MUSE Overview

Ron Gilman

Final versions of talks posted to https://indico.psi.ch/event/14120/

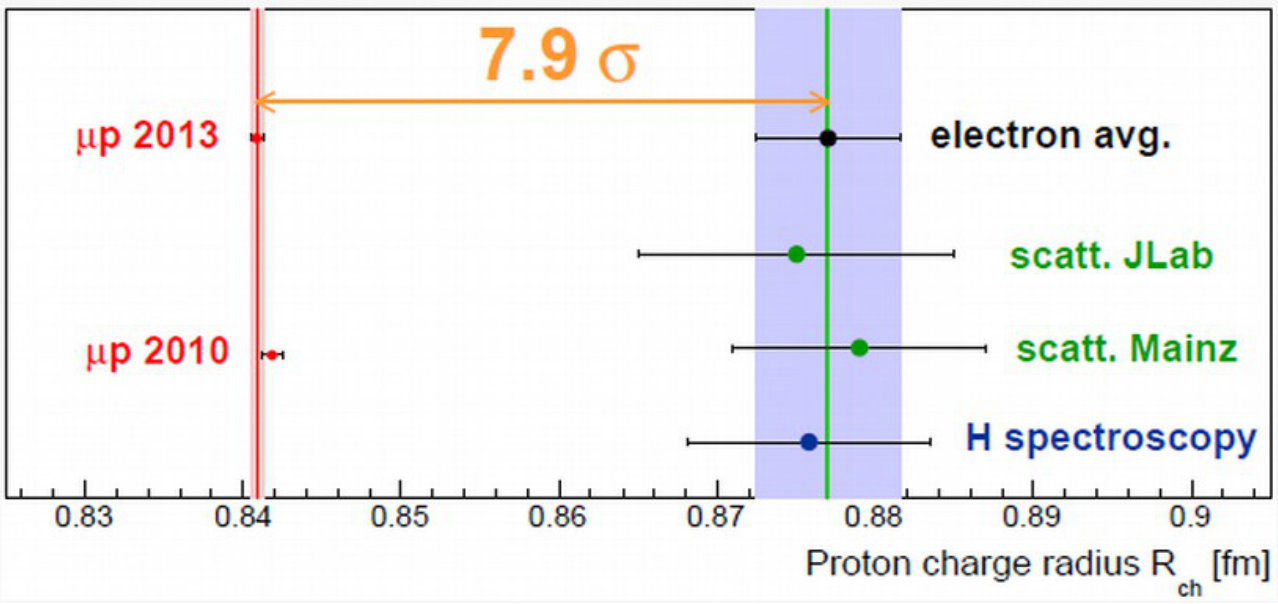
PRP and MUSE Physics
Experiment Overview

This work is supported by the National Science Foundation, grants PHY-1913653 and 2209348 to Rutgers University.
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.

Proton Radius Puzzle and MUSE Physics

Reminder: origin of PRP

- 2010: PRP arises
- 2013: confirmed in 2nd muonic hydrogen experiment



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

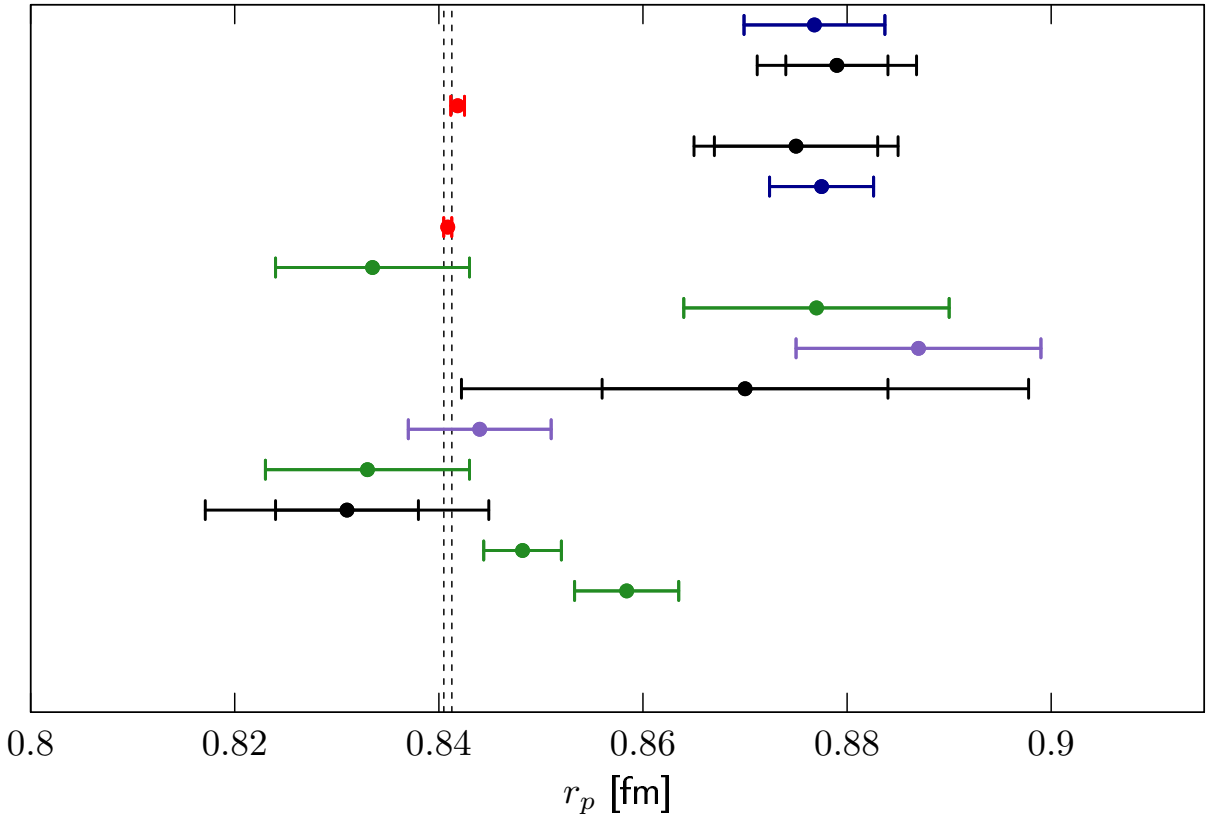
JLab: Zhan *et al.*, PLB **705,** 59-64 (2011)

