THE MUSE EXPERIMENT

Dr. Tigran Armand Rostomyan

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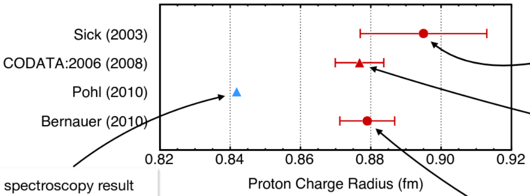
The Proton Radius Puzzle (2010)

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

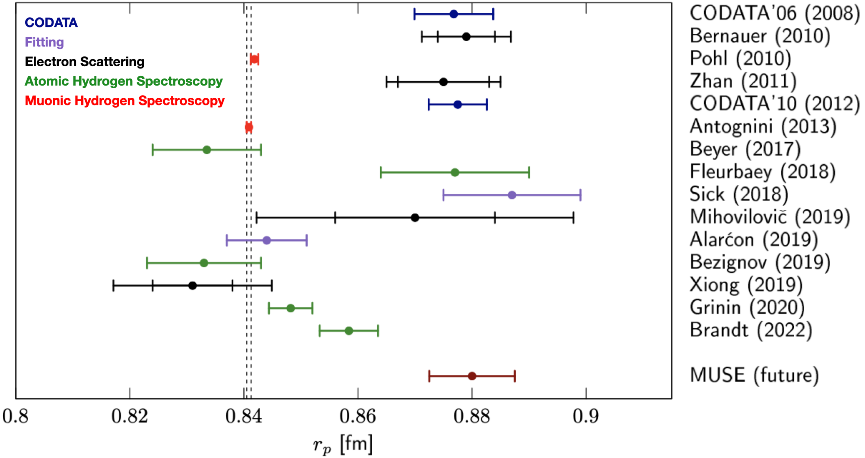
Ten times more precise, but 4% smaller than previously accepted value

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.

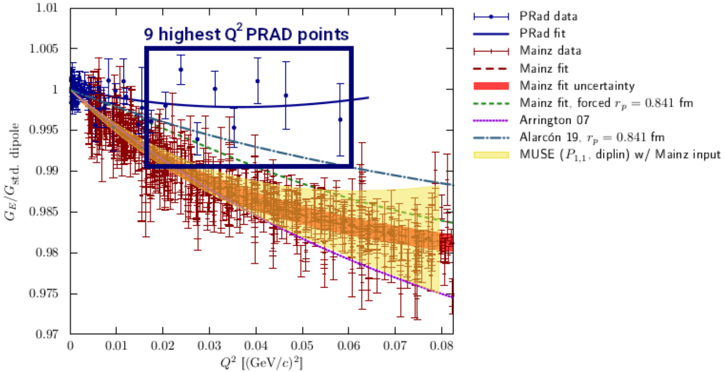
I. Sick, PLB 576, 62 (2003); P.J. Mohr et al., Rev. Mod. Phys. 80, 633 (2008); J.C Bernauer et al., PRL 105, 242001 (2010); R. Pohl et al., Nature 466, 213 (2010)

Recent Situation



Newer electronic measurements tend to show a smaller radius
Today some tension between experiments persists...

