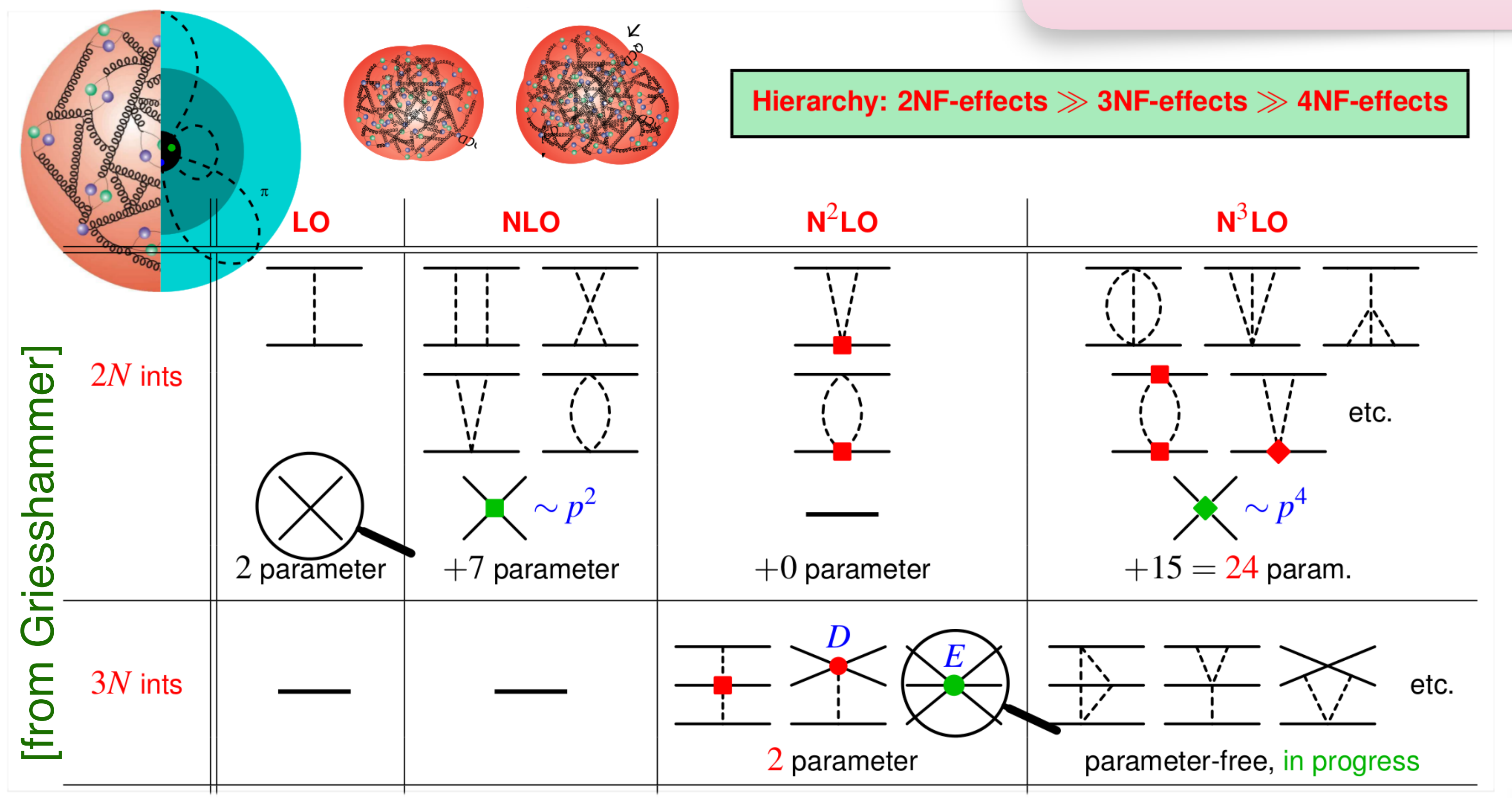
Constraints proton radius puzzle

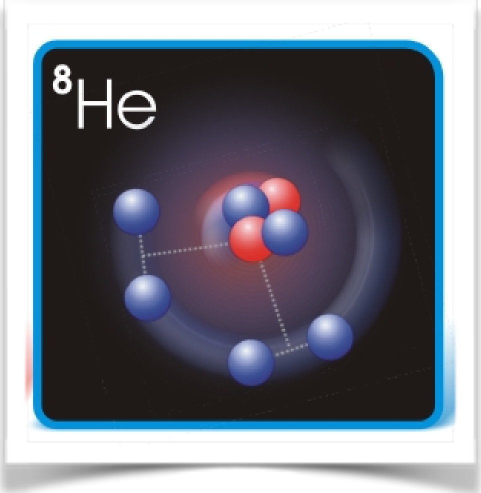
Benchmark for few-nucleon theories

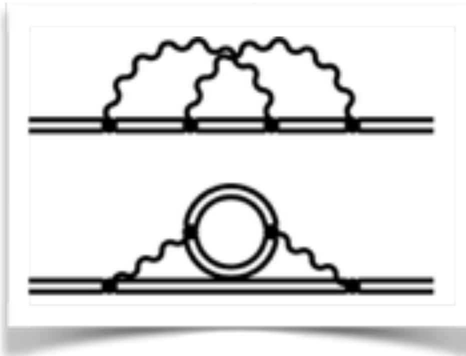
Improve absolute radii of ^{6}He and ^{8}He