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

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

Selection of Subsequent Results

Many hydrogen results over past several years - new experiments and re-analyses



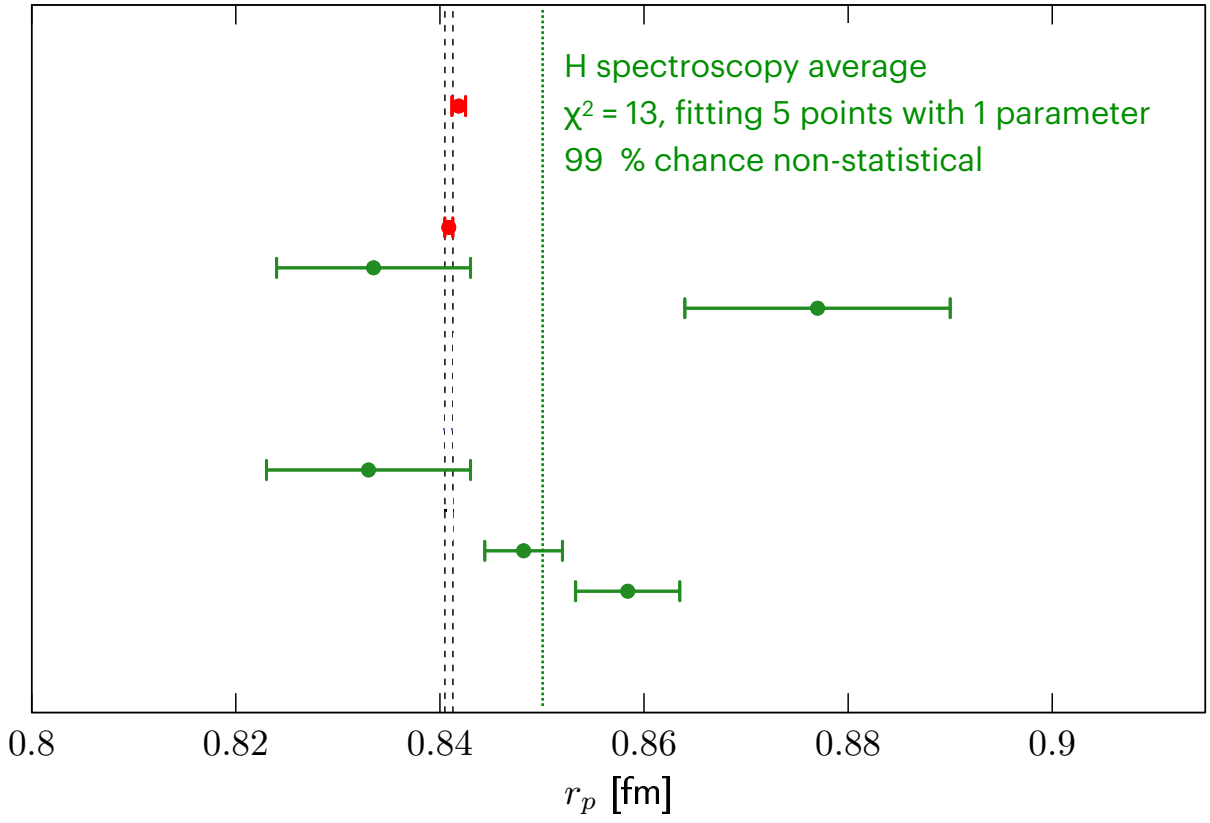
CODATA'06 (2008)
Bernauer (2010)
Pohl (2010)
Zhan (2011)
CODATA'10 (2012)
Antognini (2013)
Beyer (2017)
Fleurbaey (2018)
Sick (2018)
Mihovilovič (2019)
Alarćon (2019)
Bezignov (2019)
Xiong (2019)
Grinin (2020)
Brandt (2022)

MUSE (future) ?

CODATA 18 not shown here
Includes muonic H.

Hydrogen Spectroscopy

Poor internal consistency: Only one point within 1σ of average



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CODATA'10 (2012)
Antognini (2013)
Beyer (2017) 2S-4P
Fleurbaey (2018) 1S-3S
Sick (2018)
Mihovilovič (2019)
Alarćon (2019)
Bezignov (2019) Lamb shift
Xiong (2019)
Grinin (2020) 1S-3S
Brandt (2022) 2S-8D

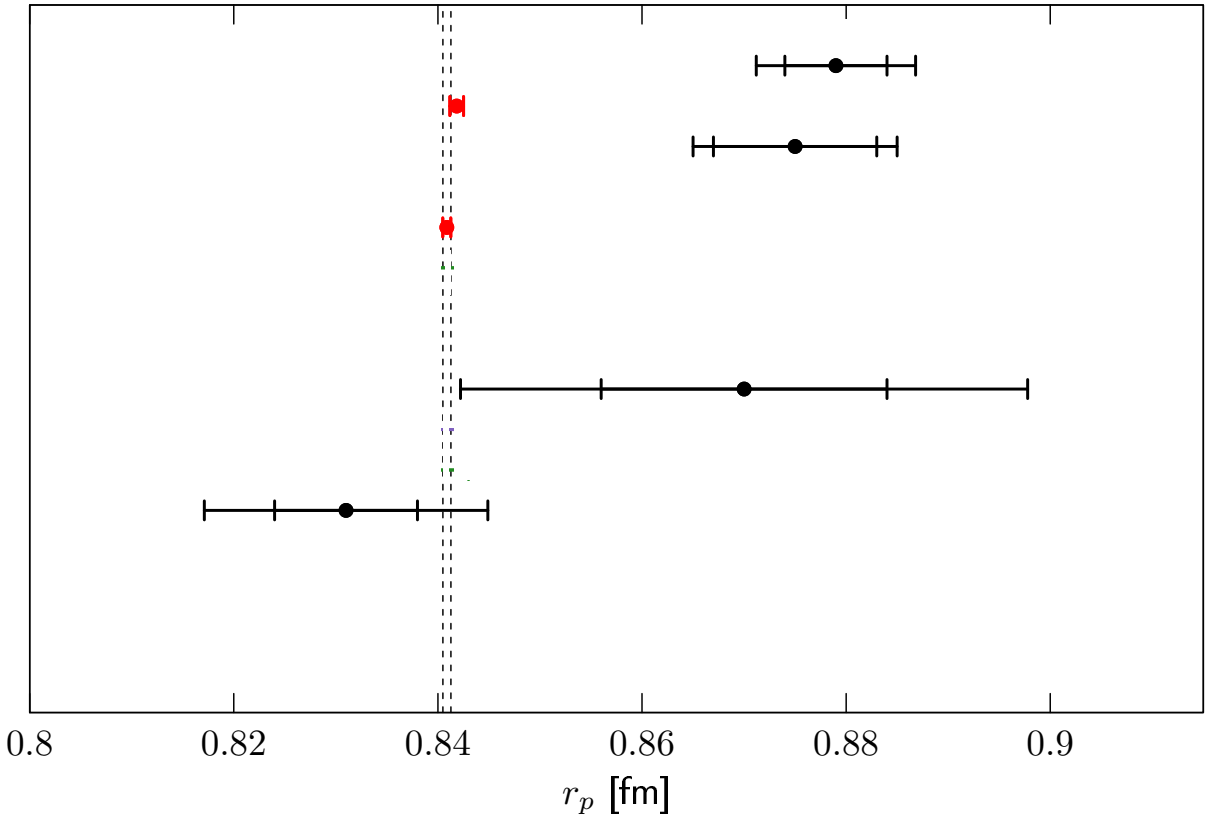
MUSE (future) ?

