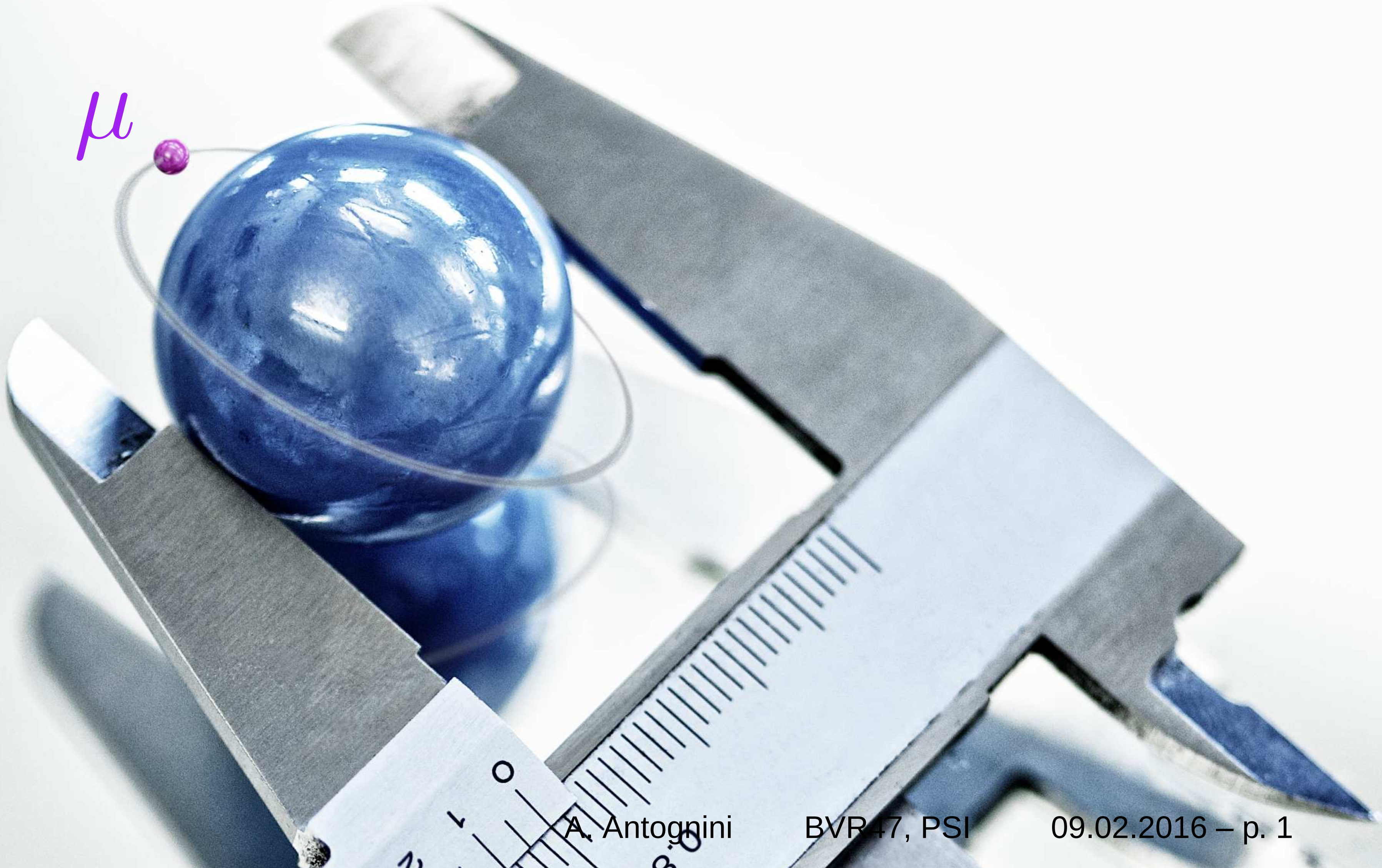
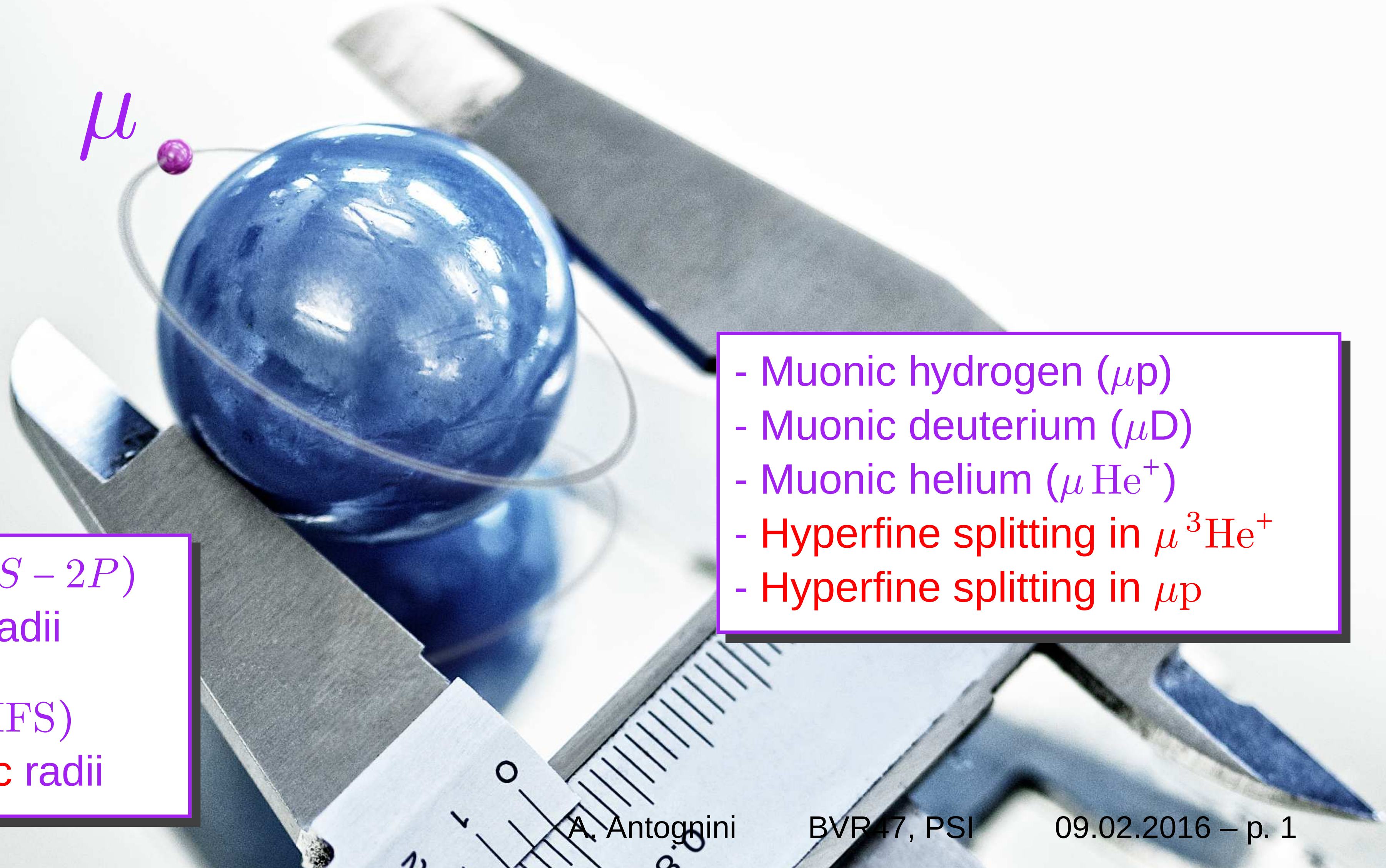
Hyperfine splitting in μp and $\mu\,^3\mathrm{He}^+$

