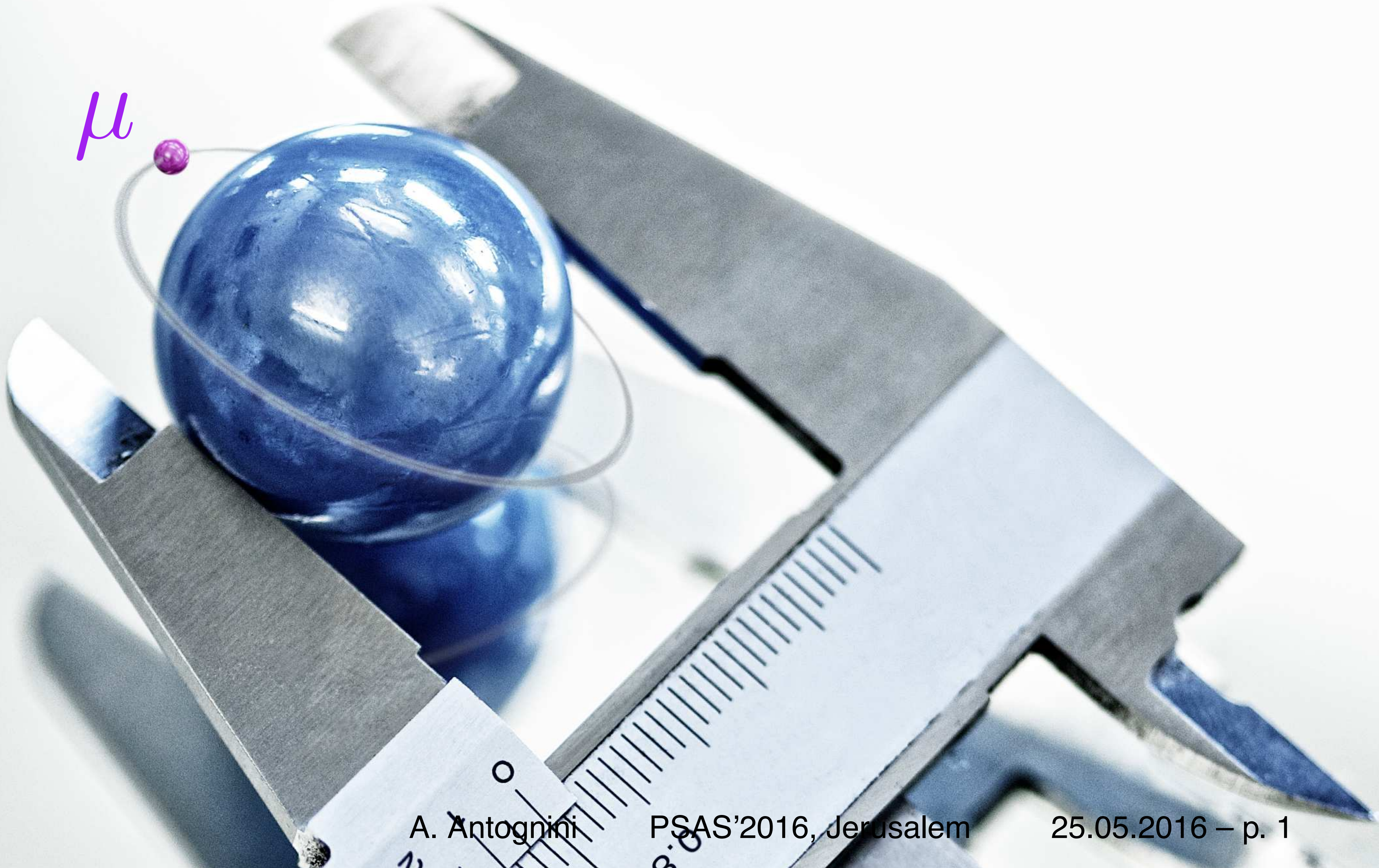
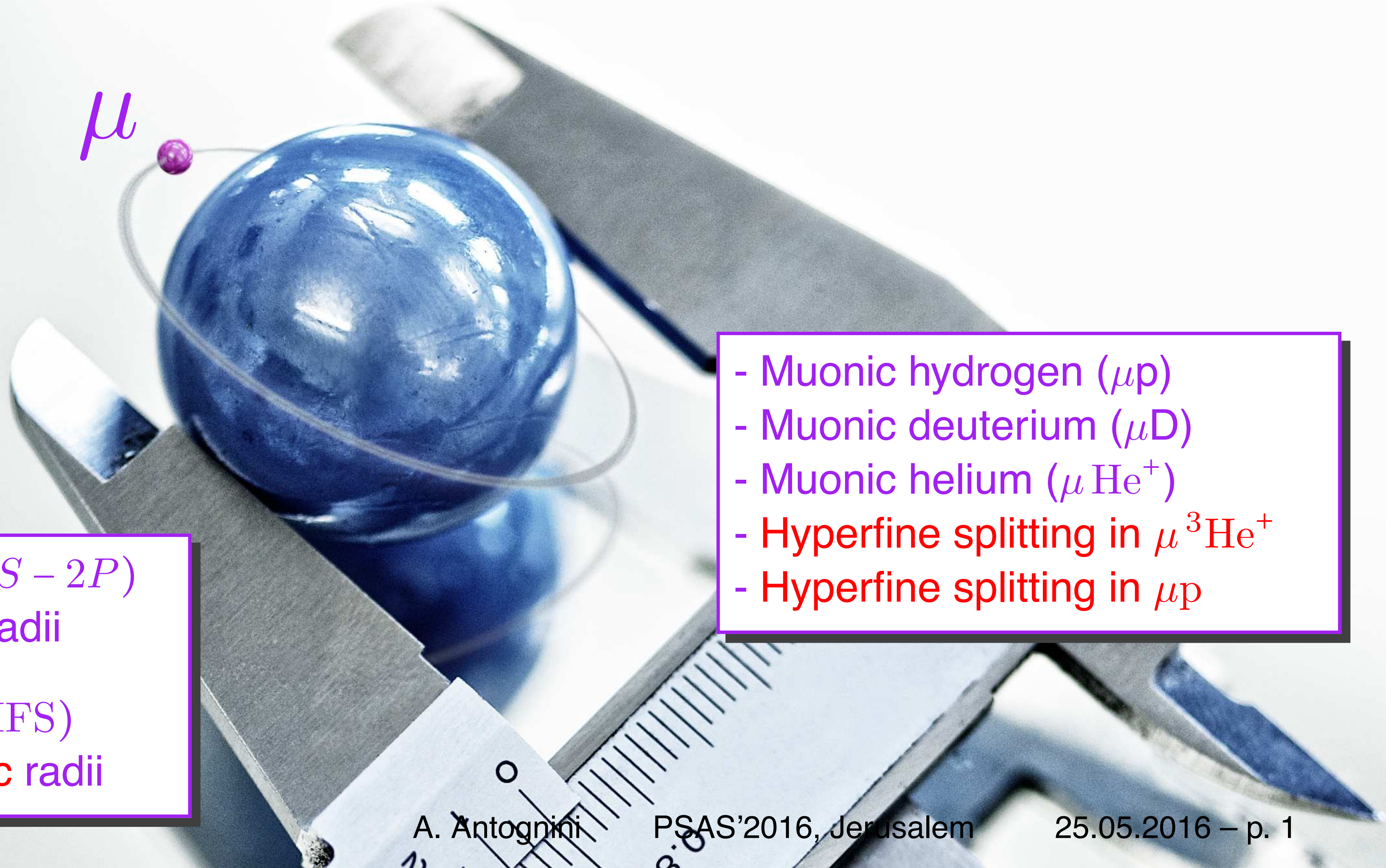
Hyperfine splitting in μp and $\mu\,^3$He$^+$

CREMA collaboration



Hyperfine splitting in μp and $\mu\,^3He^+$

CREMA collaboration

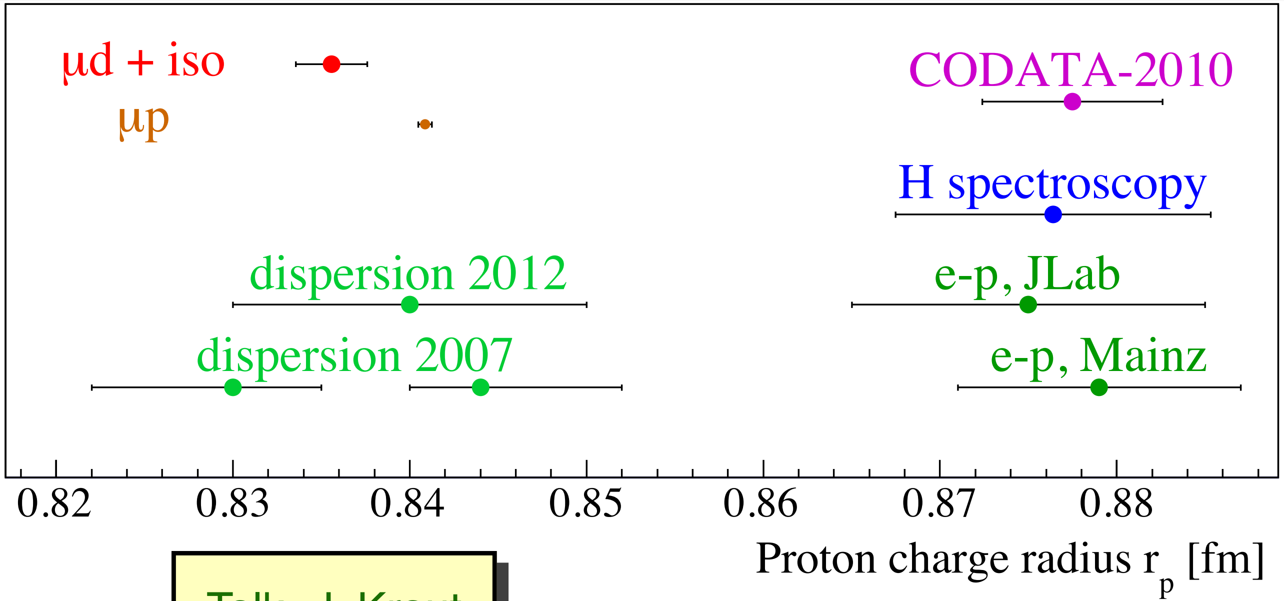


- Muonic hydrogen (μp)
- Muonic deuterium (μD)
- Muonic helium ($\mu\,He^+$)
- Hyperfine splitting in $\mu\,^3He^+$
- Hyperfine splitting in μp

