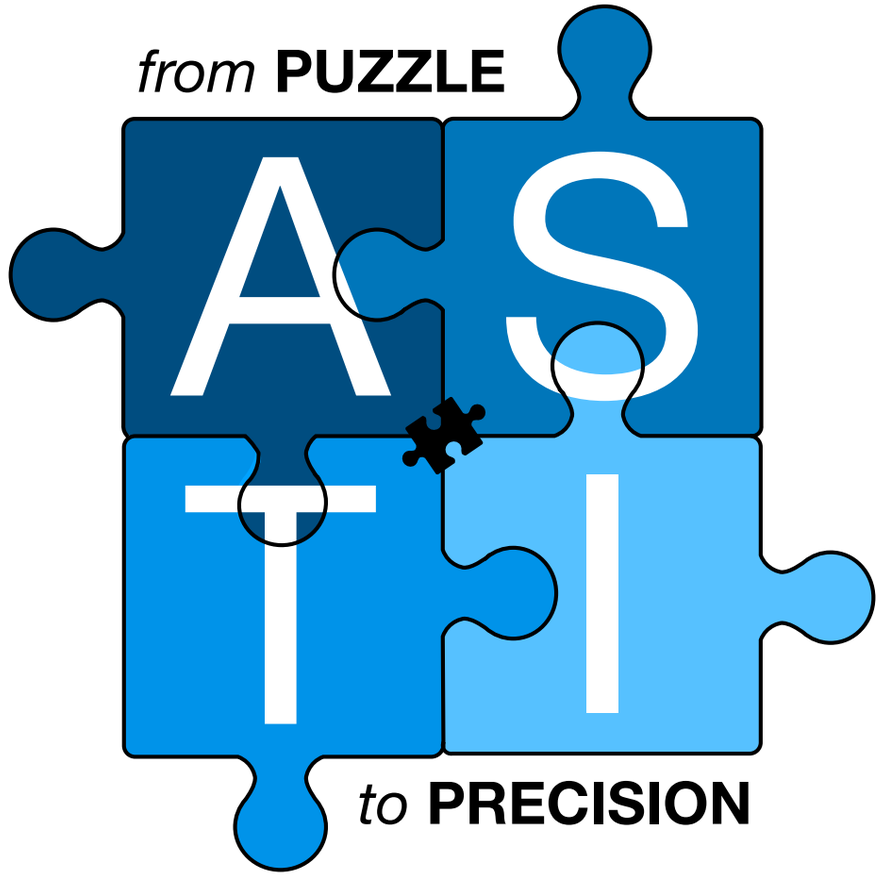
Muonic Atom Spectroscopy Theory Initiative

- "Muonic atoms @ PSI2022" / PSI, October 2022
- "Nucleon Structure at Low-Q" / Crete, May 2023
- Initials objectives:
  - Accurate theory predictions for light muonic atoms to test fundamental interactions by comparing to electronic atoms
  - Community consensus on SM predictions
  - Emphasis on the hyperfine splitting in μH



- Steering committee: Aldo Antognini, Carl Carlson, Franziska Hagelstein, Paul Indelicato, Krzysztof Pachucki, Vladimir Pascalutsa

MOTIVATION & INSPIRATION

Theory consensus on the **Lamb shift and hfs** of muonic hydrogen, deuterium, …; akin to the "g-2 Theory Initiative"

Physics Reports 887 (2020) 1–166

Contents lists available at ScienceDirect

Physics Reports

journal homepage: www.elsevier.com/locate/physrep

The anomalous magnetic moment of the muon in the Standard Model

Contribution	Section	Equation	Value $\times 10^{11}$	References
Experiment (E821)		Eq. (8.13)	116 592 089(63)	Ref. [1]
HVP LO (e^+e^-)	Section 2.3.7	Eq. (2.33)	6931(40)	Refs. [2–7]
HVP NLO (e^+e^-)	Section 2.3.8	Eq. (2.34)	−98.3(7)	Ref. [7]
HVP NNLO (e^+e^-)	Section 2.3.8	Eq. (2.35)	12.4(1)	Ref. [8]
HVP LO (lattice, *udsc*)	Section 3.5.1	Eq. (3.49)	7116(184)	Refs. [9–17]
HLbL (phenomenology)	Section 4.9.4	Eq. (4.92)	92(19)	Refs. [18–30]
HLbL NLO (phenomenology)	Section 4.8	Eq. (4.91)	2(1)	Ref. [31]
HLbL (lattice, *uds*)	Section 5.7	Eq. (5.49)	79(35)	Ref. [32]
HLbL (phenomenology + lattice)	Section 8	Eq. (8.10)	90(17)	Refs. [18–30,32]
QED	Section 6.5	Eq. (6.30)	116 584 718.931(104)	Refs. [33,34]
Electroweak	Section 7.4	Eq. (7.16)	153.6(1.0)	Refs. [35,36]
HVP (e^+e^-, LO + NLO + NNLO)	Section 8	Eq. (8.5)	6845(40)	Refs. [2–8]
HLbL (phenomenology + lattice + NLO)	Section 8	Eq. (8.11)	92(18)	Refs. [18–32]
Total SM Value	Section 8	Eq. (8.12)	116 591 810(43)	Refs. [2–8,18–24,31–36]
Difference: $\Delta a_\mu := a_\mu^{\text{exp}} - a_\mu^{\text{SM}}$	Section 8	Eq. (8.14)	279(76)	