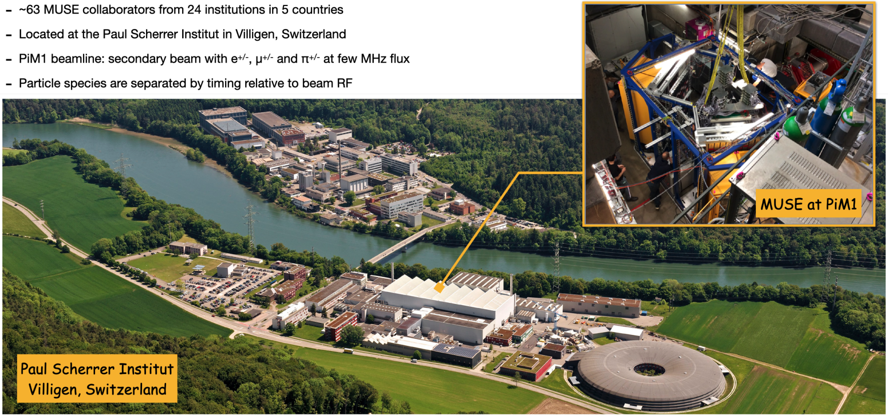
DISAGREEMENT OF DIFFERENT DATA



1,5% disagreement between **PRAD** highest Q^2 and **Mainz** form factor values leads to **3,0%** discrepancy in cross-sections. According to *Domínguez, Alarcón and Weiss* dispersion + effective field theory calculations (**radius** is treated as a **free parameter**): these discrepancy leads to ∼**0,04 fm** divergence in extraction of the radius.

The MUon proton Scattering Experiment

- ~63 MUSE collaborators from 24 institutions in 5 countries
- Located at the Paul Scherrer Institut in Villigen, Switzerland
- PiM1 beamline: secondary beam with $e^{+/-}$, $\mu^{+/-}$ and $\pi^{+/-}$ at few MHz flux
- Particle species are separated by timing relative to beam RF



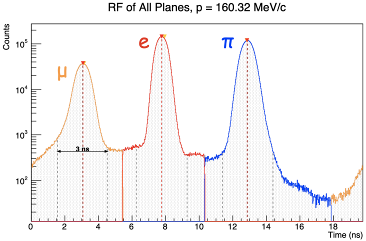
MUon Scattering Experiment MUSE

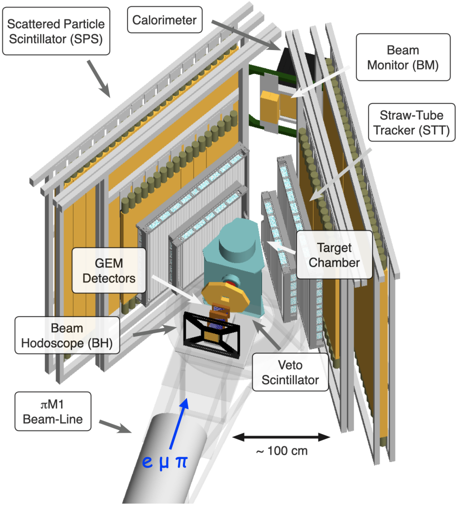
Direct comparison of ep and μp scatterings at sub-percent level precision at 3 different beam momenta: 115 MeV/c, 160 MeV/c, 210 MeV/c in $\pi M1$ area at PSI:

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

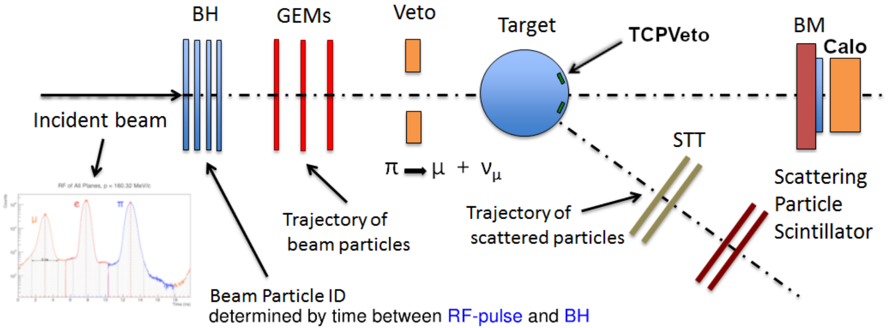
Detector Setup

Quantity	Coverage
Beam momenta	115, 160, 210 MeV/c
Scattering angle	20 - 100 degrees
Q^2 range for e	0.0016 - 0.0820 GeV^2/c^4
Q^2 range for μ	0.0016 - 0.0799 GeV^2/c^4





