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MUSE and the Proton Radius Puzzle

Evangeline J. Downie

GW Award:
PHY-2012940

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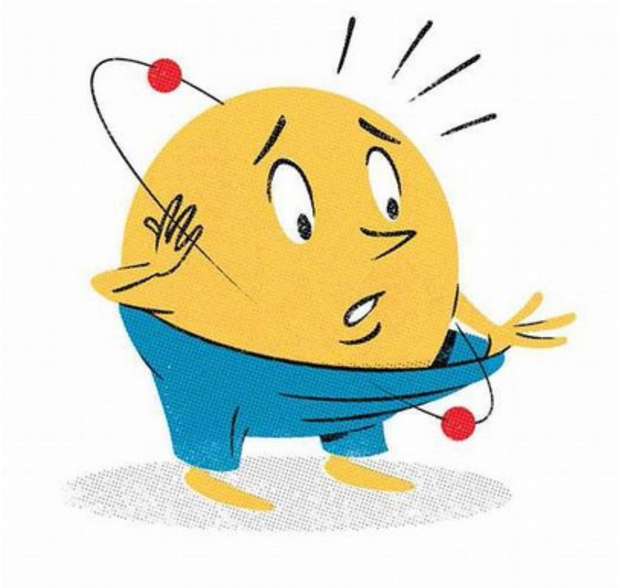
The Proton Radius Puzzle (2010)

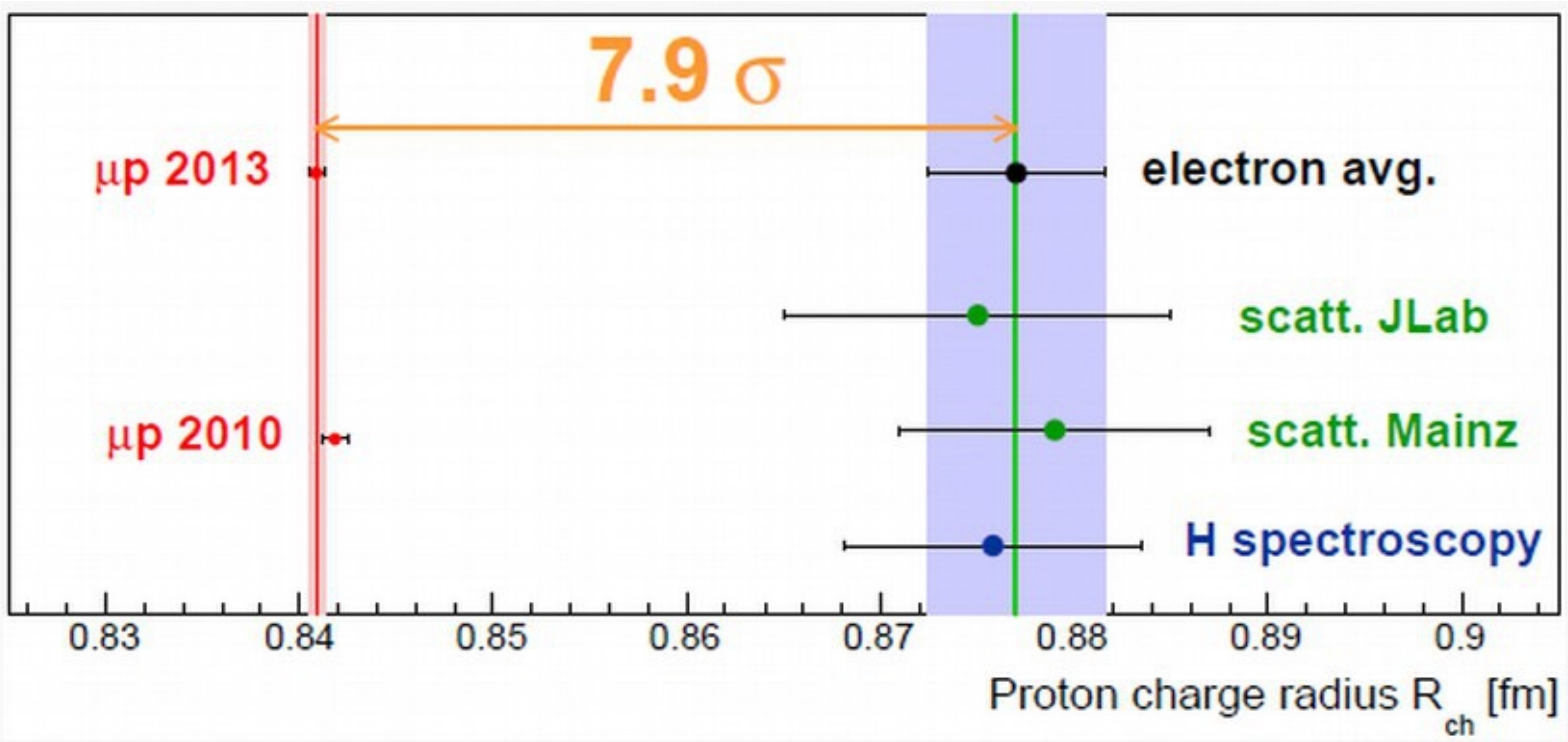
Nature **466**, 213 (2010)

Discrepancy between radius measured with electrons and muons



The New York Times

The Proton Radius Puzzle (2010)



μp 2013: Antognini *et al.*
Science **339,** 417 (2013)

Jlab: Zhan *et al.*
PLB **705,** 59-64 (2011)

Mainz: Bernauer *et al.*
PRL **105**, 242001 (2010)

μp 2010: Pohl *et al.*
Nature **466**, 213 (2010)

The Proton Radius Puzzle (2013)

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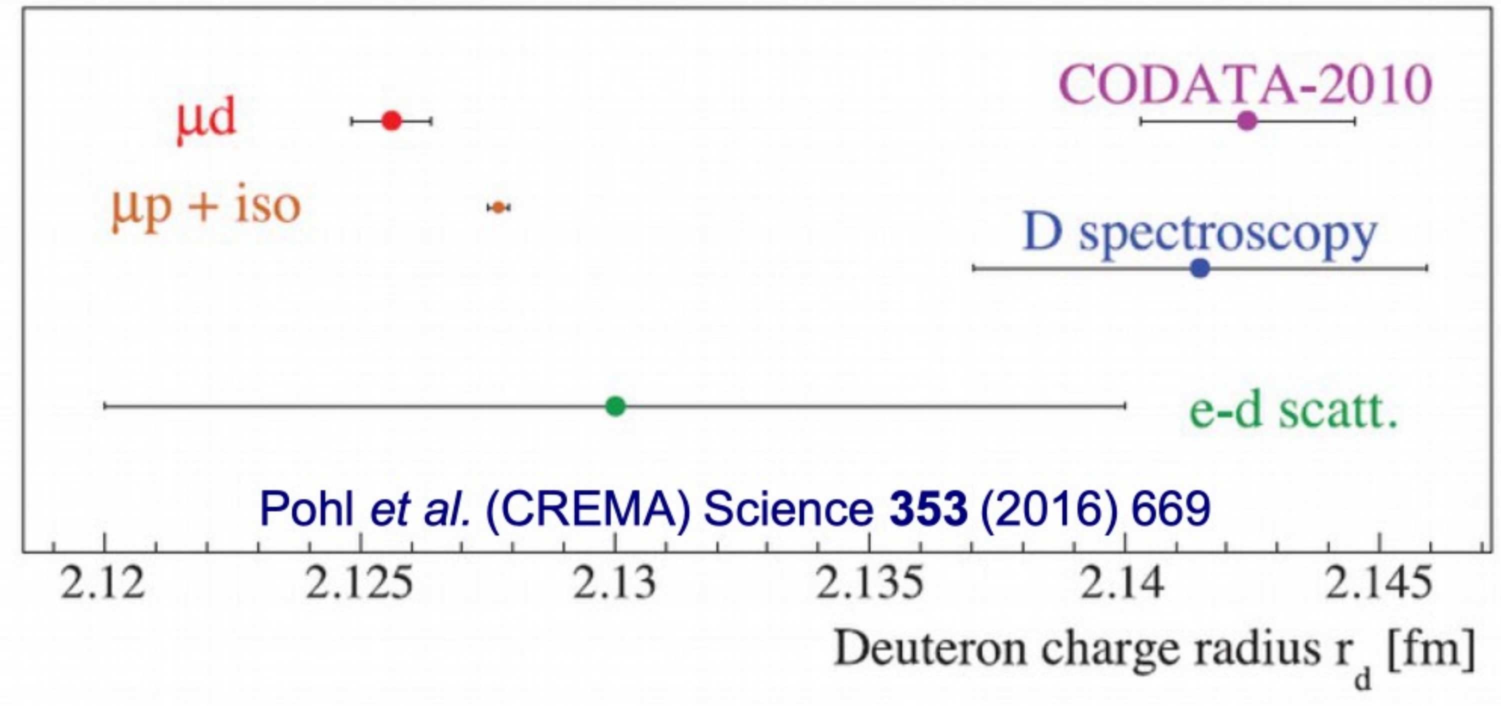
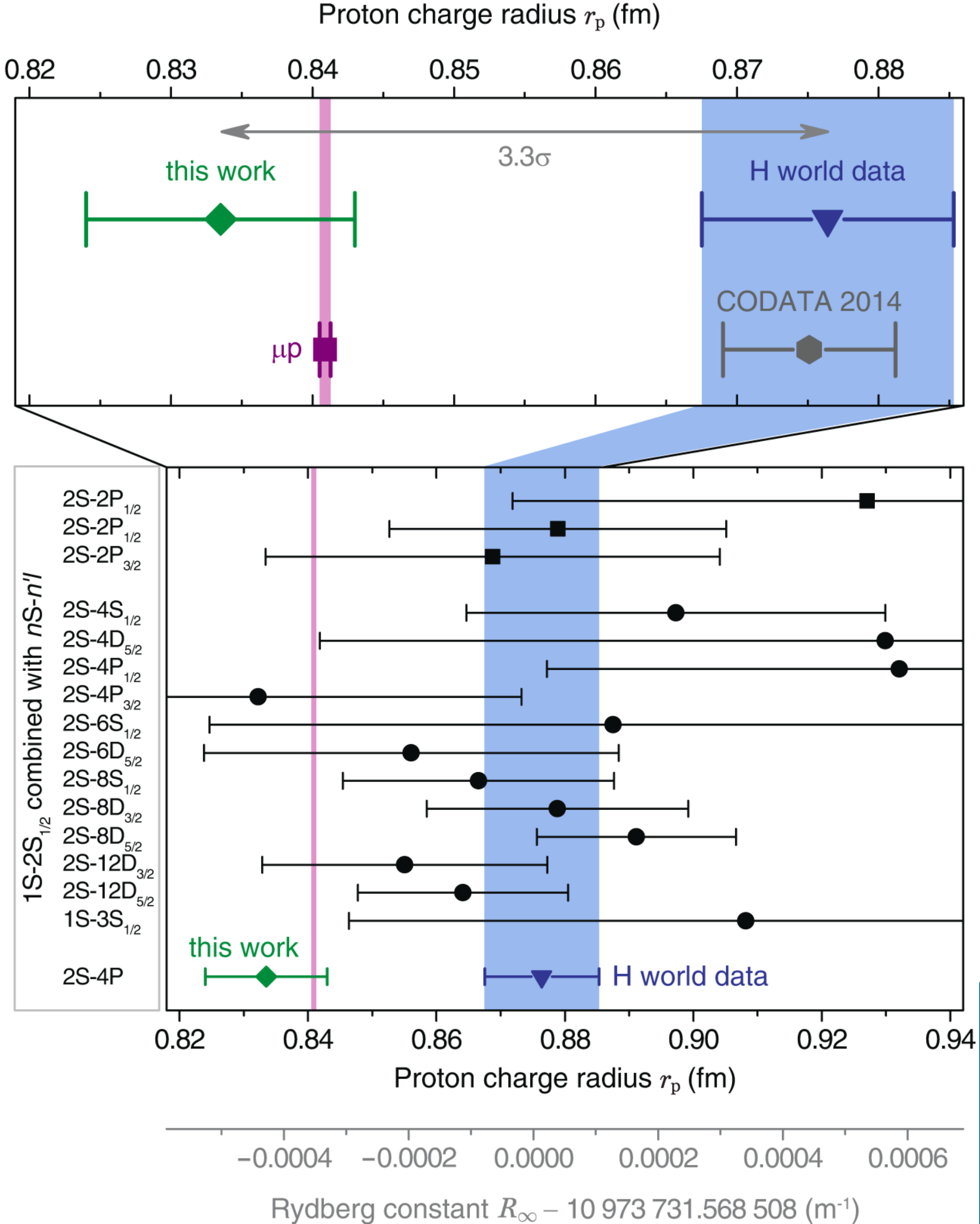


- Muonic deuterium agrees with muonic hydrogen
- Muonic 4He agrees with electronic helium: Krauth *et al.*, Nature **589**, 527 (2021)
- A Z=1 problem!
- Many recent results on hydrogen…

MPQ Result
2S – 4P

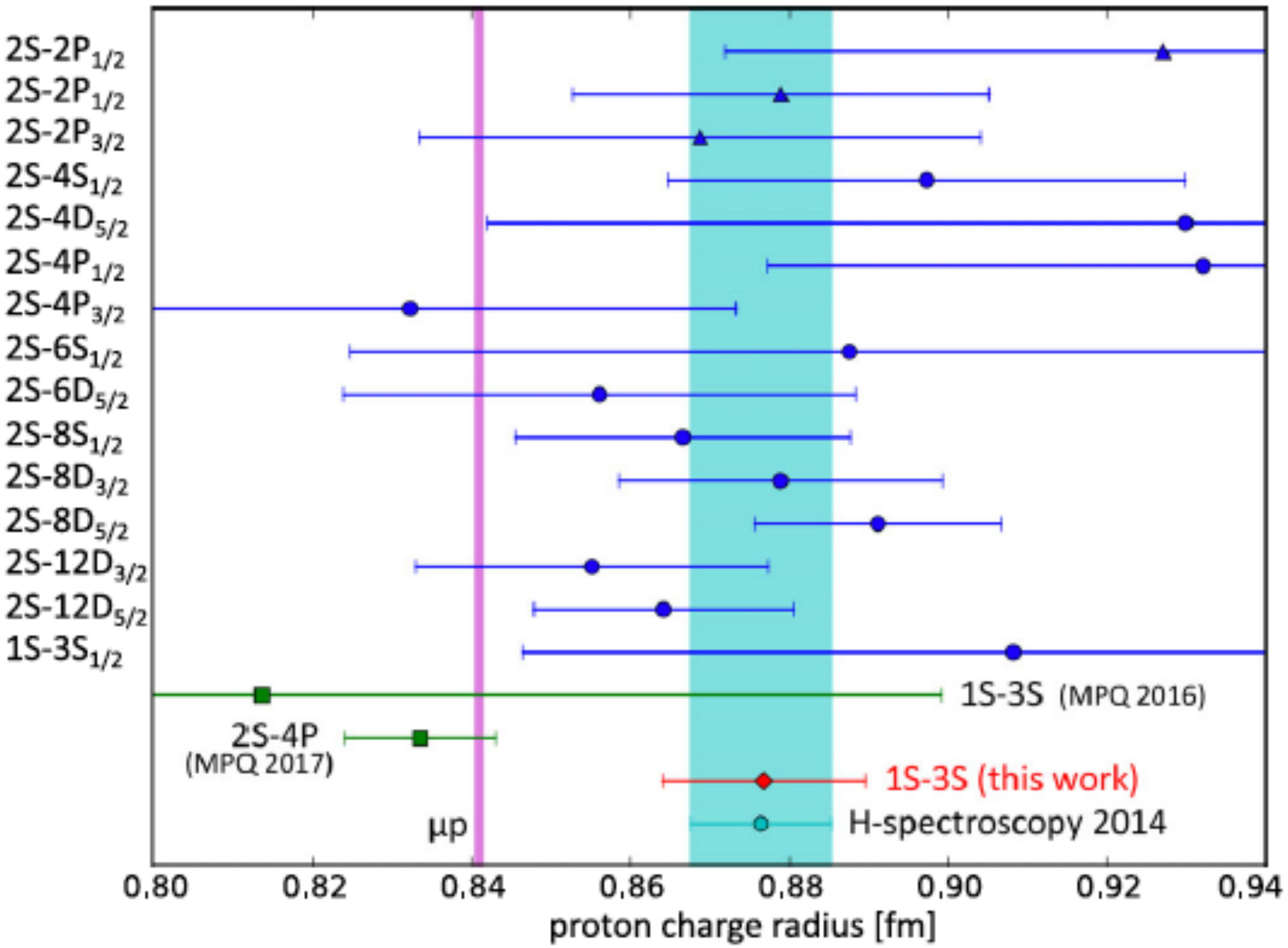
Beyer *et al.*
Science **358**, 79-85 (2017)
6 October 2017



