Spectroscopy of muonic atoms

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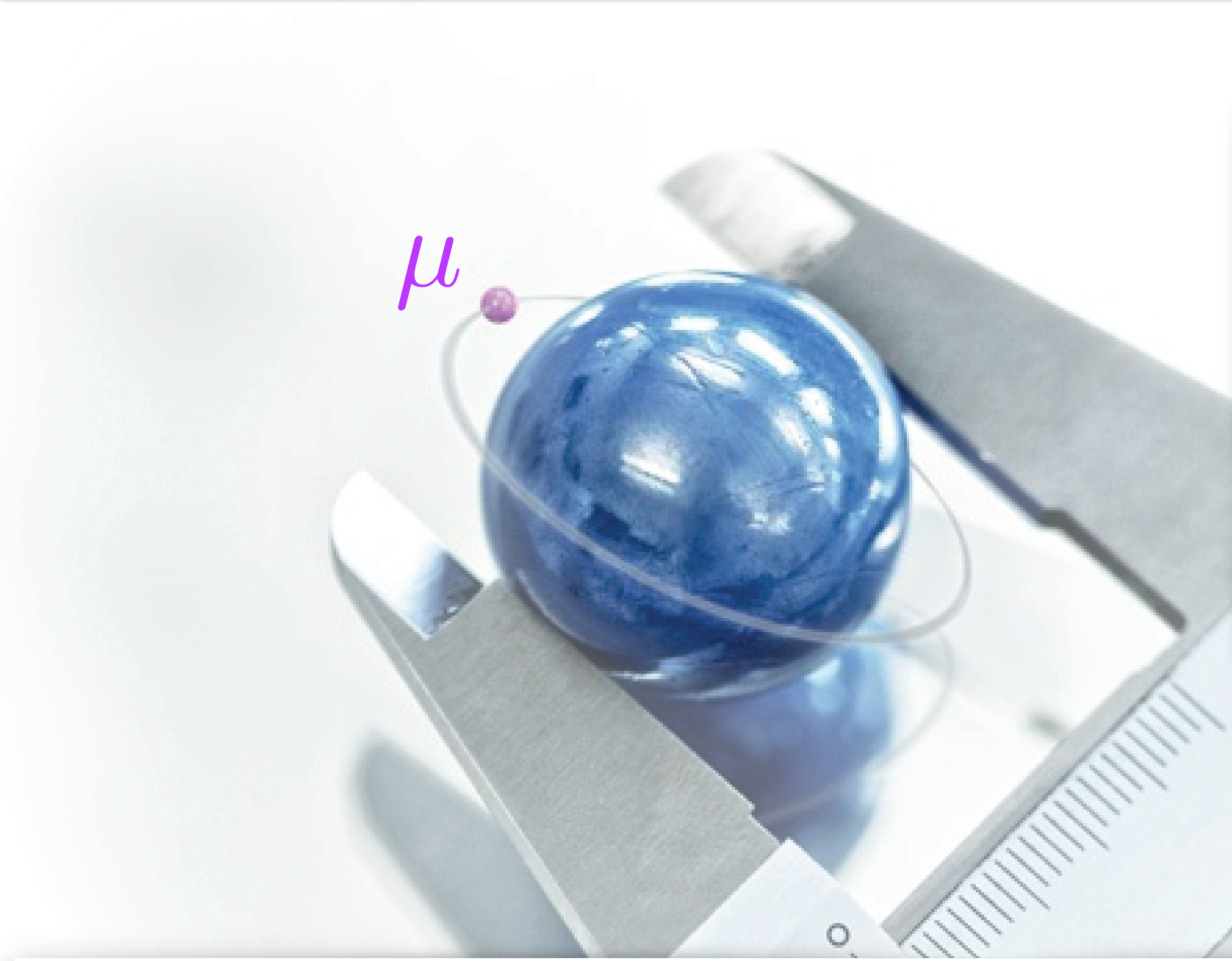
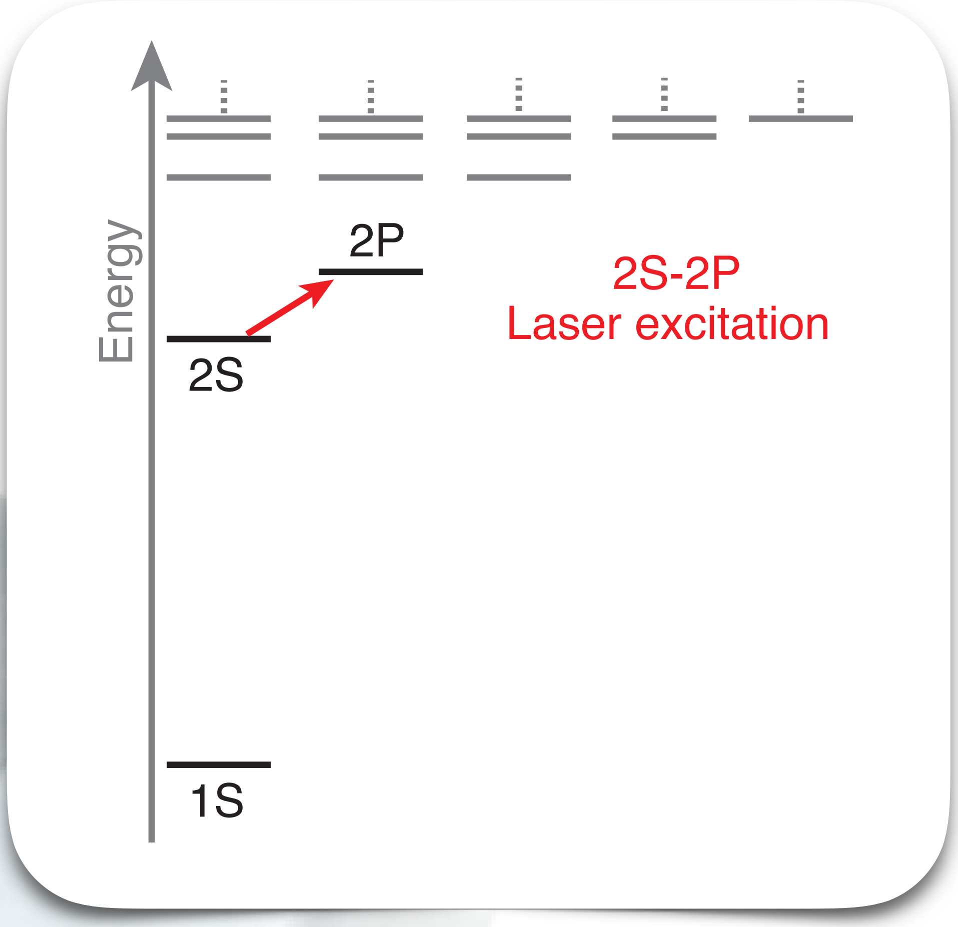
Laser spectroscopy of light muonic atoms





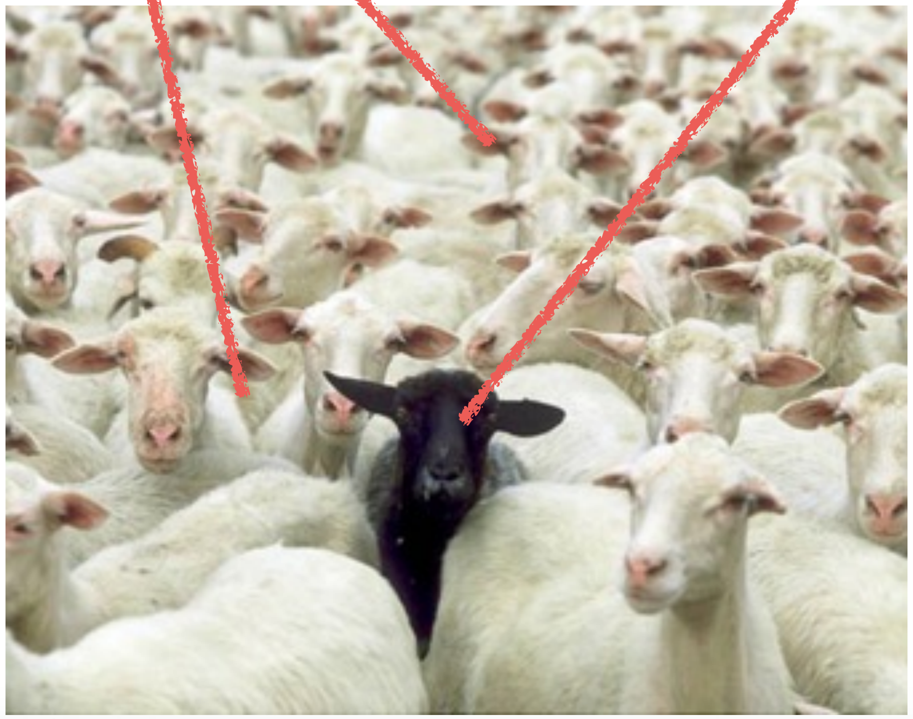
We measured 10 2S-2P transitions in μp, μd, μ^3He^+, μ^4He^+	+	Theoretical predictions: QED + Nuclear structure	⇨	p, d, ^3He, ^4He charge radii

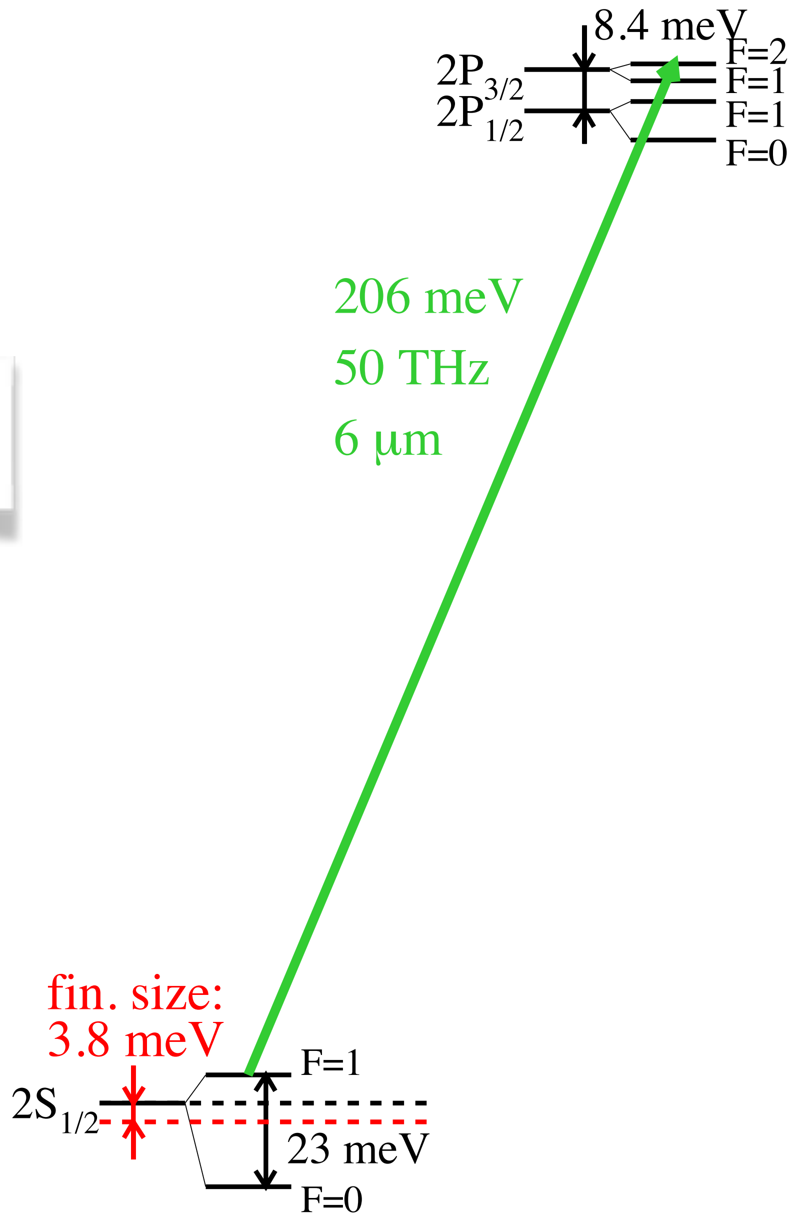
Extracting the proton radius from μp

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

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

The most interesting





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

$$m_\mu \approx 200 m_e$$

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

Principle of the μp 2S-2P experiment

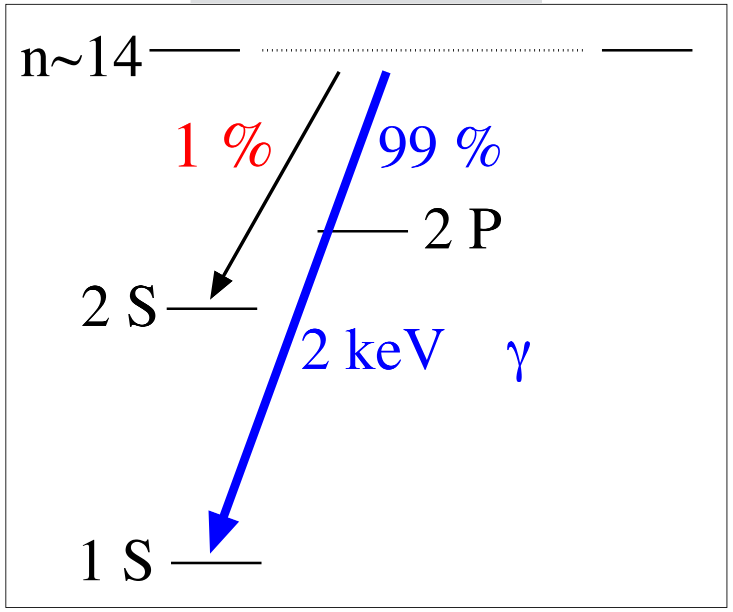
Produce many μ^- at keV energy

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

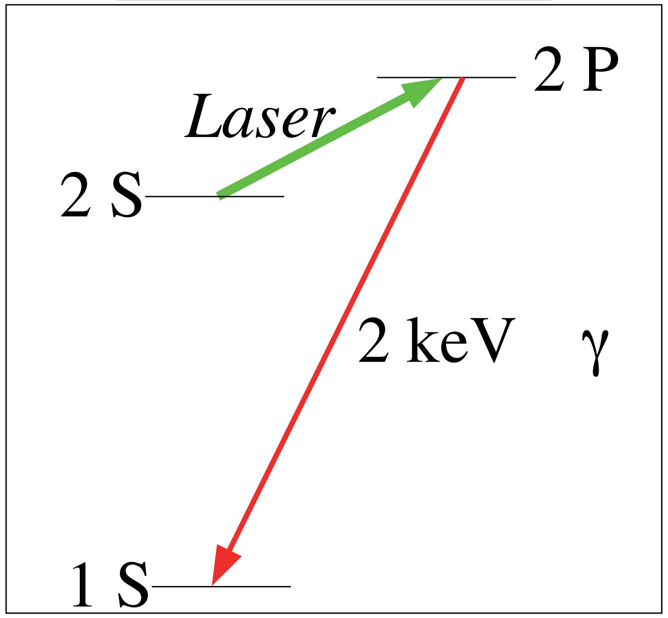
Fire laser to induce the 2S-2P transition

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

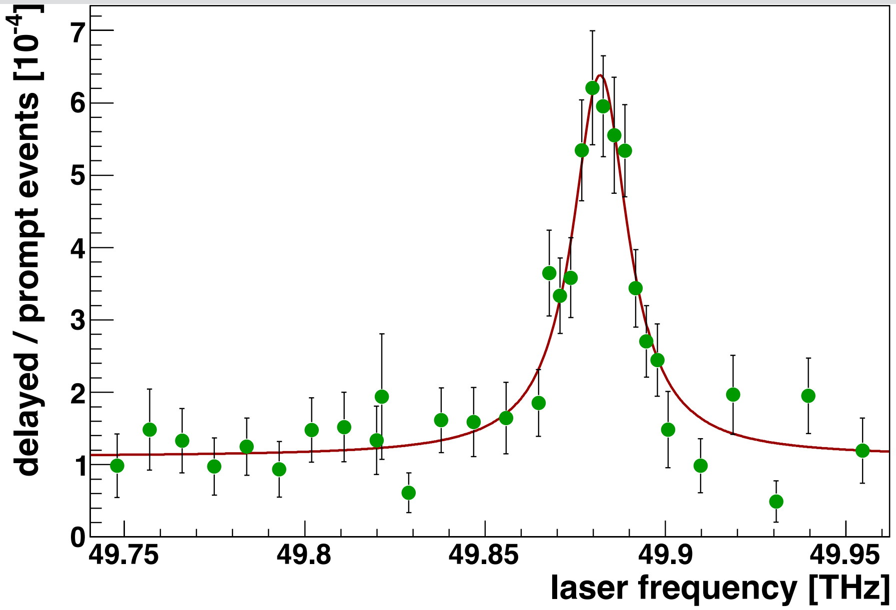
μp formation



Laser excitation

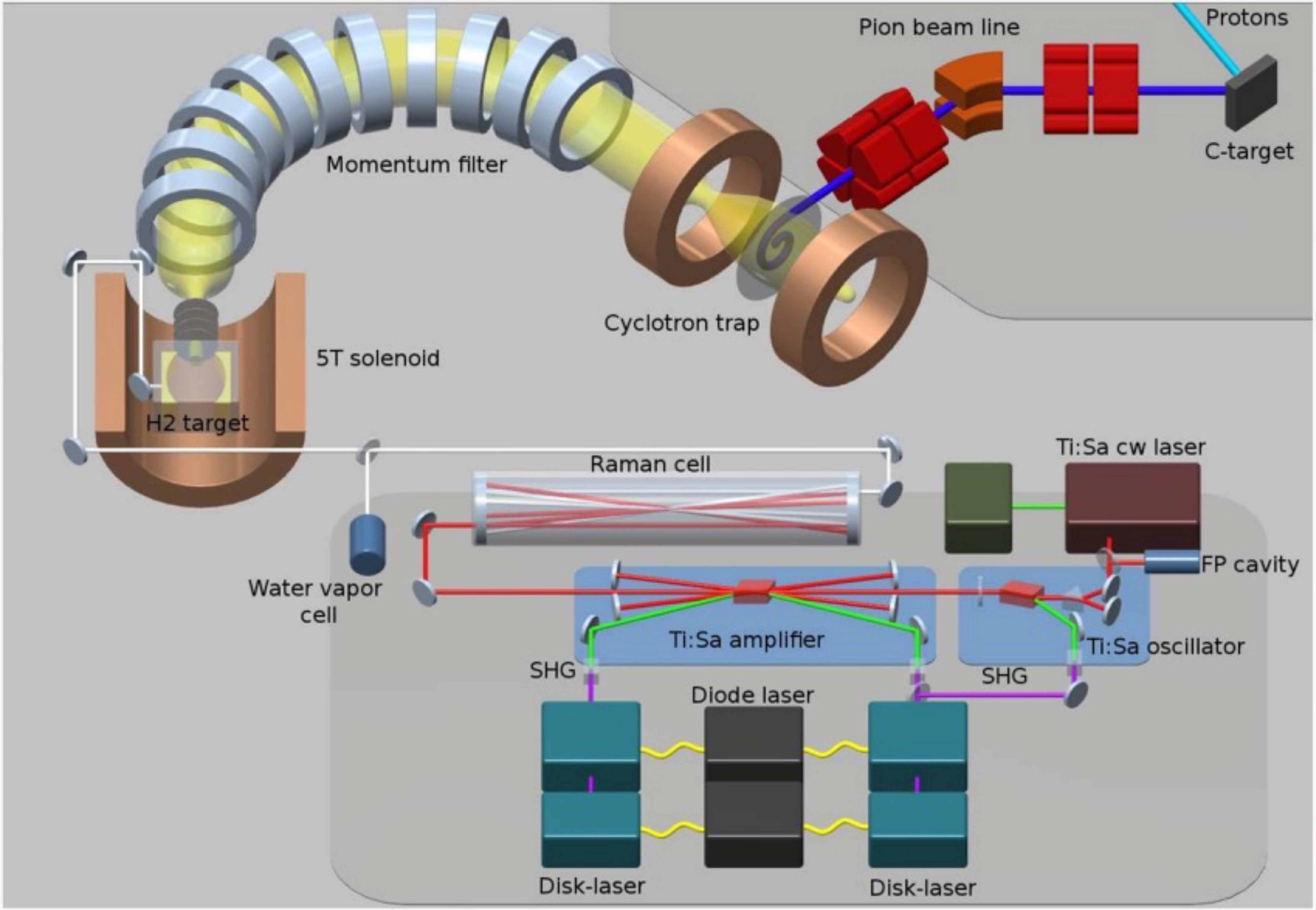


Plot number of X-rays vs laser frequency



The setup at the Paul Scherrer Institute

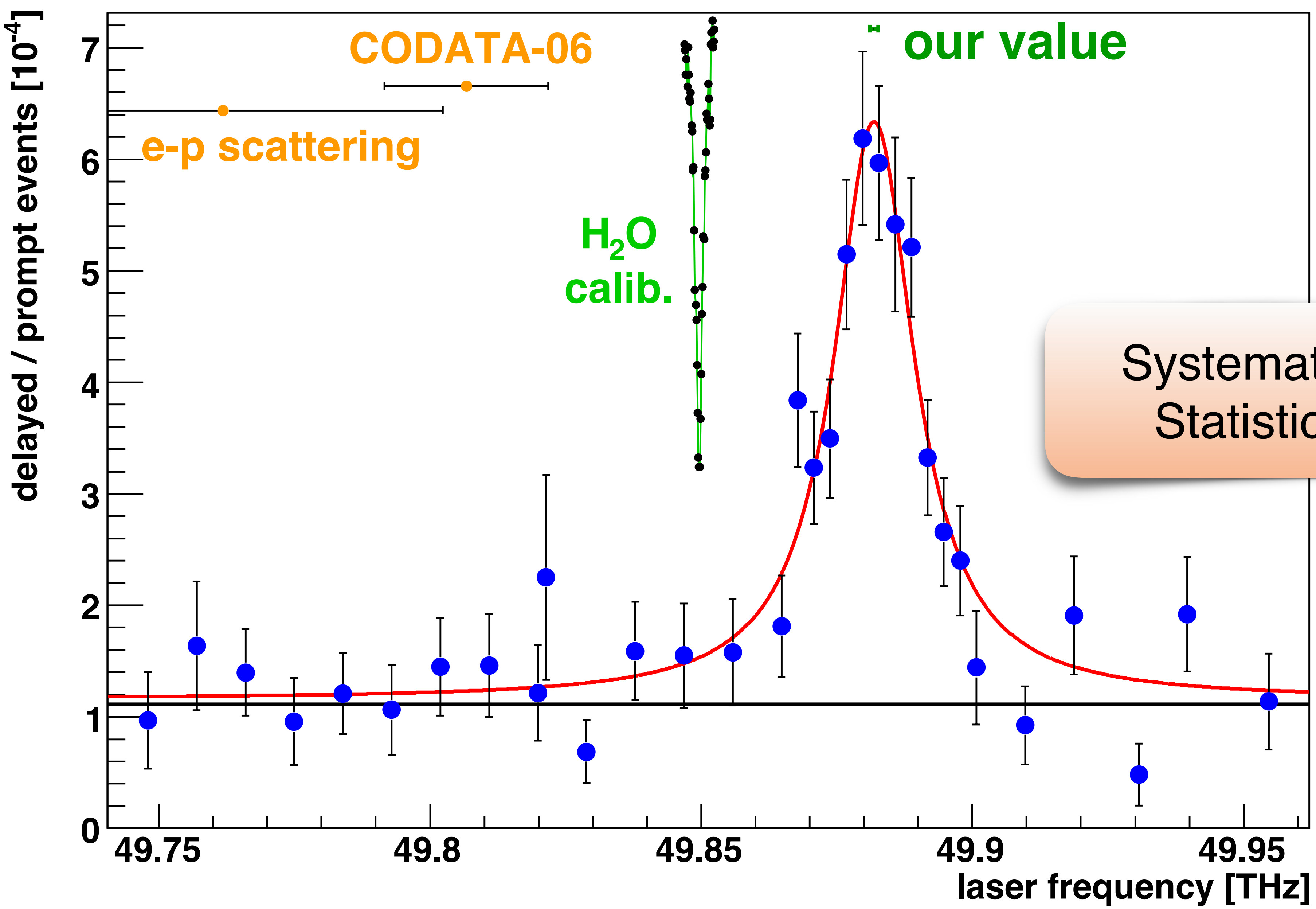
p-beam
(1 MW)
↓
π (MeV)
↓
μ (MeV)
↓
μ (keV)
↓
μp(2S)
↓
Laser
↓
X-ray



940 nm
(2 kW)
↓
1030 nm
↓
515 nm
↓
708 nm
↓
1.0 μm
↓
1.6 μm
↓
6.0 μm

The first μp resonance (2010)

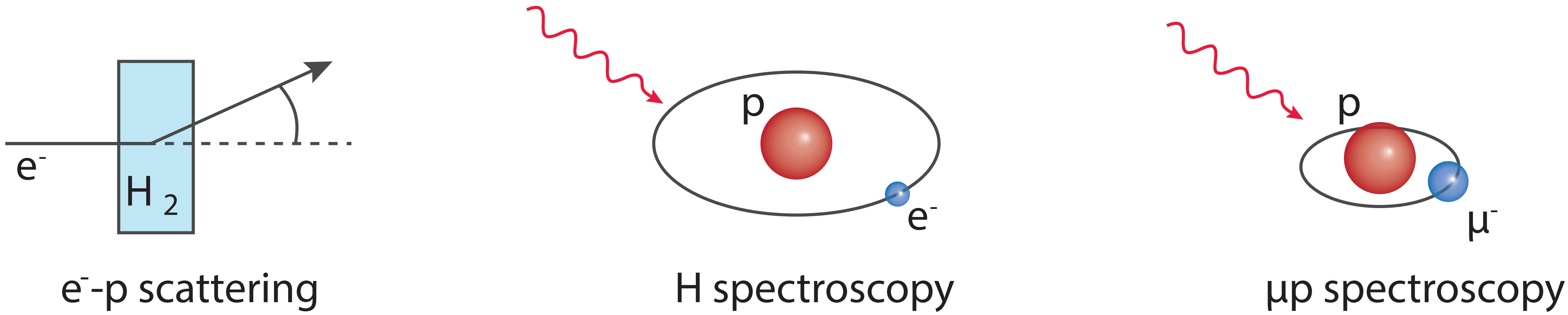
Discrepancy:
$$5.0\,\sigma \;\leftrightarrow\; 75\text{ GHz} \;\leftrightarrow\; \delta\nu/\nu = 1.5\times10^{-3}$$

