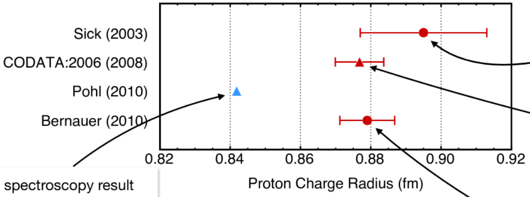
STATUS OF THE MUSE EXPERIMENT

Dr. Tigran Armand Rostomyan

PREN-2022
June 20 – 23, 2022
Paris, France

The Proton Radius Puzzle (2010)

Muonic and **electronic** measurements give **different** proton charge radii



Analysis of world electron-scattering data

Analysis of hydrogen spectroscopy data Committee on Data for Science and Technology (CODATA)

r_p = 0.8768(69) fm

Analysis of MAMI electron-scattering experiment

Muonic-hydrogen spectroscopy result

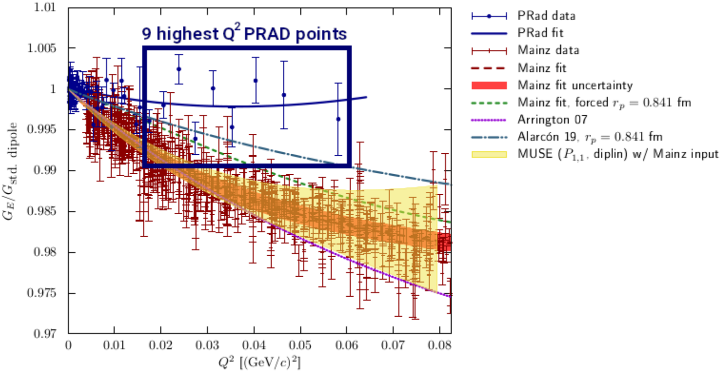
Ten times more precise, but 4% smaller than previously accepted value

r_p = 0.84184(67) fm

In 2010, the discrepancy between muonic and electronic measurements of the proton charge radius was a 5σ effect and grew to a 7σ effect in 2013.
Newer electronic measurements tend to show a smaller radius.
Today some tension between experiments persists...

I. Sick, PLB 576, 62 (2003); P.J. Mohr et al., Rev. Mod. Phys. 80, 633 (2008); J.C Bernauer et al., PRL 105, 242001 (2010); R. Pohl et al., Nature 466, 213 (2010)

DISAGREEMENT OF DIFFERENT DATA



According to *Domínguez, Alarcón and Weiss* dispersion + effective field theory calculations (**radius** is treated as a **free parameter**): these **1,5%** disagreement between **PRAD** and **Mainz** form factor values leads to **3,0%** discrepancy in cross-sections, and those to ∼**0,04 fm** divergence in extraction of the radius.

MUSE COLLABORATION

∼63 MUSE collaborators from 24 institutions in 5 countries:

A. Afanasev[a], A. Akmal[b], J. Arrington[c], H. Atac[d], C. Ayerbe-Gayoso[e], F. Benmokhtar[f], N. Benmouna[b], N. Bern[b], J.C. Bernauer[g], E. Brash[h], W.J. Briscoe[a], T. Cao[i], D. Ciofi[a], E. Cline[j], D. Cohn[k], E.O. Cohen[l], C. Collicott[a], K. Deiters[m], J. Diefenbach[n], B. Dongwi[i], E.J. Downie[a], L. El Fassi[o], S. Gilad[g], R. Gilman [j], K. Gnanvo[p], R. Gothe[q], D. Higinbotham[r], Y. Ilieva[q], M. Jones[r], N. Kalantarians[i], M. Kohl[i], B. Krusche[s], G. Kumbartzki [j], I. Lavrukhin[a], L. Li[q], J. Lichtenstadt[l], W. Lin [j], A. Liyanage[i], N. Liyanage[p], W. Lorenzon[t], Z.-E. Meziani[d], P. Monaghan[h], K.E. Mesick[u], P. Mohan Murthy[g], J. Nazeer[i], T. O'Connor[c], C. Perdrisat[e], E. Piasetzsky[l], R. Ransome [j], R. Raymond[t], D. Reggiani[m], P.E. Reimer[c], A. Richter[v], G. Ron[k], T. Rostomyan [j], A. Sarty[w], Y. Shamai[l], N. Sparveris[d], S. Strauch[q], V. Sulkosky[p], A.S. Tadepalli [j], M. Taragin[x], and L. Weinstein[o]