2S-4P

Orsay Result
1S – 3S

Fleurbaey *et al.*, Phys. Rev. Lett. **120**, 183001 (2018)

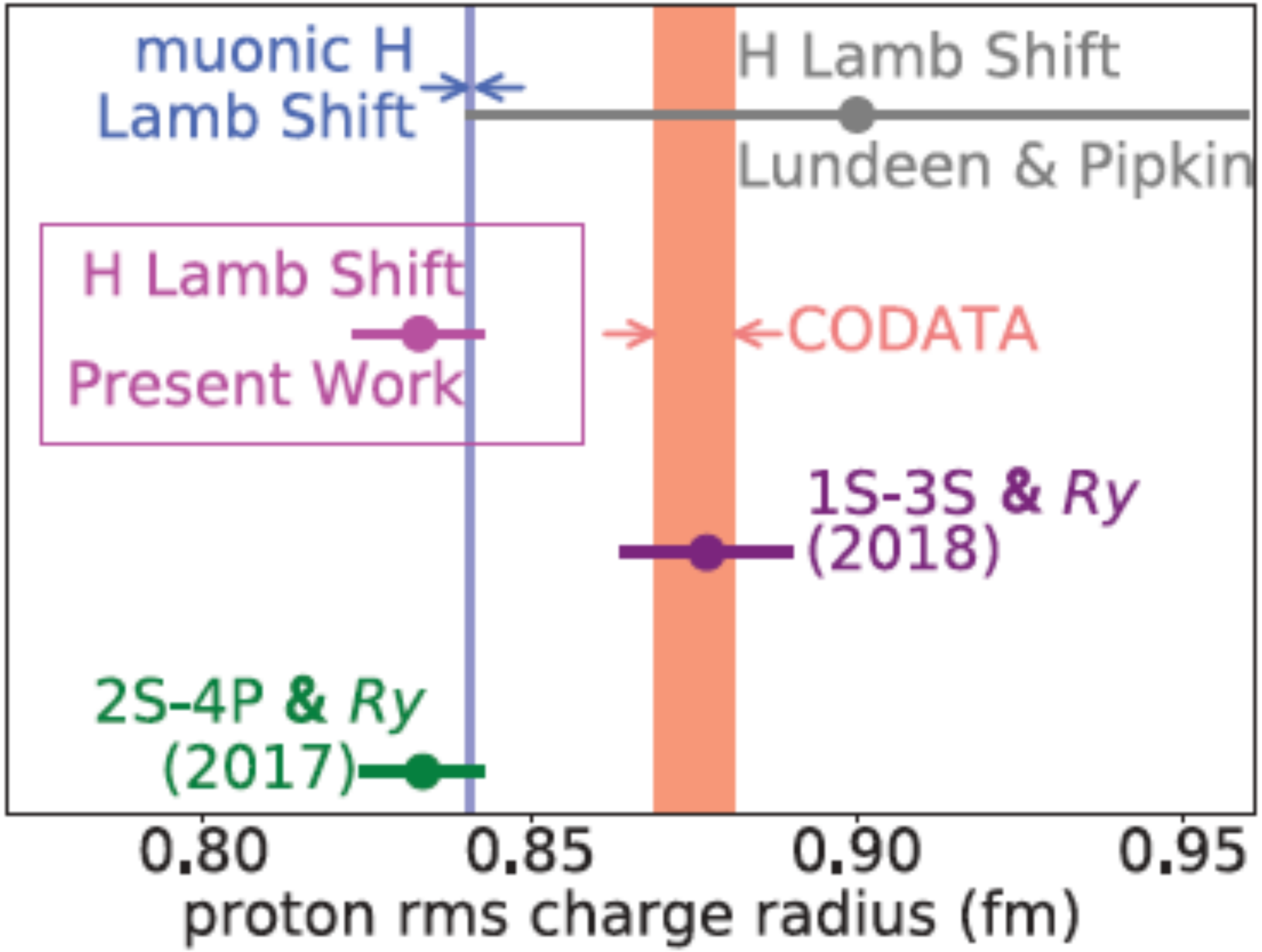


1S – 3S

York Result
2S – 2P
(Lamb Shift)

Bezginov *et al.*, Science **365**, 1007–1012 (2019)

No involvement of Rydberg



2S – 2P: Rydberg Independent

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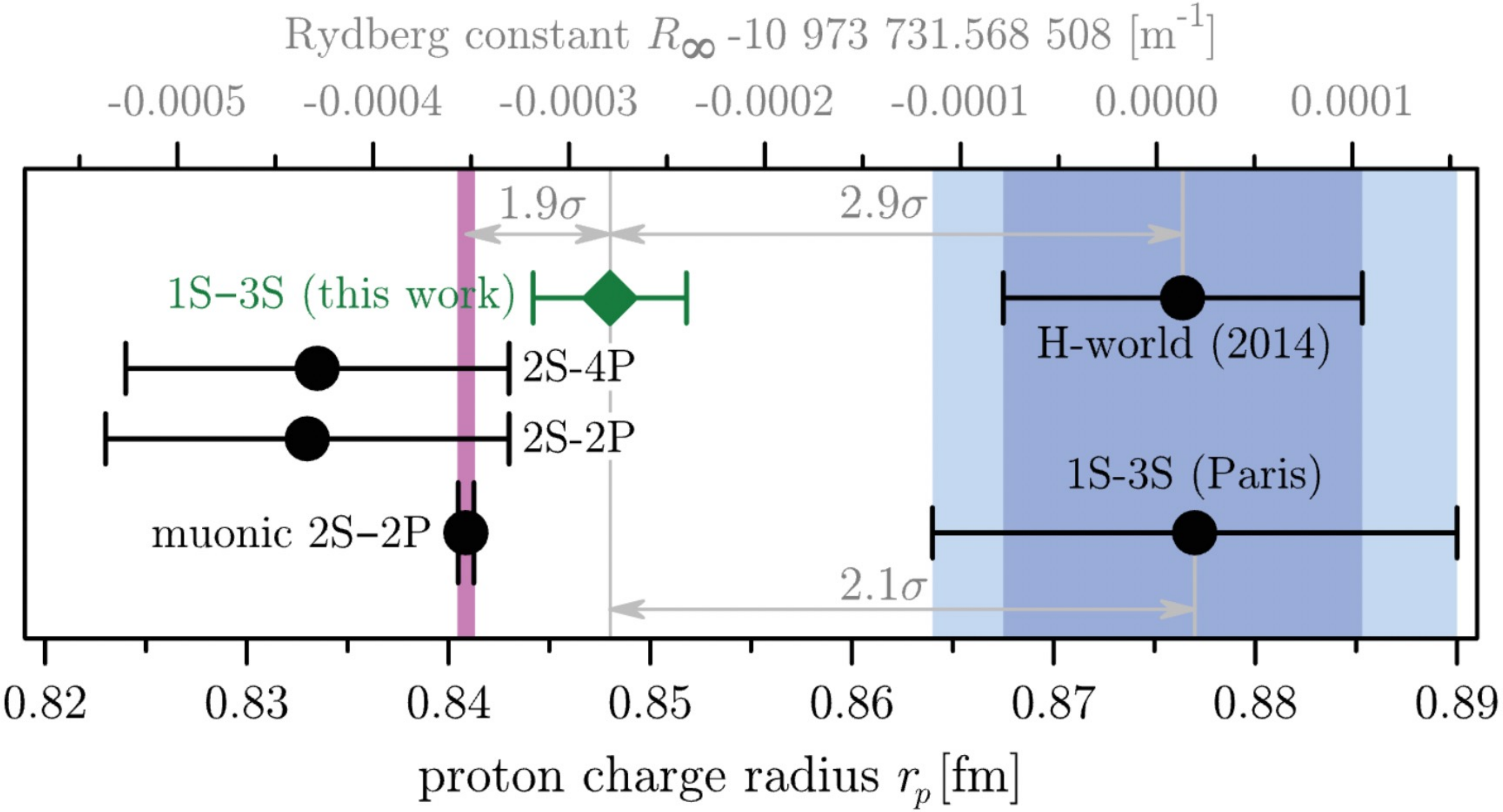
MPI Garching Result
2S – 3S

Grinin *et al.*, Science **370**, 1061–1066 (2020)



2S – 3S

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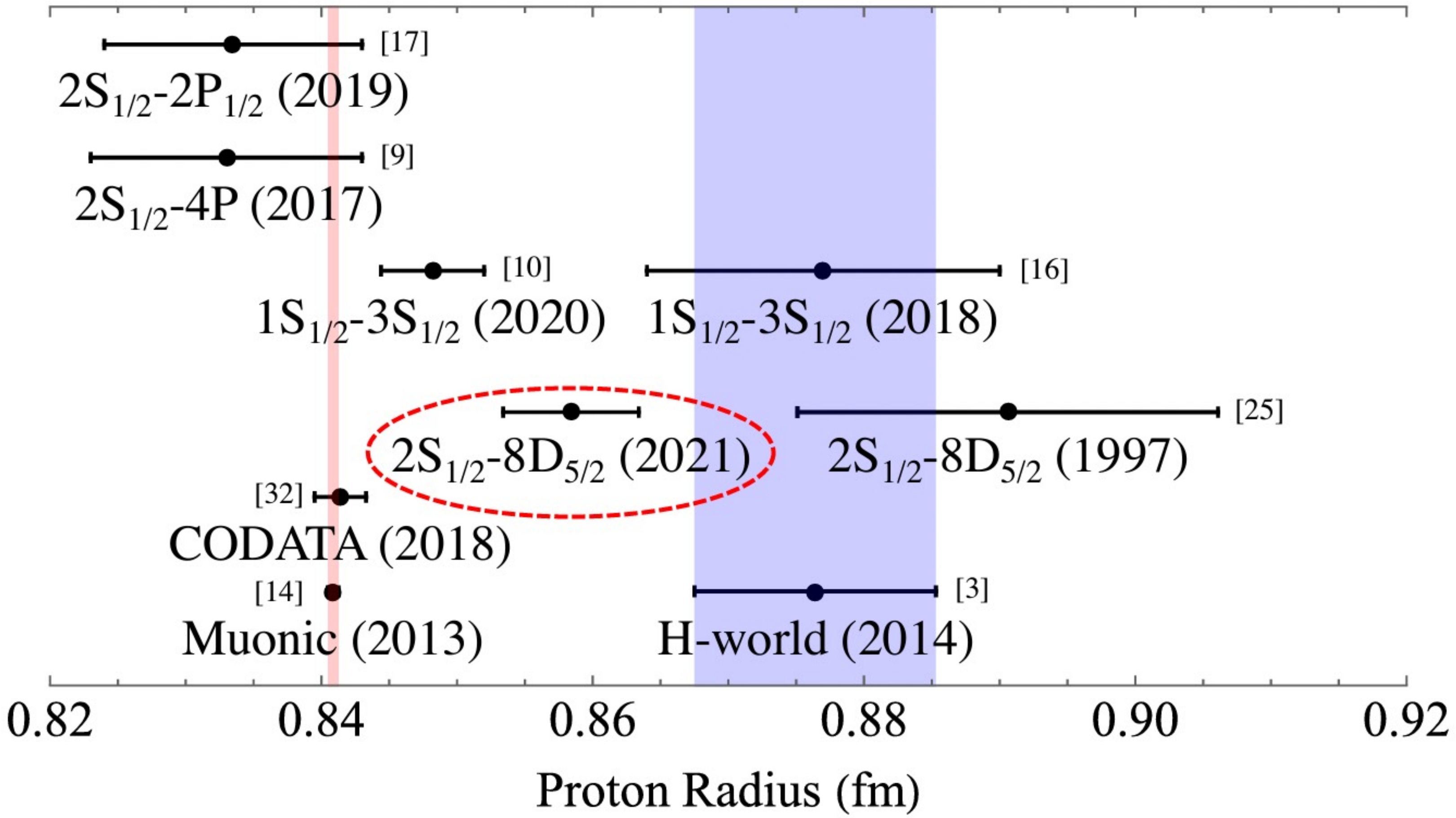
Colorado Result 2S – 8D

Brandt *et al.*, PRL **128**, 023001 (2022)



2S – 8D

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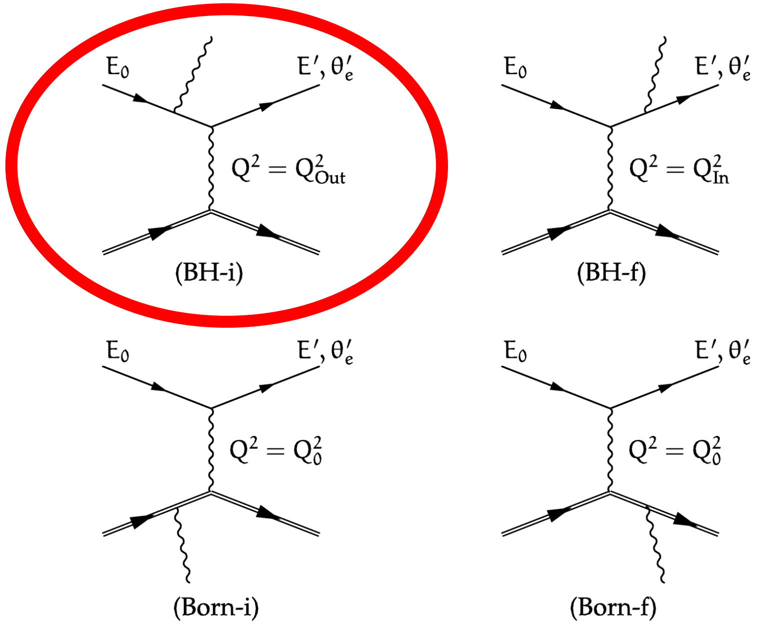
Mihovilovič *et al.*,
PLB **771**, 194 (2017)
Eur. Phys. J. A **57** 107 (2021)