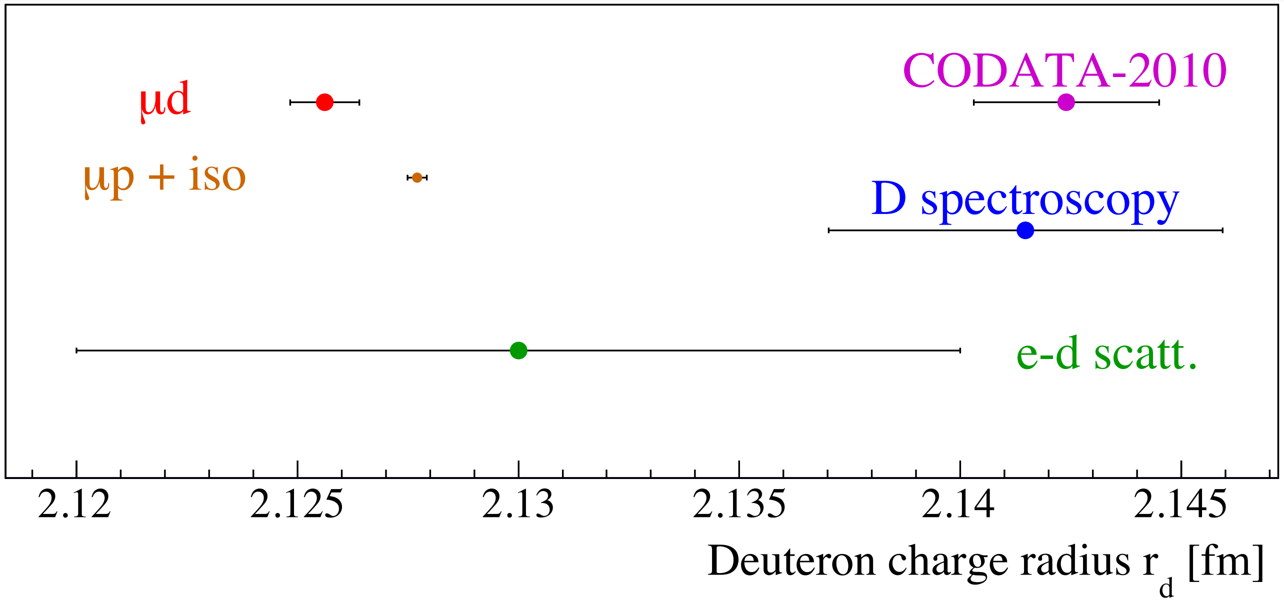
Measure $\Delta E(2S-2P)$
→ charge radii

Measure $\Delta E(\mathrm{HFS})$
→ magnetic radii

Proton and deuteron puzzles ?



Talk: J. Kraut



Charge and magnetic radii from scattering

Extraction of R_E from scattering is difficult

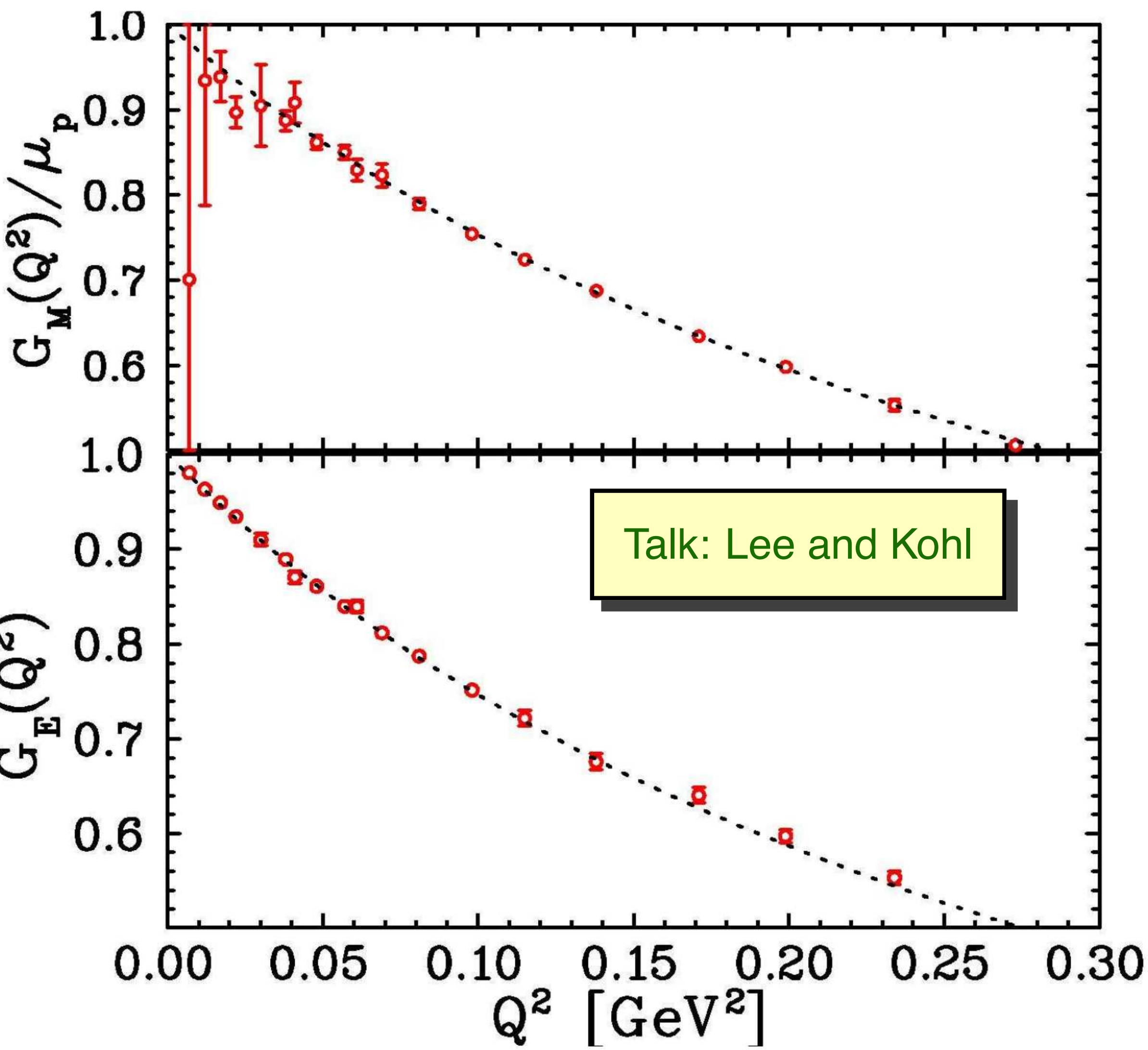
Extraction of R_M from scattering is more difficult

$$\langle R^2_{\mathrm{E/M}} \rangle = -6 \frac{dG_{E/M}(Q^2)}{dQ^2}\Big|_{Q^2=0}$$

$$G_E(Q^2) = 1 - \frac{Q^2}{6}\langle r_{\mathrm{p}}^2 \rangle + \frac{Q^4}{120}\langle r_{\mathrm{p}}^4 \rangle + \ldots$$

- Low Q^2 yields slope but sensitivity is small
- Need larger lever-arm to get slope
- Larger Q^2 more sensitive but higher-order terms
- Need to have physical model or constraints
- Need to have fit function with enough flexibility but not to much

JA, W. Melnitchouk, J. Tjon, PRC 76, 035205 (2007)



Talk: Lee and Kohl

Hyperfine splitting vs. 2S-2P spectroscopy

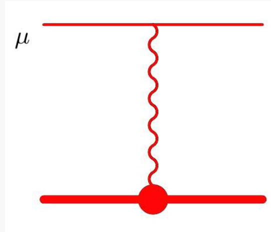
- The 2S-2P energy splitting (Lamb shift)

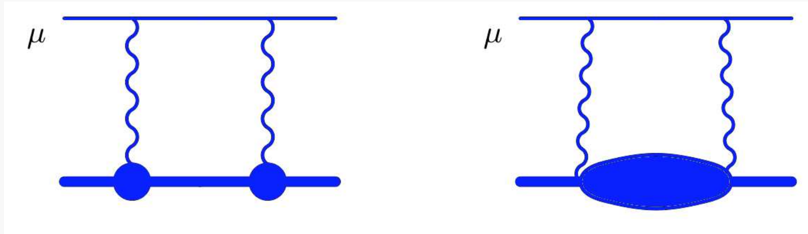
$$E_L^{\mathrm{th}} = 206.0336(15) - 5.2275(10)R_E^2 + 0.0332(20) \text{ meV}$$

$$\Delta E_{\text{finite size}} = \frac{2\pi Z\alpha}{3}|\phi(0)|^2 R_E^2$$

$$R_E = -\frac{6}{G_E(0)}\frac{dG_E}{dQ^2}\Big|_{Q^2=0}$$

$$R_E^2 \approx \int d\vec{r}\,\rho_E(\vec{r})r^2$$





TPE: Two photon exchange

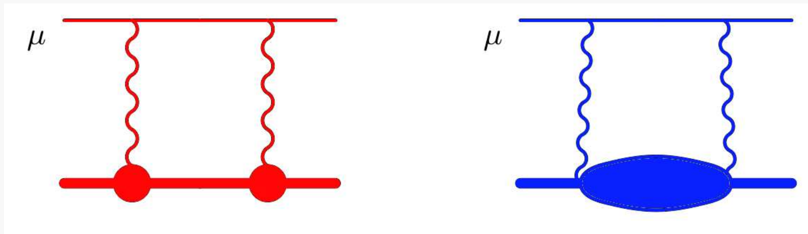
- The hyperfine splitting $\Delta E^0_{\mathrm{HFS}} \sim (Z\alpha)\langle\vec{\mu}_\mu\cdot\vec{\mu}_N\rangle\,|\phi(0)|^2$

$$\Delta E_{\mathrm{HFS}}^{\mathrm{th}} = 182.819(1) - 1.301 R_Z + 0.064(21) \text{ meV}$$

$$\Delta E_{\text{finite size}} = -2(Z\alpha)m_r\,\Delta E^0_{\mathrm{HFS}}\,R_Z$$

