MUSE Experiment & the Proton Radius Puzzle

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HUGS Student Seminar
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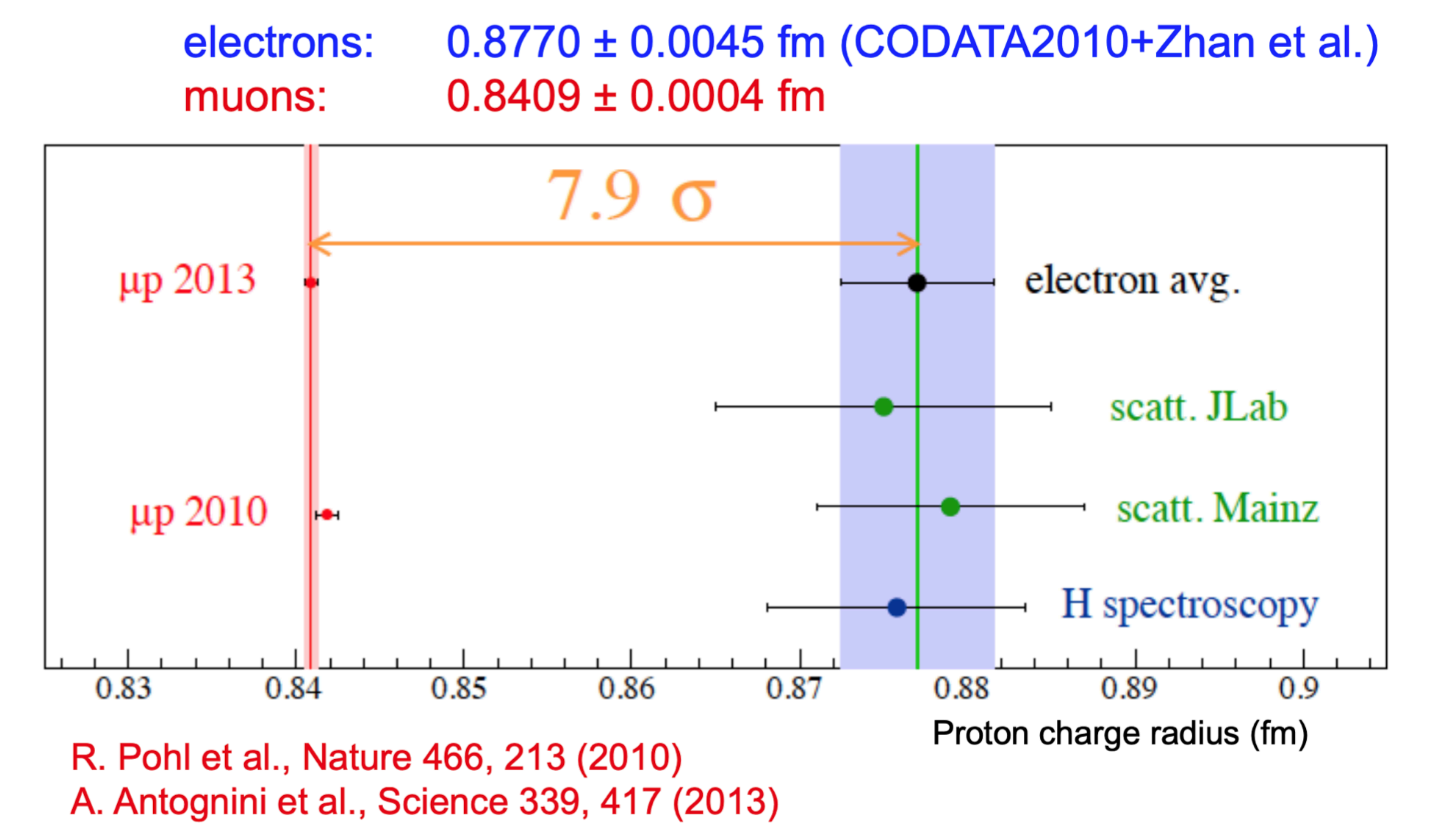
The MUSE experiment is supported by the U.S. Department of Energy, the U.S. National Science Foundation, the Paul Scherrer Institute, and the US-Israel Binational Science Foundation.

The Proton Radius Puzzle

- Originally arose from the 7σ discrepancy between muonic hydrogen measurements and electron measurements.



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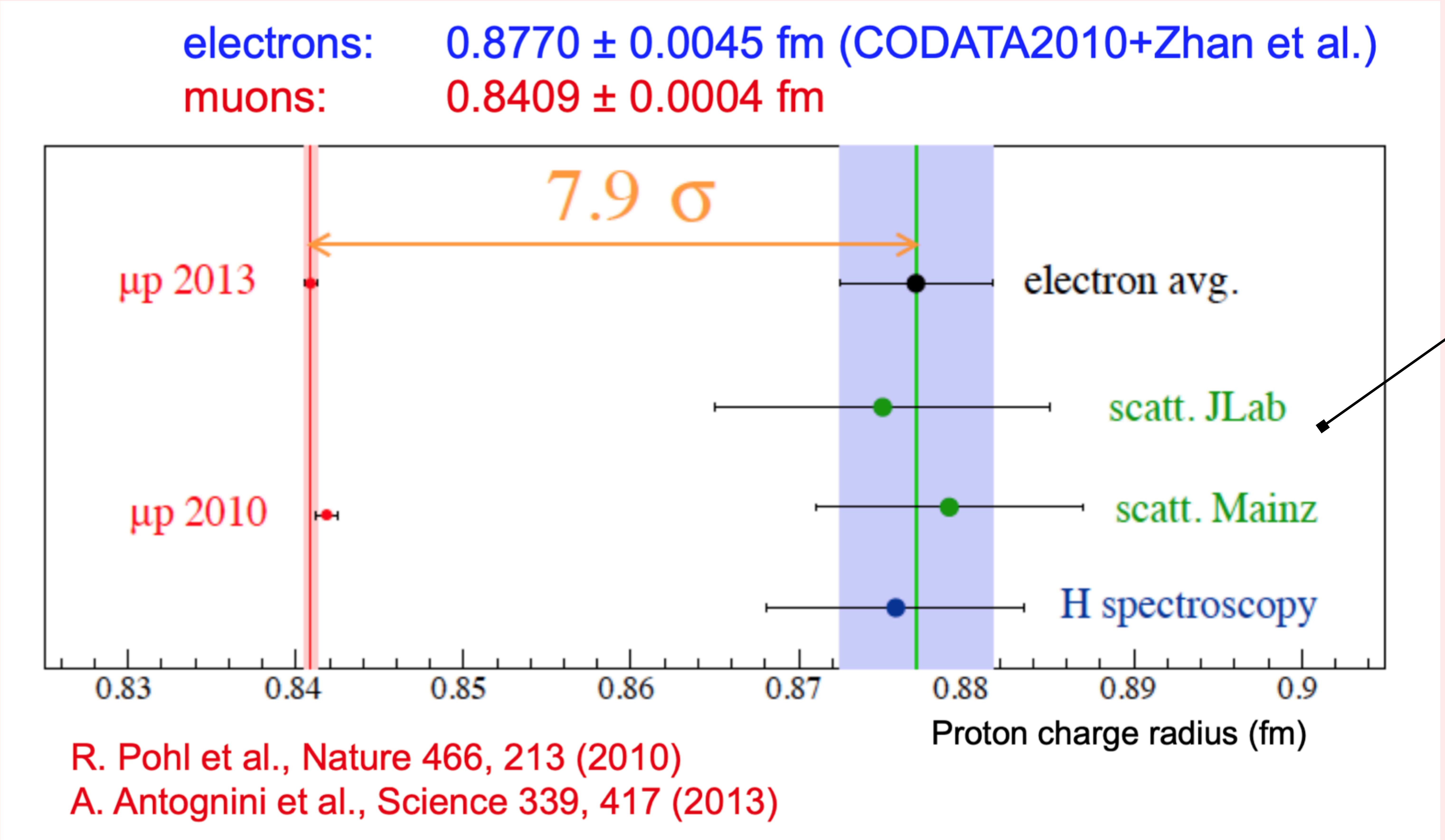

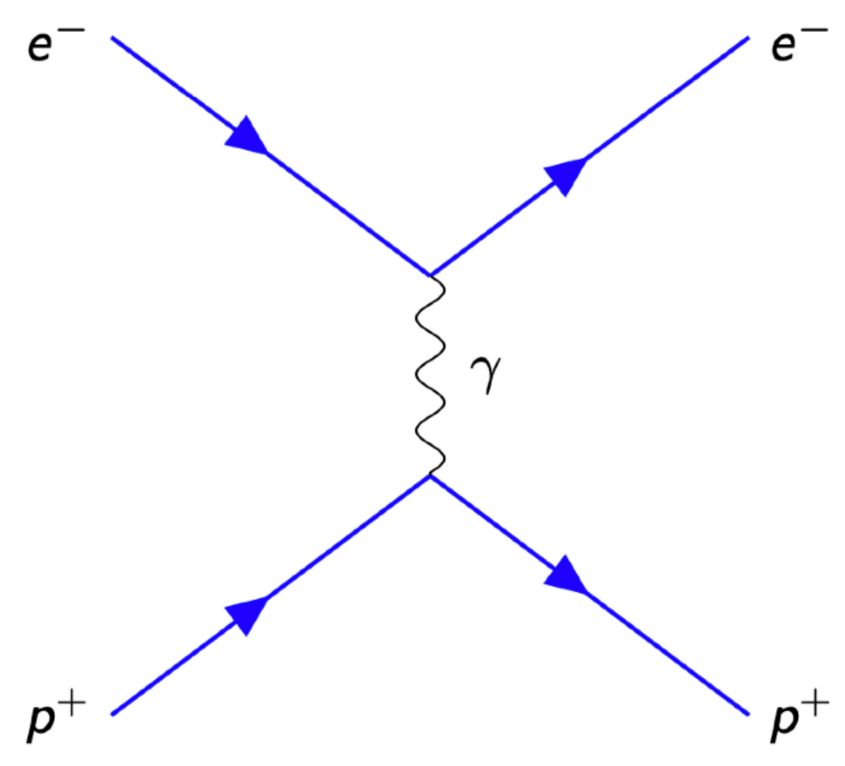

$$\frac{d\sigma_{Ros}}{d\Omega} = \left[\frac{d\sigma}{d\Omega}\right]_{\substack{\text{point}\\ \text{like}}} \left[G_E{}^2(Q^2) + \frac{\tau}{\epsilon} G_M{}^2(Q^2)\right]$$

$$\tau = \frac{Q^2}{4M^2} \qquad \epsilon = \left[1 + 2(1+\tau)\tan^2\left(\frac{\theta_c}{2}\right)\right]^{-1}$$

$$< r_p^2 > = -6\frac{dG_E}{dQ^2}\Big|_{Q^2\to 0}$$

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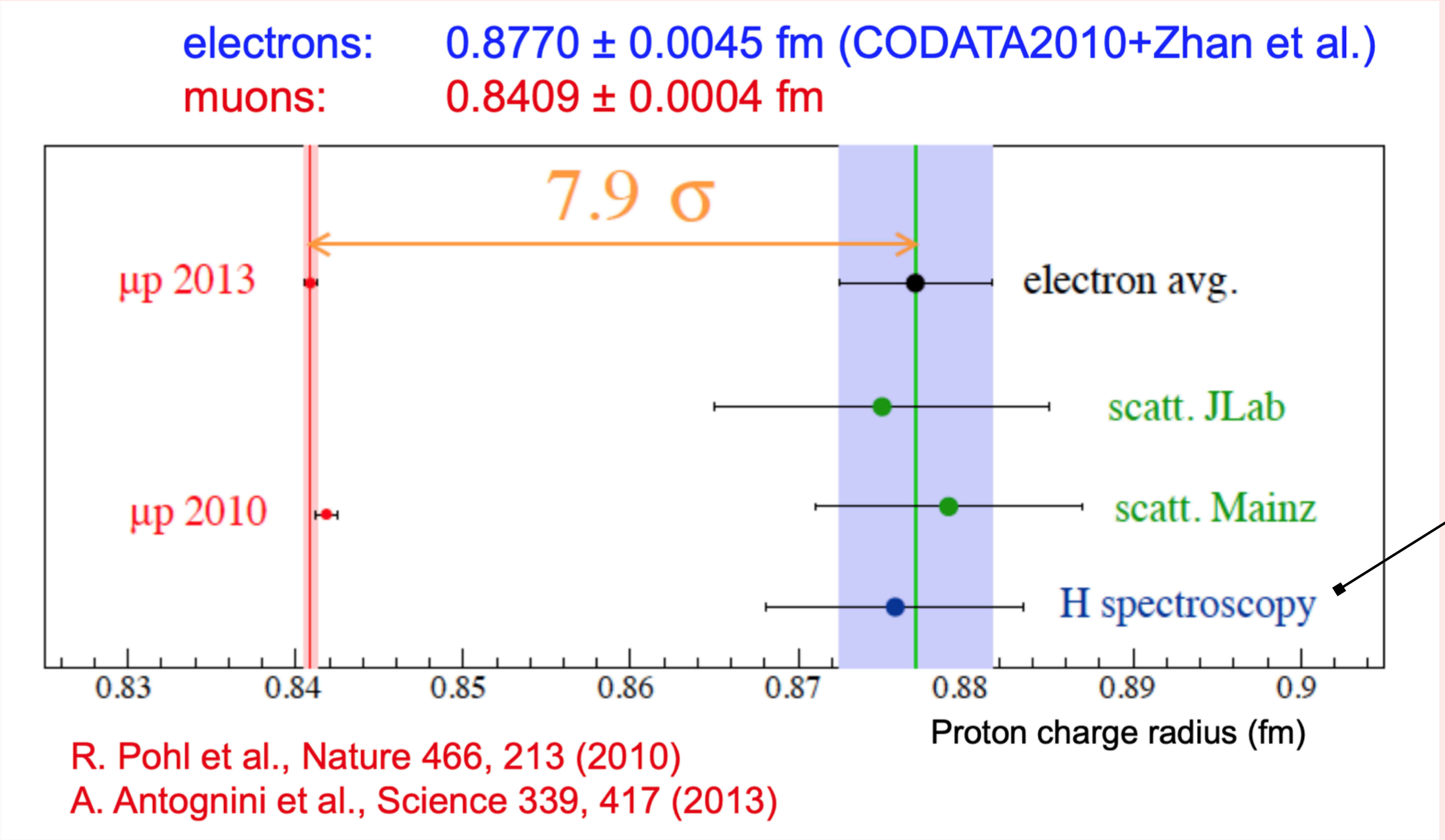