- Funded by 5 Agencies

- Technical Design Report: arXiv:1709.09753 [physics.ins-det]

[a]George Washington University, [b]Montgomery College, [c]Argonne National Lab, [d]Temple University, [e]College of William & Mary, [f]Duquesne University, [g]Massachusetts Institute of Technology, [h]Christopher Newport University, [i]Hampton University, [j]Rutgers University, [k]Hebrew University of Jerusalem, [l]Tel Aviv University, [m]Paul Scherrer Institut, [n]Johannes Gutenberg-Universität, [o]Old Dominion University, [p]University of Virginia, [q]University of South Carolina, [r]Jefferson Lab, [s]University of Basel, [t]University of Michigan, [u]Los Alamos National Laboratory, [v]Technical University of Darmstadt, [w]St. Mary's University, [x]Weizmann Institute (Oct. 2016)

Paul Scherrer Institut, Villigen, Switzerland

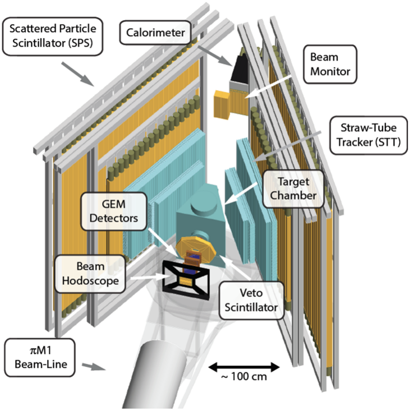
- Proton accelerator HIPA: World's most powerful 590 MeV Proton beam (2.2 mA, 1.3 MW beam, 50.6 MHz RF frequency [20 ns bunch separation])
- $\pi M1$:
  1. $e^{\pm}, \mu^{\pm}, \pi^{\pm}$ in Secondary beam-lines
  2. Flux to be used: 3.3 – 3.5 MHz
  3. Particle species are separated by timing relative to beam RF

MUon Scattering Experiment MUSE

Direct comparison of ep and μp scatterings at sub-percent level precision at 3 different beam momenta: 115 MeV/c, 153 MeV/c, 210 MeV/c in $\pi M1$ area at PSI:

1. Higher (similar) precision for muons (electrons) than previously
2. Low Q^2 kinematics for sensitivity to the **proton charge radius**
3. **Simultaneous** cross-section measurements for $e^{\pm}p$ and $\mu^{\pm}p$ elastic scattering reactions
4. Independent and combined determination of charge form factor and Proton Charge Radius in $e^{\pm}p$ and $\mu^{\pm}p$ elastic scatterings tests lepton universality
5. With μ^+, μ^- and e^+, e^- $\rightarrow$ study **Two-Photon Exchange** (TPE) mechanisms
6. Tests of initial-state radiative corrections