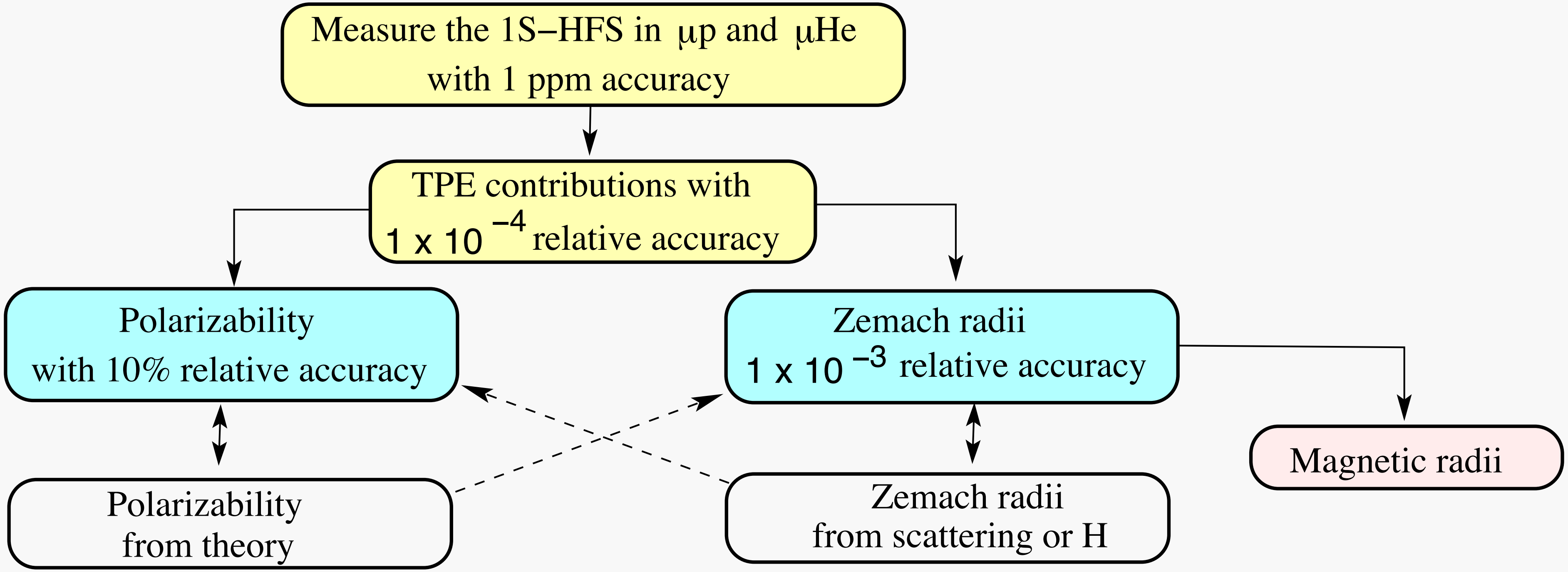
$$R_Z = -\frac{4}{\pi}\int_0^\infty \frac{dQ}{Q^2}\left(G_E(Q^2)\frac{G_M(Q^2)}{1+\kappa_p} - 1\right)$$

$$R_Z = \int d^3\vec{r}\,|\vec{r}|\int d^3\vec{r'}\rho_E(\vec{r}-\vec{r'})\rho_M(\vec{r'})$$

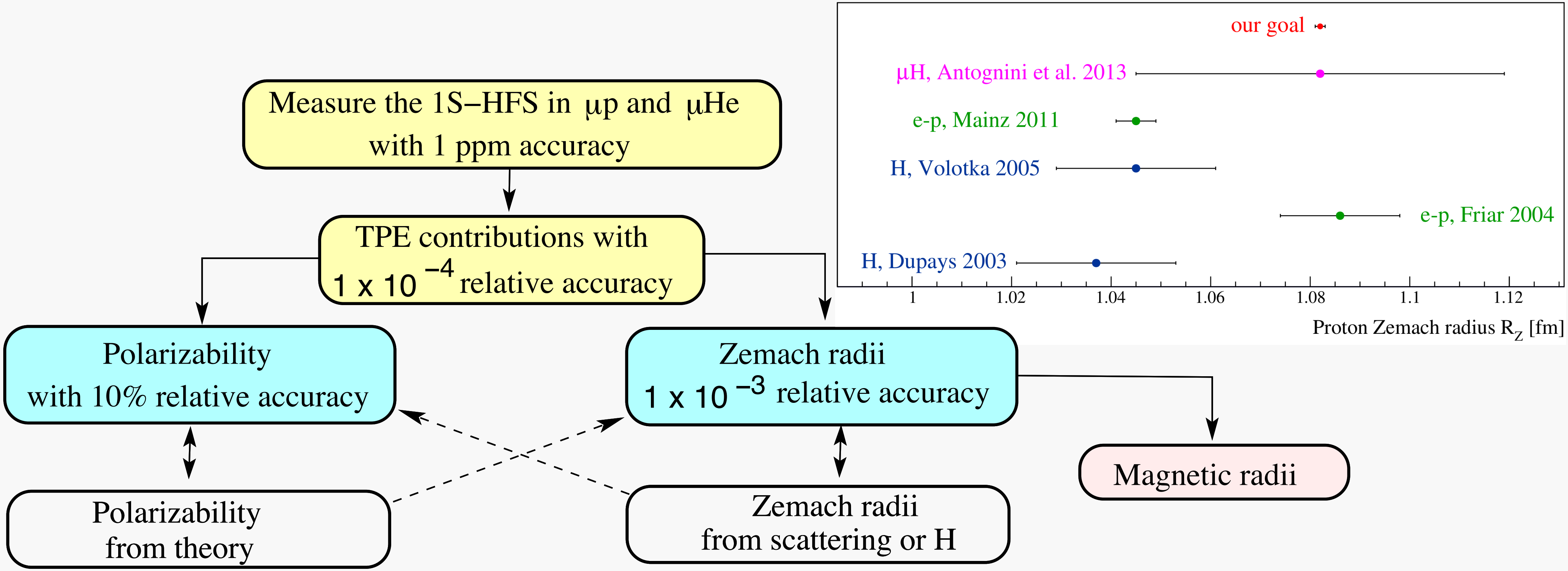


TPE: Two-photon-Exchange

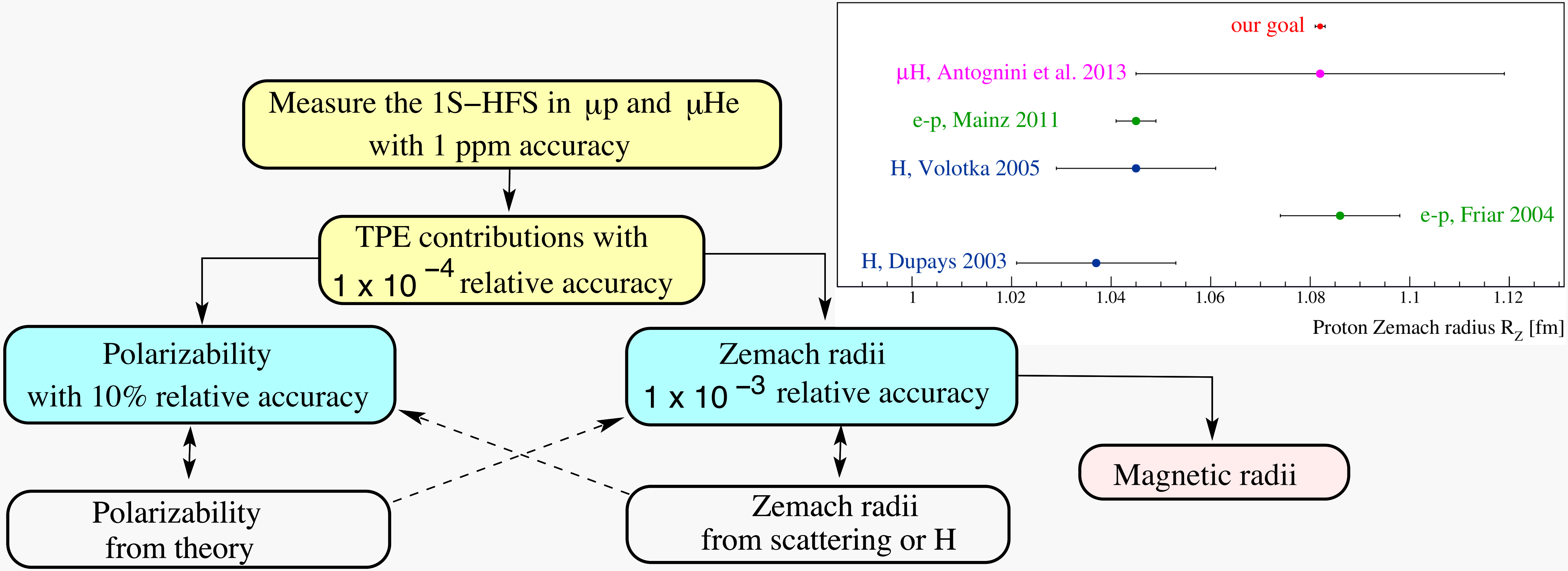
Objectives and impact



Objectives and impact



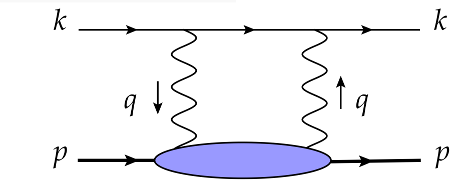
Objectives and impact



- Precision experiments: → hold the potential for surprises
- Radii: → benchmarks for lattice QCD and few-nucleon th.
  → compare with scattering and H/He spectroscopy
  → solve discrepancy between proton R_M
- Polarizablizty contributions → compare to ChPT, dispersion+data, few-nucleon th.
- TPE contributions → compare to dispersion+data, few-nucleon th.

Two ways to the polarizability contribution

ChPT



Phenomenological:

dispersion relations

+ $g_1(x, Q^2)$, $g_2(x, Q^2)$

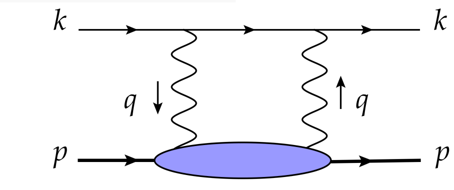
+ sum rules

2S-2P: Agreement

HFS: First preliminary ChPT results

Two ways to the polarizability contribution

ChPT



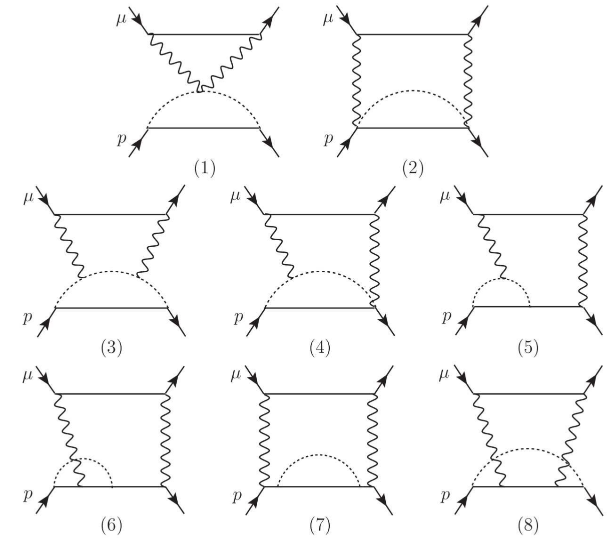
Phenomenological:

