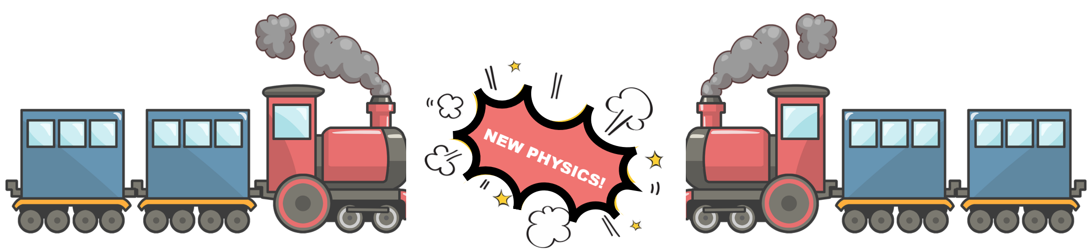
Hadronic Contributions to Precision Observables and New Physics Searches

Franziska Hagelstein (JGU Mainz & PSI)

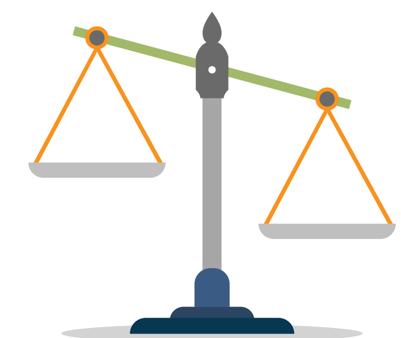
NEW PHYSICS

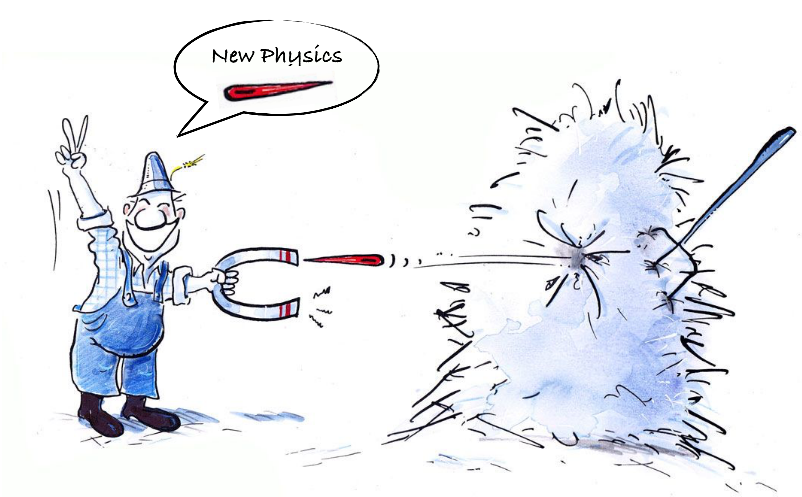
- Many indications for physics beyond the SM (BSM), aka “New Physics”
- Astrophysical observations: baryon asymmetry, dark matter, dark energy, …
- Lab searches for New Physics proceed along 3 frontiers:



HIGH-ENERGY FRONTIER

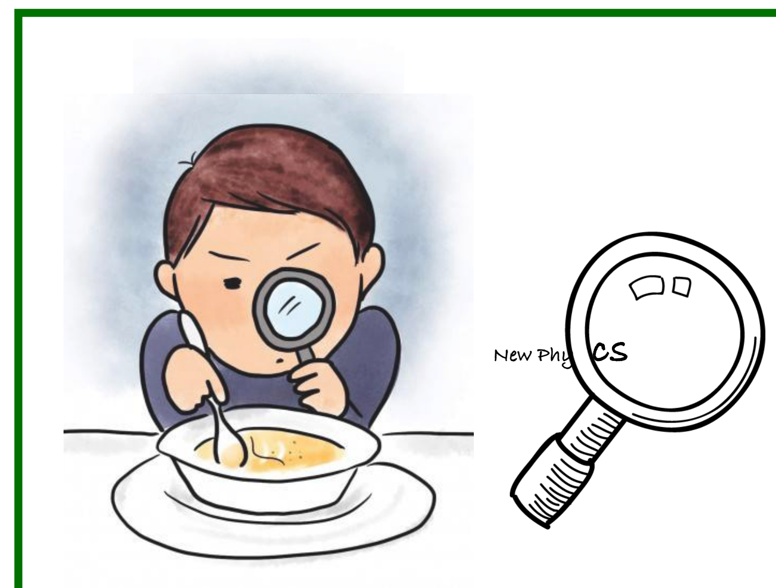
SM prediction vs. experimental observation





