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Determining the Proton's Size with MUSE

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U.S. DEPARTMENT of ENERGY

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Argonne NATIONAL LABORATORY

How to Measure the Proton's Charge Radius

What is $\langle r \rangle^2$

- What are we measuring?

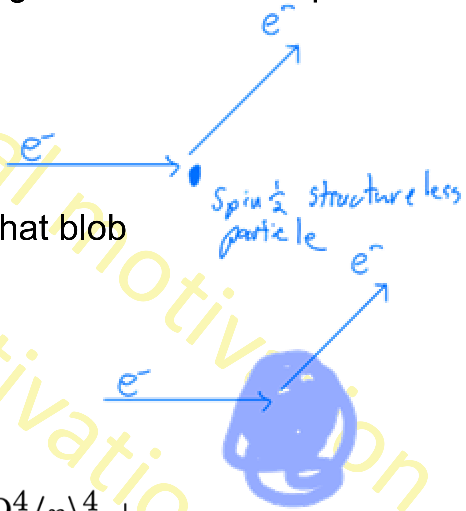
Define

$$\langle r \rangle^2 \equiv 6 \left.\frac{dG_E}{dQ^2}\right|_{Q^2=0}$$

Note this is a definition. See G. Miller *Phys.Rev.C* 99 (2019) 3, 035202

Classical motivation of definition

- Mott Cross Section: point scattering of structureless spin-½ particles
- But the proton is not structureless
- The structure functions represent that blob
- Cross section adding a form factor



$$G_E \overset{\text{classic}}{\approx} \int e^{iQr}\rho(r)d^3r$$

$$\overset{\text{classic}}{\approx} 1 - \frac{1}{3!}Q^2\langle r \rangle^2 + \frac{1}{5!}Q^4\langle r \rangle^4 + \cdots$$

$$\frac{\left.\frac{d\sigma}{d\Omega}\right|_{\text{lab}}}{\left.\frac{d\sigma}{d\Omega}\right|_{\text{Mott}}} \left(\frac{G_E^2 + \tau G_M^2}{1+\tau} \cos^2\frac{\theta}{2} + 2\tau G_M^2 \sin^2\frac{\theta}{2} \right)$$

How to Measure the Proton's Charge Radius

Elastic Scattering

- Measure the cross section at as low of Q^2 as possible and extrapolate the slope

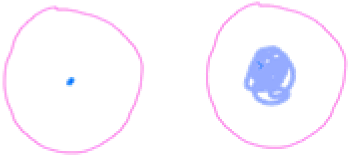
$$\frac{\left.\frac{d\sigma}{d\Omega}\right|_{\text{lab}}}{\left.\frac{d\sigma}{d\Omega}\right|_{\text{Mott}}} \left(\frac{G_E^2 + \tau G_M^2}{1+\tau} \cos^2\frac{\theta}{2} + 2\tau G_M^2 \sin^2\frac{\theta}{2} \right)$$

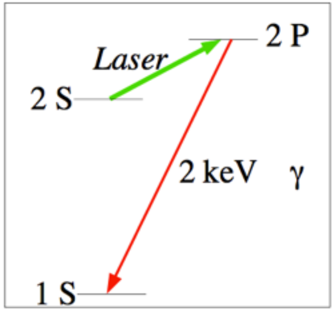
What probe?

- Electron or muon?

Atomic Spectroscopy

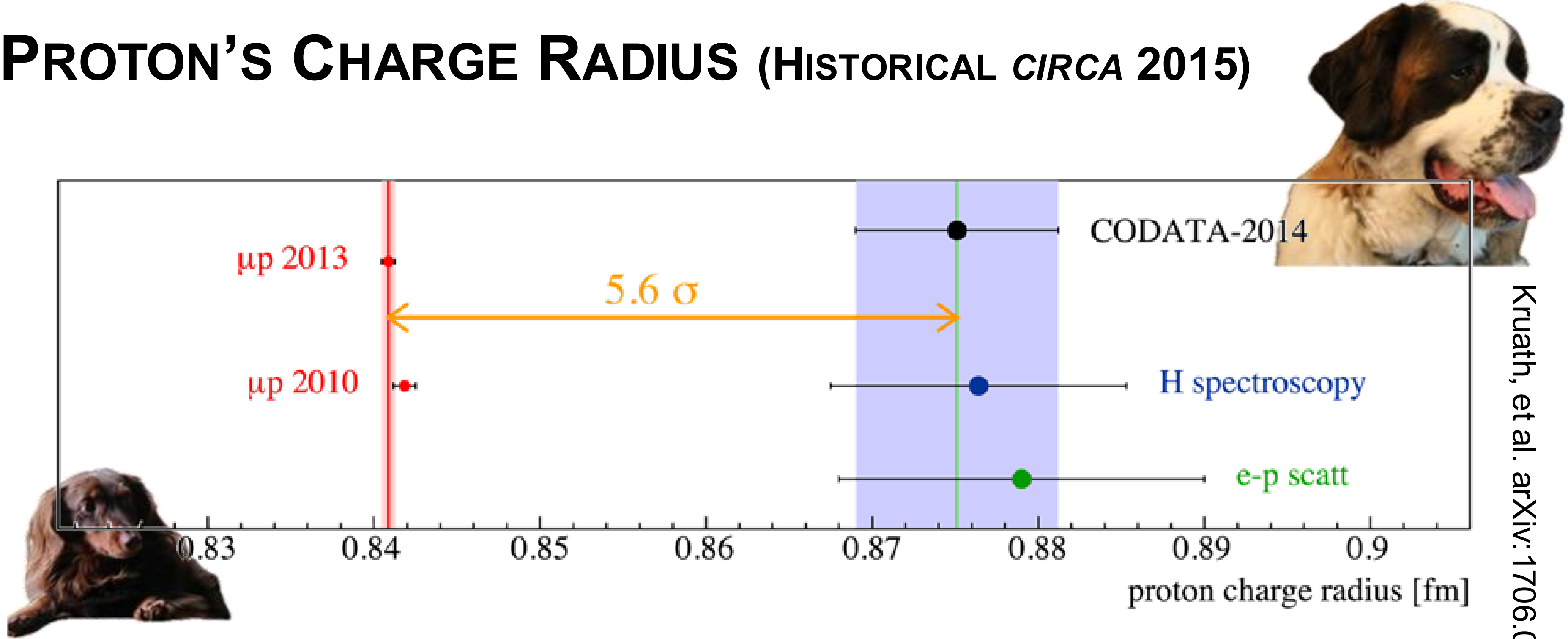
- Quantum Mechanics—solve the hydrogen atom.
- Coulomb field is distorted because the proton is not a point charge.
- This shifts atomic levels—Measure atomic levels.