CODATA 18 not shown here

Will also keep muonic hydrogen on each slide for reference.

ep Scattering

ep scattering also inconsistent - will show at the cross section level



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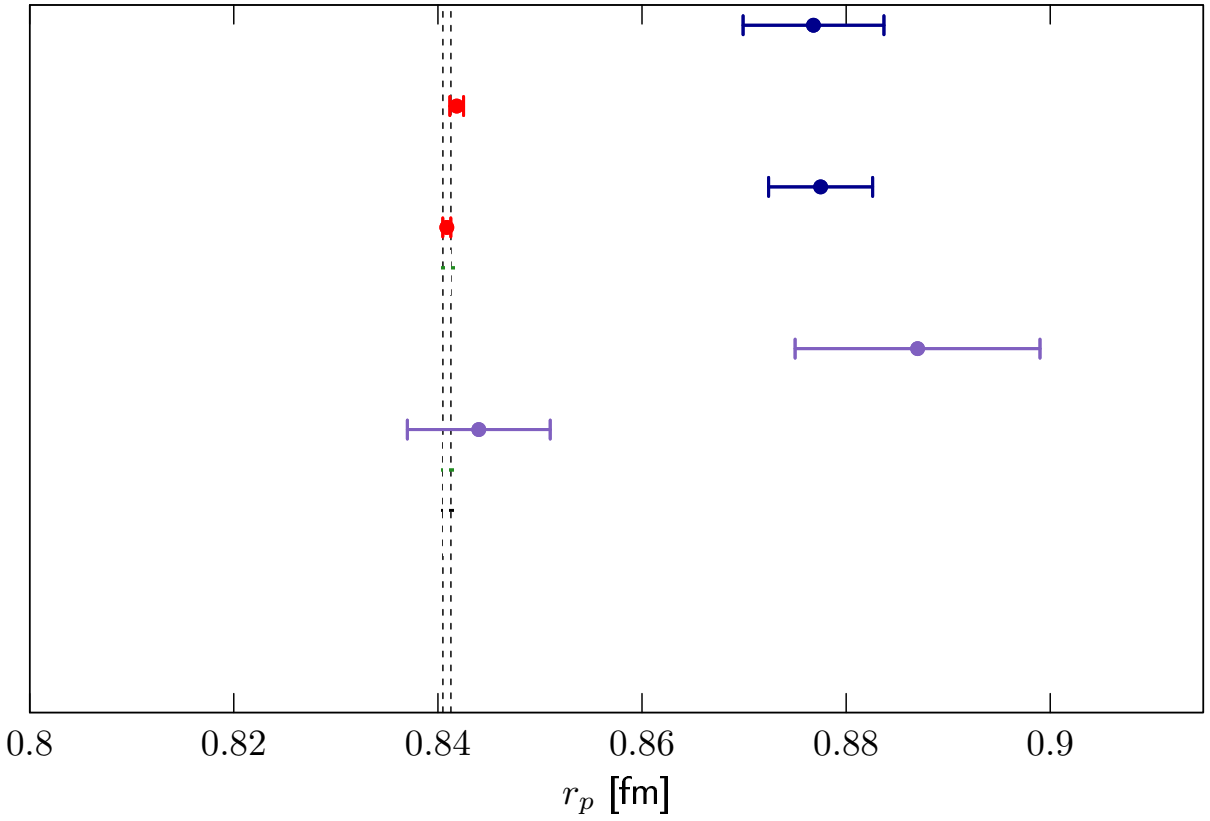
Analyses

Analyses inconsistent, even between different groups reanalyzing same scattering data



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Fleurbaey (2018)
Sick (2018)
Mihovilovič (2019)
Alarćon (2019) → predictions for MUSE
Bezignov (2019)
Xiong (2019)
Grinin (2020)
Brandt (2022)

MUSE (future) ?

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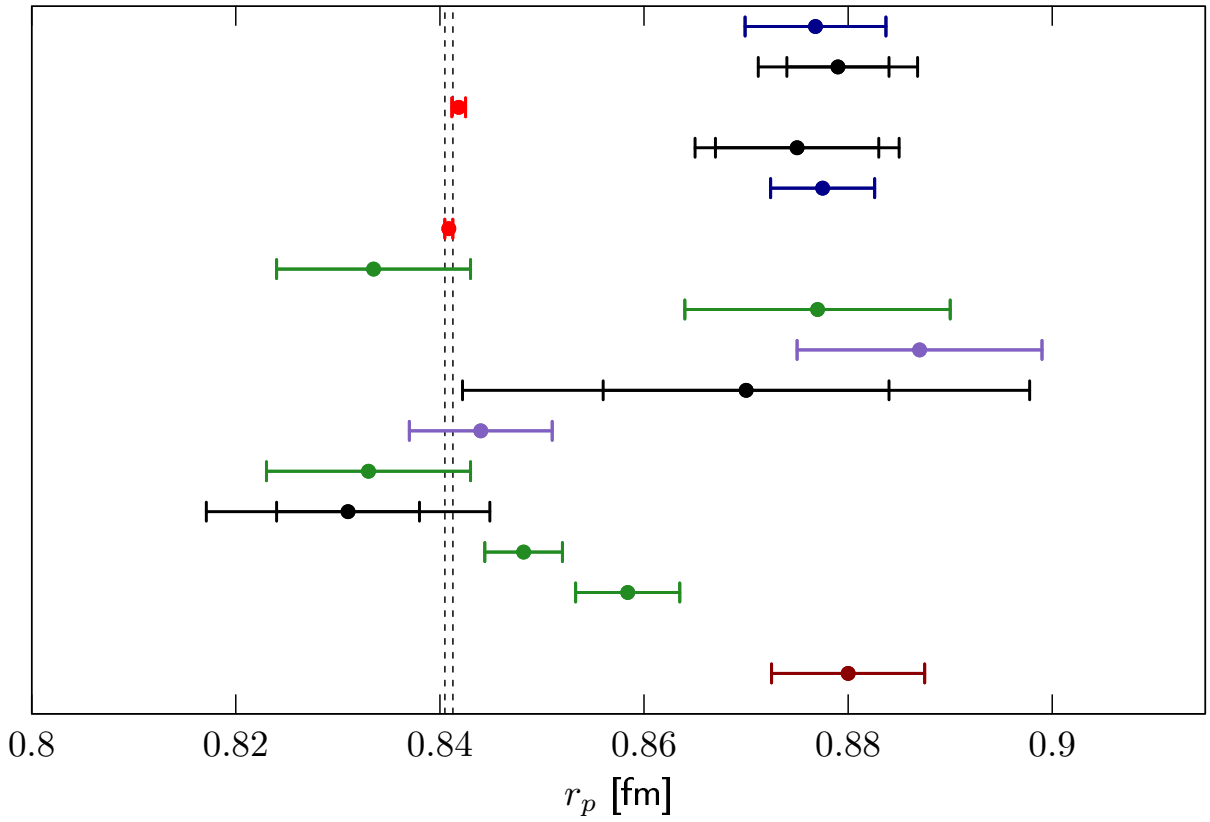
Selection of Results with MUSE

All results shown before with anticipated MUSE uncertainty arbitrarily placed at 0.88 fm.