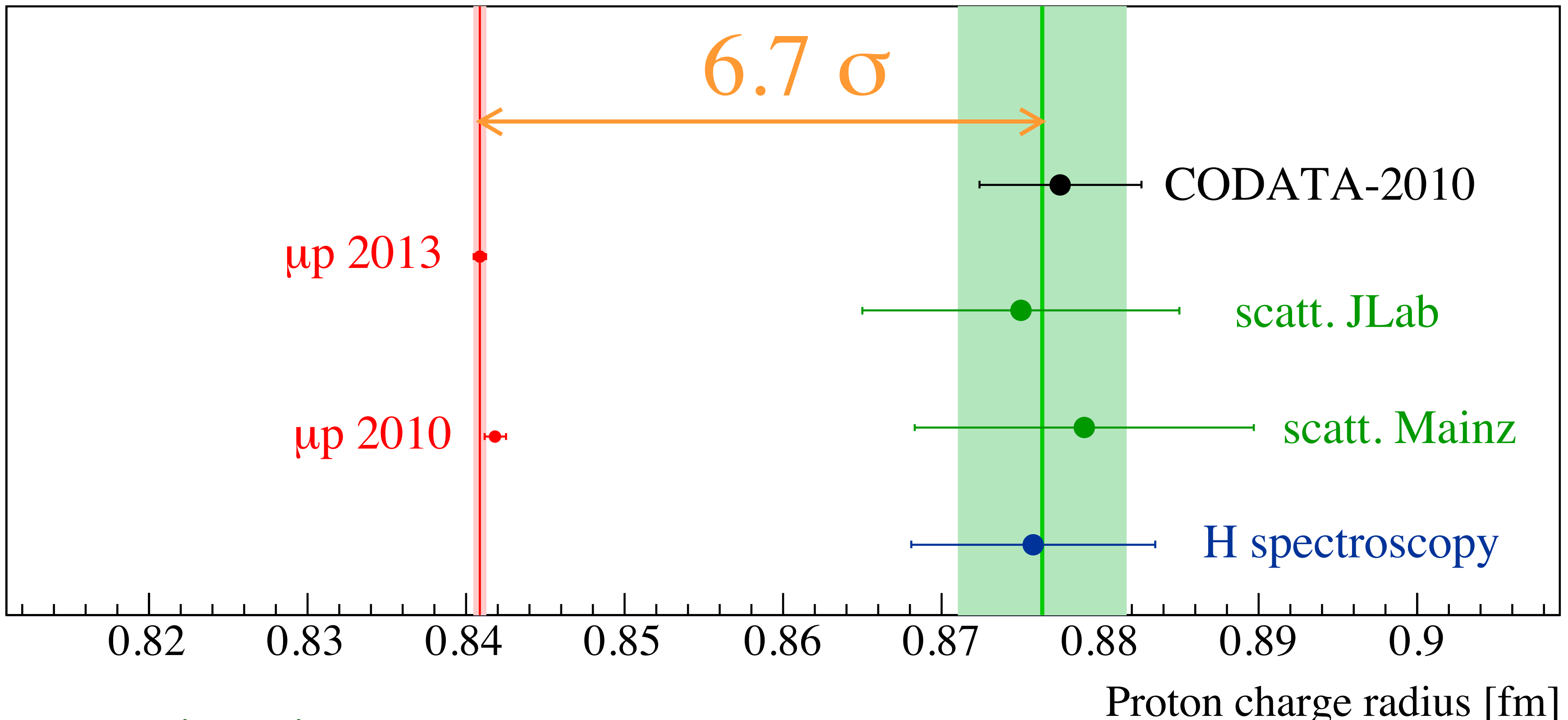


Systematics: 300 MHz
Statistics: 700 MHz

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

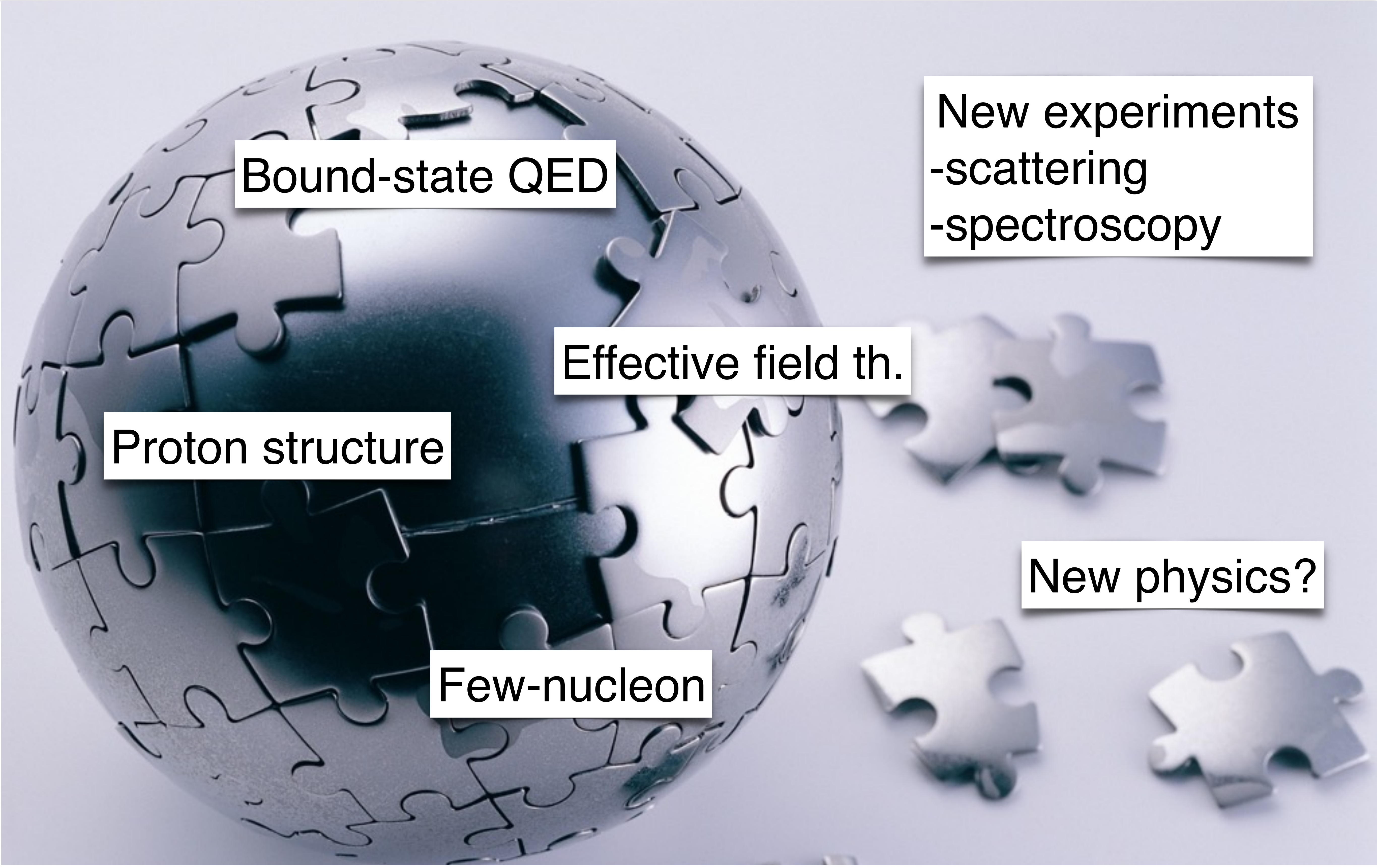
Three ways to the proton radius





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

The r_p puzzle has triggered many activities



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

$$\sim m^3 R_p^2$$ ✓

- **insensitive** to systematical effects

$$\sim 1/m$$ ✓

The proton radius puzzle

- µp experiment
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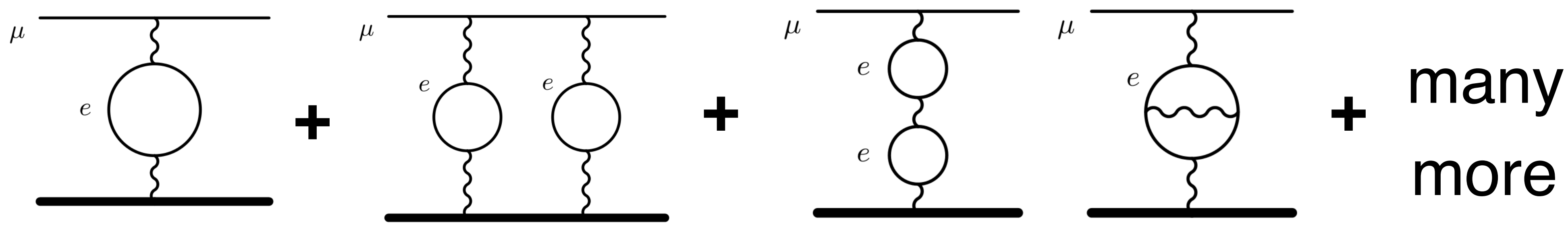
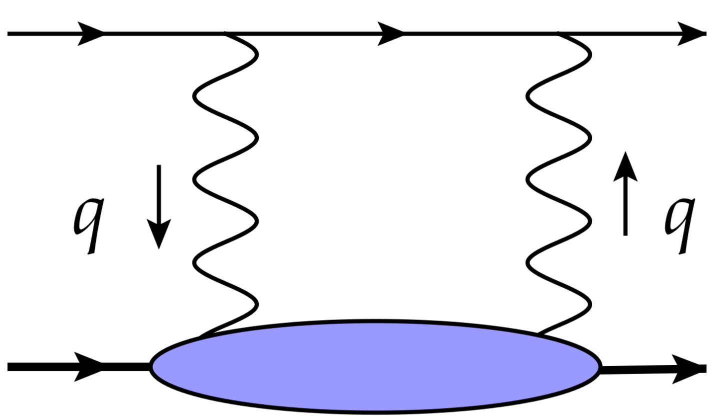
QED ✓✓✓✓

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



Two-photon exchange ✓✓✓✓ ✗



Can be computed with dispersion th. + data

But subtraction term is needed
⇒ modelling of proton

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

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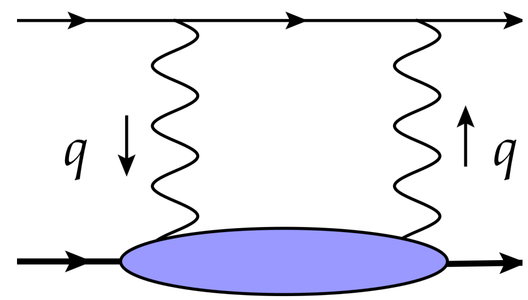
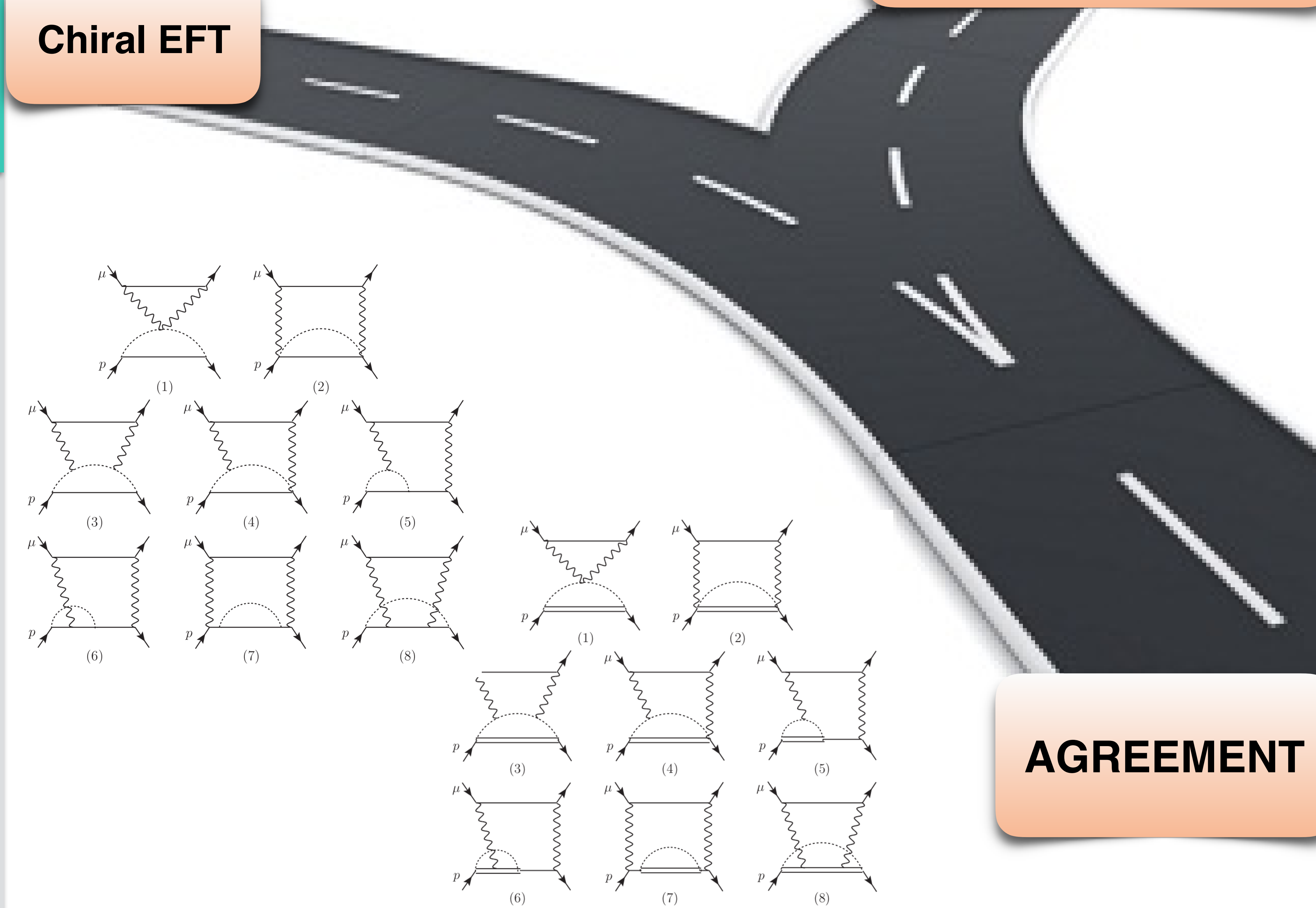


Phenomenological
- dispersion relations
- data
- subtraction term

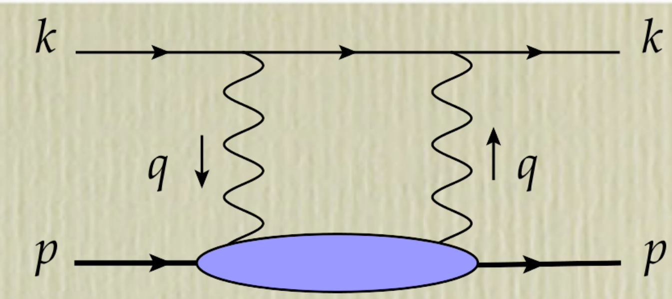
Chiral EFT



AGREEMENT

Technicalities on TPE in μp

Kinematics: 2 loop variables
q^2 and $\nu=(pq)/M$



+ crossed

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

Forward virtual Compton amplitude

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

Lamb shift (nS-nP)

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

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

The proton radius puzzle

- µp experiment
- **µp theory**
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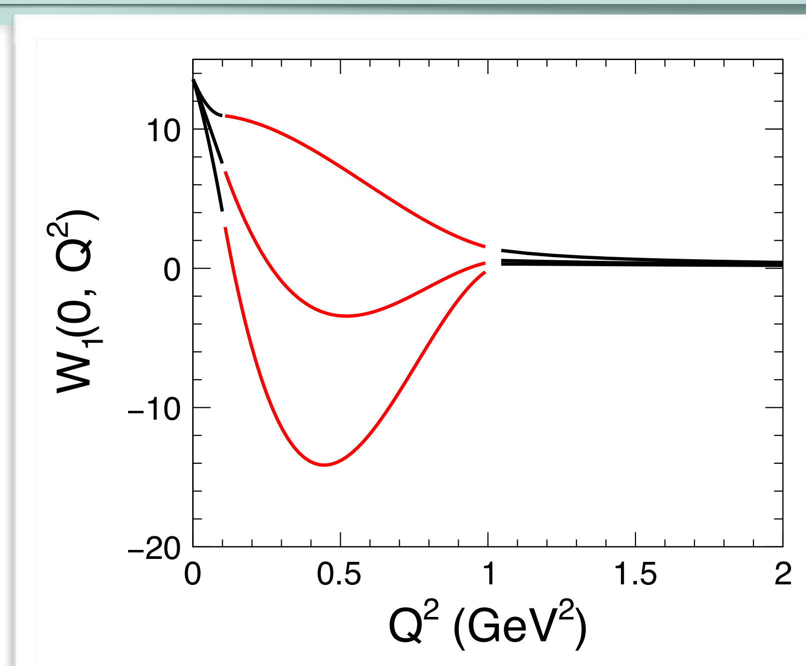
Uncertainties and discrepancy

0.3	meV	Discrepancy
0.01	meV:	TPE uncertainty (conservatively, Hill and Paz)
0.0025	meV:	Polarisability-contr. uncertainty (Pascalusa)
0.0020	meV:	TPE uncertainty (McGovern, our choice)
0.0015	meV:	QED uncertainties
0.0023	meV:	Measurement uncertainty



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

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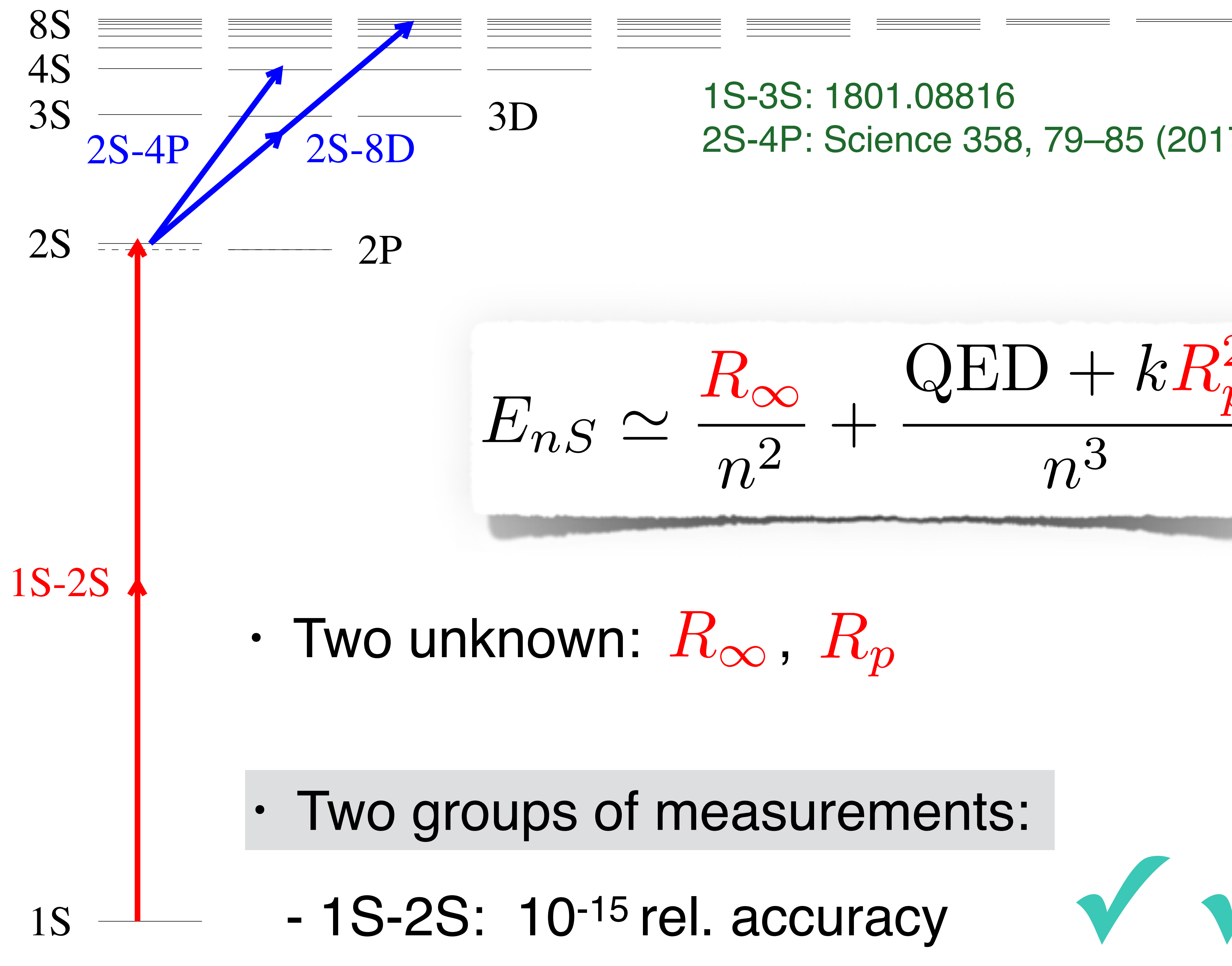

1S-3S: 1801.08816
2S-4P: Science 358, 79–85 (2017)

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

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

The proton radius puzzle

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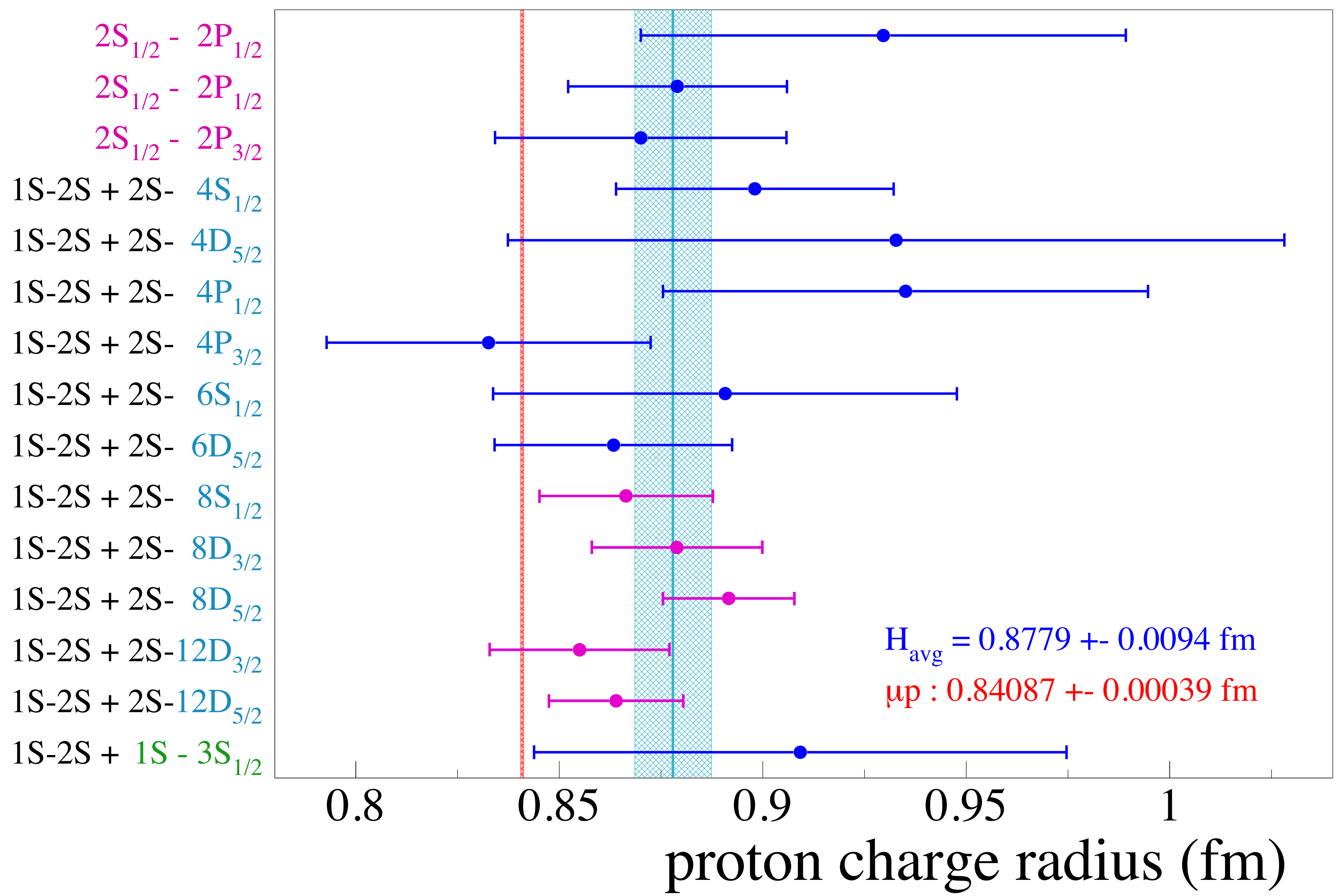

4σ only when averaging

The proton radius puzzle

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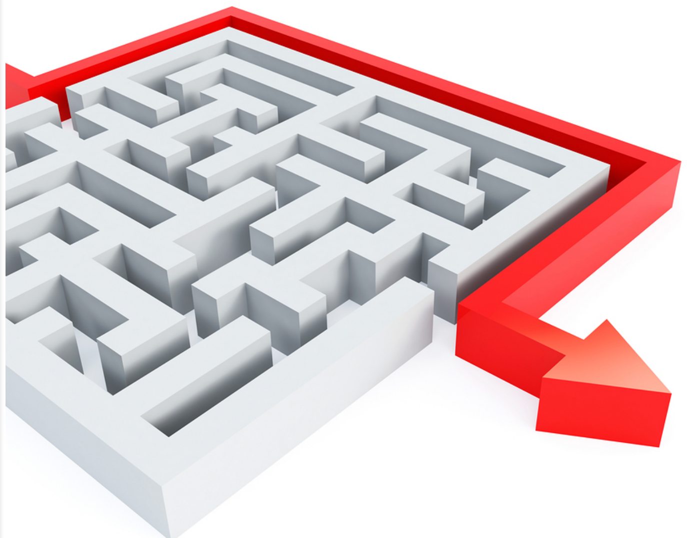

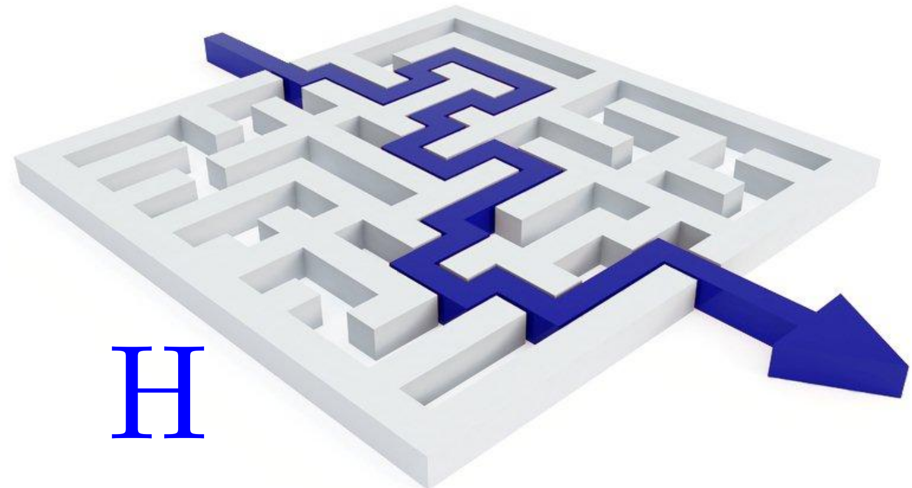

Large sensitivity to r_p
⇨ requires low-precision meas.
Large **in**sensitivity to systematics
But difficult to see the signal

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
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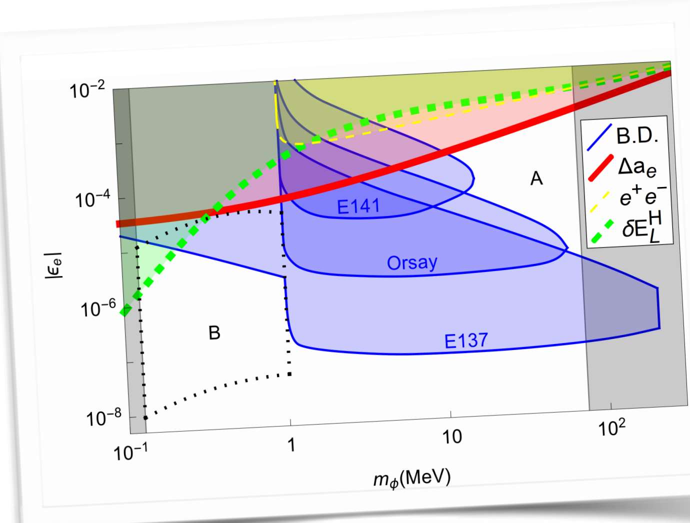
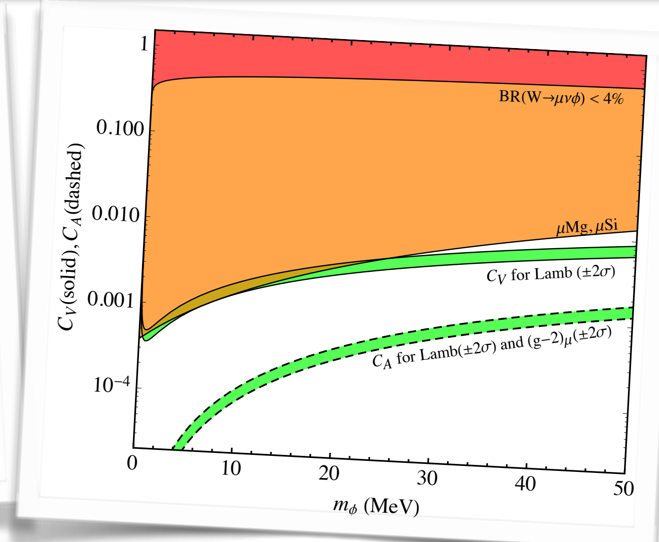
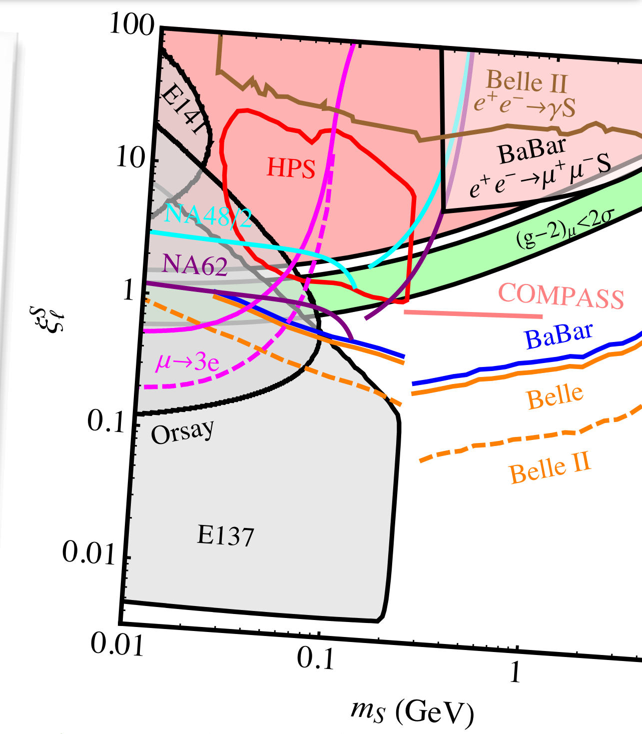


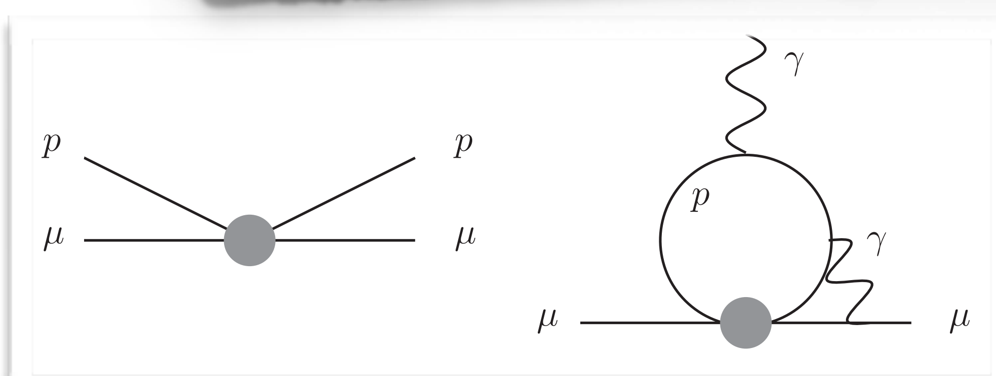




Some open regions for MeV force carrier still resist

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

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



✓✓✓

✗ ✗ ✗ ✗ ✗

The proton radius puzzle

- µp experiment
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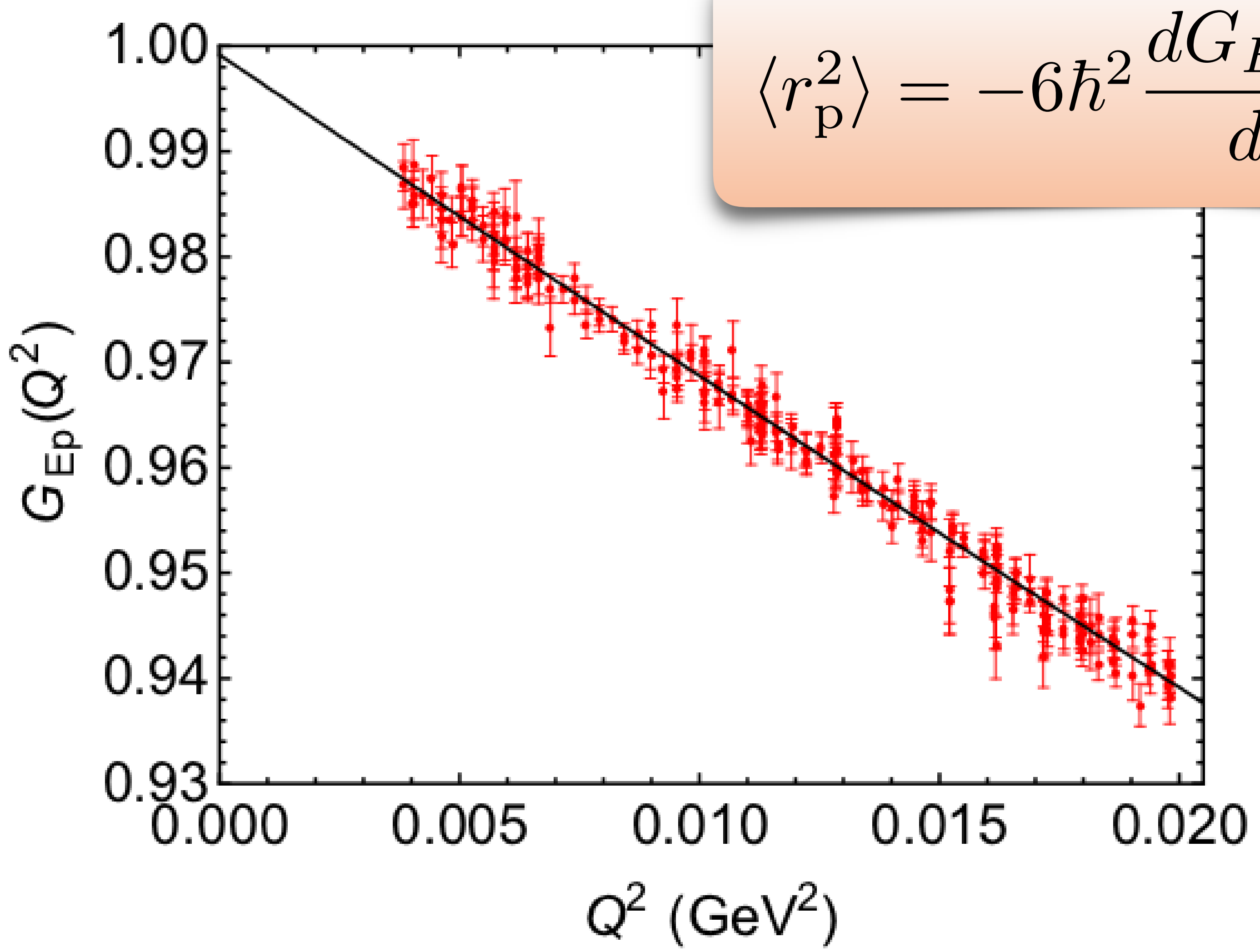
$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{Ros.}} = \left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}} \frac{1}{(1+\tau)}\left(\varepsilon G_E^2(Q^2) + \tau G_M^2(Q^2)\right)$$