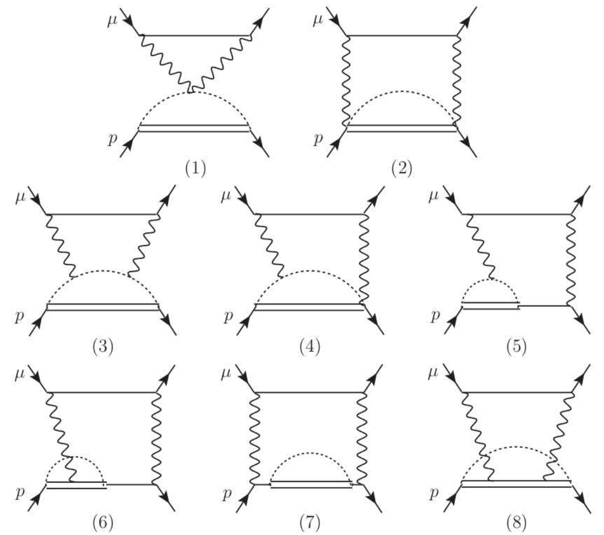
dispersion relations

+ $g_1(x, Q^2)$, $g_2(x, Q^2)$

+ sum rules

talk Carlson





2S-2P: Agreement

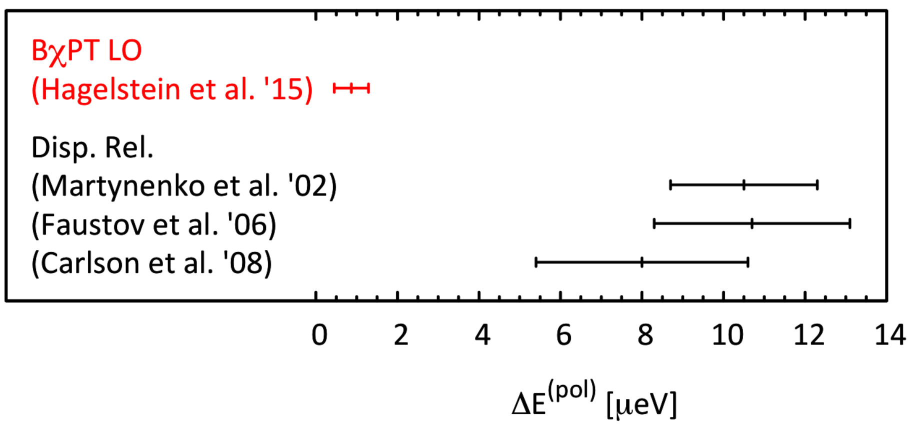
HFS: First preliminary ChPT results

HFS theory status

$$\Delta E_{\mathrm{HFS}}(1S) = [1 + \Delta_{\mathrm{QED}} + \Delta_{\mathrm{weak+hVP}} + \underbrace{\Delta_{\mathrm{Zemach}} + \Delta_{\mathrm{recoil}} + \Delta_{\mathrm{pol}}}_{\Delta_{\mathrm{TPE}}}]\Delta E_0^{\mathrm{HFS}}$$

Phys. Rev. A 68 052503, Phys. Rev. A 83, 042509, Phys. Rev. A 71, 022506

	μp		$\mu\,^3$He$^+$		
	Magnitude	Uncertainty	Magnitude	Uncertainty	
$\Delta E_0^{\mathrm{HFS}}$	182.443 meV	0.1×10^{-6}	1370.725 meV	0.1×10^{-6}	
Δ_{QED}	1.1×10^{-3}	1×10^{-6}	1.2×10^{-3}	1×10^{-6}	
$\Delta_{\mathrm{weak+hVP}}$	2×10^{-5}	2×10^{-6}			
Δ_{Zemach}	7.5×10^{-3}	7.5×10^{-5}	3.5×10^{-2}	2.2×10^{-4}	$\leftarrow G_E(Q^2), G_M(Q^2)$
Δ_{recoil}	1.7×10^{-3}	10^{-6}	2×10^{-4}		$\leftarrow G_E, G_M, F_1, F_2$
Δ_{pol}	4.6×10^{-4}	8×10^{-5}	$(3.5\times10^{-3})^*$	$(2.5\times10^{-4})^*$	$\leftarrow g_1(x,Q^2), g_2(x,Q^2)$



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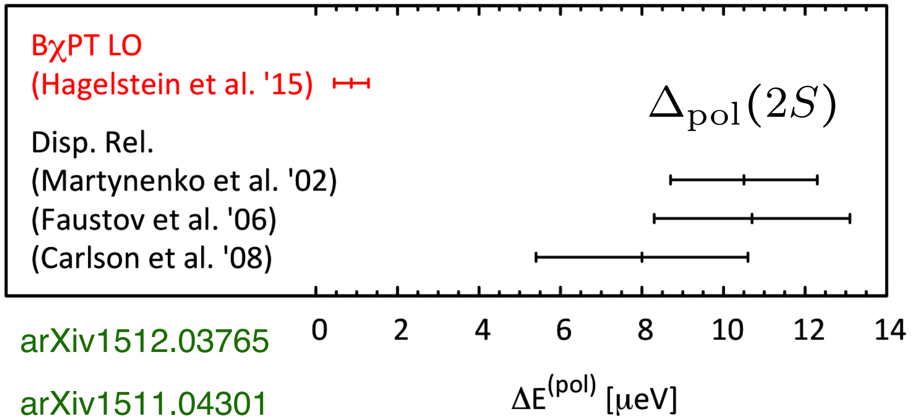

arXiv1512.03765

arXiv1511.04301

$\delta\Delta E_{\mathrm{pol}} = 15\ \mu$eV but
ChPT groups have been triggered
Ongoing measuremnts of g_2 at JLab

HFS theory status

$$\Delta E_{\rm HFS}(1S) = [1 + \Delta_{\rm QED} + \Delta_{\rm weak+hVP} + \underbrace{\Delta_{\rm Zemach} + \Delta_{\rm recoil} + \Delta_{\rm pol}}_{\Delta_{\rm TPE}}]\Delta E_0^{\rm HFS}$$

Phys. Rev. A 68 052503, Phys. Rev. A 83, 042509, Phys. Rev. A 71, 022506

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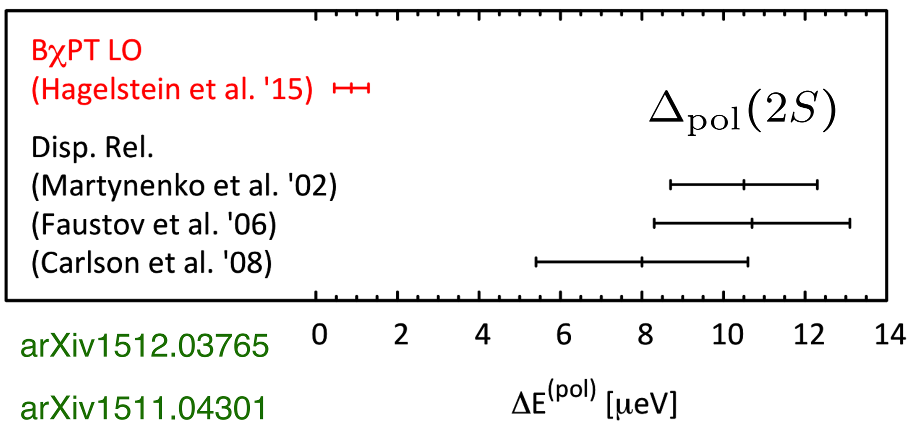


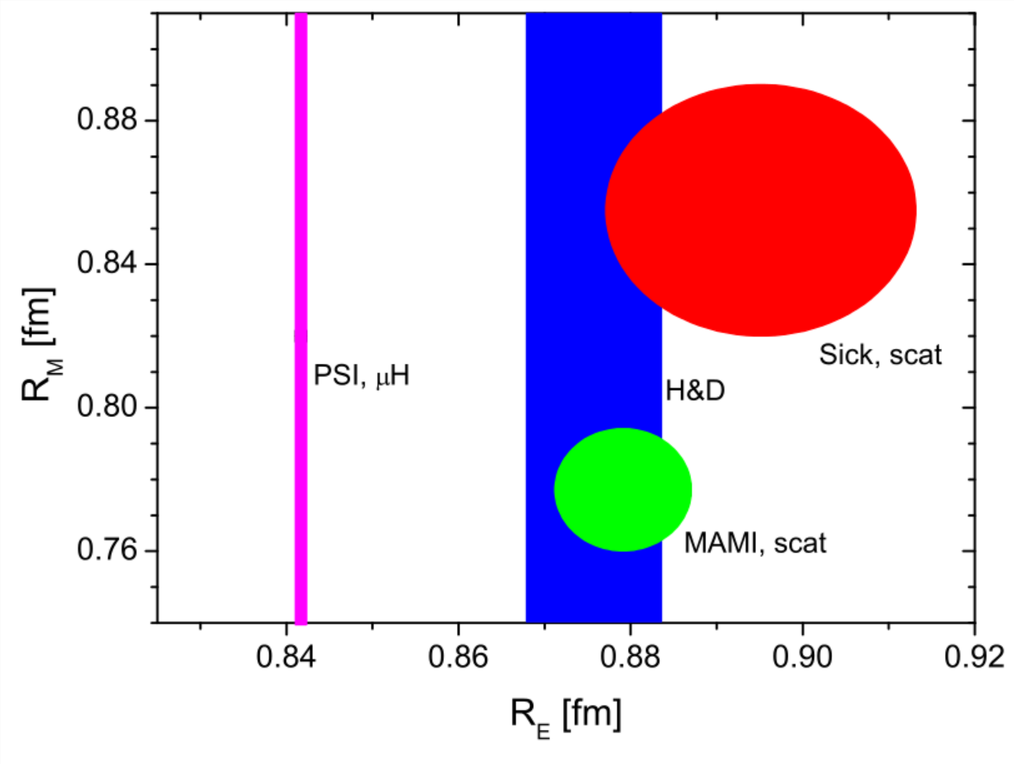
arXiv1512.03765

arXiv1511.04301

Not yet computed but
$\frac{\delta\Delta E_{\rm pol}}{\Delta E_{\rm pol}} = 5\%$ for the 2S-2P
$\frac{\Delta E_{\rm pol}}{\Delta E_{\rm Zemach}} < 10\%$ from prel. 2S-2P analysis