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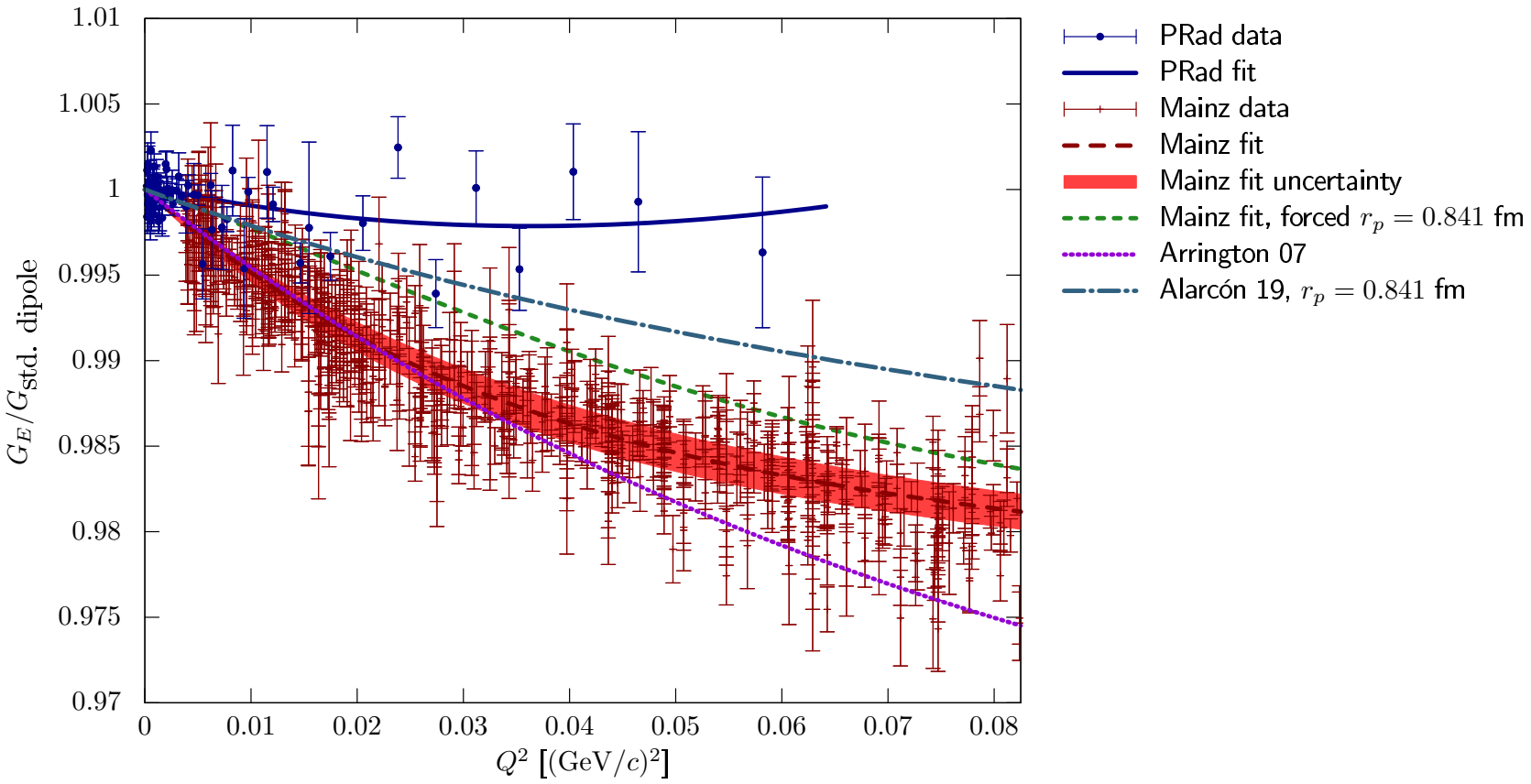
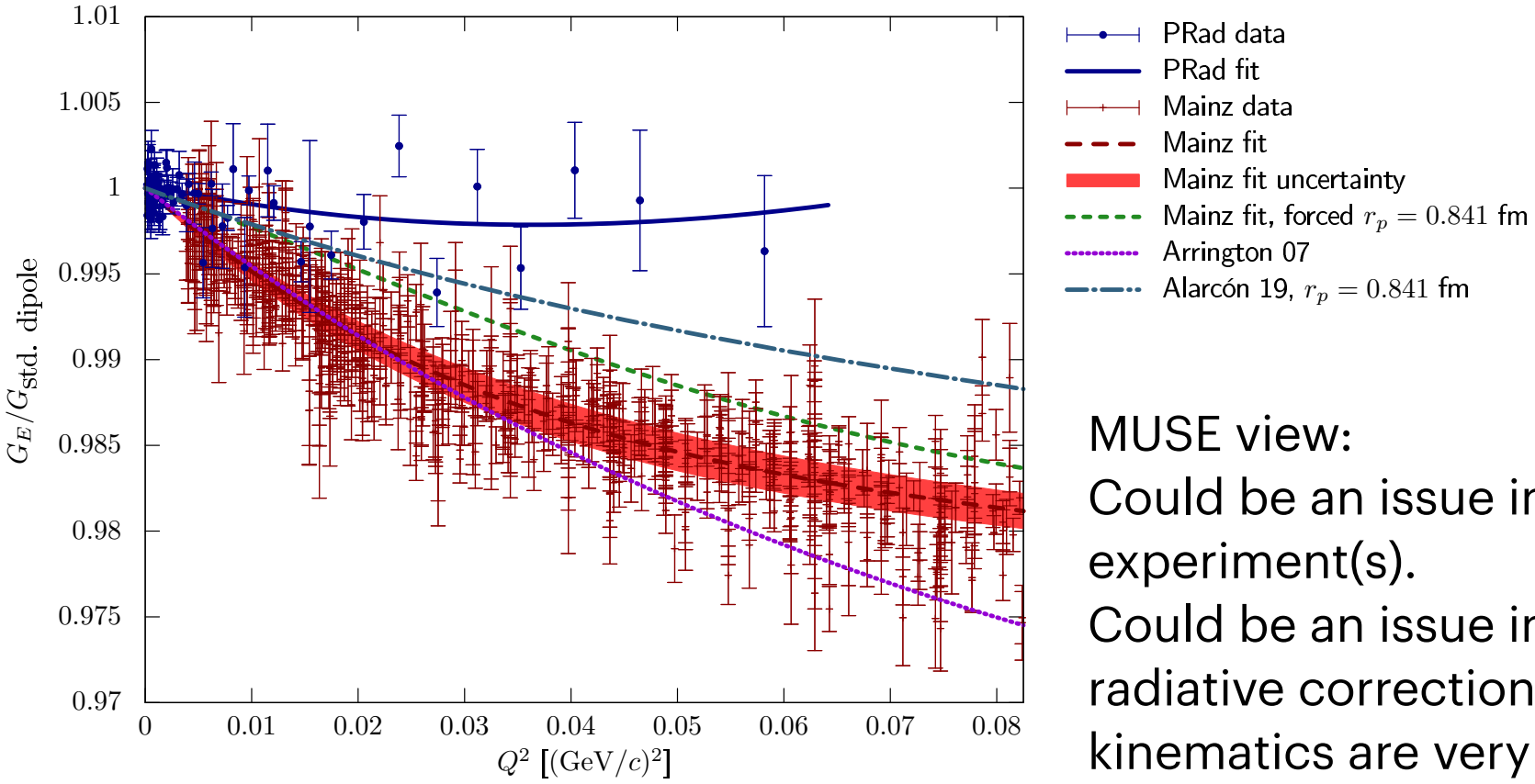
ep Scattering Comparison I