Help understanding the ^{3}He-^{4}He charge radii difference

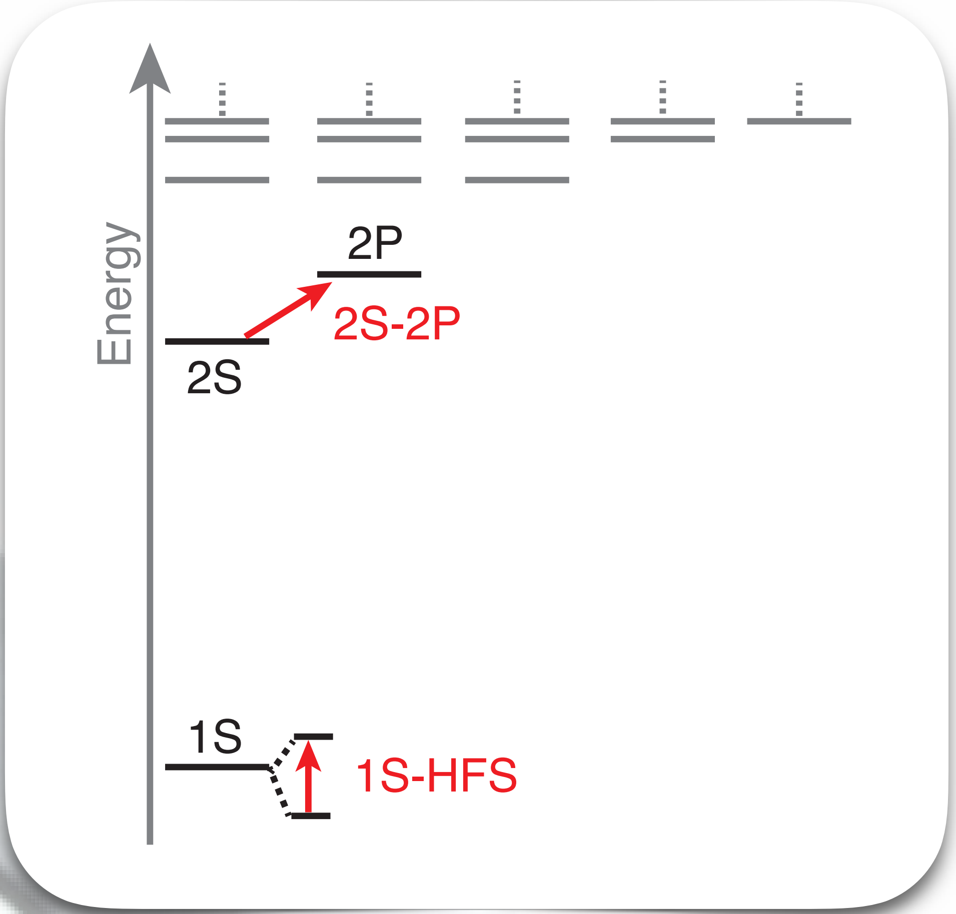
When combined with He and He$^+$ spectroscopy:
⇨Enhanced bound-state QED test , extract R_∞







From the 2S-2P to HFS measurements



- 2S-2P μp
- 2S-2P μd
- 2S-2P μ^3He, μ^4He
- 1S-HFS μp

- From 2S-2P
  → charge radii
- From HFS
  → Zemach radius

Hyperfine splitting theory and goals

Measure

the 1S-HFS in μp
with 1-2 ppm accuracy

Goals

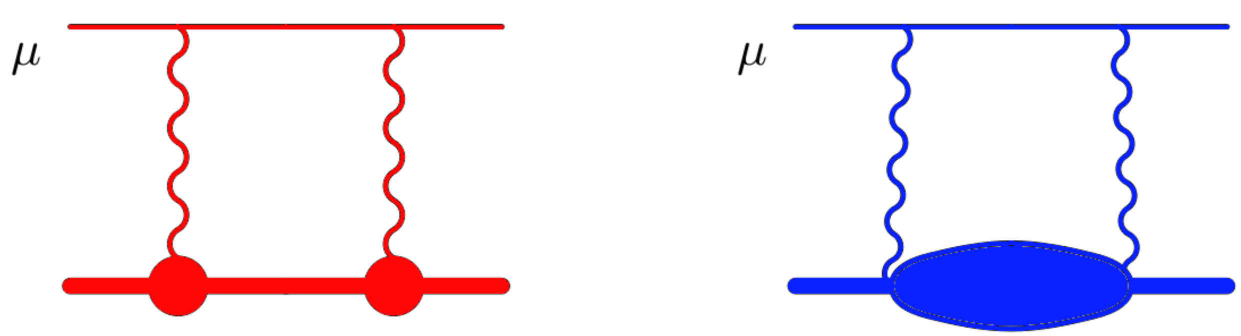
- TPE contribution with 3×10^{-4} rel. accuracy
- Zemach radius and polarisability contributions

$$\Delta E_{\mathrm{HFS}}^{\mathrm{th}} = 183.788(7) + 1.0040 \Delta E_{\mathrm{TPE}} \; [\mathrm{meV}]$$