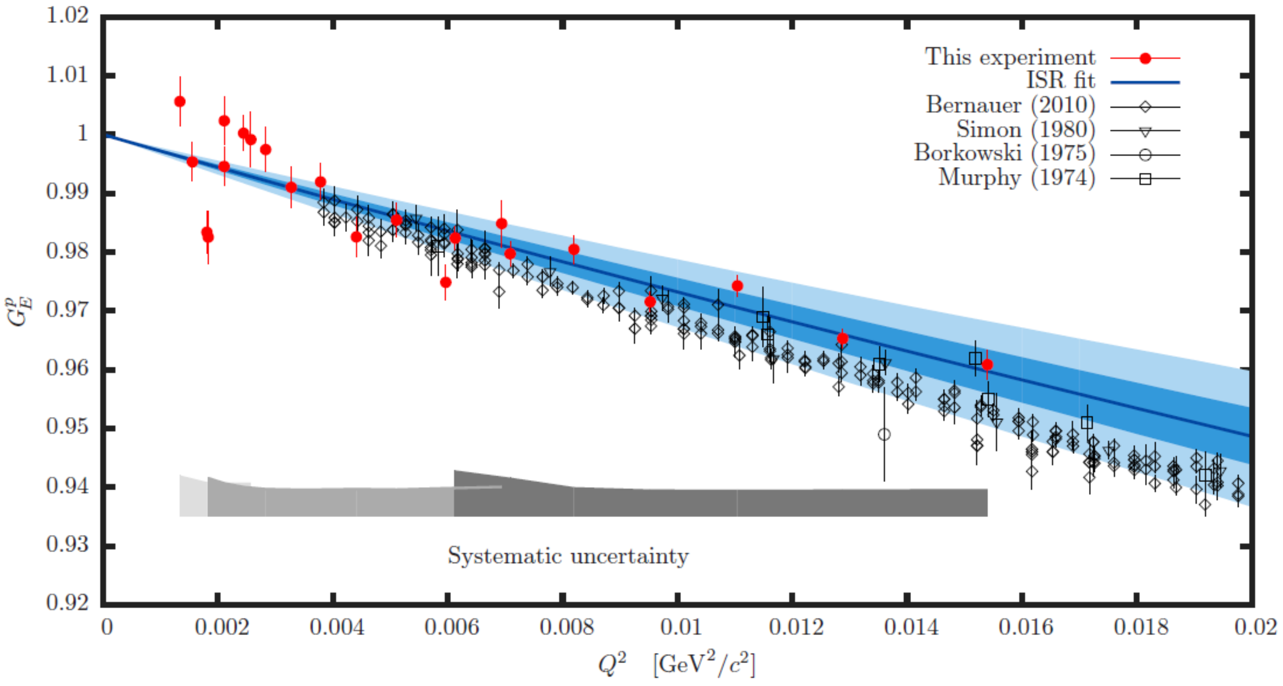


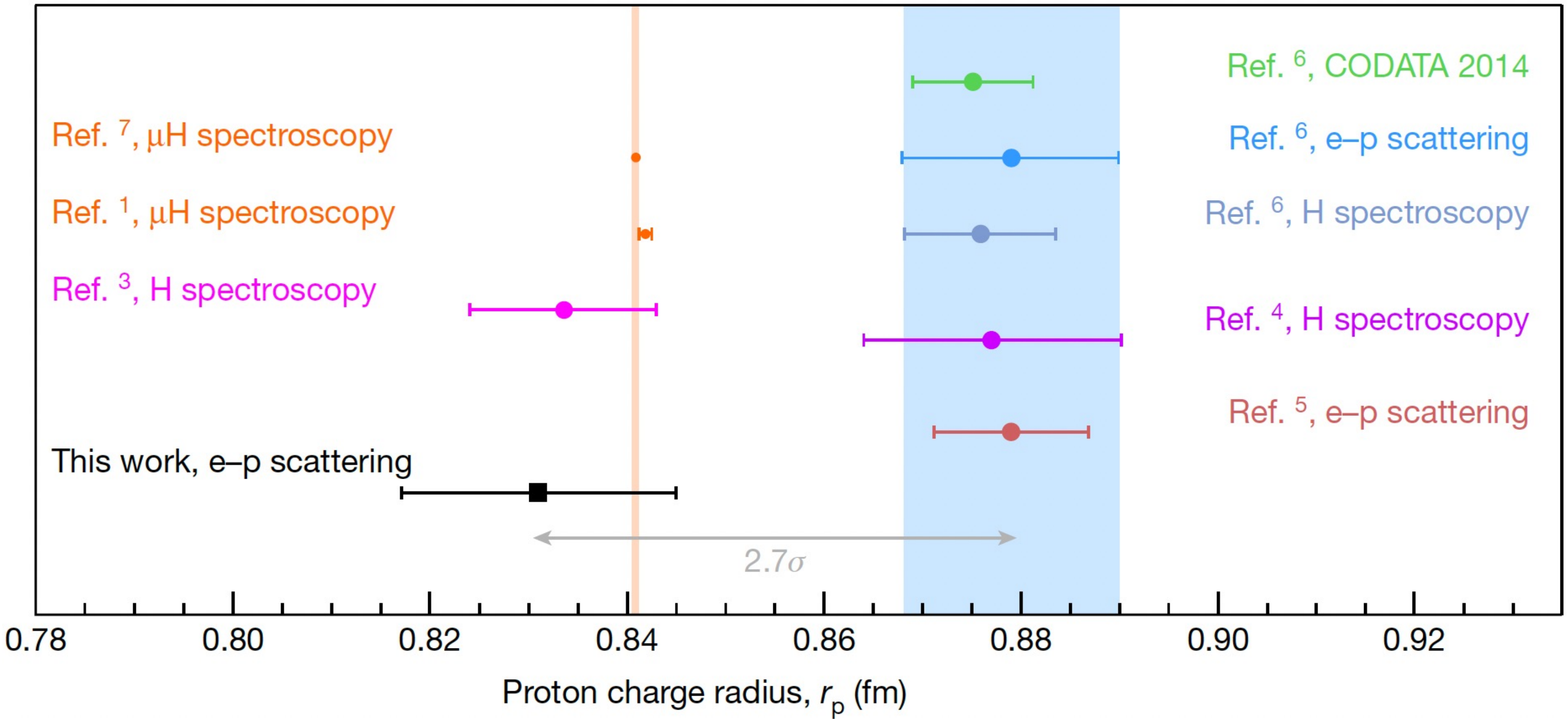
FIG. 3. (Color on-line) The proton electric form factor as a function of $Q^2 (= Q^2_{Out})$. Empty black points show previous data [19–22]. The results of this experiment are shown with full red circles. The error bars show statistical uncertainties. Gray structures at the bottom shows the systematic uncertainties for the three energy settings. The curve corresponds to a polynomial fit to the data defined by Eq. (2). The inner and the outer bands around the fit show its uncertainties, caused by the statistical and systematic uncertainties of the data, respectively.

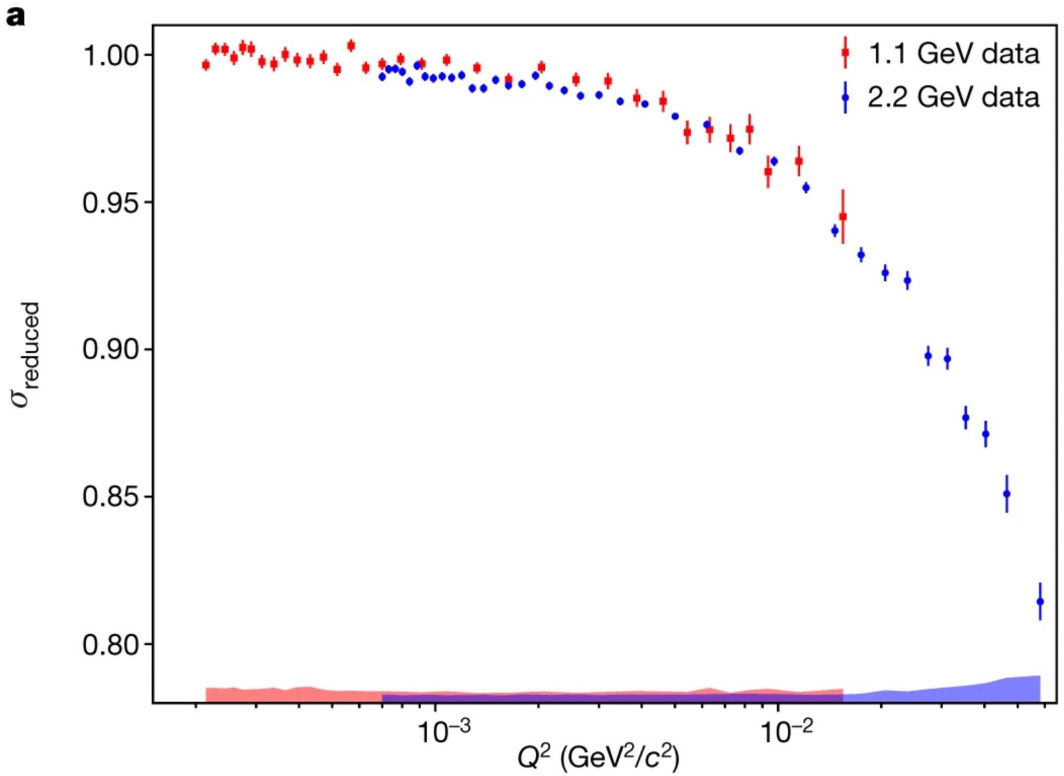
- Result: r_p=(0.810 ±0.035 stat. ±0.074 syst. ±0.003 ΔaΔb)fm, not precise enough to differentiate
- Reanalysed: r_p=(0.878 ±0.011 stat. ±0.031 syst. ±0.002 mod.)fm
- New experiment with jet target (and MESA) planned

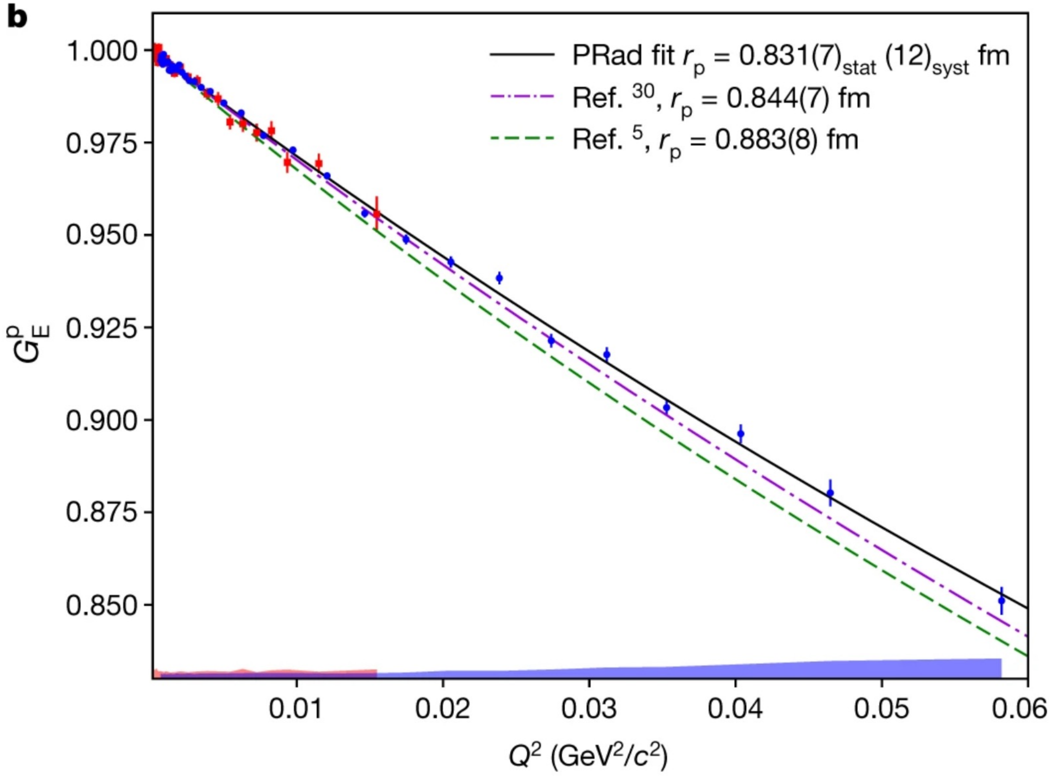
Mainz Initial State Radiation

PRad
Result
Electron Scattering

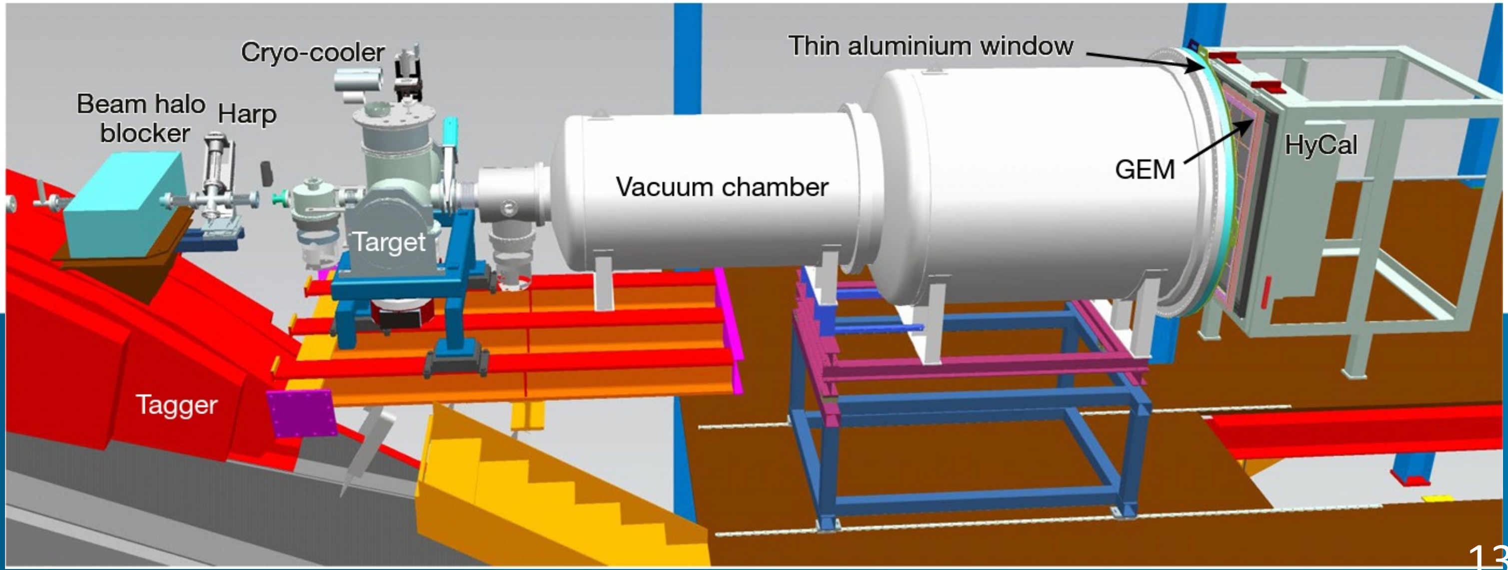
Xiong *et al.*, Nature **575**, 147 - 150 (2019)







Xiong *et al.*, Nature **575**, 147 - 150 (2019)