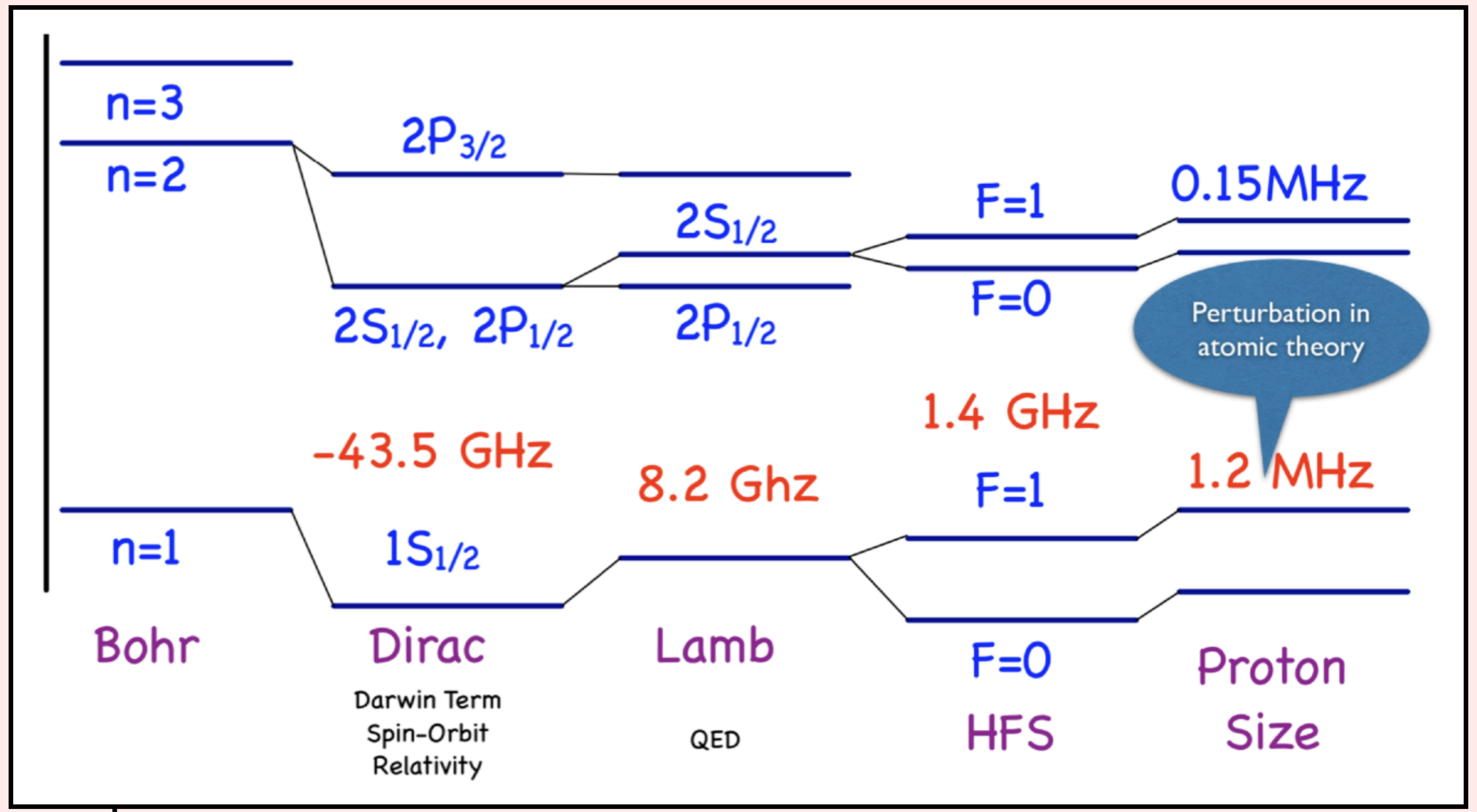

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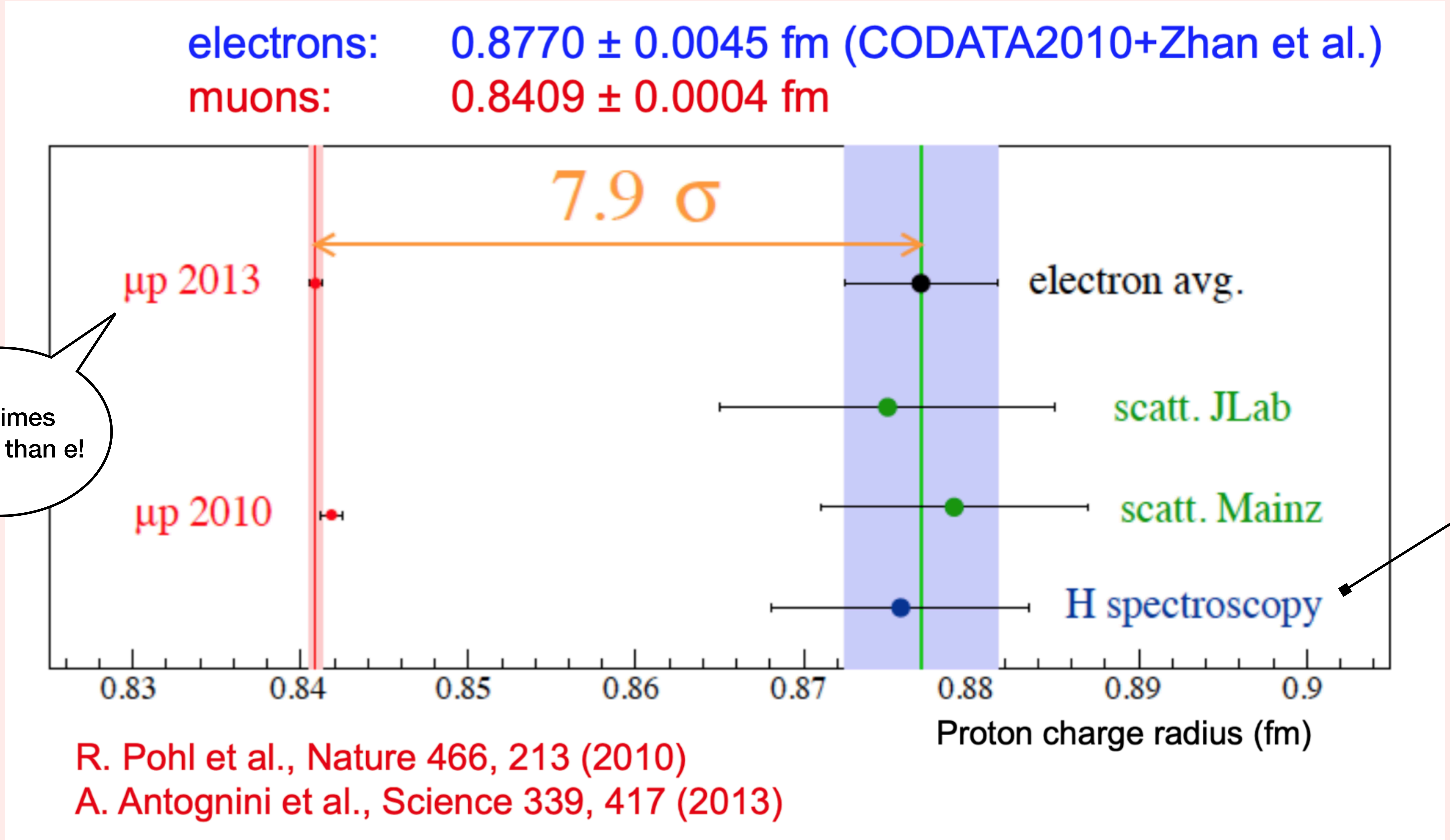
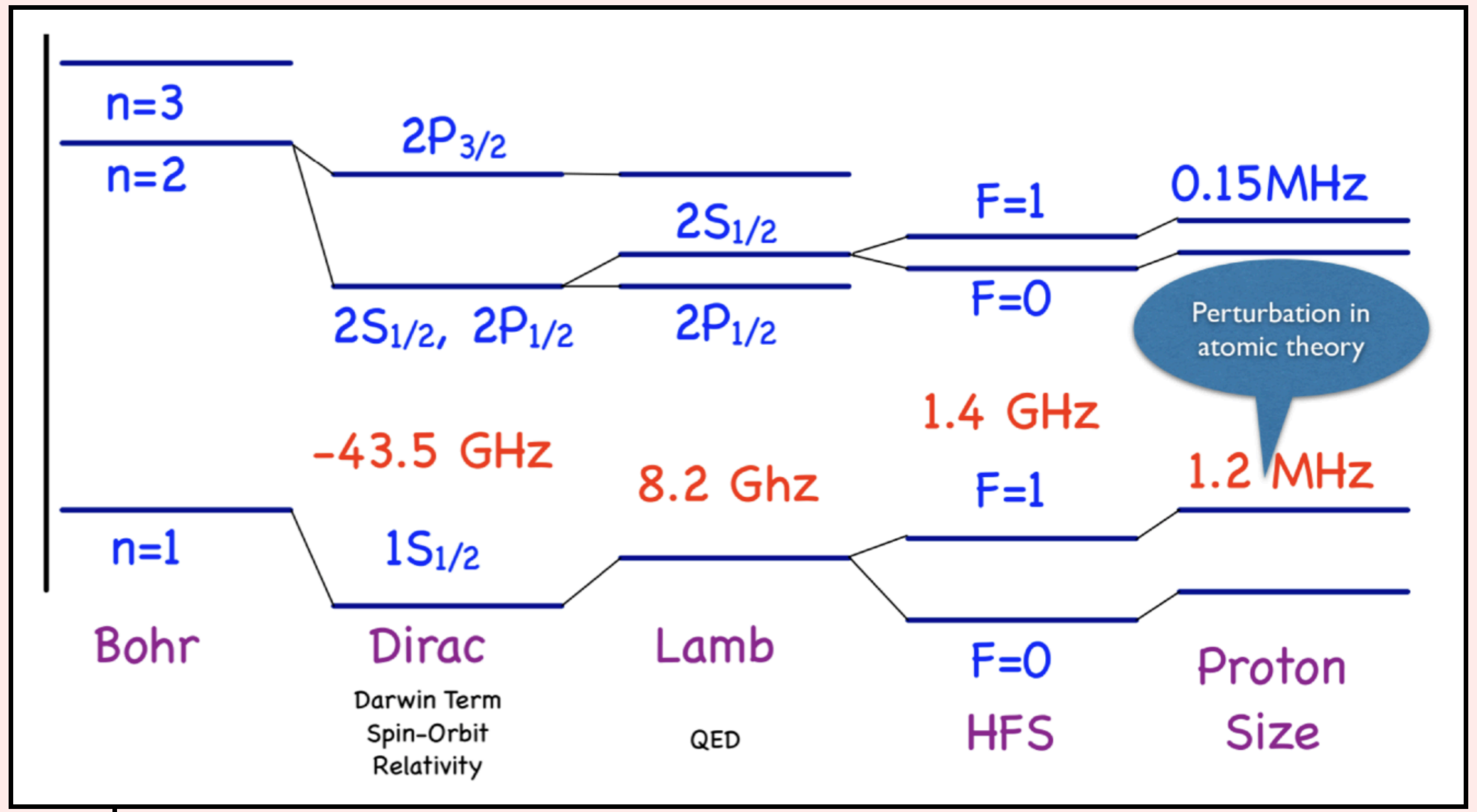


200 times heavier than e!



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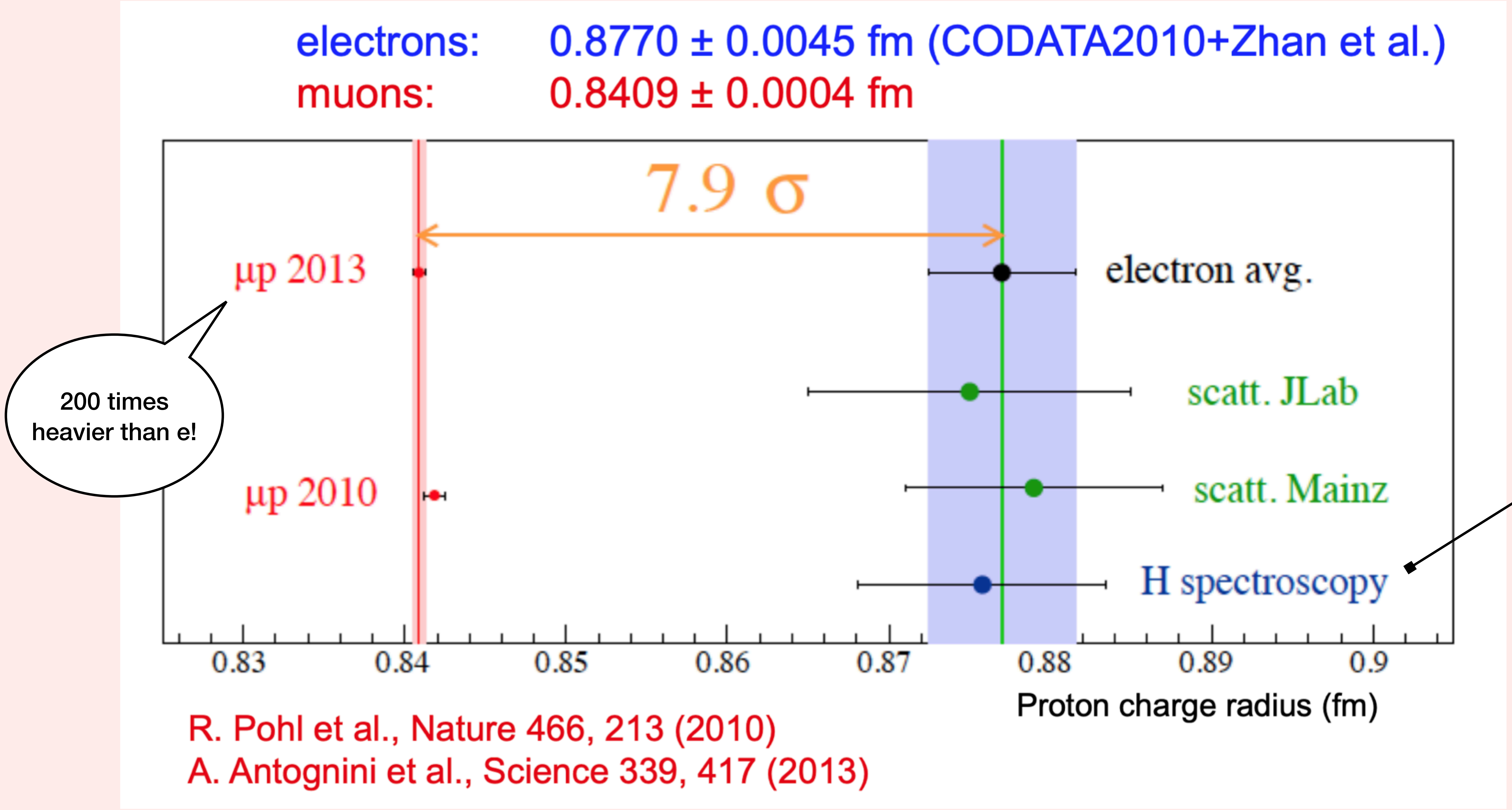