Hydrogen atom?

PROTON'S CHARGE RADIUS (HISTORICAL *CIRCA* 2015)



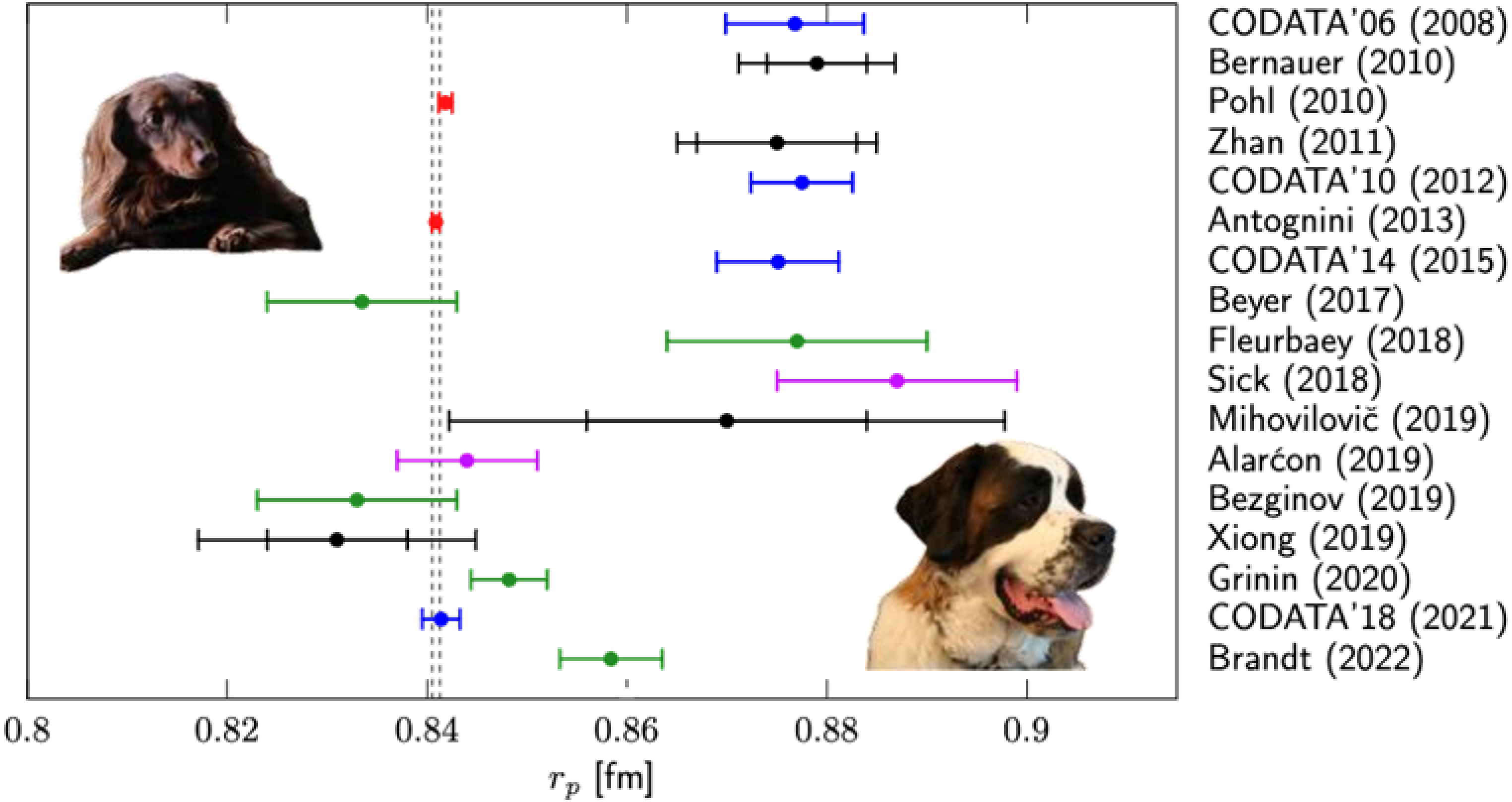
Kruath, et al. arXiv:1706.00696

The proton RMS charge radius measured with
Electrons: 0.8751 ± 0.0061 fm (CODATA2014)
Muons: 0.8409 ± 0.0004 fm

PROTON'S SIZE VS PROBE AND METHOD (2014)

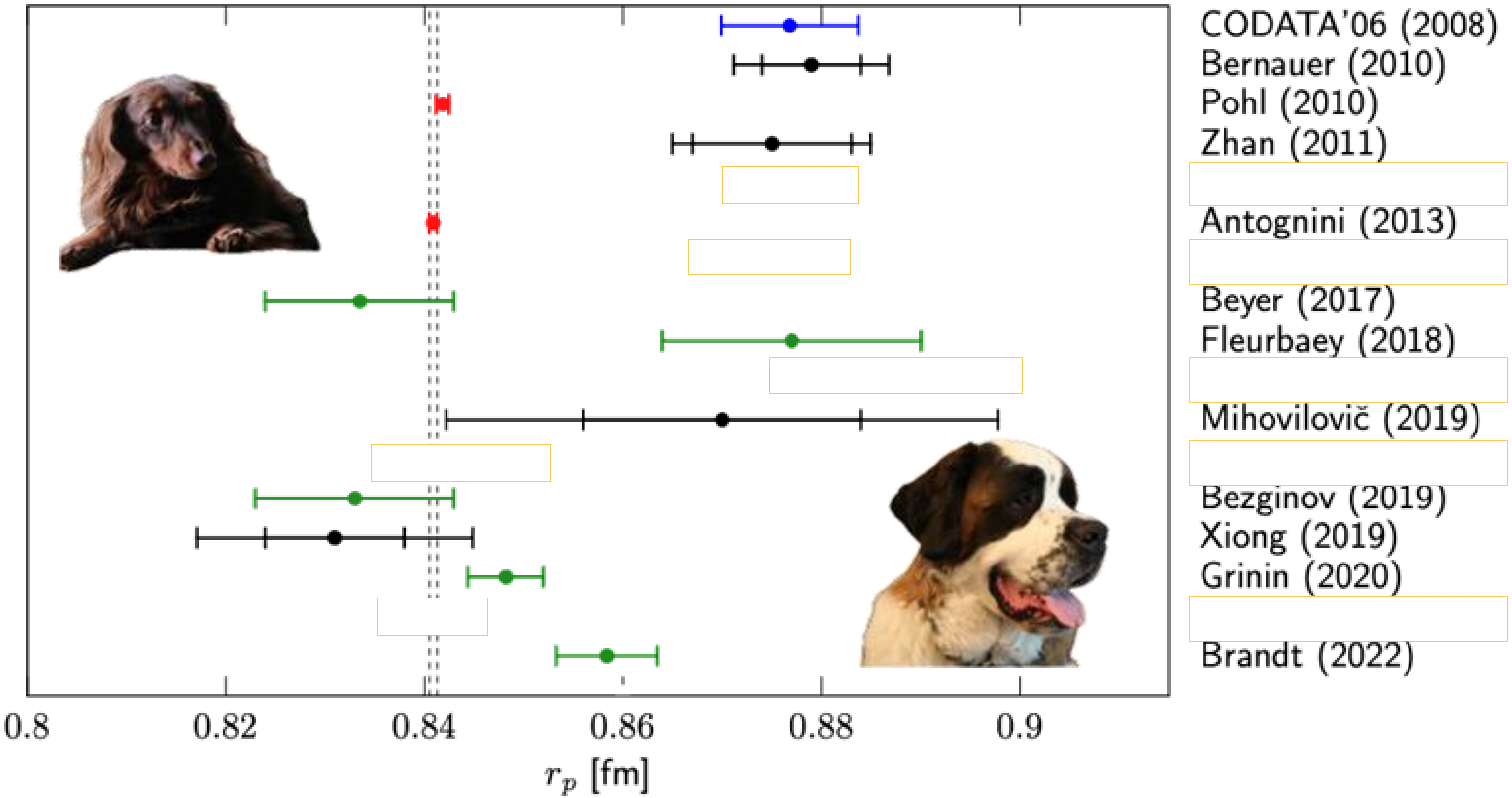
	Spectroscopy	Scattering
Electron	Large 0.876(8) 	Large 0.877(6) 
Muon	Small 0.8409(4) 	Unknown Ongoing measurements MUSE and Amber 