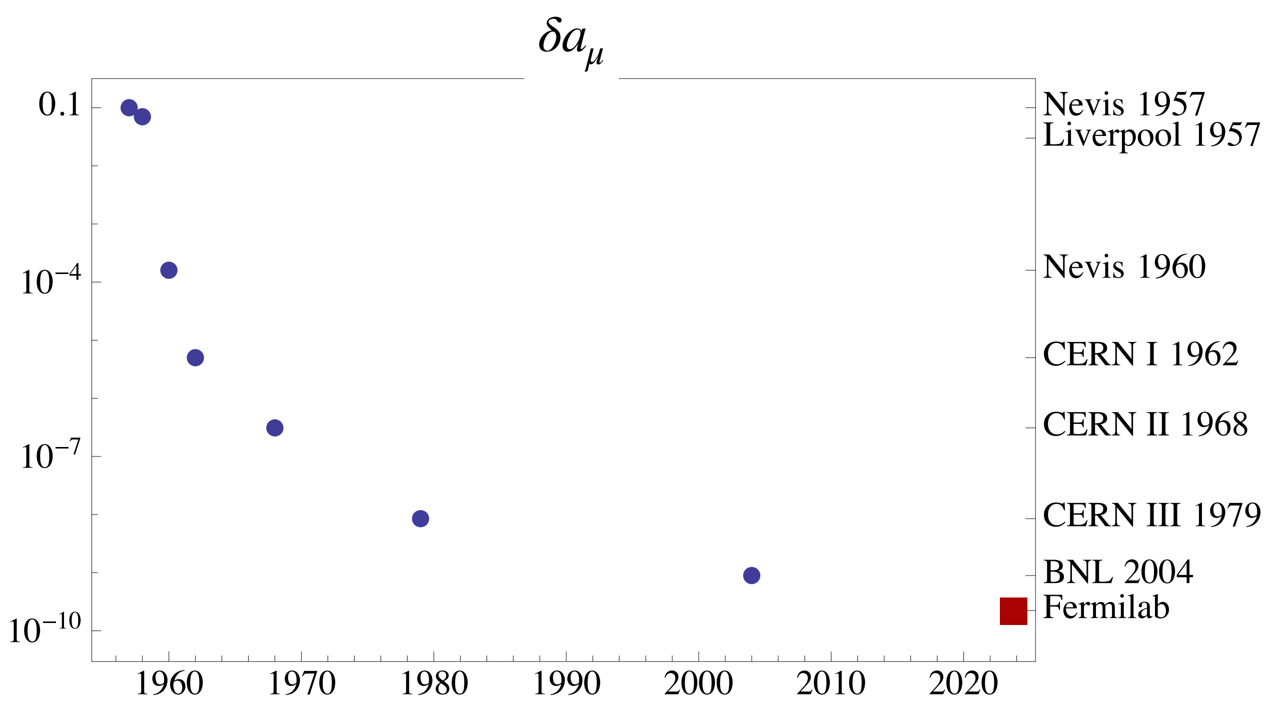
INTENSITY FRONTIER

PRECISION FRONTIER

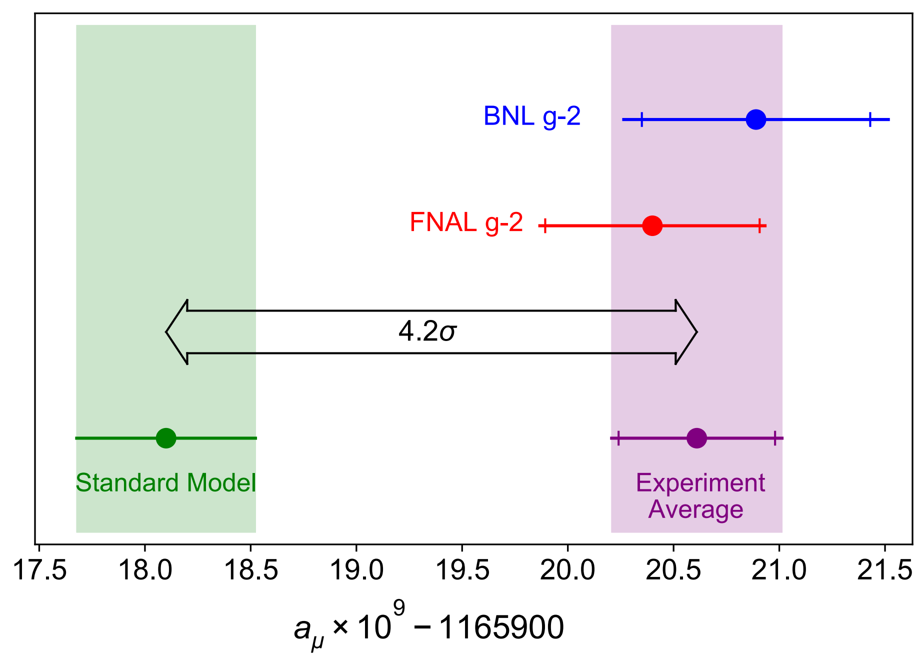


Abi, et al., Phys. Rev. Lett. 126 (2021) 14, 141801
Aoyama, et al., Phys. Rept. 887 (2020) 1-166

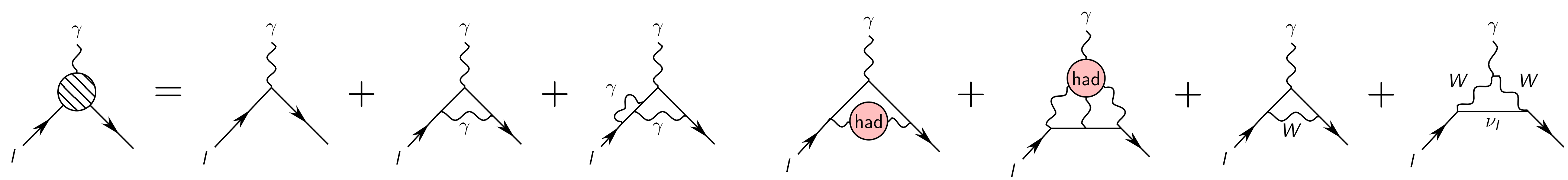
MUON g-2



- Fermilab 2021: 4.2σ discrepancy between SM prediction and experimental value
- Factor of 2 reduction of experimental uncertainty expected



Schwinger term
$a_\mu = \alpha/2\pi$



1-loop QED [1 diagram]
2-loop QED [7 diagrams]
3-loop QED [72 diagrams]
4-loop QED [891 diagrams]
5-loop QED [12 672 diagrams]

Mismatch implies "New Physics" or insufficient understanding of the SM!