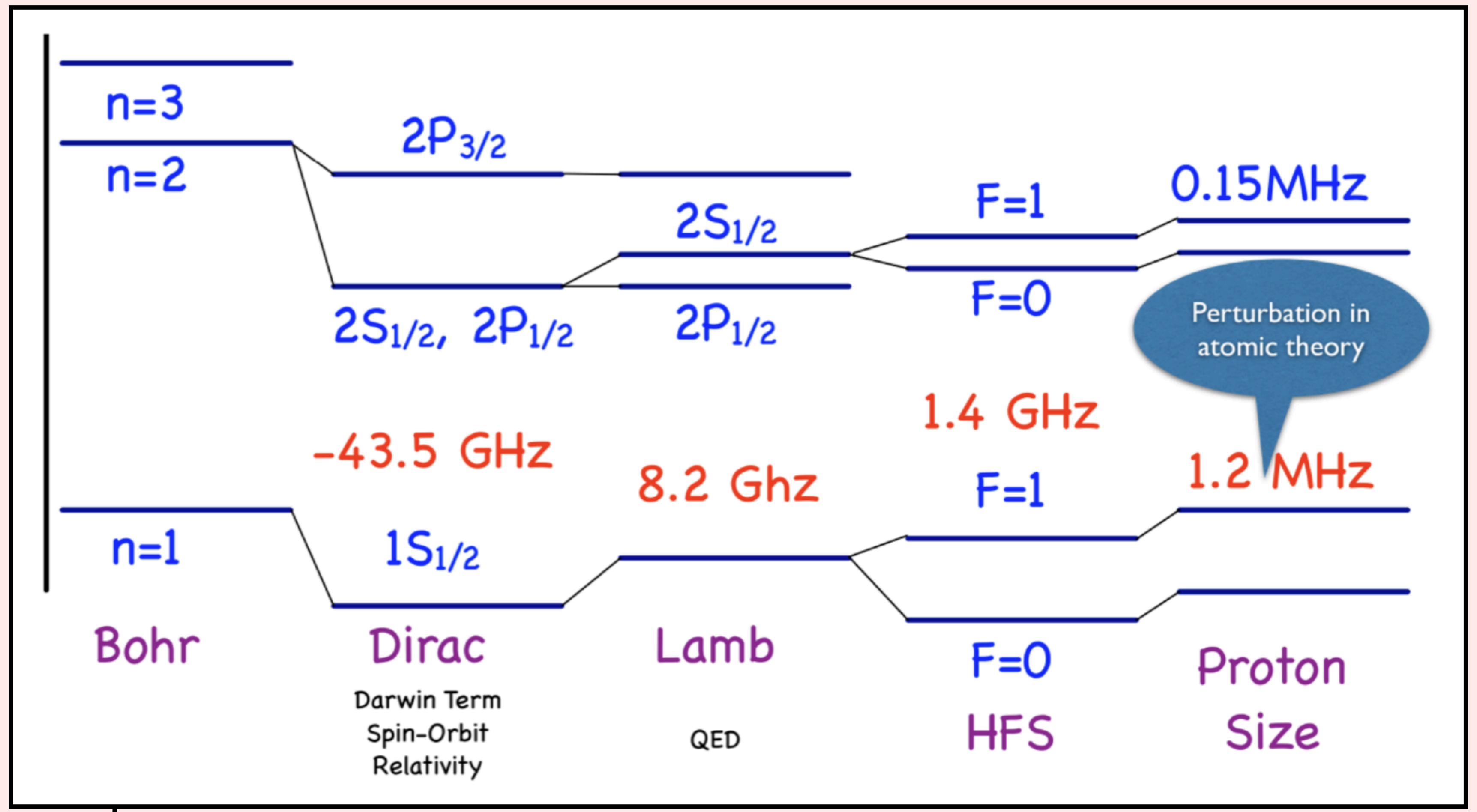

The Proton Radius Puzzle

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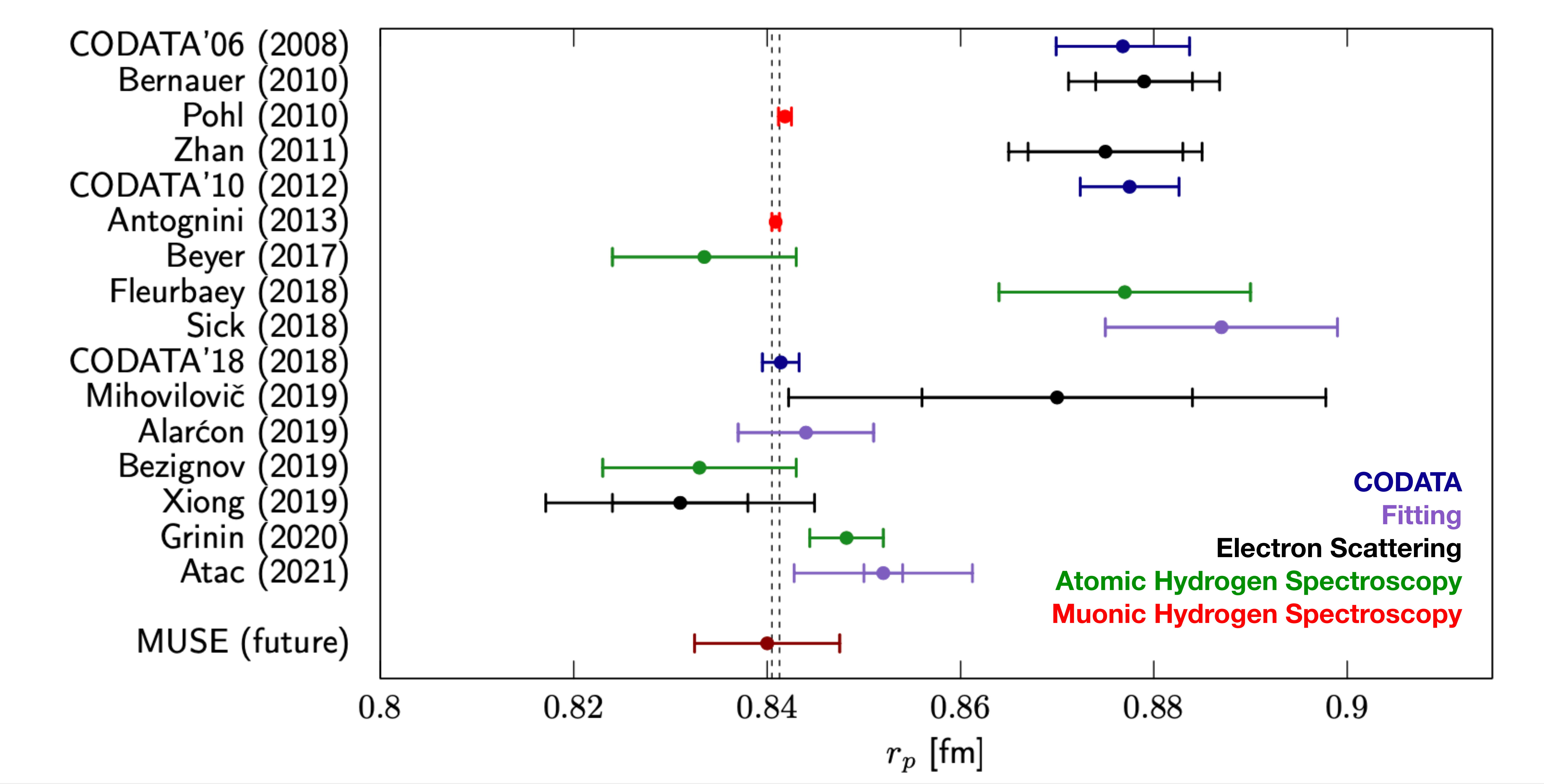
- Most recent results point to a smaller radius, but there remain issues in the data, questions about the radiative corrections, and a lack of understanding about what might be wrong with earlier results



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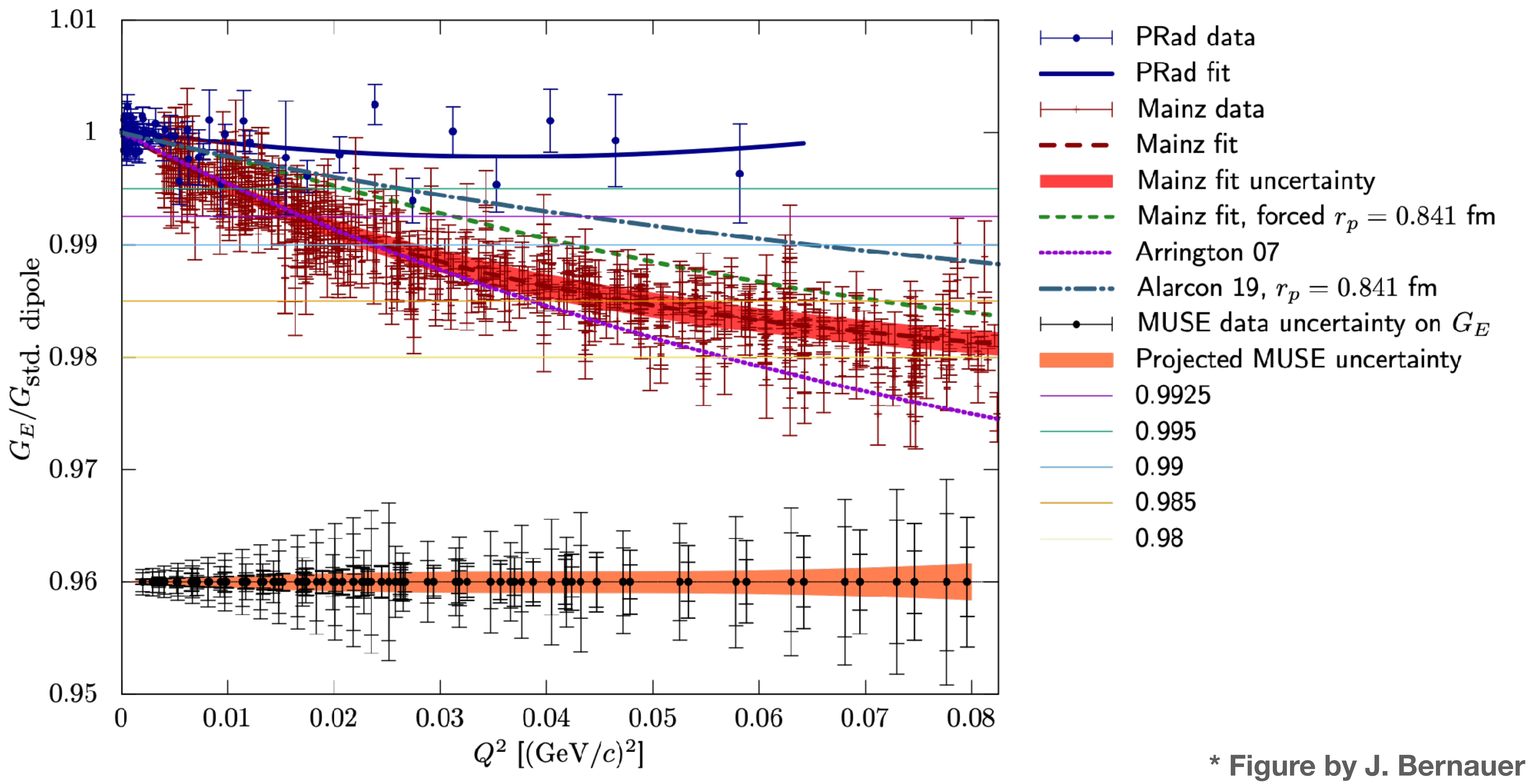


* Figure by J. Bernauer

$$< r_p^2 > = -6\frac{dG_E}{dQ^2}\bigg|_{Q^2\to 0}$$

Lepton Universality

- Standard Model assumes that all leptons have the same interactions (aside from trivial mass effects)
- Violation of lepton universality would be an important clue to new physics:
  - LHCb results show 3.1σ deviation in the branching ratio of $B^+ \to K^+e^+e^-$ vs. $B^+ \to K^+\mu^+\mu^-$
  - Muon g-2 shows 4.2σ deviation to the anomalous magnetic moment predicted by the standard model
- MUSE will directly compare form factors determined by ep and μp scattering, a more general lepton universality test than just the charge radius