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



✓✓✓✓✓ ✗✗✗✗✗

The proton radius puzzle

- μp experiment
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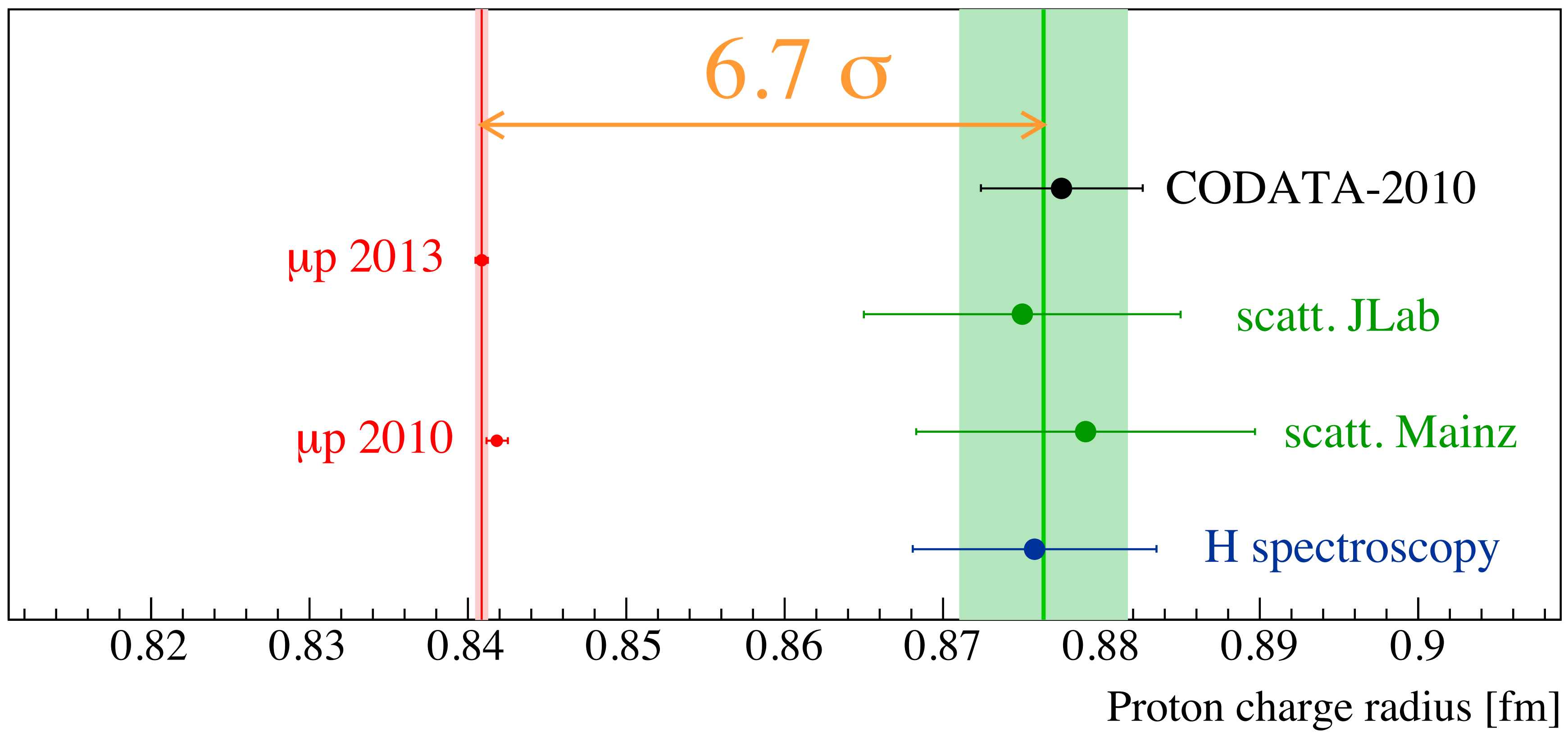
Extrapolation:

- which functionality
- analyticity
- z-expansion vs Q^2-expansion
- coefficients with perturbative scaling
- how many degrees of freedom (under-fitting, over-fitting)
- which Q^2 range
- normalisations
- physics-motivated model (VMD, chPT, dispersion, large tails, higher-moments
- statistical tests, χ^2, regressions, bias
- TPE corrections

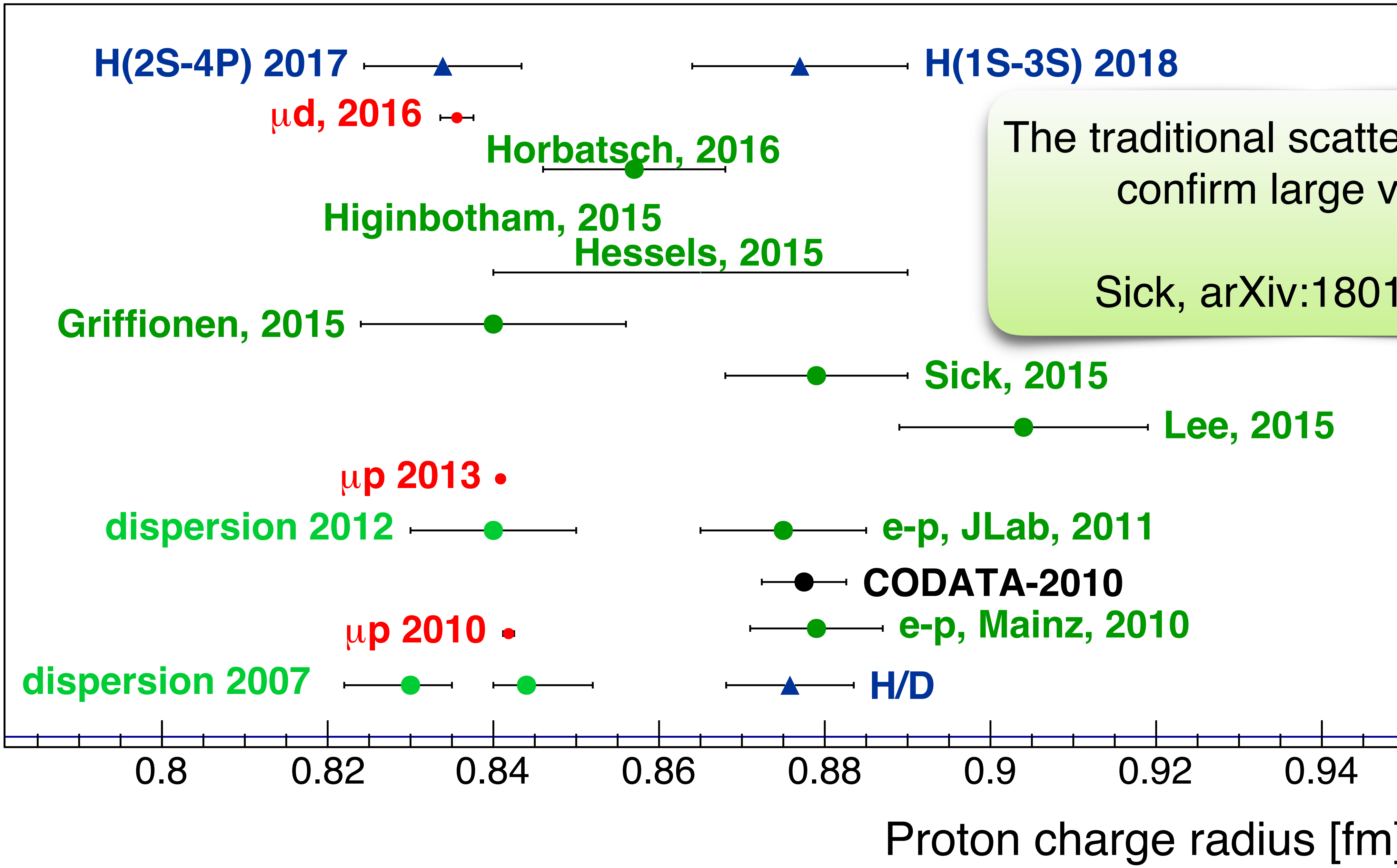
The proton charge radii



The proton charge radii

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

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

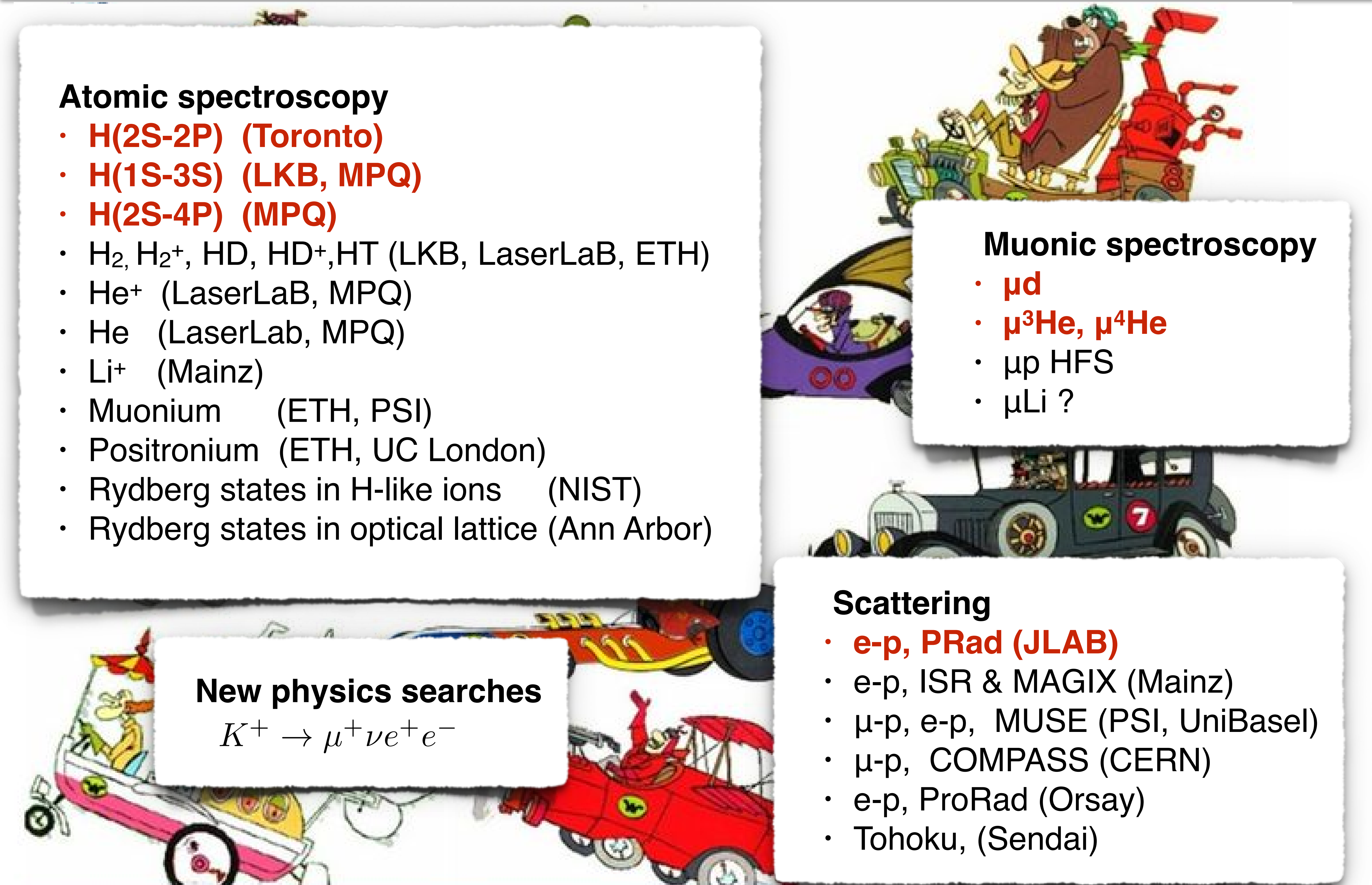


The traditional scattering experts confirm large values.

Sick, arXiv:1801.01746

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, MPQ)
- 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 ?

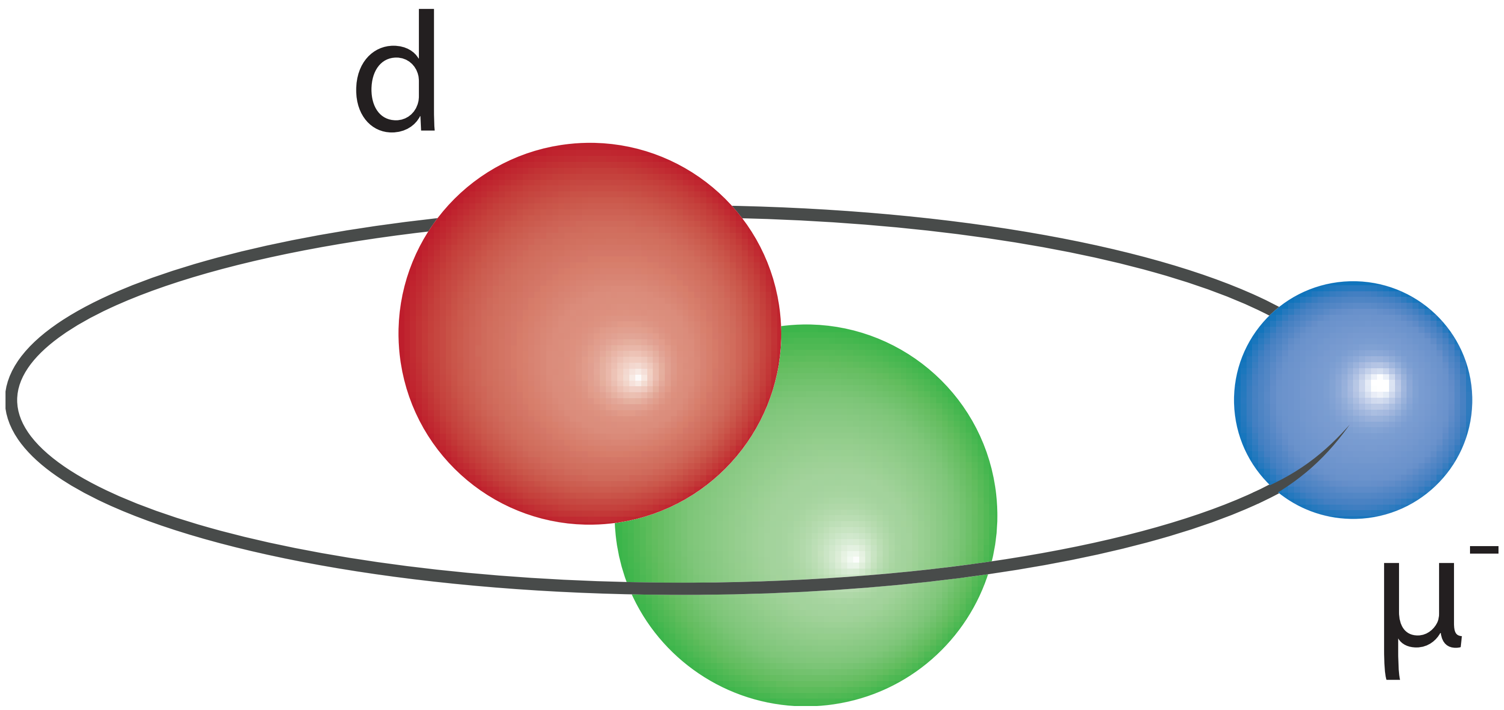
New physics searches

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

Scattering

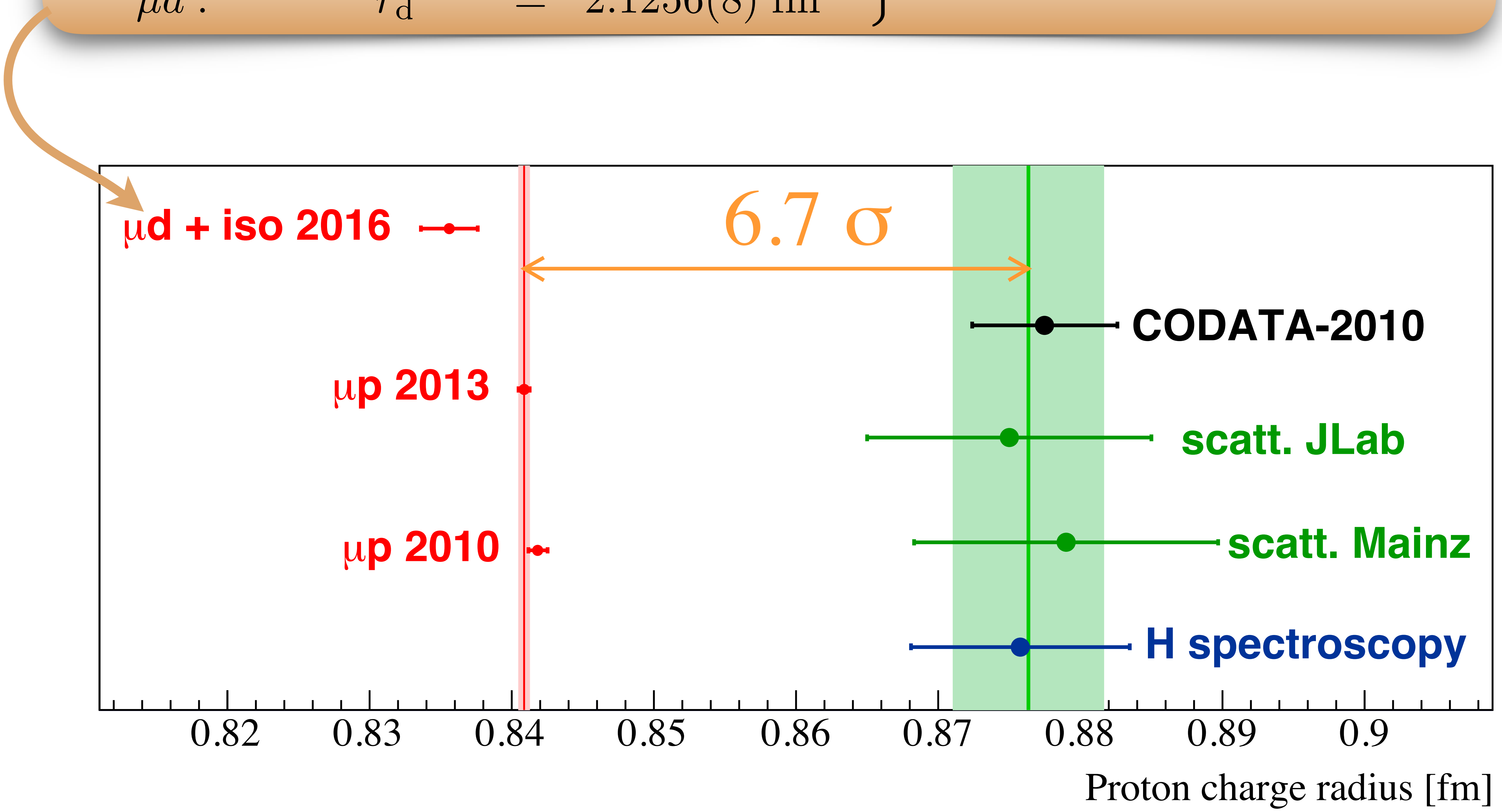
- **e-p, PRad (JLAB)**
- e-p, ISR & MAGIX (Mainz)
- μ-p, e-p, MUSE (PSI, UniBasel)
- μ-p, COMPASS (CERN)
- e-p, ProRad (Orsay)
- Tohoku, (Sendai)


LATEST
NEWS


d
μ⁻

The proton charge radius from muonic deuterium

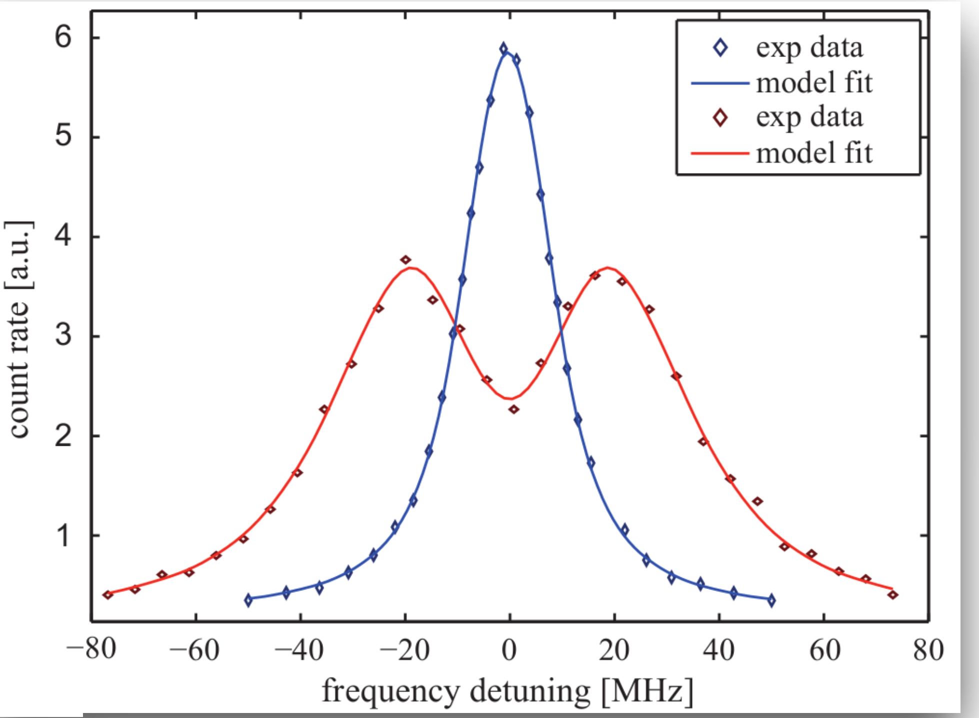
$$\left.\begin{array}{lll} \text{H/D shift:} & r_\mathrm{d}^2 - r_\mathrm{p}^2 & = 3.820\,07(65)\ \mathrm{fm}^2 \\ \mu d: & r_\mathrm{d} & = 2.1256(8)\ \mathrm{fm} \end{array}\right\} \Rightarrow \quad r_\mathrm{p} = 0.8356(20)\ \mathrm{fm}$$



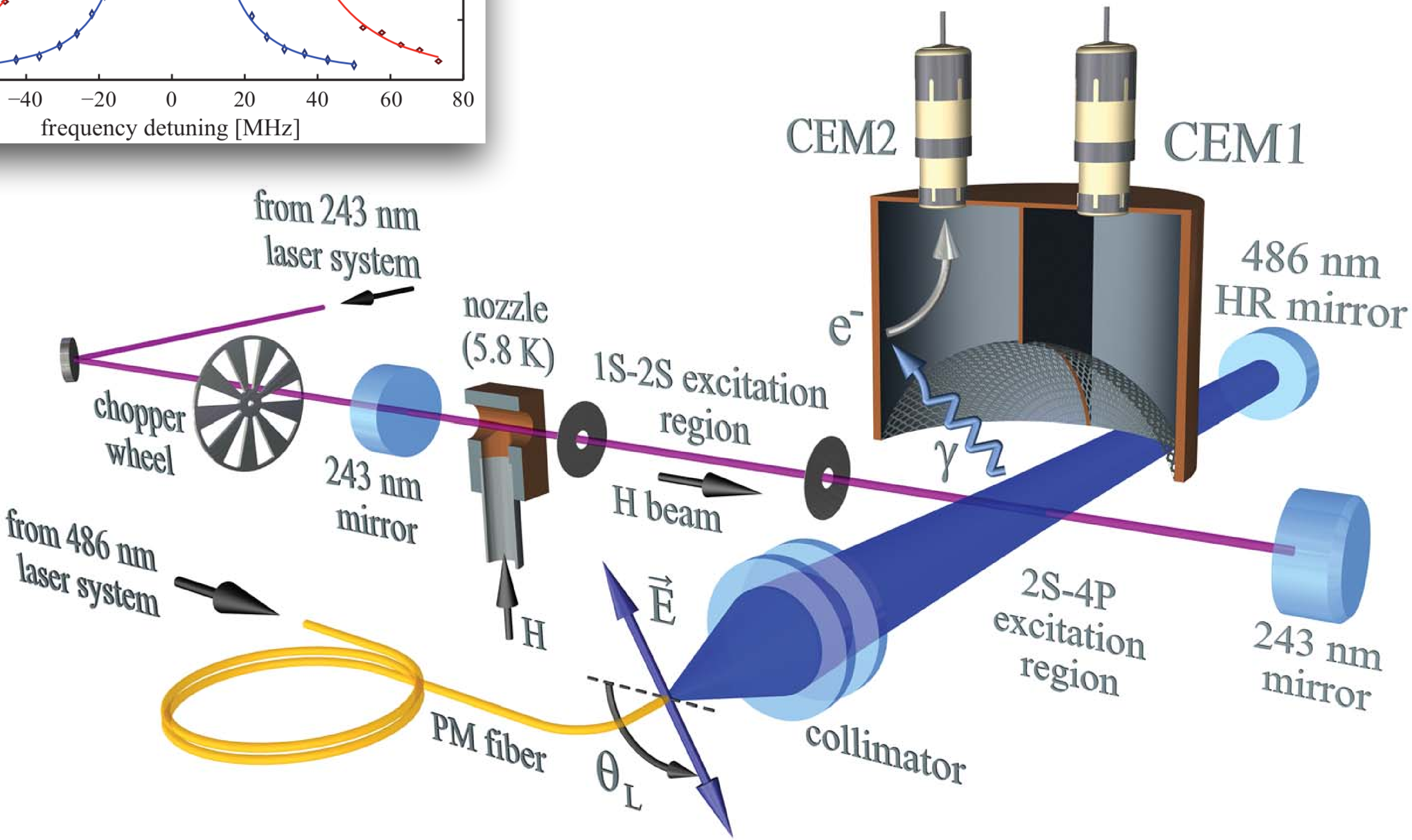
Pohl et al., Nature 466, 213 (2010)
Antognini et al., Science 339, 417 (2013)
Pohl et al., Science 353, 669 (2016)

Small value of the proton radius is confirmed from μd

New 2S-4P measurement in H (MPQ, 2017)



- Produce atomic H beam at cryogenic temperature
- Populate the 2S state using two-photons excitation
- Excite the 2S-4P transition
- Detect the 4P-1S decay (velocity resolved)
- Plot number of 4P-1S decays vs. laser frequency

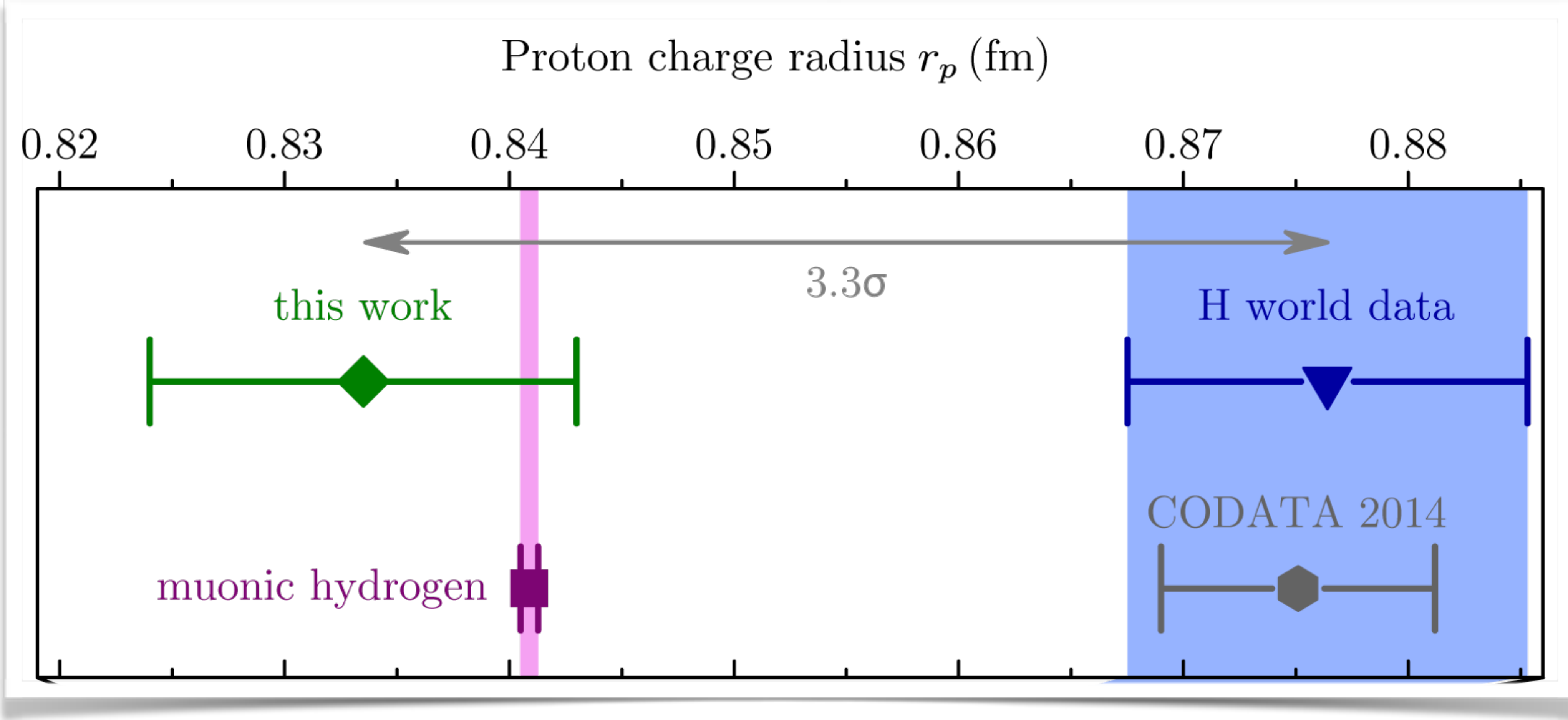


New 2S-4P measurement in H (MPQ, Munich, 2017)

- r_p discrepancy: 9 kHz
- Line width: 20’000 kHz
- Measurement uncertainty: 3.0 kHz