THEORY INITIATIVE

- 8 topical workshops
- White Paper (WP) published in 2020
- WP update to-be-published early 2023
  - Deadline (end of 11/2022) for publications to be considered for WP update

Plenary workshop at the Helmholtz Institute Mainz (2018)

Physics Reports 887 (2020) 1–166

Contents lists available at ScienceDirect

Physics Reports

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

ELSEVIER

The anomalous magnetic moment of the muon in the Standard Model

Check for updates

Submitted to the Proceedings of the US Community Study
on the Future of Particle Physics (Snowmass 2021)

FERMILAB-CONF-22-236-T LTH 1303 MITP-22-030

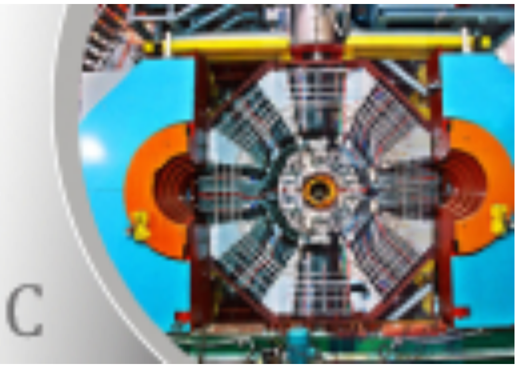
Prospects for precise predictions of a_μ in the Standard Model

- Lattice QCD: Mainz (Meyer, von Hippel, **Wittig**, …) , Regensburg (**Lehner**, …), Wuppertal (BMW)
- Data-driven dispersive approach: Bonn (Kubis, …), Mainz (Danilkin, Denig, Pascalutsa, Redmer, Vanderhaeghen, FH, …)
- Dyson-Schwinger approach: Gießen (Fischer, …)
- Electroweak corrections: Dresden (Stöckinger, Stöckinger-Kim, …)

Research Unit FOR 5327

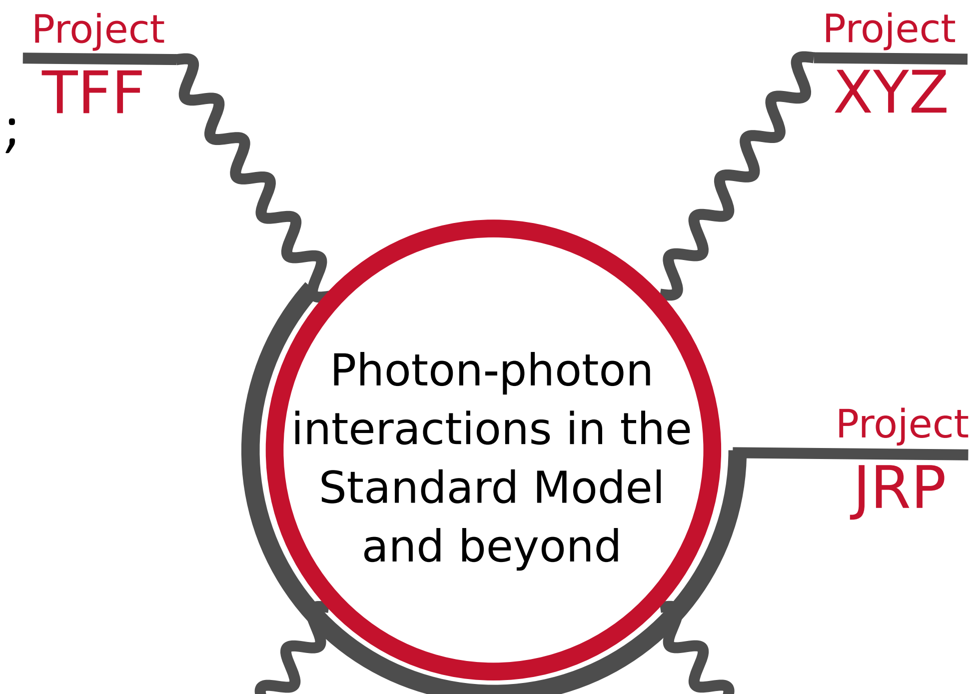
Photon-photon interactions in the Standard Model and beyond

Exploiting the discovery potential from MESA to the LHC



Measurement of Meson Transition Form Factors (**TFF**s) at BESIII and A2/MAMI;
Dispersive Theory
& Lattice QCD

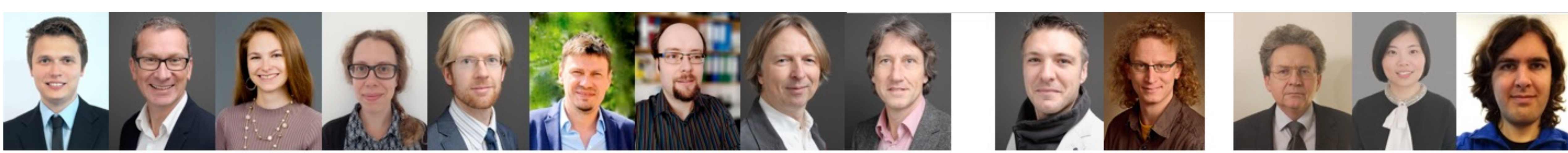
Exotic Meson Spectroscopy (**XYZ** particles) at BESIII exploiting **dispersive methods**