Unresolved issue: disagreement at cross section / form factor level of PRad vs. Mainz



ep Scattering Comparison II

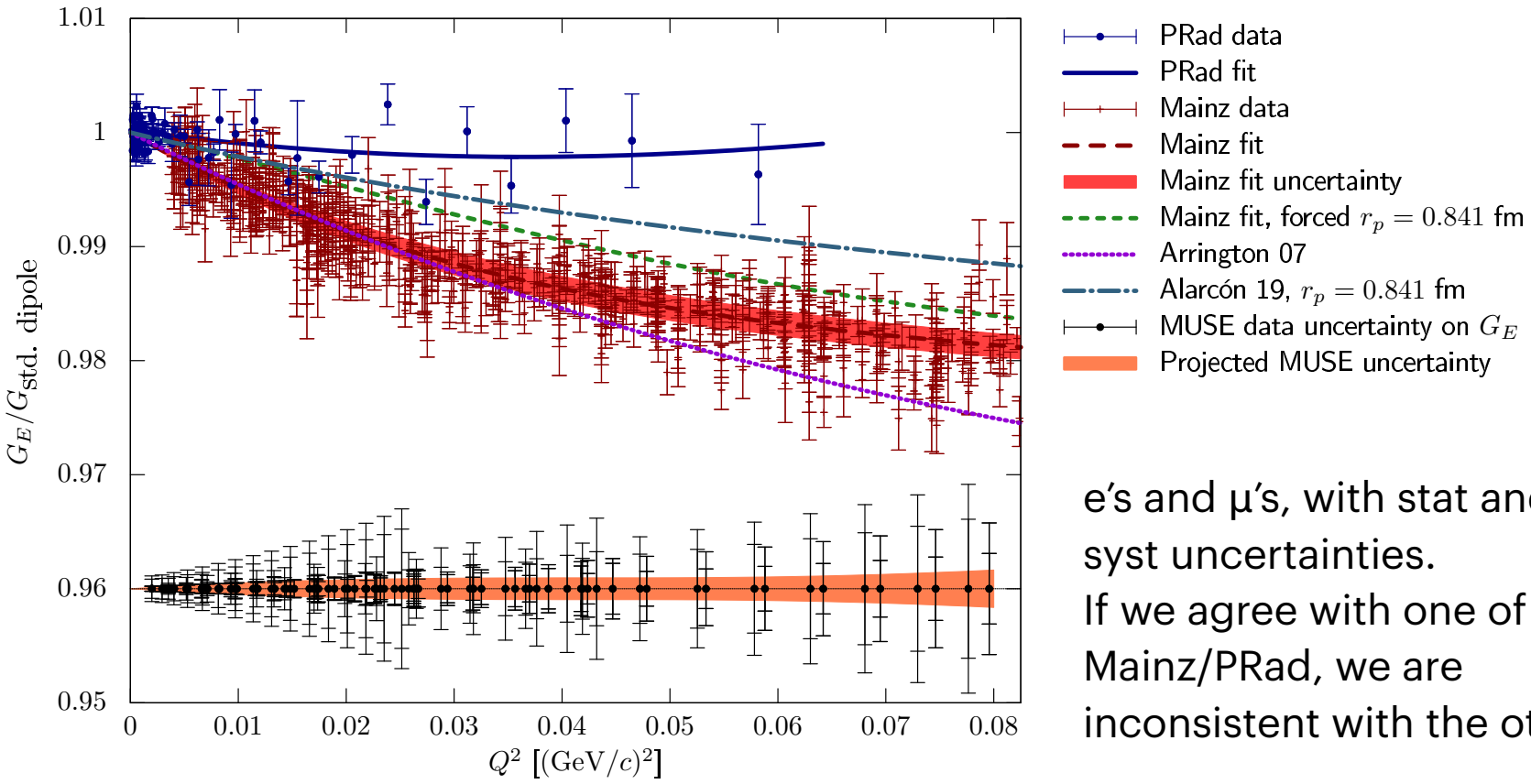
Unresolved issue: disagreement at cross section / form factor level of PRad vs. Mainz



MUSE view:
Could be an issue in the experiment(s).
Could be an issue in the radiative corrections — kinematics are very different.

ep Scattering Comparison III

Unresolved issue: disagreement at cross section / form factor level of PRad vs. Mainz



e's and μ's, with stat and syst uncertainties.
If we agree with one of Mainz/PRad, we are inconsistent with the other.

From E. Cline, *et al.*, SciPost Phys. Proc. 5, 023 (2021)

CODATA 2018 evaluation

Rev. Mod. Phys., Vol. 93, No. 2, April–June 2021 025

The tension between the two approaches determining r_p and r_d has not been fully resolved. In fact, to obtain consistency among the many input data that contribute to the determination of R_∞, r_p, and r_d, a multiplicative expansion factor of 1.6 is applied to their uncertainties. Further experiments are needed.

CODATA 2018 (2021) inflates uncertainties by 1.6, says that **further experiments are needed**.

MUSE view: treating all experimental results as having equally (fractionally) wrong uncertainties is only justified by convenience.

Recent RMP

Evaluations of the current state of the PRP

REVIEWS OF MODERN PHYSICS, VOLUME 94, JANUARY–MARCH 2022

The proton charge radius

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(published 21 January 2022)

the muonic hydrogen results. We believe more experiments, especially those with improved precision from electron scattering, and new results from muon scattering will be essential to fully resolve this puzzle. To answer a more provocative question, whether there is a difference in the proton charge radius determined from experiments involving electronic (e-p and ordinary hydrogen) versus muonic systems, significantly improved precision from lepton scattering and also measurements from ordinary hydrogen spectroscopy with precision comparable to that of Grinin *et al.* (2020) will be critical. Pushing the precision frontier has more than once proven to be the harbinger of new discoveries.

Note efforts towards PRad-II at JLab

Summary Evaluation

Proton Radius Workshops and PREN Meetings:
Trento, Mainz, Losinj, Paris (2012,'14,'16,'18, '19, '22)

Latest meeting:
PREN, Paris, 2022: https://indico.mitp.uni-mainz.de/event/308/

- 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

Highlighting Muon Scattering

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MUSE and AMBER (2023 test planned)

MUSE Viewpoint

Comment:

- With some newer ep results consistent with muonic hydrogen, casual observers tend to assume the larger radius ep results are wrong (no explanation needed) and accept the muonic hydrogen radius.
- Those in the field tend to see unresolved issues and the need for additional measurements.
- There is a problem at the cross section level with the scattering measurements.
- There is no clear agreement on spectroscopy.