Pineda & Peset (2017)

$$\Delta E_{\mathrm{TPE}} = \Delta E_{\mathrm{Z}} + \Delta E_{\mathrm{Recoil}} + \Delta E_{\mathrm{pol}}$$

$$R_Z = \frac{4}{\pi} \int_0^\infty \frac{dQ}{Q^2} \left[\frac{G_E(Q^2) G_M(Q^2)}{1+\kappa} - 1 \right]$$



TPE: dispersion based approach

Elastic part (Zemach)

$$\Delta_{\rm Z} = \frac{8Z\alpha m_r}{\pi}\int_0^\infty \frac{{\rm d}Q}{Q^2}\left[\frac{G_E(Q^2)G_M(Q^2)}{1+\kappa}-1\right] \equiv -2Z\alpha m_r R_{\rm Z},$$

Distler, Bernauer, Sick

Recoil finite-size

$$\Delta_{\rm recoil} = \frac{Z\alpha}{\pi(1+\kappa)}\int_0^\infty \frac{{\rm d}Q}{Q}\left\{\frac{8mM}{v_l+v}\frac{G_M(Q^2)}{Q^2}\left(2F_1(Q^2)+\frac{F_1(Q^2)+3F_2(Q^2)}{(v_l+1)(v+1)}\right) - \frac{8m_r G_M(Q^2)G_E(Q^2)}{Q} - \frac{m}{M}\frac{5+4v_l}{(1+v_l)^2}F_2^2(Q^2)\right\}.$$

Polarisability

$$\Delta_{\rm pol.} = \frac{Z\alpha m}{2\pi(1+\kappa)M}\left[\delta_1+\delta_2\right] =$$

with:

$$\delta_1 = 2\int_0^\infty \frac{{\rm d}Q}{Q}\left(\frac{5+4v_l}{(v_l+1)^2}\left[4I_1(Q^2)/Z^2+F_2^2(Q^2)\right]+\frac{8M^2}{Q^2}\int_0^{x_0}{\rm d}x\, g_1(x,Q^2)\left\{\frac{4}{v_l+\sqrt{1+x^2\tau^{-1}}}\left[1+\frac{1}{2(v_l+1)(1+\sqrt{1+x^2\tau^{-1}})}\right]-\frac{5+4v_l}{(v_l+1)^2}\right\}\right),$$

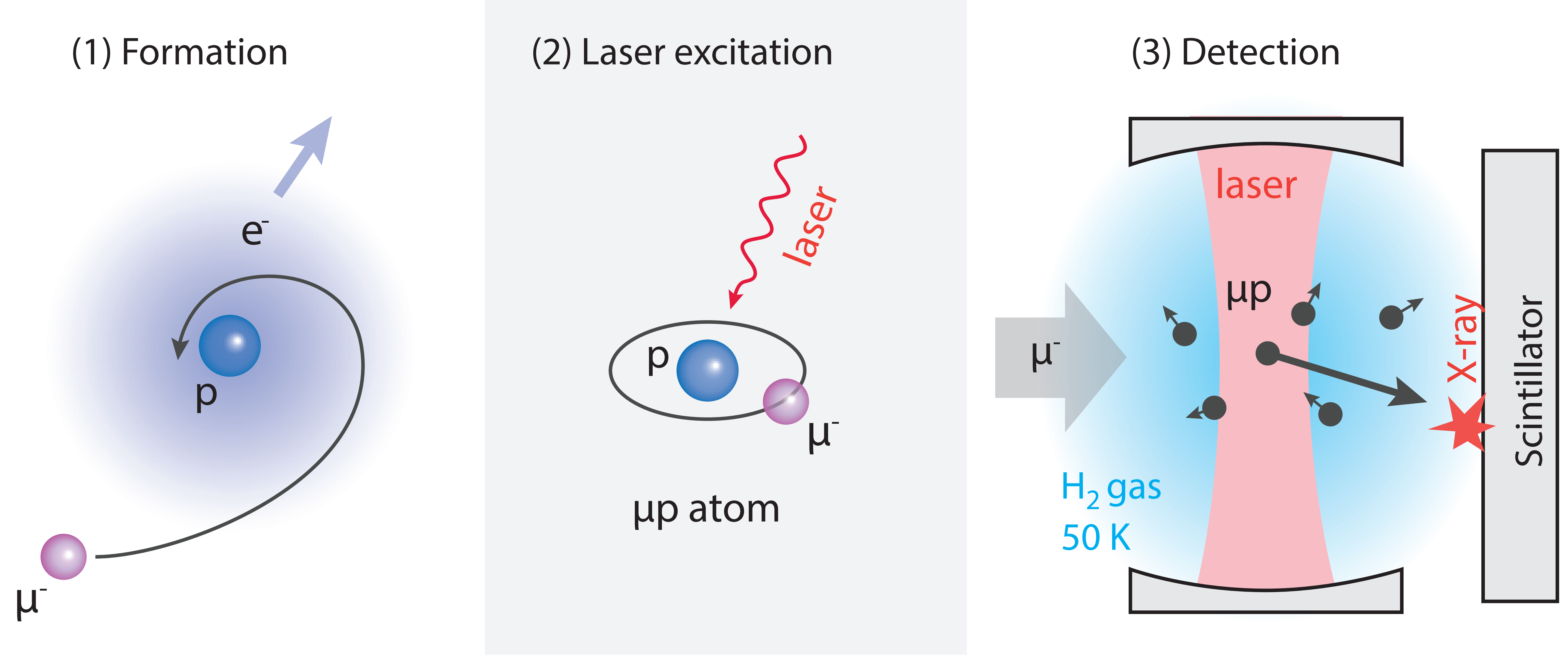
$$= 2\int_0^\infty \frac{{\rm d}Q}{Q}\left(\frac{5+4v_l}{(v_l+1)^2}\left[4I_1(Q^2)/Z^2+F_2^2(Q^2)\right]-\frac{32M^4}{Q^4}\int_0^{x_0}{\rm d}x\, x^2 g_1(x,Q^2)\left\{\frac{1}{(v_l+\sqrt{1+x^2\tau^{-1}})(1+\sqrt{1+x^2\tau^{-1}})(1+v_l)}\left[4+\frac{1}{1+\sqrt{1+x^2\tau^{-1}}}+\frac{1}{v_l+1}\right]\right\}\right)$$