Measurements of the Proton's Charge Radius



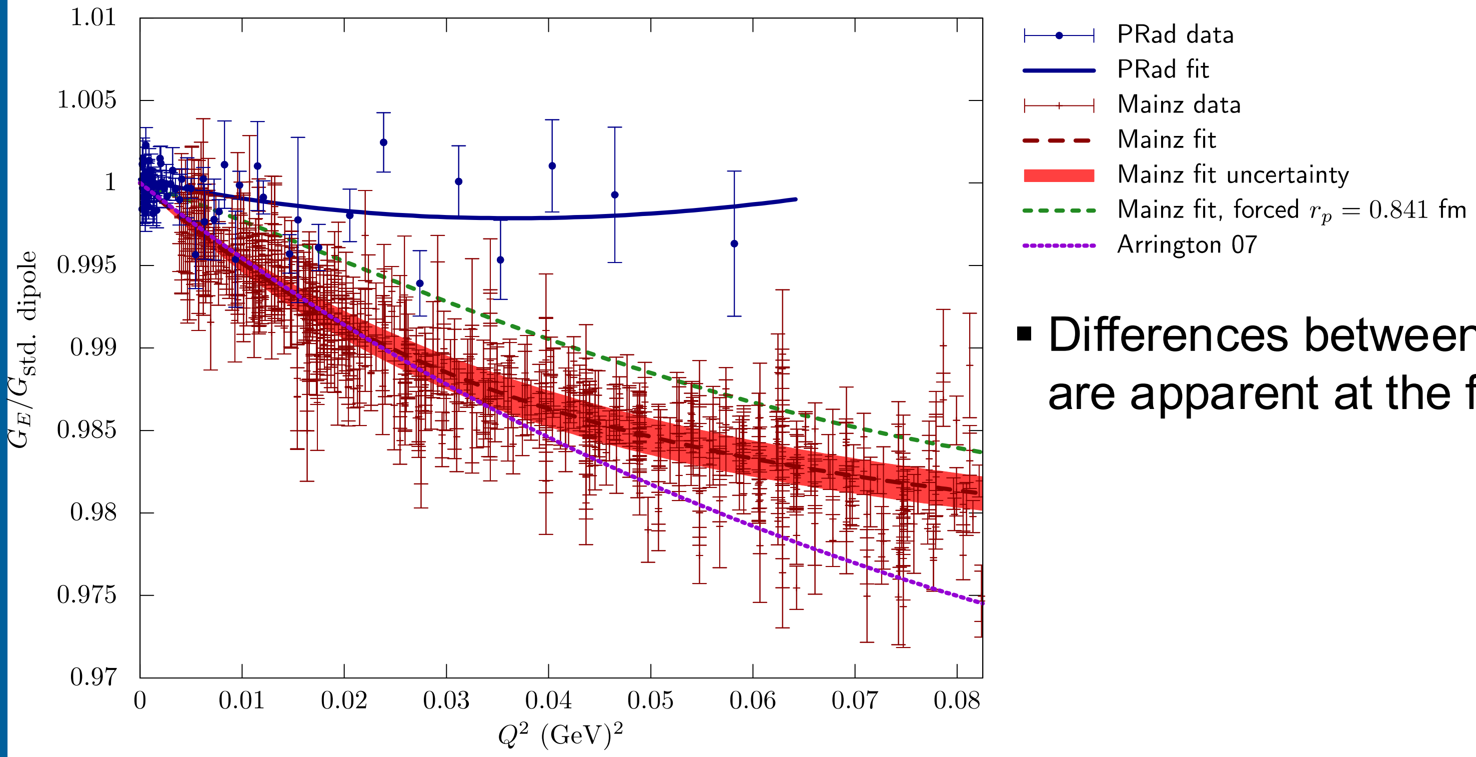
Muonic Hydrogen, Atomic Hydrogen, Electron Scattering, CODATA, Global Analyses

Measurements of the Proton's Charge Radius



Muonic Hydrogen, Atomic Hydrogen, Electron Scattering

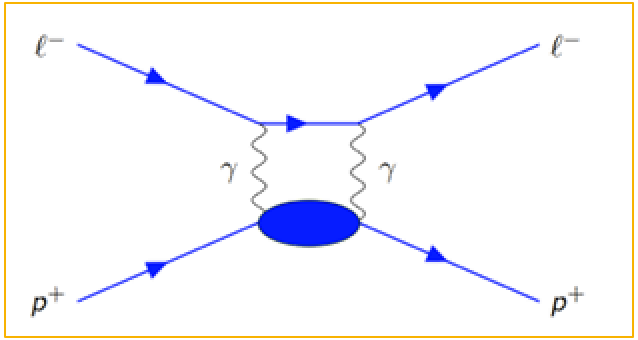
e-P Form Factor Data



- Differences between measurements are apparent at the form factor level.