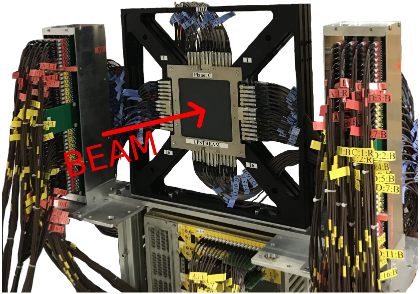
Detector Setup

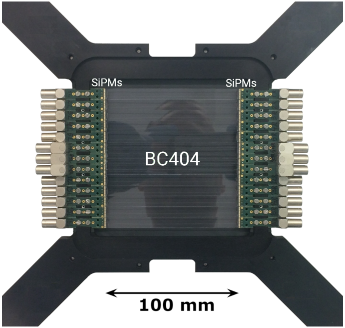


- **Liquid hydrogen** target
- **TIMING:** Beam-Hodoscope (BH), Scattered Particle Scintillators (SPS) and Beam Monitor (BM)
  1. **PID** for Beam-particle ID
  2. **TOF** for scattered (BH→SPS) reaction type
  3. **TOF** for unscattered (BH→BM) particles for **Beam Momentum** determination
- **TRACKING:** GEMs + Straw-Tube Tracker (STT) to determine scattering angle
- Calorimeter for **Radiative corrections**

Beam Hodoscope (BH) Planes

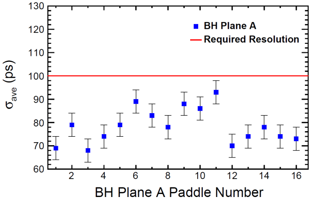
- 5 BH-Planes built: 16 (13) paddles per plane
- 2 (3) mm thick x 4&8 mm wide x 100 mm long **BC404** + Hamamatsu **S13360-3075PE**
- **BH** counts the total incident beam **flux** and provides precise **timing** and **position** information for beam particles

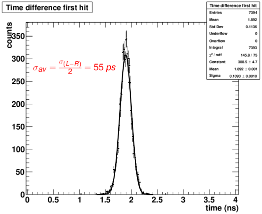


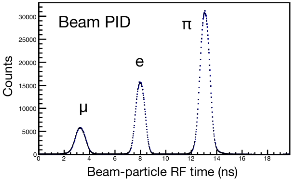


BH Planes: results

- For all paddles: $\sigma_T < 100ps$ (**Best:** $\sigma_T = 55ps$); $\epsilon \geq 99.9\%$
- **RF** time to **BH** $\rightarrow$ beam-particle ID





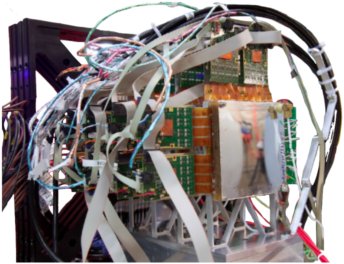


Exceed requirements!

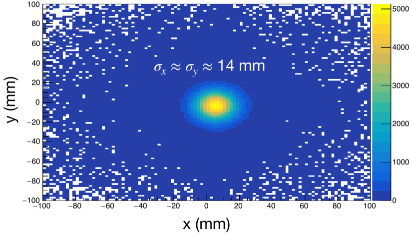
GEM as incident-particle tracker

- Set of 3x 10cm x 10cm **GEM** detectors (from OLYMPUS) measure trajectories into the target to reconstruct the scattering kinematics
- Gas mixture: Ar:CO2 70:30

- Successful operation of DAQ with MPD v4 digitizer modules
- 70 μm (100 μm) spatial resolution
- $\epsilon = 97 - 99\%$ (98.0%)



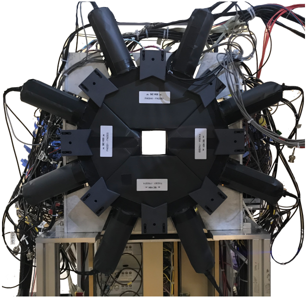
Projected beam-particle distribution at the target (p = 210 MeV/c)

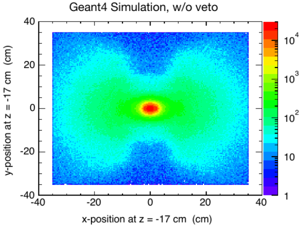


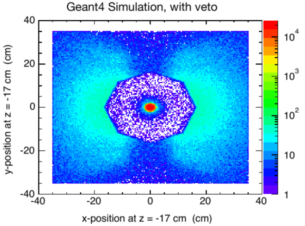
Meets requirements!