PRad

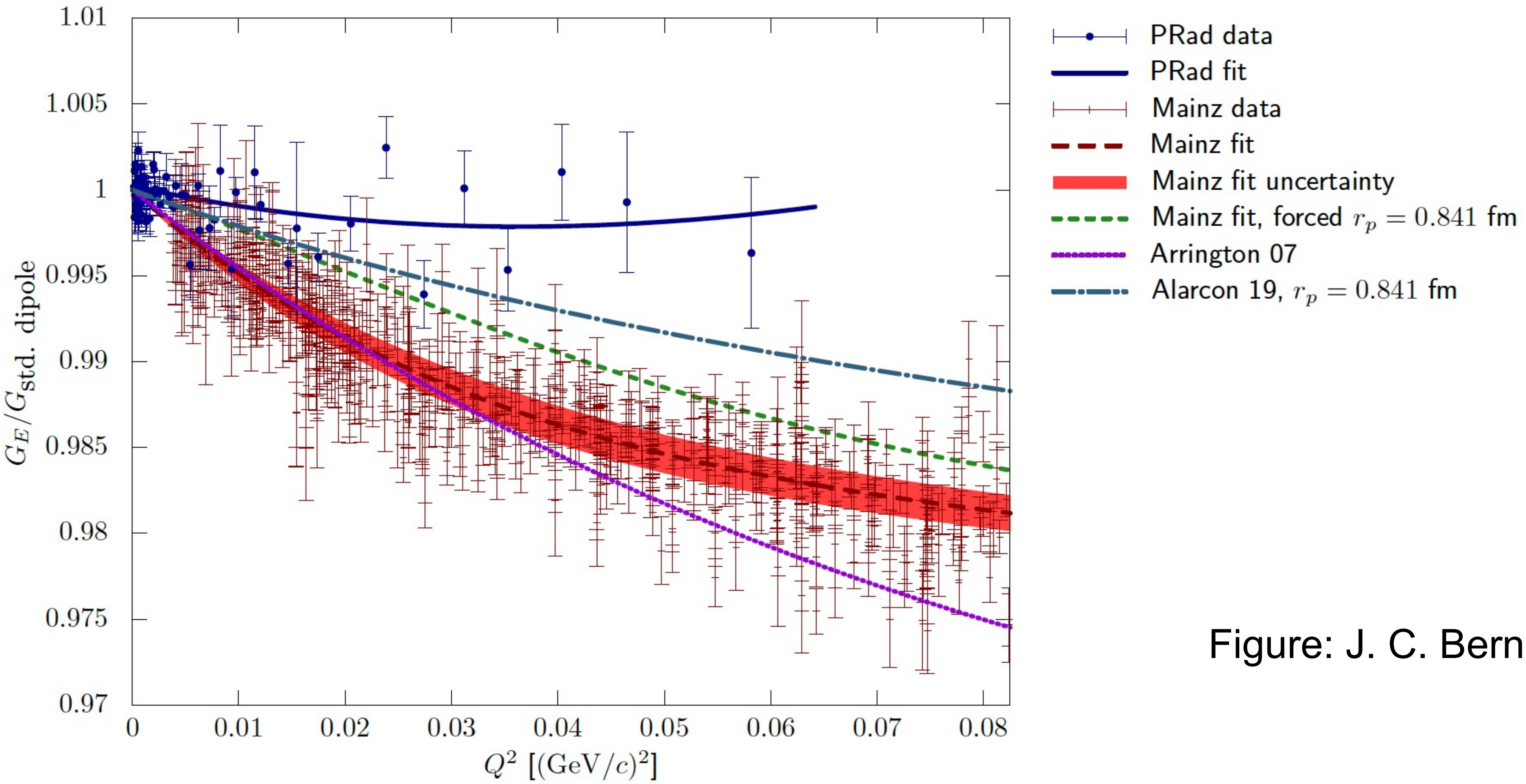
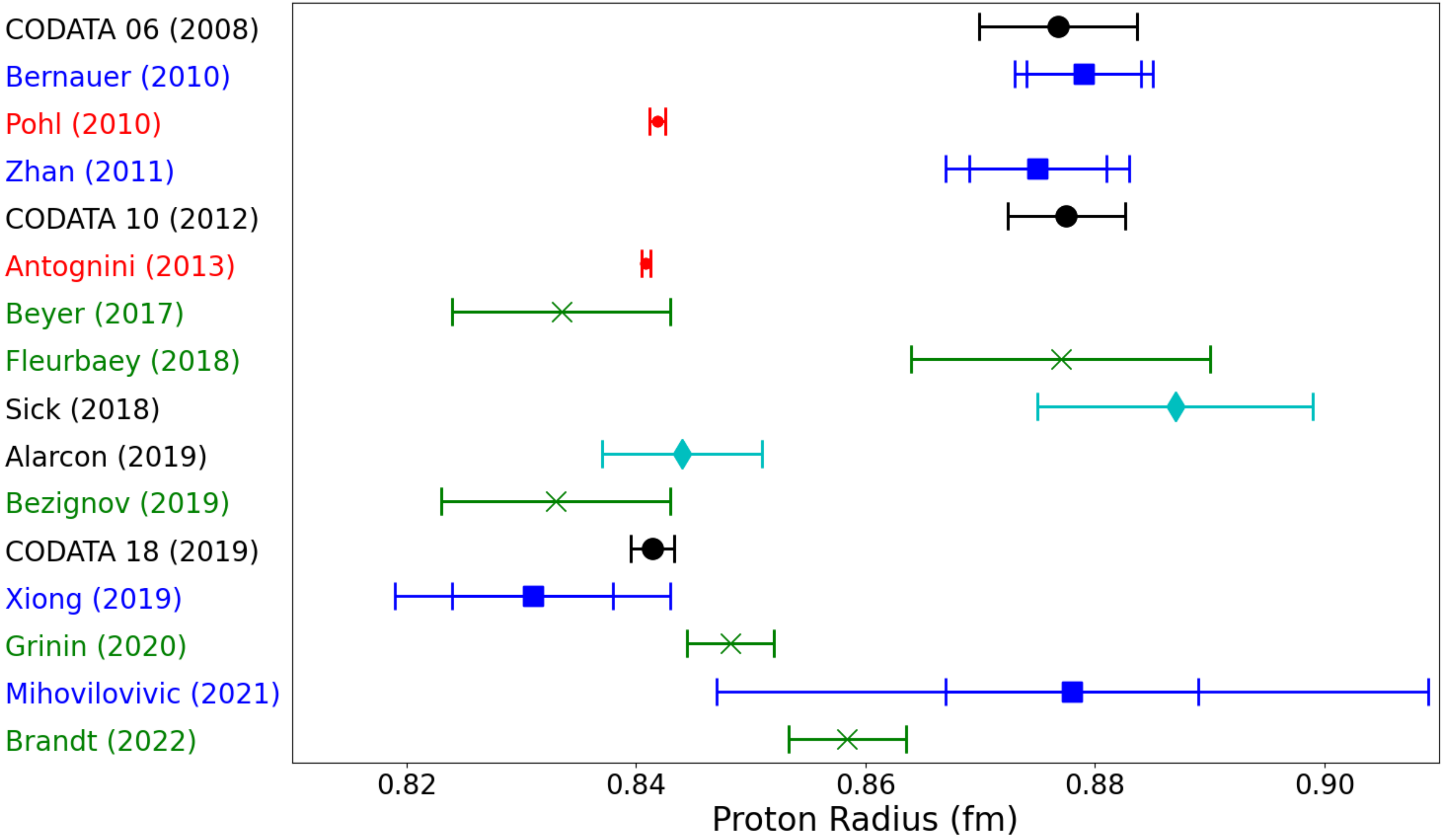


Figure: J. C. Bernauer

Comparison of PRad & Mainz



Proton Radius Puzzle Status (2022)

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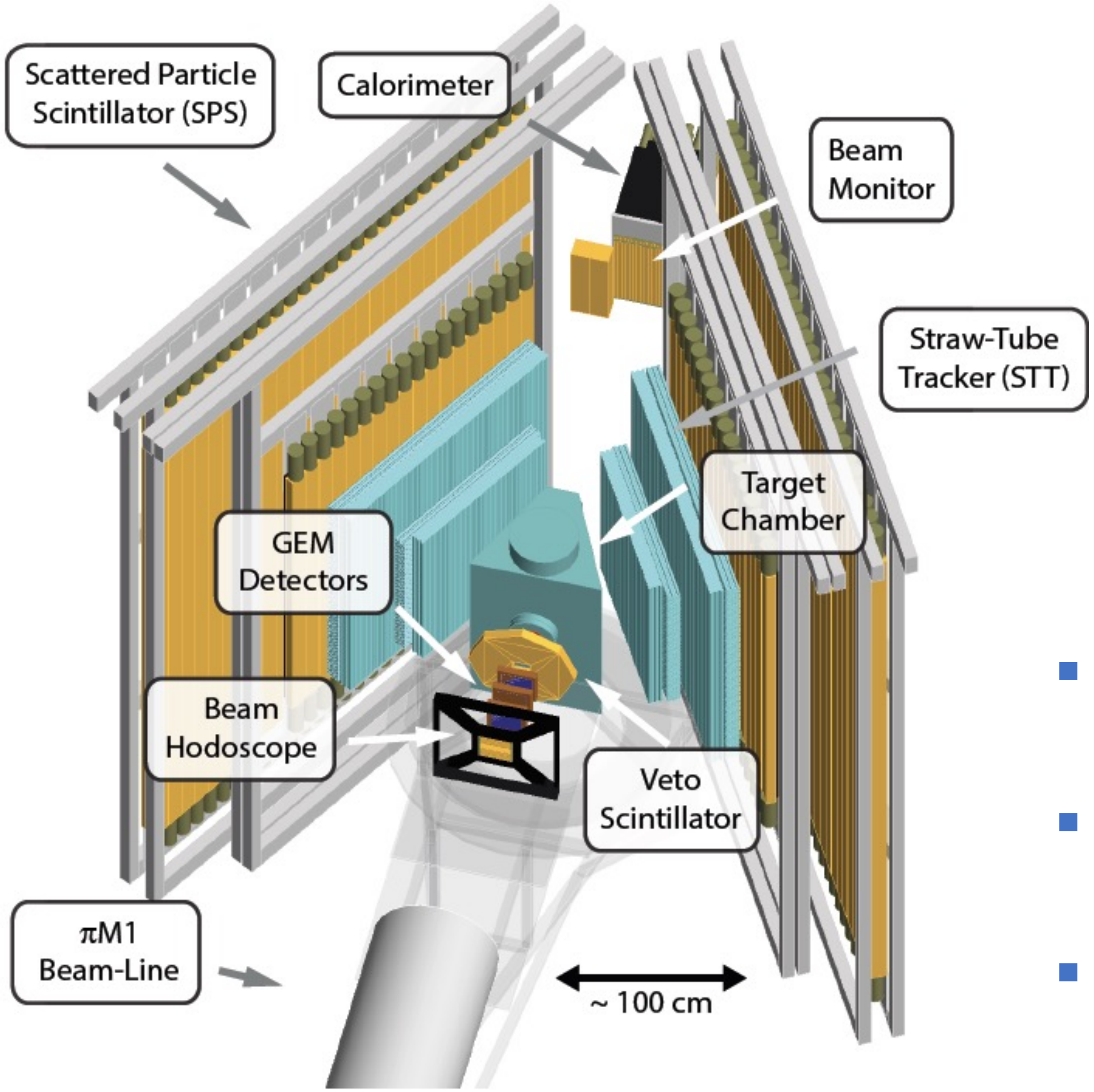
- CODATA now quote r_p = (0.8414± 0.0019) fm including **all** values
- Small uncertainties on μH measurements push CODATA towards lower value
- Discrepant results not explained
  - ✓ Discussions on fitting – varying viewpoints remain
  - ✓ Inconsistency between PRad and Mainz results
  - ✓ No explanation of larger / medium atomic H results
- Should understand why the PRP exists / existed
- To date, no measurements of muon elastic scattering of sufficient precision

- **Proton Radius Workshops:**
  - Trento, Mainz, Losinj (2012,'14,'16,'18, '19)
- ***Latest meetings:***
  - *https://indico.mitp.uni-mainz.de/event/132/*
  - https://indico.cern.ch/event/806319/timetable/#all

Proton Radius Summary

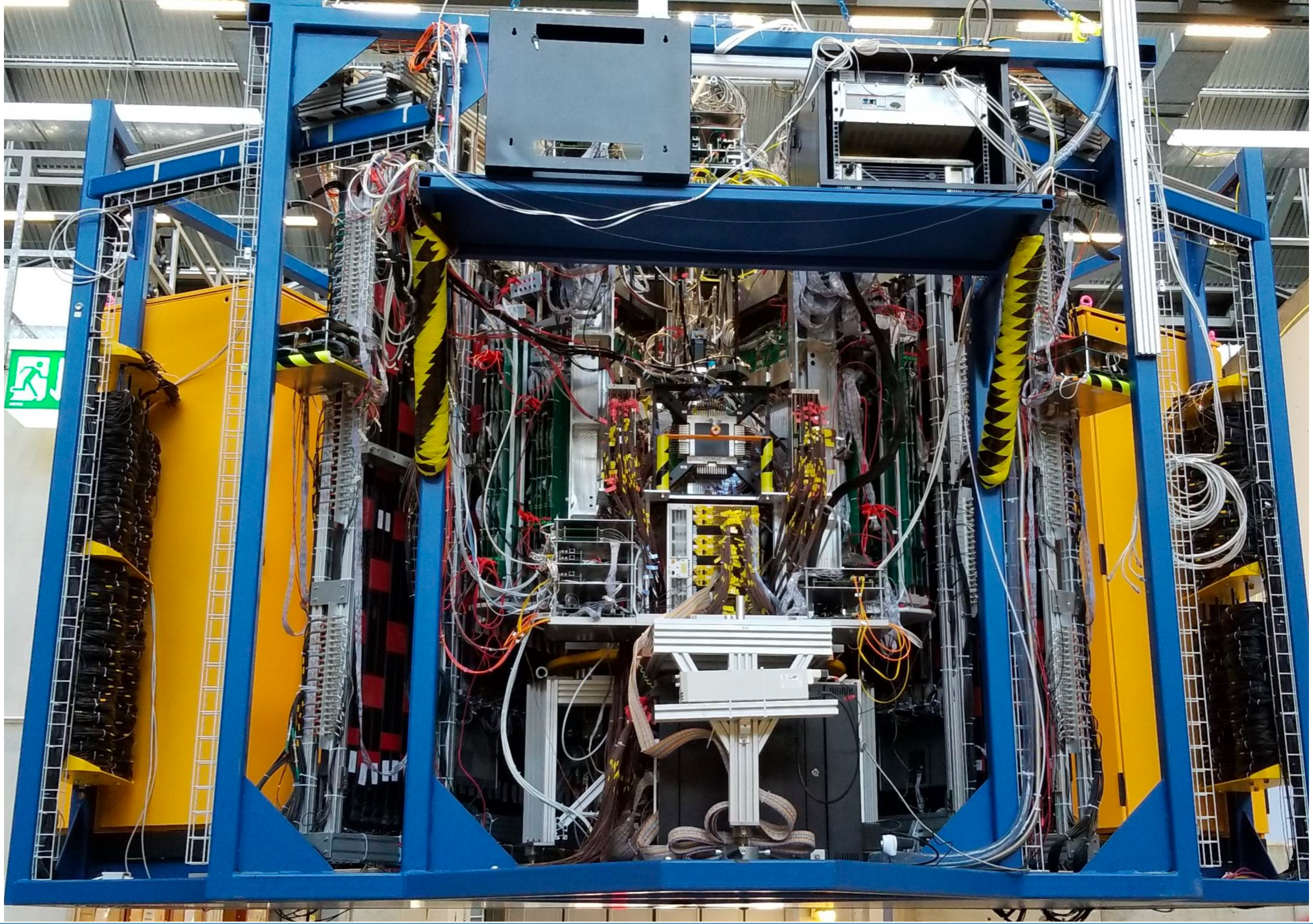
- MUSE in mixed $\mu/e/\pi$ PiM1 beamline of Paul Scherrer Institute
- Allows direct comparison of μ and e, cross sections, form factors
- Comparison of charge states, $\mu+/\mu-$, e+/e-, two photon effects
- Extraction of radii using e and μ in same experiment