MUSE Trigger



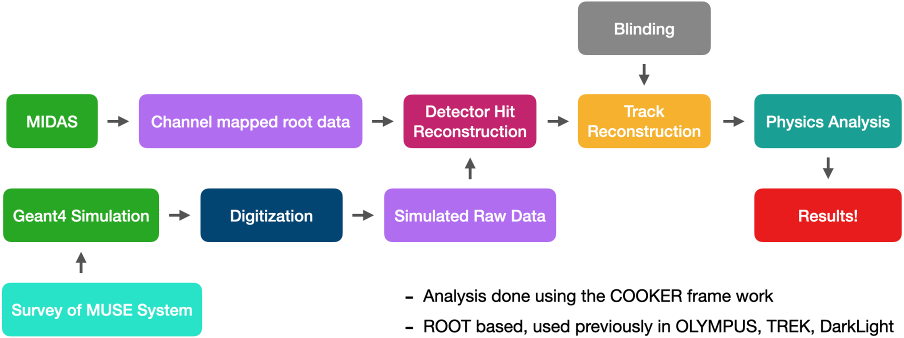
Trigger Logic: TRB3 FPGA-based:

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

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

PID is the Hardest Part

Analysis Trajectory



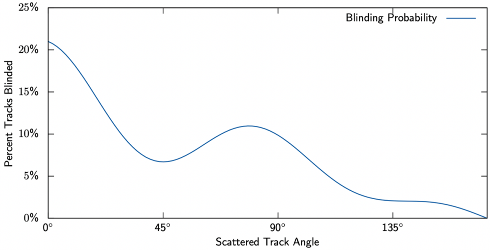
- Analysis done using the COOKER frame work
- ROOT based, used previously in OLYMPUS, TREK, DarkLight
- Decompose analyses into individual modules
  - Low-level: Typically one per detector
  - Mid-level: Tracking, TOF, blinding etc.
  - High-level: Physics analysis

Data Blinding

- Fraction of scattered tracks at each angle are stored and hidden for blinding data
- Whether or not a track is blinded is calculated by:

$$P = s \times \frac{3-\theta}{3}, \text{ where } s = 0.2(A + 0.3cos(B \times \theta)), \text{ and } A = 0.25 \rightarrow 1, B = 0.25 \rightarrow 1$$

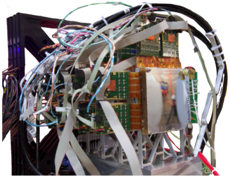
- If $P \geq R$, where R is a uniformly distributed random number between 0 and 1, then the track is blinded
- Can blind up to 25% of tracks at any given angle



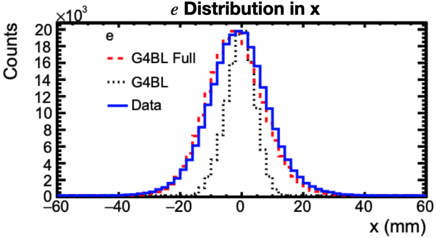
Chance of blinding a track for A = 0.75 and B = 4.2 as a function of STT angle.

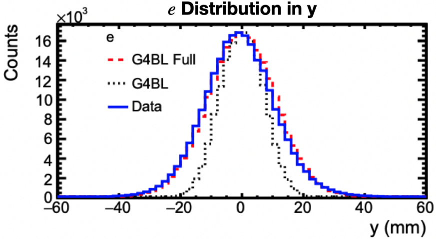
GEM AS INCIDENT-PARTICLE TRACKER

- Incoming beam is tracked by the GEM detectors
- Tracking using “GenFit”; Require hits in at least 2 out of 3 GEM planes
- Particle distribution of the PiM1 beam is well understood



Comparison of G4beamline simulations and data at the MUSE target

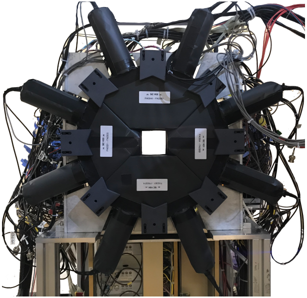


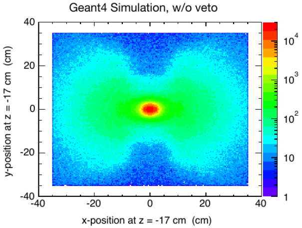


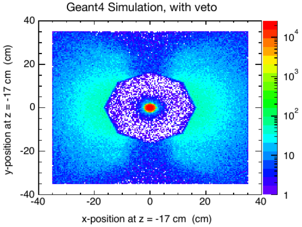
E. Cline *et. al.*, Phys. Rev. C 105, 055201