VETO DETECTOR

- Annular 8-element **VETO** detector, surrounding target entrance window
- Eliminates upstream scattering and beam decays, reduces trigger rate from background events by $\sim$ 25%
- $\sigma_T \leq$ 200 ps (1 ns); $\epsilon >$ 99.0%

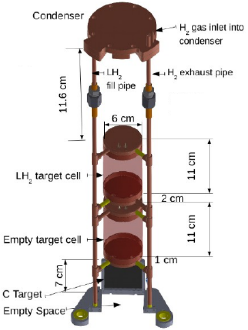


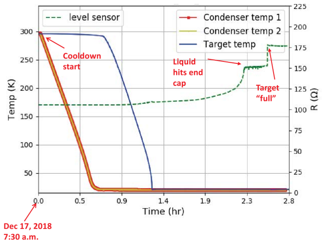


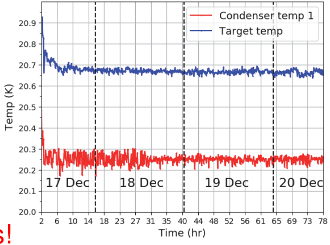


Meets requirements!

Liquid Hydrogen Target





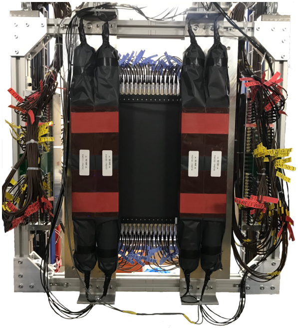


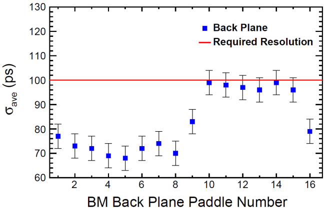
- 280 ml LH2 target
- Target T = 20.67 K, stable at σ_T = 0.01 K level
- **Density = 0.070 g/cm^3**, stable at 0.02% level
- Safety review passed (PSI; Aug.2018)

Meets requirements!

Beam Monitor (BM)

- 3 mm x 12 mm x 300 mm **BC404** + **S13360-3075PE**
- 6 mm shifted 2 planes: 16 paddles per plane (all $\sigma_T < 100ps$; $\epsilon \geq 99.9\%$) + 4 front scintillator bars ($\sigma_T \approx 30ps$)
- **BM** determines particle flux downstream of the target
- **BM** monitors beam **stability**





Meets requirements!

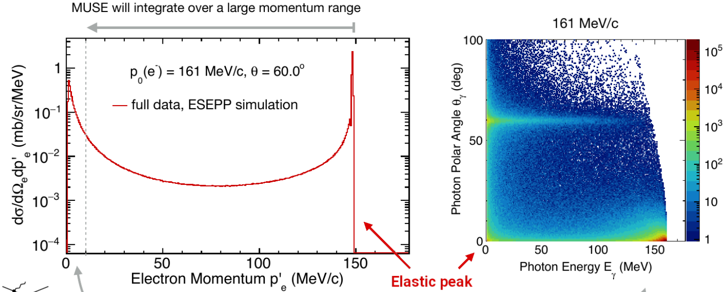
- **RF time** to **BM** → independent beam-particle ID
- Acts as Veto for **Møller** / **Bhabha scattering background**
- **TOF BH** to **BM** → Muon and Pion beam momenta

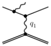
Radiative Corrections

Radiative Corrections are significant for *e*'s.