CREMA collaboration



Hyperfine splitting in $\mu\mathrm{p}$ and $\mu\,^3\mathrm{He}^+$

CREMA collaboration



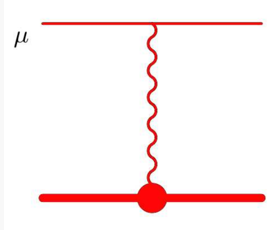
- Muonic hydrogen (μp)
- Muonic deuterium (μD)
- Muonic helium ($\mu\,\mathrm{He}^+$)
- Hyperfine splitting in $\mu\,^3\mathrm{He}^+$
- Hyperfine splitting in $\mu\mathrm{p}$

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

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

Hyperfine splitting vs. 2S-2P spectroscopy

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

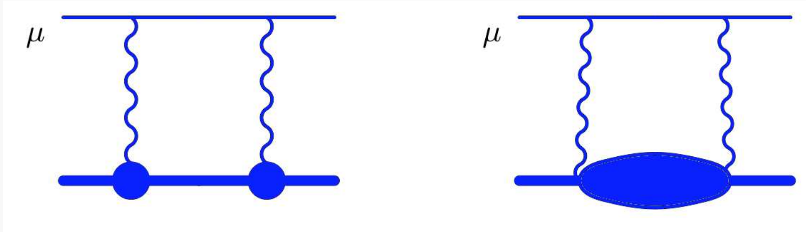


$$E_L^{\rm th} = 206.0336(15) - 5.2275(10) R_E^2 + 0.0332(20) \text{ meV}$$

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

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

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



TPE: Two photon exchange

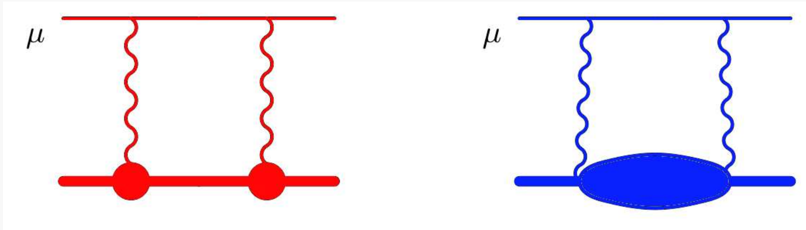
- The hyperfine splitting $\Delta E^0_{\rm HFS} \sim (Z\alpha)\langle \vec{\mu}_\mu \cdot \vec{\mu}_N \rangle |\phi(0)|^2$

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

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

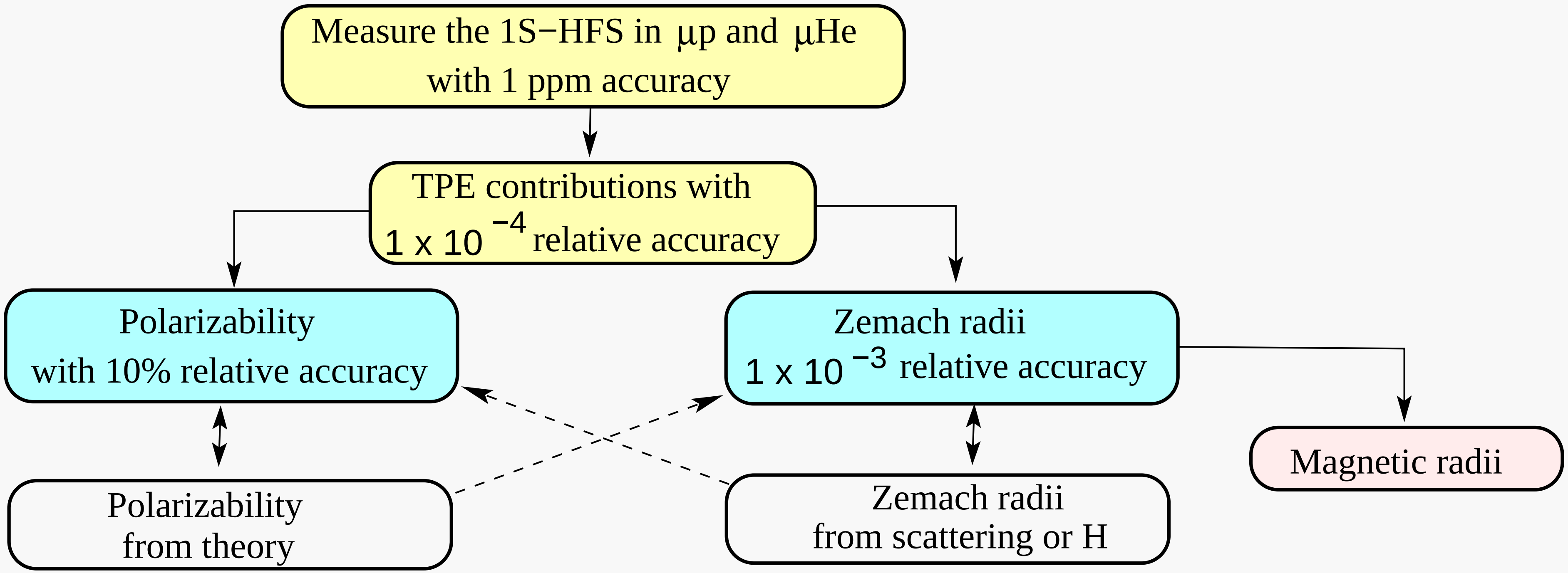
$$R_Z = -\frac{4}{\pi} \int_0^\infty \frac{dQ}{Q^2} \left(G_E(Q^2) \frac{G_M(Q^2)}{1+\kappa_p} - 1 \right)$$