VETO DETECTOR

- Annular 4-element, with double PMT read-out, **VETO** detector, surrounding target entrance window
- Eliminates upstream scattering and beam decays, reduces trigger rate from background events by $\sim$ 30%
- $\sigma_T \leq$ 200 ps (1 ns); $\epsilon > 99.0\%$

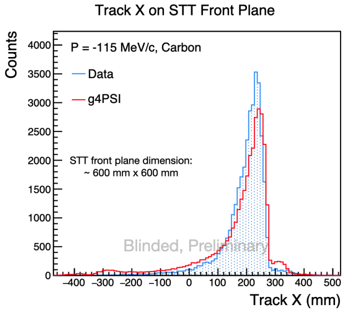


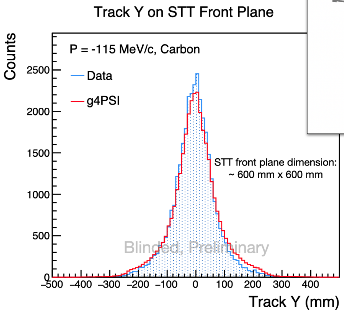


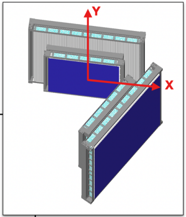


STT Tracking

- STT, based on PANDA STT-design, **2 chambers**, **5 planes** each in **x and y**; in total **2850** Straws
- Tracking using "GenFit"; Require hits in at least 3 x-planes and at least 3 y-planes on the same side
- Good agreement between data and simulation for the track position on STT
- Beam is expected to center at about Y = 0 and positive X





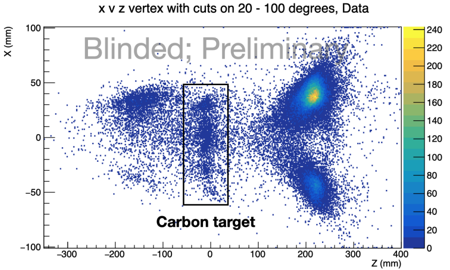


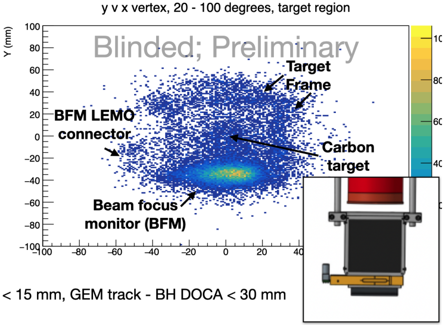
* In STT local coordinates

Vertex Reconstruction: Carbon

- Shown is an example of carbon target reconstruction for p = -115 MeV/c

Carbon Target, -115 MeV/c

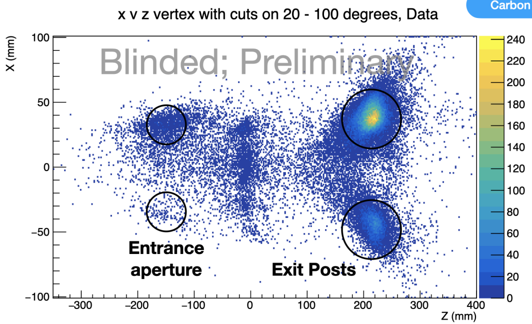


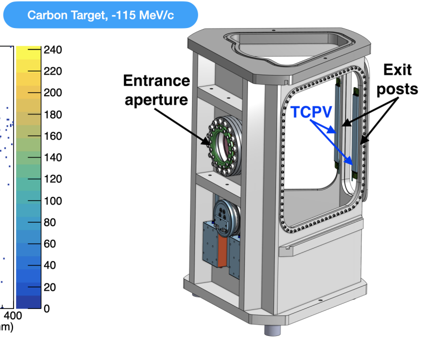


* cuts: electron events, vertex DOCA < 10 mm, STT track - SPS DOCA < 15 mm, GEM track - BH DOCA < 30 mm