Greatest sensitivity is to pre-radiation. **Photon** flies **forward.**

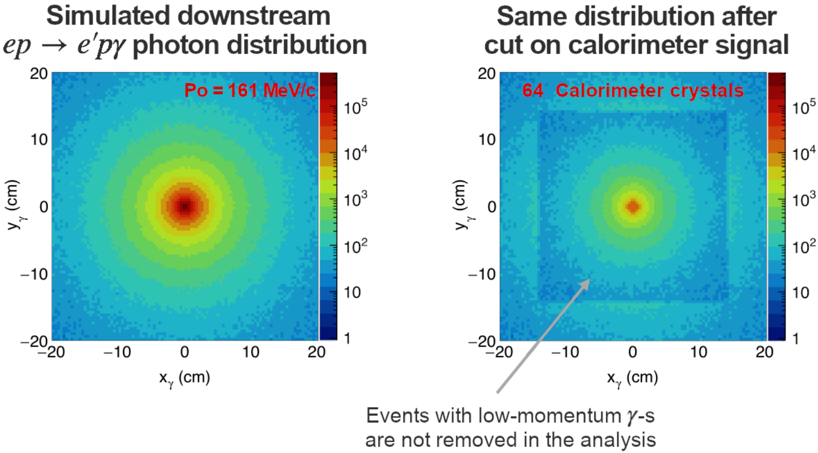
$ep \rightarrow e'p\gamma$ Cross section in MUSE kinematics





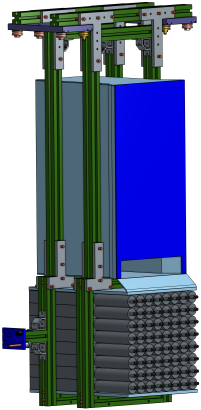
If the incident lepton loses energy due to the emission of a hard photon, then the probability for this lepton to be scattered by the proton increases.

Improvements using Calorimeter



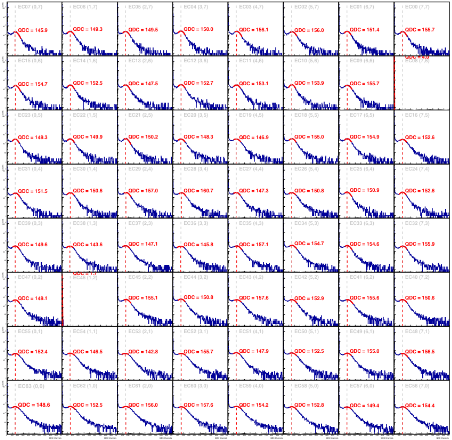
MUSE forward-angle Calorimeter

- **64x** (4 cm x 4 cm x 30 cm) **Lead-Glass** crystals
- Removes events with high-energy γ in beam direction

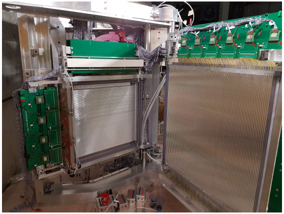


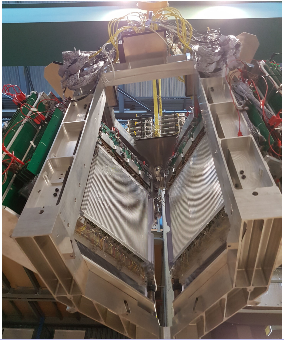
Calorimeter Calibration

- Found **2** crystals with lose **PMT**s. Replaced!
- All **64** crystals are gain matched
- Took Energy scan data for **Energy calibration** (To be analyzed)



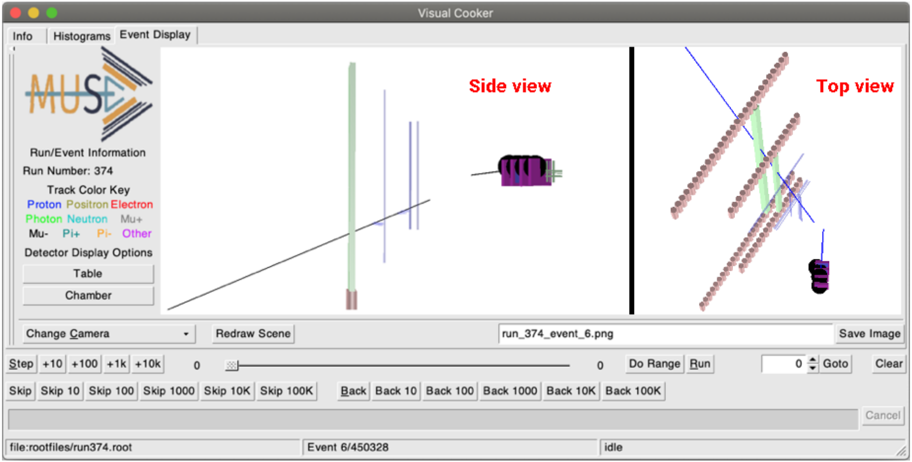
Straw Tube Tracker (STT)