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

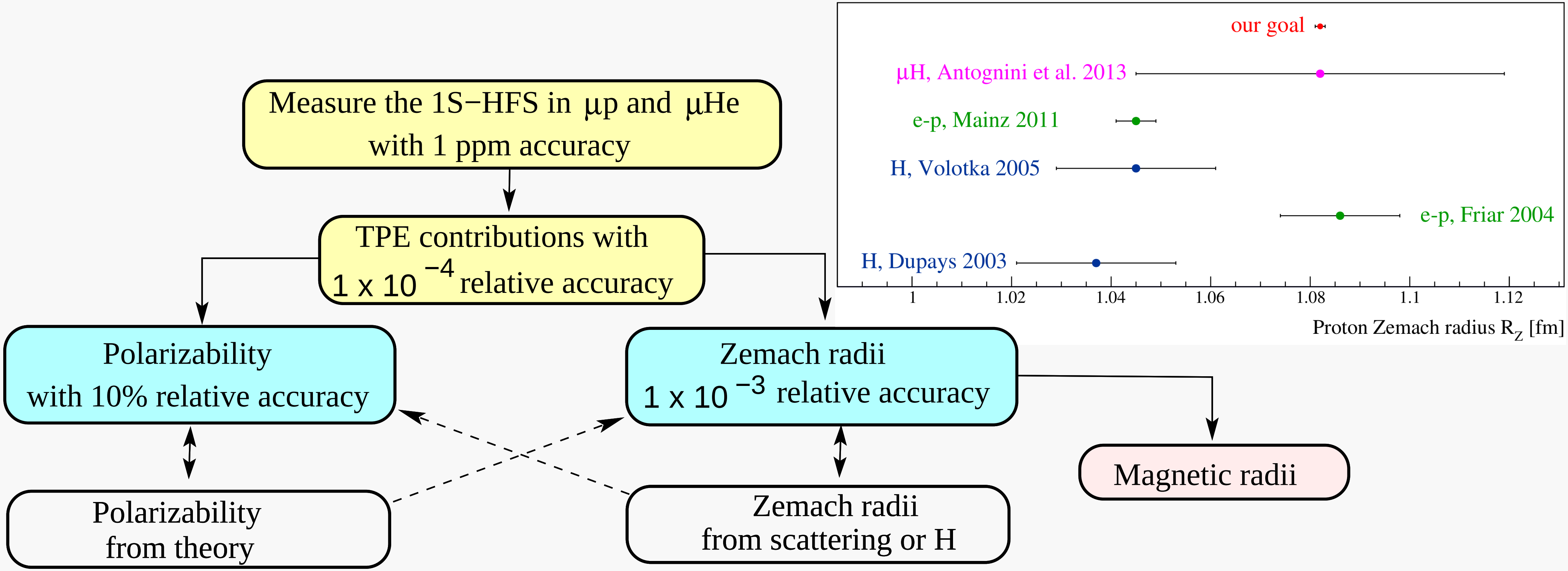


TPE: Two-photon-Exchange

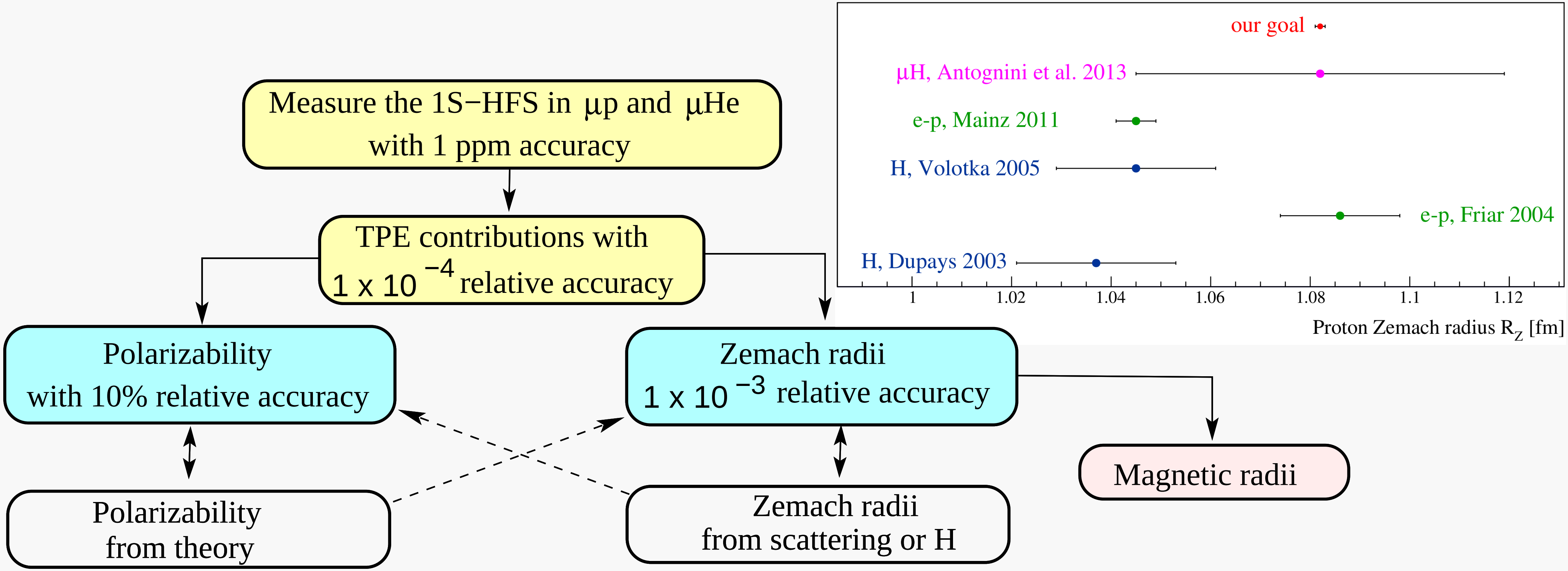
Objectives and impact



Objectives and impact



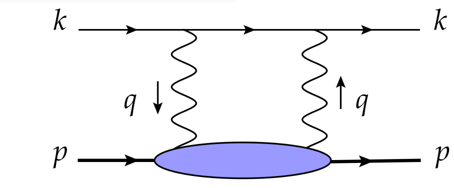
Objectives and impact



- Precision experiment:	→	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
- Polarizabilizty contributions	→	compare to ChPT, dispersion+data, few-nucleon th.
- TPE contributions	→	compare to dispersion+data, few-nucleon th.

Two ways to the two-photon-exchange

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 two-photon-exchange

ChPT

Phenomenological:
dispersion relations
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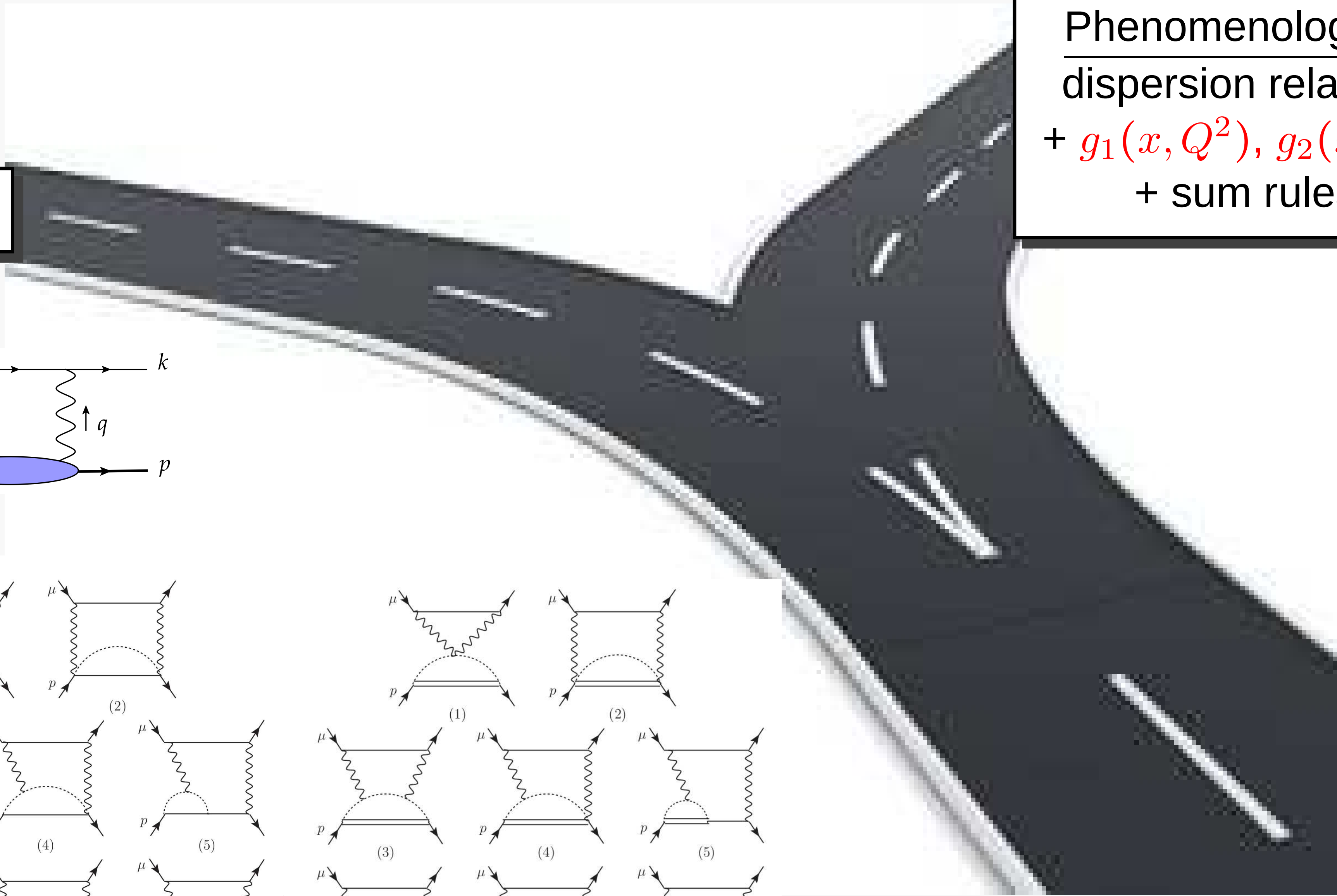
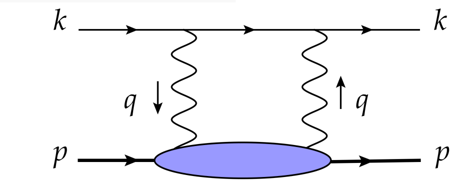
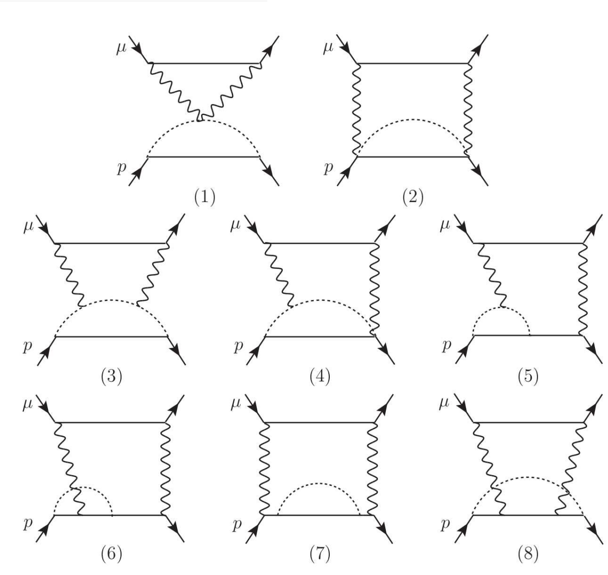