Many Explanations Have Been Offered

- Proton structure issues in theory
  - Off-shell proton in *two-photon* exchange leading to enhanced effects differing between μ and e
  - Hadronic effects different for μp and ep: *e.g.* proton polarizability (effect ~m_l^4)



https://www.particlezoo.net/collections/leptons

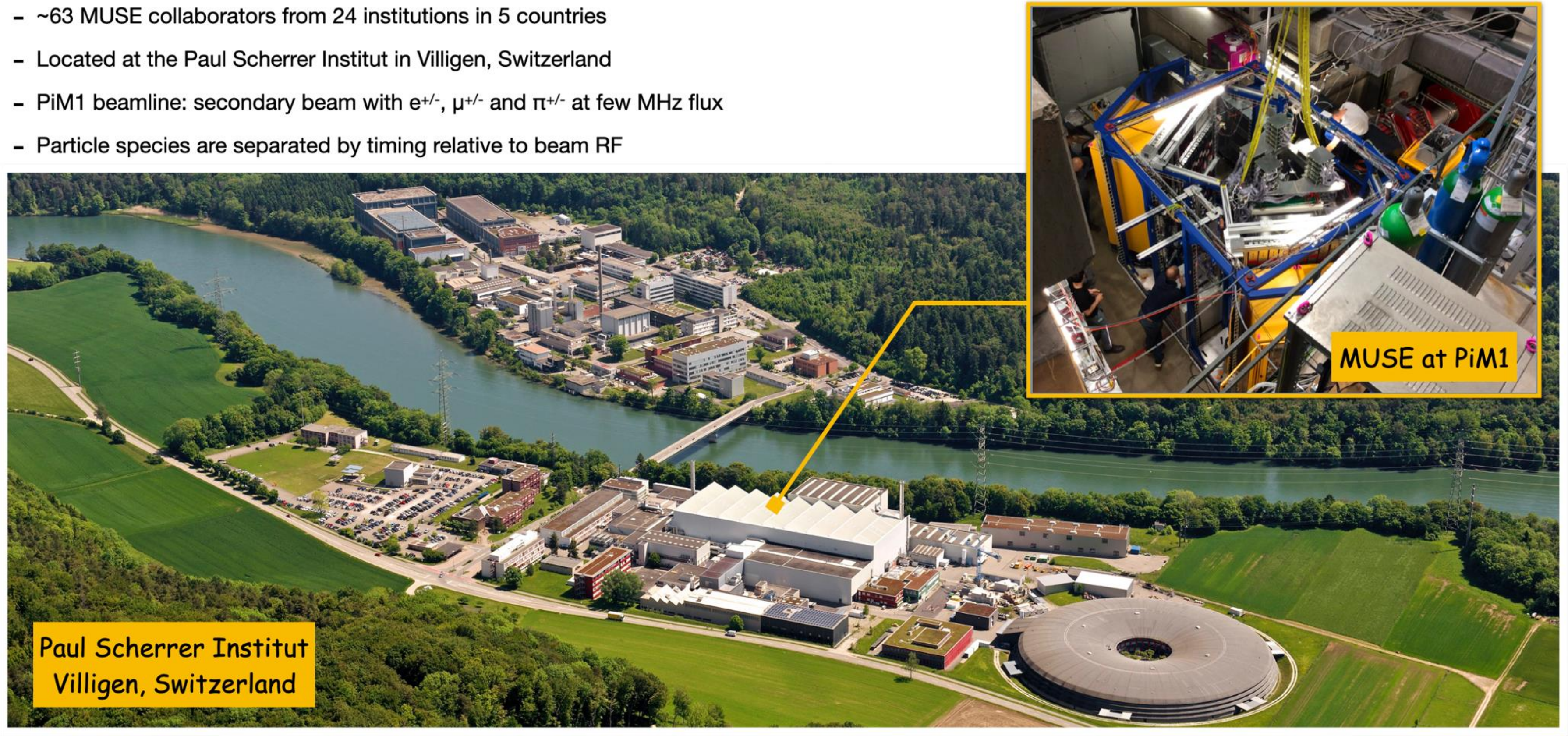
- Imaginative Physics (BSM) differentiating μ and e
  - Lepton universality violation, light massive gauge boson
  - Constraints on new physics *e.g.* from kaon decays (TREK@J-PARC)

5x comparative mass

https://www.particlezoo.net/collections/leptons

The MUon proton Scattering Experiment (MUSE)

- ~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



MUSE's Contribution to the Solution

- **Simultaneous** measurement of e^+p, μ^+p and of e^-p, μ^-p elastic scattering
- Sub-percent precision
- 3 overlapping beam momenta
- Low Q^2 kinematics