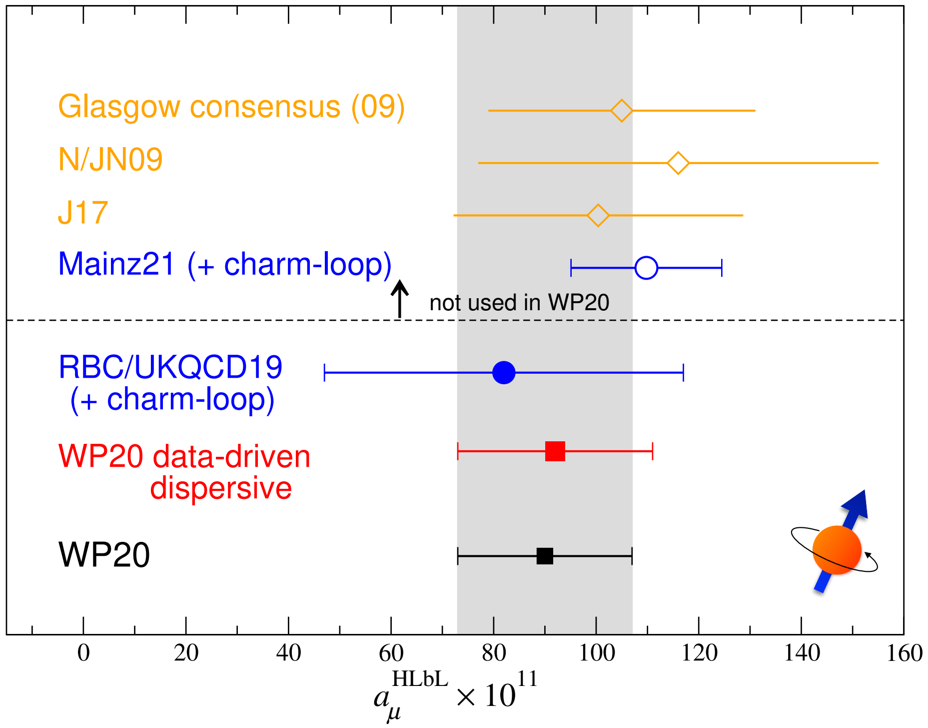
Joint Research Project (JRP): HLbL contribution to (g-2)$_\mu$

Search for axion-like particles (**ALP**s) in $\gamma\gamma$-processes at BESIII and ATLAS/LHC

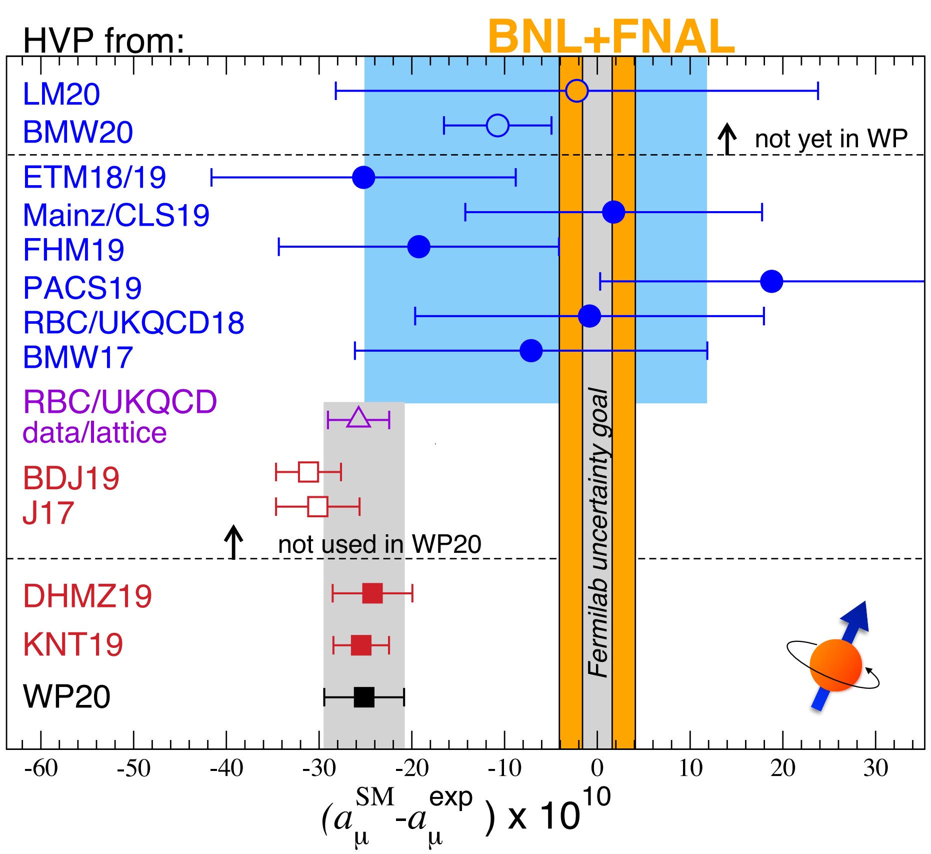
Exploiting the potential of the recent direct observation of **LBL scattering** at the LHC;
& Lattice QCD



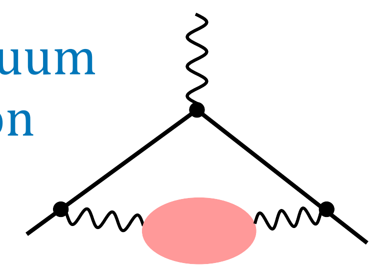
THEORY STATUS



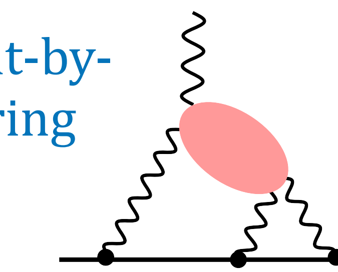
	$a_\mu \times 10^{14}$	$\delta a_\mu \times 10^{14}$	$\delta a_\mu / a_\mu$
Experiment	116 592 061 000	41 000	4×10^{-7}
SM	116 591 810 000	43 000	4×10^{-7}
QED	116 584 718 931	104	9×10^{-10}
HVP	6 845 000	40 000	6×10^{-3}
Electroweak	153 600	1 000	7×10^{-3}
HLbL	92 000	18 000	2×10^{-1}



Hadronic vacuum polarization (HVP)