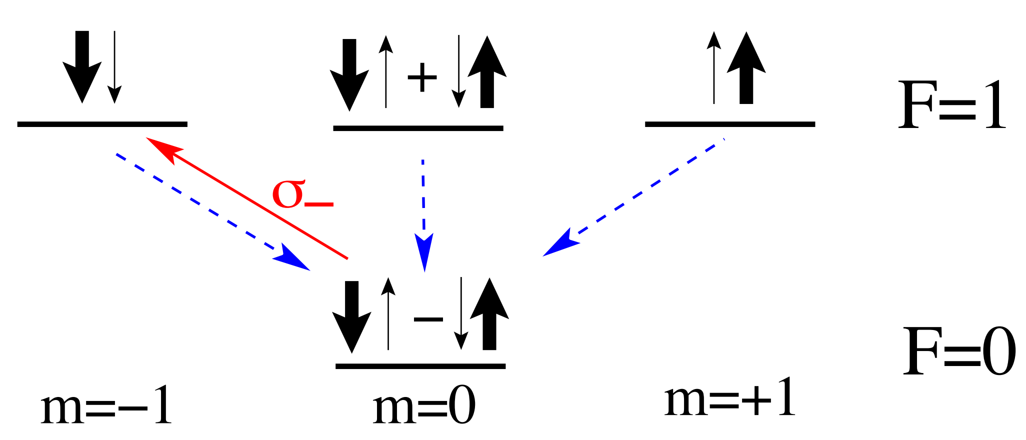
$$\delta_2 = 96M^2\int_0^\infty \frac{{\rm d}Q}{Q^3}\int_0^{x_0}{\rm d}x\, g_2(x,Q^2)\left\{\frac{1}{v_l+\sqrt{1+x^2\tau^{-1}}}-\frac{1}{v_l+1}\right\}.$$

New g_1, g_2 data from JLAB almost available

Hagelstein, Pascalutsa, Carlson, Martynenko, Tomalak Faustov, Vanderhaegen….