2S-2P: Agreement

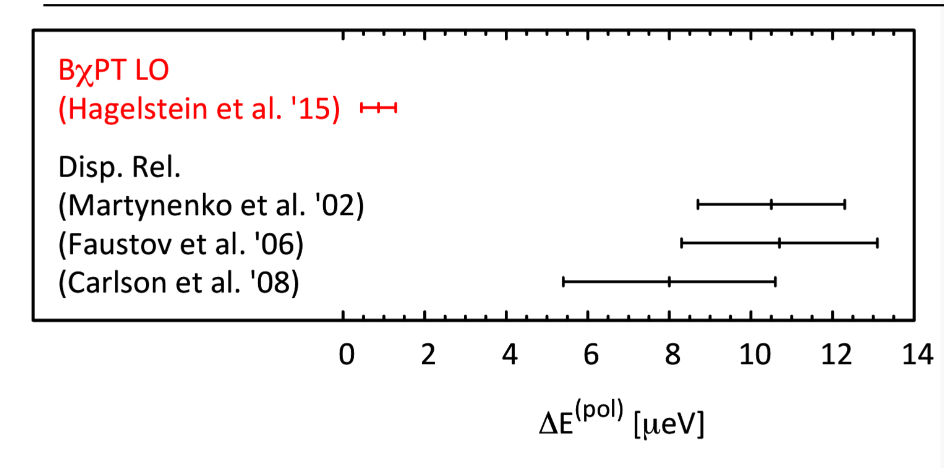
HFS: First preliminary ChPT results

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}	$(3.5 \times 10^{-3})^*$	$(2.5 \times 10^{-4})^*$	$\leftarrow g_1(x, Q^2), g_2(x, Q^2)$



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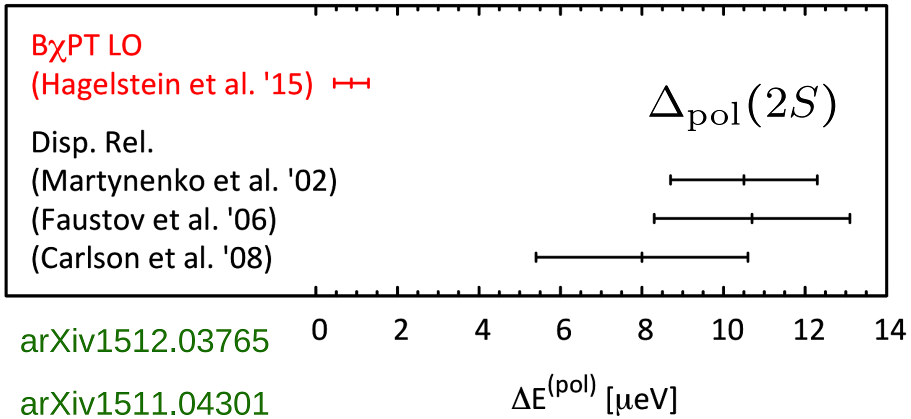

arXiv1512.03765

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

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

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

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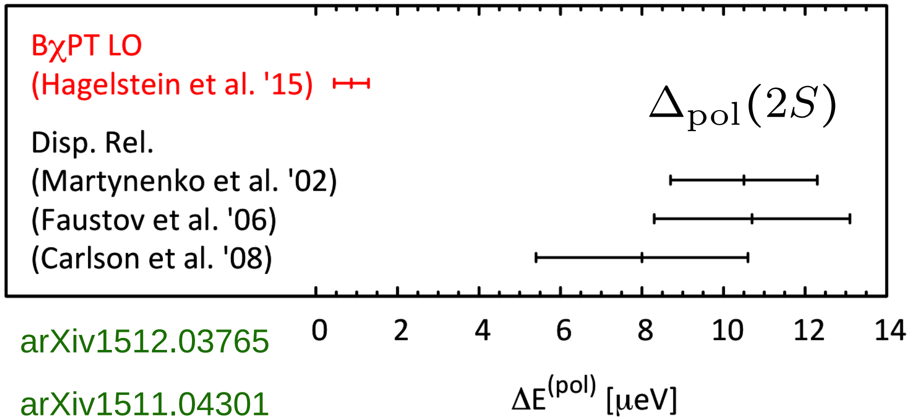


arXiv1512.03765

arXiv1511.04301

Not yet computed but

$\frac{\delta \Delta E_{\text{pol}}}{\Delta E_{\text{pol}}} = 5\%$ for the 2S-2P

$\frac{\Delta E_{\text{pol}}}{\Delta E_{\text{Zemach}}} < 10\%$ from prel. 2S-2P analysis

$\delta \Delta E_{\text{pol}} = 15\ \mu$eV but

ChPT groups have been triggered

Ongoing measuremnts of g_2 at JLab

Principle of the HFS experiments

μ^- stops in gas and forms a muonic atom

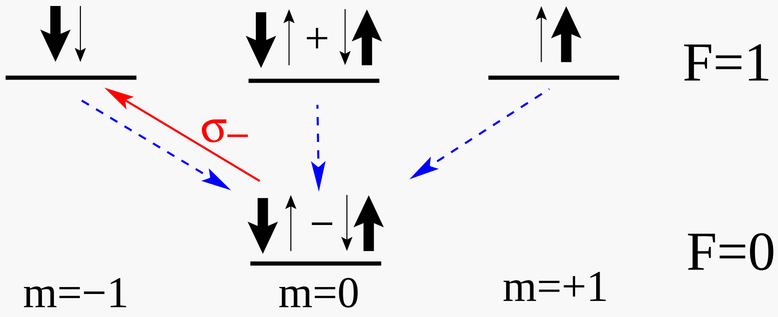
A laser pulse drives the hyperfine transition