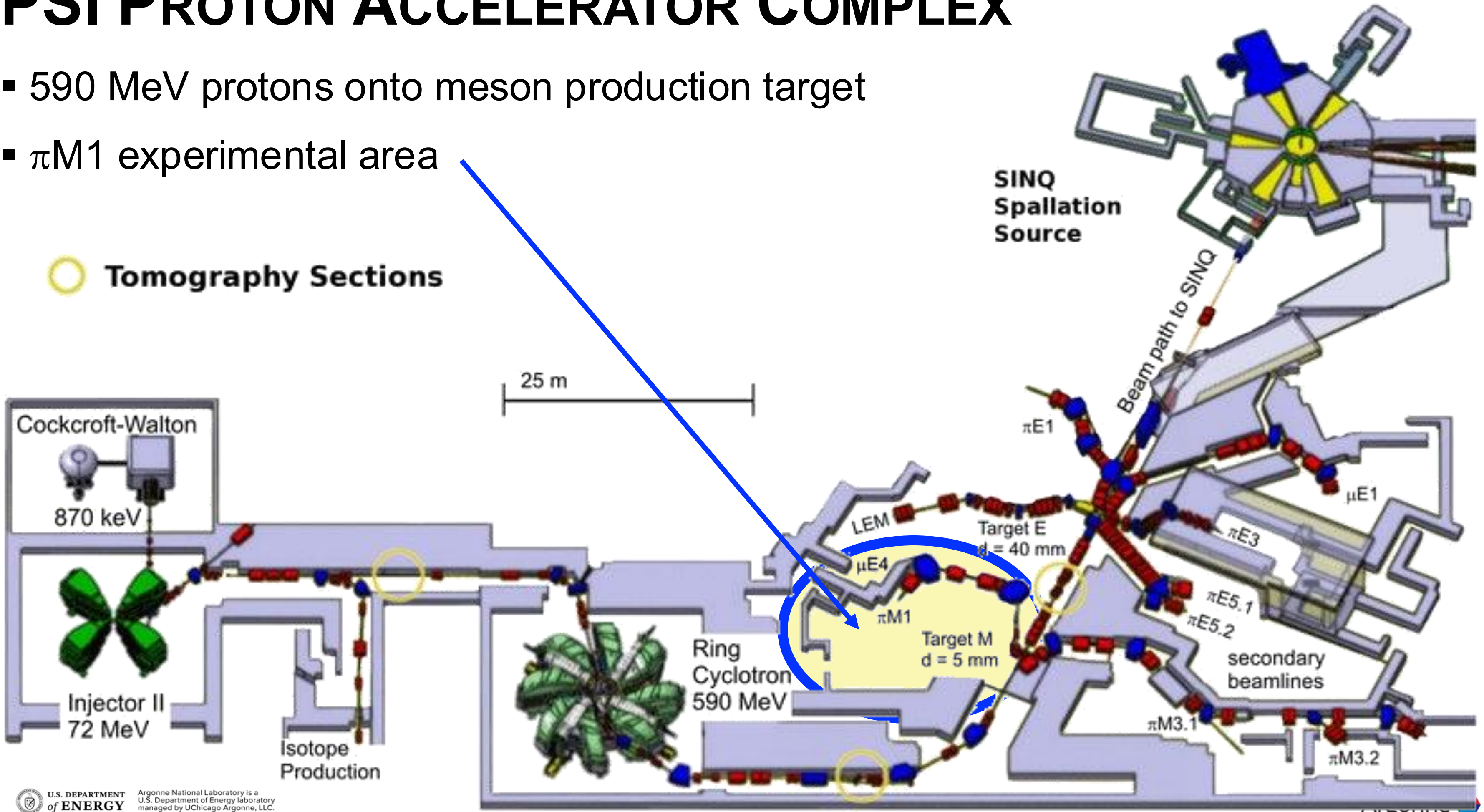
Quantity		Coverage
Beam Momenta		115, 160, 210 MeV/c
Scattering Angles		20-100°
Q^2 range	e	0.0016-0.0820 $(\mathrm{GeV}/c^2)^2$
	μ	0.0016-0.0799 $(\mathrm{GeV}/c^2)^2$

Goals

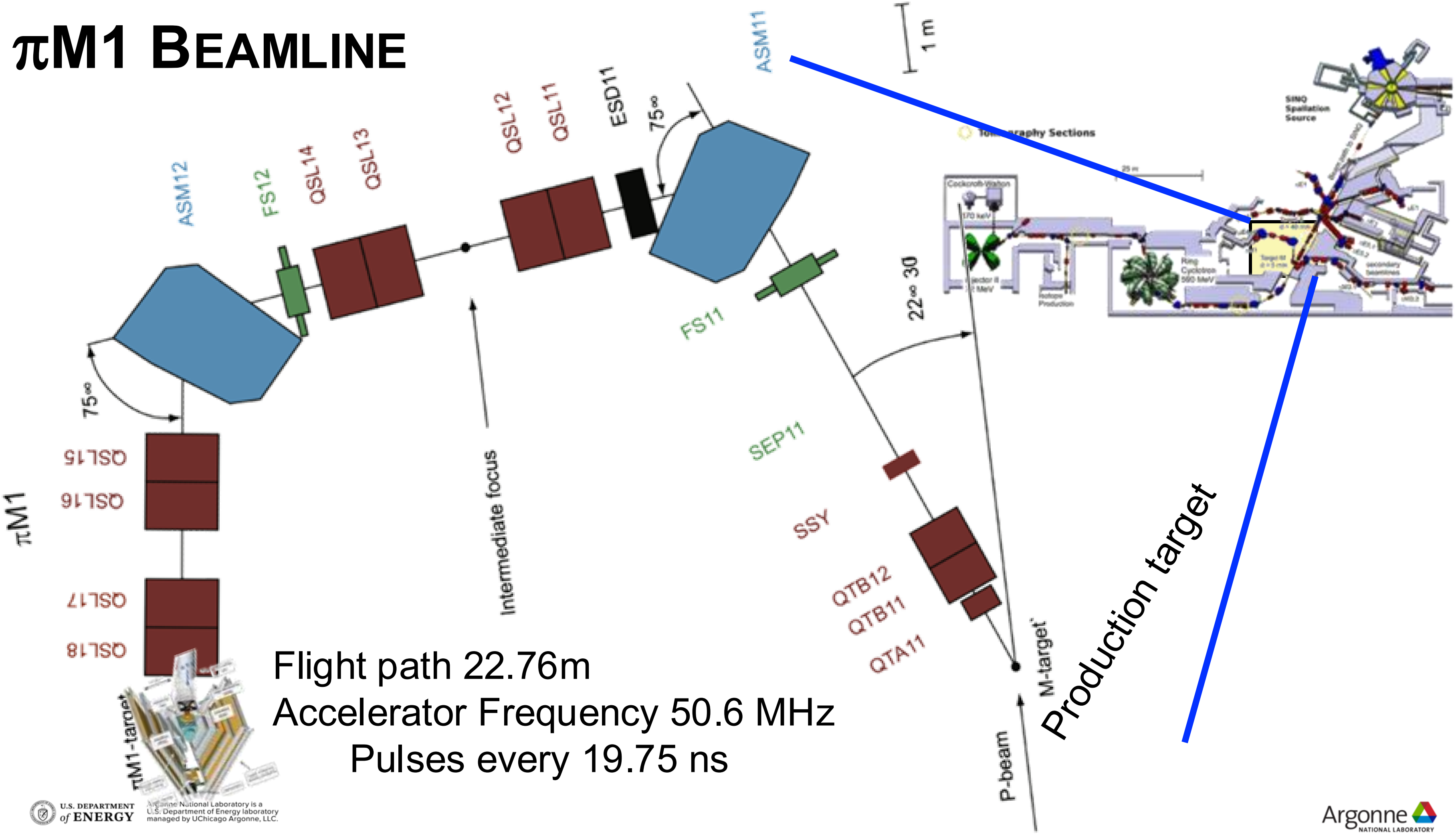
- Independent and combined determination of the charge form factor and Proton Charge Radius in $e^{\pm}p$ and $\mu^{\pm}p$ elastic scatterings
- μ^+, μ^- and e^+, e^- comparisons for Two-Photon Exchange (TPE) studies.