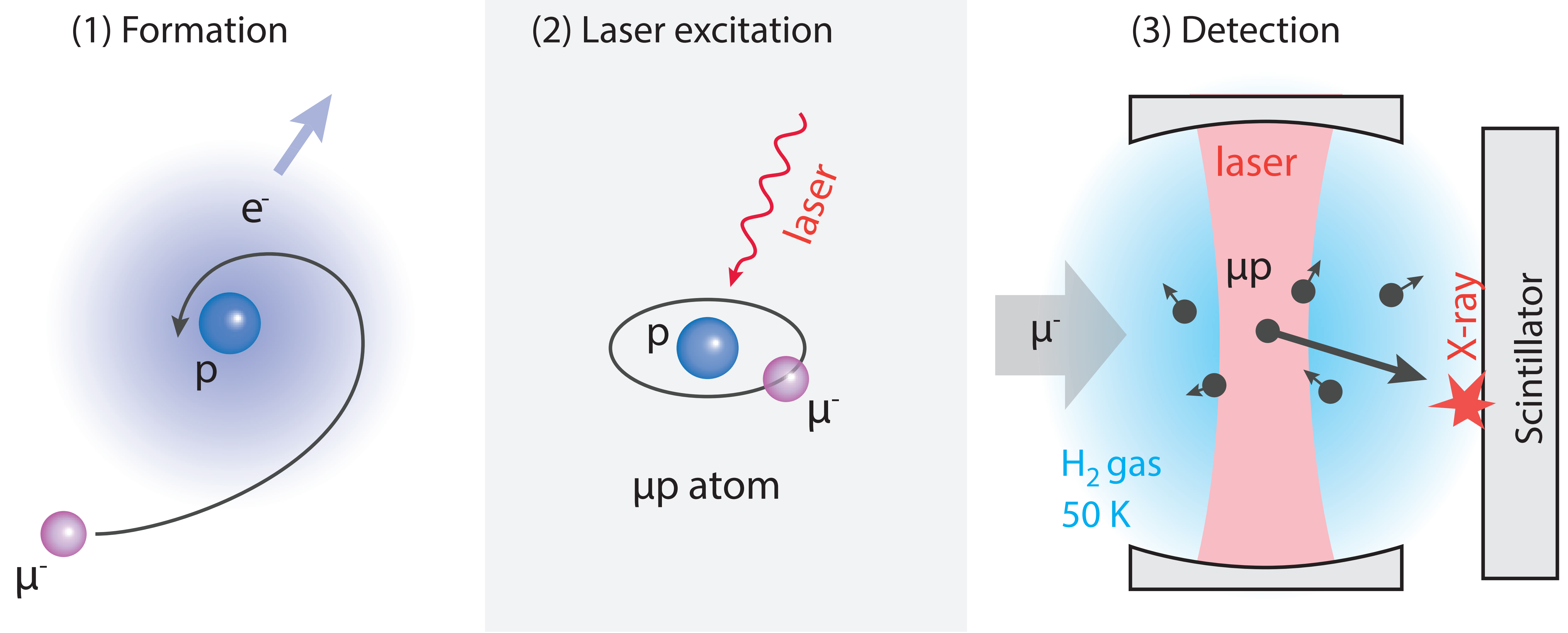
The principle of the μp HFS experiment





- Laser pulse: μp(F=0)$\longrightarrow\mu$p (F=1)
- Collision: μp(F=1)+ H_2 $\longrightarrow$ H_2 +μp(F=0) + E_{kin}
- Diffusion: the faster μp reach the target walls
- Resonance: plot number of X-rays vs. frequency

The principle of the μp HFS experiment



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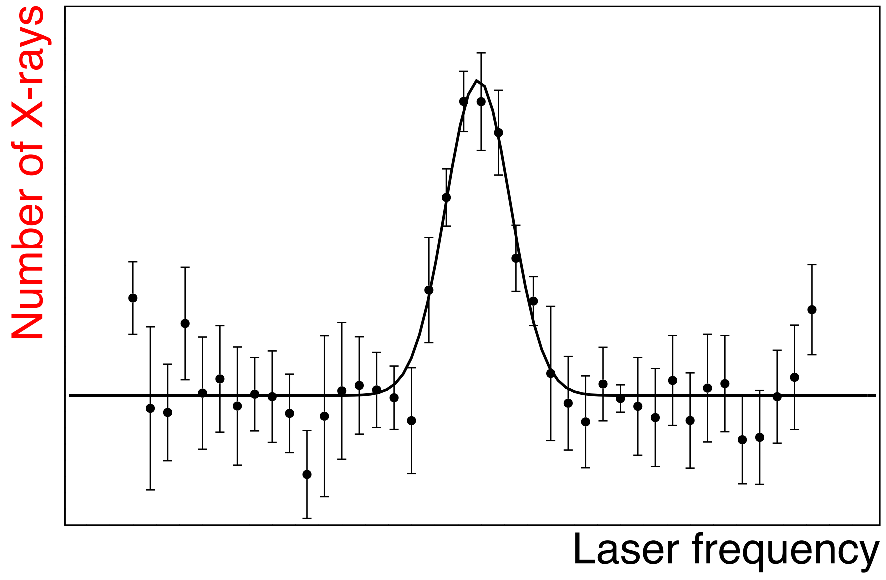
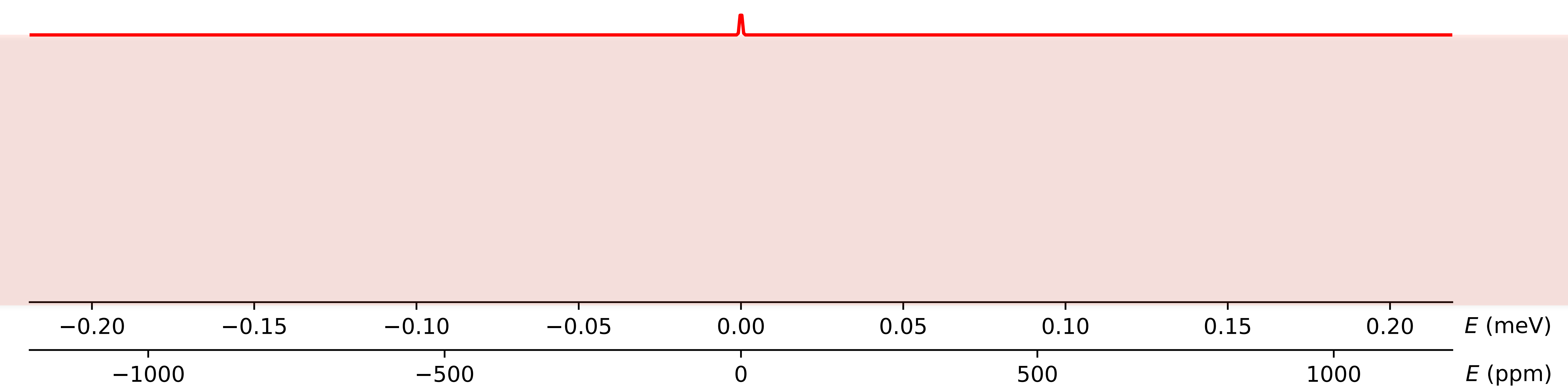