Need a method to detect the occurred transition

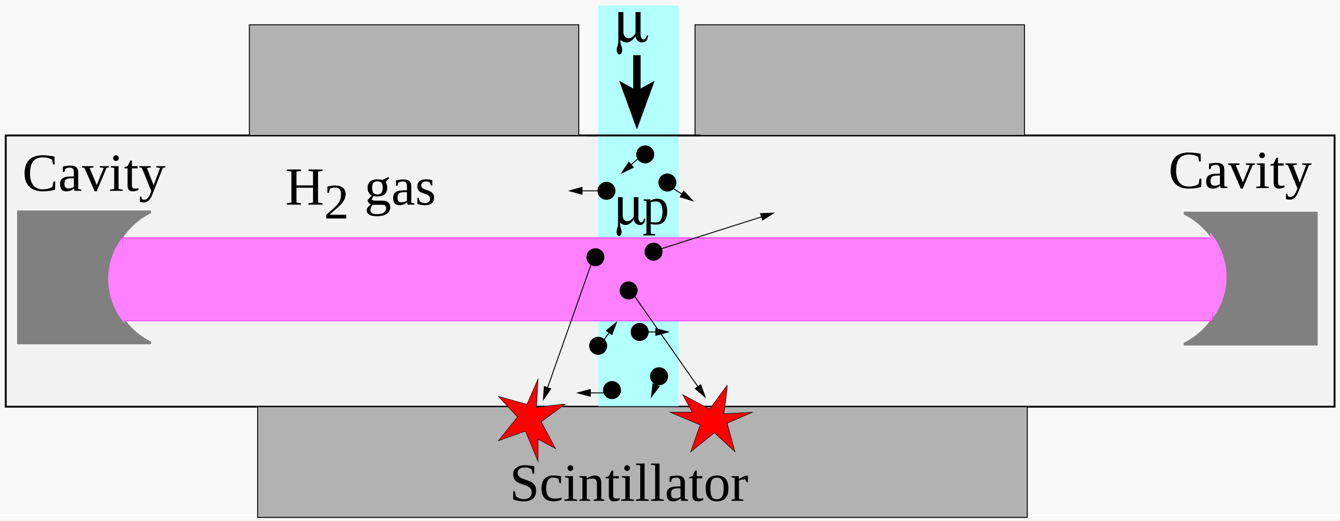
Plot number of detected transitions versus the laser frequency

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

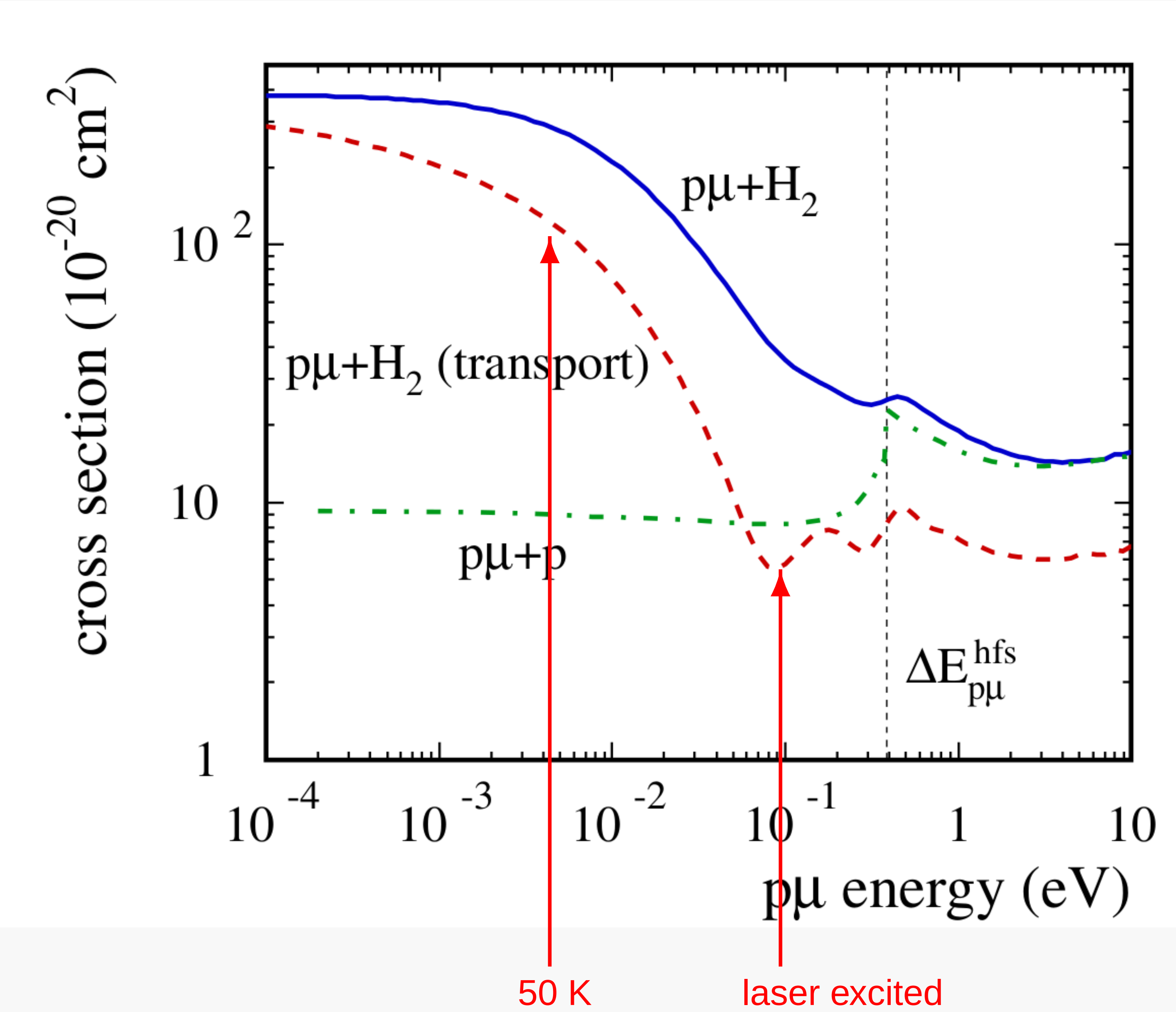
Background events:

Thermalized μp

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

$\Rightarrow$ Cool target to 50 K

Cross sections: thermalized vs. laser excited



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

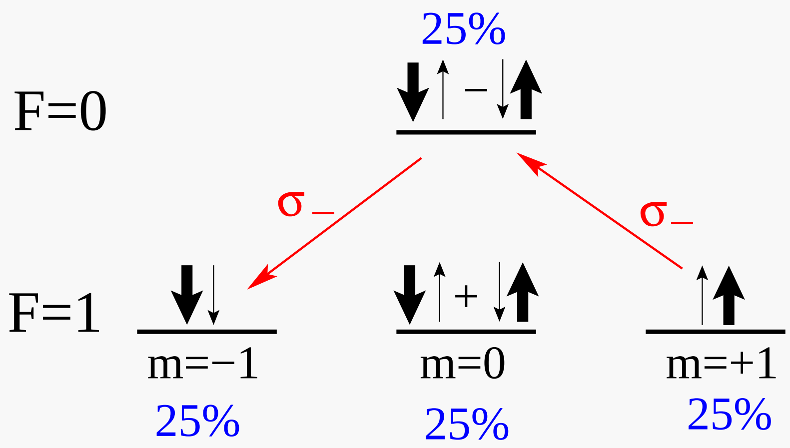
laser: large energy

cryogenic cavity

$\pm 3\sigma$ theory uncertainty

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

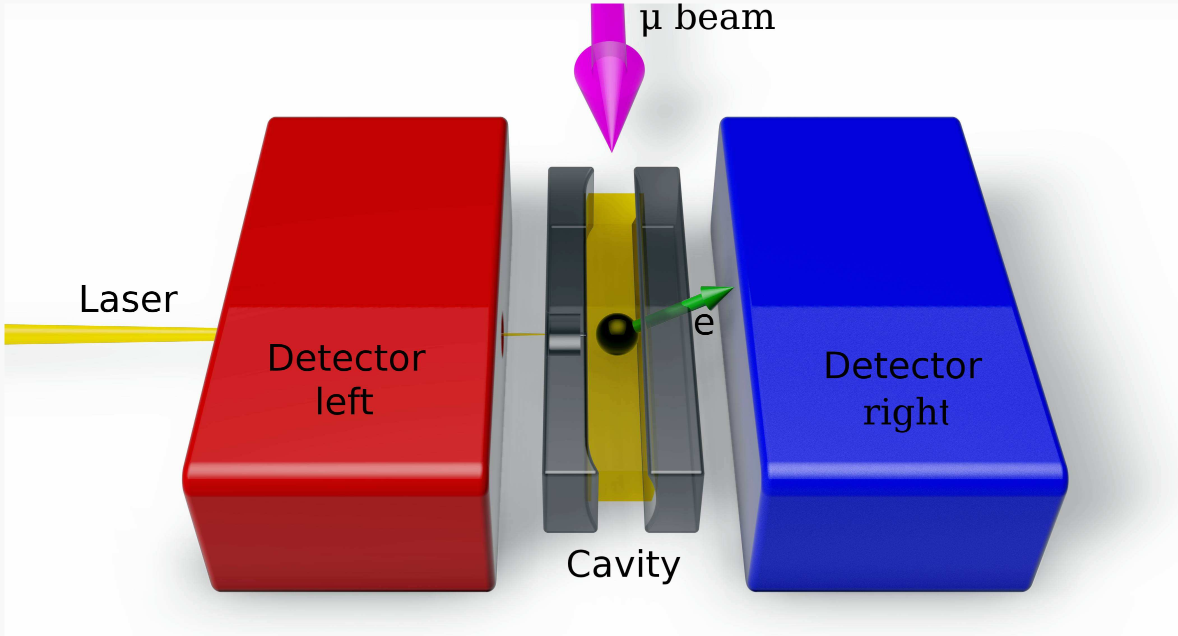
- μ^- of 10 MeV/c are detected $\longrightarrow$ trigger a laser
  - μ^- stop in ^{3}He gas (50 mbar, 300 K) $\longrightarrow$ $\mu\,{}^3\mathrm{He}^+$

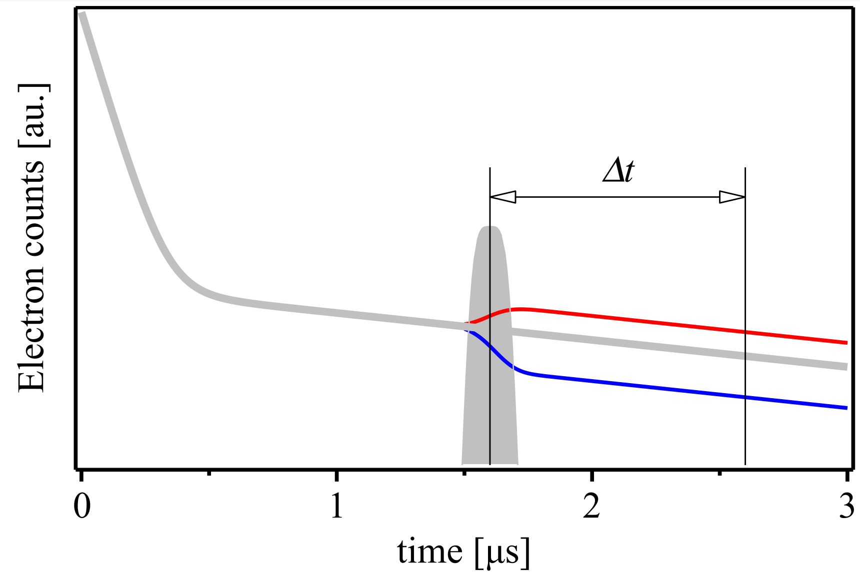


- Laser pulse: drives F=0→F=1 and F=1→F=0 transitions

  ⇒ 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

πE5

anti-coincidence

laser: short delay

laser: large energy

cavity: 1500 reflections

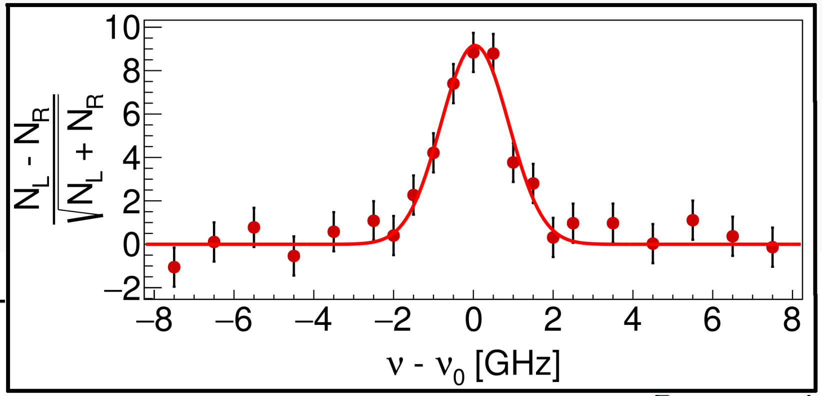
cavity: large fluence

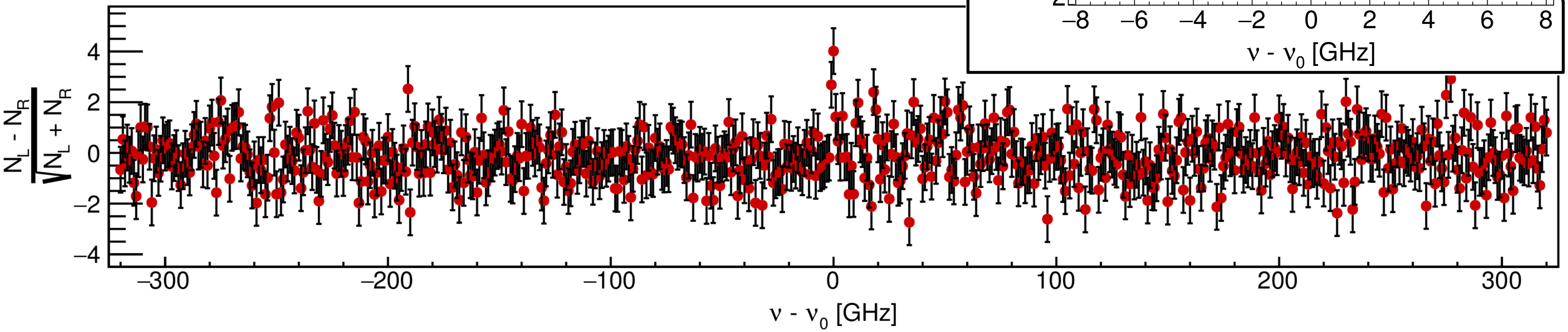
uncertainty of theory

$$(\mu\mathrm{He})^+ + \mathrm{He} + \mathrm{He} \rightarrow \mathrm{He}(\mu\mathrm{He})^+ + \mathrm{He}$$

$$\Longrightarrow \tau(\mu\,^3\mathrm{He}^+) = 1.8\ \mu\text{s (50 mbar)}$$

Number of frequency points:	650
Time needed for a 4σ effect over BG	2 h
Beam time needed for resonance search (70% uptime)	12 weeks
Beam time needed for resonance scan	2 weeks