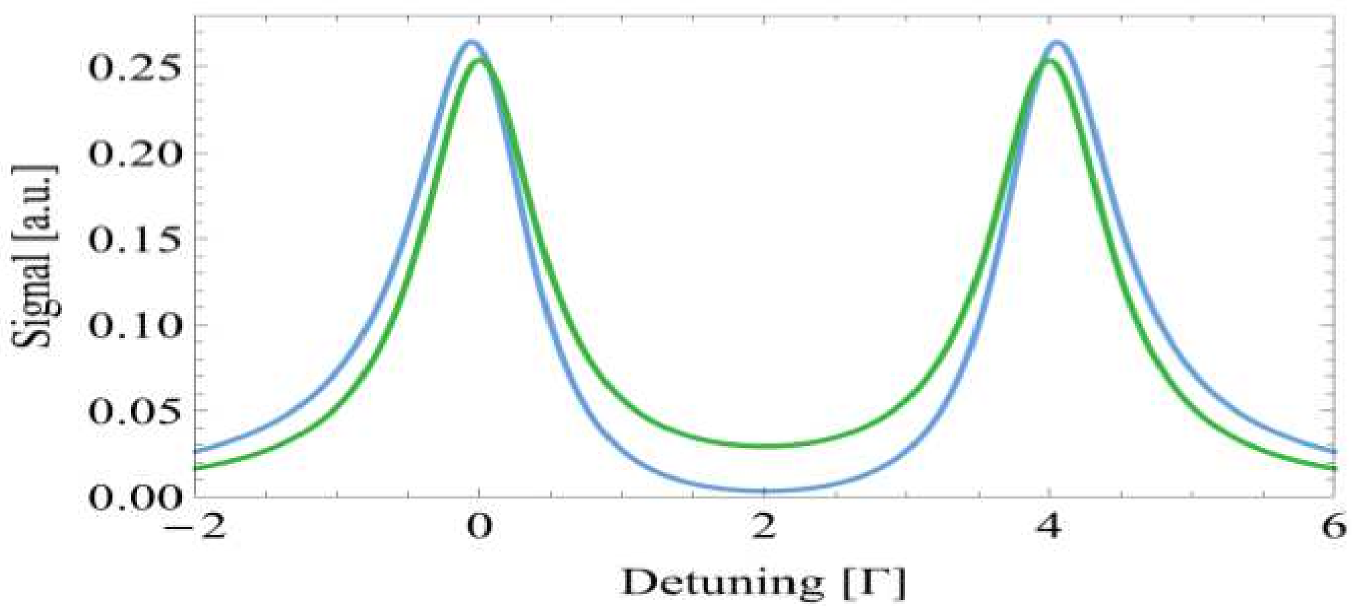
⇨ split an asymmetric line to 10^{-4}

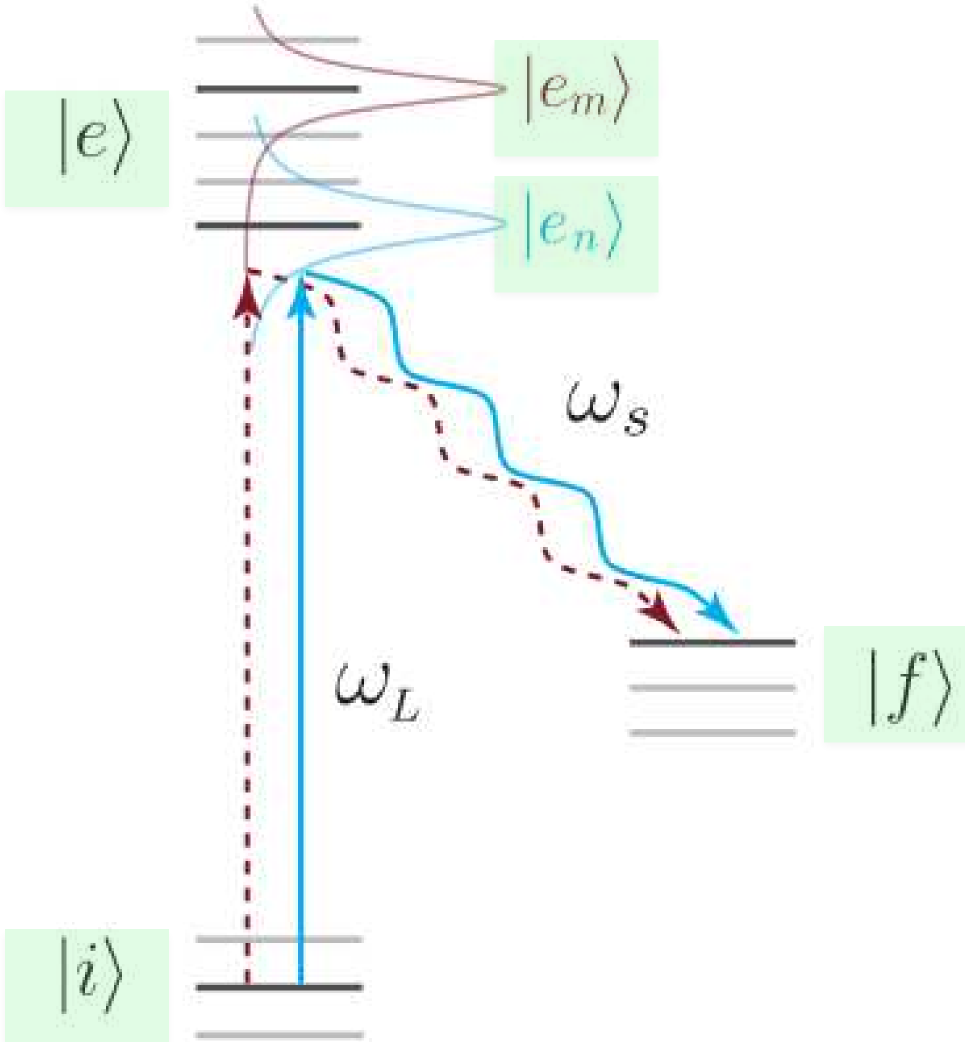
Beyer et al.,
Science 358, 79 (2017)



Quantum interference: an old-new systematics

Sansonetti et al., PRL 107, 023001 (2011)
Brown et al., PRA 87, 032504 (2013)
Horbatsch & Hessels, PRA 82, 052519 (2010); PRA 84, 032508 (2011)
Amaro et al., PRA 92, 022514 (2015); PRA 92, 062506 (2015)

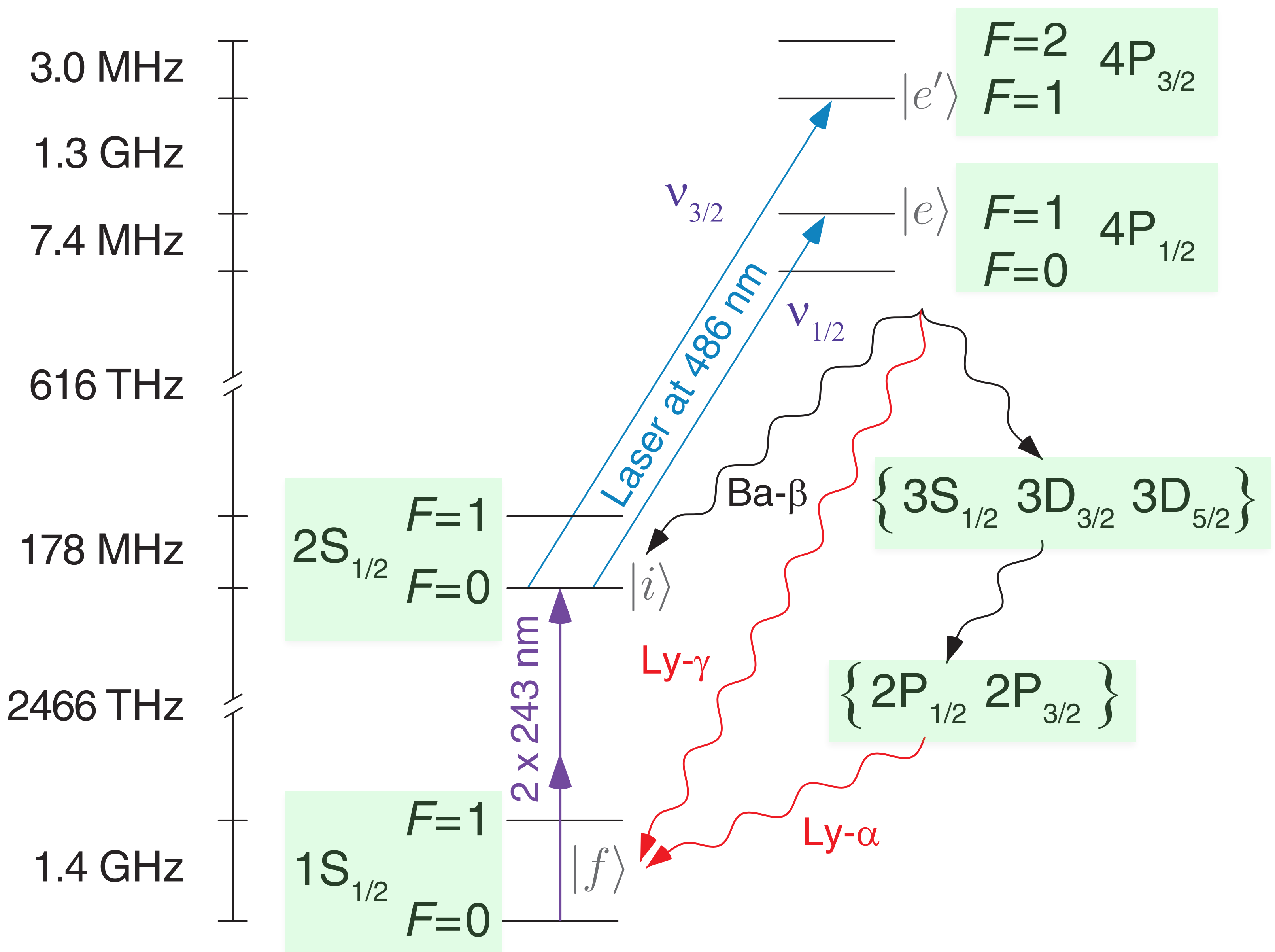




$$I(\omega) \sim \left| \frac{\vec{D}\cdot\vec{d}_1}{\omega - \omega_1 + i\Gamma_1} + \frac{\vec{D}\cdot\vec{d}_2}{\omega - \omega_2 + i\Gamma_2} \right|^2$$

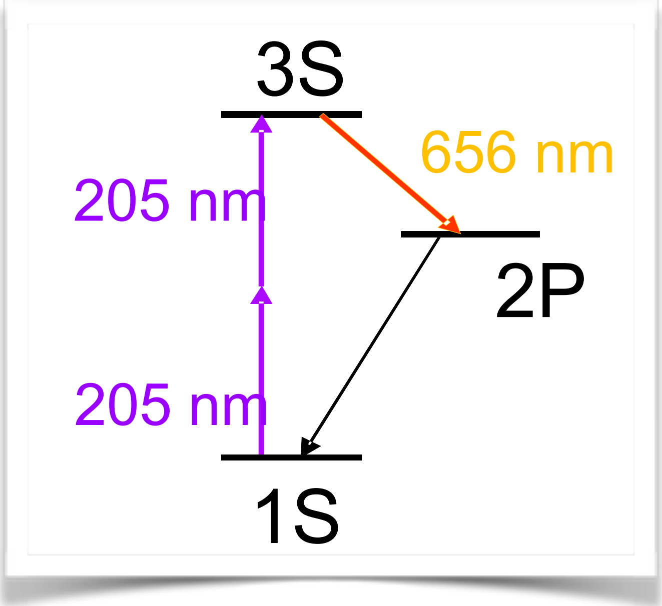
$$= \frac{(\vec{D}\cdot\vec{d}_1)^2}{(\omega-\omega_1)^2 + \Gamma_1^2} + \frac{(\vec{D}\cdot\vec{d}_2)^2}{(\omega-\omega_2)^2 + \Gamma_2^2} + 2\mathrm{Re}\left(\frac{(\vec{D}\cdot\vec{d}_2)(\vec{D}\cdot\vec{d}_2)^*}{(\omega-\omega_1+i\Gamma_1)(\omega-\omega_2-i\Gamma_2)} \right)$$

Quantum interference: an old-new systematics

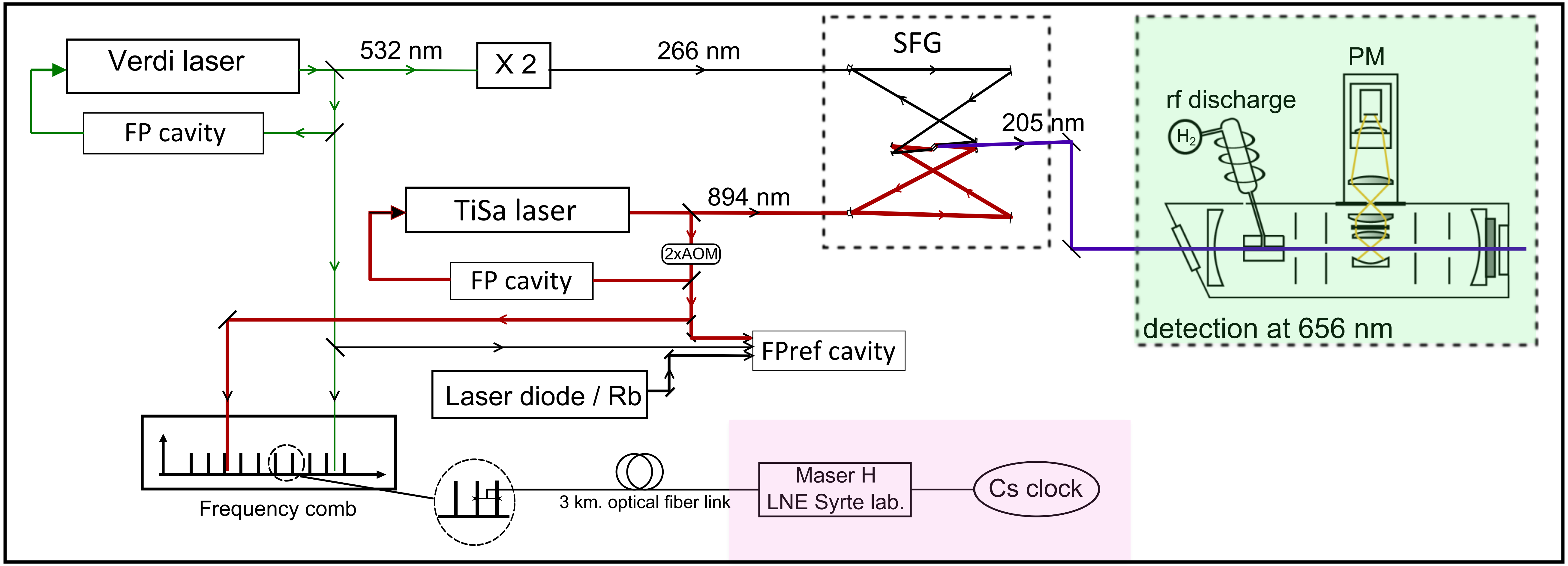


Quantum interference is complex. Its computation requires several thousands of coupled differential equations, depends on geometry, laser polarisation, detection scheme, initial state population, efficiencies etc.

New 1S-3S measurement in H (LKB, Paris)



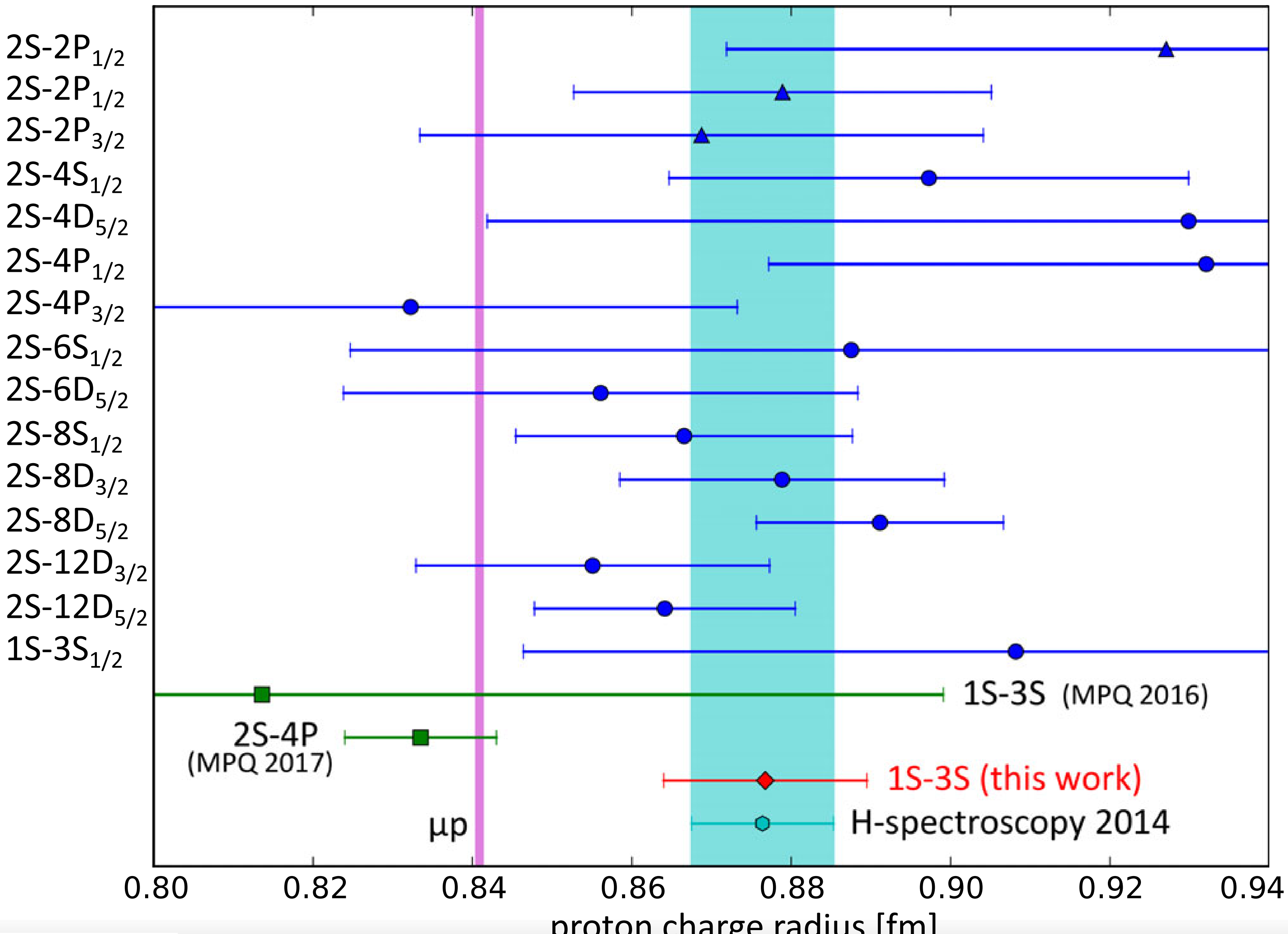
- Produce atomic H beam (room temperature)
- Excite the two-photons 1S-3S transition
- Detect the 3S-2P decay
- Plot number of 3S-2P decay vs laser frequency



New 1S-3S measurement in H (LKB, Paris, 2017)

- Line width: 1500 kHz
- Statistical uncertainty: 2.1 kHz
- Total uncertainty: 2.7 kHz

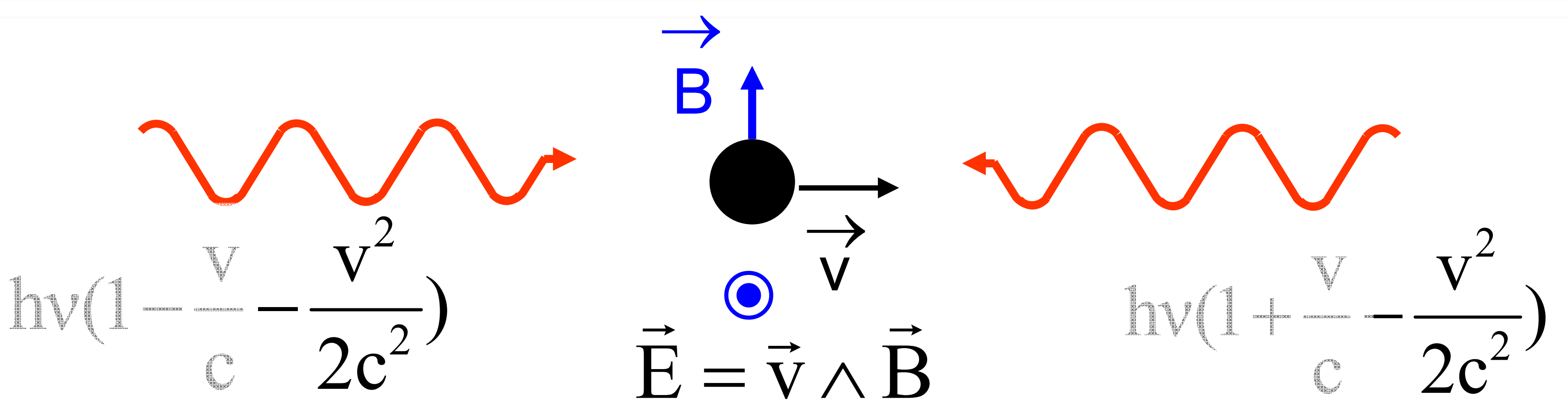
- r_p discrepancy: 9 kHz



Fleurbaey et al.,
PRL120, 183001 (2018)

New 1S-3S measurement in H (LKB, Paris)

Sources of frequency shift:
- second order Doppler effect (120 kHz)
- light shift
- pressure shift

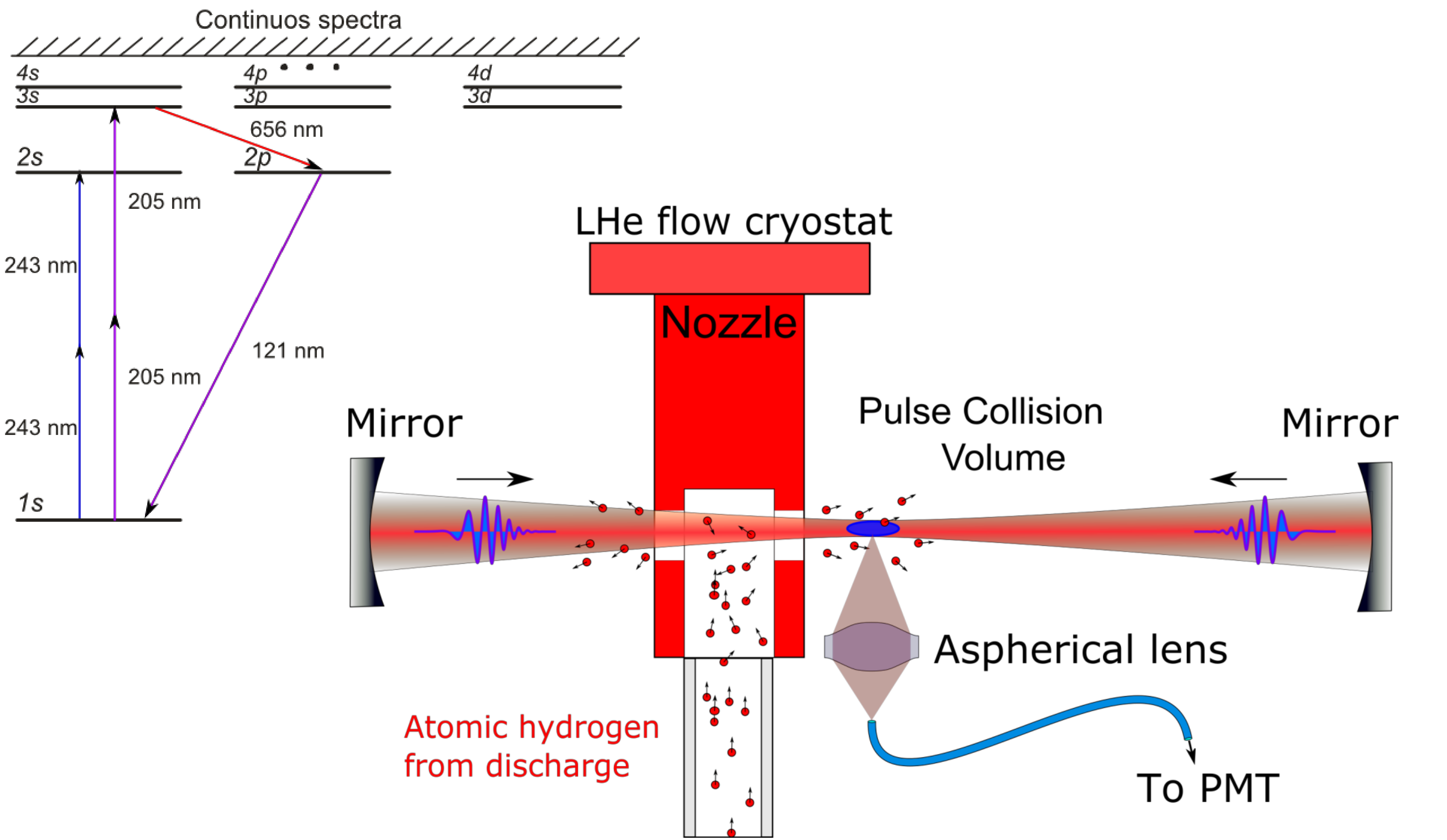


$$\delta_{Stark} = \frac{E^2}{\Delta\nu_{SP}} = \frac{v^2 B^2}{\Delta\nu_{SP}}$$

$$\delta_{dop} = -\nu_{at} \frac{v^2}{2c^2}$$

Biraben, Julien, Plon and Nez, Europhys. Lett. 15, 831 (1991)
Galtier et al., J. Phys. and Chem. Ref. Data **44**, 031201 (2015)

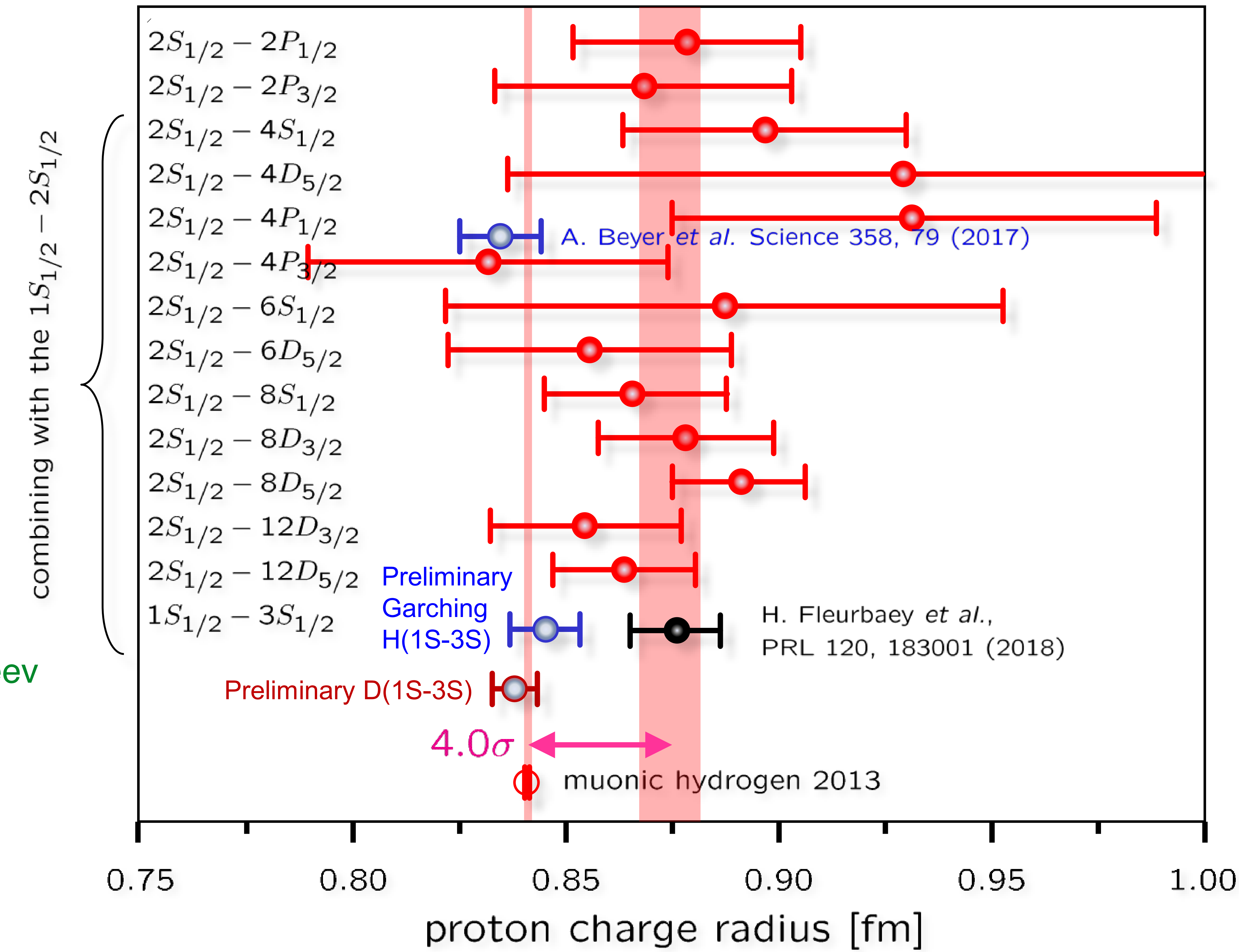
Preliminary 1S-3S measurement in H/D (MPQ, 2018)