Radiative Corrections

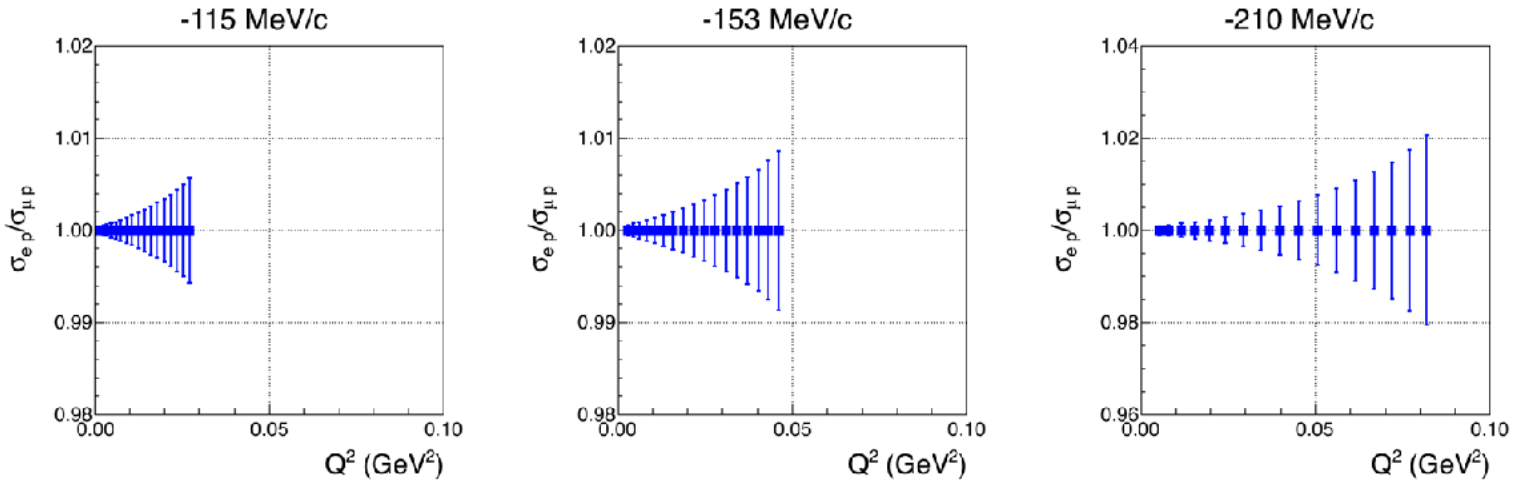
Radiative Corrections Workshop: E. Cline, lead organizer

https://indico.ectstar.eu/event/146/

Two MUSE talks:
S Strauch: Radiative Corrections for the MUSE Experiment
R Gilman: Two Photon Exchange at MUSE

Several theorists contributed related to MUSE: A Afanasev, N Kaiser, F Myhrer*, G Paz, A Signer and Y Ulrich

MUSE Projected Result



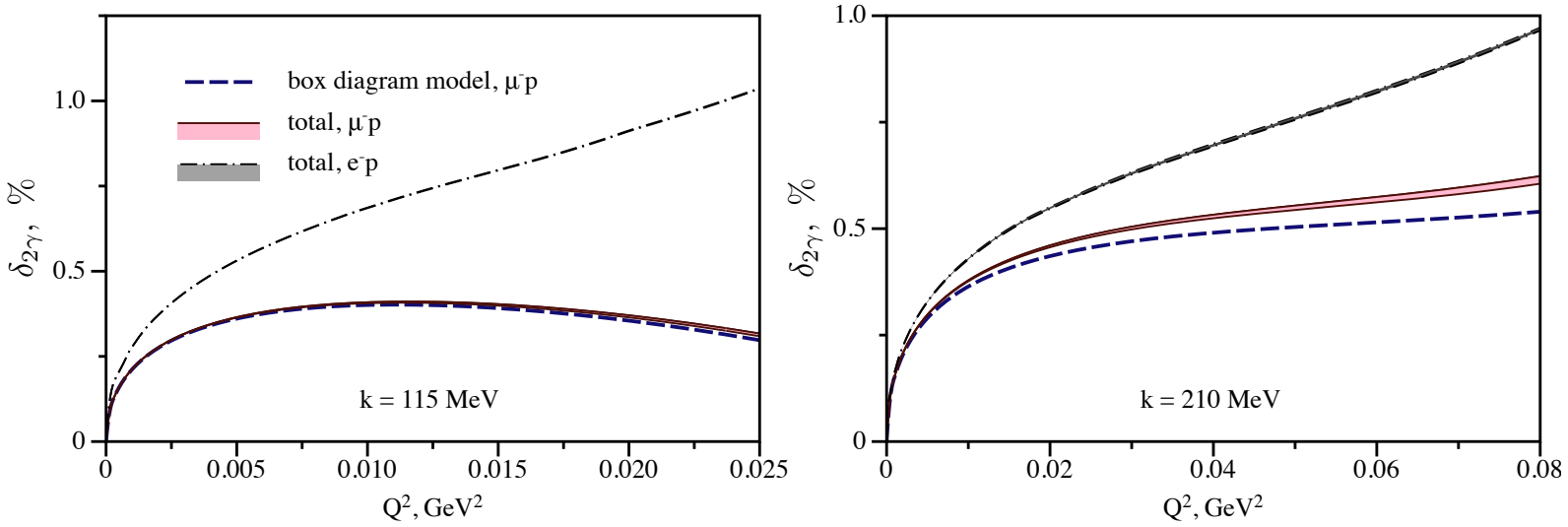
- Comparison of ep and μp cross sections provides a more general lepton universality test
- Statistical uncertainty shown, systematics better than 0.5%
- The MUon Scattering Experiment at PSI (MUSE), MUSE Technical Design Report, arXiv:1709.09753 [physics.ins-det]

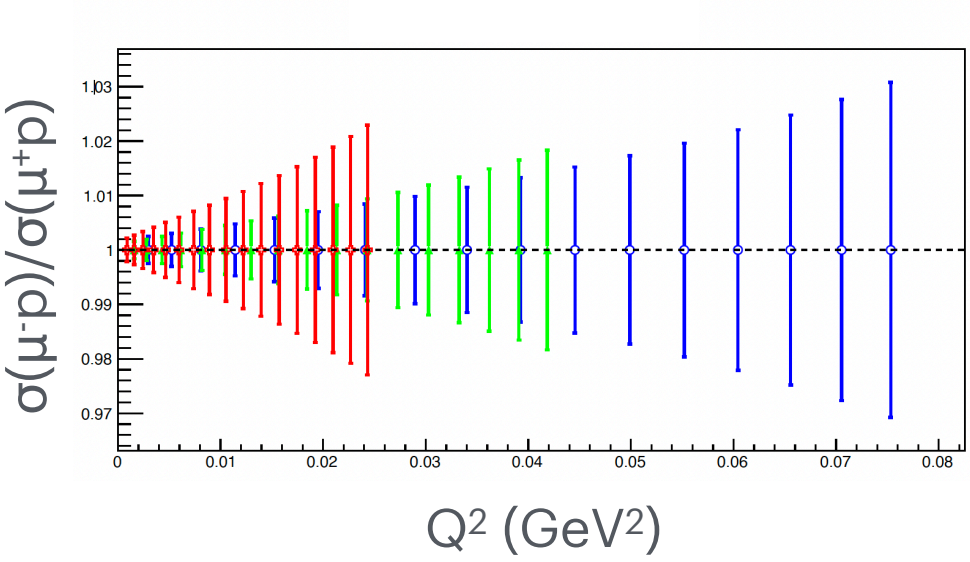
Lepton Universality

- "The proton radius and its relatives - much ado about nothing?", Ulf-G. Meißner, https://arxiv.org/pdf/2211.05419.pdf
- "**7. Final thoughts** DRs are arguably the best tool to analyze the electromagnetic form factors of the nucleon as they allow for a consistent description of all data in the space- and timelike regions based on fundamental principles. DR analyses always led to a small proton charge radius and a slightly bigger magnetic one. Also, most recent experiments tend to the small radius, so the attention has turned from a puzzle to precision [68]. ... Experimental challenges are a measurement of of the proton form factor ratio at $Q^2 \simeq 10$ GeV^2, more resolved form factor measurements in the timelike region and the investigation of μp scattering (MUSE, AMBER) to test lepton flavor universality."