- **STT** provides high-resolution and high-efficiency tracking of the scattered from the target particles
- Based on PANDA STT-design
- 2 chambers, 5 planes each in **x and y**
- In total **2850** Straws
- Readout $\rightarrow$ PASTTREC/TRB3
- STT all planes are ready, wire mapping in process
- Gas manifold improvement in progress

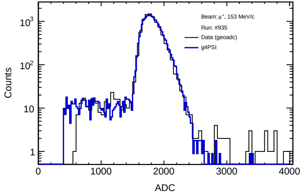
TRACKING


Visual Cooker
Info
Histograms
Event Display
Run/Event Information
Run Number: 374
Track Color Key
Proton Positron Electron
Photon Neutron Mu+
Mu- Pi+ Pi- Other
Detector Display Options
Table
Chamber
Side view
Top view
Change Camera
Redraw Scene
run_374_event_6.png
Save Image
Step +10 +100 +1k +10k
0
0
Do Range Run
0 Goto
Clear
Skip Skip 10 Skip 100 Skip 1000 Skip 10K Skip 100K
Back Back 10 Back 100 Back 1000 Back 10K Back 100K
Cancel
file:rootfiles/run374.root
Event 6/450328
idle

Scattered Particle Scintillator (SPS)

- Based on Jefferson Lab CLAS12 FTOF12 system
- 2 walls on each side of beam. 92 bars, double-ended readout
- Determines **Energy** and **Time** of the scattered off the target particles
- **Muon Decays** in flight can be removed with **TOF** (BH$\rightarrow$SPS)

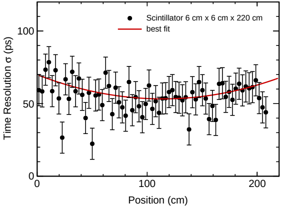
Front wall: 18 bars
(**6cm x 3cm x 120cm**)
Rear wall: 28 bars
(**6cm x 6cm x 220cm**)



Peak: particles going through the bar

Low energy tail: particles going out the side of the bar

- For all particles: 2-wall coincidence $\epsilon \geq 98\%$

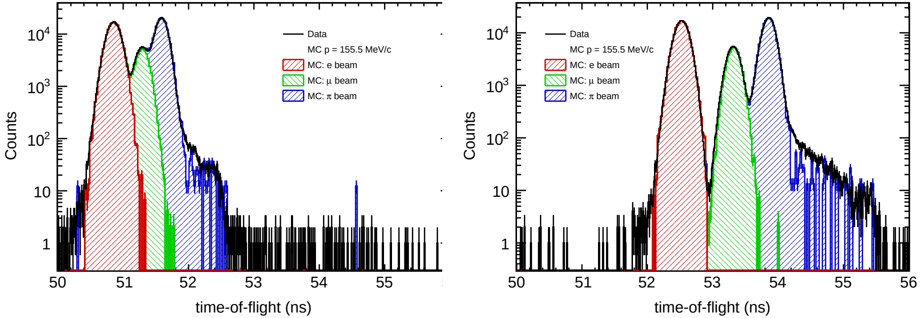


- **220 cm** BC404 bars: $\sigma_{av.} = 52ps \pm 4ps$
- **120 cm** BC404 bars: $\sigma_{av.} = 46ps \pm 4ps$

Meets requirements!