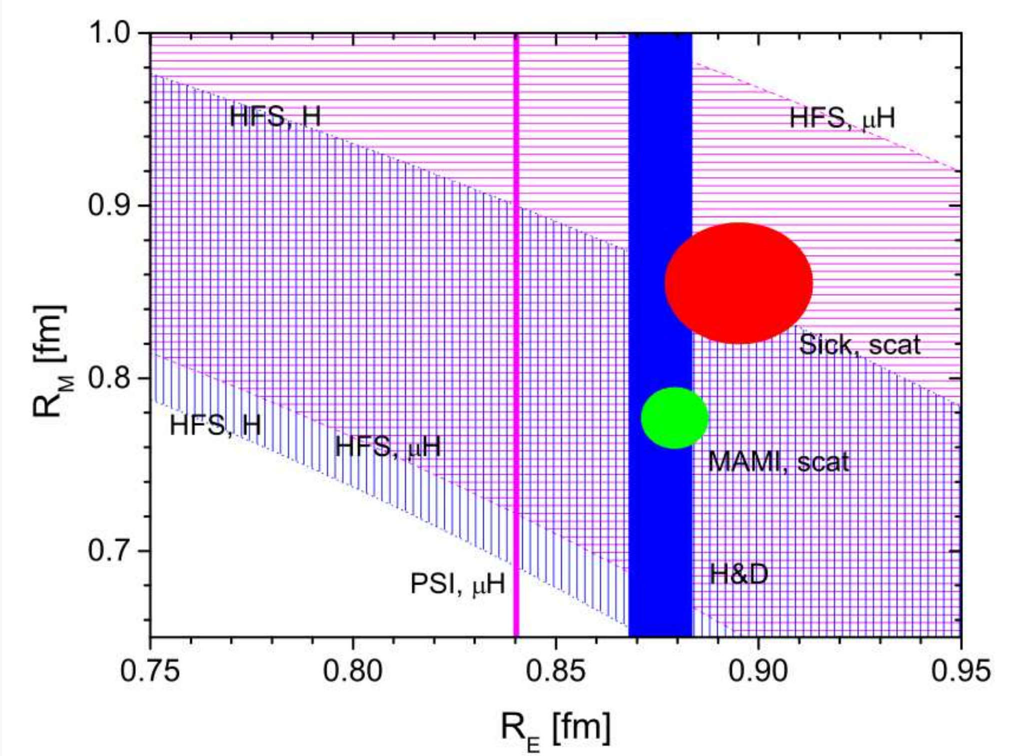
$\delta\Delta E_{\rm pol} = 15\ \mu$eV but
ChPT groups have been triggered
Ongoing measuremnts of g_2 at JLab

Magnetic radius from the hyperfine splitting



Extraction of R_M from R_Z

requires models for the form factors



Model-independent determinations:

$R_E^2 + R_M^2 = 1.35(12)$ fm^2 (H)

$R_E^2 + R_M^2 = 1.49(18)$ fm^2 (μp)

Karshenboim, arXiv:1405.6515

Principle of the HFS experiments

μ^- stops in gas and forms a muonic atom

A laser pulse drives the hyperfine transition

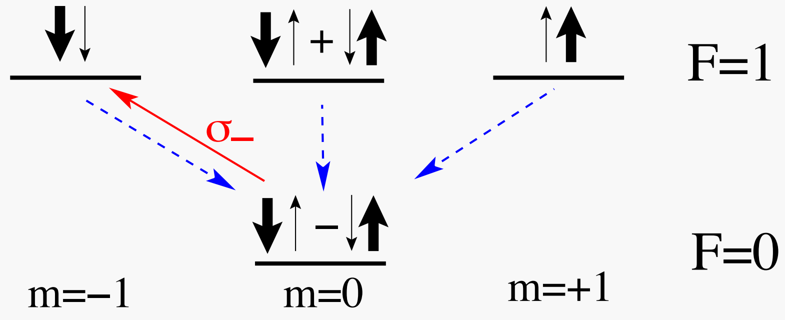
Need a method to detect the occurred transition

Plot number of detected transitions versus the laser frequency

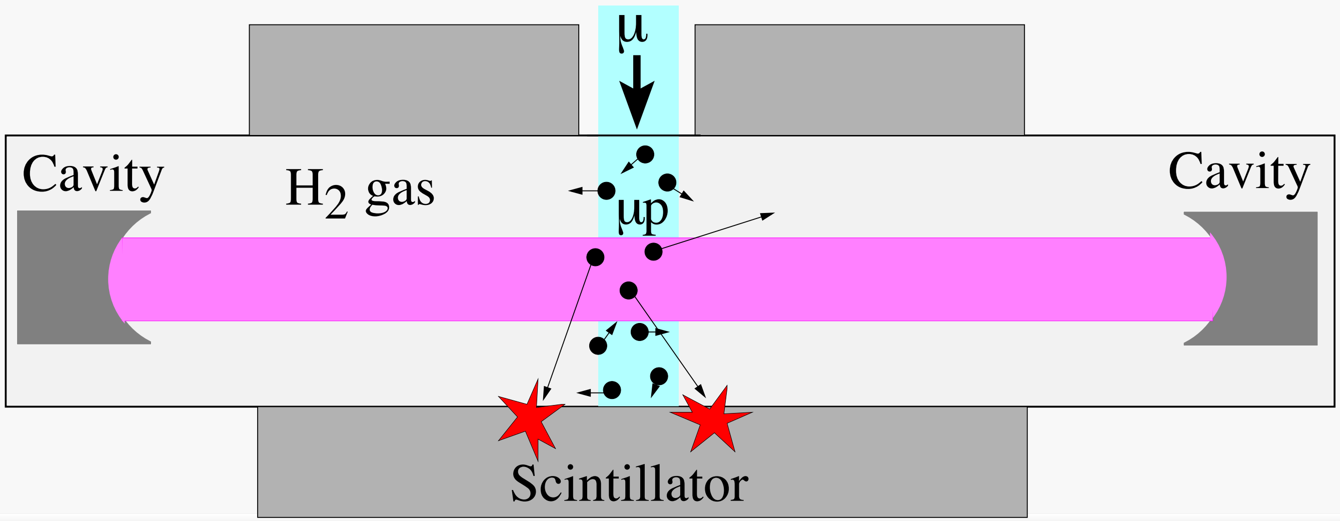
see also talk A. Vacchi

Principle of the μp HFS experiment

- μ^- of 10 MeV/c are detected $\longrightarrow$ trigger the laser
  - μ^- stops in H_2 gas (500 mbar, 50 K) $\longrightarrow$ μp(F=0) formation



- 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
- At the wall: μ^- transfer to high-Z atom $\longrightarrow$ $(\mu Z)^*$ formation
  - $(\mu Z)^*$ de-excitation → MeV X-rays, e$^-$ and μ^- capture
    - Resonance: Number of X-rays/e$^-$/capture signals after laser excitation versus laser frequency



Signal events:

Laser excited μp

reach wall in $t \in [t_{\text{laser}}, t_{\text{laser}} + \Delta t]$

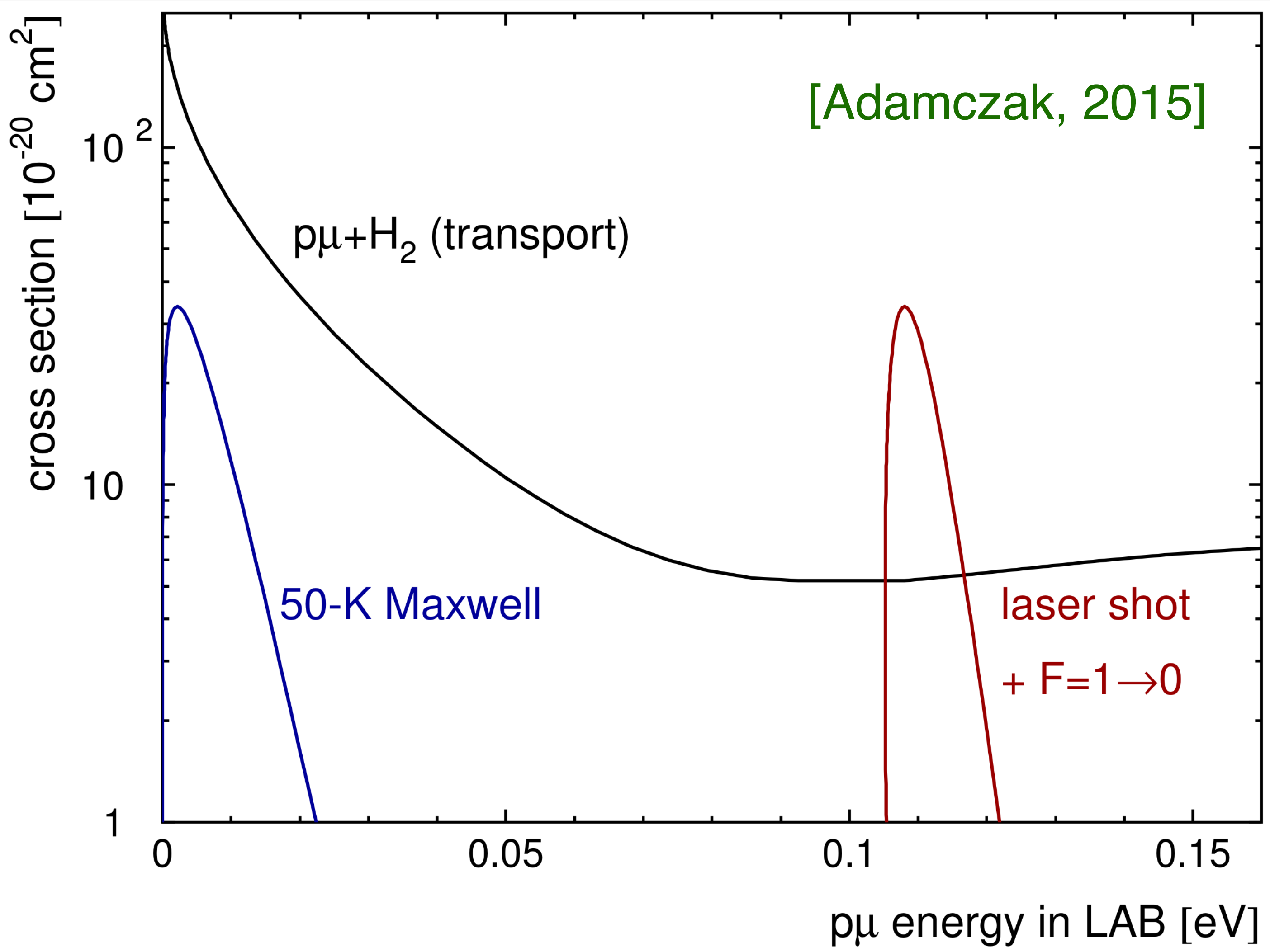
Background events:

Thermalized μp

reach wall in $t \in [t_{\text{laser}}, t_{\text{laser}} + \Delta t]$

$\Rightarrow$ Cool target to 50 K

Cross sections: thermalized vs. laser excited



Diffusion radius of μp in H_2 gas

$$R \approx \sqrt{\frac{vt}{\sigma_{\mathrm{trans}} N}}$$

[Adamczak, EPJD 41, 493 (2007)]