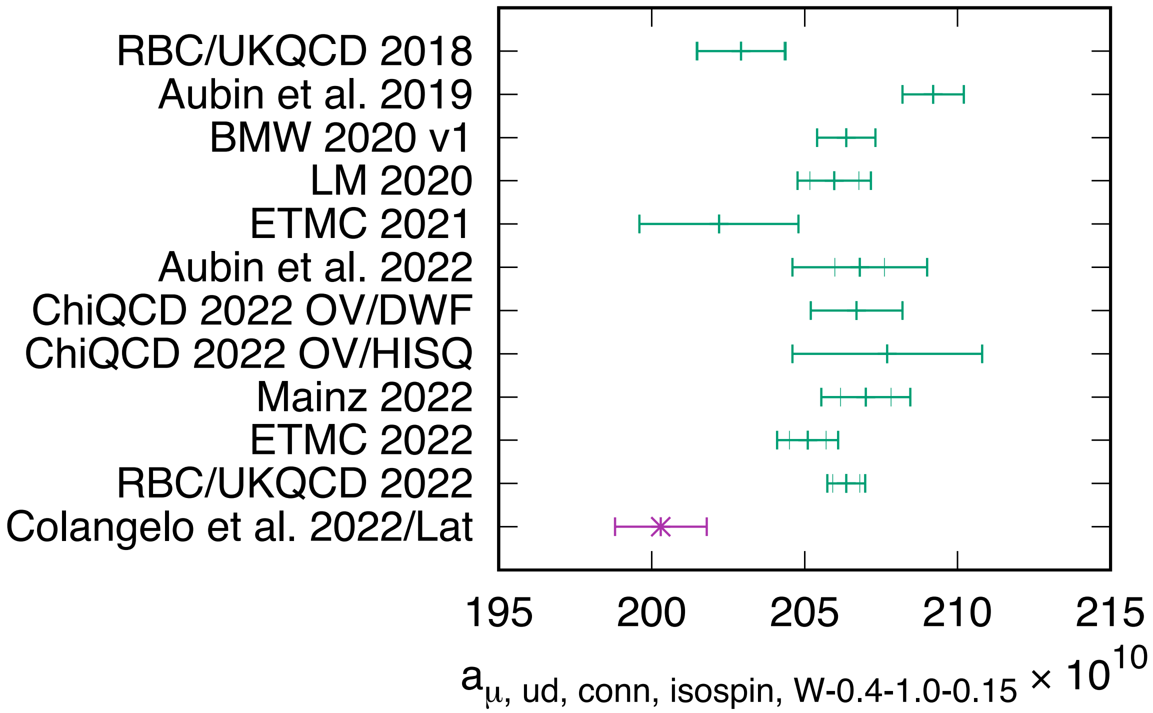


Hadronic light-by-light scattering (HLbL)

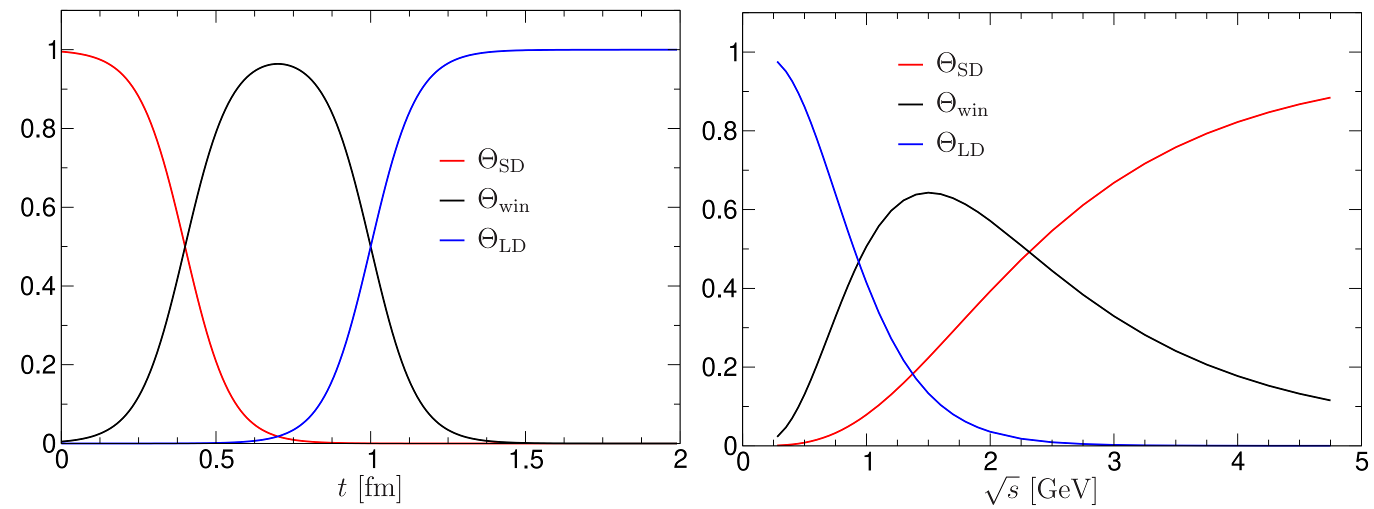


- HLbL: data-driven and lattice QCD predictions are consistent $\Longrightarrow$ 10% uncertainty feasible (by 2025)
- HVP: 2.1σ disagreement between lattice QCD prediction from BMW Coll. and average of data-driven calculations