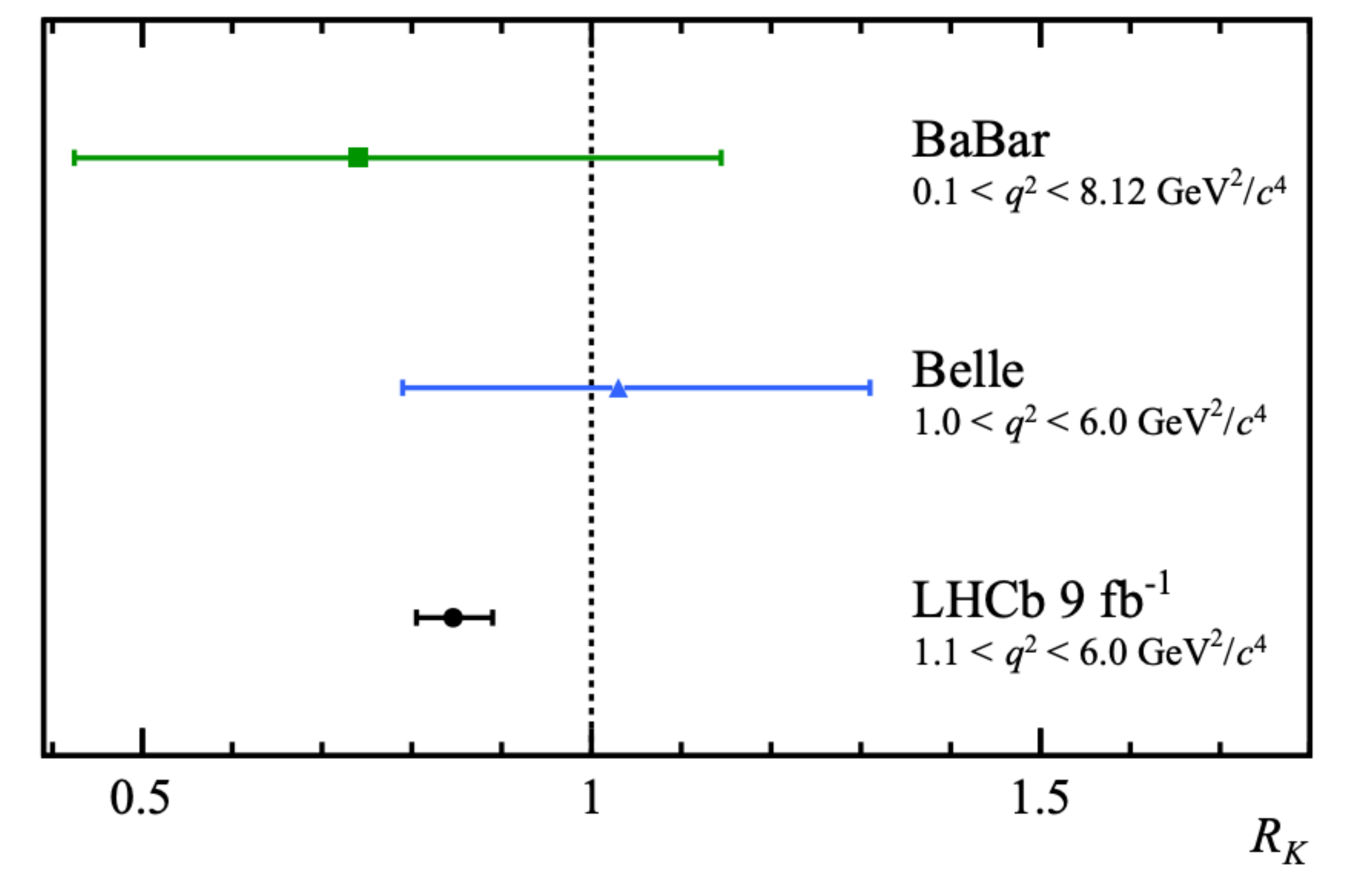
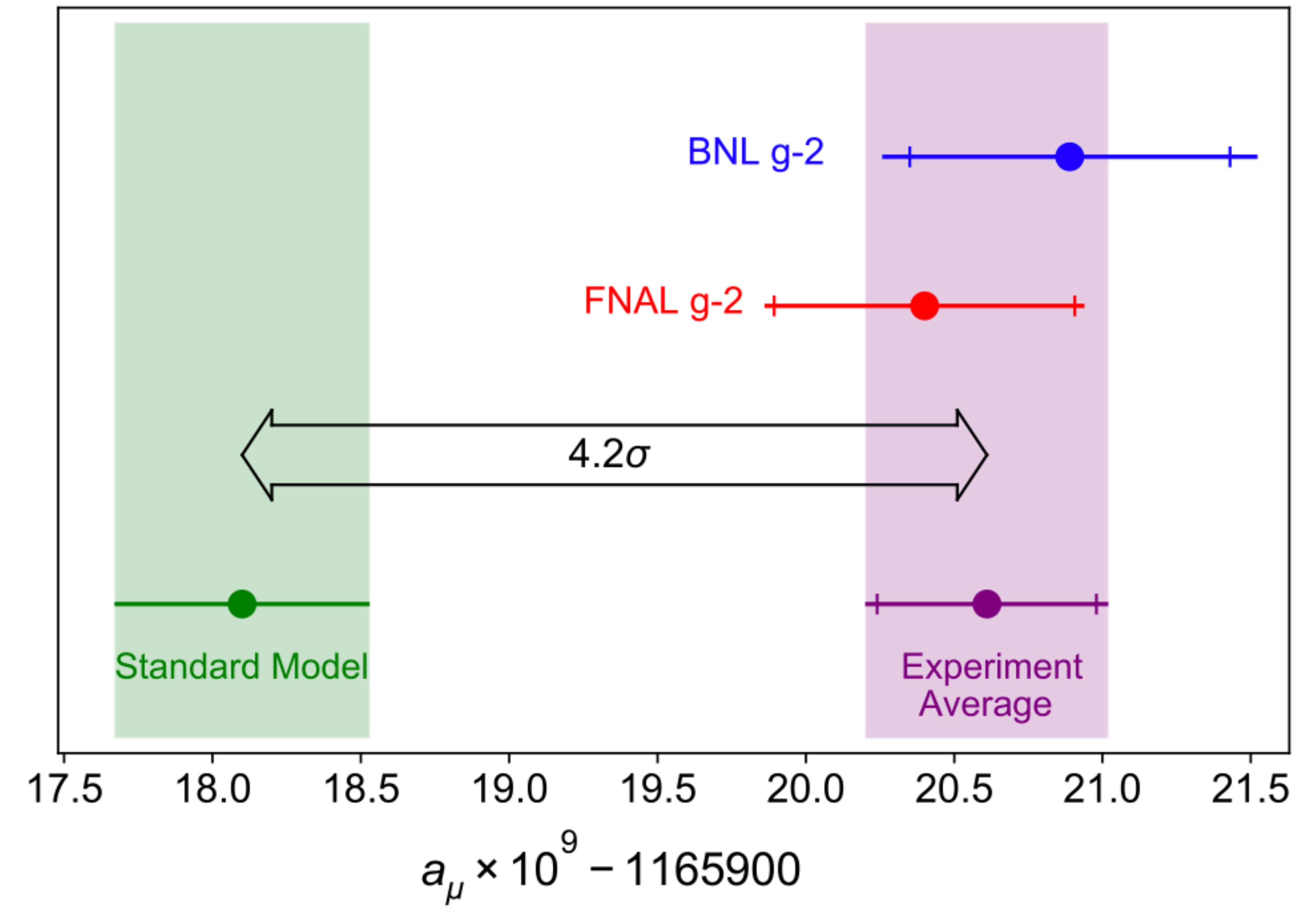


Figure 4: Comparison between R_K measurements. In addition to the LHCb result, the measurements by the BaBar [113] and Belle [114] collaborations, which combine $B^+ \to K^+\ell^+\ell^-$ and $B^0 \to K^0_S\ell^+\ell^-$ decays, are also shown.

LHCb collaboration, *Test of Lepton Universality in beauty-quark decays*, arXiv:2103.11769



The Muon g - 2 Collaboration, *Measurement of the Positive Muon Anomalous Magnetic Moment to 0.46 ppm*, arXiv: 2104.03281

The Proton Radius Puzzle

- More new data are needed to understand the puzzle
- In need of high precision data for μp scattering
- Good to have more ep scattering data to compare results

r_p(fm)	ep	μp
Spectroscopy	0.877 +/- 0.007	0.841 +/- 0.0004
Scattering	0.875 +/- 0.006	???

*Original motivation of MUSE in 2012

The Proton Radius Puzzle

- MUSE will directly compare ep and μp scattering results at sub-percent level precision
- MUSE will test the two photon exchange contribution by comparing measurements of both polarities

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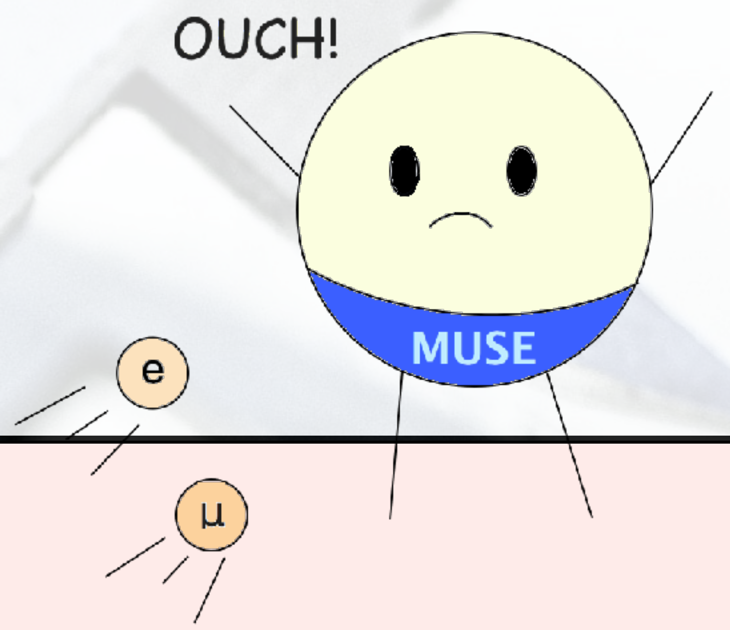
Scattering	0.875 +/- 0.006	



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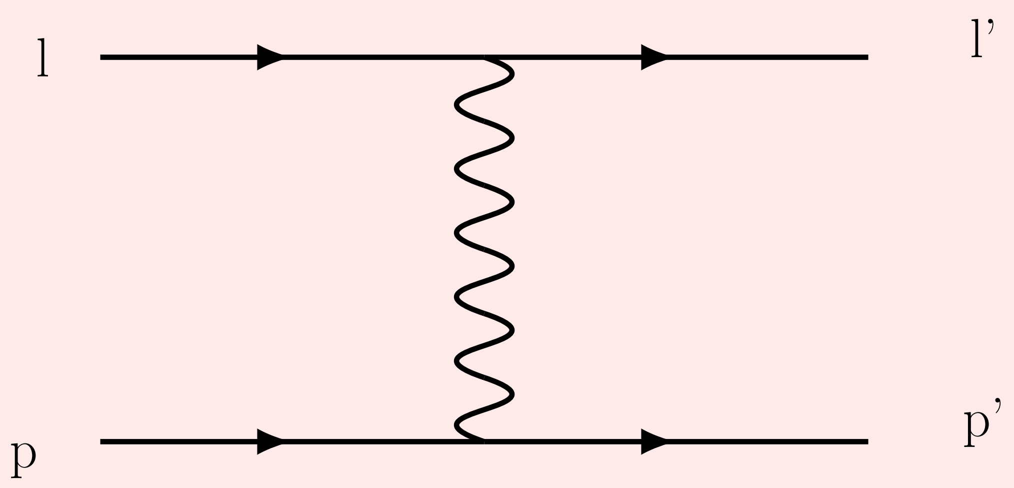
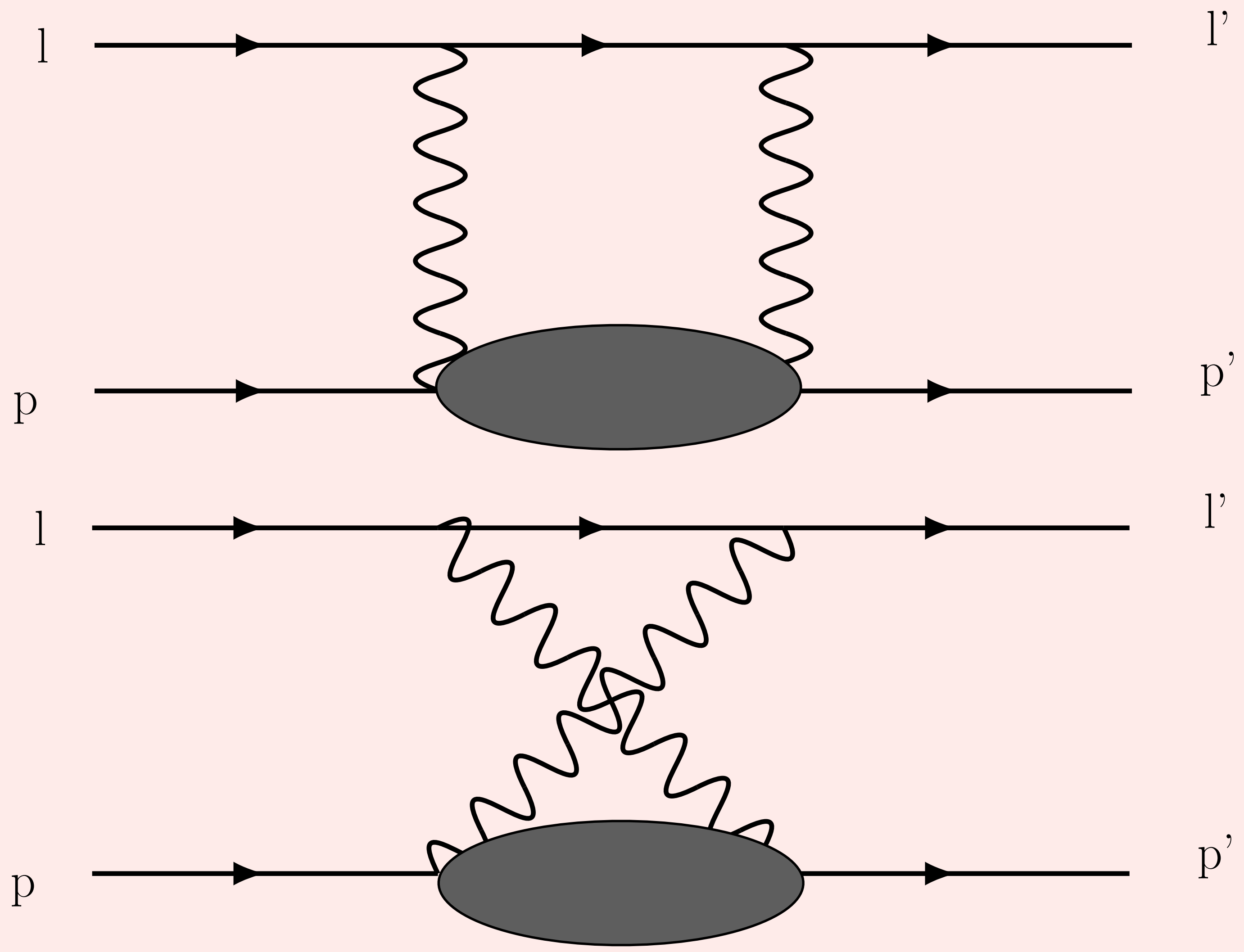
Two Photon Exchange