MUSE Projected Result

Oleksandr Tomalak, Few-Body Systems, **59**, 87 (2018)

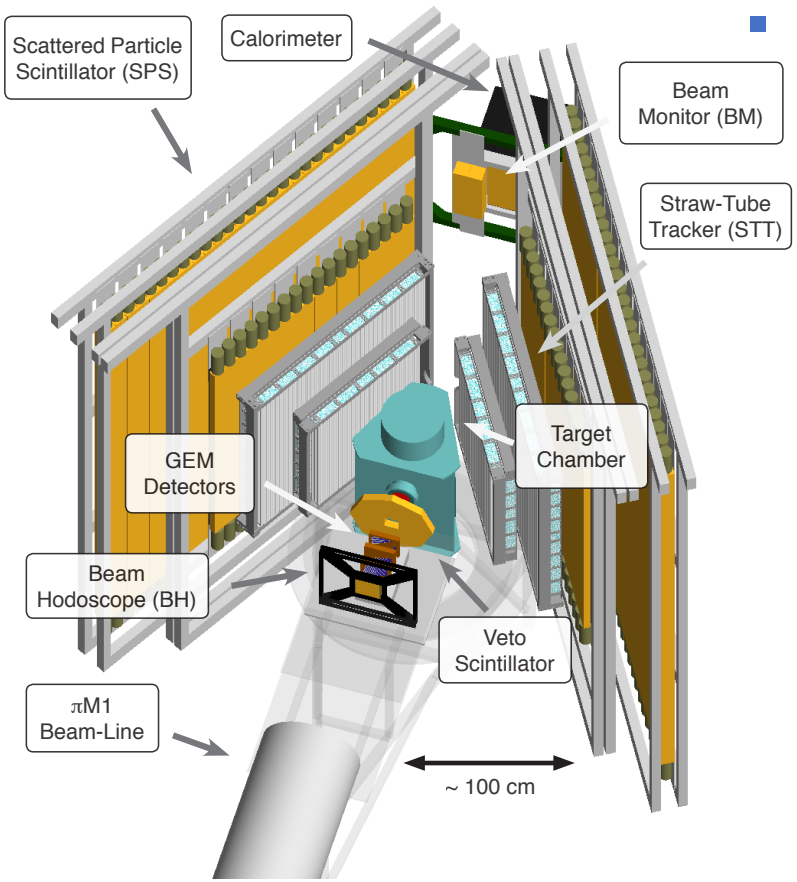




- Investigation of e+/e-, μ+/μ-
- Direct measurement of 2-photon effects
- Predictions at Trento show O(1 %) effect

Experiment Overview

MUSE Experiment Overview



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

$\theta \approx 20° - 100°$

$Q^2 \approx 0.002 - 0.07\ GeV^2$

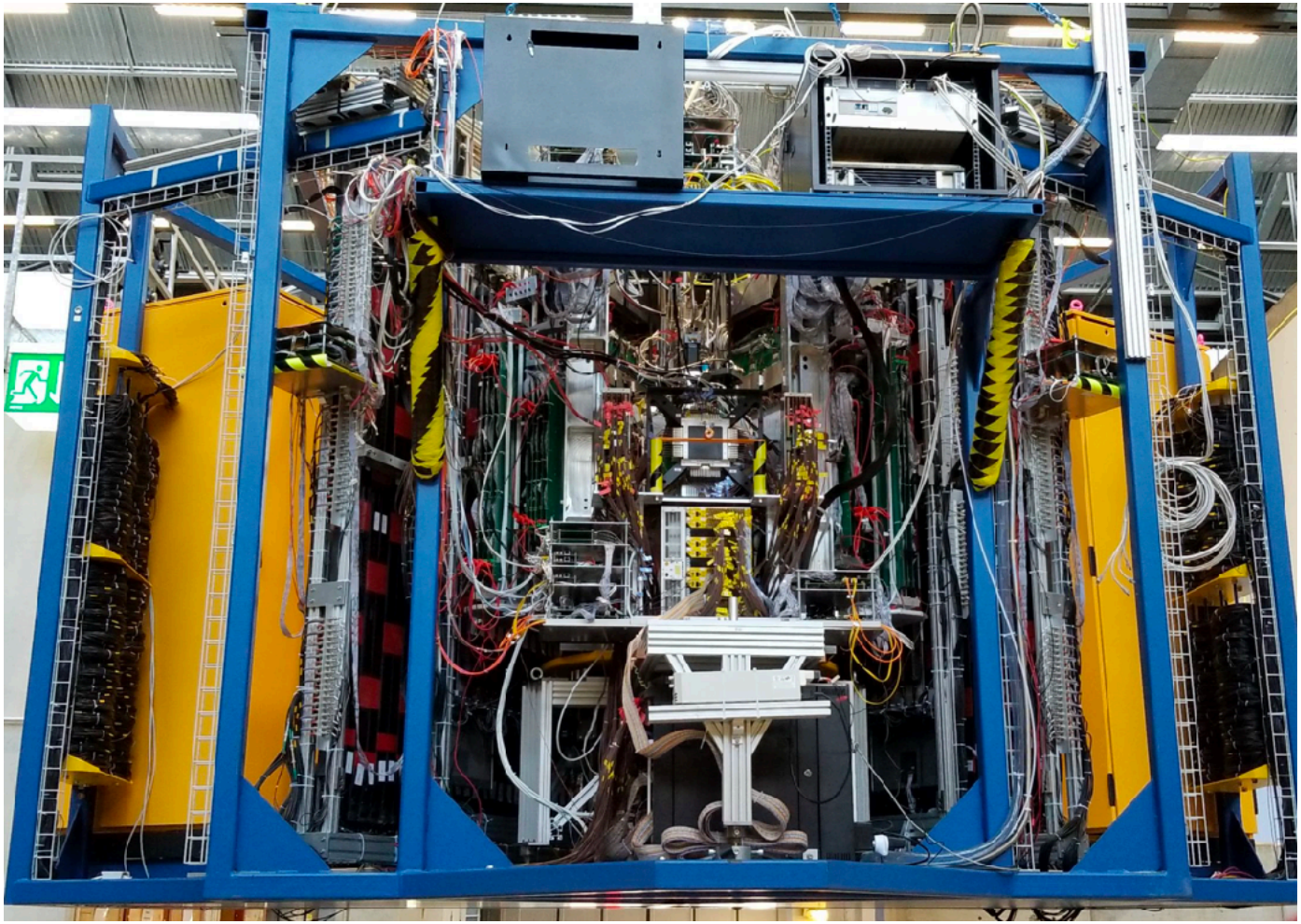
up to 3.3 MHz beam flux

≈ 2-15% μ's

≈ 10-98% e's

≈ 0-80% π's

Platform being craned



BVR53 Notes

- Target interruptions in 2021
  - ➢ Implement target mitigation measures and have PSI review
- STT incident in 2021
  - ➢ Implement STT interlock measures and have PSI review
- Hardware readiness report by June 30, 2022
- Analysis Report by December 1, 2022
  - "This implies that, at a minimum, a limited data set of real data be analyzed to provide a physics measurement."