HVP



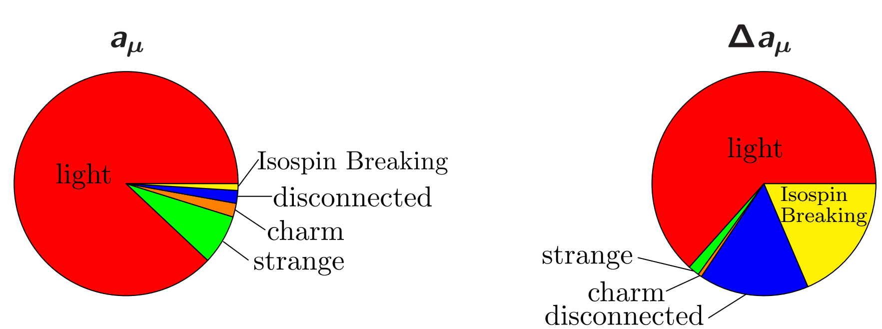
weighting functions for space- and time-like regions:



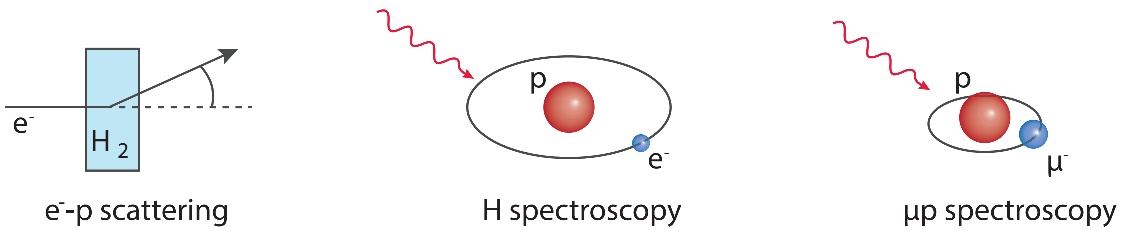
- Window quantities disentangle statistical and systematic uncertainties
- Lattice QCD can compute intermediate window with high precision

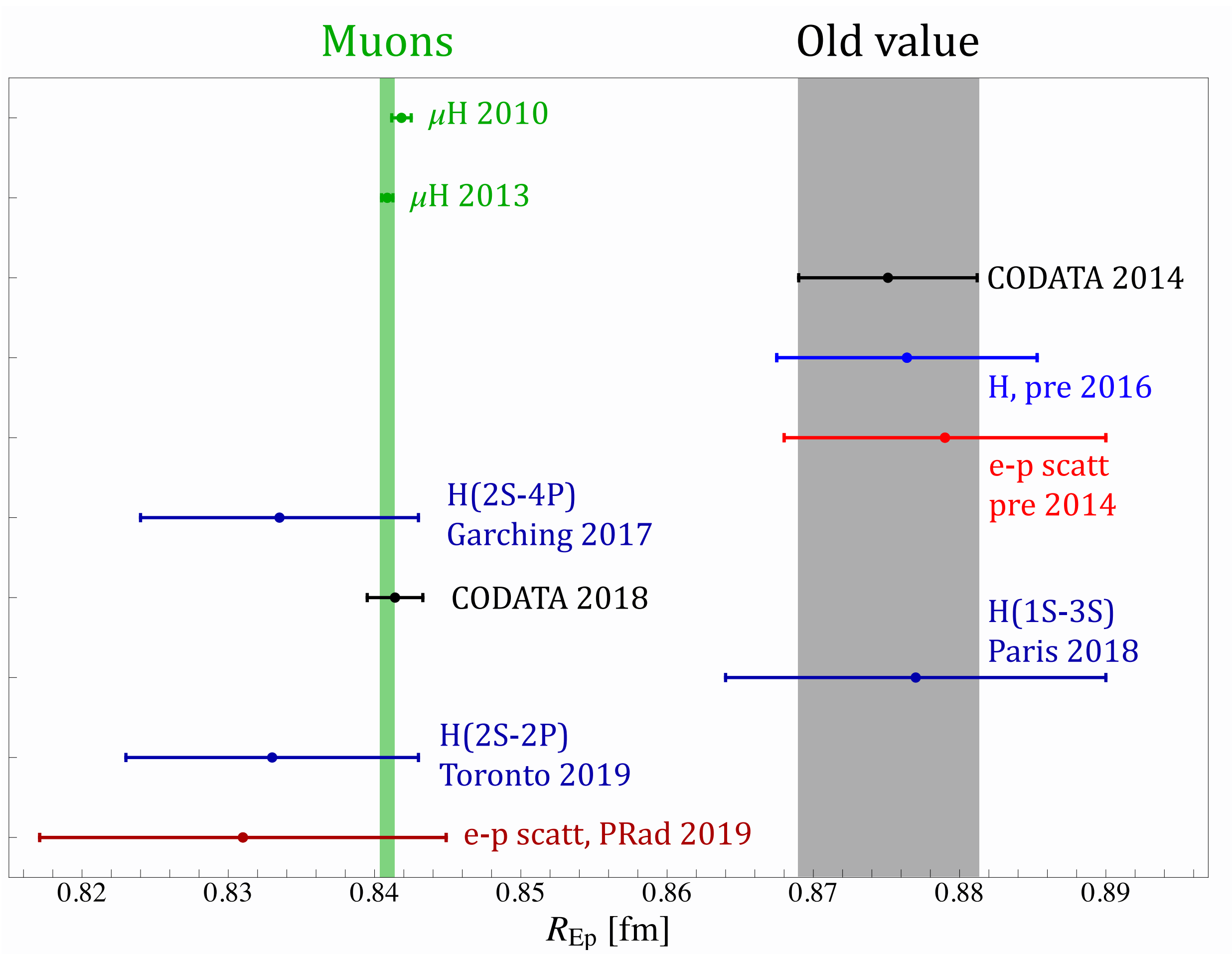
  $\Longrightarrow$ 3.7σ tension with the data-driven evaluation