A. Matveev

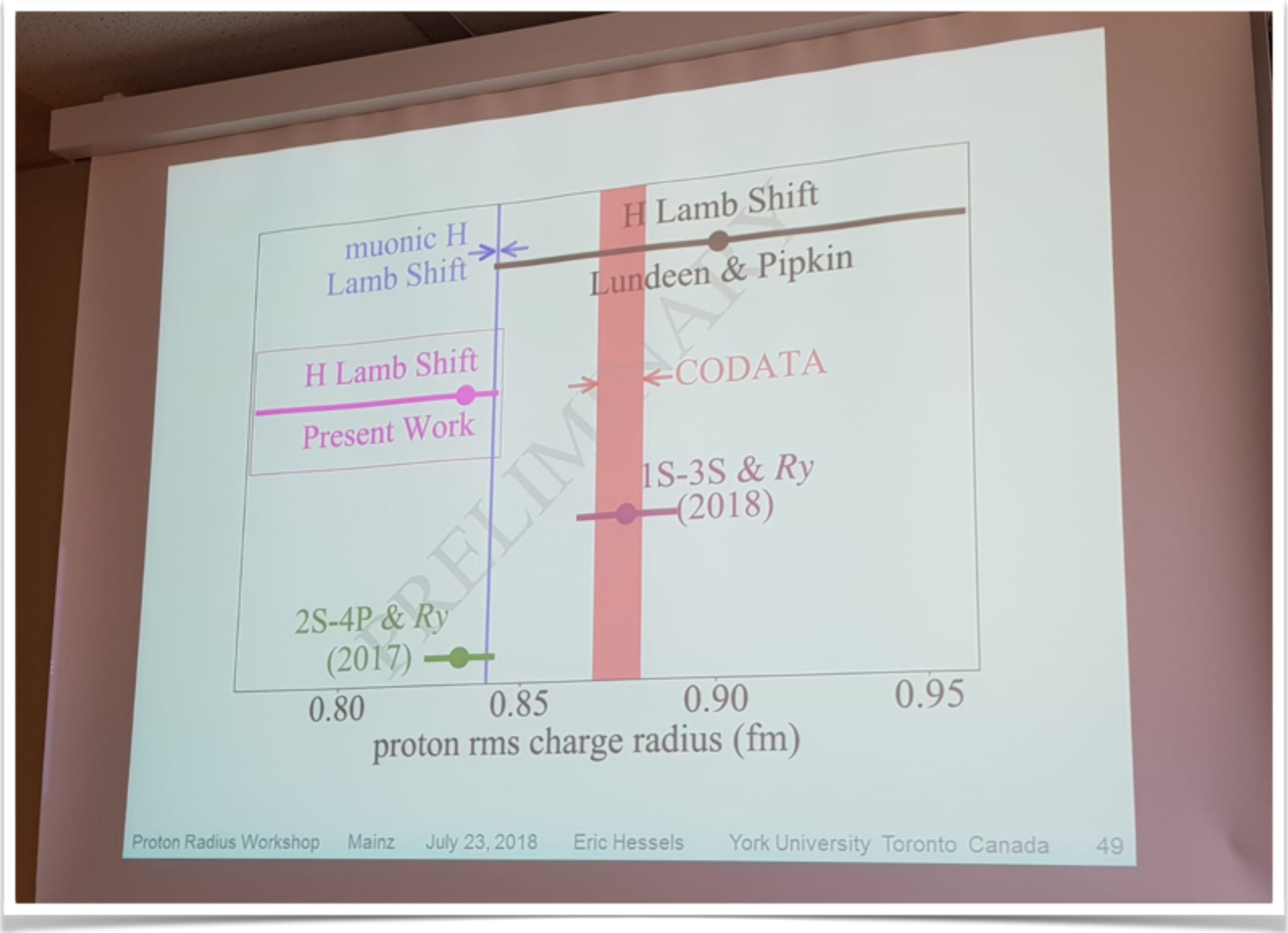
Preliminary 1S-3S measurement in H/D (MPQ, 2018)

A. Matveev



Preliminary 2S-2P measurement in H (Torornto, 2018)

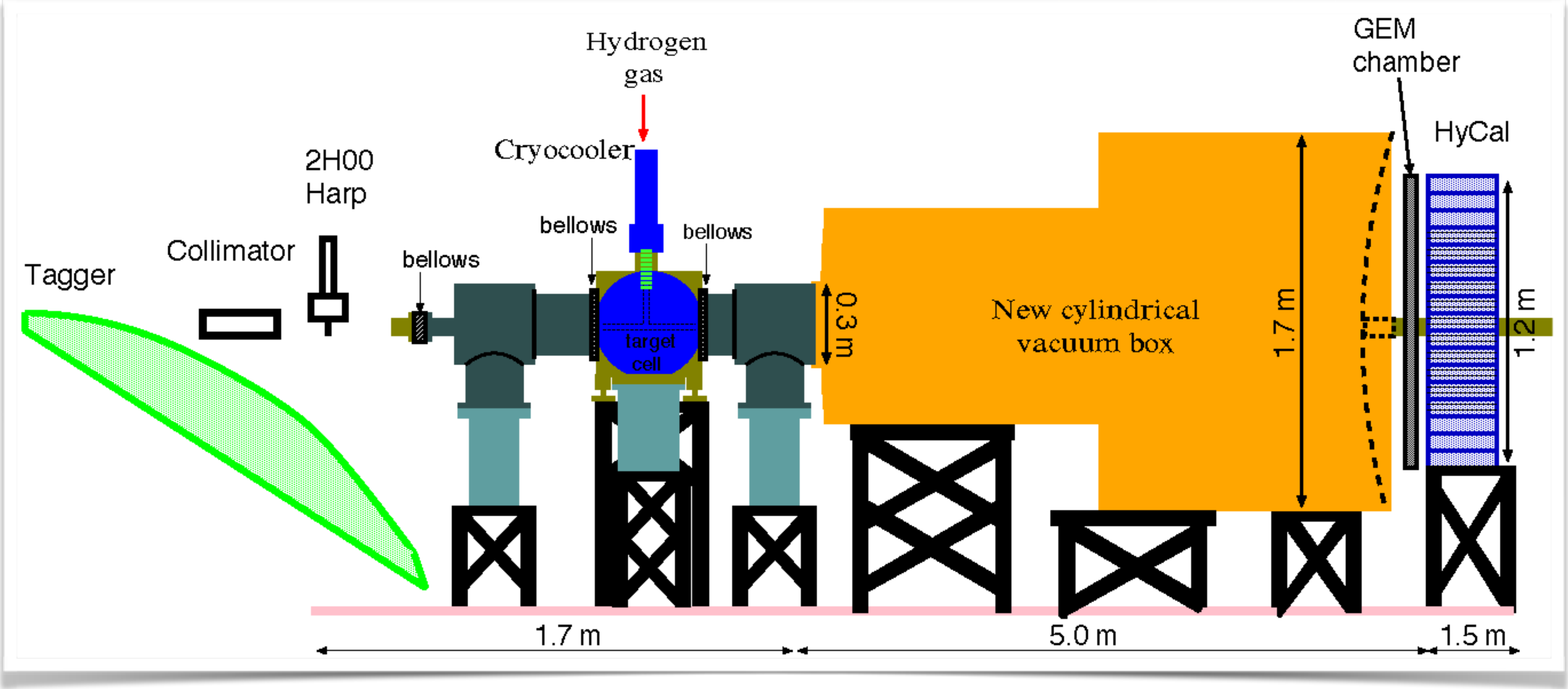
E. Hessels



Preliminary results from new e-p scattering (PRad, 2018)

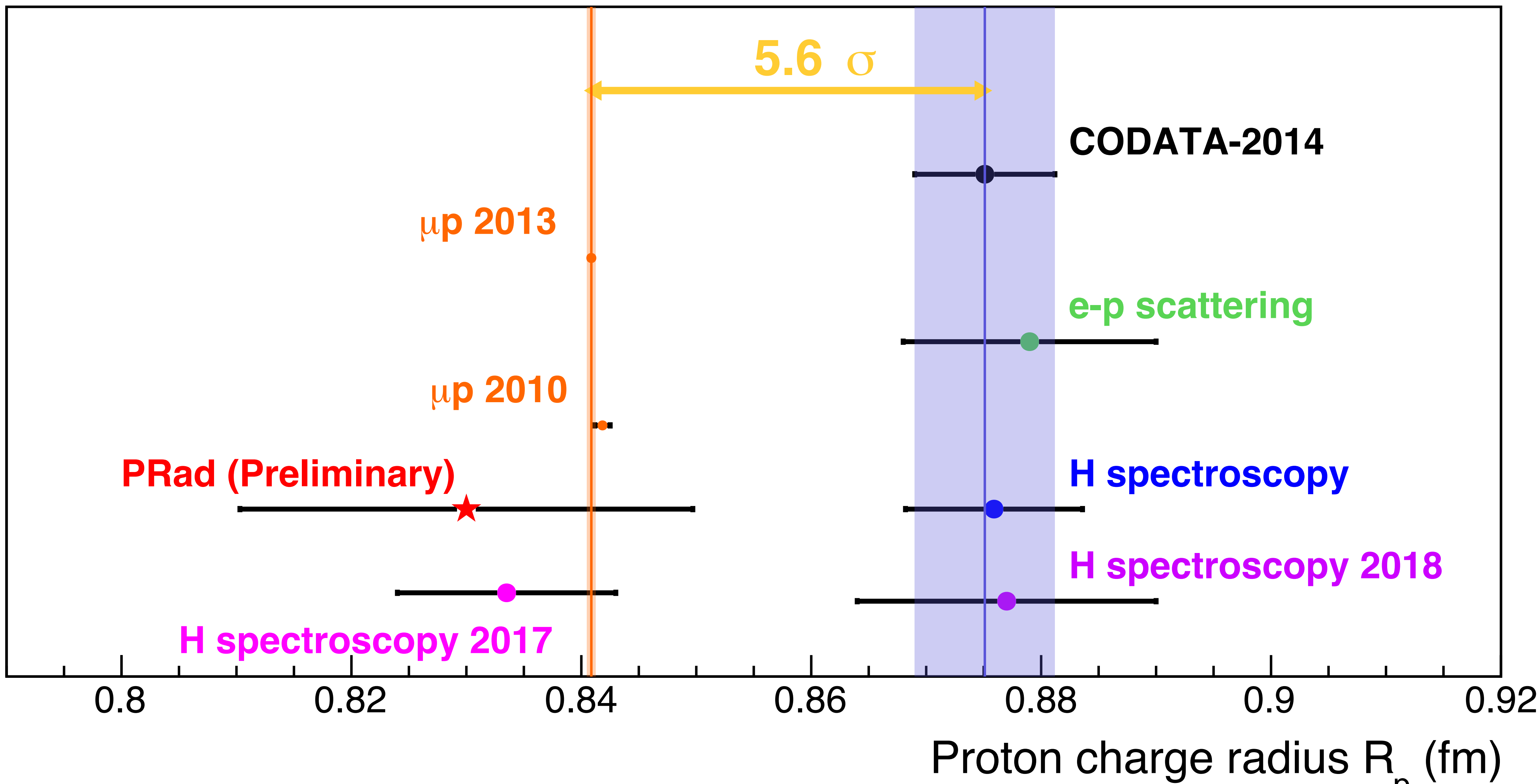
- windowless target
- non-magnetic calorimeter
- large GEM + scintillators
- Minimal angle
- Q^2_{min} reduced by 20 to 2×10^{-4} GeV^2
- Normalise with Møller scatt.

$$\left(\frac{d\sigma}{d\Omega}\right)_{ep} = \frac{N_{exp}(ep \to ep \; in \; \theta_i \pm \Delta\theta)}{N_{exp}(ee \to ee)} \cdot \frac{\epsilon^{ee}_{geom}}{\epsilon^{ep}_{geom}} \cdot \frac{\epsilon^{ee}_{det}}{\epsilon^{ep}_{det}} \cdot \left(\frac{d\sigma}{d\Omega}\right)_{ee}$$

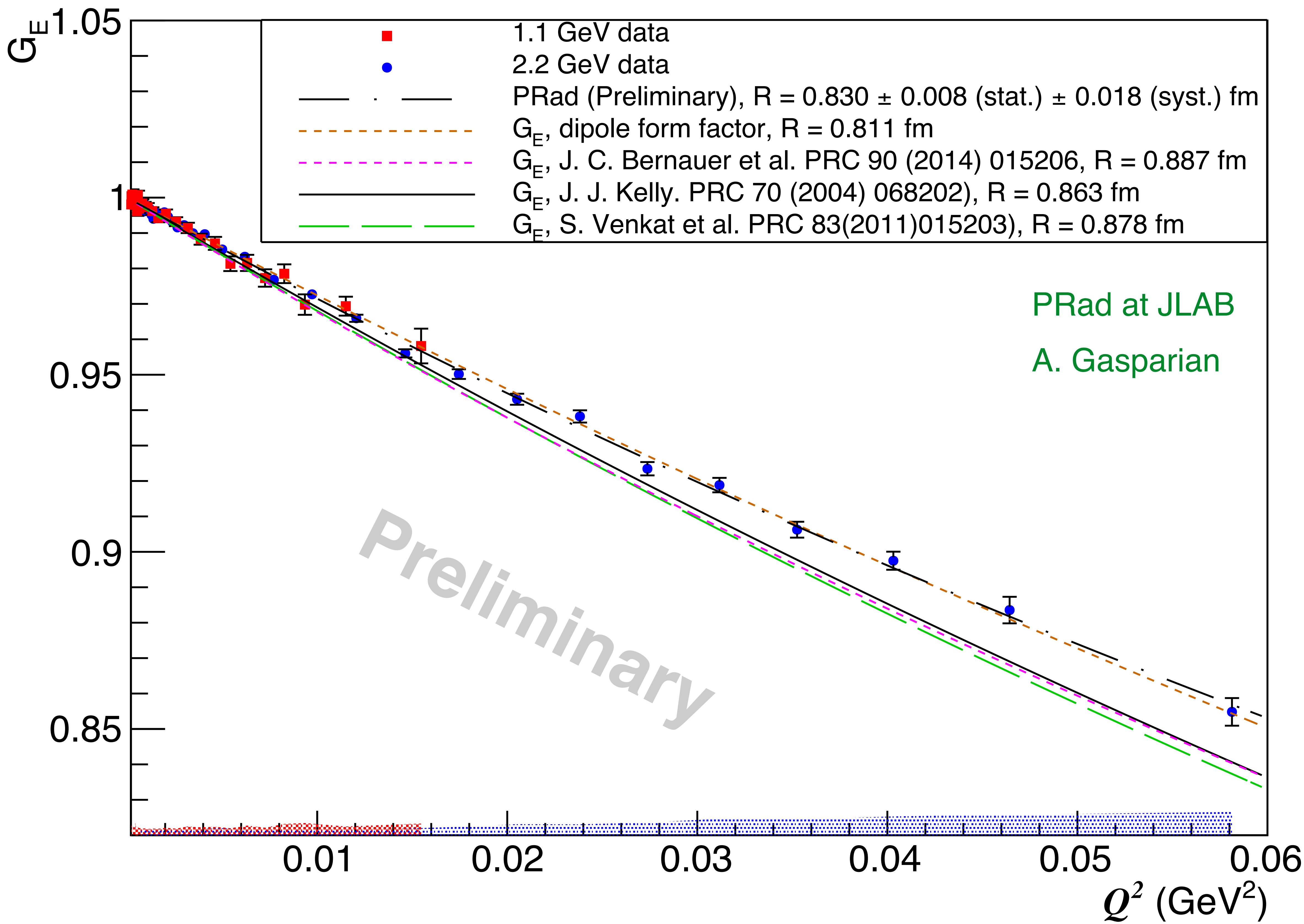


Preliminary results from e-p scattering (JLAB, 2018)

A. Gasparian



Preliminary results from e-p scattering (JLAB, 2018)

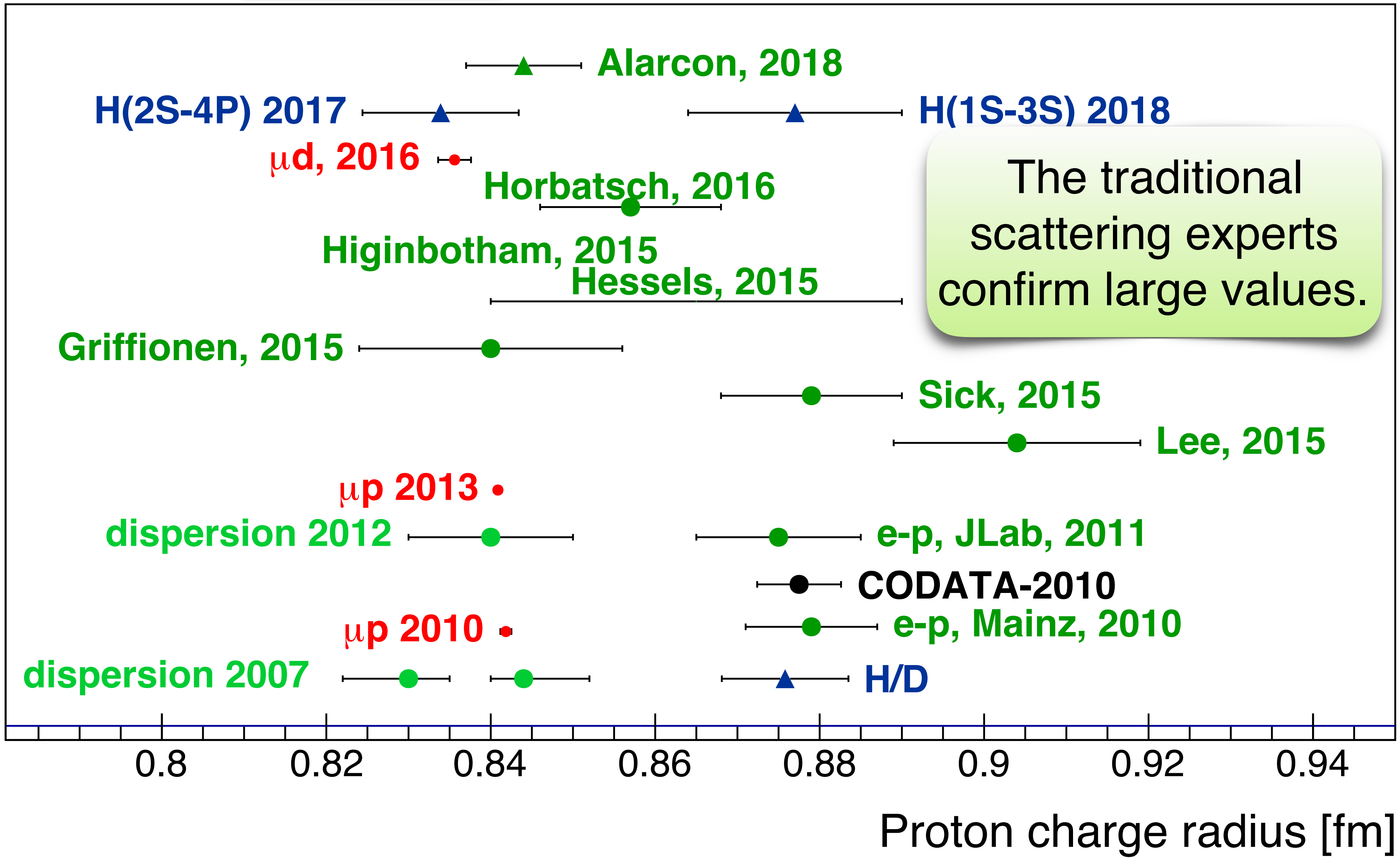


Present status

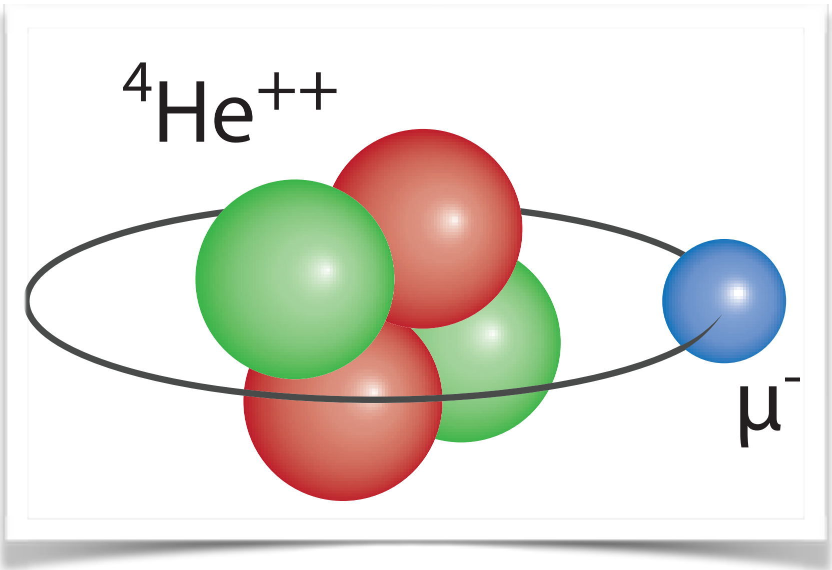
e-p scattering
PRad 2018

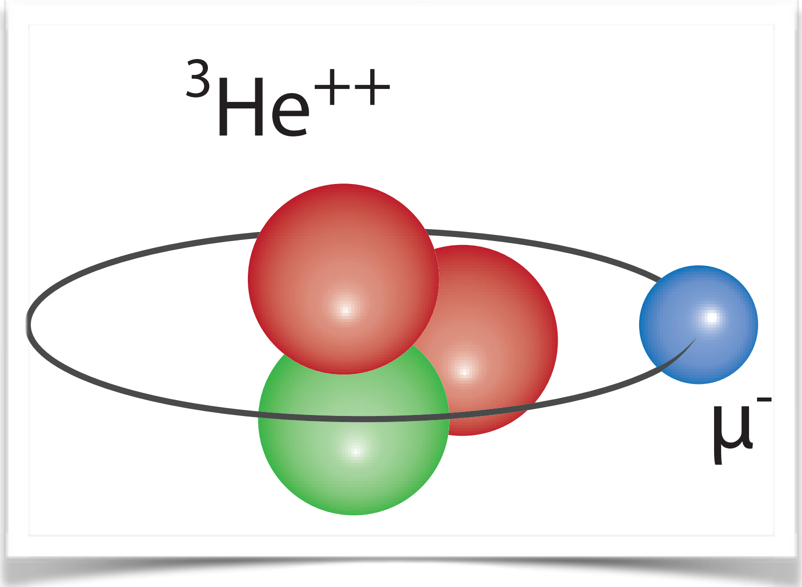
H/D (1S-3S)
MPQ 2018

H(2S-2P)
Toronto 2018

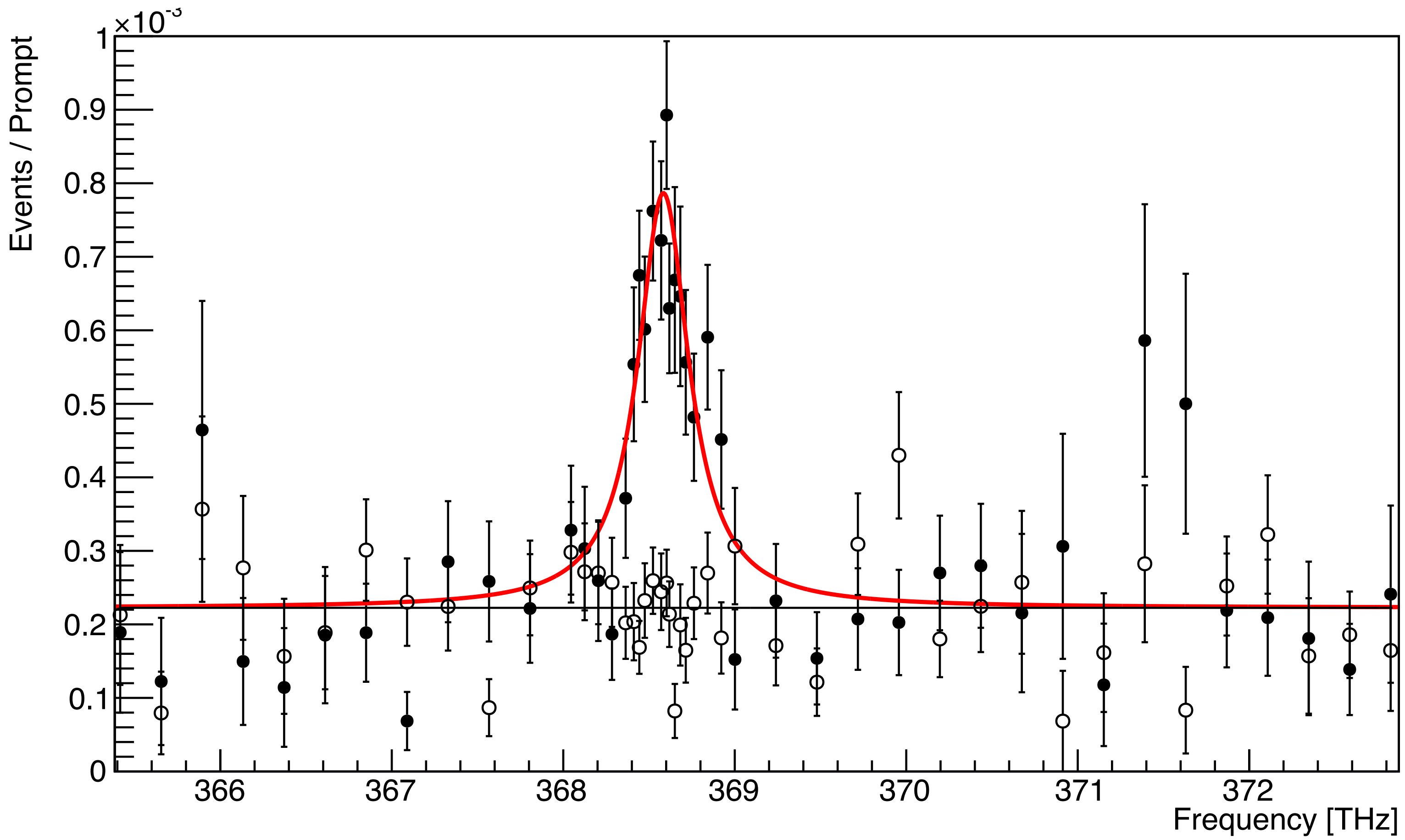


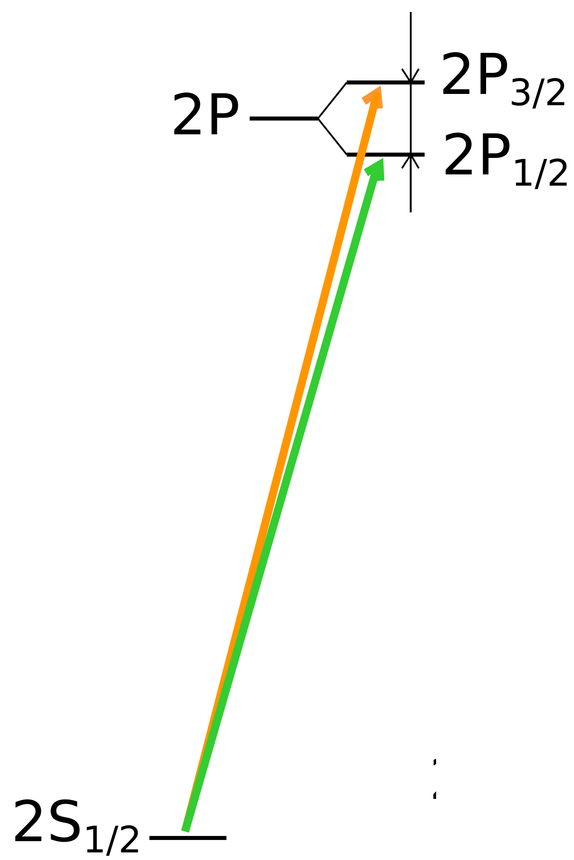
The traditional scattering experts confirm large values.


$^4He^{++}$
μ^-


$^3He^{++}$
μ^-

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

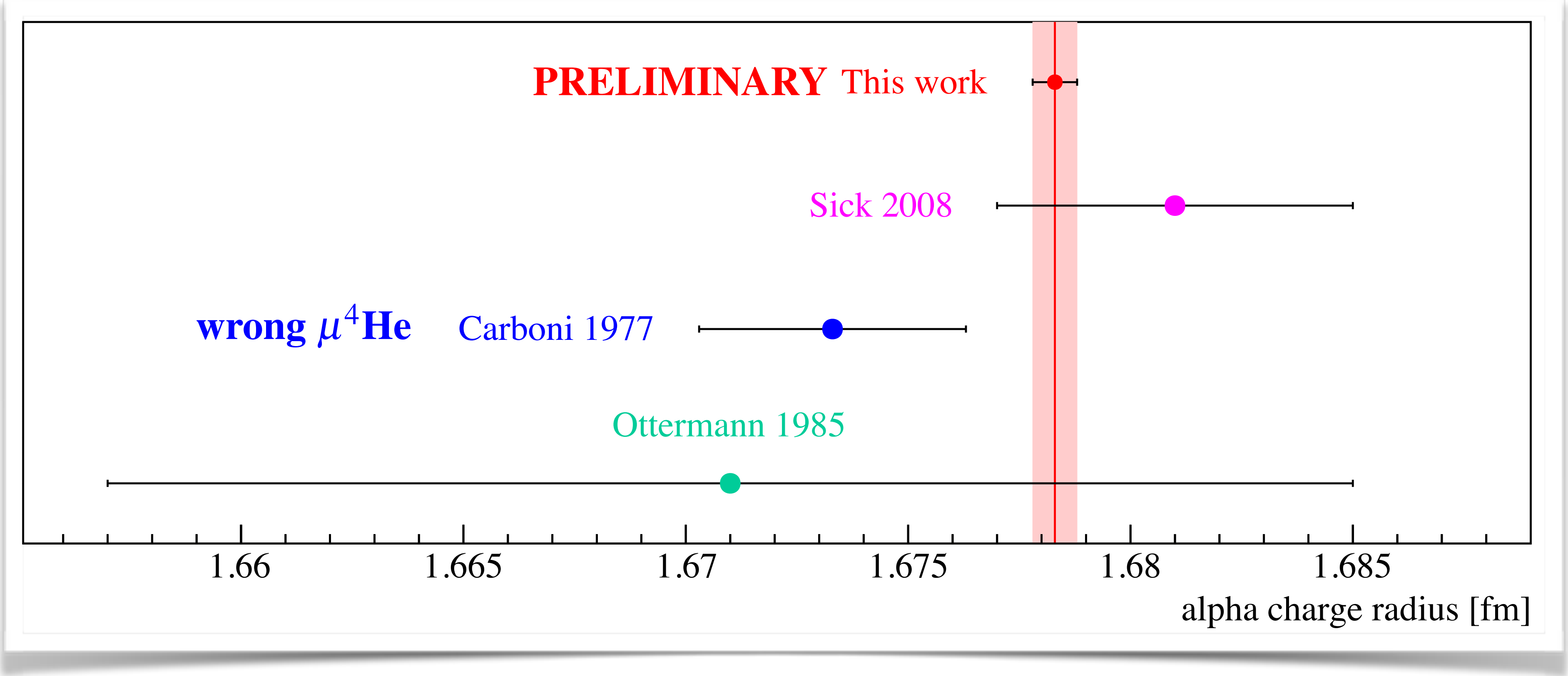




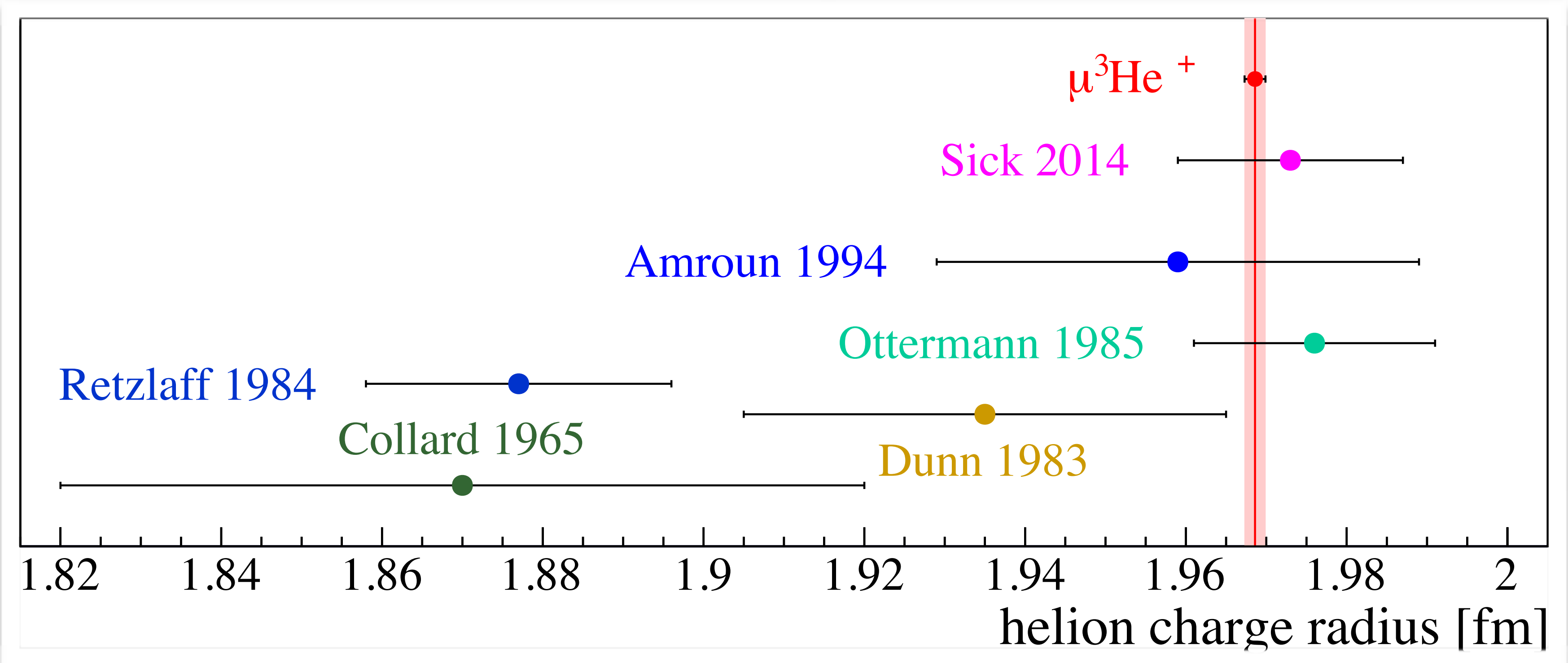
Experimental accuracy:	17 GHz (0.066 meV)
Statistics / Laser freq. / systematics unc.:	17 GHz / 100 MHz / 10 MHz
Theory uncertainty:	0.205 meV

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

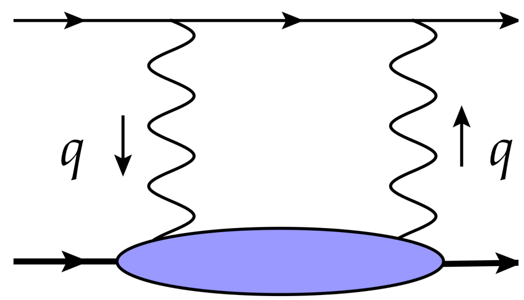
Alpha-particle and hellion radii from μHe^+ spectroscopy



Extraction of these charge radii from muonic helium is limited by the polarisability contributions.