Laser requirements

Experiment	μp 2S-2P (2009)	μp HFS	μHe^+ 2S-2P (2014)	$\mu\,^3He^+$ 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	< 1.2	< 1.2	< 1.2
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 $\left(\frac{\Delta\nu}{\nu}\right)_{\mu He^+} = 7\times 10^{-6}$

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

Narrow lines:

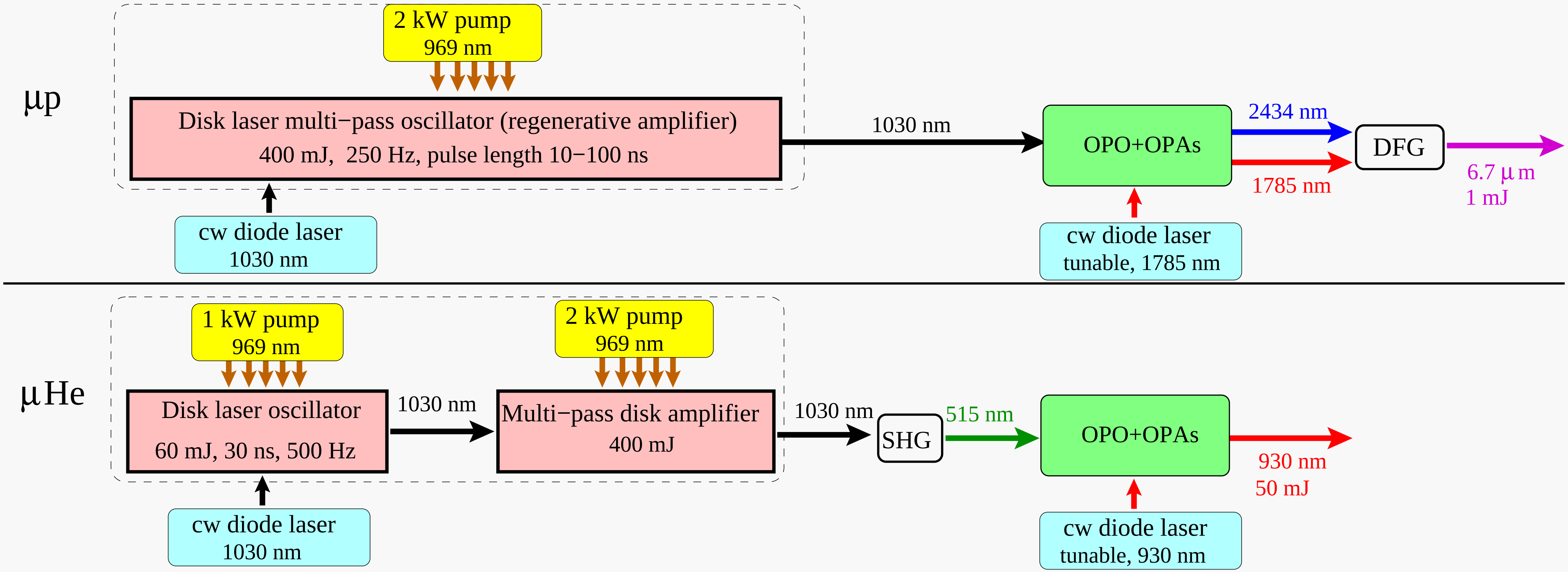
⇒ Difficult to find the line

⇒ Sub-ppm accuracy require little statistics

Systematics

$$=0$$

The laser systems



Needs to develop cutting-edge thin-disk laser technologies

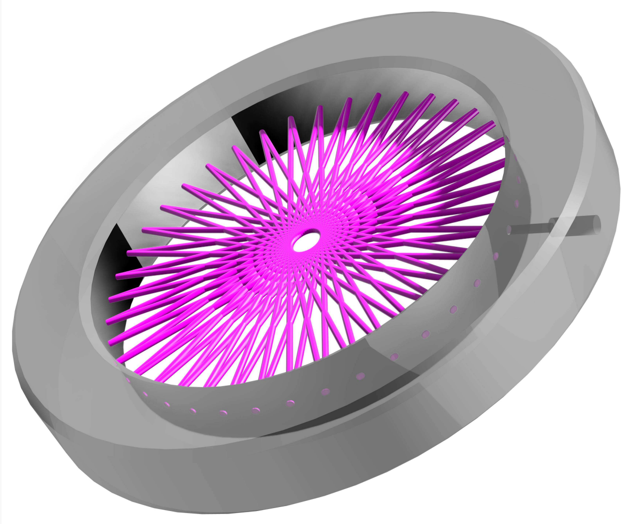
Needs to develop cutting-edge parametric down-conversion stages