TOF

2 TOF measurements (1 BH-Plane → SPS) with **50 cm** difference in detector spacing, compared to Geant4 (Horizontal scale has arbitrary offset)



Preliminary data analysis determine $p_\pi(p_\mu)$ to 0.2%(0.3%)

Meets requirements!

p_e

E. Cline *et al.*, **Physical Review C 105 (2022) 055201**
Characterization of μ and *e* beams in the PSI PiM1 channel:

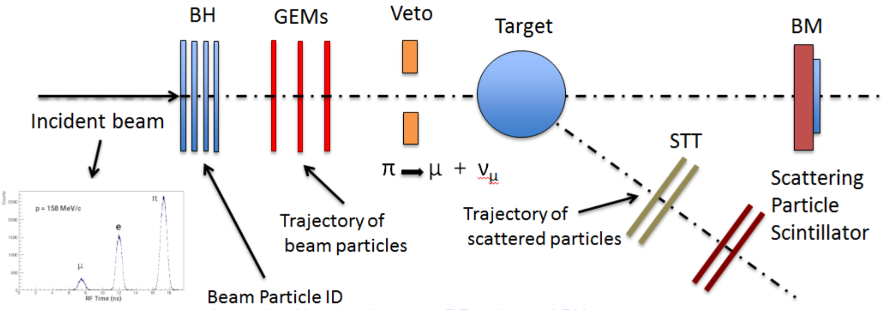
- Average momentum of particles passing through the channel agrees with the central set momentum to within **0.03%**
- The positions of the different particle species were observed to be consistent at roughly **2 mm** level, indicating their momenta are consistent to within approximately **0.02%**
- RF time measurements of particles propagating through the channel showed approximately **0.1%** agreement with the set momentum
- Muon and electron beams have quite similar properties to the pion beam and to each other: knowing p_π or p_μ means we know p_e quite precisely

SUMMARY OF DETECTORS

Detector	$\sigma_T(ps)$ / $\sigma_S(\mu m)$	ϵ (%)	Material Thickness
1 BH Plane	$\sim$ 70 ps	$>$ 99.5	2 mm BC404
2-4 BH Planes	50 – 35 ps	$>$ 99.5	4 – 8 mm BC404
GEMs	70 μm	$\approx$ 98	0.5% Radiation Length
VETO	$\approx$ 200 ps	$>$ 99	4 mm BC404
BM	59 ps	$\approx$ 99.9	3 mm BC404
STT	120 μm	$\approx$ 99	30 μm mylar
SPS	55	$>$ 99	3 – 6 cm BC404

While some improvements, testing remains, data shows that
all requirements are met!!!

MUSE TRIGGER



determined by time between RF-pulse and BH

Trigger Logic: TRB3 FPGA-based:

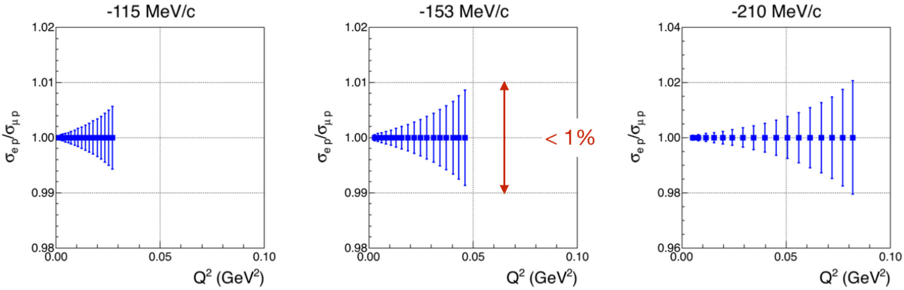
accept $e^{\pm}$, $\mu^{\pm}$, reject $\pi^{\pm}$

(e OR μ) AND (no π) AND (scatter) AND (no veto)

PID is the Hardest Part

MUSE DIRECT COMPARISON OF $\mu + p$ AND $e + p$

Projected relative statistical uncertainties in the ratio of μp to ep elastic **cross sections**.
Systematics $\approx$ 0.5%.