Vertex Reconstruction: Carbon

- Shown is an example of carbon target reconstruction for p = -115 MeV/c
- In circles: beam tracks hitting circular window aperture and exiting tracks hitting the chamber exit posts
- TCPV detector built to online veto tracks hitting target chamber exit posts





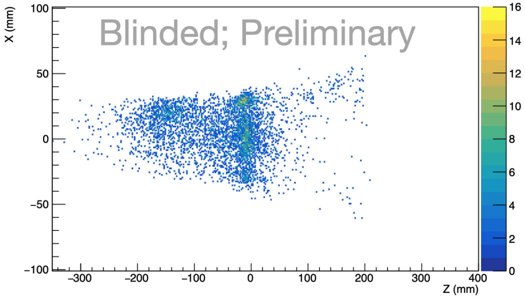
* cuts: electron events, vertex DOCA < 10 mm, STT track - SPS DOCA < 15 mm, GEM track - BH DOCA < 30 mm

Vertex Reconstruction: Carbon

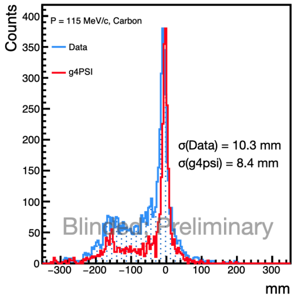
- Shown is an example of carbon target reconstruction for p = -115 MeV/c
- Cuts on beam tracks hitting circular window aperture and exiting tracks hitting chamber exit posts
- Preliminary simulation shows similar vertex distributions

Carbon Target, -115 MeV/c

x v z vertex with cuts on 20 - 100 degrees, Data



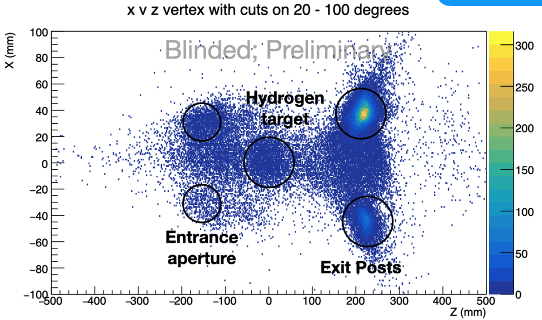
z vertex with cuts on 20 - 100 degrees

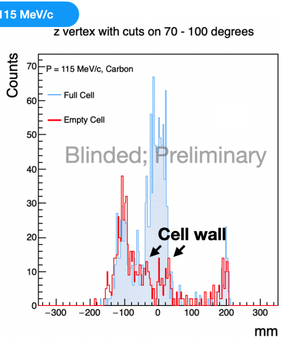


* cuts: electron events, vertex DOCA < 10 mm, STT track - SPS DOCA < 15 mm, GEM track - BH DOCA < 30 mm

Vertex Reconstruction: LH2

- Shown is an example of vertex reconstruction of LH2 target and empty cell data at 160 MeV/c
- After applying target chamber wall cuts and subtracting the empty cell events, LH2 target is cleanly separated



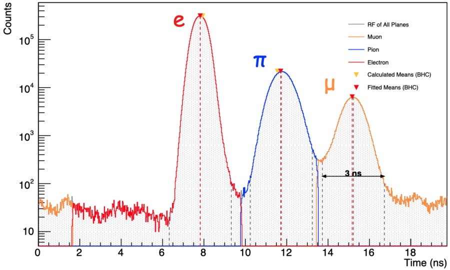


* cuts: electron events, vertex DOCA < 10 mm, STT track - SPS DOCA < 15 mm, GEM track - BH DOCA < 30 mm

Incoming Particle Identification

- RF time: time of particles in BH planes relative to accelerator 50.6 MHz RF signal