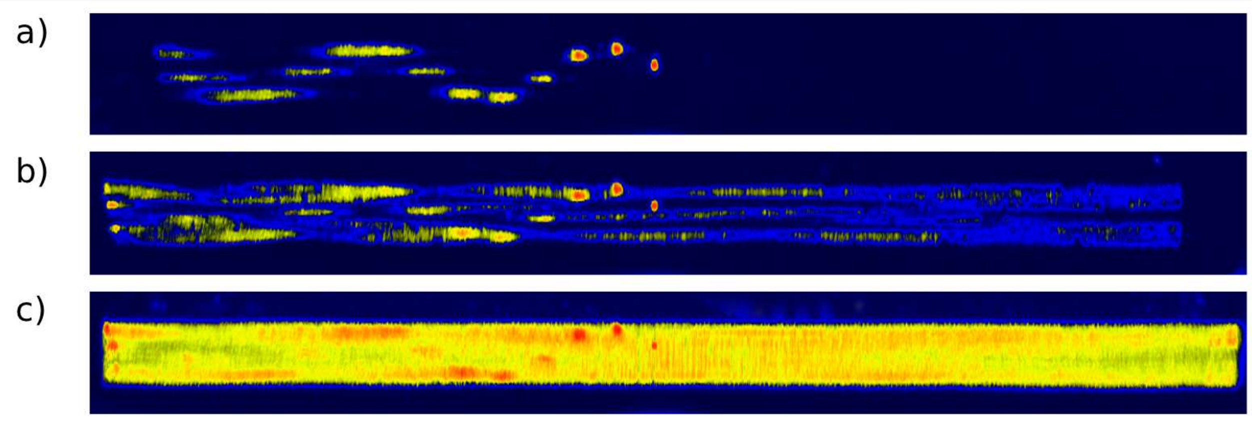
The multi-pass cavities

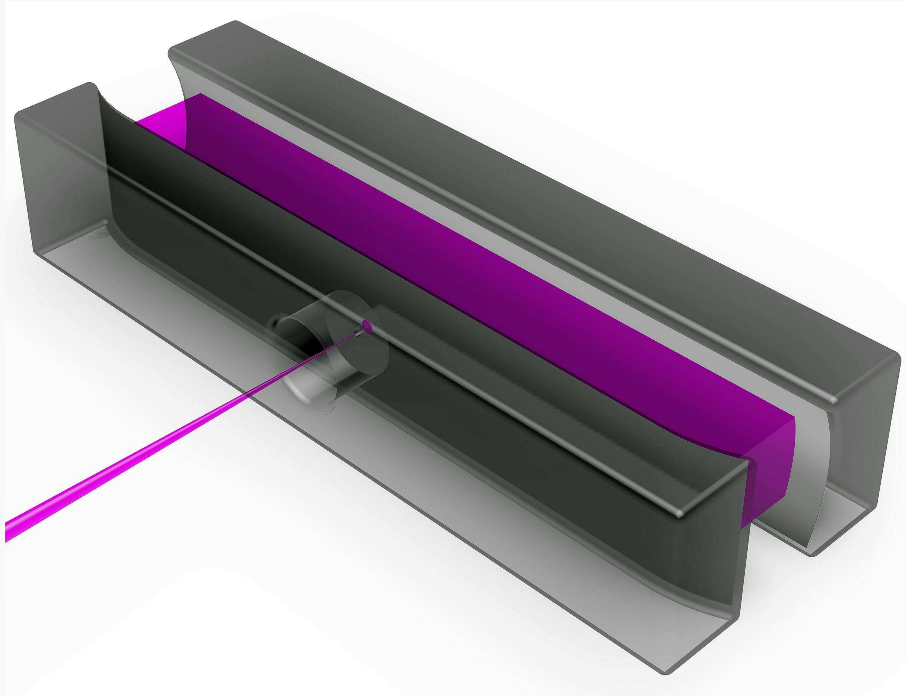
$$N = \frac{1}{1 - L_{\rm tot}}$$

$$L_{\rm tot} = L_{\rm ref} + L_{\rm hole} + L_{\rm scat} + L_{\rm defect}$$

	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







Plan

Detailed simulation of both experiments

- Simulations of cavities, excitation probabilities, diffusion, detection system, anti-coincidence
- Needs measured beam parameters, electron contamination...

Development needed

- thin-disk laser

  $\rightarrow$ energy $\times 5$, shorter pulses, single frequency

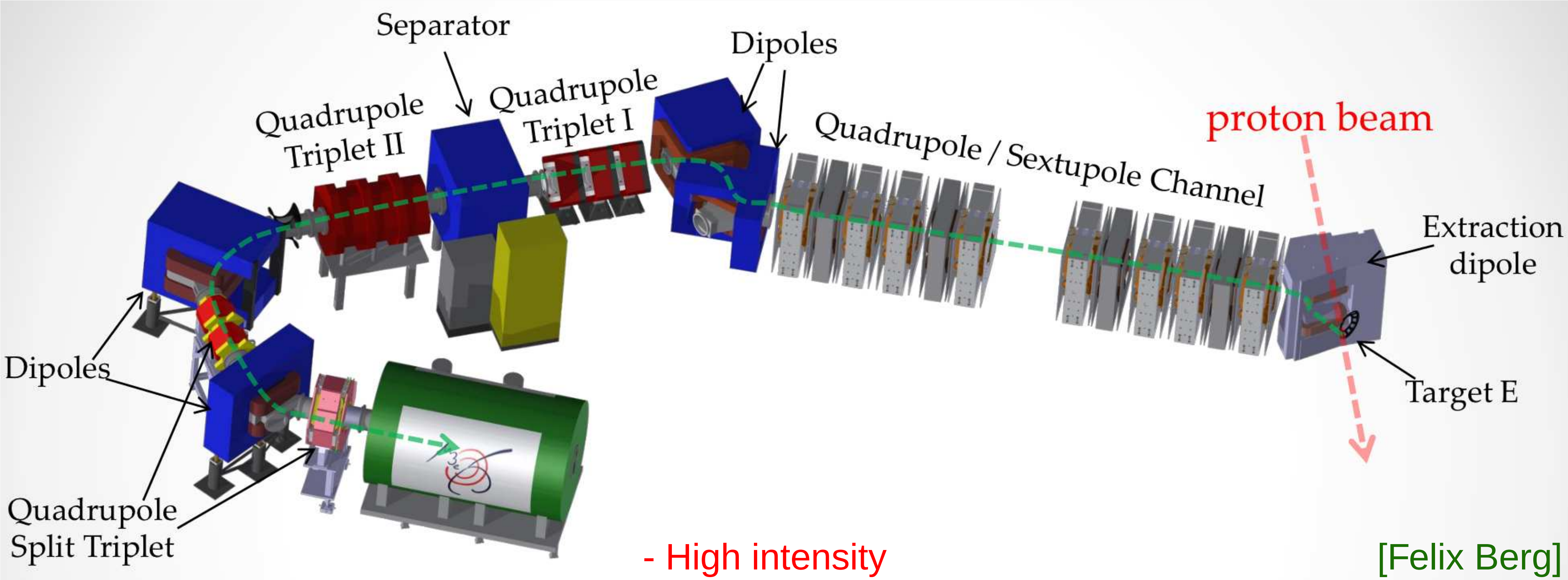
- parametric down-conversion stages

  500 Hz, bandwidth < 300 MHz, TEM00-mode, tunability, mJ energy (MISURG)

- multi-pass cavities

	2016	2017	2018	2019
Funding, laser hut refurbishment				
Simulations				
Cavities development				
Develop the thin-disk laser				
Develop parametric down-conversion				
Detectors development				
Setup realization, first resonance search				
Beam line test		? ? ? ?	? ? ? ?	? ? ? ?

Beam time request for 2016



- High intensity
- Low electron contamination

μp		
$I_{\text{estimated}}(\phi = 5\text{ mm})$	=	1200/s
$I_{\text{assumed}}(\phi = 5\text{ mm})$	=	600/s

$\mu\,^3\text{He}^+$		
$I_{\text{estimated}}(30 \times 5\text{ mm}^2)$	=	9300/s
$I_{\text{assumed}}(30 \times 5\text{ mm}^2)$	=	3000/s

Use “compact muon beam line”
and replace solenoid with our target
$\Rightarrow$ change from mu3e $\rightarrow$ CREMA in ~ 1 week

We ask for 1 week of beam time in December to test suitability of “compact muon beam line”

CREMA collaboration

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J.F.C.A. Veloso	*Uni Aveiro, Portugal*
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International Workshop on

Hadronic Contributions to New Physics Searches (HC2NP 2016)

Puerto de la Cruz, Tenerife, Spain

September 26–30, 2016

Organizers:
Jorge Martin Camalich
Vladimir Pascalutsa

Workshop Secretary:
Myriam Gonzalez de Aledo

1st Circular

Along with the direct searches of new particles at the LHC, low-energy phenomenology offers many complementary ways to search for physics beyond the Standard Model. The low-energy searches, however, are often hindered by the insufficiently precise knowledge of hadronic contributions. The purpose of this meeting is to cross-examine the empirical and theoretical progress in the understanding of these contributions in the context of various searches of new physics. The SCOPE is limited to systematically improvable calculations in QCD (e.g., pQCD, lattice QCD, EFTs) and model-independent dispersive frameworks. This time we plan to focus on the high-precision analyses in the following SUBTOPICS:

- $(g-2)_\mu$: hadronic vacuum polarization, light-by-light scattering
- Flavor transitions of light hadrons and interplay with B-decay anomalies
- Hadronic inputs for direct searches of Dark Matter: σ terms
- Proton radius puzzle: muonic hydrogen Lamb shift and hyperfine structure

THE VENUE for this meeting, seen in the picture below (the red building, not the volcano!), is located in Tenerife — a gorgeous Canary Island. The hotel will allow us to host up to 50 participants at very moderate accommodation rates and conference fees.