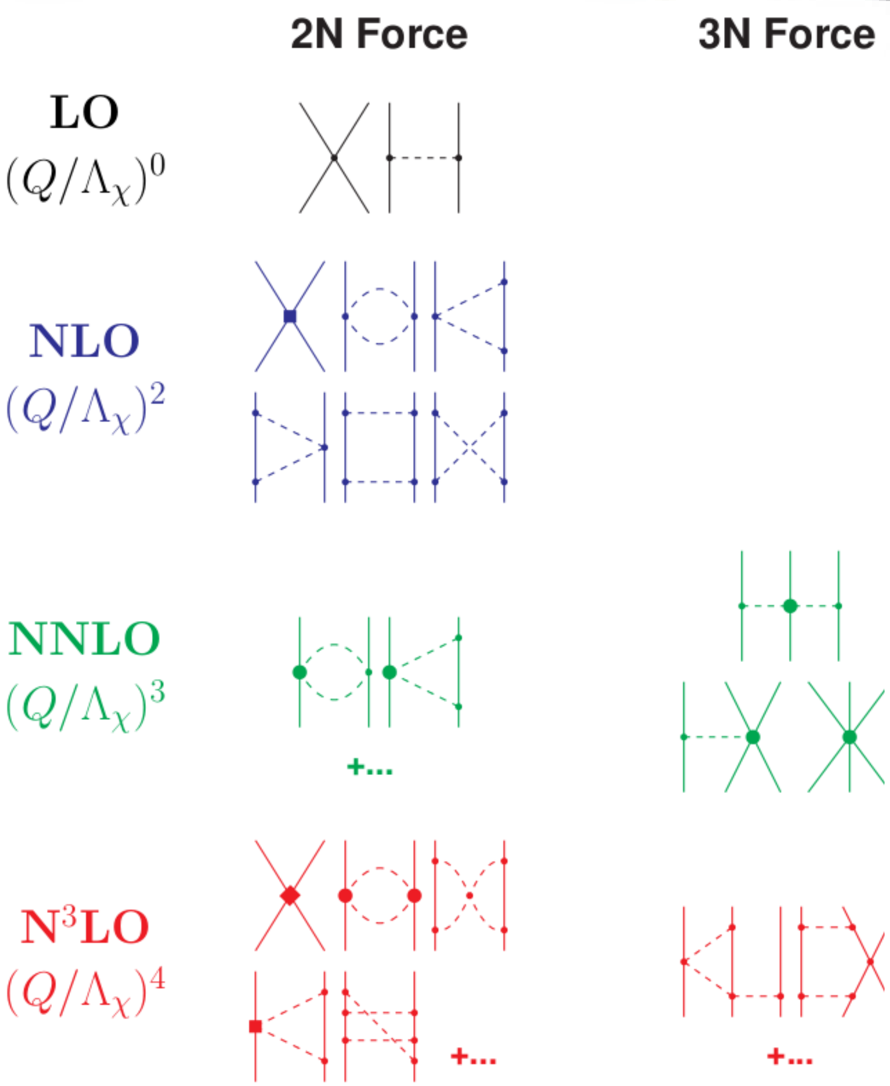


TPE: the key to extract precise charge radii



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

Impact of muonic helium (μHe) measurements

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

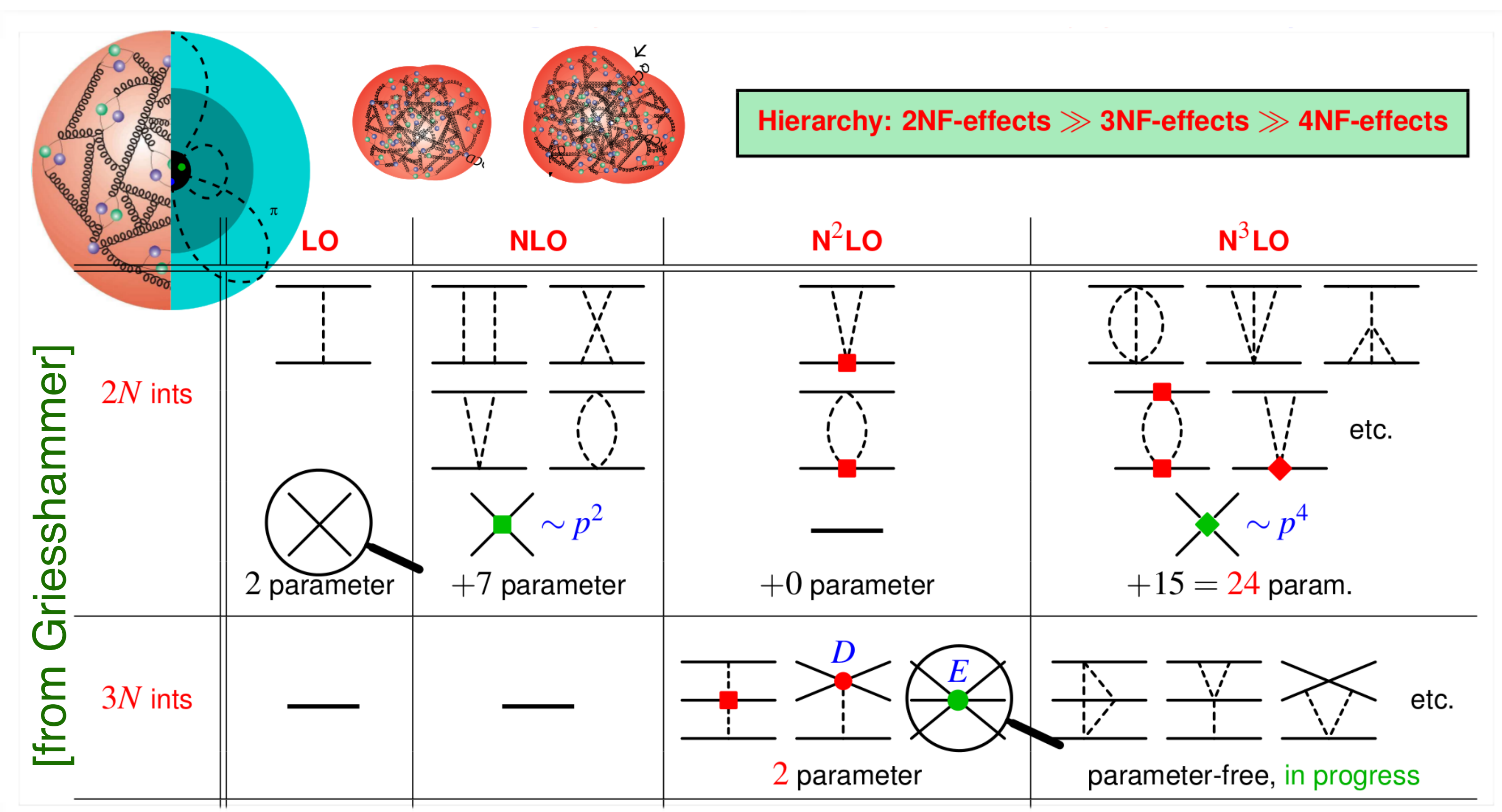
Constraints proton radius puzzle
Expose existence/absence of muonic force

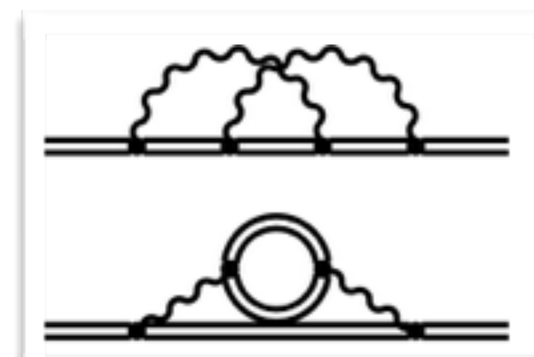
Benchmark for few-nucleon theories

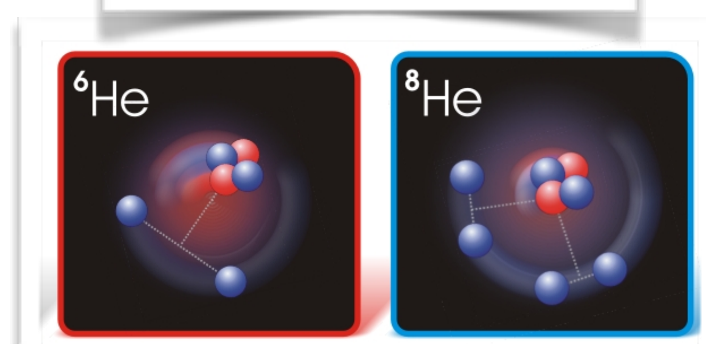
Improve absolute radii of ^6He and ^8He

Enhanced bound-state QED test when combined with He and He^+ spectroscopy

Pachucki, Indelicato, Jentschura, Yerokhin, Eides, Karshenboim…

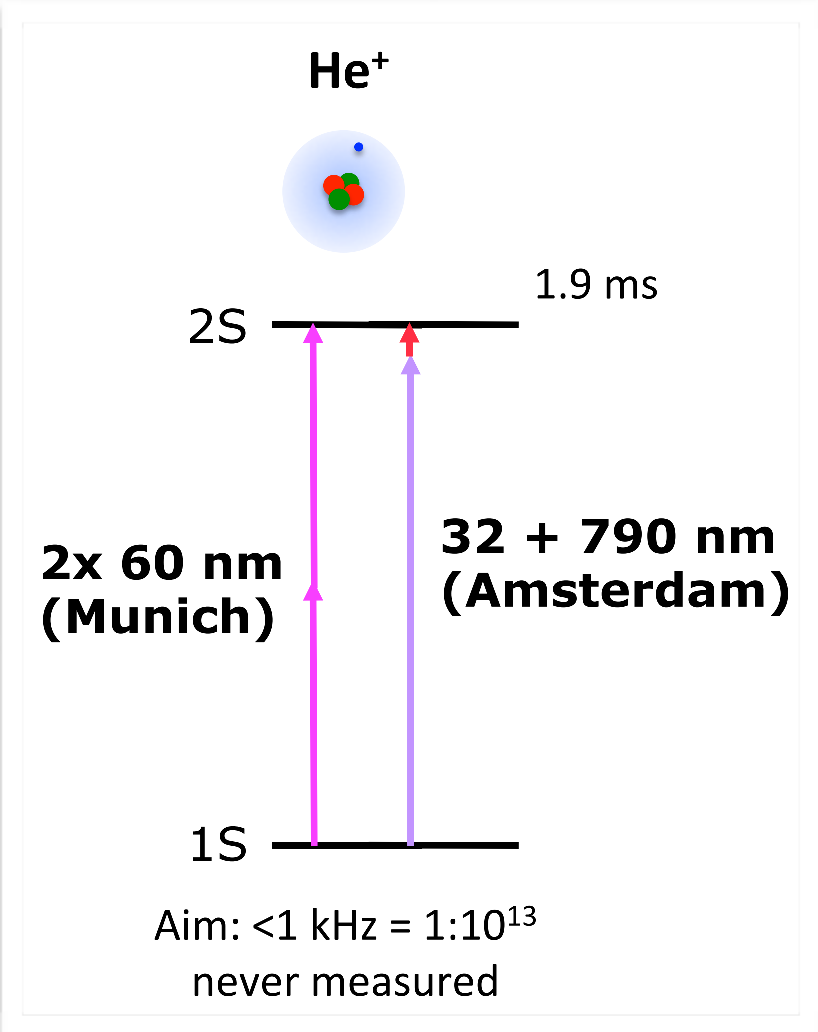






Lu et al., RMP 85 1383 (2013)

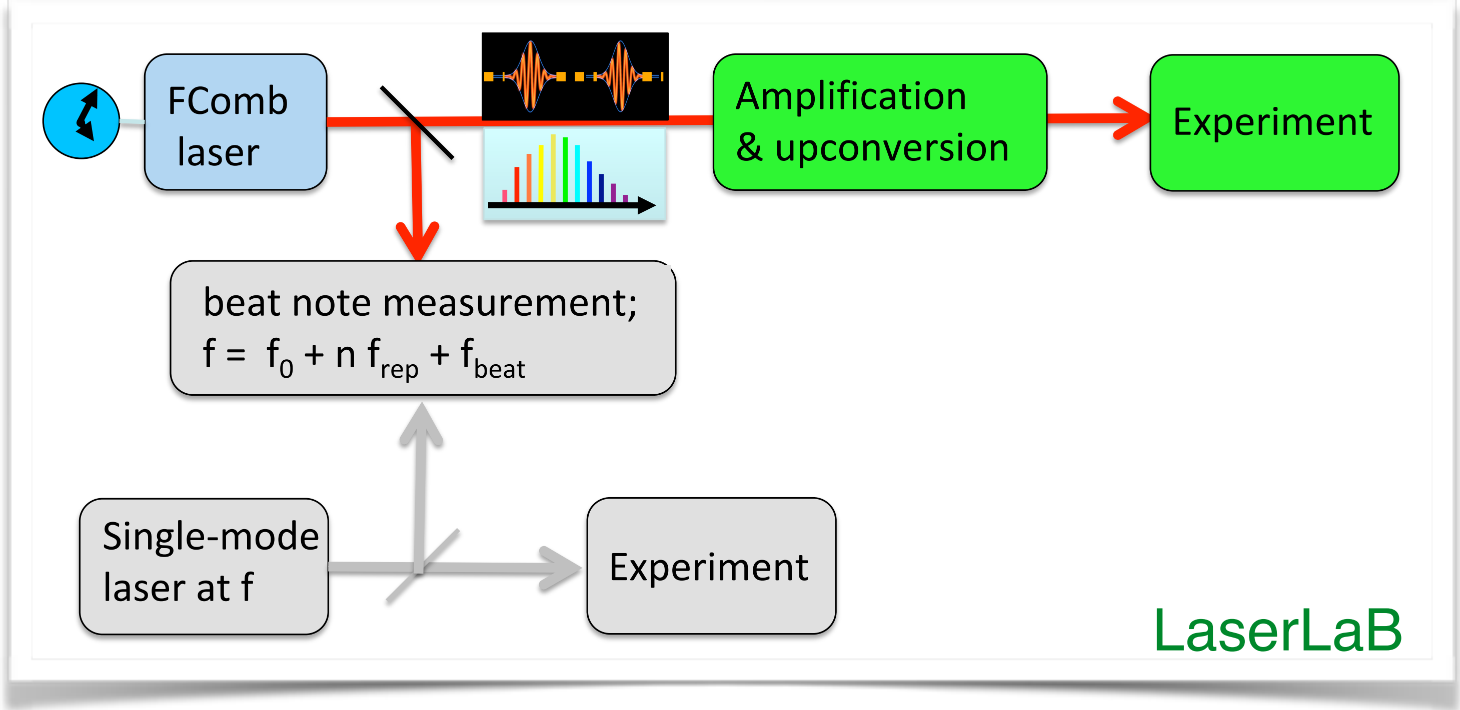
Challenging spectroscopy of He and He⁺

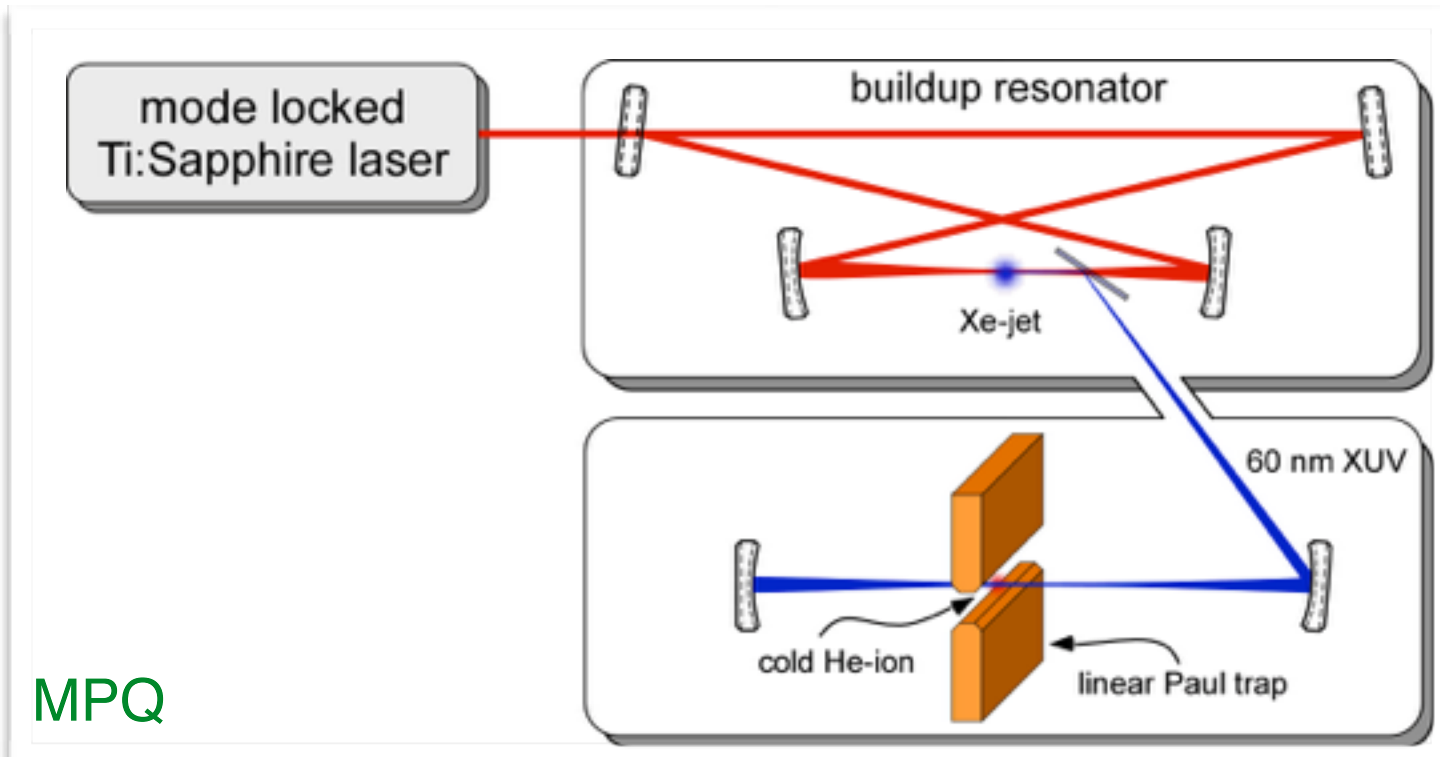


T. Udem

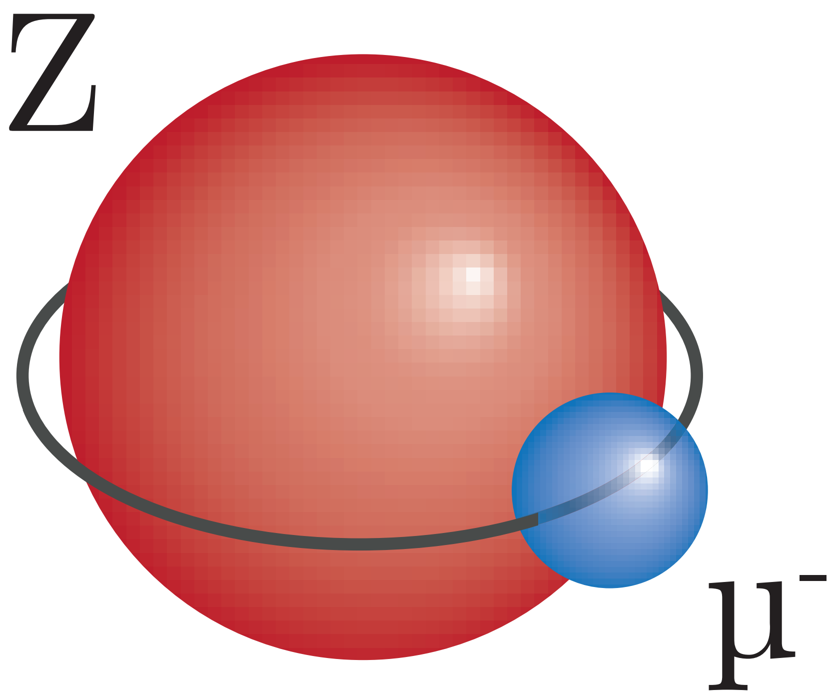
T.W. Hänsch

K. Eikema



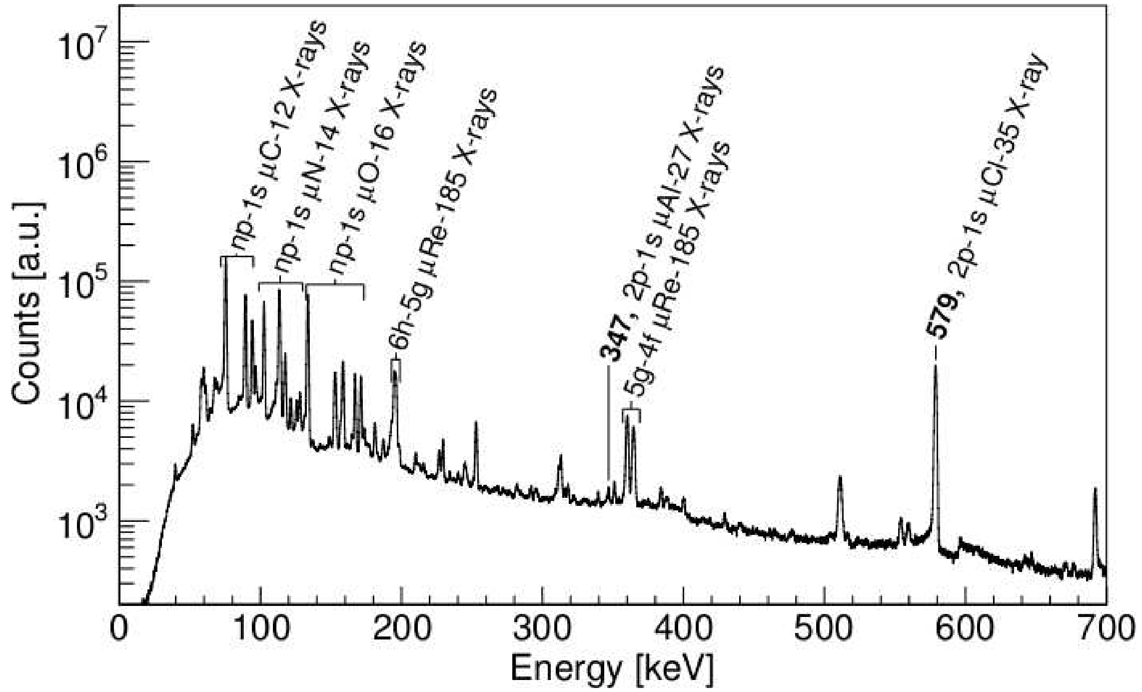


The muX project (PSI, ongoing)



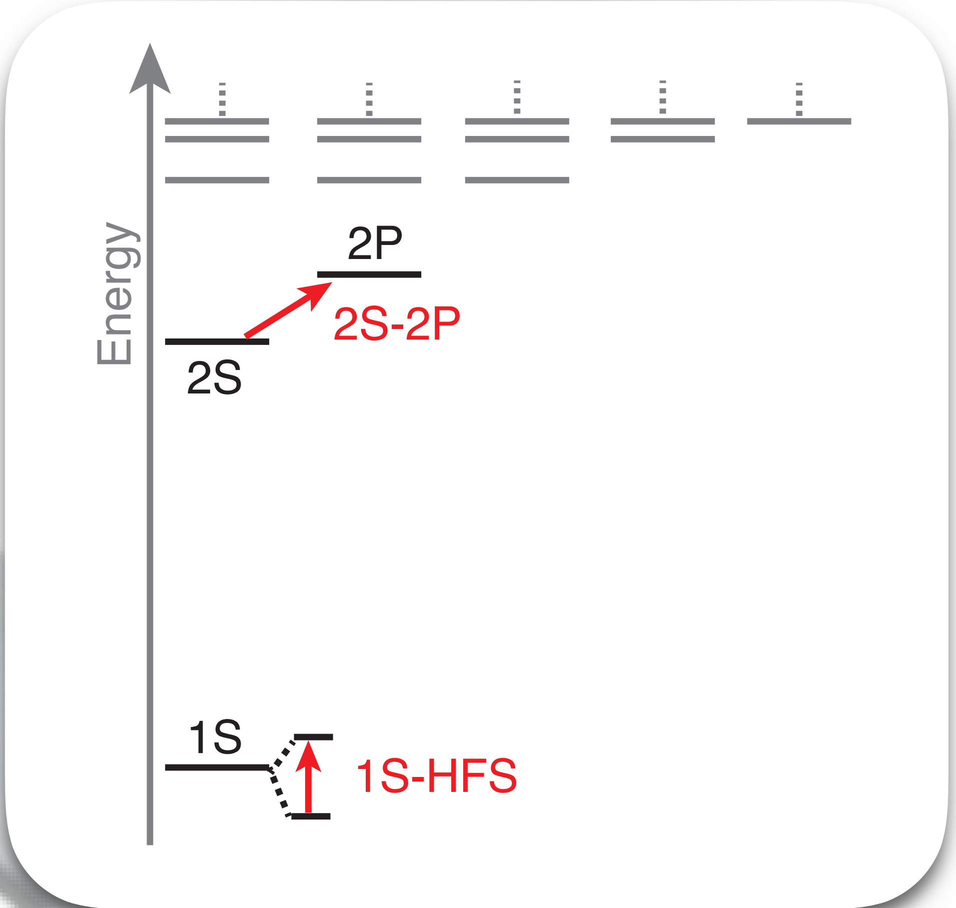
- charge radii
- quadrupole moments

for radioactive nuclei



- H-like atoms
- MeV transition energies
- ΔE_{size}: MeV finite-size effects
- ΔE_{QED}: easy QED corrections
- ΔE_{el}: small atomic electron corrections
- ΔE_{pol}: difficult nuclear polarisability correc.