Efficiencies and event rates

		Signal	Background
#1	Muon beam at 10 MeV/c with 5 mm diameter	600 /s	600 /s
#2	Anti-coincidence rejection	6×10^{-1}	6×10^{-1}
#3	$\Longrightarrow$ Laser and DAQ trigger rate	240 /s	240 /s
#4	Stops in gas (after anti-rejection)	6×10^{-1}	7×10^{-1}
#5	Overlap laser volume/μ stop volume	2×10^{-1}	
#6	μp density decrease due to diffusion	3×10^{-1}	2×10^{-1}
#7	μ^- decay prior to laser time	5×10^{-1}	5×10^{-1}
#8	Laser excitation probability ($E = 0.6$ mJ, $N = 400$)	9×10^{-2}	
#9	Fraction of μp with kinetic energy > 0.1 eV	4×10^{-1}	
#10	μp reaching the walls (diffusion + decay...)	1.5×10^{-1}	2×10^{-2}
#11	Detection efficiency for cascade/capture events	5×10^{-1}	5×10^{-1}
#12	Multiplication of efficiencies	5.0×10^{-5}	7.3×10^{-4}
#13	Event rate per hour on resonance	43	635
#14	Time needed to see a 4σ effect over BG	5.5 h	
#15	Time needed for wavelength change	1 h	
#16	Number of points to be measured	170	
#17	Beam time duration (70% up-time + setting up)	12 weeks	

πE5

anti-coincidence

laser: short delay

laser: large energy

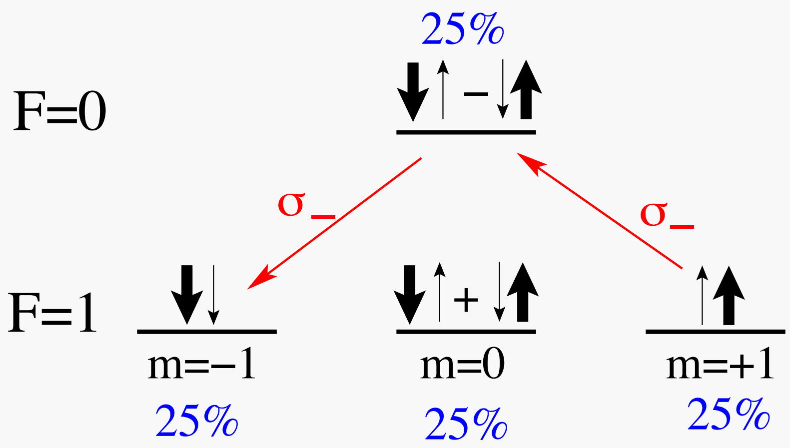
cryogenic cavity

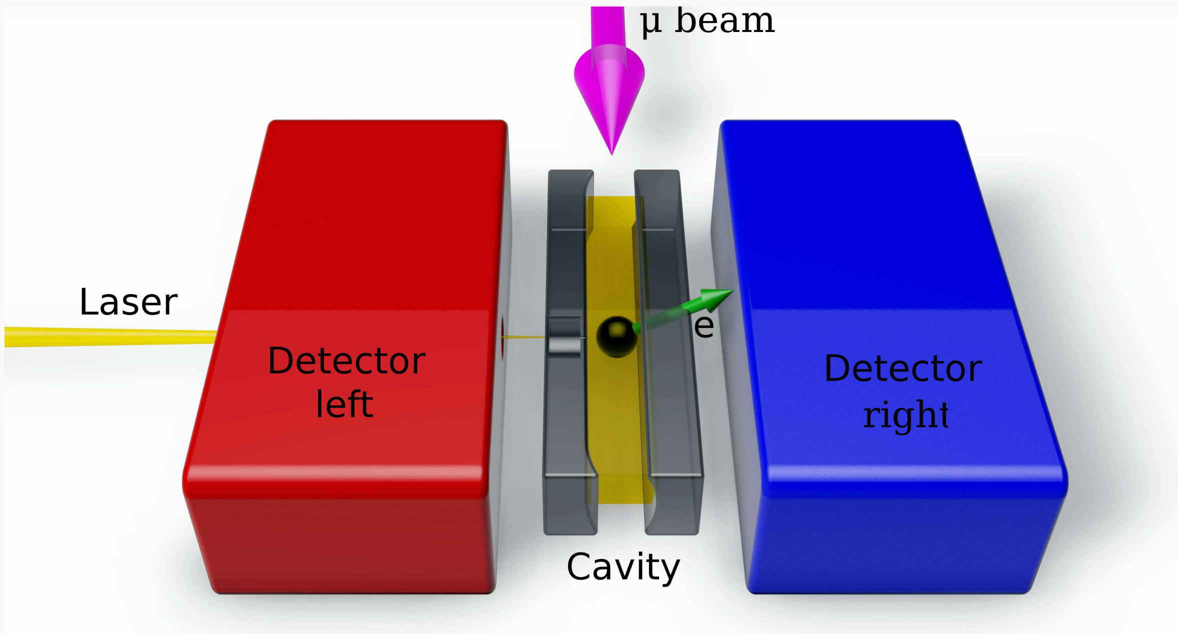
$\pm 3\sigma$ theory uncertainty

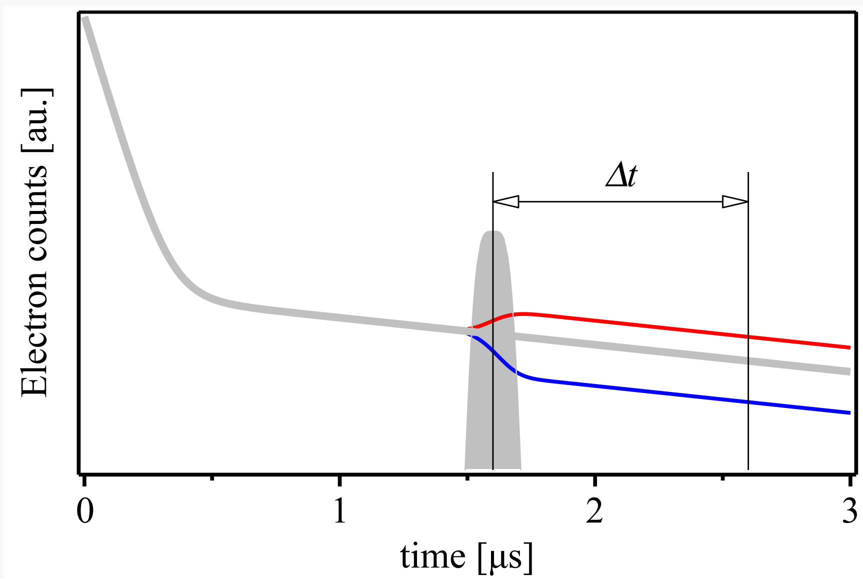
Principle of the $\mu\,^3\mathrm{He}^+$ HFS experiment

- μ^- of 10 MeV/c are detected $\longrightarrow$ trigger a laser
  - μ^- stop in ^{3}He gas (50 mbar, 300 K) $\longrightarrow \mu\,^3\mathrm{He}^+$
- Laser pulse: drives F=0→F=1 and F=1→F=0 transitions

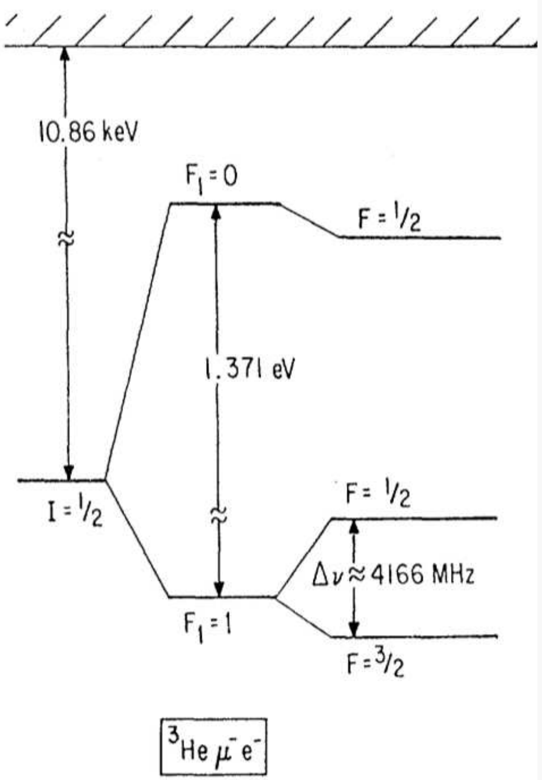
  ⇒ change of the avg. muon polarization
- Detect electron from muon decay
  - Decay asymmetry: $N_e(left)$ increaese, $N_e(right)$ decreaese
    - Resonance: $N_e(left) - N_e(right)$ vs. laser frequency





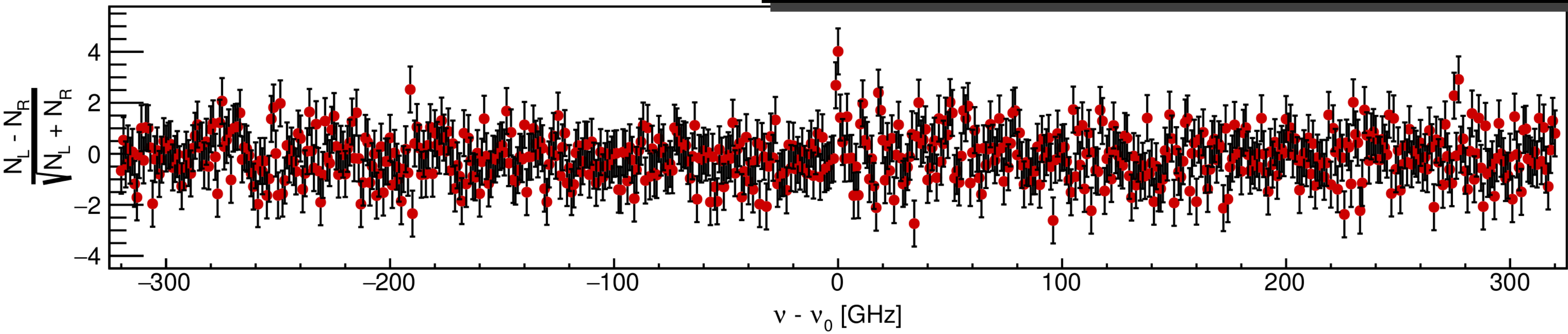


$\mu\,^3\mathrm{He}^+$ resonance search



- $(\mu\mathrm{He})^+ + \mathrm{He} + \mathrm{He} \rightarrow \mathrm{He}(\mu\mathrm{He})^+ + \mathrm{He}$
  - for precision experiment: p = 50 mbar $\left(\tau_{\mu\,\mathrm{He}^+} = 1.8\,\mu s\right)$
  - for resonance search: p = few bar (all muons in molecular state)
- How much the muonic transition is disturbed by the molecule?
  - Shift? Upper limit from μHe-e: 6 ppm [Pachucki and Karr PC]
  - Splitting? Upper limit from μHe-e: 4 GHz / 323 THz = 13 ppm

Number of frequency points:	650
Time needed for a 4σ effect over BG	2 h
Weeks needed for resonance search (scan)	12 (2)



Laser requirements

Experiment	μp 2S-2P (2009)	μp HFS	$\mu\,$He$^+$ 2S-2P (2014)	$\mu\,^3$He$^+$ HFS
Wavelength	6.0 μm	6.7 μm	840-960 nm	930 nm
Pulse energy	0.15 mJ	1.5 mJ	12-6 mJ	50 mJ
Avg. Rate	220 Hz	250 Hz	220 Hz	500 Hz
Bandwidth	300 MHz	$\lesssim 300$ MHz	< 300 MHz	$\lesssim 500$ MHz
Delay	< 1.2 μs	< 1.2 μs	< 1.2 μs	< 1.2 μs
Pulse energy in cavity	0.1 mJ	0.6 mJ	3.5 mJ	40 mJ
Avg. number of reflections	1000	400	1000	1500

$\left(\frac{\Delta\nu}{\nu}\right)_{\mu p} = 5 \times 10^{-6}$ and $\left(\frac{\Delta\nu}{\nu}\right)_{\mu\,\mathrm{He}^+} = 7 \times 10^{-6}$

$\Delta\nu_{\mu p} = 0.22$ GHz and $\Delta\nu_{\mu\,\mathrm{He}^+} = 2.2$ GHz.