- Isospin-breaking corrections are important for uncertainty

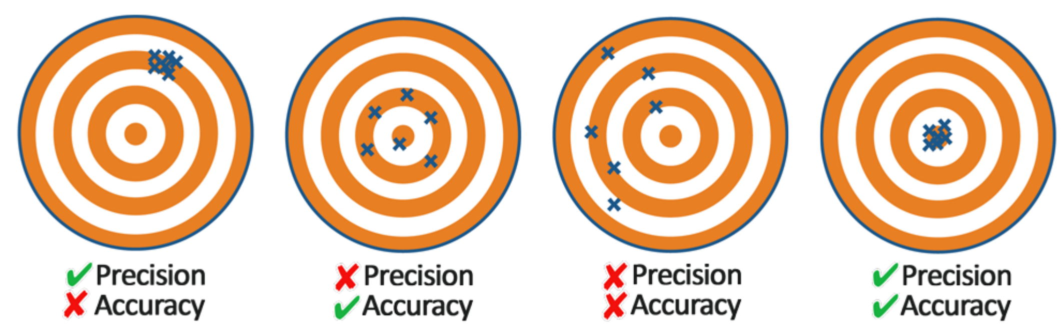


PROTON CHARGE RADIUS





- Muonic atoms allow for PRECISE extractions of nuclear charge and Zemach radii
- CODATA since 2018 included the μH result for r_p
- Still open issues: H(2S-8D) and H(1S-3S)
- Precise and accurate!



FROM PUZZLE TO PRECISION

- Several experimental activities ongoing and proposed:
  - 1S hyperfine splitting in μH (ppm accuracy) and μHe
  - Improved measurement of Lamb shift in μH, μD and μHe^+ possible ($\times 5$)
  - Medium- and high-Z muonic atoms

- **Theory Initiative** is needed!

Muonic Atom Spectroscopy Theory Initiative

- First brainstorming meeting October 2022
- 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, FH, Paul Indelicato, Krzysztof Pachucki, Vladimir Pascalutsa (Mainz)
- Kick-off meeting (PREN 2023): 26.06.2023 - 30.06.2023 @ JGU, Mainz

Satellite Workshop to PSI2022 conference (14. and 15.10.2022)

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	$33\ \mu\text{eV} \pm 2\ \mu\text{eV}$	Antognini et al. (2013)	$2.3\ \mu\text{eV}$	Antognini et al. (2013)
μD	$1710\ \mu\text{eV} \pm 15\ \mu\text{eV}$	Krauth et al. (2015)	$3.4\ \mu\text{eV}$	Pohl et al. (2016)
$\mu^3\text{He}^+$	$15.30\ \text{meV} \pm 0.52\ \text{meV}$	Franke et al. (2017)	0.05 meV	
$\mu^4\text{He}^+$	$9.34\ \text{meV} \pm 0.25\ \text{meV}$ $-0.15\ \text{meV} \pm 0.15\ \text{meV}$ (3PE)	Diepold et al. (2018) Pachucki et al. (2018)	0.05 meV	Krauth et al. (2020)

μH: present accuracy comparable with experimental precision

μD, μ^3He$^+$, μ^4He$^+$: present accuracy factor 5-10 worse than experimental precision

$$r_p = 0.84087(12)_{\text{sys}}(23)_{\text{stat}}(29)_{\text{theory}}\ \text{fm}$$

(25) 2PE (mainly subtraction term)
(15) QED

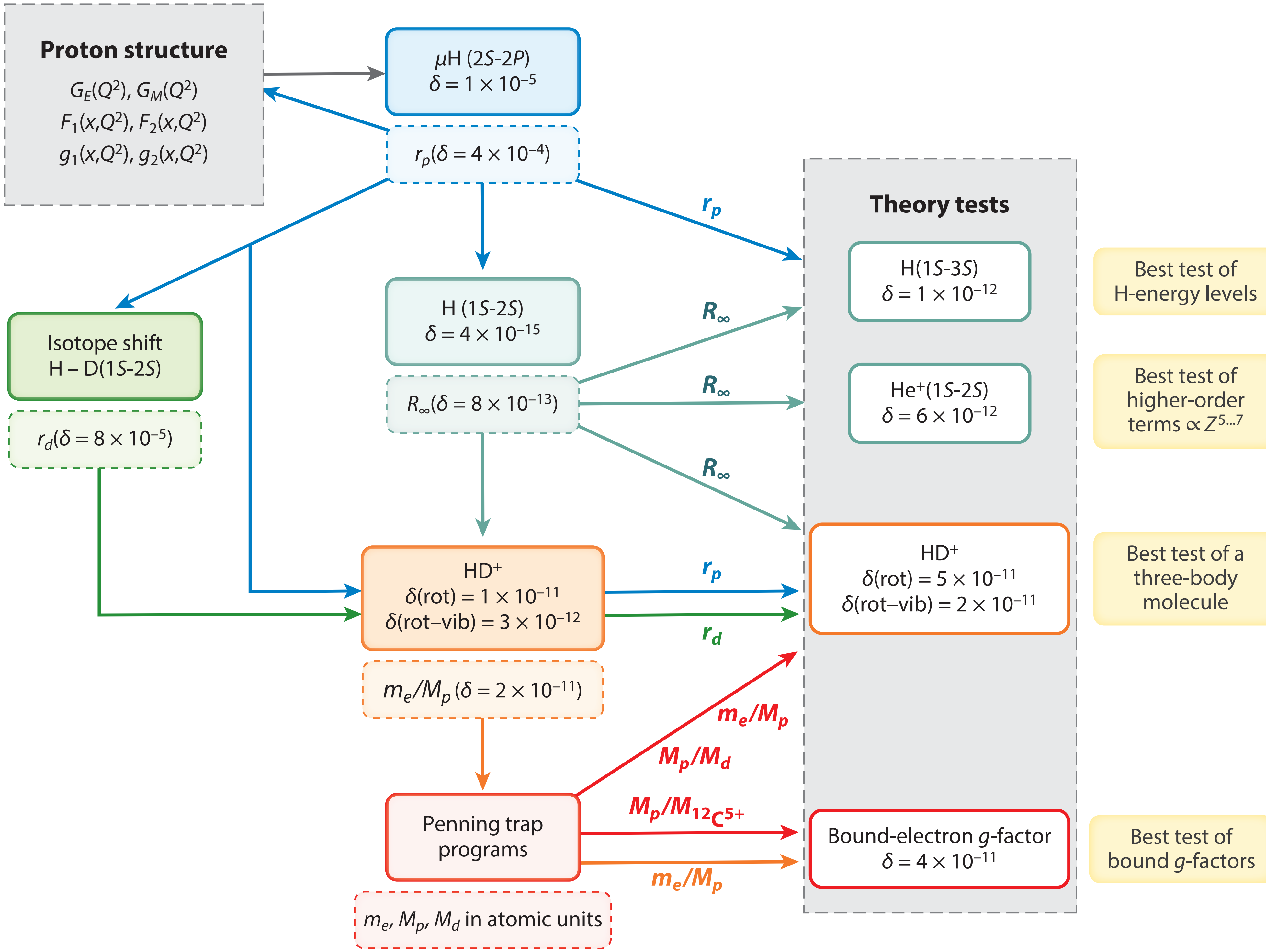
$$r_d = 2.12562(5)_{\text{sys}}(12)_{\text{stat}}(77)_{\text{theory}}\ \text{fm}$$