The hyperfine splitting in μp (PSI, ongoing)

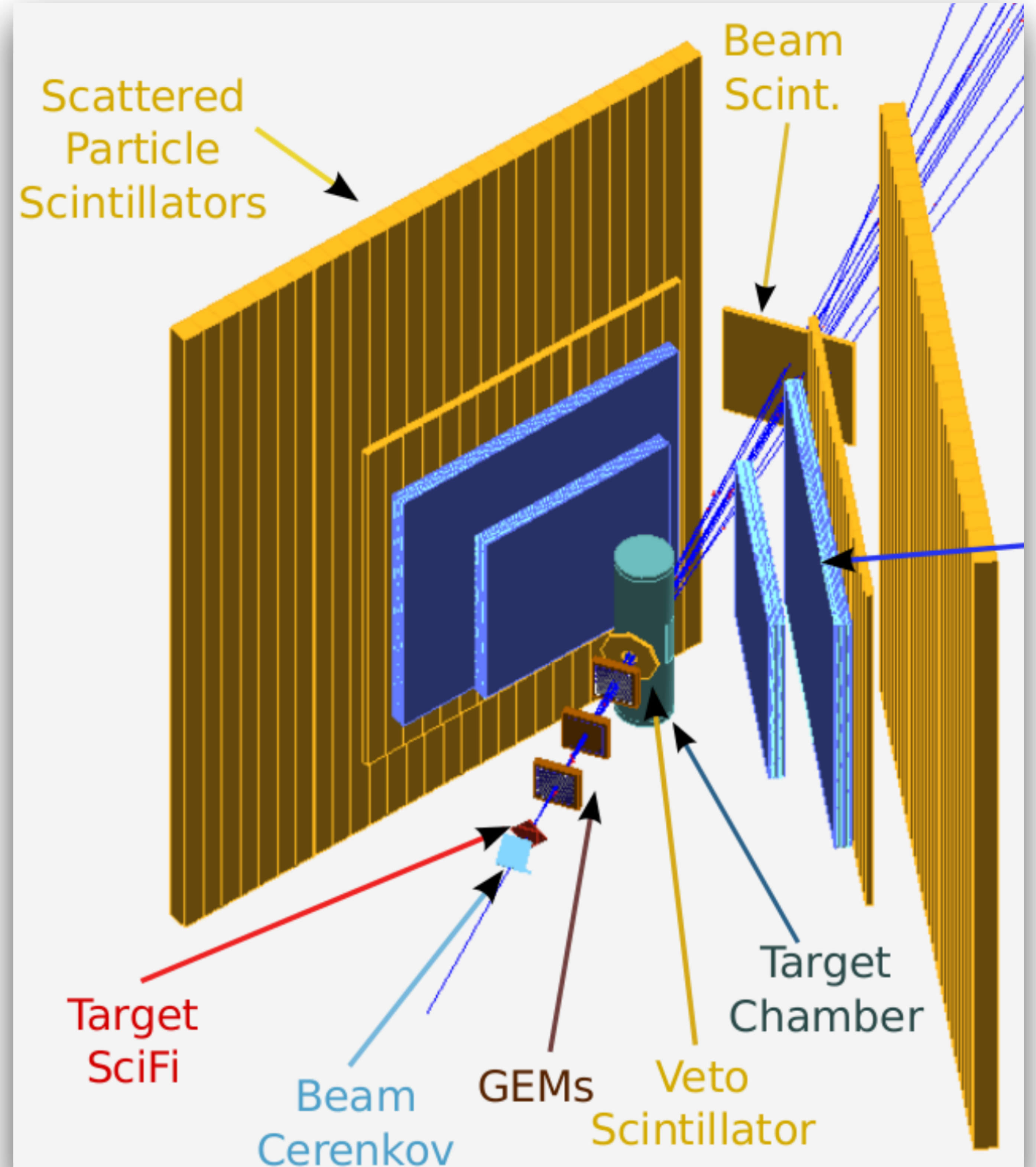


- 2S-2P μp
- 2S-2P μd
- 2S-2P μ^3He, μ^4He
- 1S-HFS μp

- From 2S-2P
  → charge radii

- From HFS
  → magnetic (Zemach) radii

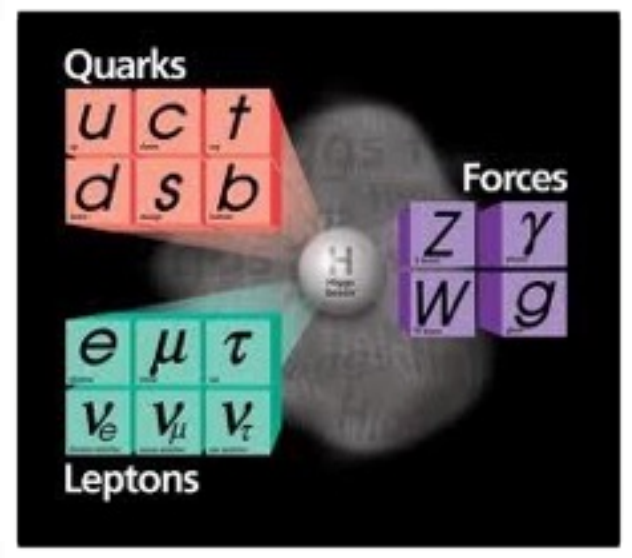
MUSE: Muon scattering (PSI, ongoing)



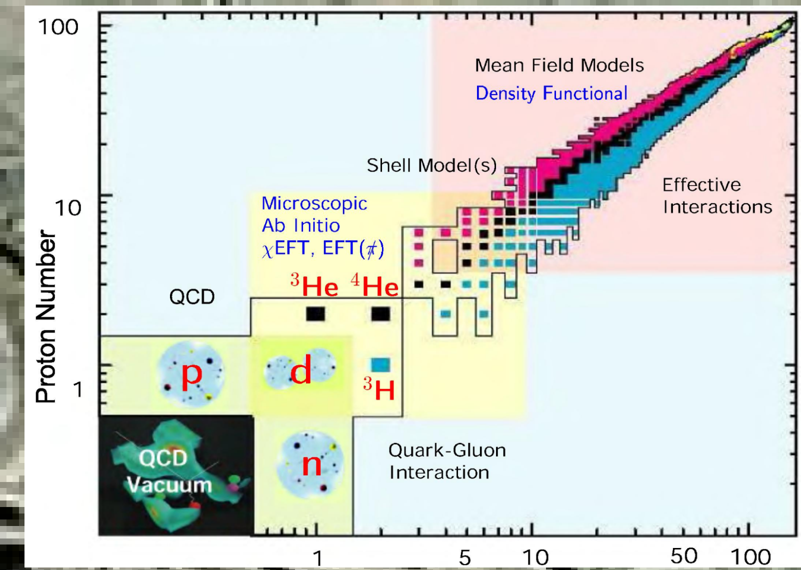
MUSE at PSI

- $\mu^{\pm}$-p, $e^{\pm}$-p scattering down to $Q^2_{min} = 2\times10^{-3}$ GeV^2
- Common uncertainties
  ⇨ precise $\Delta r = r_p^{\mu} - r_p^{e}$
- test μ-e universality
- measure TPE

arXiv:1709.09753



Test of H energy levels
Bound-state QED



BSM physics

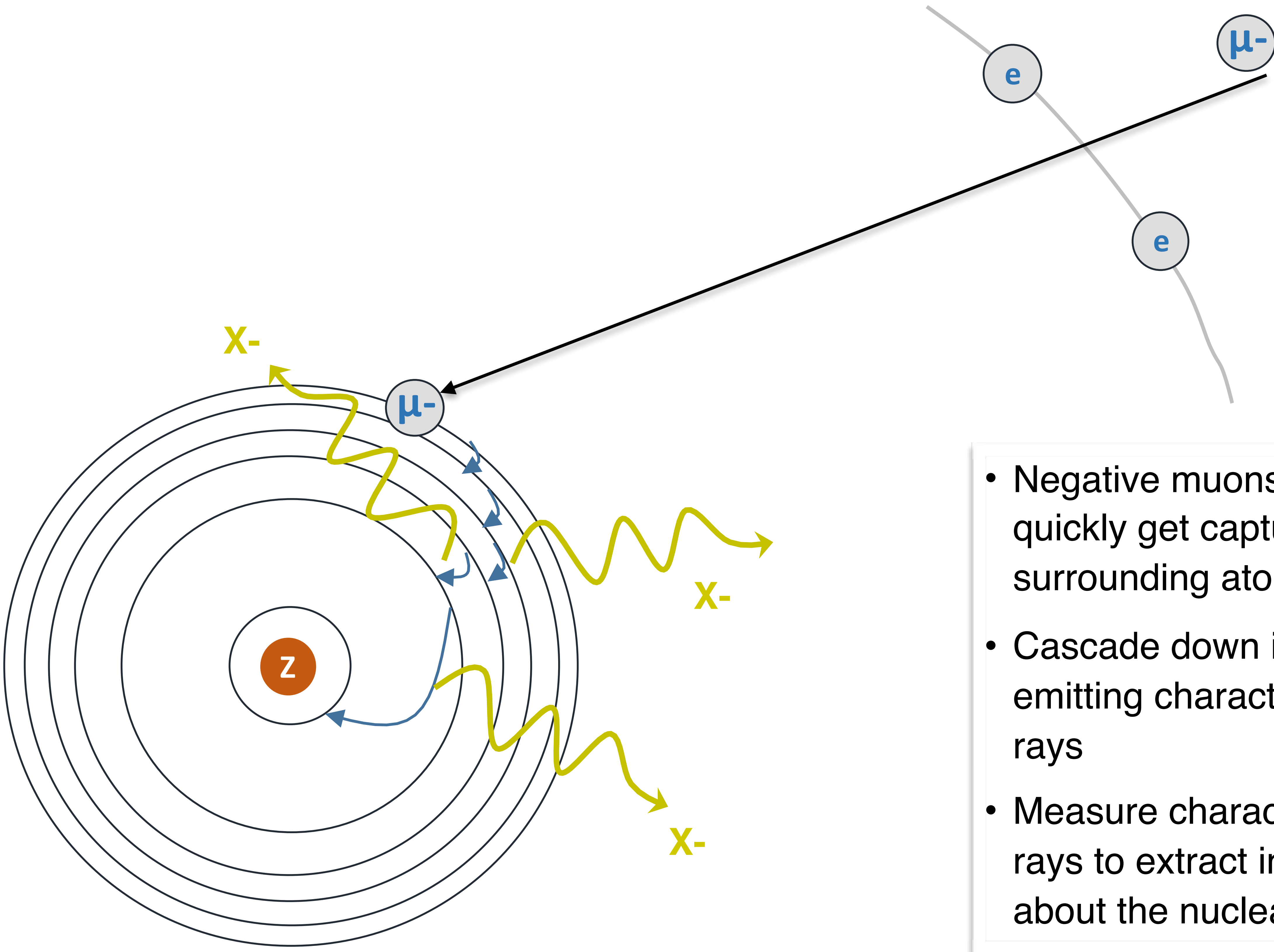
nuclear charge radii
form factors,
EFT, chiral th., lattice,
few-nucleon th.

electron scattering

H, H_2, H_2^+, He, He^+
spectroscopy

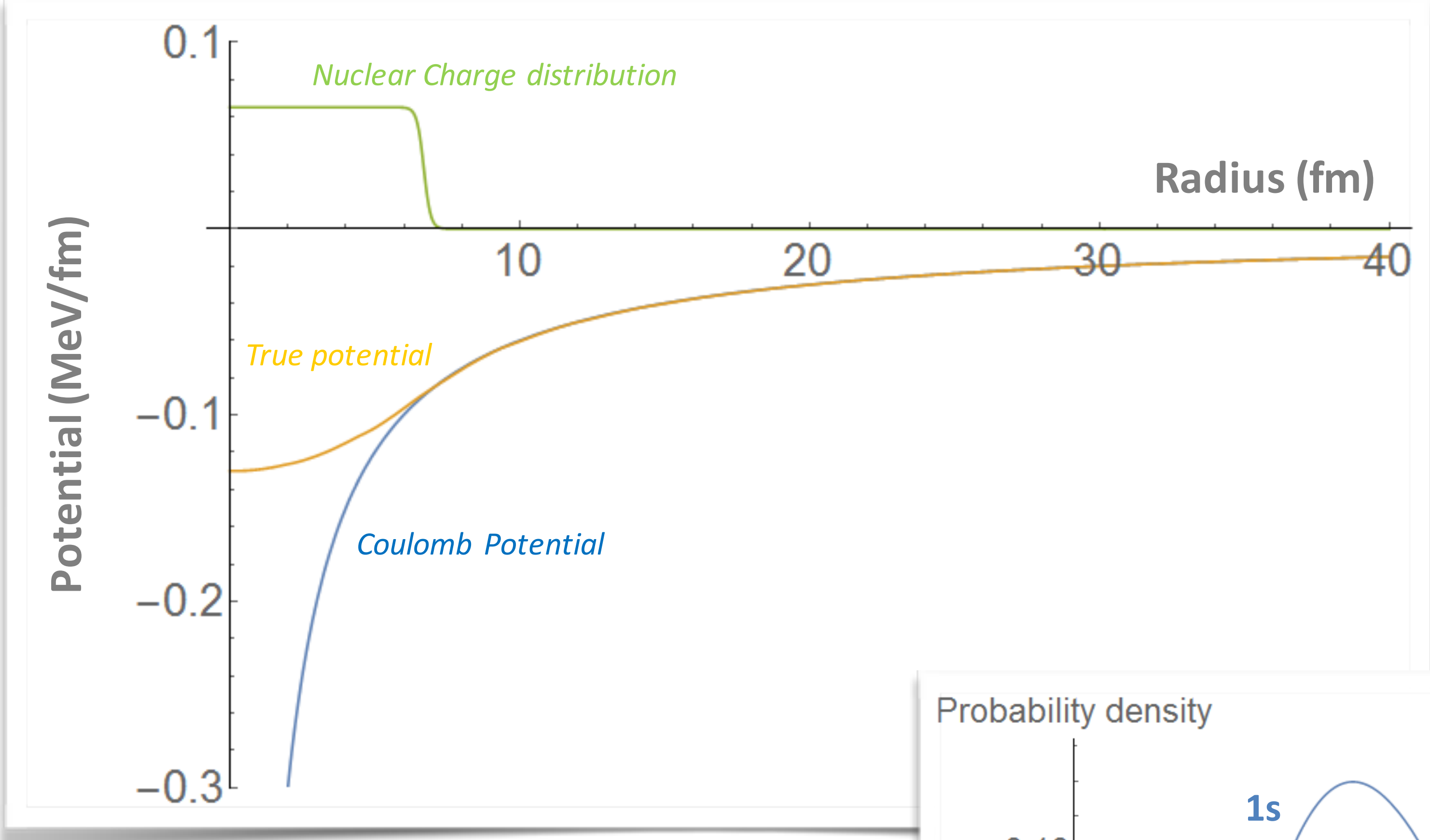
μp, μd, μHe (2S-2P)
high-Z muonic atoms
hyper-fine splitting

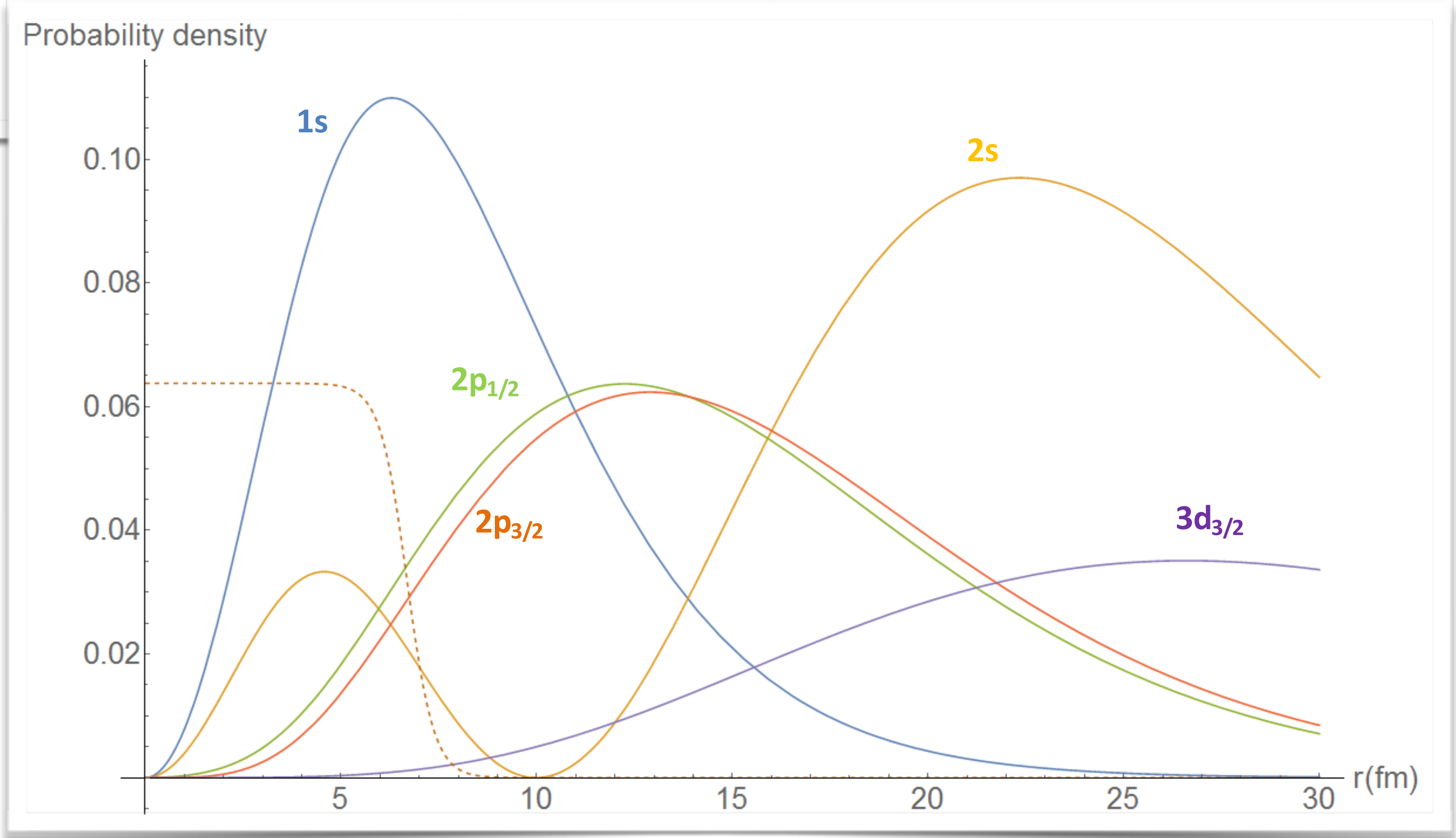
X-ray spectroscopy of high-Z muonic atoms



- Negative muons at rest quickly get captured by surrounding atoms
- Cascade down into 1s state emitting characteristic X-rays
- Measure characteristic X-rays to extract information about the nuclear structure

Finite size effect is huge

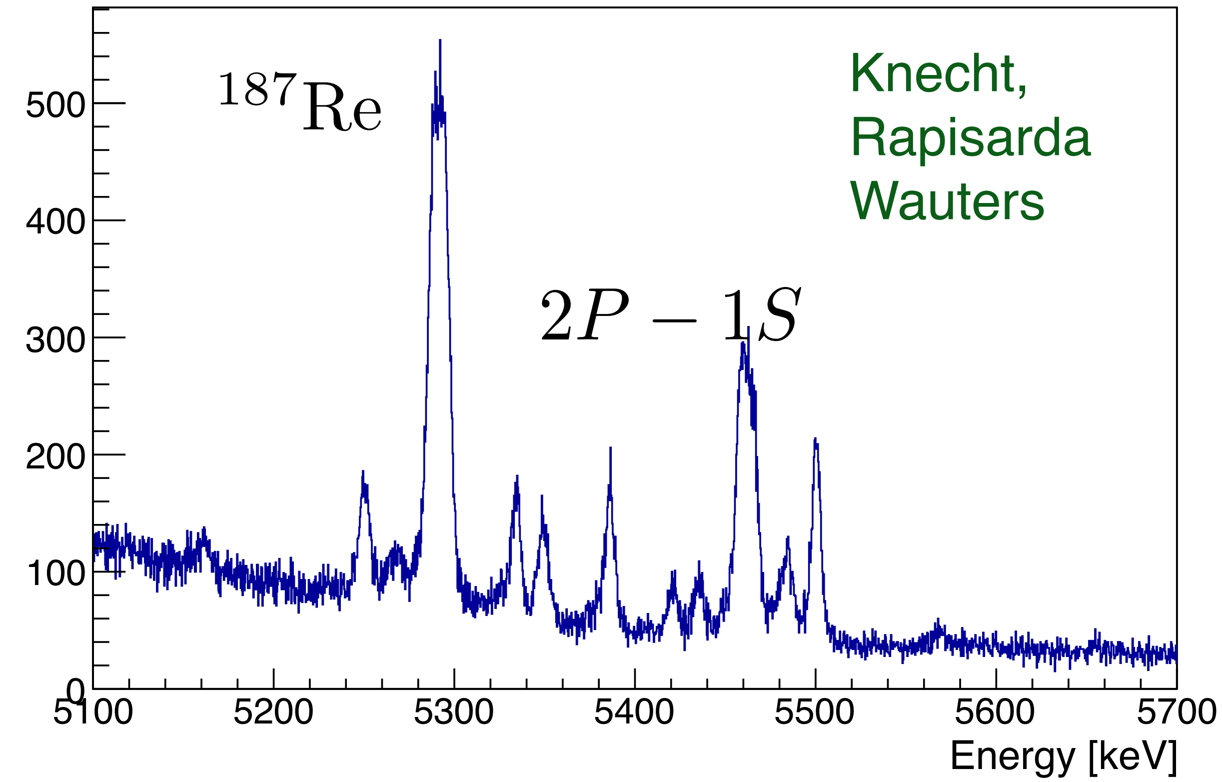




High-Z muonic ions (μZ)

$$E \simeq \frac{m_\mu}{m_e} R_\infty Z^2 \left(\frac{1}{n_f^2} - \frac{1}{n_i^2} \right) + \Delta E_{\mathrm{QED}} - \Delta E_{\mathrm{size}} + \Delta E_{\mathrm{pol}} + \Delta E_{\mathrm{el}}$$

- H-like atoms
- MeV transition energies
- ΔE_{size}: MeV finite-size effects
- ΔE_{QED}: easy QED corrections
- ΔE_{el}: small atomic electron corrections
- ΔE_{pol}: difficult nuclear polarisability correc.



- Measure X-rays with Ge detectors (0.1 keV acc.)
- Extract charge radii and quadrupole moments

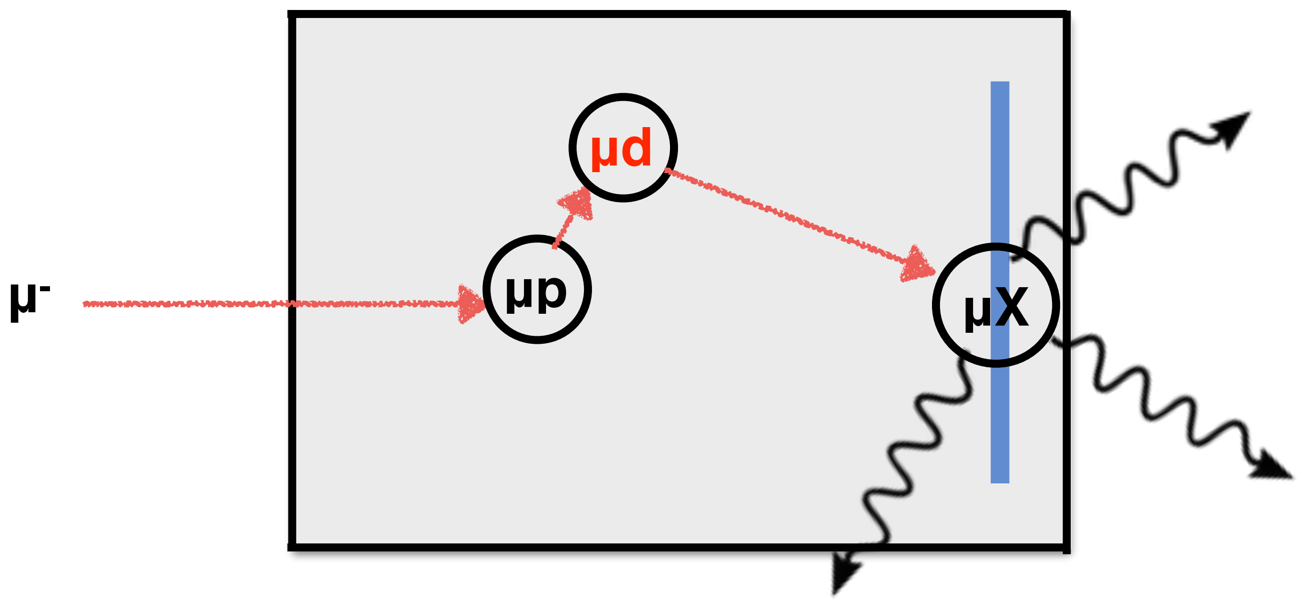
Complications
- nuclear polarisability
- nuclear excitation in final state

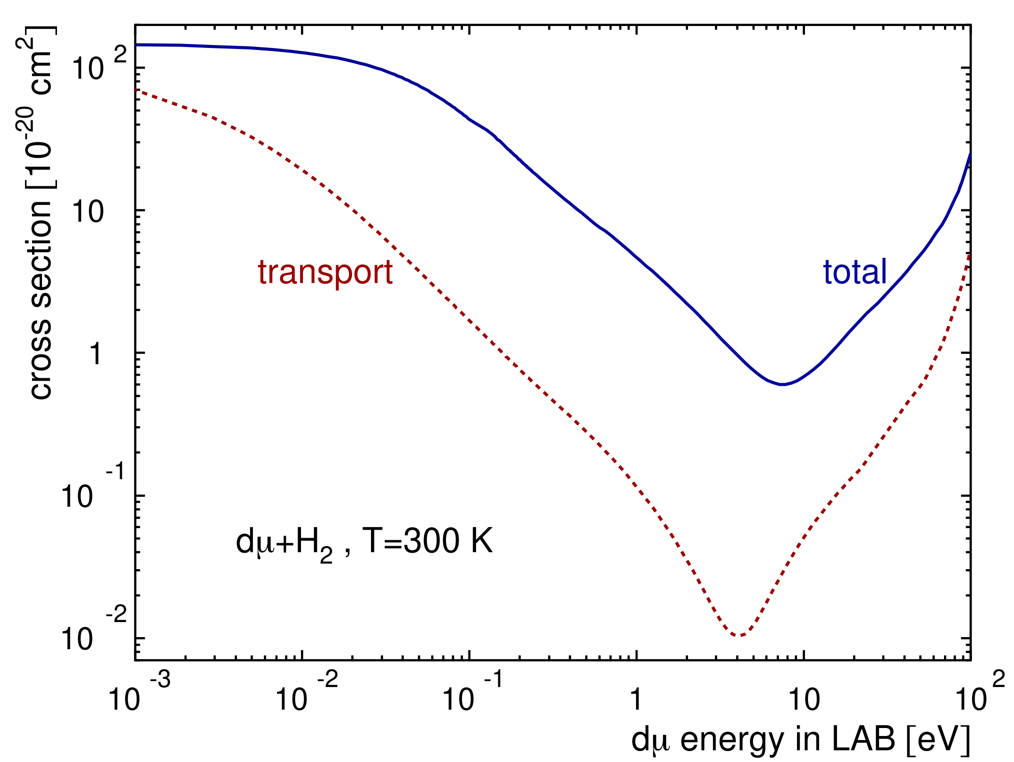
Natalia Oreshkina & Niklas Michel, MPI Heidelberg

muX principle: spectroscopy for radioactive nuclei

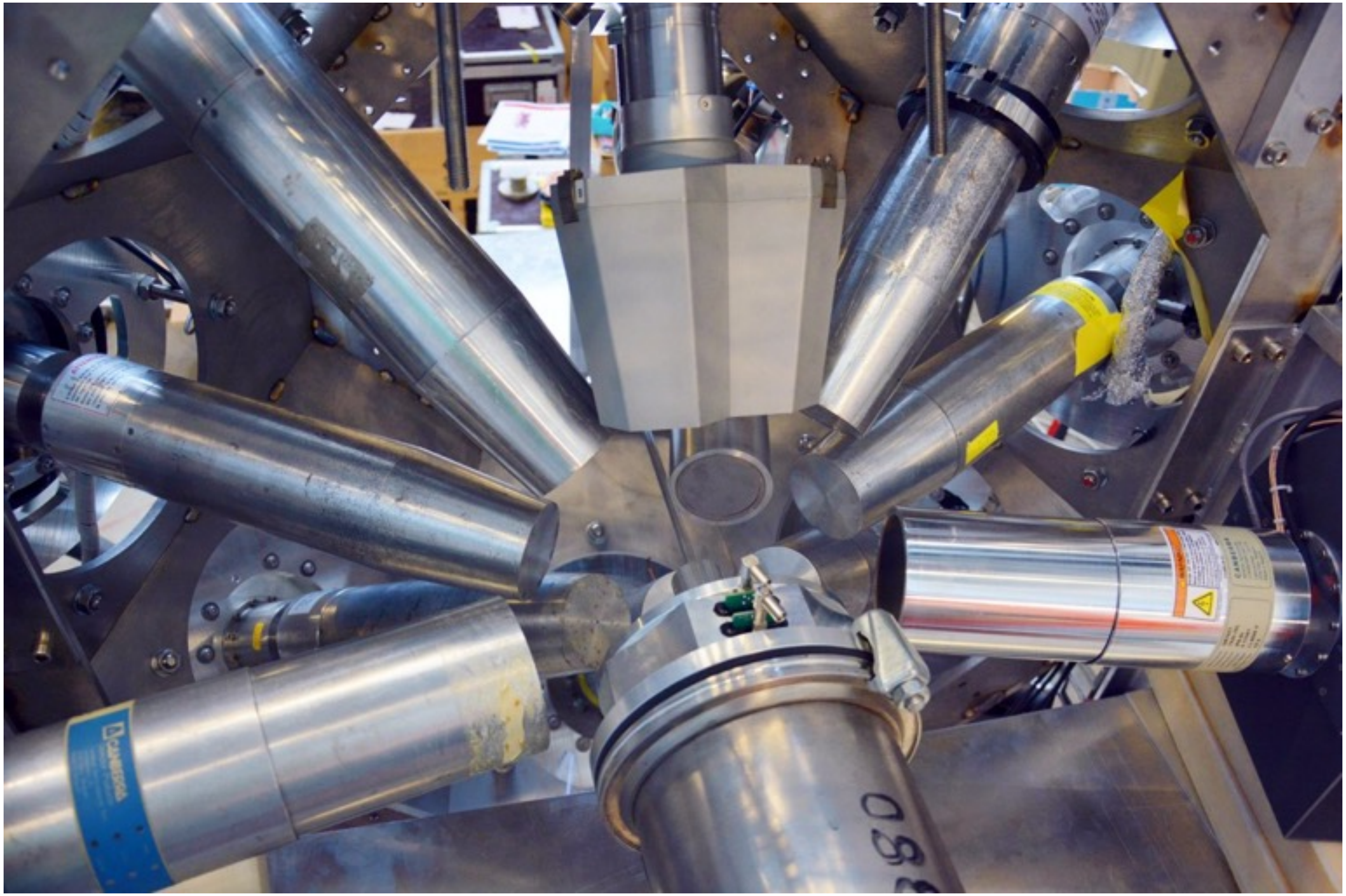
Radioactive ⇨ µg material

- Stop muons in 100 bar H_2 target with 0.25% D_2 admixture
- Muonic hydrogen (µp) is formed
- In a collision (µp + D_2 → µd + …) the muon transfers to deuterium forming µd, with kinetic energy of 45 eV
- Hydrogen gas is quasi transparent for µd at ~5 eV (Ramsauer-Townsend effect)
- µd reaches the X target and transfers to it to form µX*
- µX* de-excite emitting x-rays
- Measure x-rays with Ge-detectors