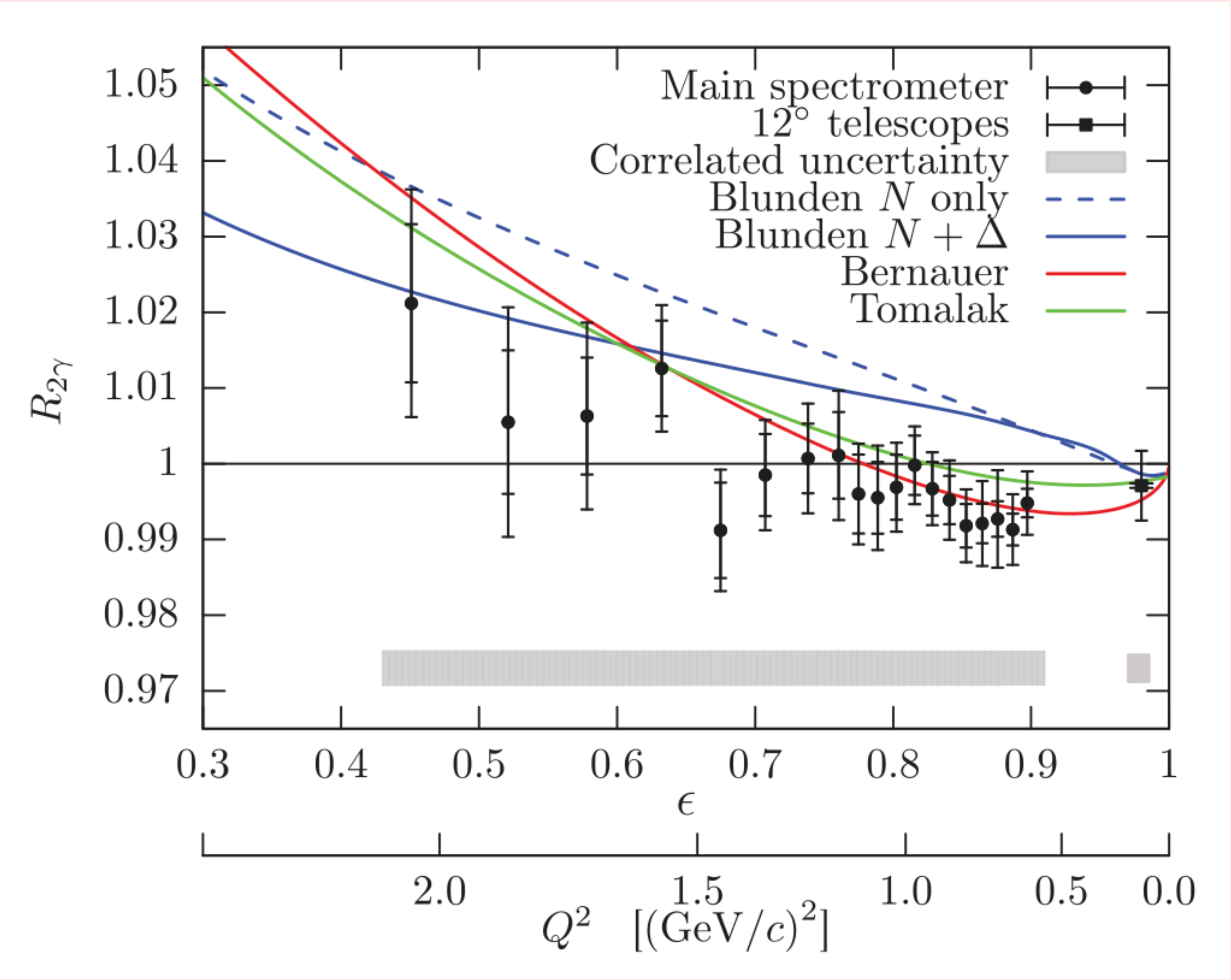
- Extractions of form factors and the radius might be affected by higher-order Feynman diagrams
- TPE can be measured by comparing the elastic scattering cross section of + vs - beam polarities
- Recent data shows $R_{2\gamma} = \sigma_{e^+p}/\sigma_{e^-p}$ is within a few percent of unity, but these percent level effects can change the slope of the form factor and affect the radius extraction
- MUSE will directly test TPE in ep and μp scattering at low Q^2 in the range of ε from 0.26 - 0.94

OPE diagram phase is - for electrons, + for positrons



Phase of TPE diagram is always +



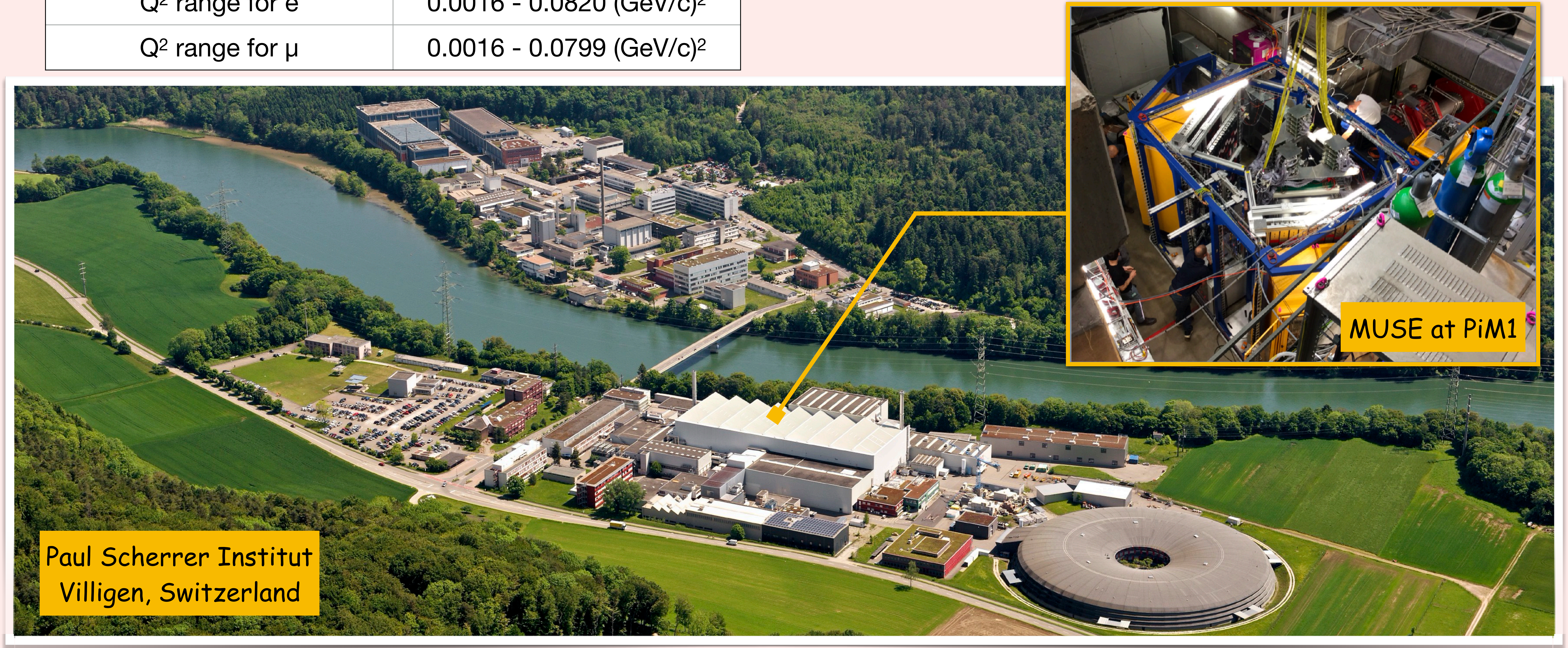


B.S Henderson et al. (OLYMPUS Collaboration) Phys. Rev. Lett. 118, 092501

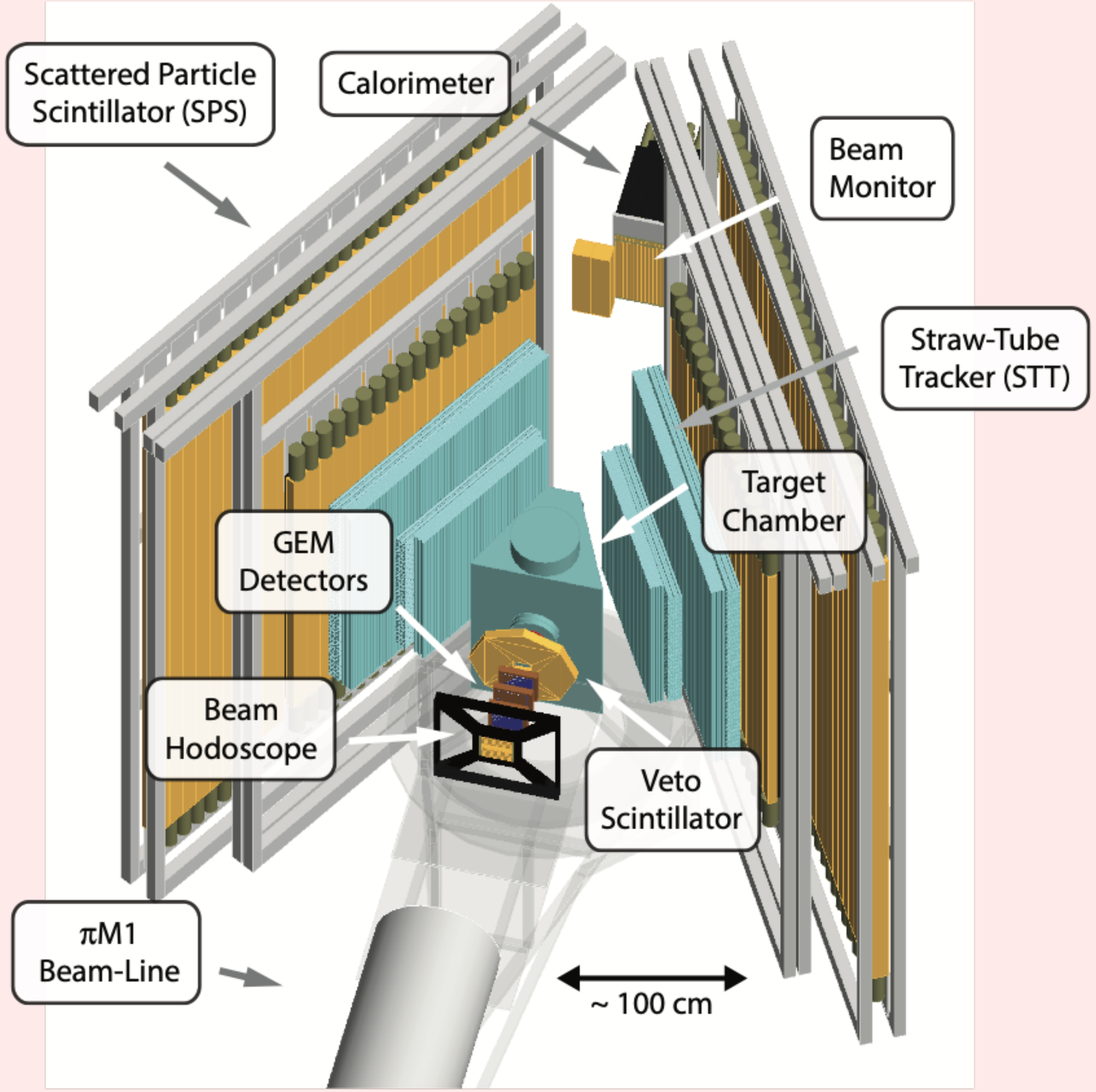
The MUon proton Scattering Experiment

Quantity	Coverage
Beam momenta	115, 160, 210 MeV/c
Scattering angle	20 - 100 degrees
Q^2 range for e	0.0016 - 0.0820 $(GeV/c)^2$
Q^2 range for μ	0.0016 - 0.0799 $(GeV/c)^2$

- Located at the Paul Scherrer Institut in Villigen, Switzerland
- Uses the PiM1 beamline: secondary beam with $e^{+/-}$, $\mu^{+/-}$ and $\pi^{+/-}$ at 3.3 MHz beam flux



MUSE Detectors



* Geant4 simulation by S. Strauch

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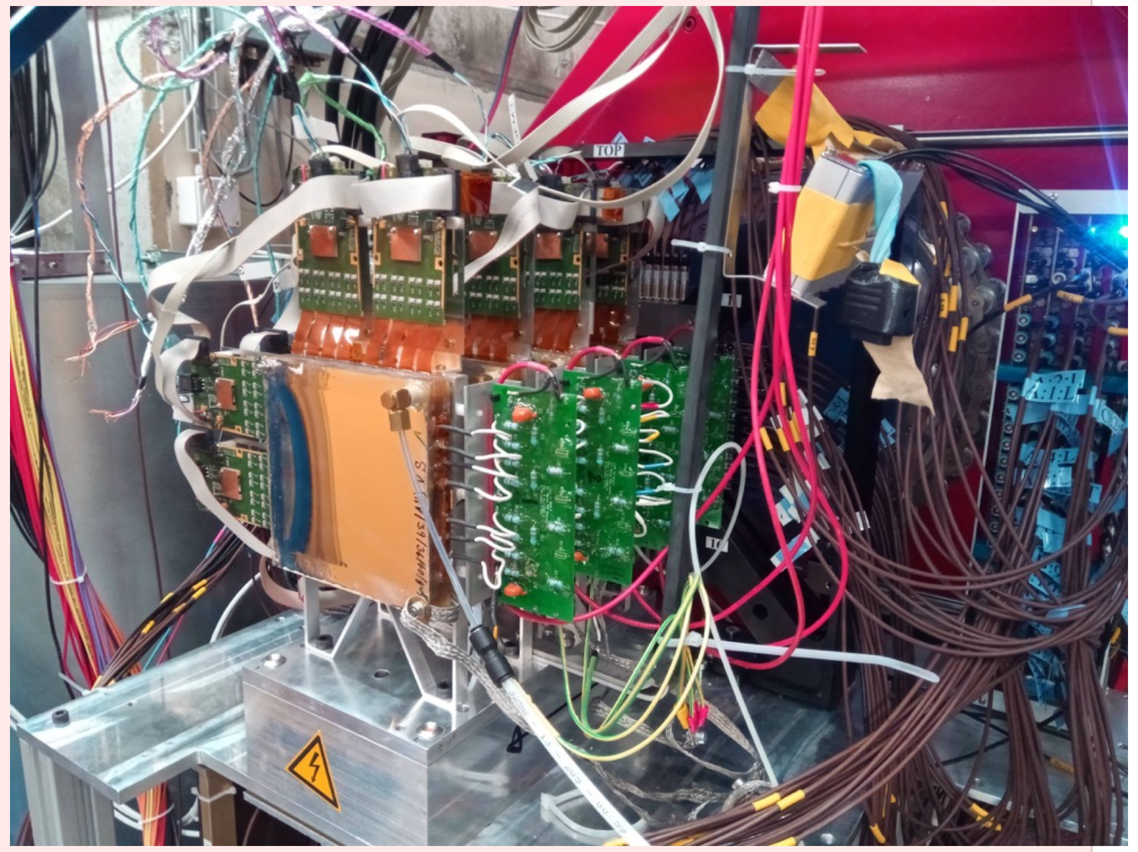
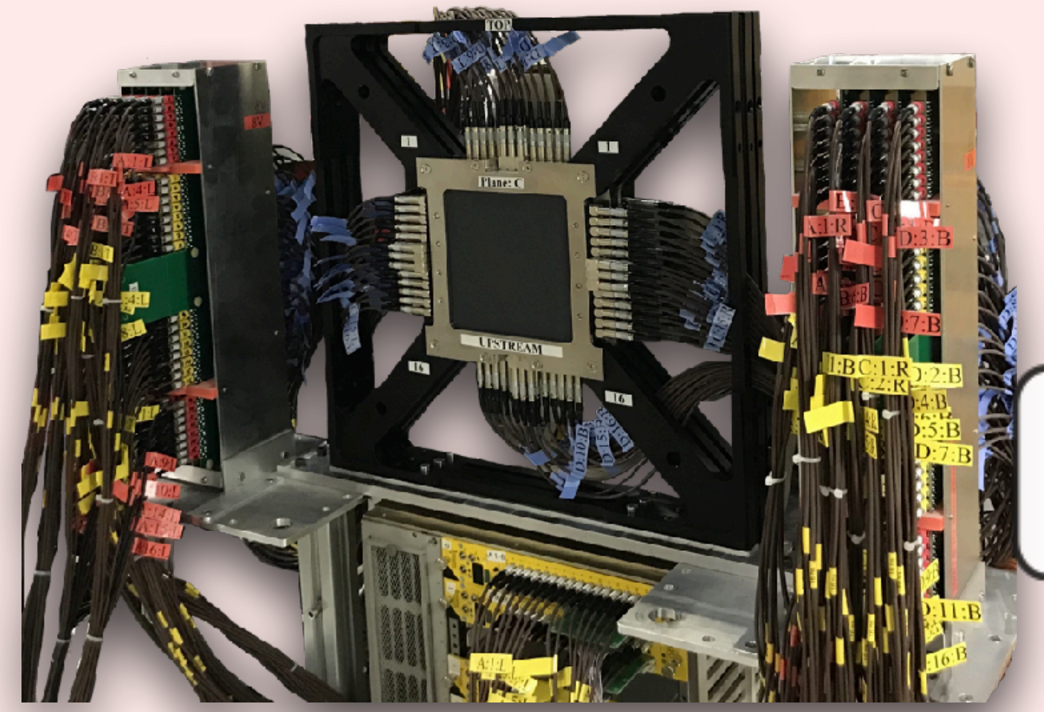
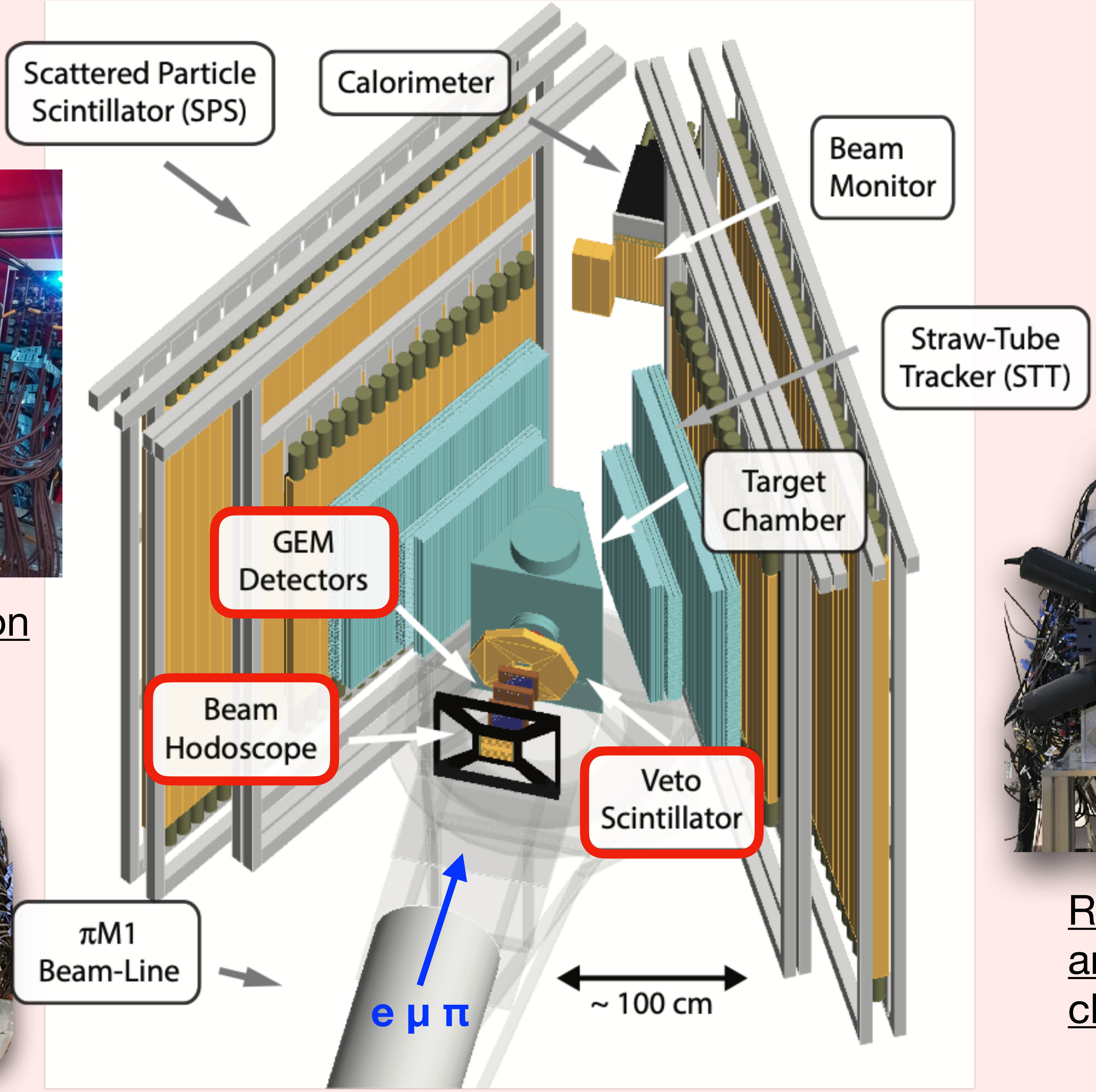