Uncertainties and scanning range

Large BG/Signal ratio

Narrow transition

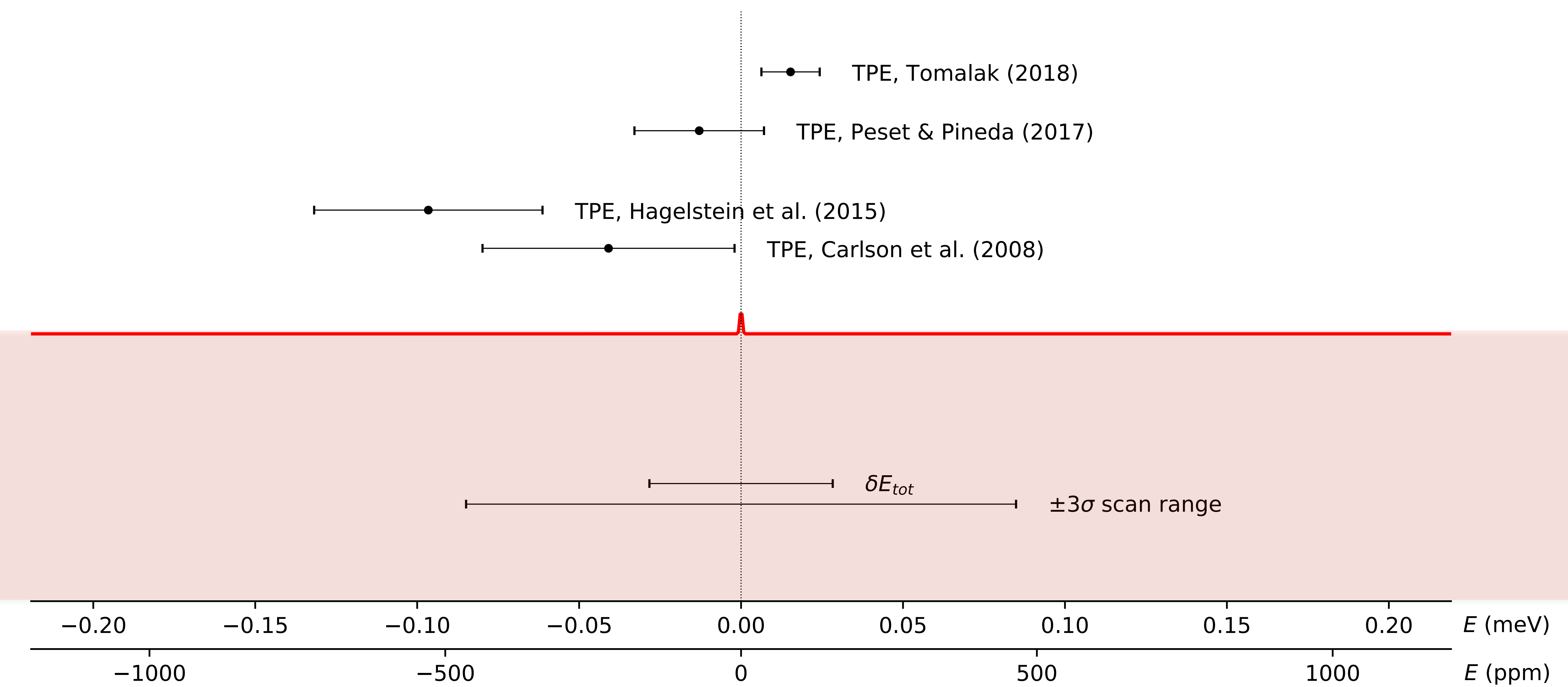
Large scan range



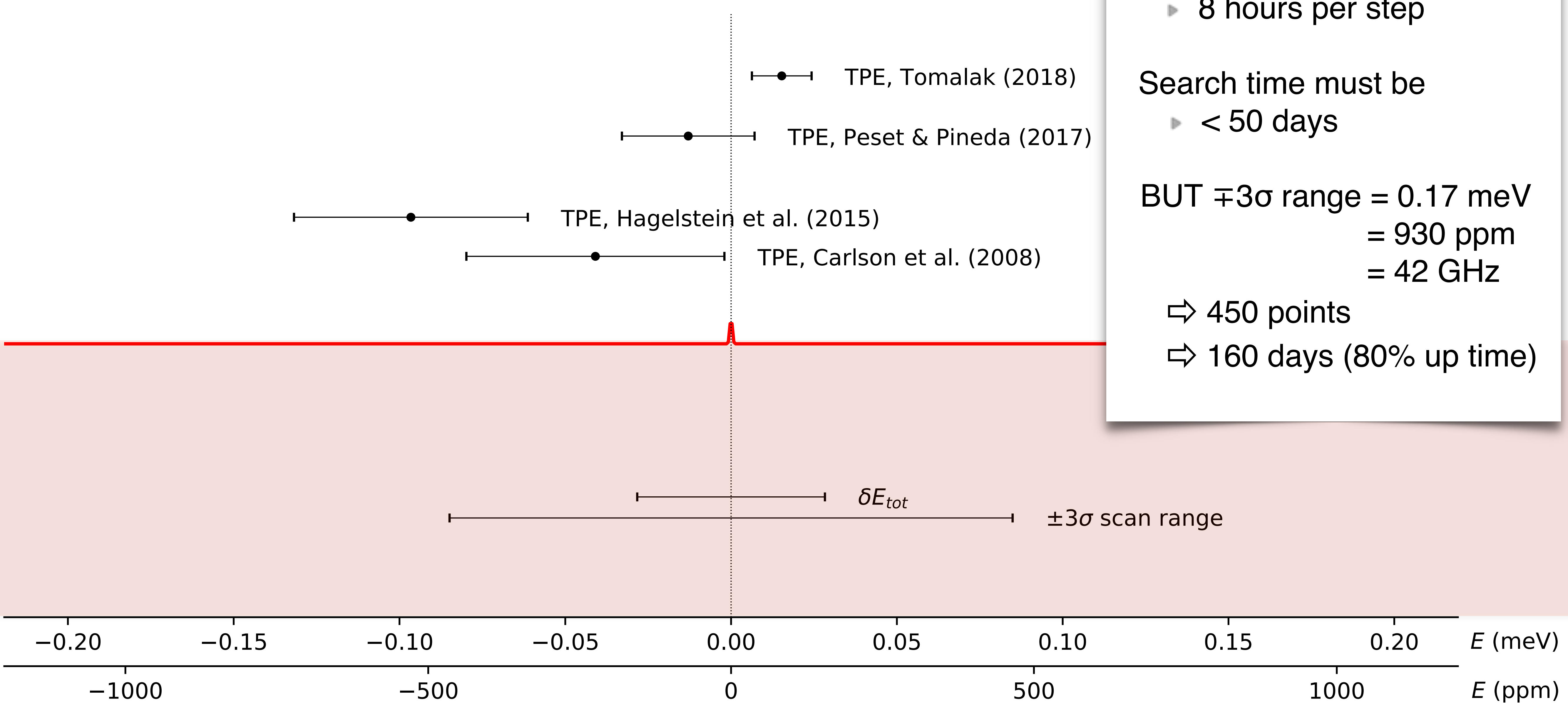
Uncertainties and scanning range

3ɣ exchange≈50 ppm

Kalinowski, Pachucki



Uncertainties and scanning range



Need to search the line with

- steps of 0.1 GHz (2 ppm of HFS)
- 8 hours per step

Search time must be

- < 50 days

BUT $\mp 3\sigma$ range = 0.17 meV
= 930 ppm
= 42 GHz

⇨ 450 points

⇨ 160 days (80% up time)

Nucleon Spin Structure at low-Q: A hyperfine view

QED
- check QED contributions in H to improve the TPE(H)