Homepage and mailing list → https://asti.uni-mainz.de

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Atomic Spectroscopy Theory Initiative

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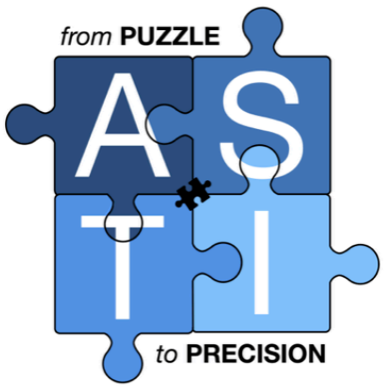
Muonic Atom Spectroscopy Theory Initiative

Inspired by the success of the Muon g-2 Theory Initiative we are launching the Muonic Atom Spectroscopy Theory Initiative (μASTI).

The initiative aims to support the experimental effort on the spectroscopy of light muonic atoms by improving the Standard Model theory predictions for the Lamb shift and hyperfine splitting in muonic hydrogen, deuterium, and helium, in order to match the anticipated accuracy of future measurements. An initial focus will be on the ground state hyperfine splitting in muonic hydrogen.

The **upcoming kick-off event** for the Theory Initiative is organized as a joint meeting with the Proton Radius European Network (PREN) at the Johannes Gutenberg University Mainz (June 26-30, 2023).



μASTI

- Working groups, possible divisions:
  1. **μH, μD**, …, μX, Mu(?)
  2. **Lamb shift**, fine structure, **hyperfine splitting**
  3. QED, **QCD** = (EFTs, data-driven dispersive, lattice QCD)

- QCD working group
  - Elastic nucleon structure — form factors
  - Inelastic nucleon structure — polarizabilities
  - Other hadronic effects — HVP