Precise 2D tracking information for incoming particles



PID and initial timing for incident particle, trigger



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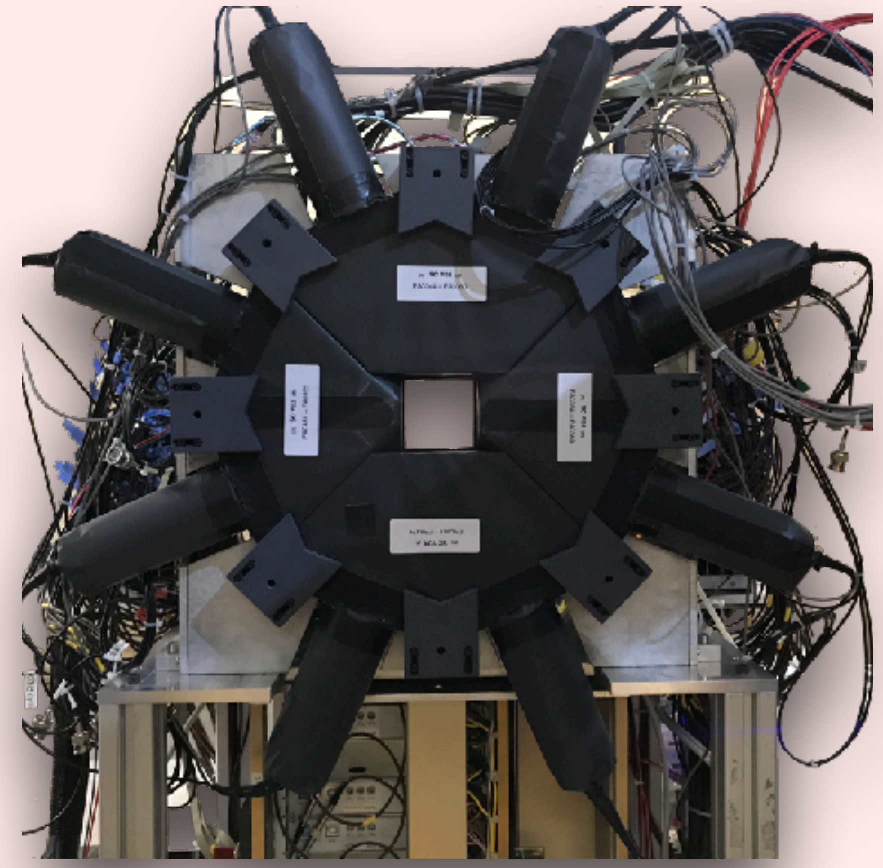
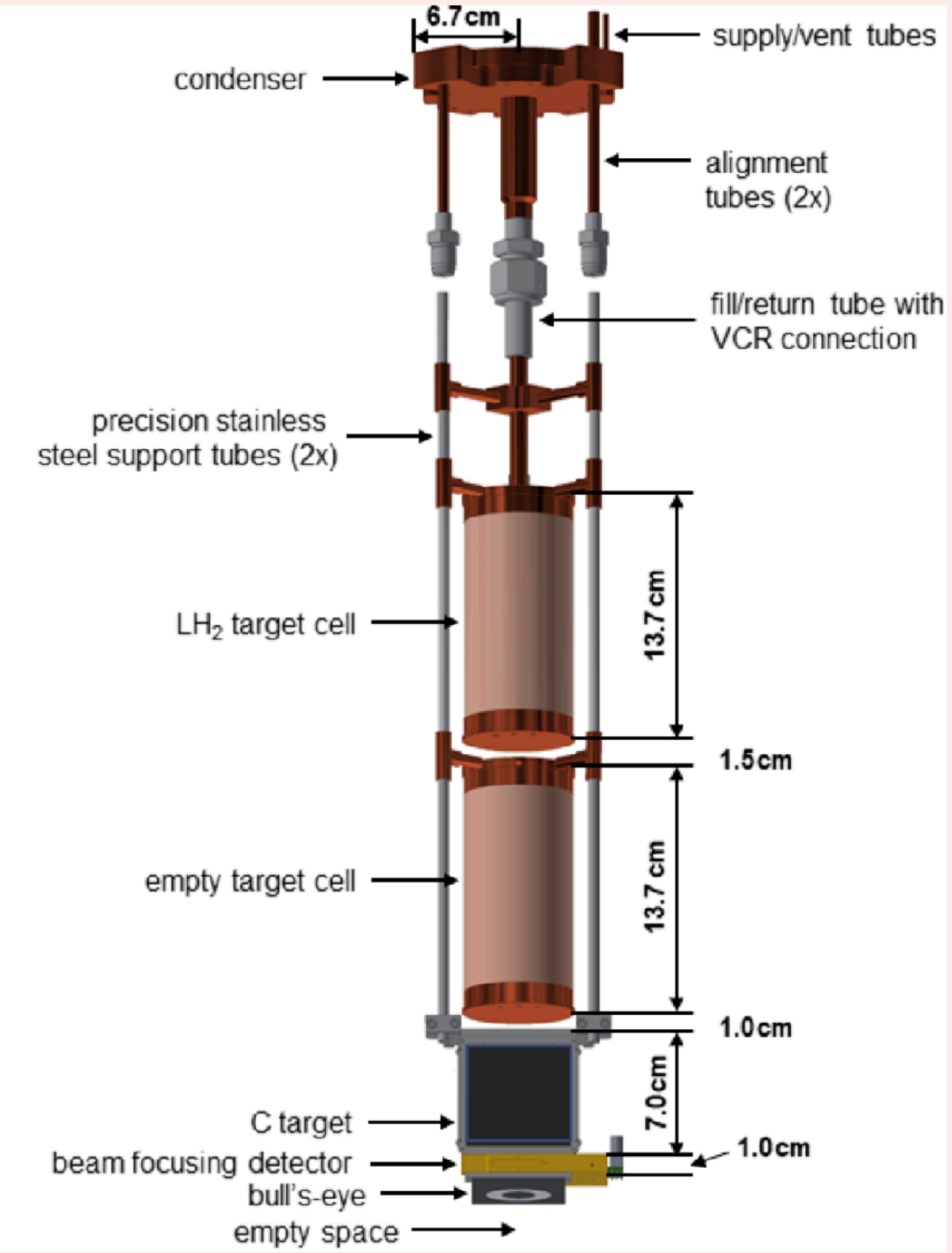
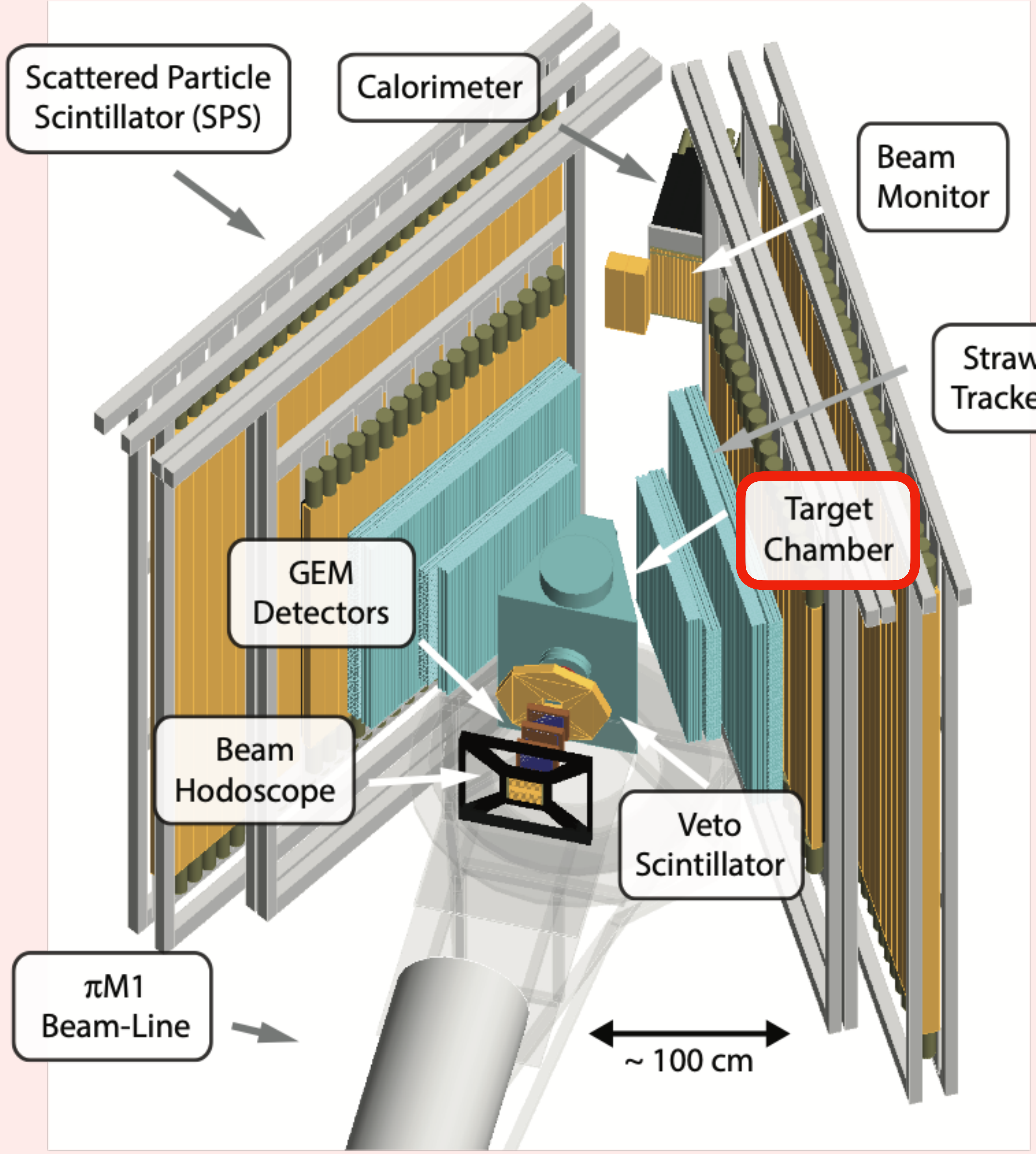
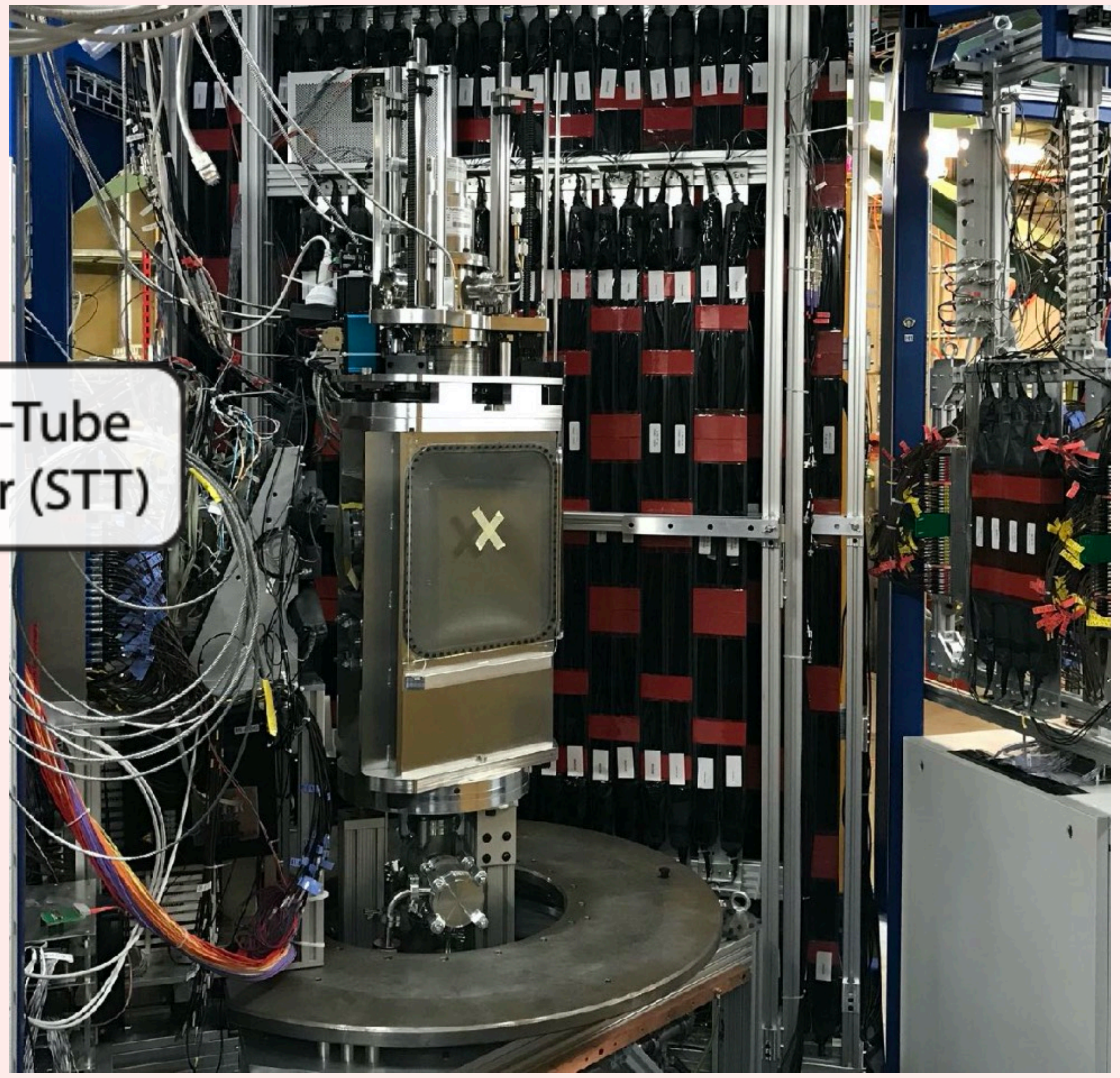