basically only nuclear 2PE

$$r_\alpha = 1.67824(2)_{\text{sys}}(13)_{\text{stat}}(82)_{\text{theory}}\ \text{fm}$$

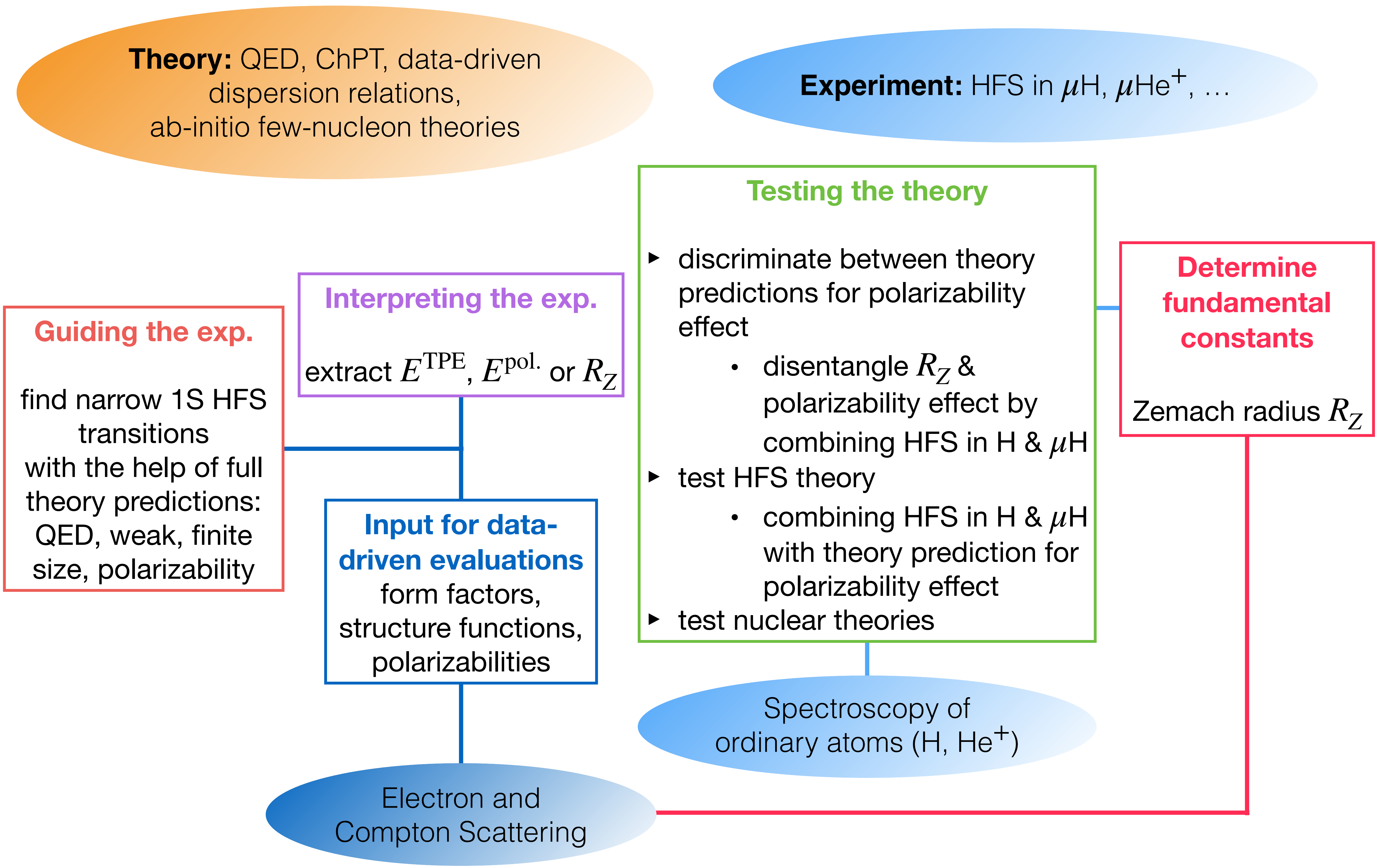
(70) 2PE (elastic 25, nuclear inelastic 36, nucleon inelastic 56)
(42) 3PE (inelastic contribution missing)
(4) QED

COMBINING μH, H, He, HD+, ...



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

HYPERFINE SPLITTING



Thank you for your attention!