Narrow lines:

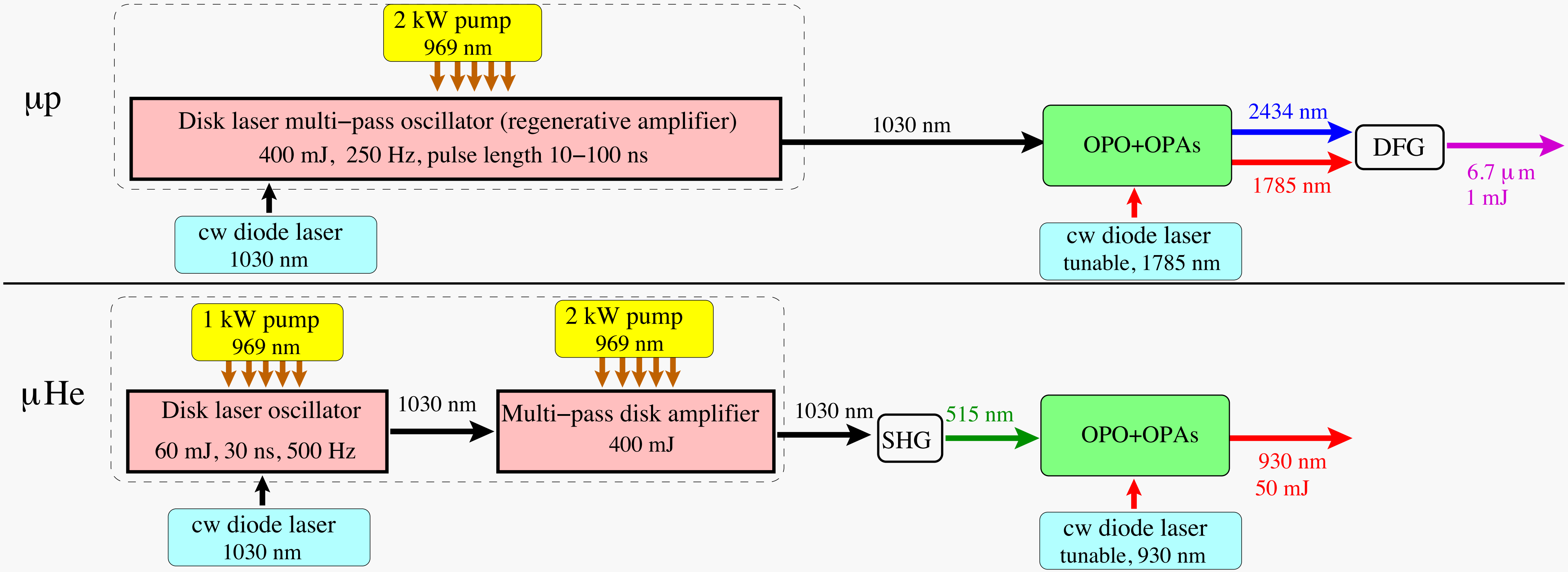
⇒ Difficult to find the line

⇒ Sub-ppm accuracy require little statistics

Systematics

$$=0$$

The laser systems

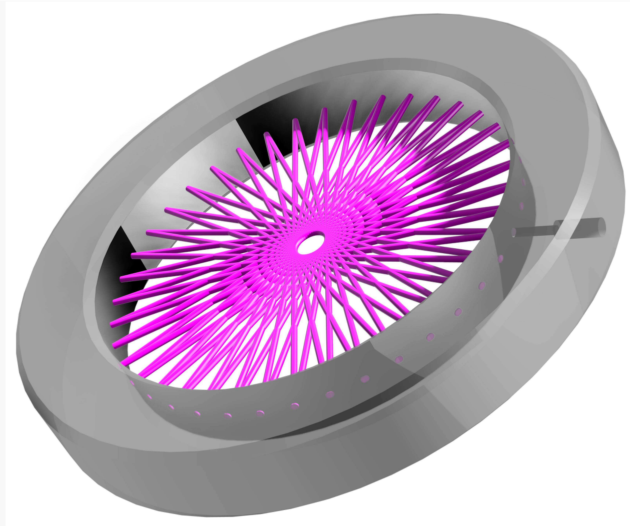


Needs to develop cutting-edge thin-disk laser technologies

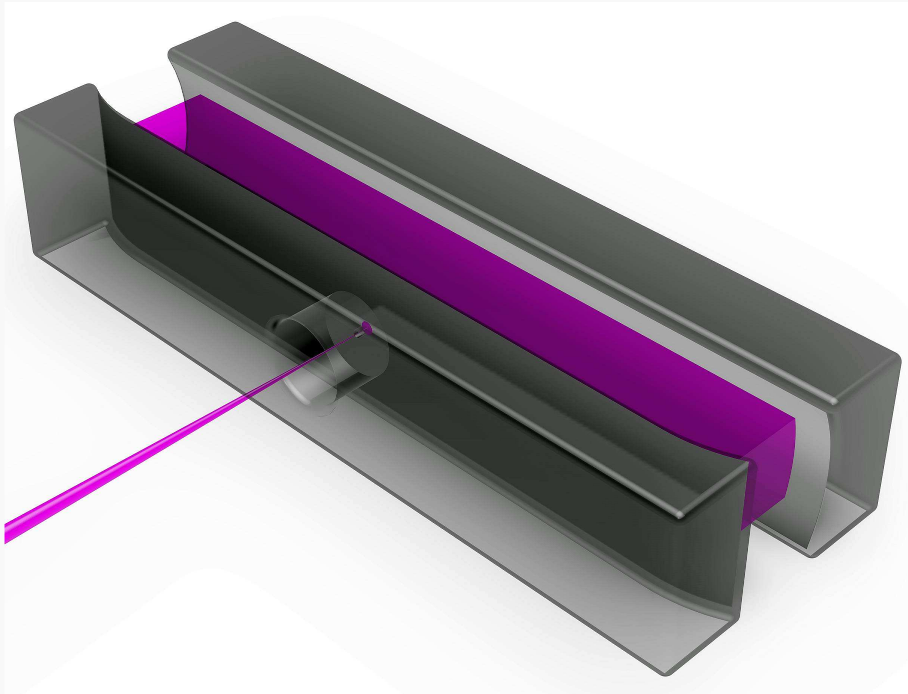
Needs to develop cutting-edge parametric down-conversion stages

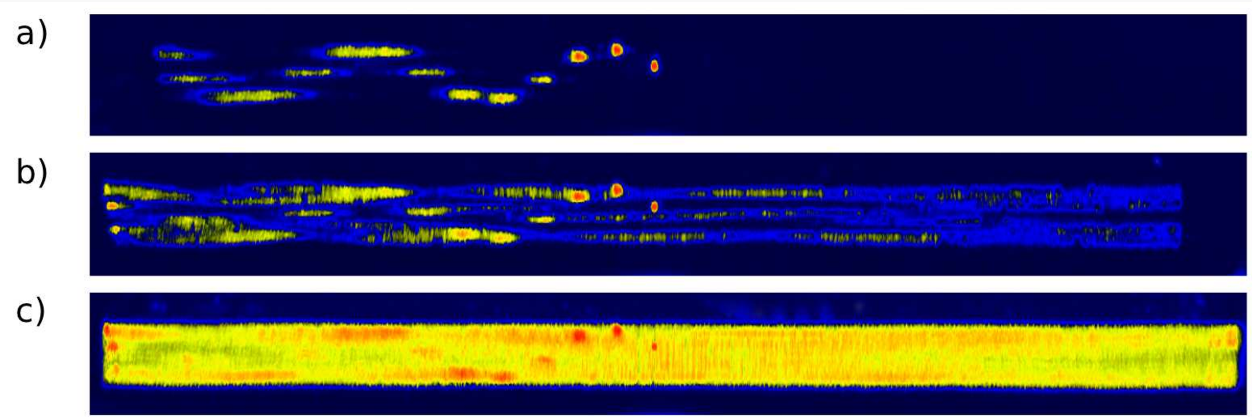
The multi-pass cavities

$$N = \frac{1}{1 - L_{\rm tot}} \qquad\qquad L_{\rm tot} = L_{\rm ref} + L_{\rm hole} + L_{\rm scat} + L_{\rm defect}$$



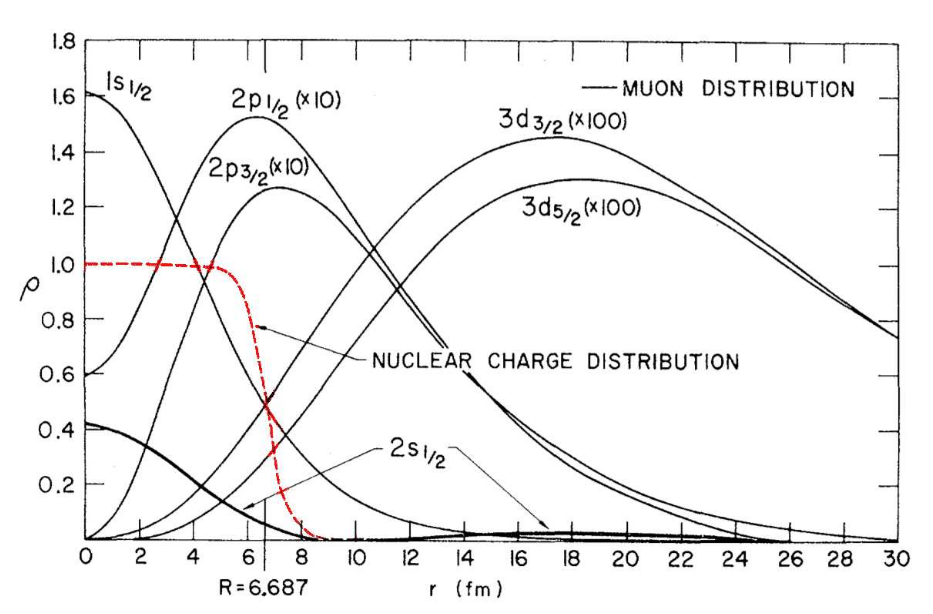
	N	$L_{\rm tot}$	λ	challenge
μp	500	2×10^{-3}	6.7 μm	cryogenics
$\mu\,^3$He$^+$	1500	6×10^{-4}	930 nm	50 mJ pulses