BVR53 Notes

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  - ➢ Implement target mitigation measures and discussed with PSI ✓
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  - ➢ Implement STT interlock measures and discussed with PSI ✓
- Hardware readiness report by June 30, 2022 ✓
- Analysis Report by December 1, 2022 ✓
  - "This implies that, at a minimum, a limited data set of real data be analyzed to provide a physics measurement."

Other Notable Upgrades during 2022

- Upgrades to simulation: digitization…
- Target chamber exit post veto detector
  - T. Rostomyan (PSI/MUSE), S. Strauch (MUSE), F. Barchetti (PSI), M. Gantert (PSI), A. Hofer (PSI), M. Hildebrandt (PSI)
- Blinded analysis in use
- High voltage supplies upgraded to new CAEN system
- Petabyte disk systems (upgradeable)

New CAEN HV system purchased by GW, UM, PSI, and USC.
~1 PB storage system purchased by ANL and RU.
Spare Mesytec CFDs and QDCs purchased by GW and RU.

2022 Time Line

- **Beam Time:** July 25th – Aug 24th: test and calibration measurements
- **Beam Time:** Sep 19th – Dec. 19th: set up and data-taking
- **New Article Published:** *Characterization of muon and electron beams in the Paul Scherrer Institute PiM1 channel for the MUSE experiment,* E. Cline *et al*. Phys. Rev. C **105**, 055201 (2022)
- **Featured at Town Meetings for NSAC Long Range Plan:** QCD & Fundamental Symmetries, Neutrons and Neutrinos (EJD, T. Gorringe)
- **Several Conference Talks:** APS April Meeting; International Workshop on New Scientific Opportunities with the TRIUMF ARIEL e-linac; PREN-2022; ECT* Workshop "Radiative Corrections from medium to high-energy experiments"; CIPANP 22; QNP22; PSI2022; NSTAR 2022; APS DNP

Statistics Taken

Events taken (millions) during fall 2022 and 2021 runs

Momentum (MeV/c)	LH2 (millions)	Empty Cell (millions)	Calibration (millions)
115 (2022)	120	80	50
-115 (2022)	110	80	50
160 (2022)	110	80	70
-160 (2022)	110	80	70
210 (2022)	110	70	60
-210 (2022)	60	40	50
115 (2021)	470	340	140
-115 (2021)	320	160	85

Note: O(1%) of these are scattering from target

Personnel for Beam Times

During 2022 beam times:

- 2 full-time MUSE personnel based at PSI + ~ 5 visitors (on average) during beam times to work shifts, etc.
- 2 shift workers, one on site and one remote, was common
- Always one LH2 target expert on-site at PSI, when target cooled

During 2023 runs:

- Plan similar staffing arrangements

Student / Postdoc Overview

new, since BVR53

departed / departing before BVR55

MUSE Student / Postdoc Overview

Students:

- Graduated: Lin Li (USC), Dan Cohen (HUJI), Orion Yeung (RU, MS)
- Intended 2023 graduation: Anne Flannery (USC, MS), Jesmin Nazeer (HU), Shraddha Dogra (RU), Win Lin (RU)
- Senior: Tanvi Patel (HU), Haley Reid (UM)
- Junior: Subham Das (RU), Rachel Ratvasky (GW), Kyle Salamone (SBU), Dvir Yaari (HUJI)

Postdocs:

- Alexander Golossanov (HU via Basel, to March 2023)
- Ethan Cline (SBU, ~50%)
- Hamza Atac (TU, ~50%)
- Ievgen Lavrukhin (UM, ~50%)
- Matthew Nicol (USC)
- Stefan Lukenheimer (UM, via Basel)

% given for 3 postdocs with significant commitments to other experiments during 2023, other postdocs are full-time MUSE

Thesis Titles

- Lin Li, South Carolina: Study of Radiative Corrections in the Muon Scattering Experiment
- Dan Cohen, HUJI: Comparing Electron-Proton and Pion-Proton Elastic Scattering in the Low Momentum Transfer Squared Region for Extracting MUSE Efficiency
- Orion Yeung, RU (MS): DAQ Trigger Analysis in the MUon-proton Scattering Experiment (MUSE)

Funding

Grants starting 2022:

- Rutgers (R Gilman) - NSF renewal
- Temple (N Sparveris) - DOE renewal

Grants proposals 2022, for start in 2023:

- Stony Brook (J Bernauer) - NSF renewal
- George Washington (E Downie) - NSF renewal

2023 Plans

- Analysis: various upgrades / calibrations, re-analyzing data
- Some hardware work, mainly “maintenance”, outlined in status report
- Requested 6 months of beam time - we can support this long a run
- Strong preference for contiguous beam time (start of data taking after late Sep 2022 move into PiM1 plagued by lots of unexpected issues, took longer than expected)

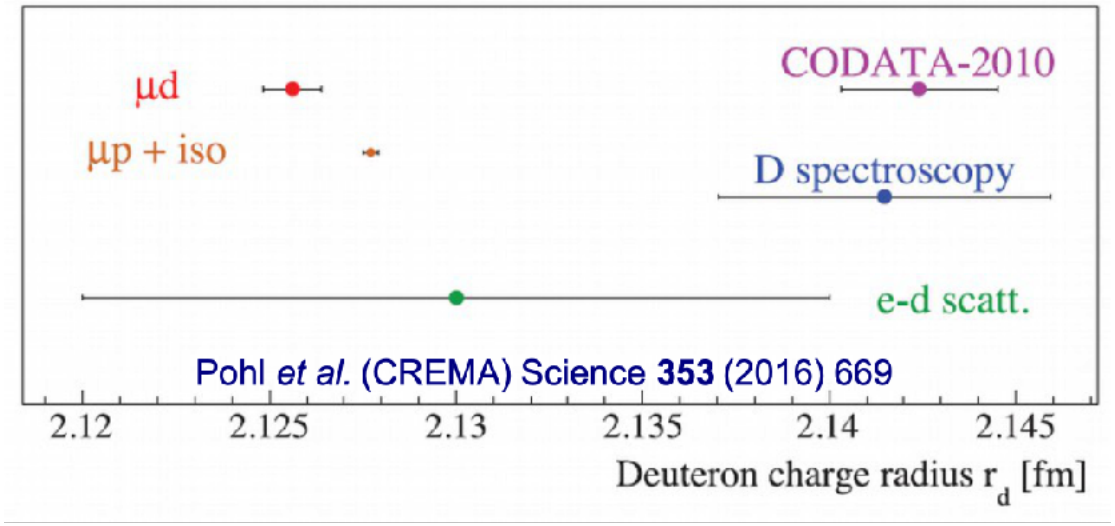
Today's Review Schedule

- Overview: Ron Gilman
- Simulation: Steffen Strauch
- Analysis I: Win Lin
- Coffee Break
- Analysis II: Ethan Cline
- Hardware and 2023 Plans: Paul Reimer

Backup

The Proton Radius Puzzle and MUSE Physics

Subsequently: shown to be a Z = 1 problem



- Muonic deuterium agrees with muonic hydrogen, ed scattering
- (not shown) Muonic 4He agrees with electronic helium: Krauth *et al.*, Nature **589**, 527 (2021)