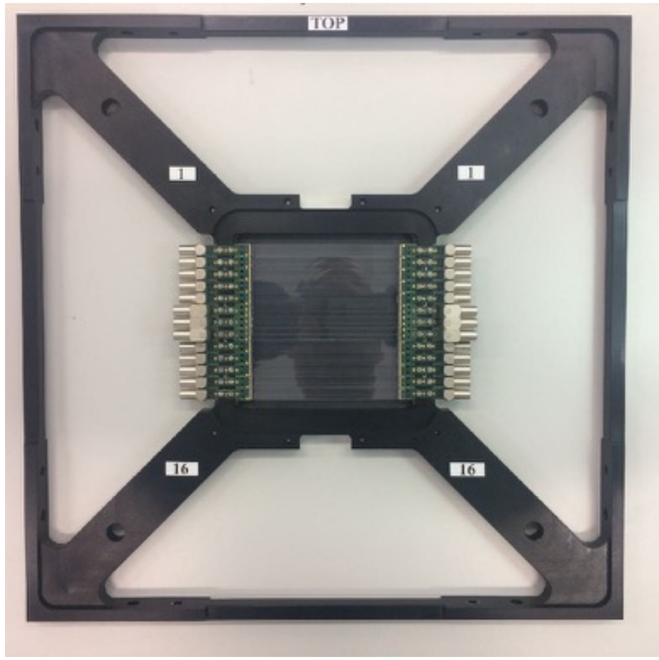
$\theta \approx 20^o - 100^o$
$Q^2 \approx 0.002$ - 0.07 GeV^2
3.3 MHz total beam flux
≈ 2-15% μ's
≈ 10-98% e's
≈ 0-80% π's

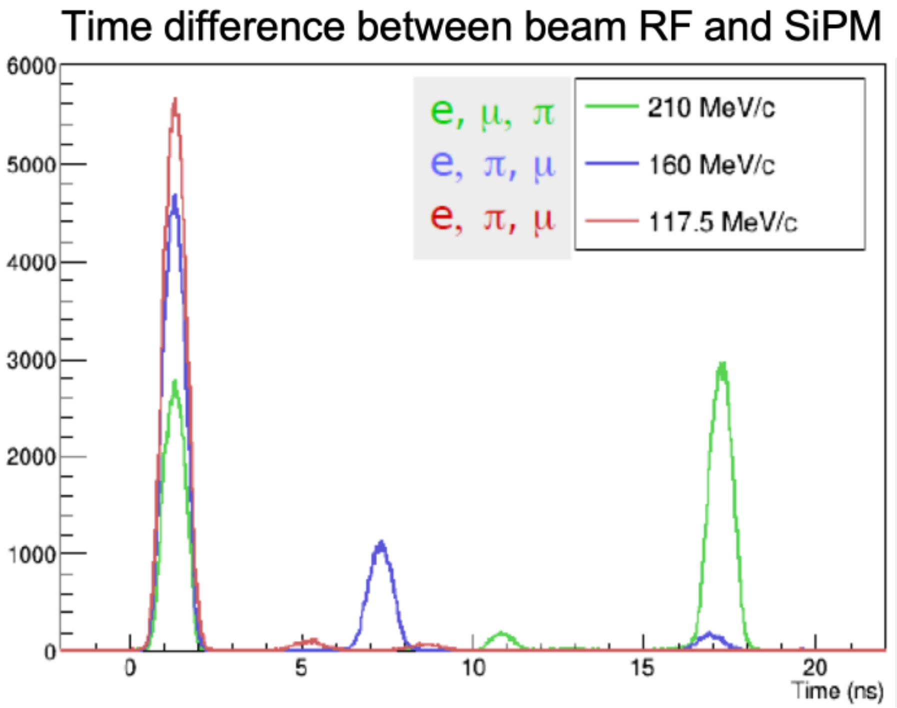
- Low beam flux
  - ✓ Large angle, non-magnetic detectors
- Secondary beam
  - ✓ Tracking of beam particles to target
- Mixed beam
  - ✓ Identification of beam particle in trigger

MUSE



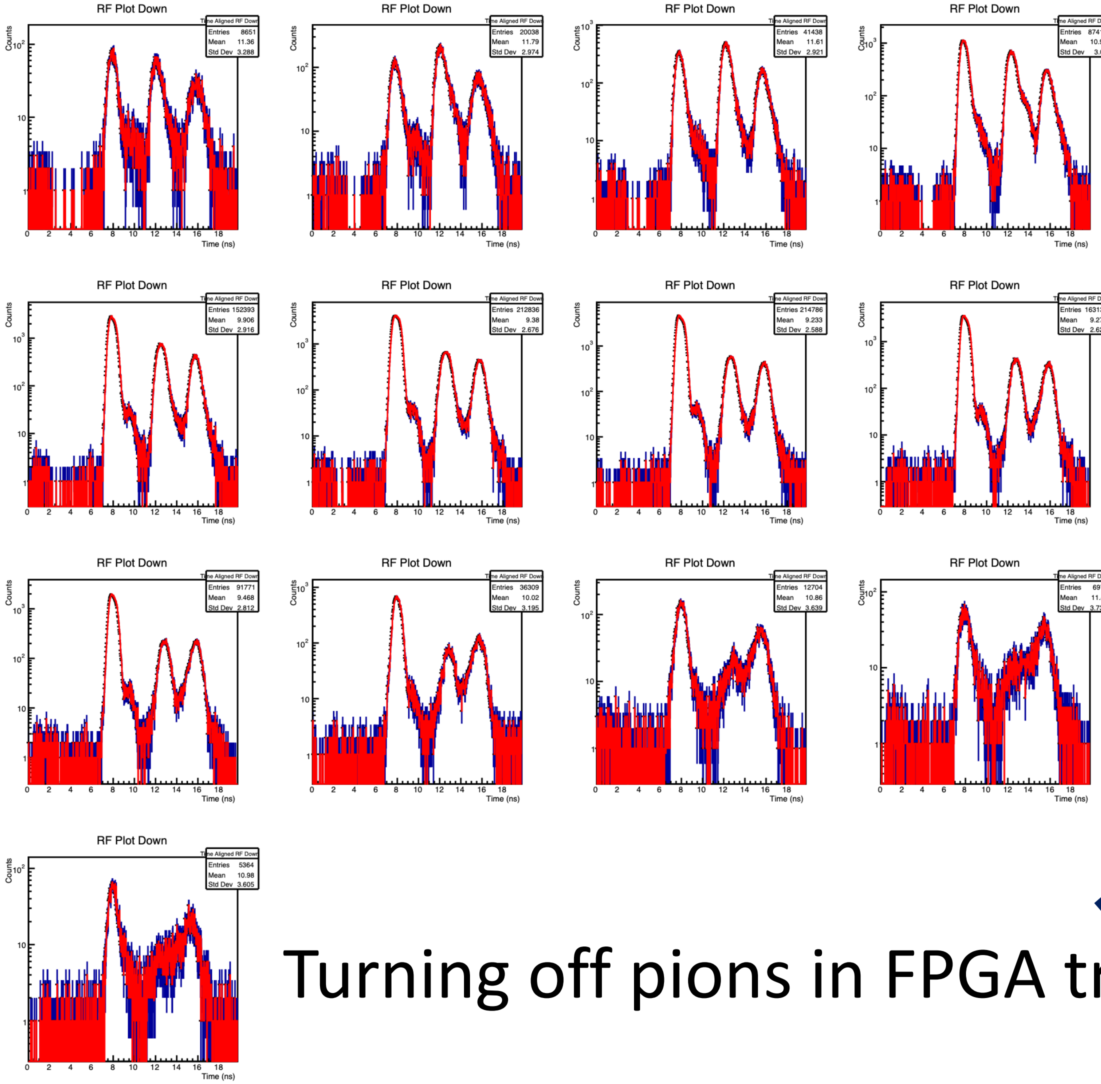
MUSE



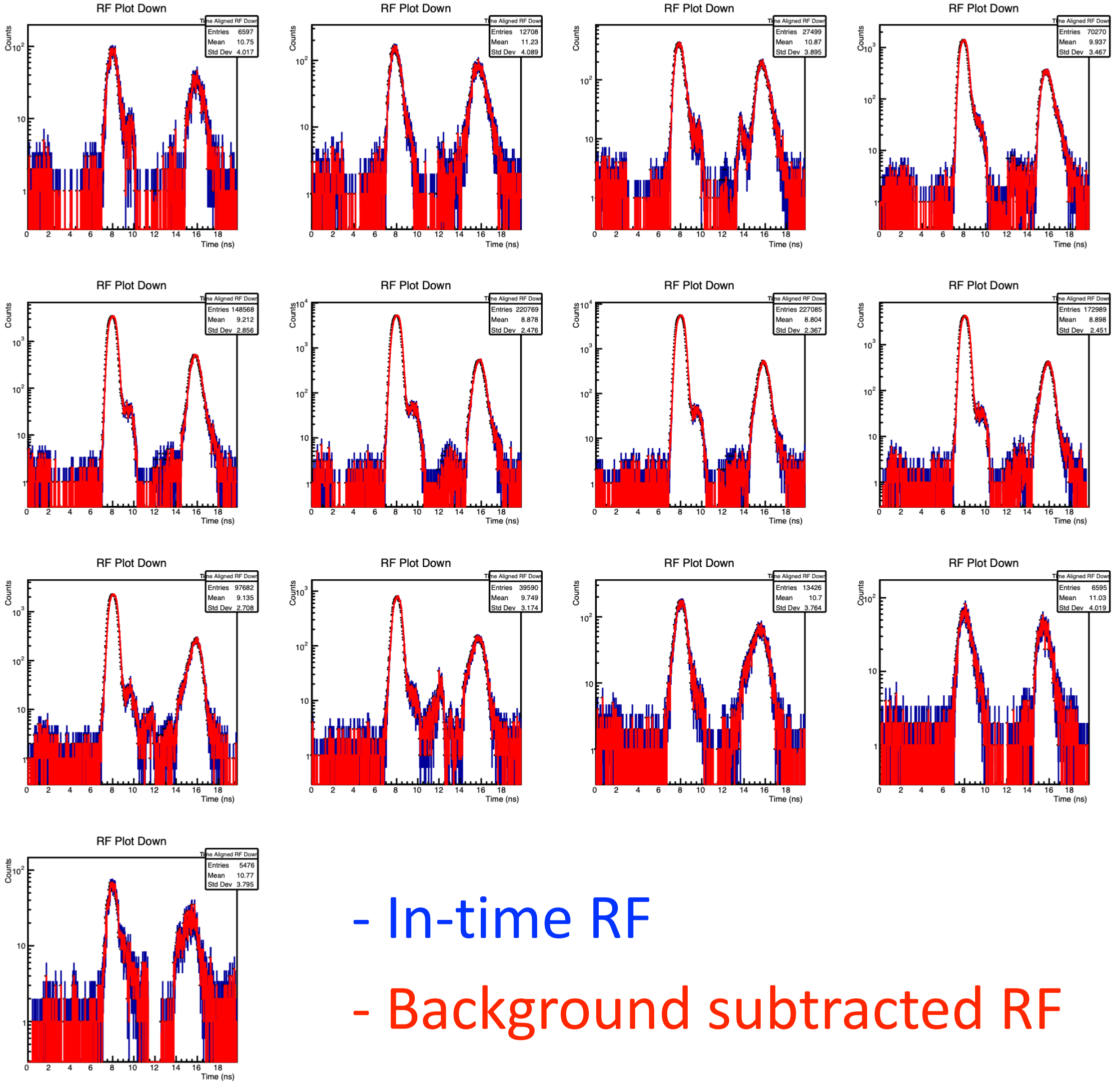


- Upto four planes of 8mm-wide, 2mm-thick, plastic scintillators
- Read out by SiPMs, better than 80ps timing resolution
- Used to trigger on particle type using time difference with accelerator RF
- Described in: Rostomyan *et al.*, NIM A **986** (2021) 164801