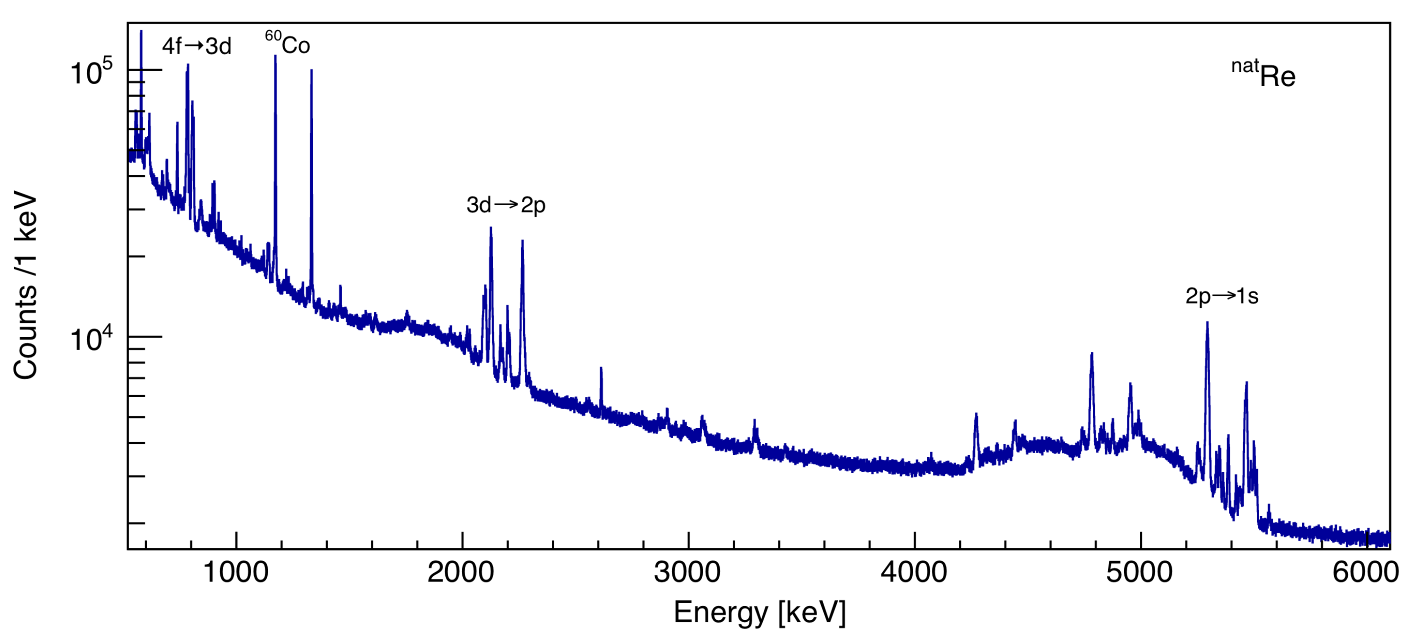


μZ atoms

Properties:
- H-like atoms (electrons can be neglected)
- MeV transition frequencies
- MeV finite size effects



Measure:
- X-ray emitted during the muonic cascade
- using high-resolution Ge detectors



Complications:
- nuclear polarizability
- nuclear excitation during the cascade

μZ atoms: motivation

Atomic parity violation in Ra:

- Measure E1 admixture in E2 transition

  $\rightarrow$ Weinberg angle with 5 fold improvement over Cs

- Charge radius with 0.2% rel. accuracy needed

Measure radioactive nuclei (only μg allowed):

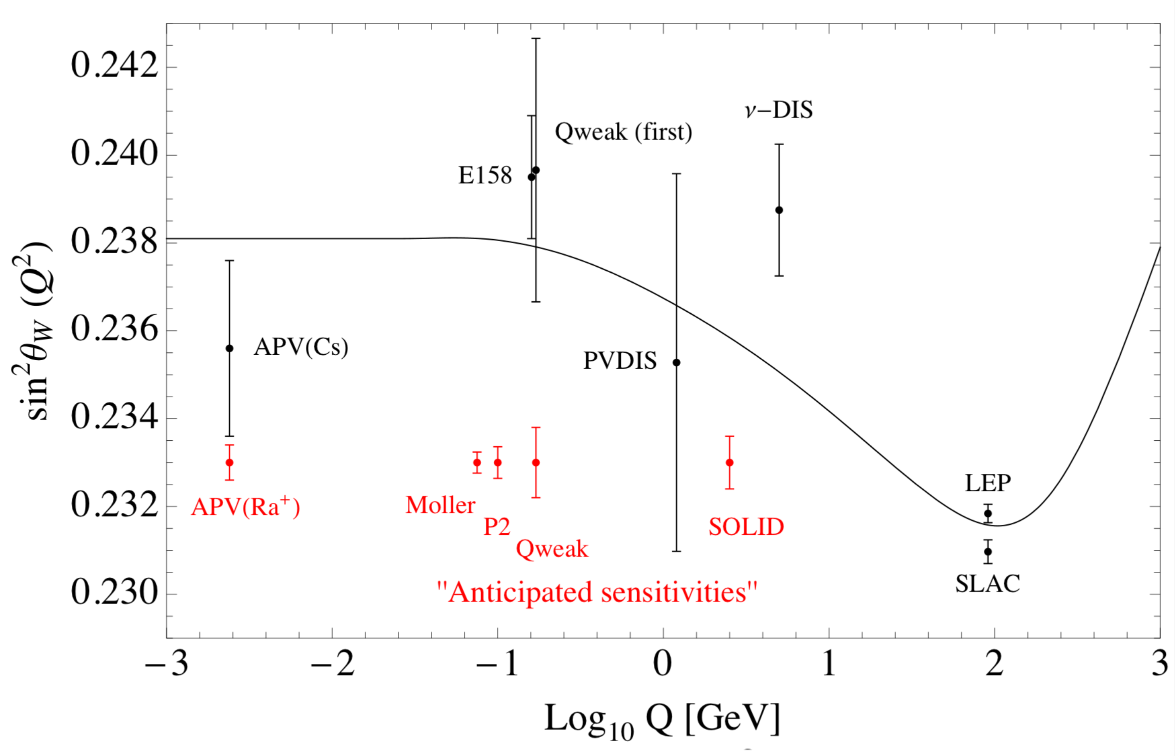
- most of the stable nuclei already measured

  $\rightarrow$ charge radii with 2×10^{-4} rel. accuracy

- some radioactive nuclei

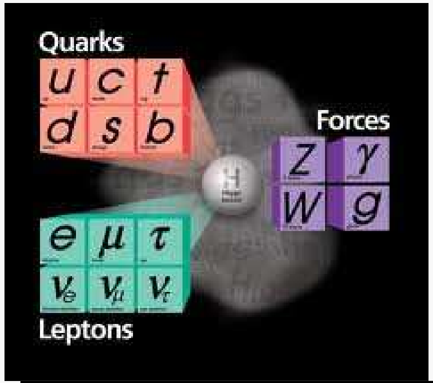
  measurable with our low-energy μ^- beam line

Atomic parity violation with muons (speculative)



Wansbeek et al., PRA **78**, 050501 (2008)
Wood et al., Science **275**, 1759 (1997)
Lee, arXiv:1511.03783 (2015)

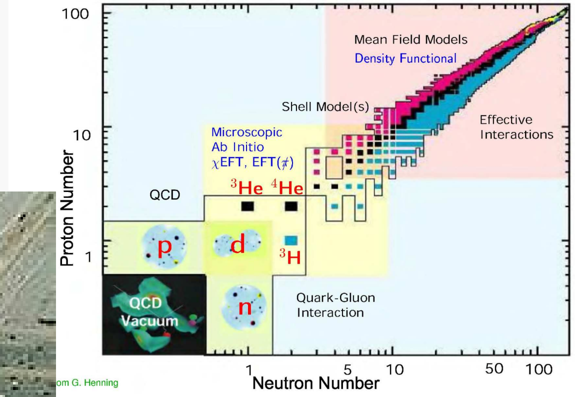
Motivation, summary, outlook



Test of H energy levels
Bound-state QED

Mu= μ^+e^-

Ps= e^+e^-



New physics?
Parity violation?

Scattering

$e + p \rightarrow e + p$

$e + d \rightarrow e + d$

$\mu + p \rightarrow \mu + p$

$\gamma + p \rightarrow \gamma + p$

$e + Z \rightarrow e + Z$

...

r_p, r_d, r_{He}

EFT, χpt, lattice
few-nucleon th.

high-Z radii
quadrupole mom.
mean-field nucl. th.

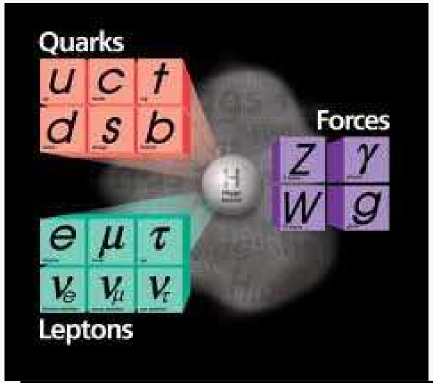
magnetic radii

H, He, H_2^+ spectroscopy

μp, μd, $\mu\mathrm{He}^+$ (2S-2P)
high-Z muonic atoms (radioactive)
HFS in μp and $\mu\mathrm{He}^+$

Fundamental constants

Motivation, summary, outlook



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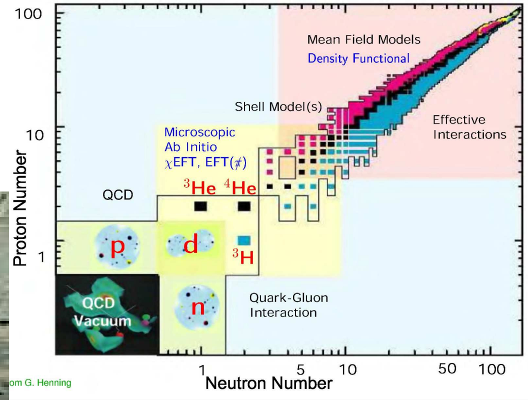

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Fundamental constants

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