- higher-order QED corrections in μp
- Summary of all contributions would be very helpful (at 1 ppm level).

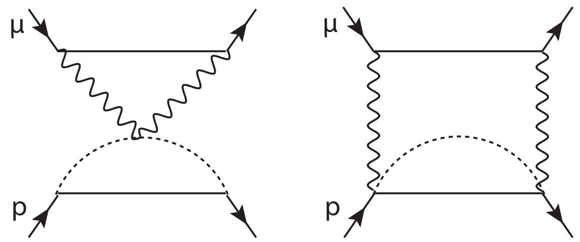
Zemach radius
- improve determination of Zemach radius, mainly through magnetic FF
- Study correlations R_z vs R_p

Polarisability contribution
- re-evaluate the pol contribution given the new g_1 and g_2 data
- improve chPT prediction also in view of interpretation of HFS measurement
- subtraction term really absent?

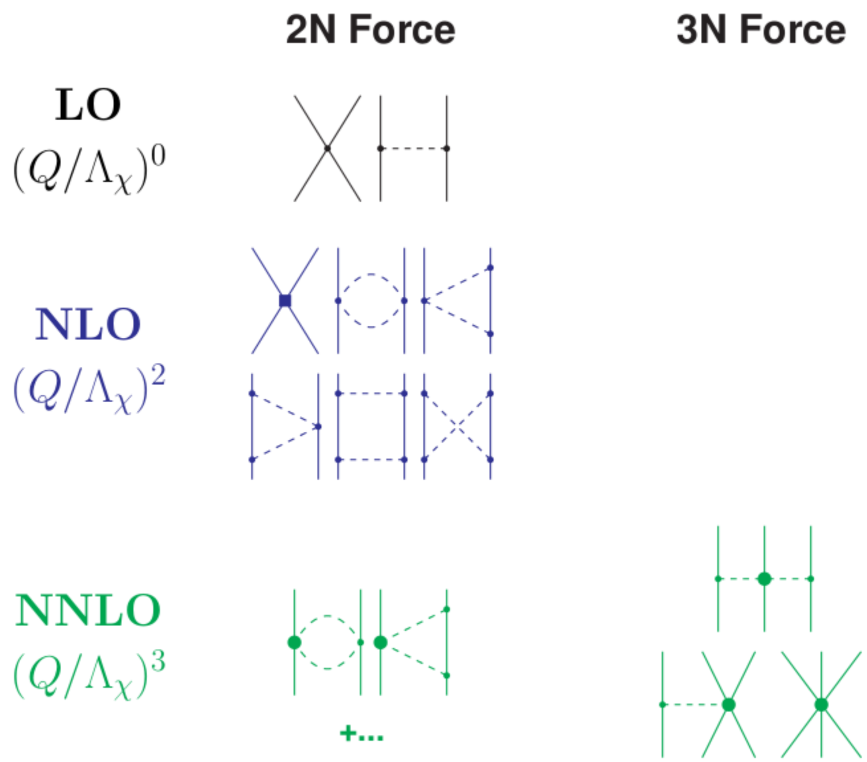
A TPE contribution with an accuracy of 25 ppm of HFS is needed to find the line