Beam Hodoscope

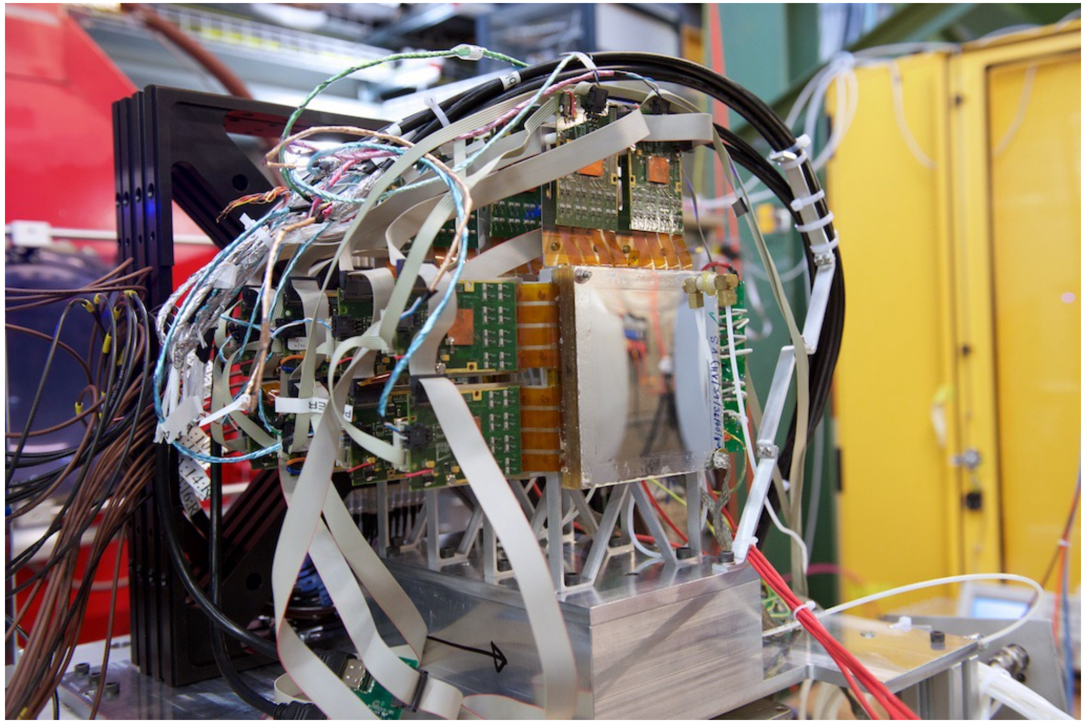


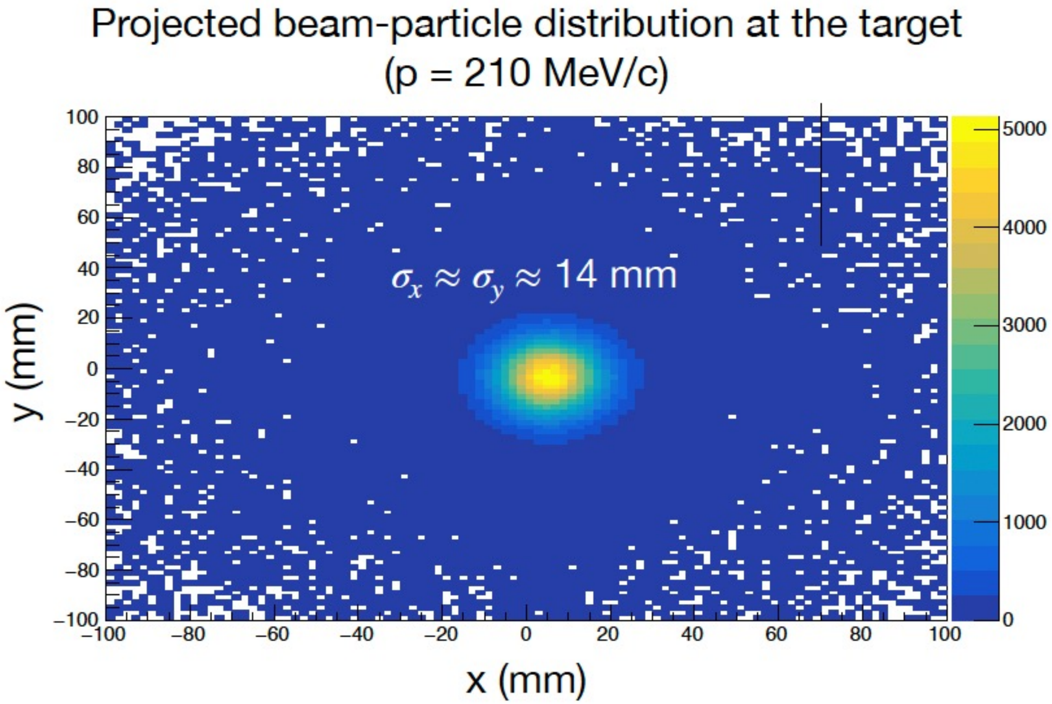
Turning off pions in FPGA trigger



- In-time RF
- Background subtracted RF

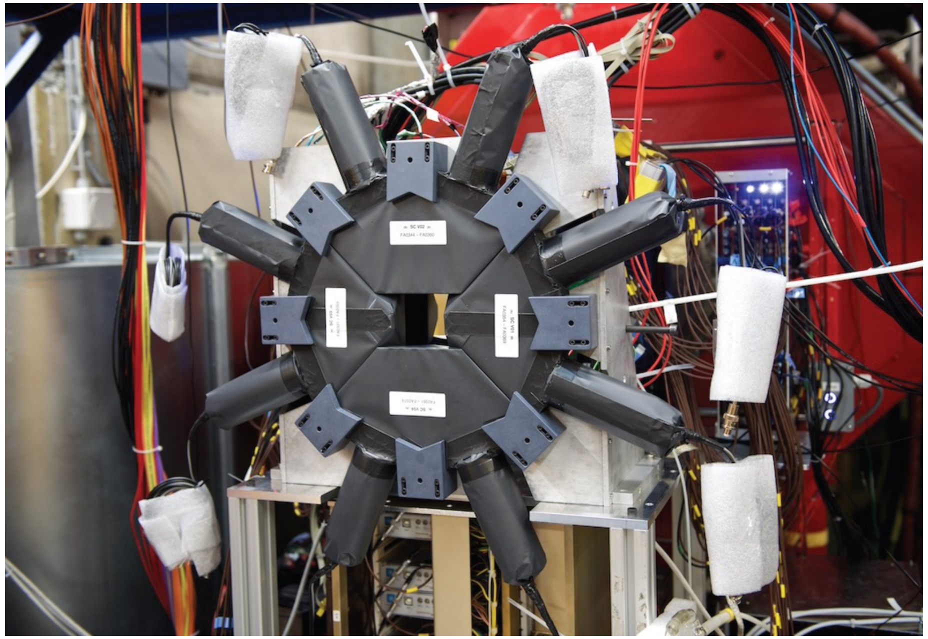
Beam Hodoscope

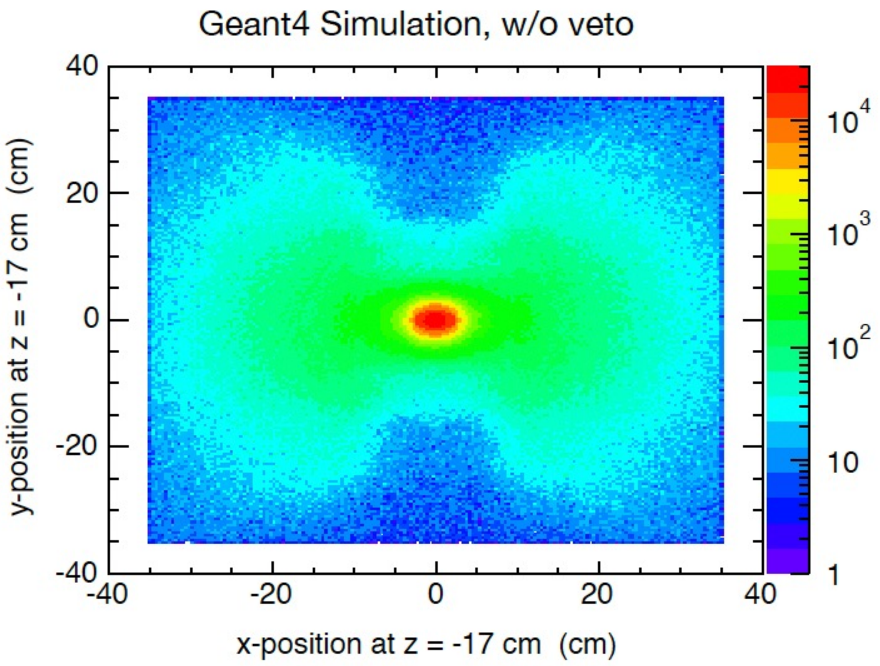


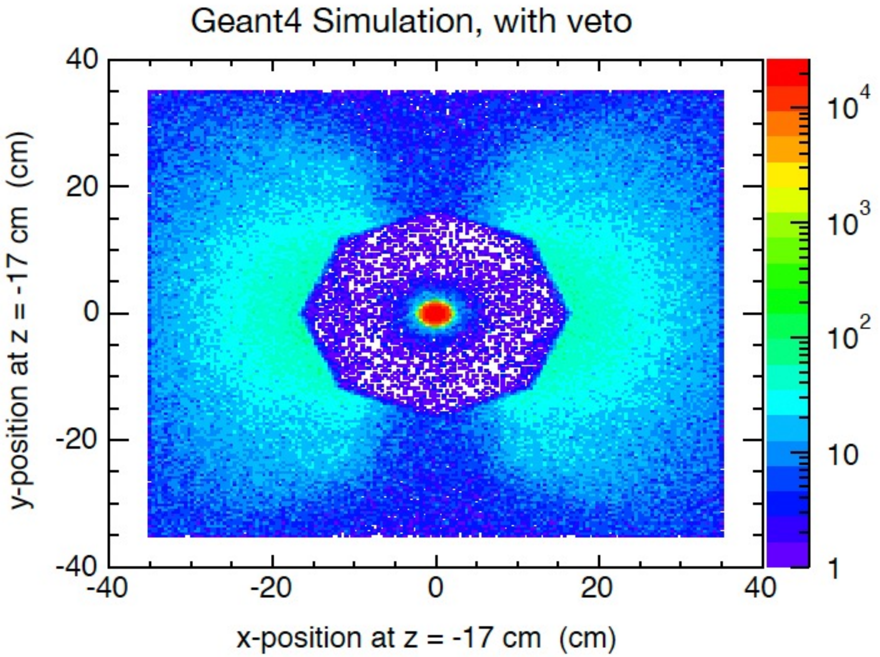


- Stack of three GEM Chambers
- Built for and used in OLYMPUS experiment
- Track beam in to target – give scattering angle with STT, 70μm resolution

GEM Chambers

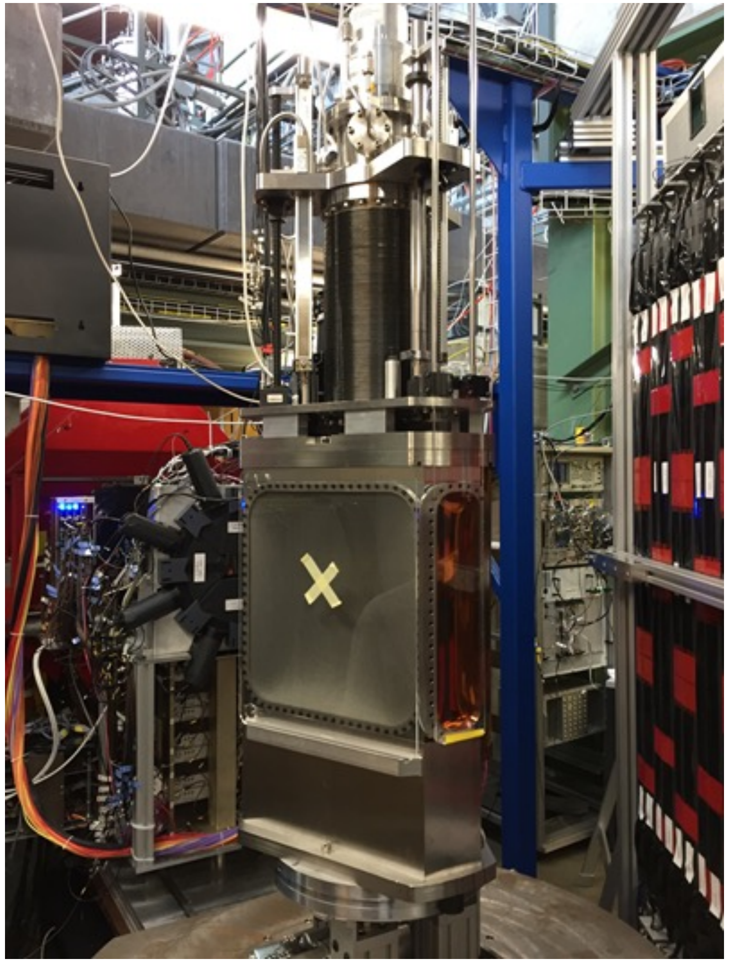






- Remove events due to upstream scatter / decay
- Reduce data rate by approx. 25%

Veto Detector



Liquid hydrogen target

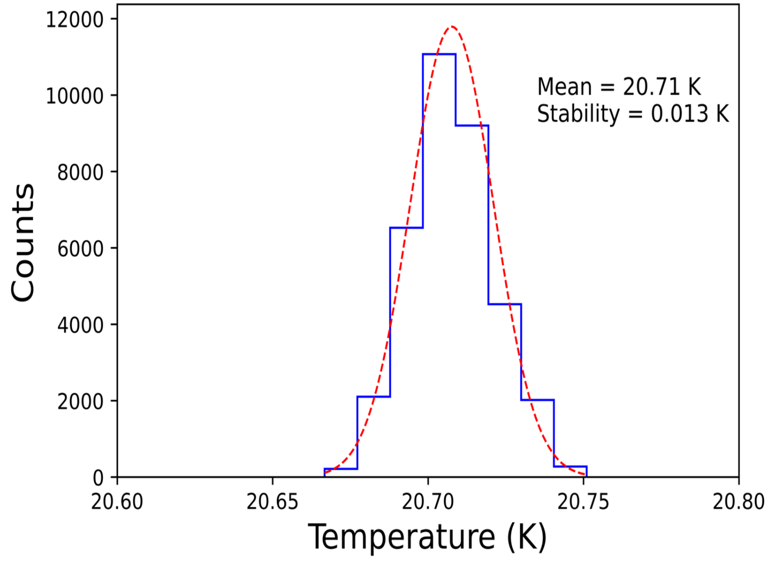
→ 280 ml Kapton cylinder

→ Full and empty cells

→ Carbon foil target

→ Beam Focus Monitor

P. Roy et al., NIM A **949**, 162874 (2020)



- Target Temperature: 20.71 ± 0.013 K during Fall 2021 run time
  - ✓ corresponds to a pressure of ~1.1 bar
- Target density: 0.070 g/cm3 (stable to 0.02%)
  - ✓ once equilibrium concentration of para (>99%) and ortho (<1%) hydrogen has been reached

Target

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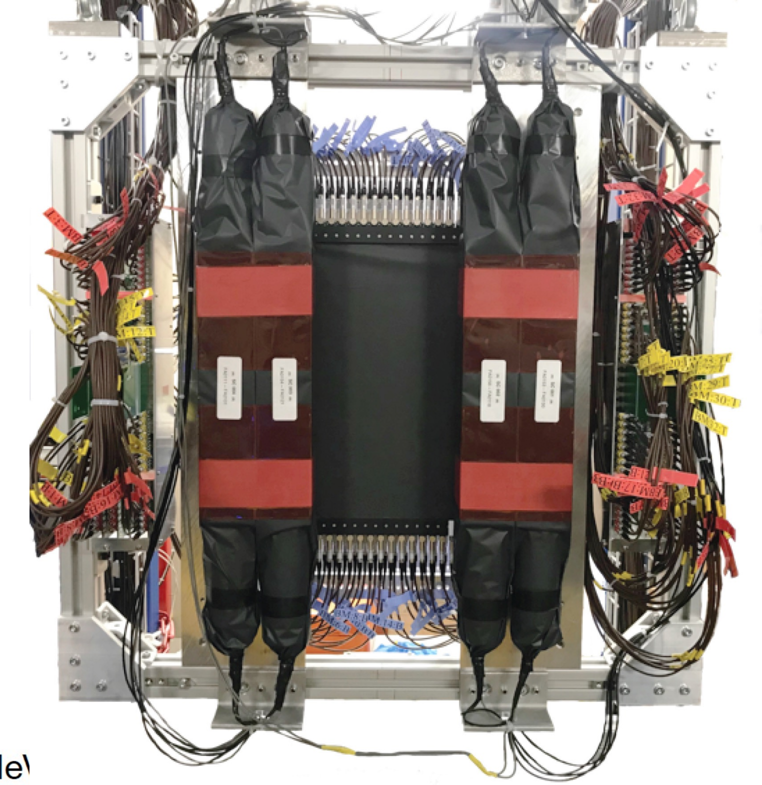
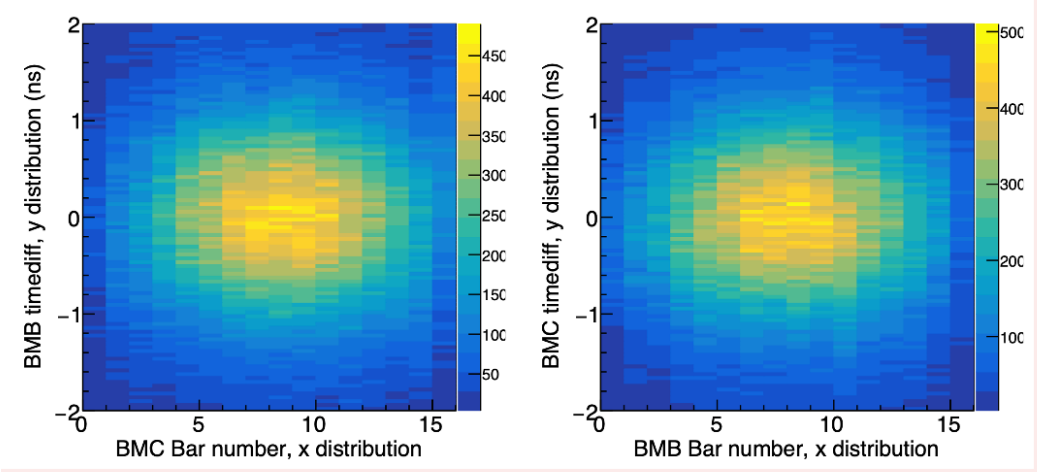
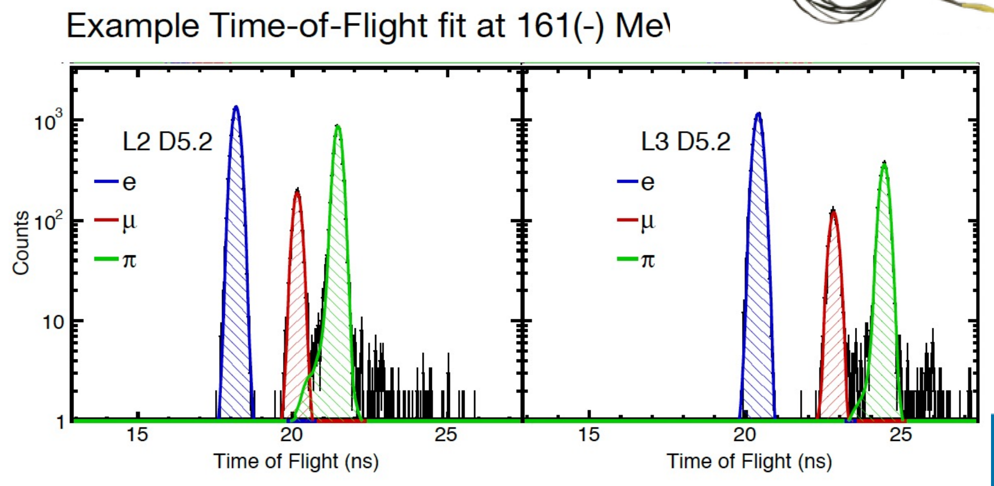
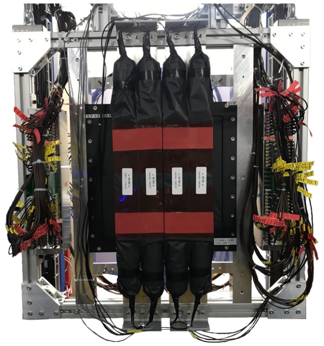
- Thin plastic scintillators read out by SiPMs
- Flanked by short thick bars with 30 ps resolution
- Monitors beam position and flux
- Short bars moved into middle for TOF calibration measurements
- BH—BM TOF determines energies of π, μ in beam