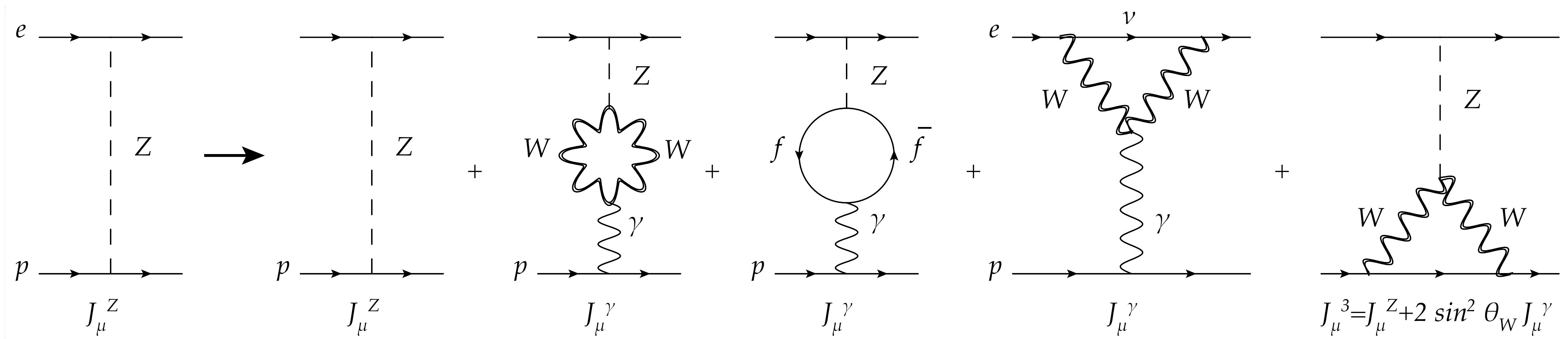


The muX setup



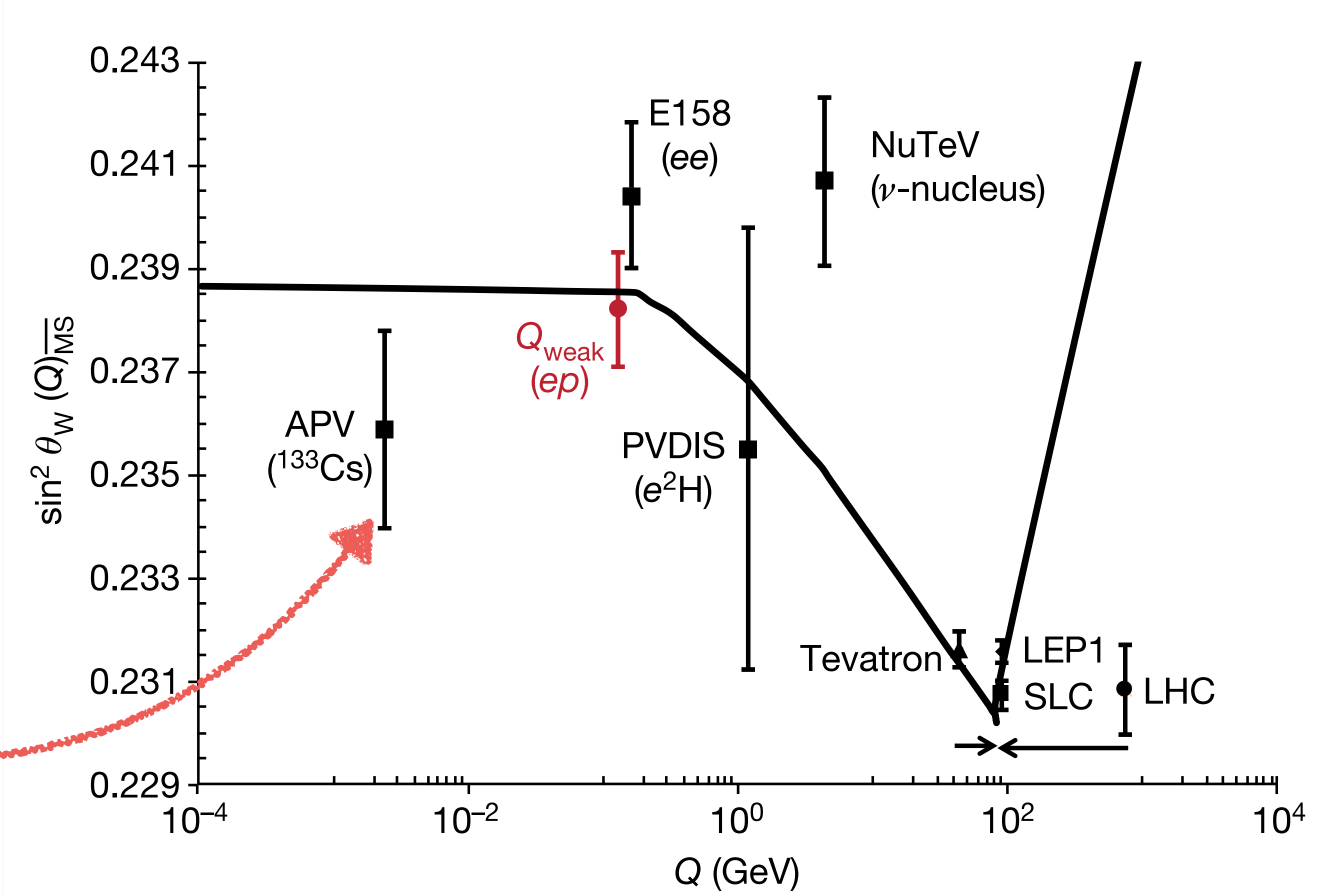
- 11 germanium detectors in an array from French/UK loan pool, Leuven, PSI
- First time a large array is used for muonic atom spectroscopy

Other goal of muX: Running of the Weinberg angle



$$J_\mu^Z = J_\mu^3 - 2\sin^2\theta_W J_\mu^\gamma$$
$$= \ldots (J_\mu^3 - 2\kappa(Q^2)\sin^2\theta_W J_\mu^\gamma) \equiv \ldots (J_\mu^3 - 2\sin^2\theta_W(Q^2)\, J_\mu^\gamma)$$

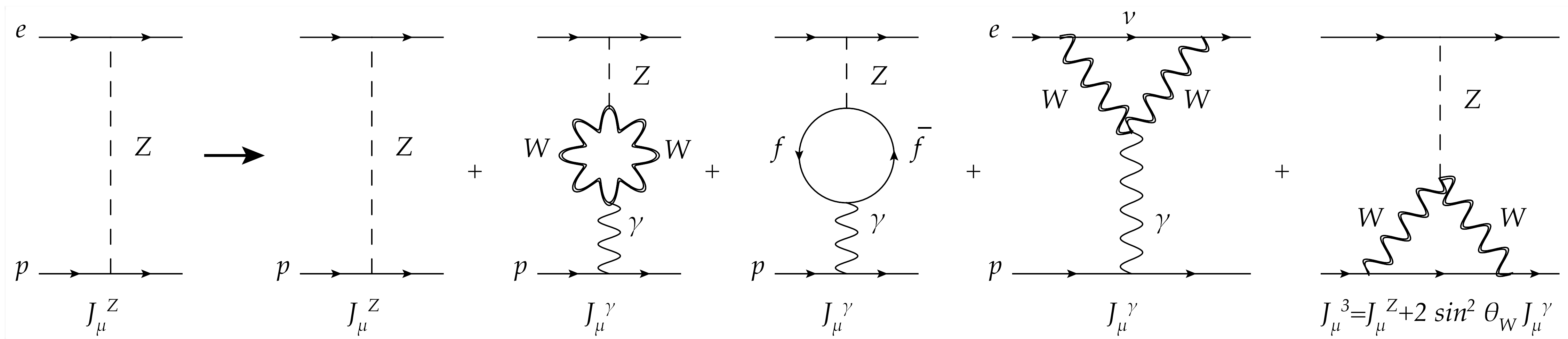
Marciano, Czarnecki ….



Nature 557, 207(2018)

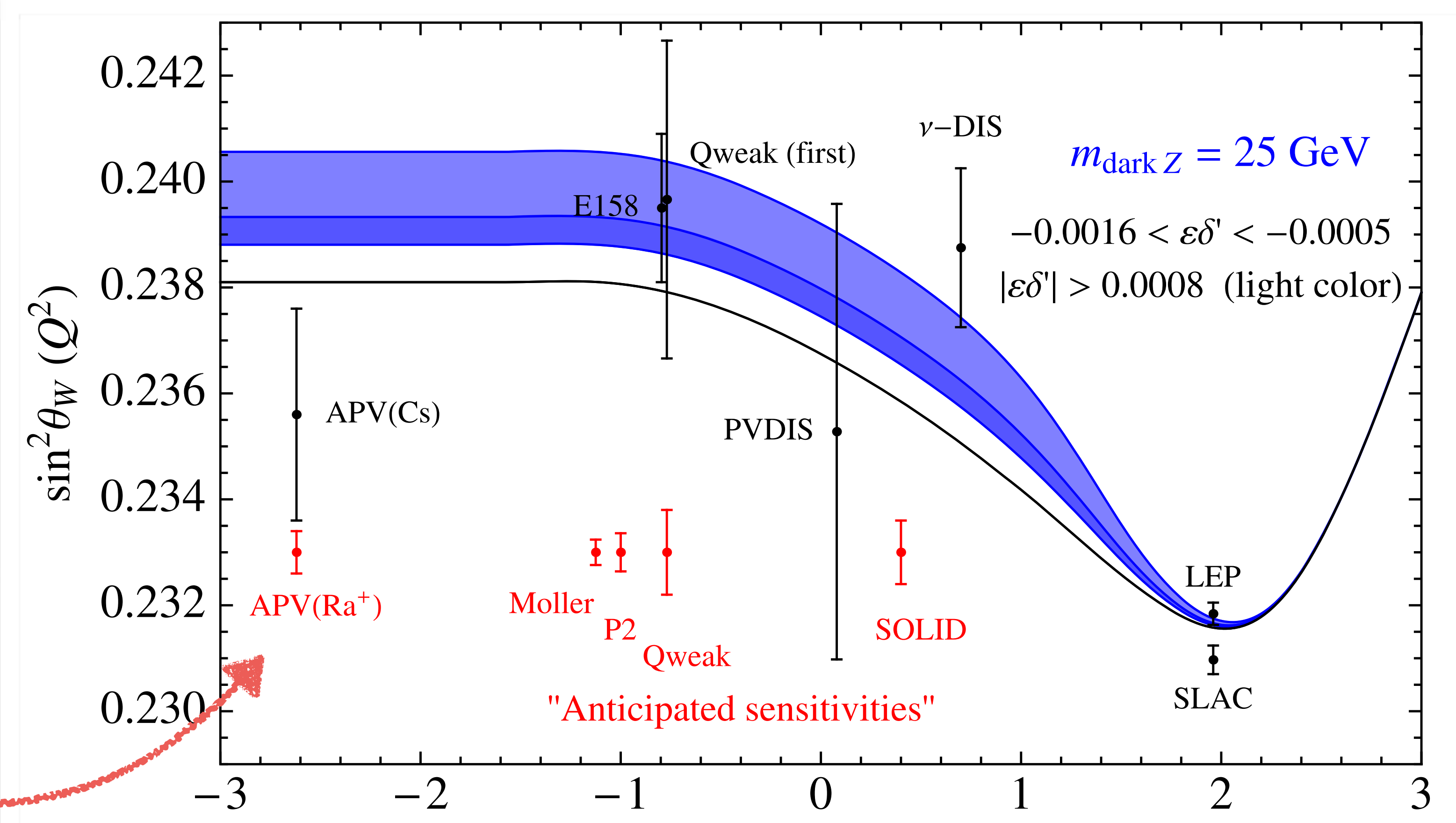
APV (Ra)
5x better than
APV(Cs)

Running of the Weinberg angle



$$J_\mu^Z = J_\mu^3 - 2\sin^2\theta_W J_\mu^\gamma$$

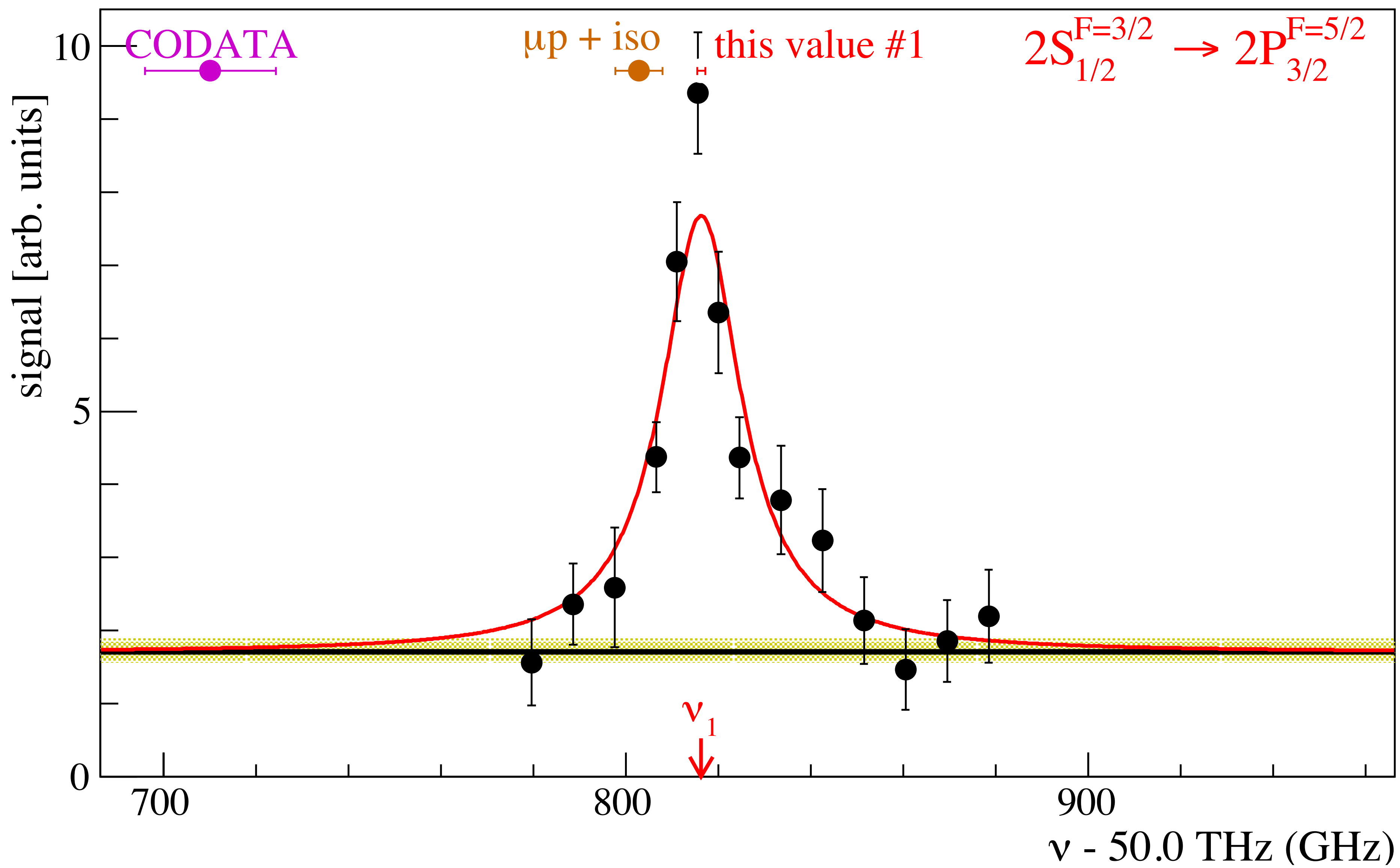
$$= \ldots (J_\mu^3 - 2\kappa(Q^2)\sin^2\theta_W J_\mu^\gamma) \equiv \ldots (J_\mu^3 - 2\sin^2\theta_W(Q^2)\, J_\mu^\gamma)$$

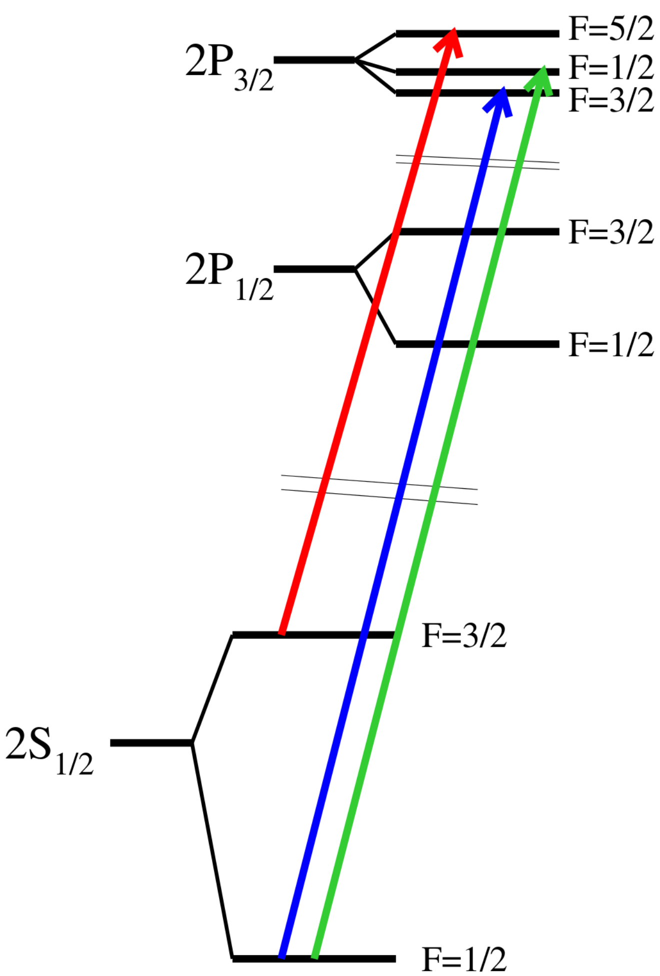


PRD 92, 055005 (2015)

APV (Ra)
5x better than
APV(Cs)

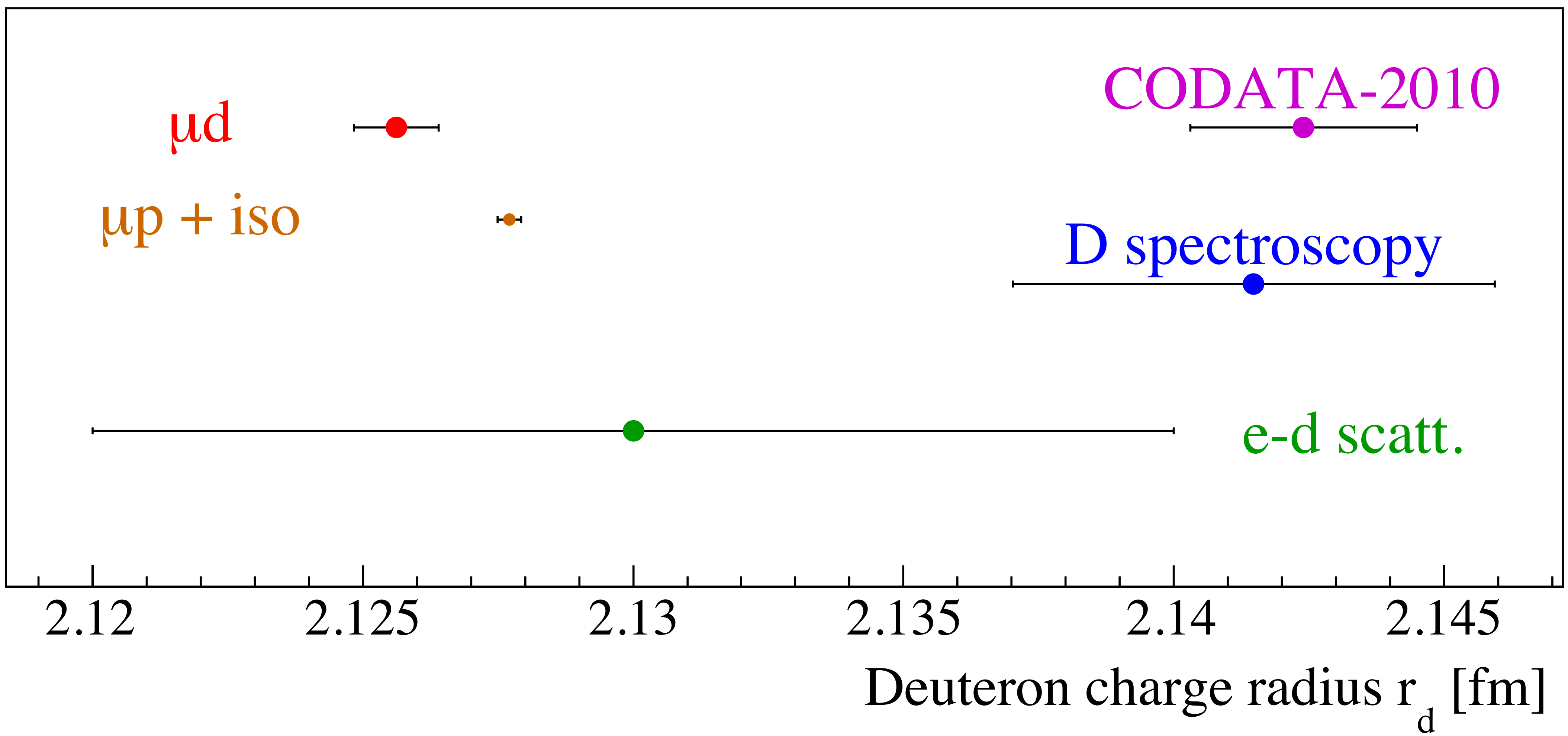
2S-2P spectroscopy of muonic deuterium (μd)





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

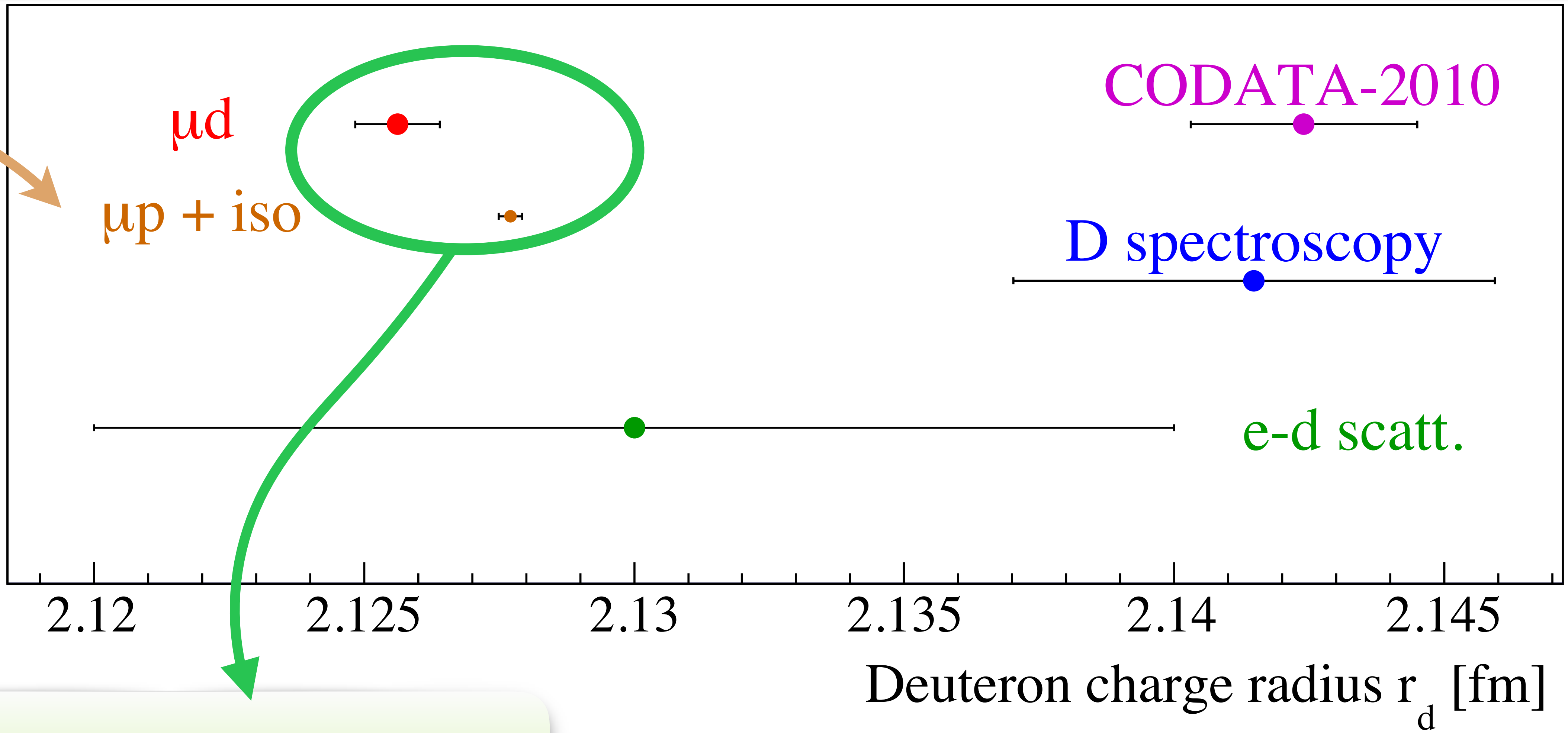
2S-2P spectroscopy of muonic deuterium (μd)



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)

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



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

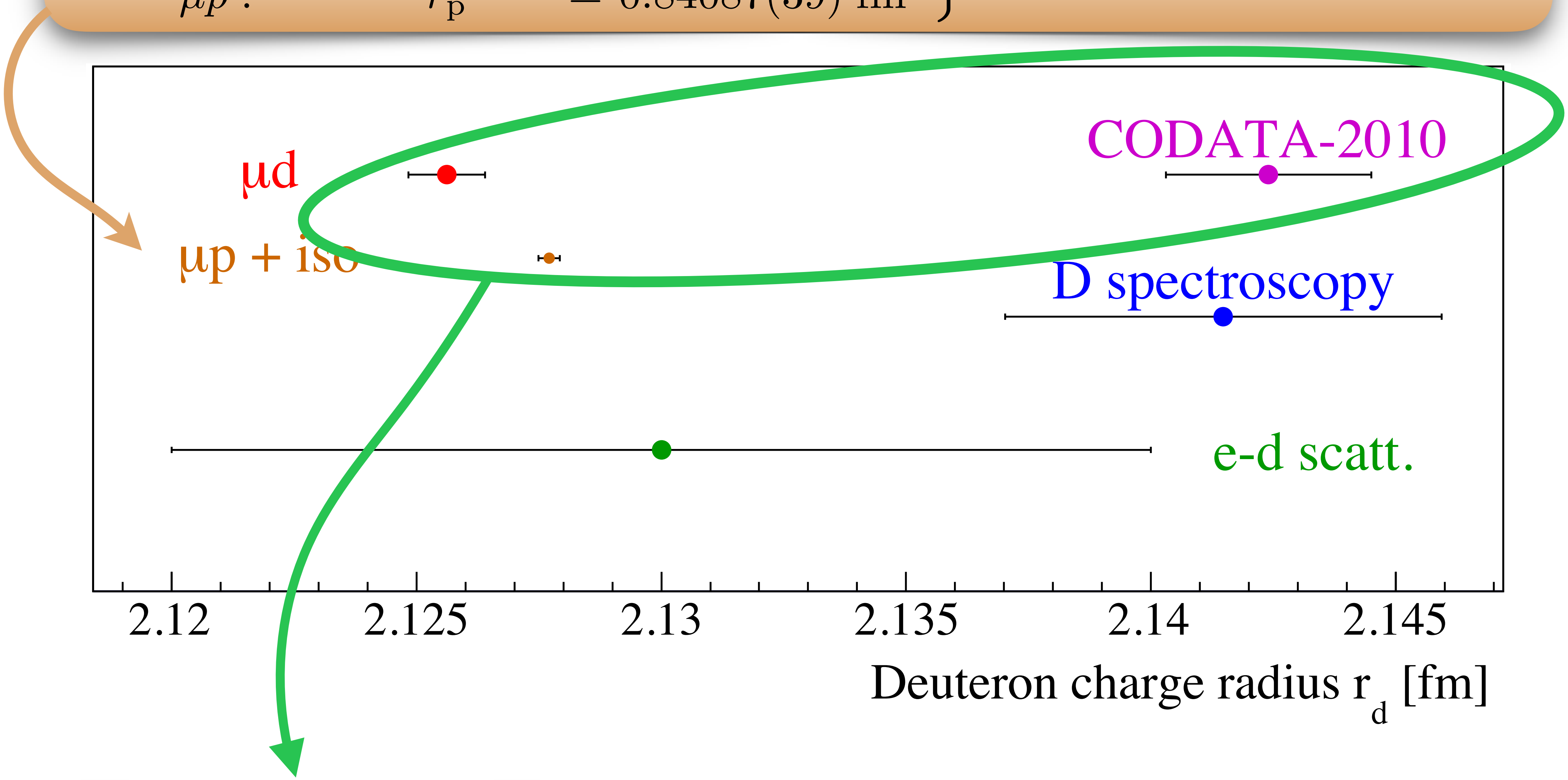
The 2.5σ difference:

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

Pachucki, Bacca, Barnea, Gorchtein, Carlson….

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

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

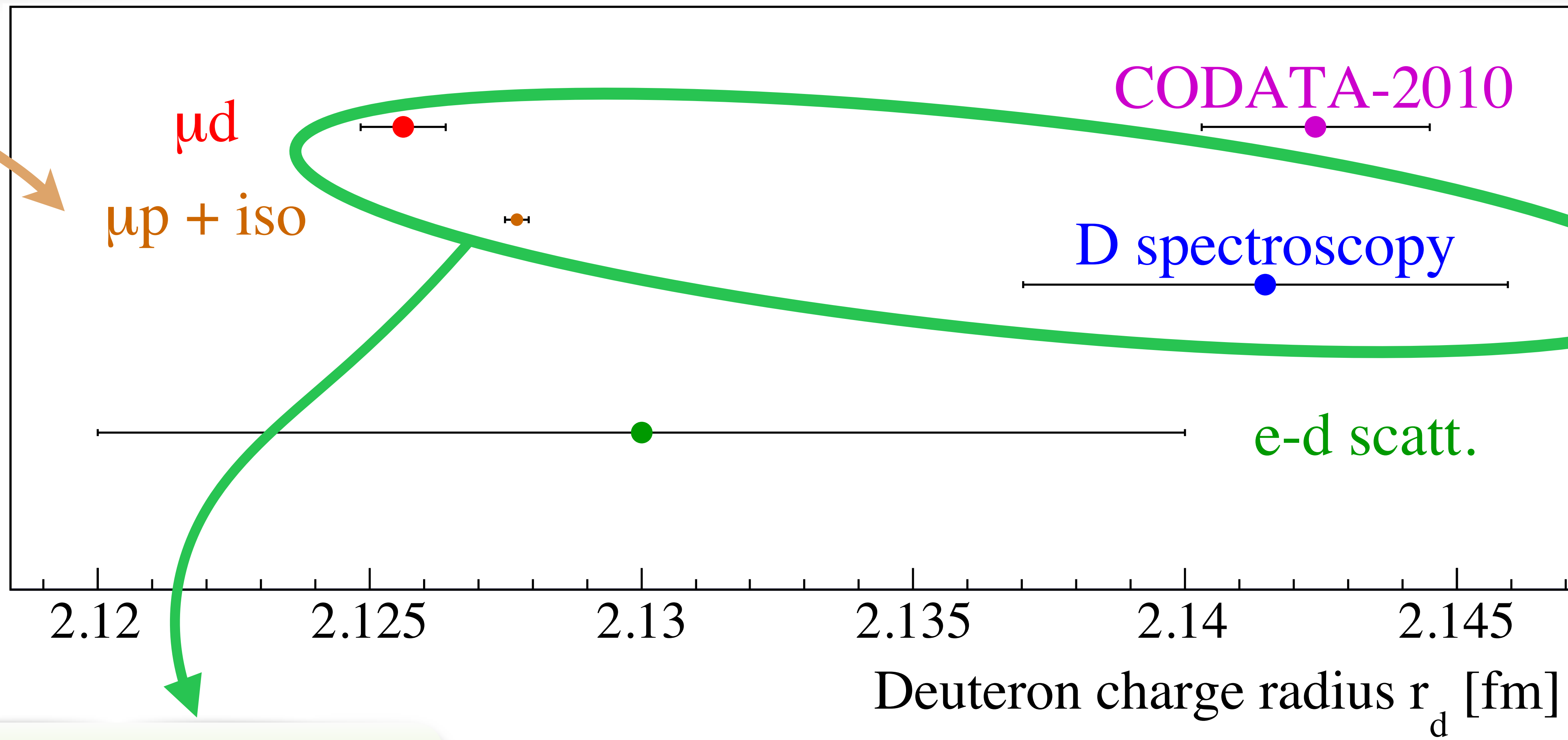


7σ from CODATA

BUT CODATA contains proton-data

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

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



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?