related to…

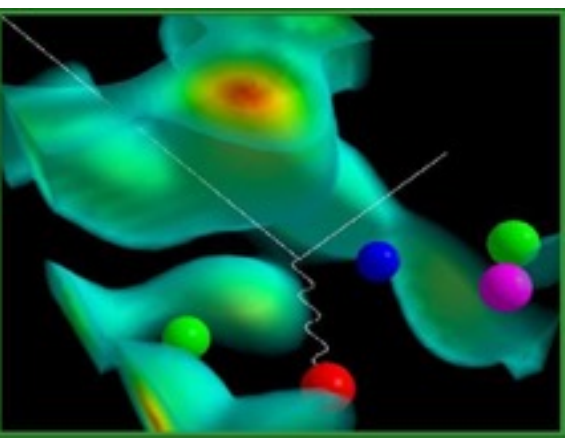
Chiral PT



Few-Nucleon EFT

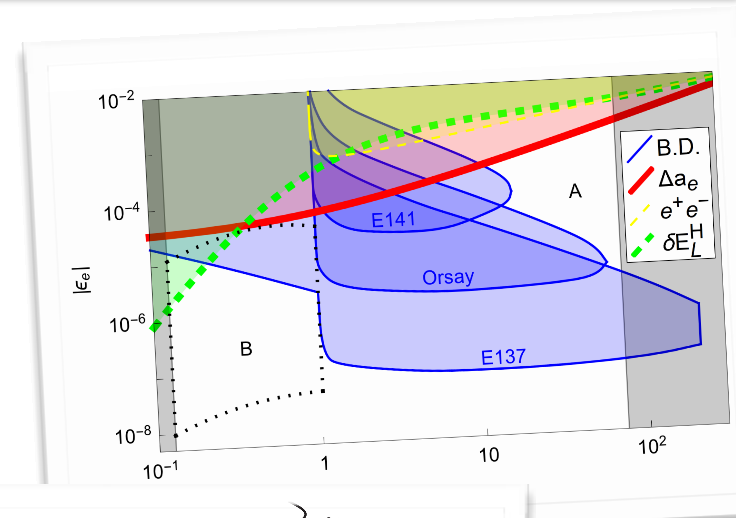


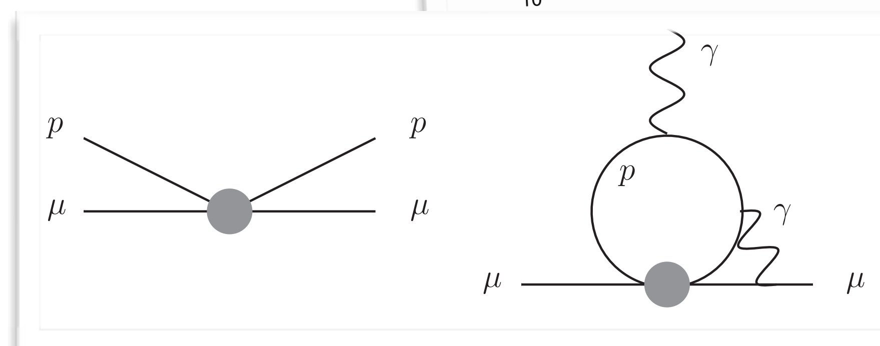
Lattice



BSM

?



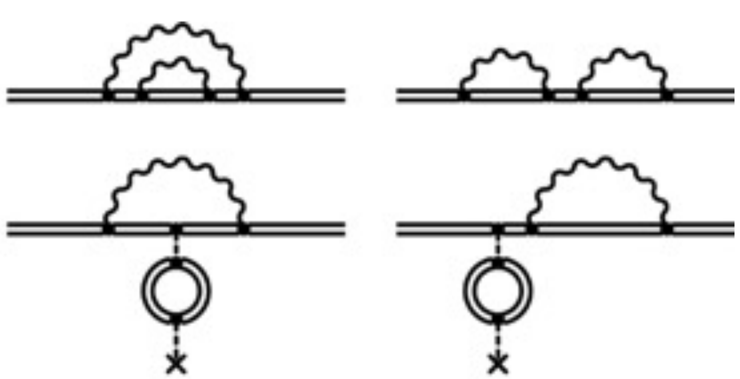


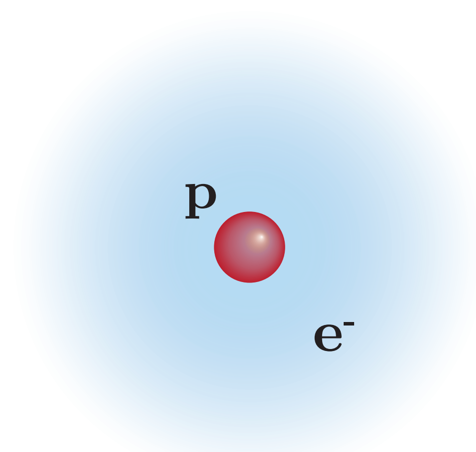
New hadronic effects?

Dispersion-based approaches.

Polarizabilities, form factors and structure functions program

Bound-state QED, ions, molecules, Rydberg atoms and R_∞





Analysis of e-p scattering

The same issues are critical for the HEP accelerator neutrino program.