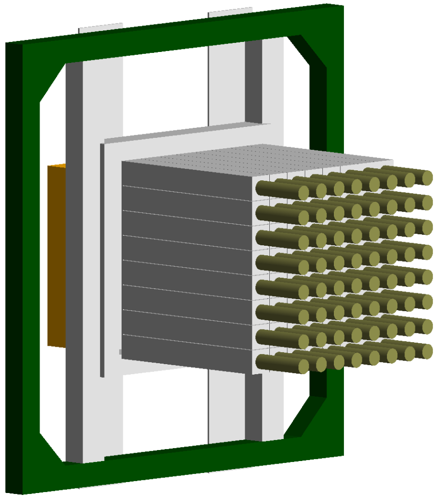


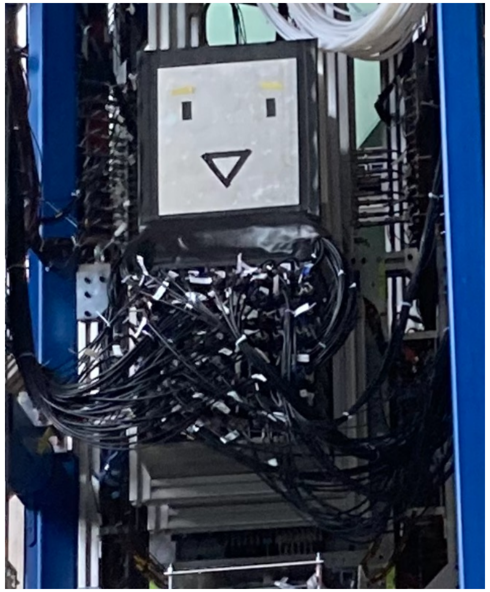


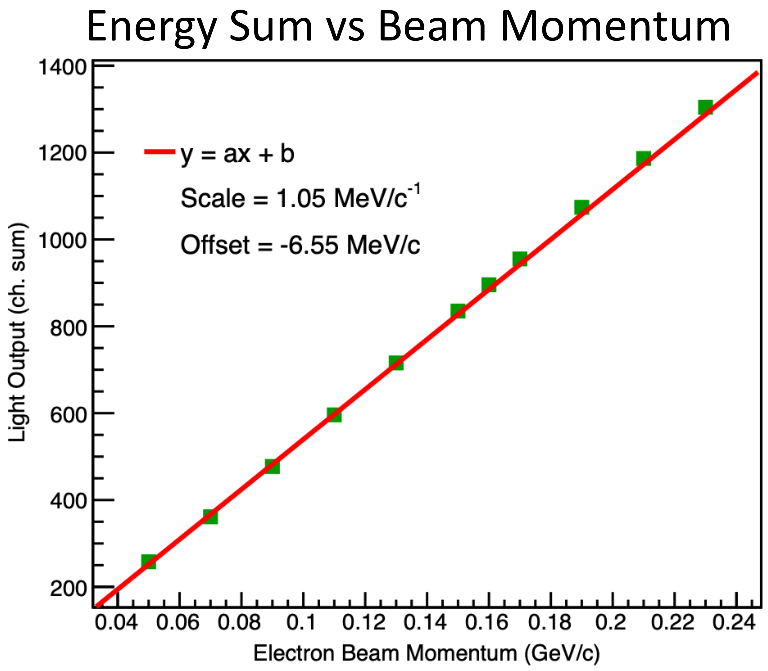


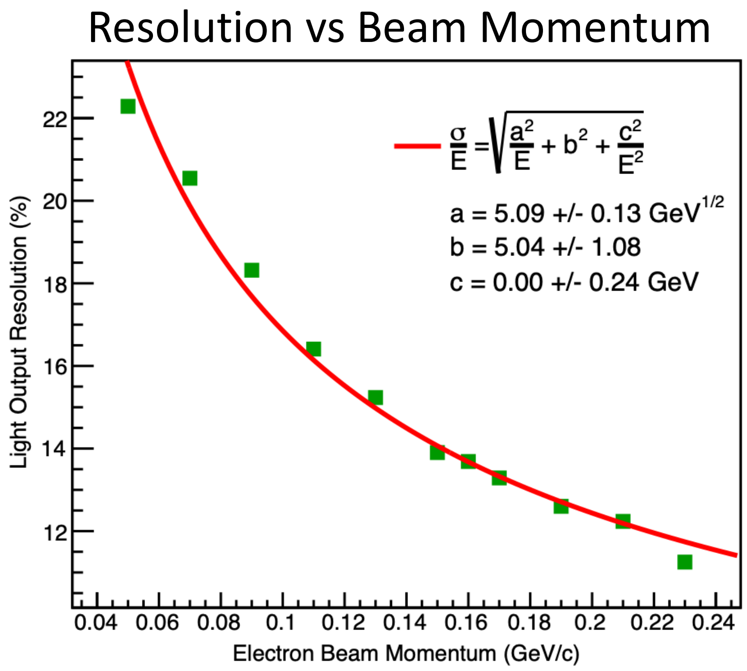


Beam Monitor









- Array of 64 (4cm by 4cm by 30cm) lead glass scintillators
- Veto events with hard initial state radiation
- Control radiative corrections for ep scattering

Calorimeter

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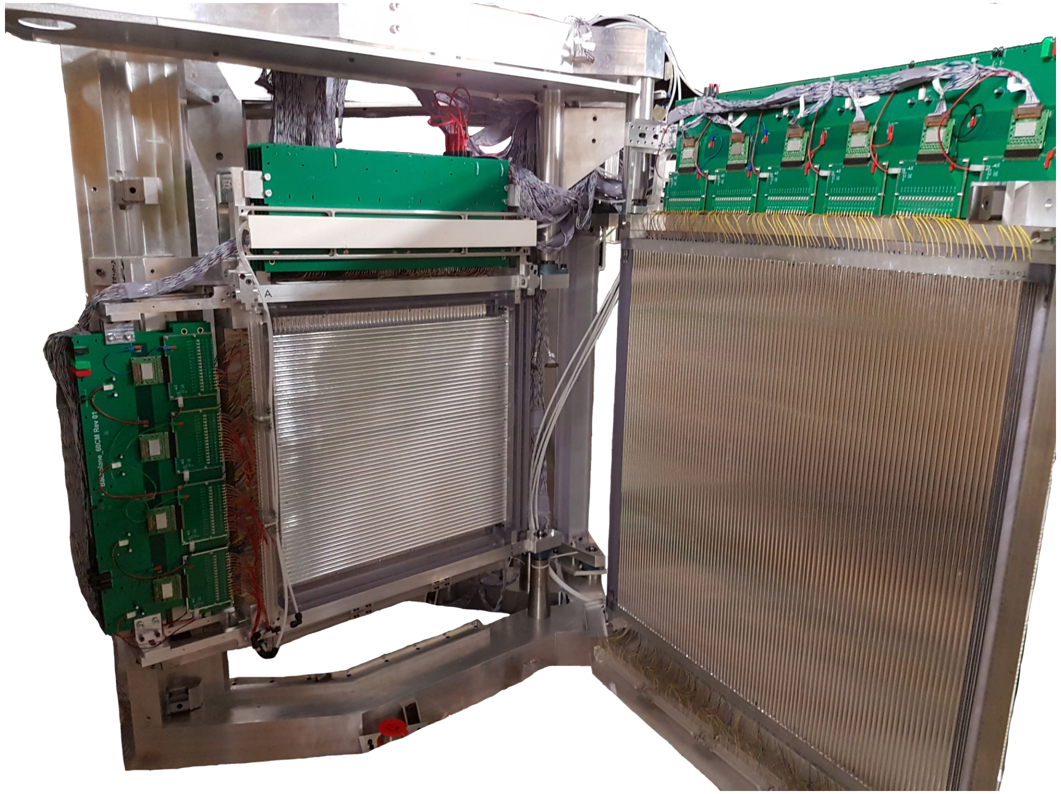
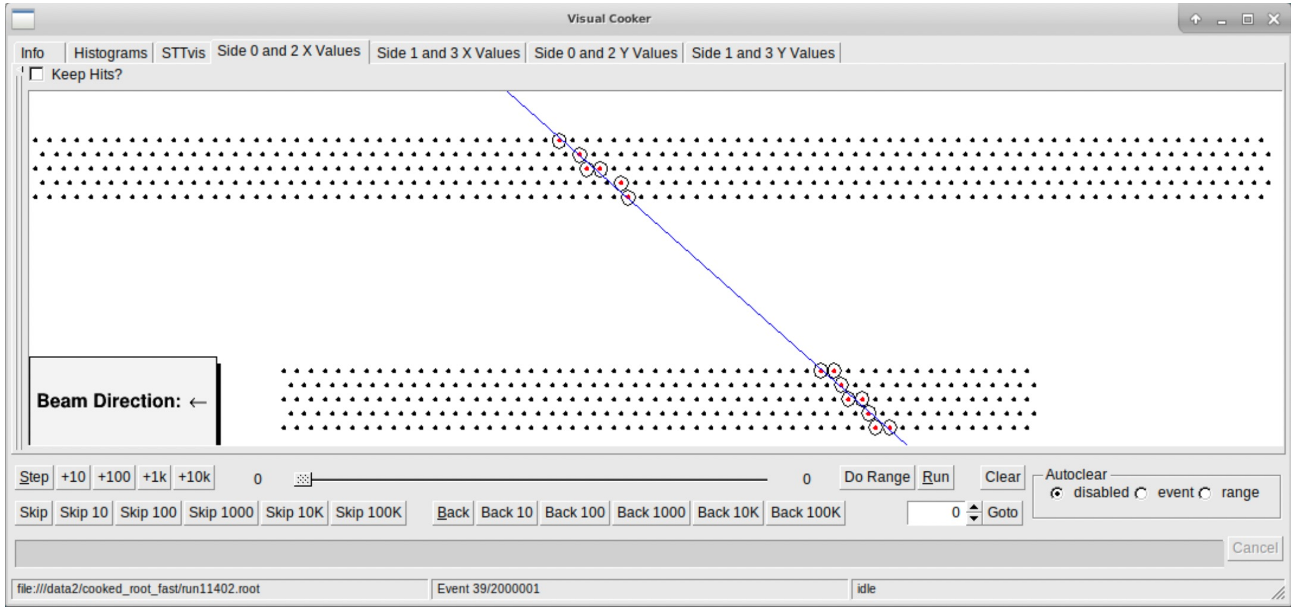
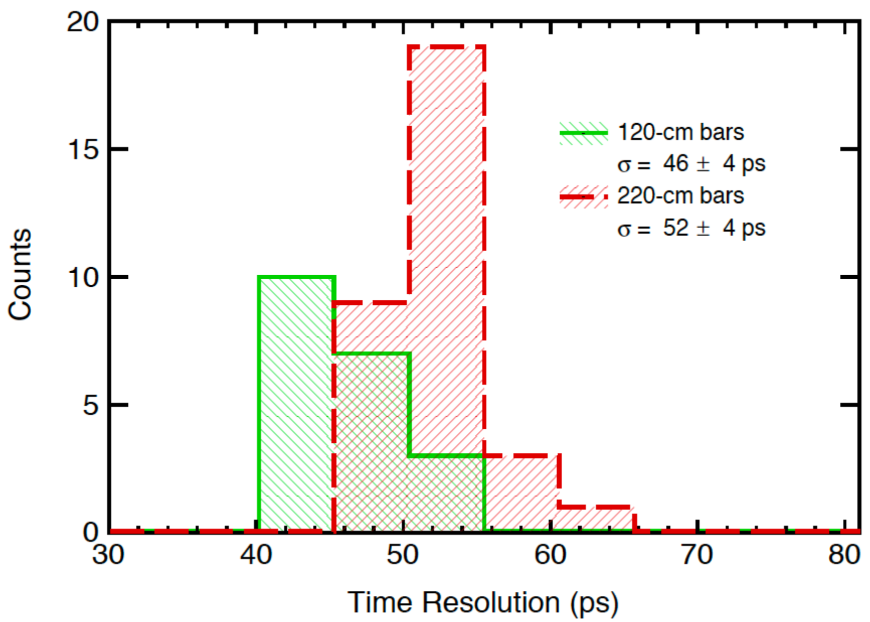
- Based on PANDA design, PASTREC & TRB3 readout
- Four five-layer chambers on each side
- Horizontal and vertical, 60cm and 90cm

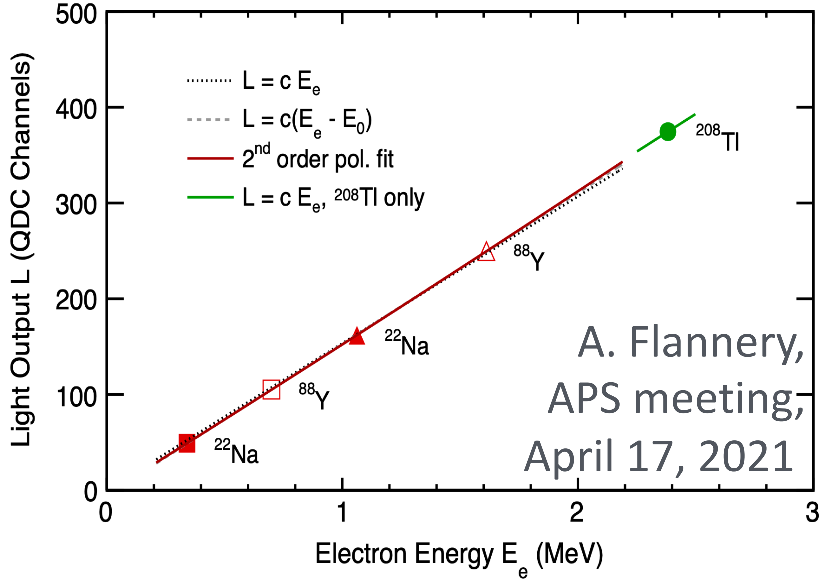




Example STT Track

Straw Tube Tracker





Front wall: 18 bars (6 cm x 3 cm x 120 cm)
Rear wall: 28 bars (6 cm x 6 cm x 220 cm)

- Front and rear Scattered Particle Scintillator walls
- Used for triggering – scattered particle trigger
- Used for TOF to ensure consistent scattered particle ID
- Exceed required time resolution: σ(Front) < 50 ps, σ(Rear) < 60 ps