Reject incident decay events and particles that hit the target chamber wall

MUSE Detectors







<u>5 target positions available: LH2, empty cell, carbon target, beam focus monitor, empty space</u>

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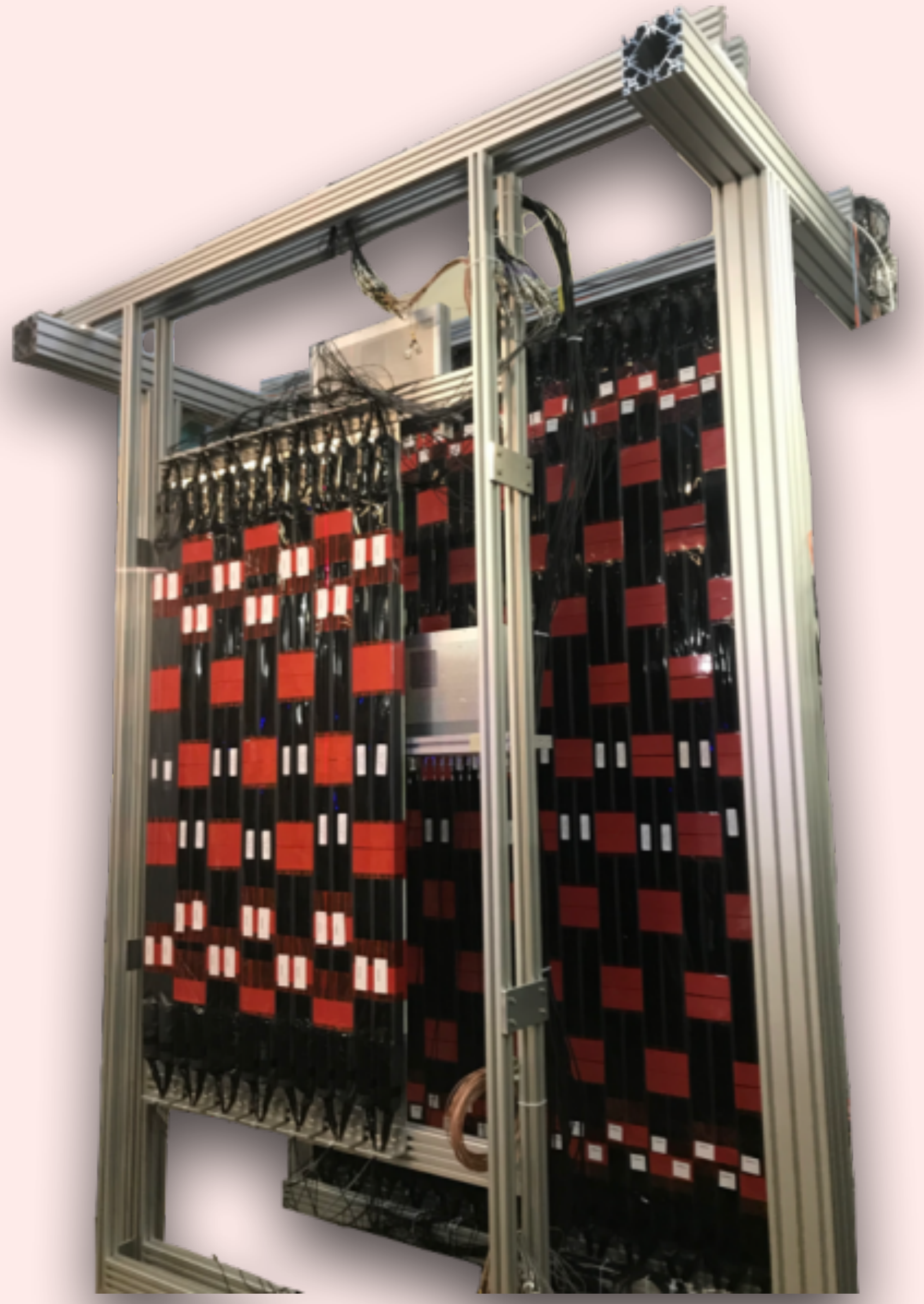
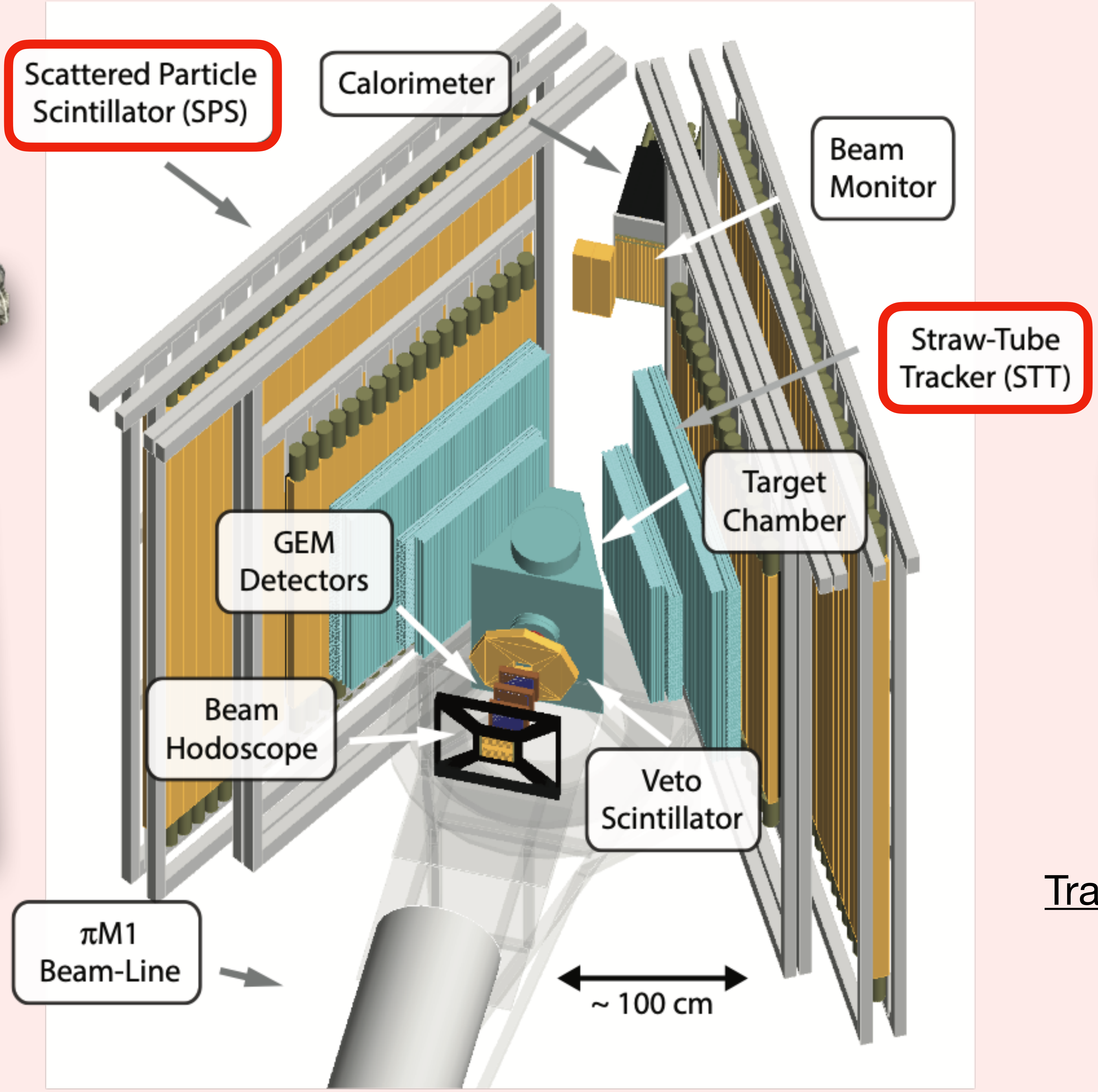