RF of All Planes, p = -115.29 MeV/c

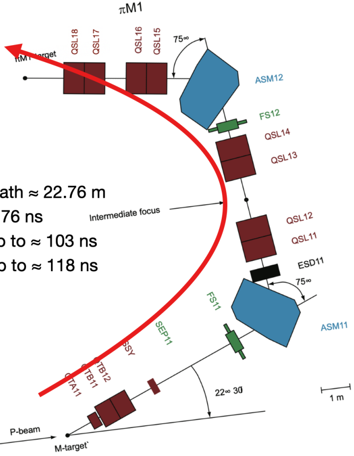


Flight path ≈ 22.76 m

TOF_e ≈ 76 ns

TOF_μ up to ≈ 103 ns

TOF_π up to ≈ 118 ns

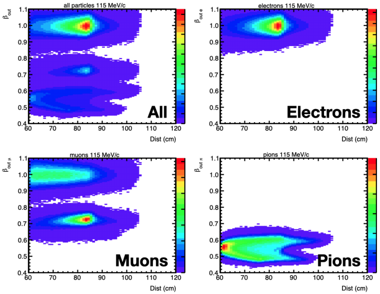


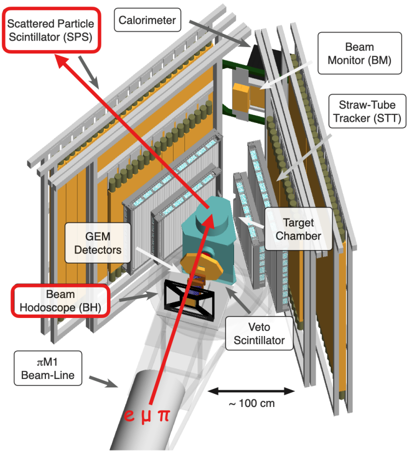
Proton beam RF 50.6 MHz → pulses every 19.75 ns

Reaction Identification

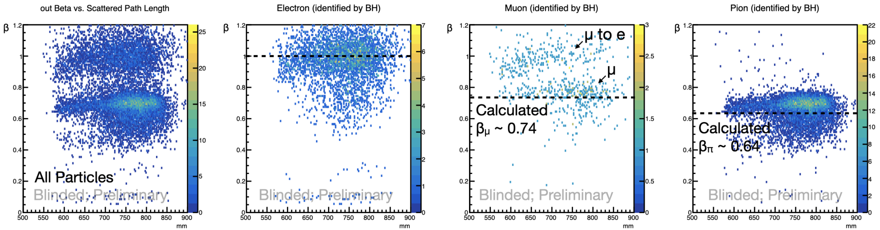
- Reaction is identified from the TOF (SPS - BH) and the path length between BH and SPS
- From the track reconstruction, we can get the path length
- Knowing the incoming particle momentum and the TOF, we can find $\beta_{incoming}$ and $\beta_{outgoing}$

Simulation of outgoing Beta vs Scattered Path Length



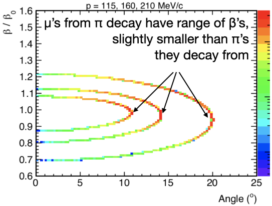


Reaction Identification



Carbon Target, -115 MeV/c

Momentum of μ from $\pi \rightarrow \mu + \nu_\mu$

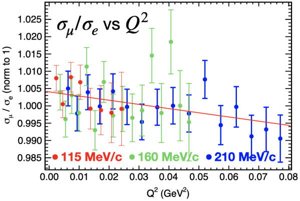


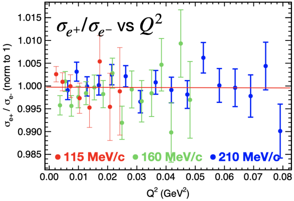
β_π and Most probable $\beta_{decay\ \mu}$

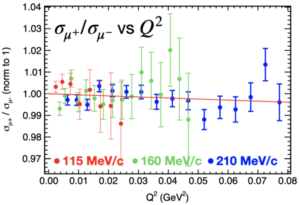
p	115 MeV/c	160 MeV/c	210 MeV/c
π	0,64	0,75	0,83
decay μ	0,60	0,72	0,82