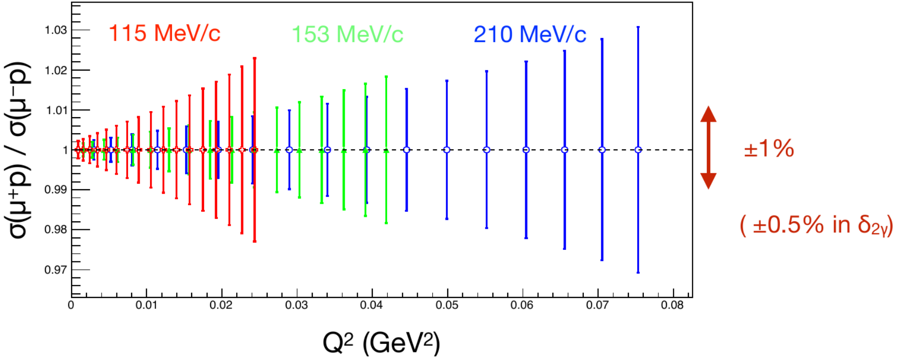


The relative statistical uncertainties in the **form factors** are half as large.

The MUon Scattering Experiment at PSI (MUSE), MUSE technical Design Report, arXiv:1709.09753 [physics.ins-det]

MUSE DIRECT COMPARISON OF $\mu^+ + p$ AND $\mu^- + p$

Projected relative statistical uncertainties in the ratio of $\mu^+ p$ to $\mu^- p$ elastic **cross sections**.
Systematics $\approx$ 0.2%.



The MUon Scattering Experiment at PSI (MUSE), MUSE technical Design Report, arXiv:1709.09753 [physics.ins-det]

Outlook

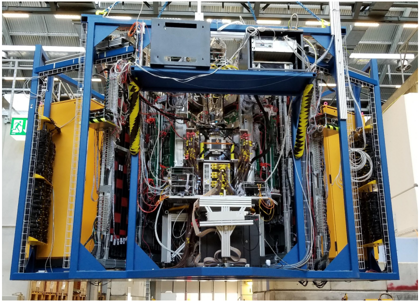
MUSE suited to verify 5.6σ effect (CODATA 2014) with even higher significance:

- Uncertainties mostly well controlled: largest from **angle** and **radiative** corrections. Many uncertainties are common to all extractions in the experiment and cancel in $(e^+ + p)/(e^- + p)$, $(\mu^+ + p)/(\mu^- + p)$ and $(e + p)/(\mu + p)$ comparisons
- Compare e^+p to e^-p and μ^+p to μ^-p elastic cross sections for **TPE**. Charge ratio to determine **TPE** to 0.2 %
- Directly compare μ, e cross-sections, form factors and extract the radii.
- Each of the 4 sets of data will allow the extraction of the **proton charge radius**. Individual radius extractions from $e^\pm p$, $\mu^\pm p$ each to 0.01 fm
- From $(e + p)/(\mu + p)$ cross-section **ratios**: extract $R_e - R_\mu$ radius difference with minimal truncation error to 0.005 fm
  $R_e - R_\mu = 0.034 \pm 0.006$ fm (5.6σ), **MUSE**: $\delta_r = 0.005$ fm ($\sim 7\sigma$)
- If no difference, extract **Proton radius** to 0.007 fm (2nd-order fit)

MUSE activities

- 2011: Ron Gilman & Michael Kohl came up with an idea
- 2012-2017: MUSE experiment was built up
- 2018-2022: Completing technical upgrades and fine-tunings
- 2020-2022: Got delayed due to **COVID-19**
- 2021: Obtained **first** high statistics scattering data set at $\pm$115 MeV/c.
- 2022: Implementing alignment data to Analysis and Simulation
- 2022-2024: Production data taking: 6 months / year
- 2024-2025: Data Analysis and Publications.

THANK YOU FOR YOUR ATTENTION!



MUSE will be the **first** muon scattering measurement with the required precision to address the Proton Radius Puzzle!

MUSE publications:

- P. Roy *et al.*, **NIM A 949 (2020) 162874**
- T. Rostomyan *et al.*, **NIM A 986 (2021) 164801**
- E. Cline *et al.*, **Physical Review C 105 (2022) 055201**