Timing and PID for scattered particles, trigger



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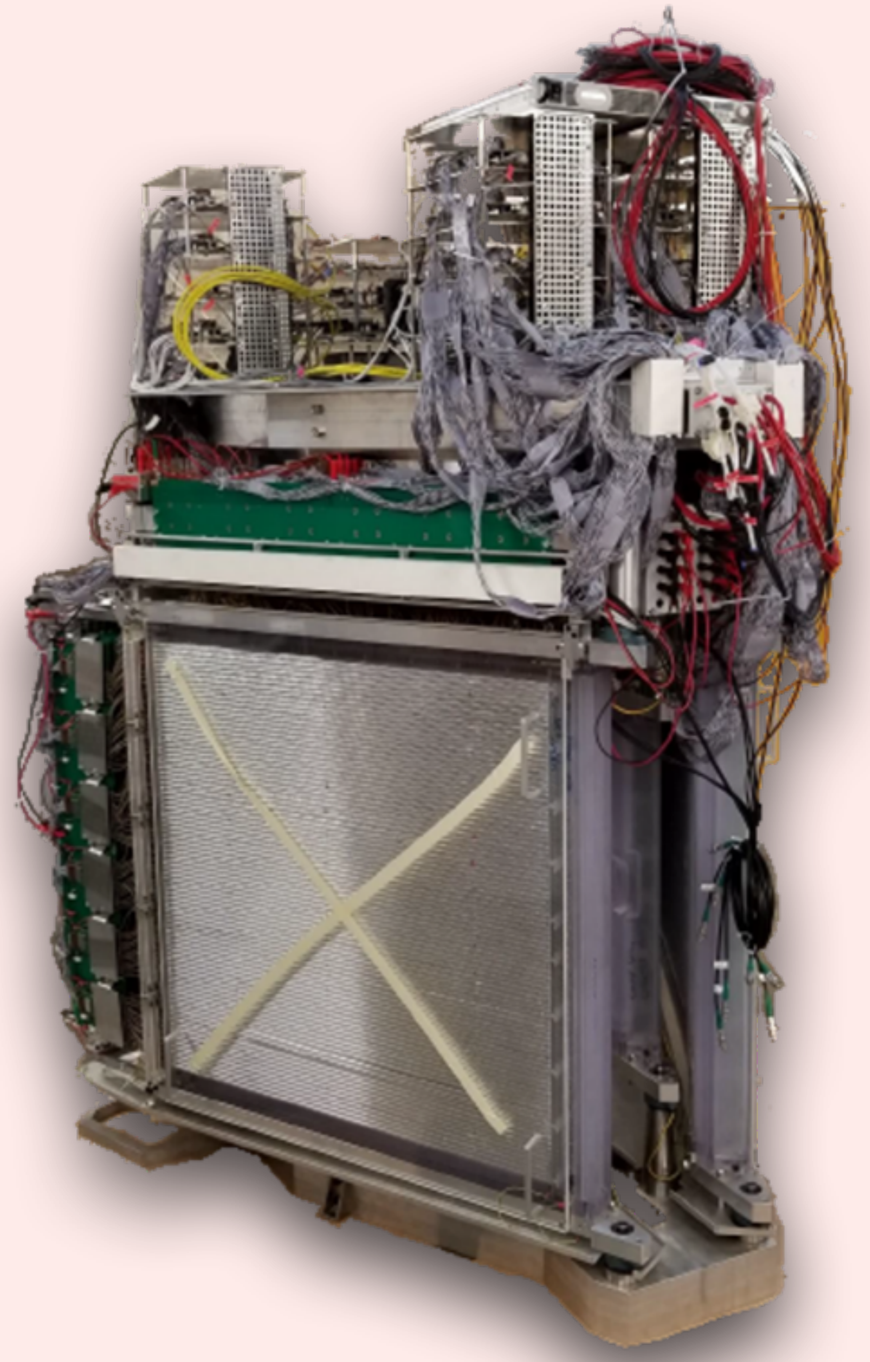
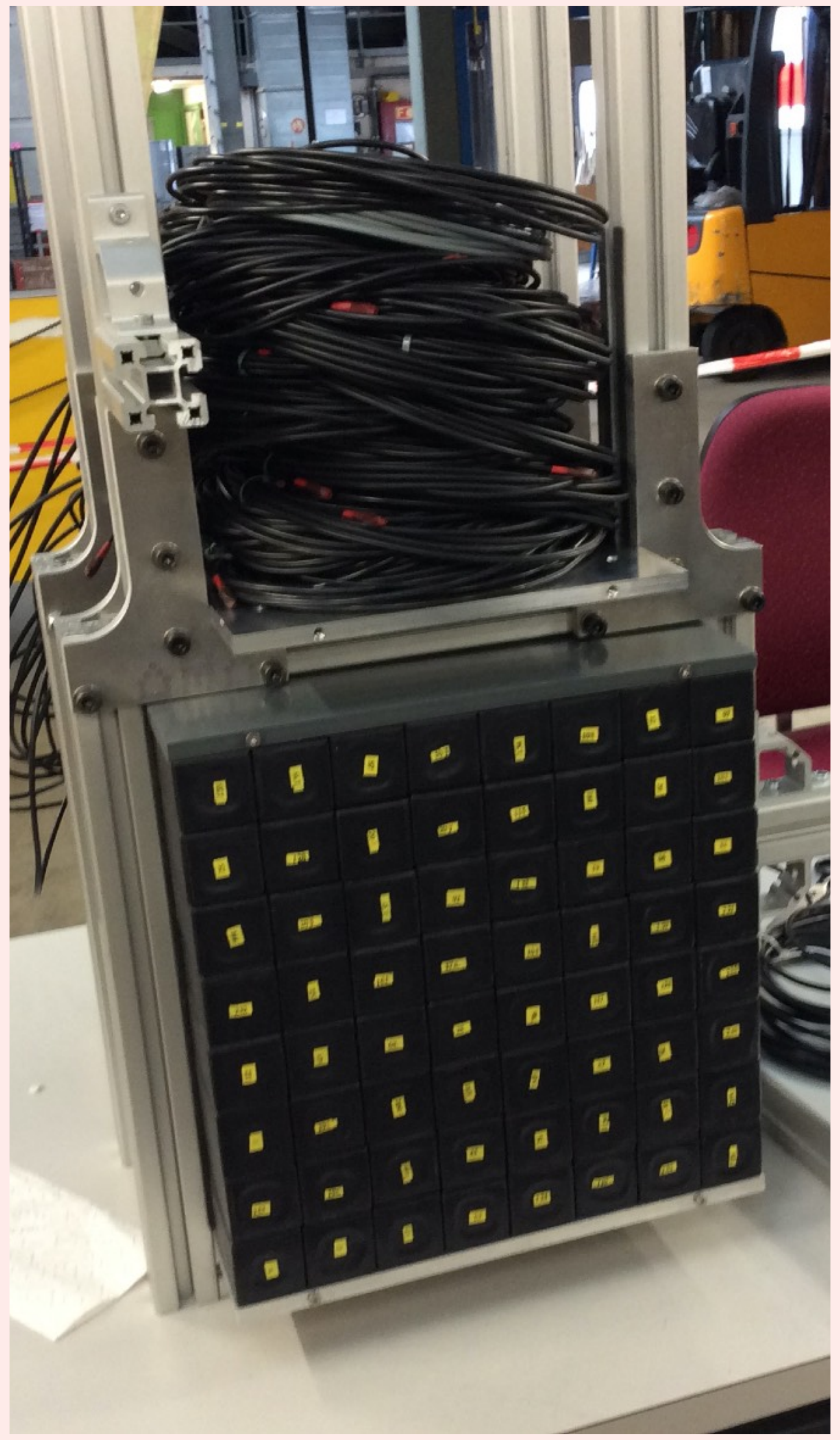
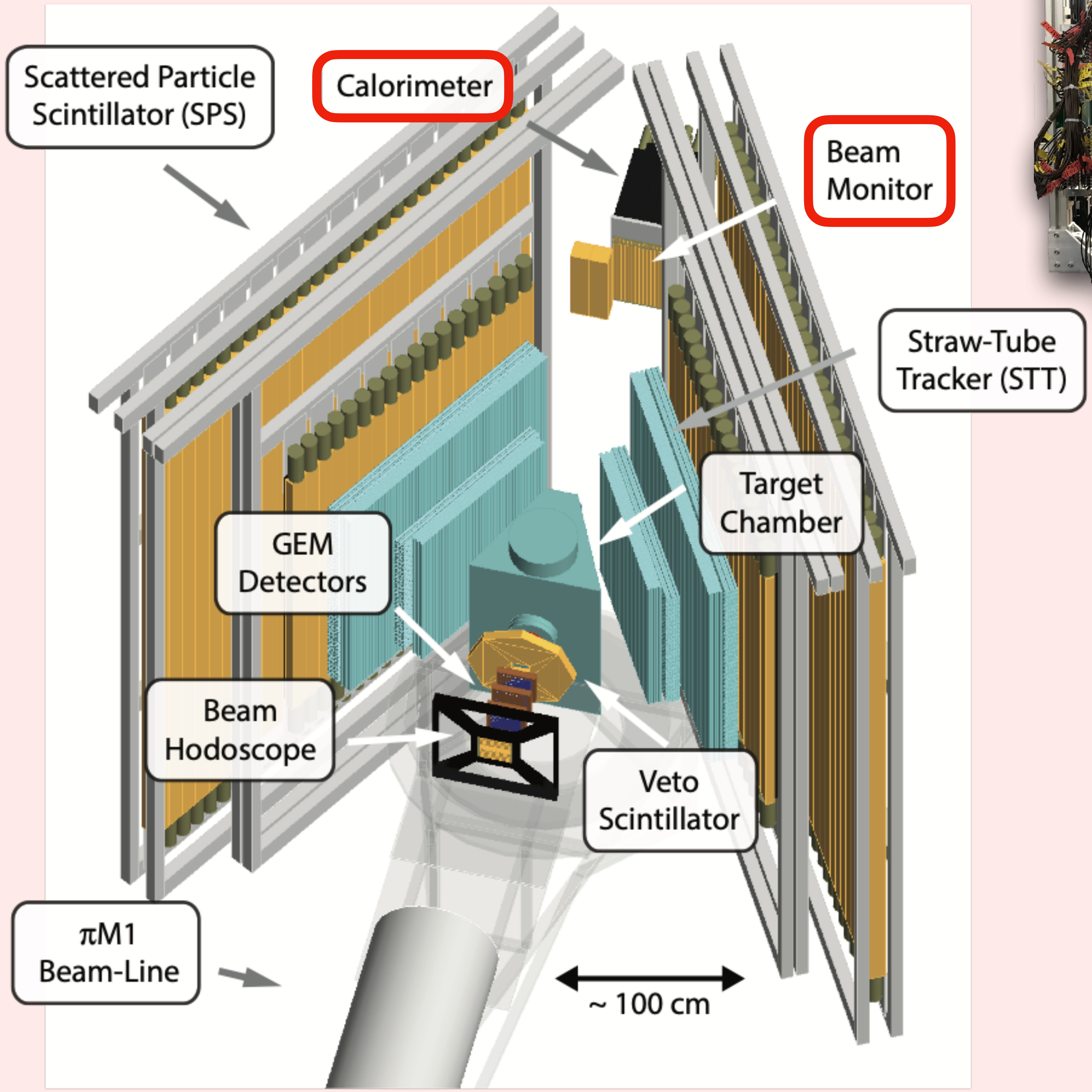


Tracking for scattered particles

MUSE Detectors



Veto events with high-energy forward-going photons to reduce sensitivity to radiative corrections



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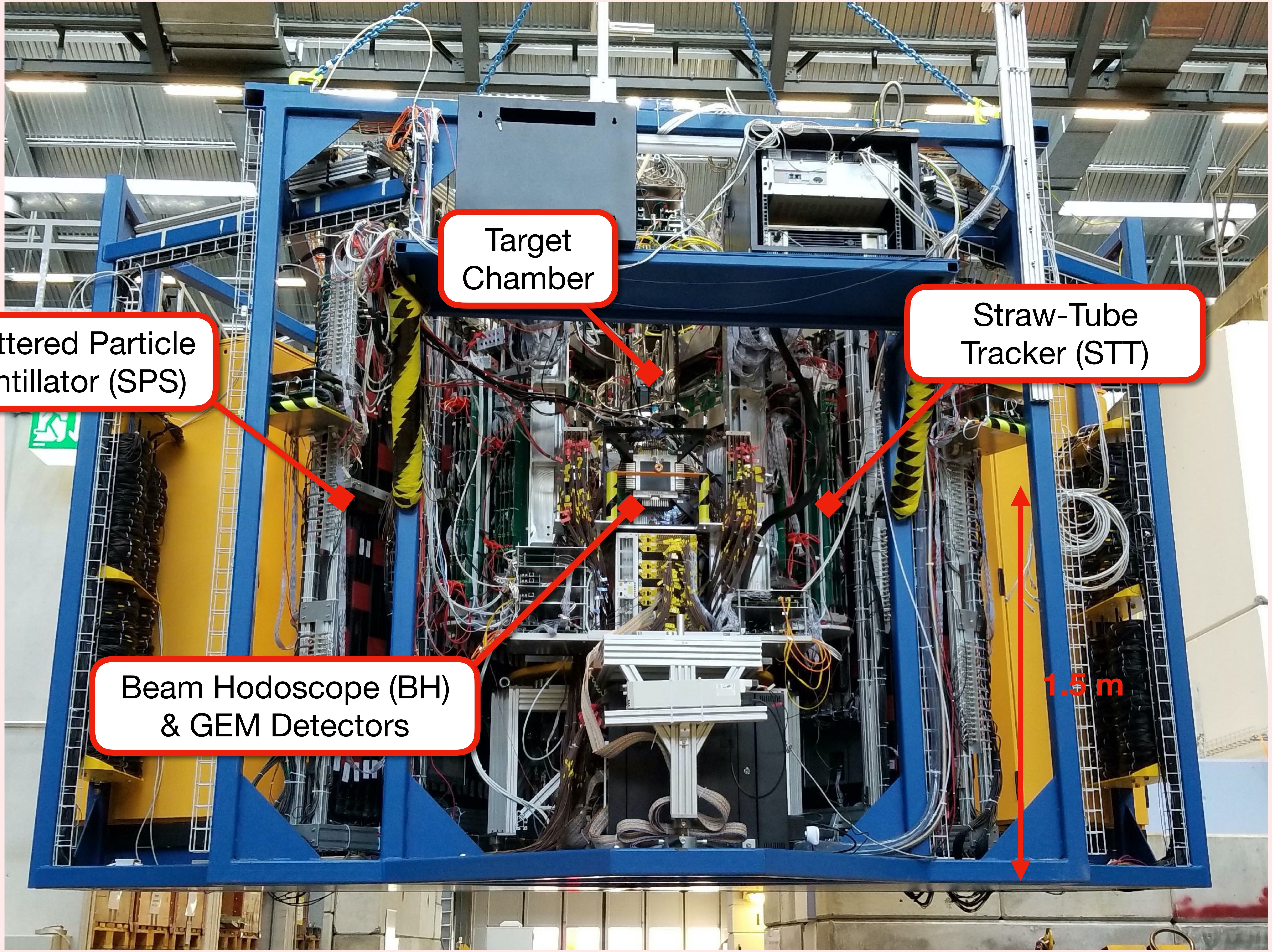
Monitor stability of beam and provide timing for TOF

Full View of the Experiment



Current plan and schedule

- We will start production data in September - December 2021
- Further plan includes 6 months of data taking in 2022 and 3 months in 2023

Publications:

- E. O. Cohen *et al.*, *Development of a scintillating-fiber beam detector for the MUSE experimen*t, NIM A
  https://doi.org/10.1016/j.nima.2016.01.044
- P. Roy *et. al.*, *A Liquid Hydrogen Target for the MUSE Experiment at PSI*, NIM A
  https://doi.org/10.1016/j.nima.2020.164801
- T. Rostomyan *et al.*, *Timing Detectors with SiPM read-out for the MUSE Experiment at PSI*, NIM A
  https://doi.org/10.1016/j.nima.2019.162874
- (In press) E.Cline, J Bernauer, E.J. Downie, R. Gilman, *MUSE: The MUon Scattering Experiment,* SciPost Physics
- (In preparation) E. Cline *et. al.*, *High Precision Muon and Electron Beams in the PiM1 Channel at the Paul Scherrer Institut*

MUSE Collaborators:

72 collaborators from 25 institutions in 5 countries:

A. Afanasev, A. Akmal, A. Atencio, J. Arrington, H. Atac, C. Ayerbe-Gayoso, F. Benmokhtar, K. Bailey, N. Benmouna, J. C. Bernauer, W. J. Briscoe, T. Cao, D. Cioffi, E. Cline, D. Cohen, E.O. Cohen, C. Collicott, K. Deiters, J. Diefenbach, S. Dogra, E.J. Downie, I. Fernando, A. Flannery, T. Gautam, D. Ghosal, R. Gilman, A. Golossanov, R. Gothe, D. Higinbotham, J. Hirschman, D. Hornidge, Y. Ilieva, N. Kalantarians, M.J. Kim, M. Kohl, O. Koshchii, G. Korcyl, K. Korcyl, B. Krusche, I. Lavrukhin, L. Li, J. Lichtenstadt, W. Lin, A. Liyanage, W. Lorenzon, K.E. Mesick, Z. Meziani, P. M. Murthy, J. Nazeer, T. O'Connor, P. Or, T. Patel, E. Piasetzky, R. Ransome, R. Raymond, D. Reggiani, H. Reid, P.E. Reimer, A. Richter, G. Ron, P. Roy, T. Rostomyan, P. Salabura, A. Sarty, Y. Shamai, N. Sparveris, S. Strauch, N. Steinberg, V. Sulkosky, A.S. Tadepalli, M. Taragin, and N. Wuerfel

George Washington University, Montgomery College, Argonne National Lab, Temple University, College of William & Mary, Duquesne University, Massachusetts Institute of Technology, Christopher Newport University, Rutgers University, Hebrew University of Jerusalem, Tel Aviv University, Paul Scherrer Institut, Johannes Gutenberg-Universität, Hampton University, University of Michigan, University of Virginia, University of South Carolina, Jefferson Lab, Los Alamos National Laboratory, Norfolk State University, Technical University of Darmstadt, St. Mary's University, Soreq Nuclear Research Center, Weizmann Institute, Old Dominion University

Thank you!