PSI PROTON ACCELERATOR COMPLEX

- 590 MeV protons onto meson production target
- πM1 experimental area



πM1 Beamline



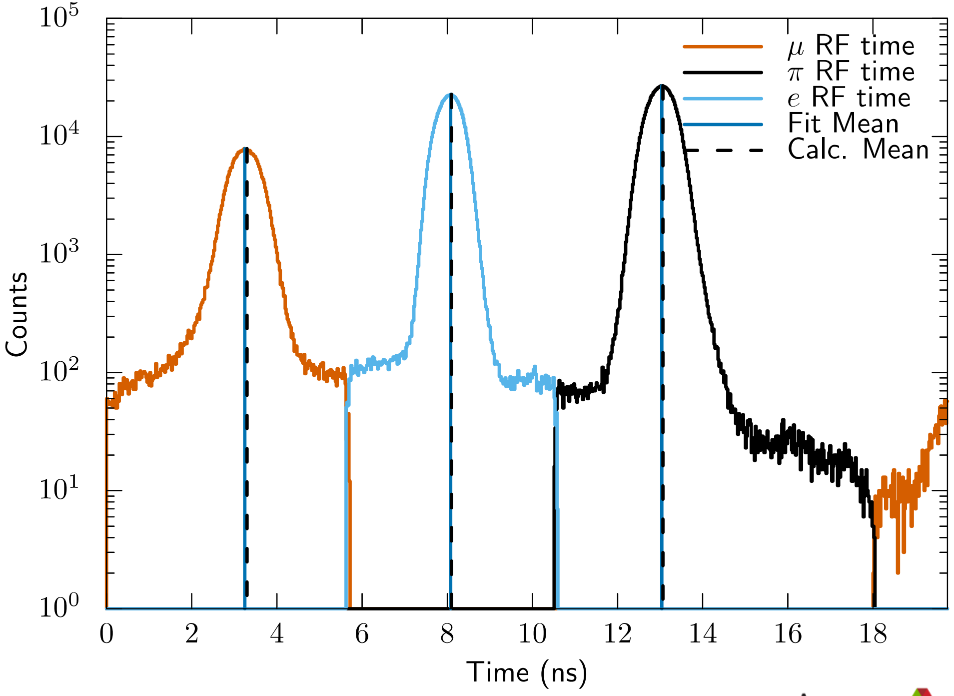
Flight path 22.76m
Accelerator Frequency 50.6 MHz
Pulses every 19.75 ns

BEAM PARTICLE IDENTIFICATION

- Flight path 22.76 m
- Accelerator Frequency 50.6 MHz
  - Pulses every 19.75 ns

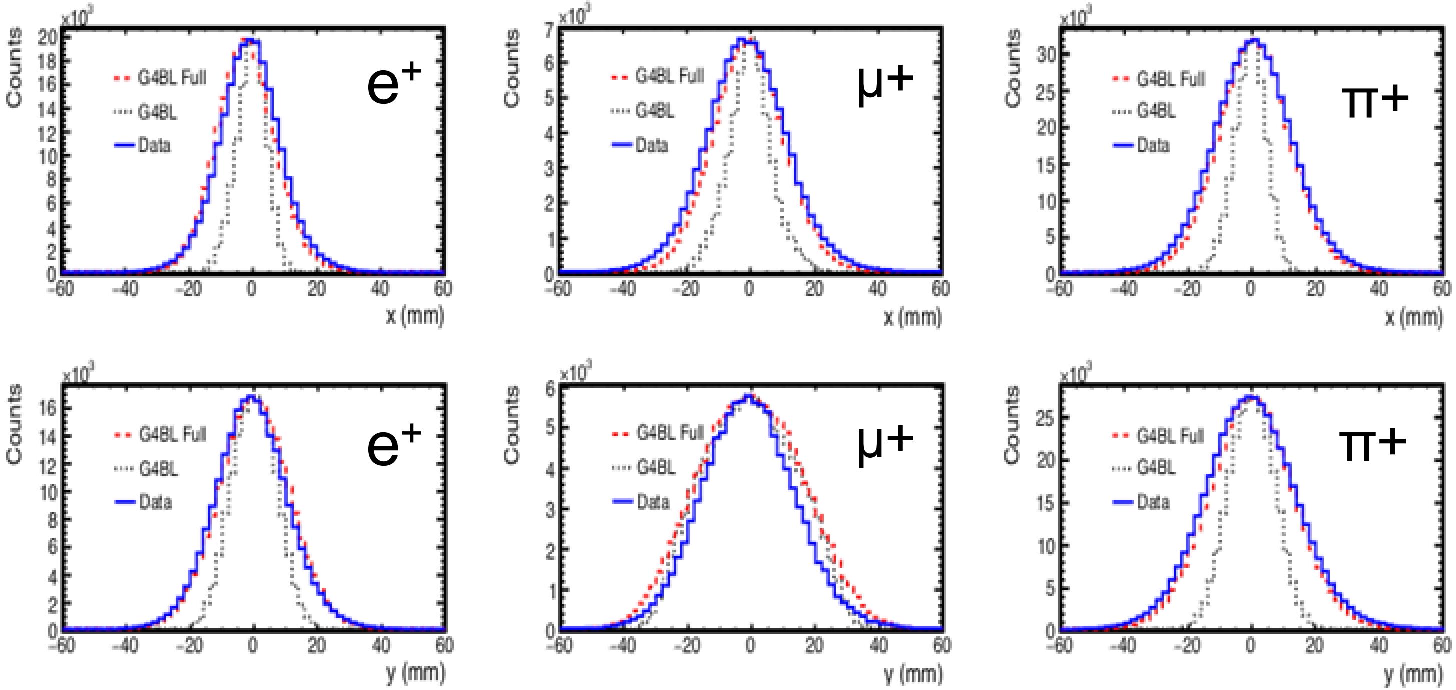
Moment (GeV/c)	115	160	210
	Time-of-Flight (ns)		
e	75.9	75.9	75.9
μ	103.1	91.0	85.0
π	119.4	100.8	91.2