- β_e is normalised to 1, β_μ is faster than calculated value and β_π is even faster
- Might be due to the time walk; dE\dx(π) > dE/dx(μ) > dE/dx(e)
- With better walk correction, we will be able to achieve 100 ps / 5 ns ~ 2% for β

MUSE Pseudo-data for Cross Section Ratios



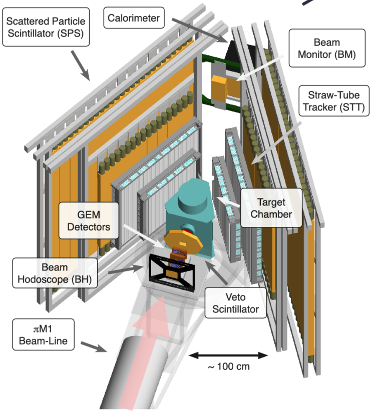




- Projected uncertainties of one full year of scattering data taking
- Estimated how we divided the time, with more time at the highest momentum
- Statistics is based on 2022 data set
- Estimated systematics from the current readout rate is included
- Take away message: on average we will be able to reach 1% uncertainties
- More work to be done

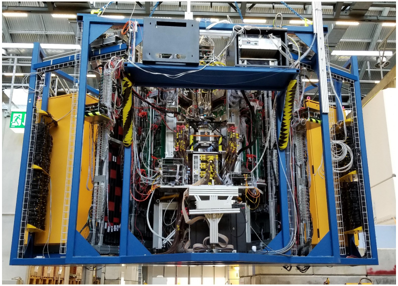
OUTLOOK

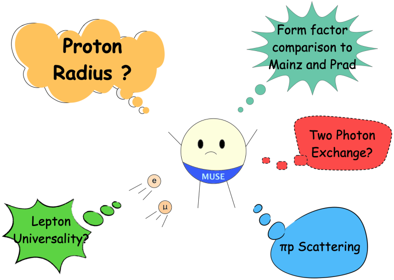
- **Proton form factor + radius + 2γ + lepton universality measurement at PSI with elastic scattering of $e^{\pm}$, $\mu^{\pm}$ from hydrogen**
- **Fall 2022: Scattering data**
  - **Took data in all experiment kinematics on H, C, empty cell**
  - **Second veto detector, inside the target chamber, used to reduce background**
- **Upgrades since Fall 2022**
  - **Progress in analysis, improving coding, debugging, geometry, noise suppression, corrections, tracking, reconstructed time and position resolutions**
- **2023: Successful review at BVR54**
  - **5 months beam time awarded and scheduled**
  - **Reviewed 2022 operations at spring 2023 collaboration meeting, for 2023 operation planning**
- **2024 and 2025: Similar beam times expected**



$e/\pi/\mu$ at p = 115-210 MeV/c

THANK YOU FOR YOUR ATTENTION!





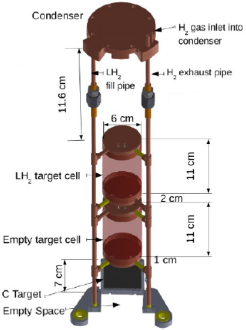
MUSE will be the **first** muon scattering measurement with the required precision to address the Proton Radius Puzzle!

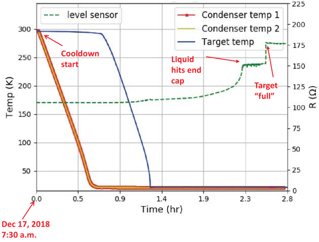
MUSE publications:

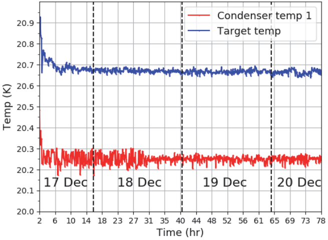
- P. Roy *et al.*, **NIM A 949 (2020) 162874**
- T. Rostomyan *et al.*, **NIM A 986 (2021) 164801**
- E. Cline *et al.*, **SciPost Phys. Proc. 5, 023 (2021)**
- E. Cline *et al.*, **Physical Review C 105 (2022) 055201**

Backup Slides

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)

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