Scattered Particle Scintillators

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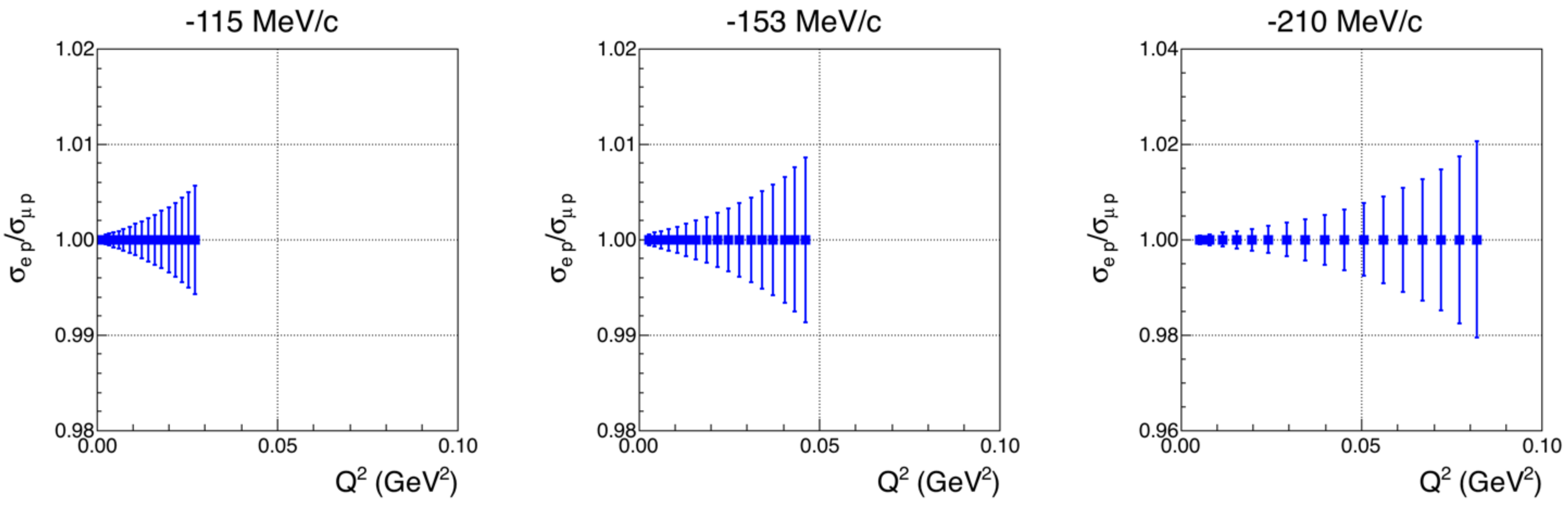

- Comparison of ep and μp cross section statistical uncertainty, systematic better than 0.5%
- The MUon Scattering Experiment at PSI (MUSE), MUSE Technical Design Report, arXiv:1709.09753 [physics.ins-det]

Anticipated Results

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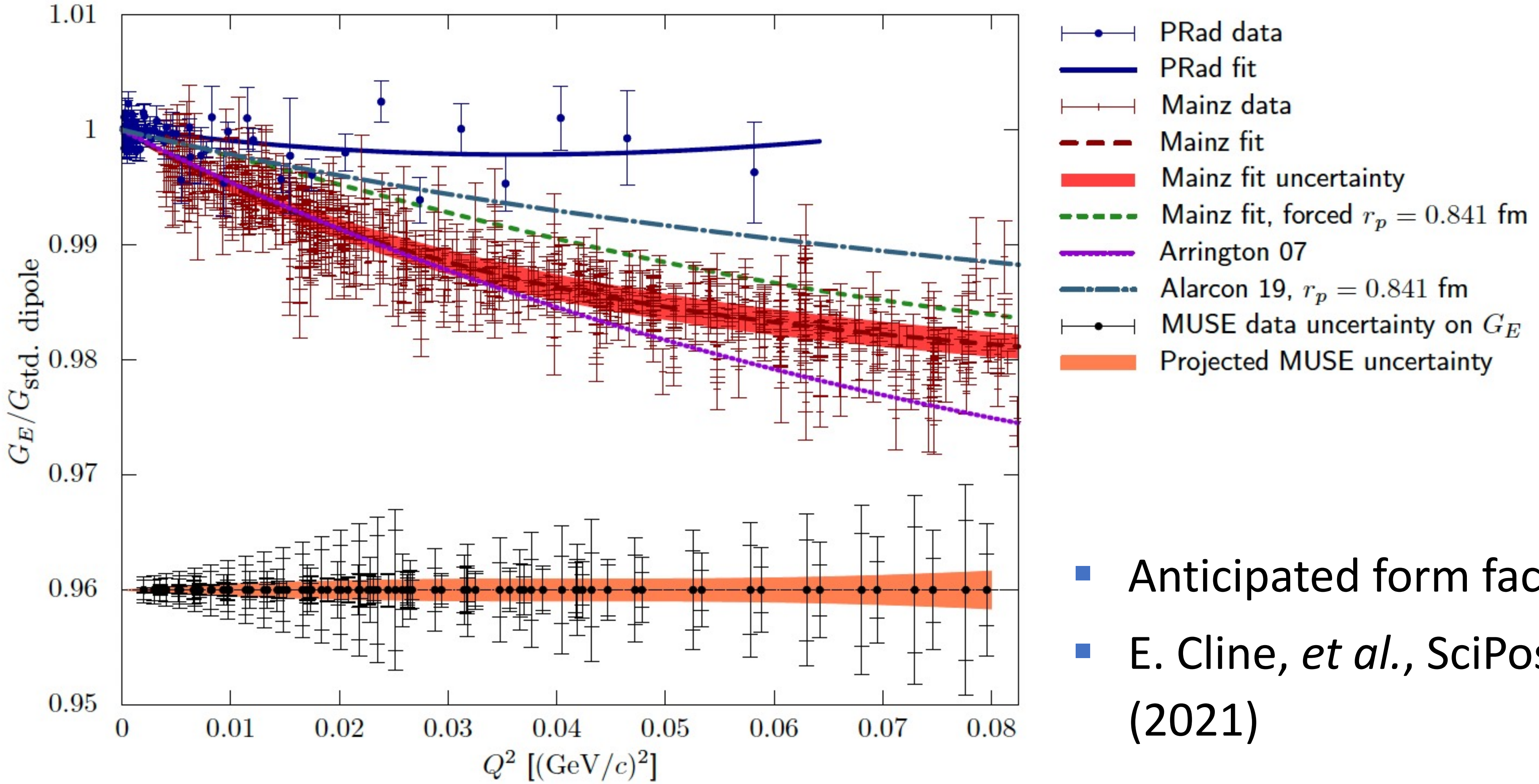

- Anticipated form factor uncertainty
- E. Cline, *et al.*, SciPost Phys. Proc. 5, 023 (2021)

Anticipated Results

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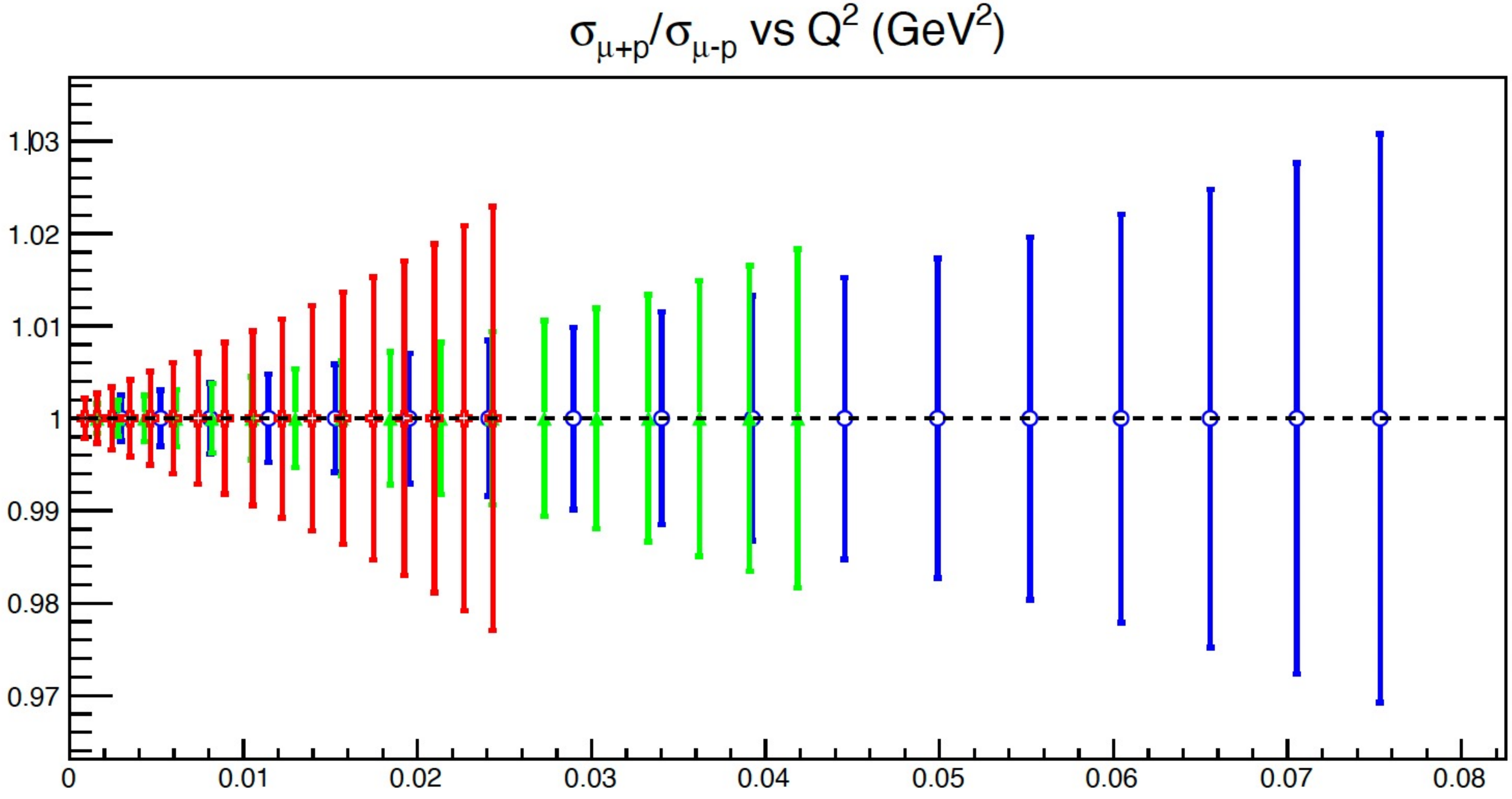

- Investigation of e+/e-, μ+/μ-
- Direct measurement of 2-photon effects

Anticipated Results

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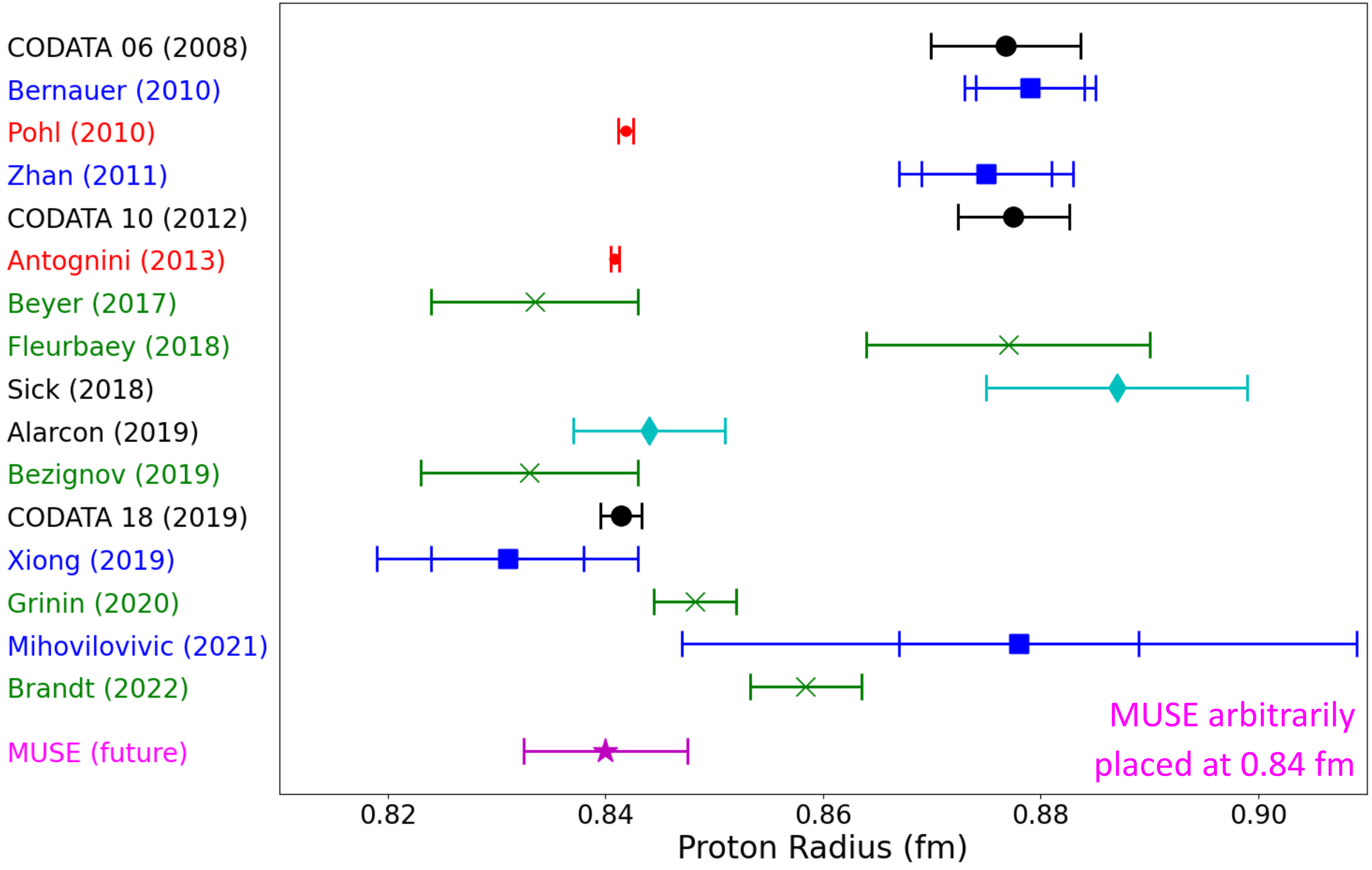
Anticipated Results



- MUSE only experiment measuring with e and μ in same experiment
- MUSE accesses both charge states
- Cancellation of uncertainties gives $\sigma(r_e - r_\mu) \cong 0.5$ fm

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Approximately 70 Collaborators, past and present, from four countries, supported by countless PSI staff!

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

George Washington University, Montgomery College, Argonne National Lab, Temple University, Duquesne University, Stony Brook University, Rutgers University, Hebrew University of Jerusalem, Tel Aviv University, University of Basel, Paul Scherrer Institute, Johannes Gutenberg-Universität Mainz, Hampton University, University of Michigan, University of South Carolina, Jefferson Lab, Massachusetts Institute of Technology, Weizmann Institute, Old Dominion University

MUSE Collaboration

BSF NSF

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Conclusion

- Proton Radius Puzzle remains unresolved
- MUSE will:
  - ✓ Compare cross sections, form factors with e, μ
  - ✓ Compare charge states in e, μ giving direct measurement of two-photon effect
- Production data taking starting in Fall 2022
- Continues in 2023/24
- Anticipate unblinding of radius result in 2024/25

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