mod(ToF, 19.75 ns)
P = 160 GeV/c



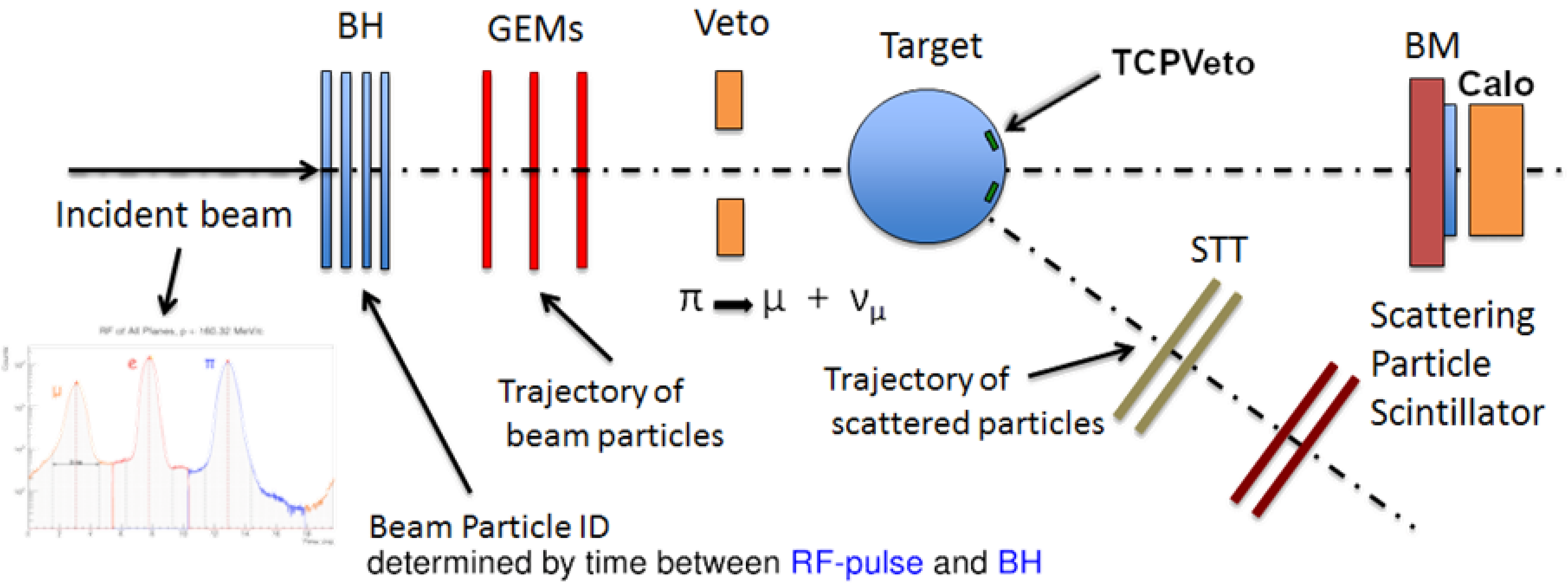
πM1 Beam Line Simulations

E. Cline, et al.,
PRC 105 (2022) 5, 0552
01 arXiv:2109.09508

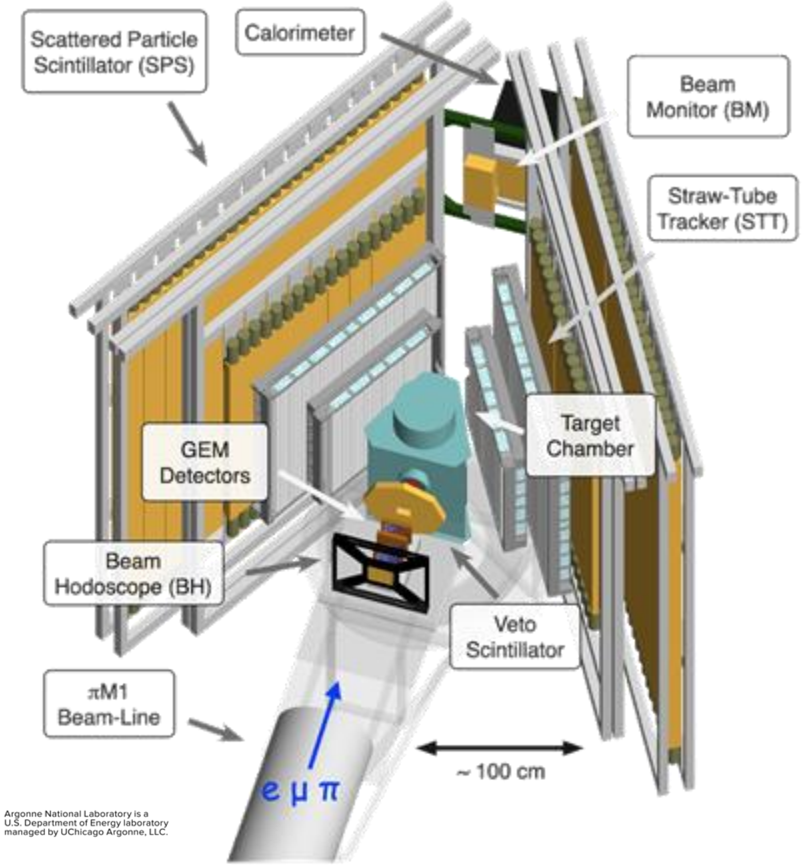


- Beam line was carefully simulated using Turtle and G4Beamline
- Simulations were verified with optics studies, e.g. dispersion measurements at the IMF