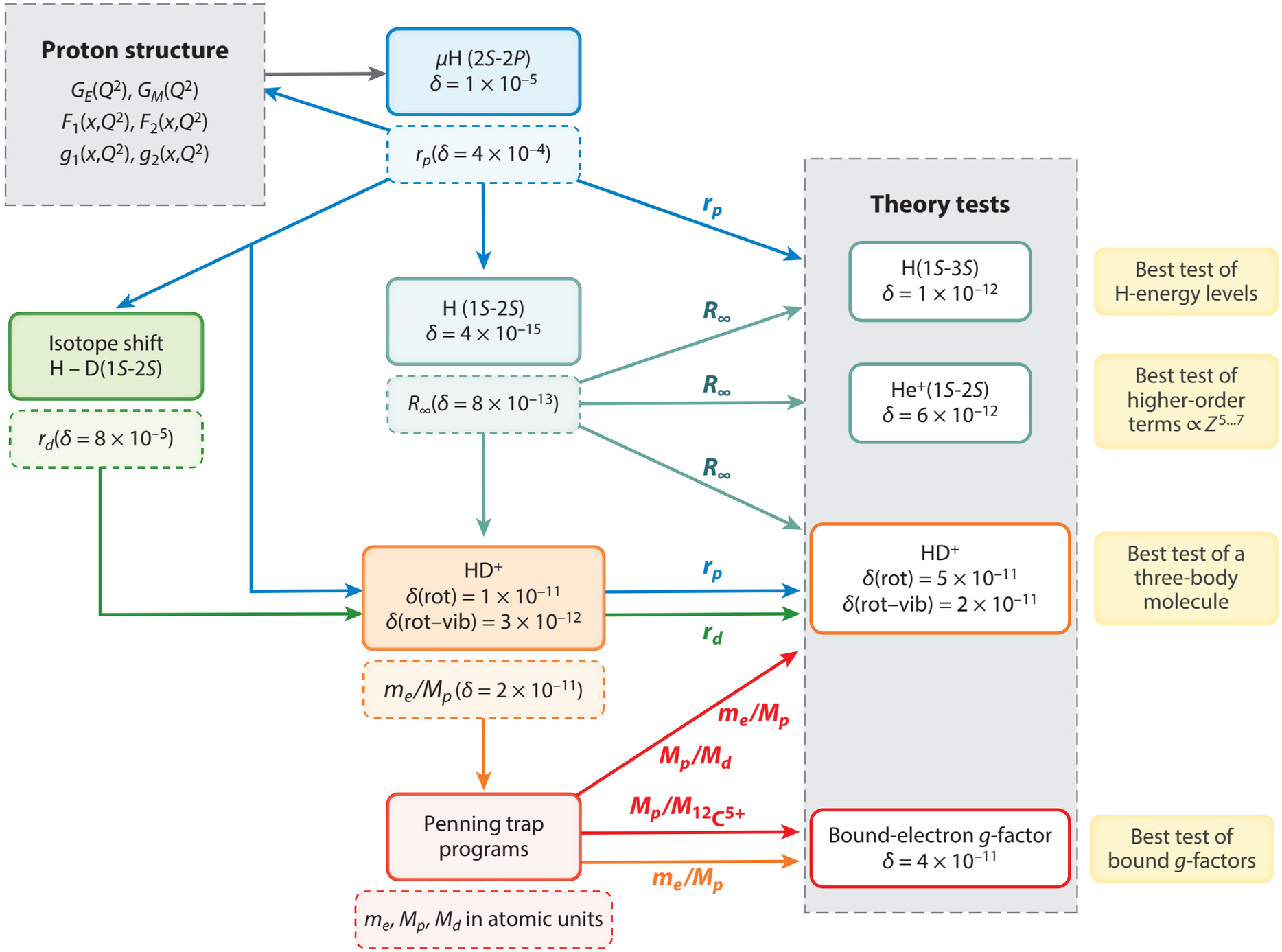
SOME QUESTIONS

- Refine exact terminology
- Interplay of experiments and theory: fundamental constant determinations, theory tests, …
- Prospects for NP searches
- Recoil contributions
- μD HFS, He isotope shift
- …

<u>QCD WORKING GROUP</u>

- New form factor data (elastic TPE contribution, …)
- Subtraction function contributions
- Neutron TPE contributions to light muonic atoms
- …

COMBINING μH, H, He, HD+, …



A. Antognini, FH, V. Pascalutsa, Ann. Rev. Nucl. Part. **72** (2022) 389-418

LAMB SHIFT IN MUONIC ATOMS

	THEORY (Bacca, Gorchtein, FH, Lensky, Vanderhaeghen, Pascalutsa, …)		**EXPERIMENT** (Pohl, Wauters, …)	
	$\Delta E_{TPE} \pm \delta_{theo}\ (\Delta E_{TPE})$	Ref.	$\delta_{exp}(\Delta_{LS})$	Ref.
μH	33 μeV $\pm$ 2 μeV	Antognini et al. (2013)	2.3 μeV	Antognini et al. (2013)
μD	1710 μeV $\pm$ 15 μeV	Krauth et al. (2015)	3.4 μeV	Pohl et al. (2016)
μ^3He$^+$	15.30 meV $\pm$ 0.52 meV	Franke et al. (2017)	0.05 meV	
μ^4He$^+$	9.34 meV $\pm$ 0.25 meV $-$0.15 meV $\pm$ 0.15 meV (3PE)	Diepold et al. (2018) Pachucki et al. (2018)	0.05 meV	Krauth et al. (2020)

μH: present accuracy comparable with experimental precision

μD, μ³He⁺, μ⁴He⁺: present accuracy factor 5-10 worse than experimental precision

$r_p = 0.84087(12)_{\rm sys}(23)_{\rm stat}(29)_{\rm theory}$ fm — (25) 2PE (mainly subtraction term); (15) QED

$r_d = 2.12562(5)_{\rm sys}(12)_{\rm stat}(77)_{\rm theory}$ fm — basically only nuclear 2PE

$r_\alpha = 1.67824(2)_{\rm sys}(13)_{\rm stat}(82)_{\rm theory}$ fm — (70) 2PE (elastic 25, nuclear inelastic 36, nucleon inelastic 56); (42) 3PE (inelastic contribution missing); (4) QED

HYPERFINE SPLITTING IN μH

wish list

THEORY INITIATIVE

$$E_{\rm HFS} = \underbrace{182.443}_{E_F} + \underbrace{1.350(7)}_{\text{QED+weak}} + \underbrace{0.004}_{\text{hVP}} + E_F \Big(\underbrace{1.01958(13)\Delta_Z + 1.01656(4)\Delta_{\rm recoil} + 1.00402\Delta_{\rm pol}}_{2\gamma} \Big) \quad [\text{meV}]$$

	7400(38)	20	7403(21)	837(3)	364(89) 37(95)	[ppm]

Experiment (<1)

<1 ppm ?

New FF measurements?

Spin program?
ChPT?

Theory **compilations**, including **mixed terms** (recoil-finite size-radiative), hadronic effects, meson contributions.

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HYPERFINE SPLITTING IN μH

- Discrepancy between polarizability contribution
- Comparison of structure function data to theory predictions
- Low-Q region:
  - Extrapolation of fit to data?
  - Approximate formula?
- …