MUSE SPECTROMETER



MUSE Spectrometer
Slightly less schematically



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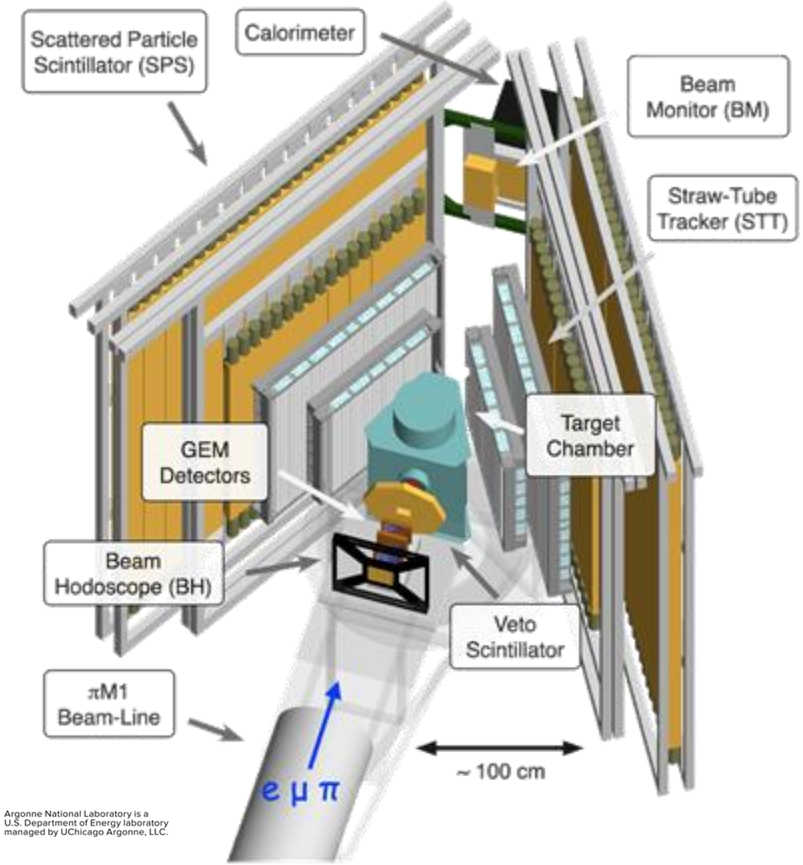
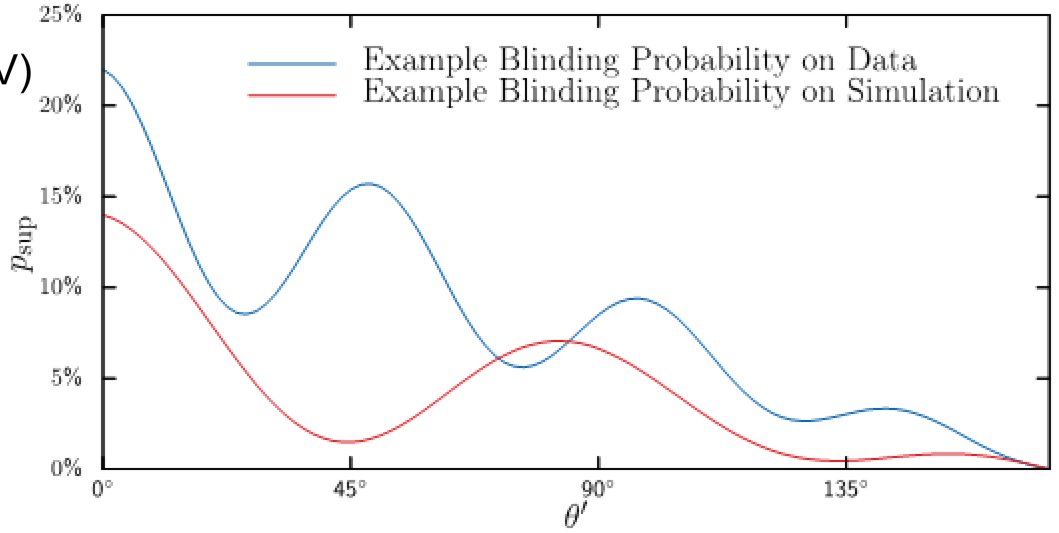
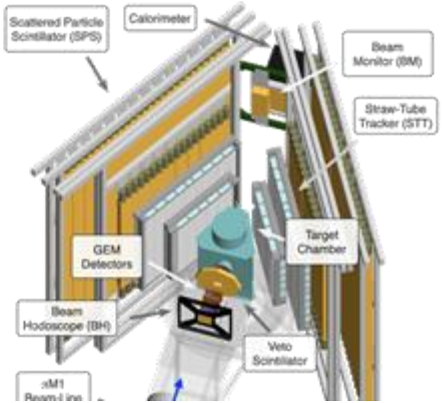


Experimental Bias Removal—Blinding

- Randomly selected scattered tracks are removed from the data
- $P = f(\theta)\frac{3-\theta}{3}$ with $f(\theta) = 0.2(A + 0.3\ \cos B\theta)$
- Where A and B are randomly chosen numbers $A, B \in [0.25, 1.0]$
- (A,B) are chosen separately for:
  - Each momentum (115, 160, 210 MeV)
  - Each particle species (e, μ, π)
  - Each polarity (e.g. μ^+ vs μ^-)
  - Data and Monte Carlo (2)
  - 36 sets of (A,B) blinding parameters

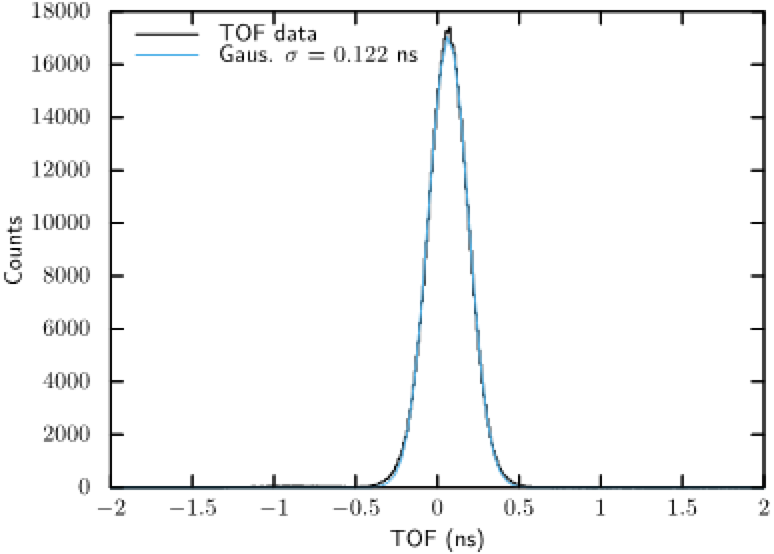


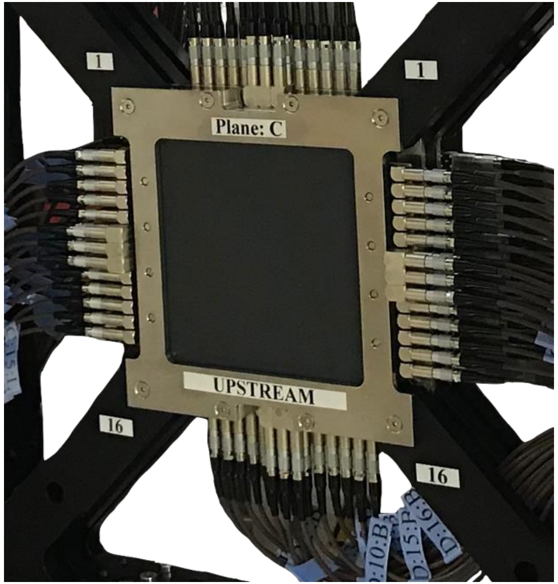
Beam Hodoscopes—BH



- First element which beam encounters in MUSE
- Essential element in ToF

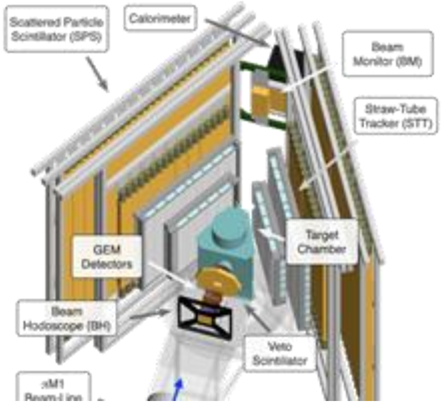
Electron ToF between BH planes C and D





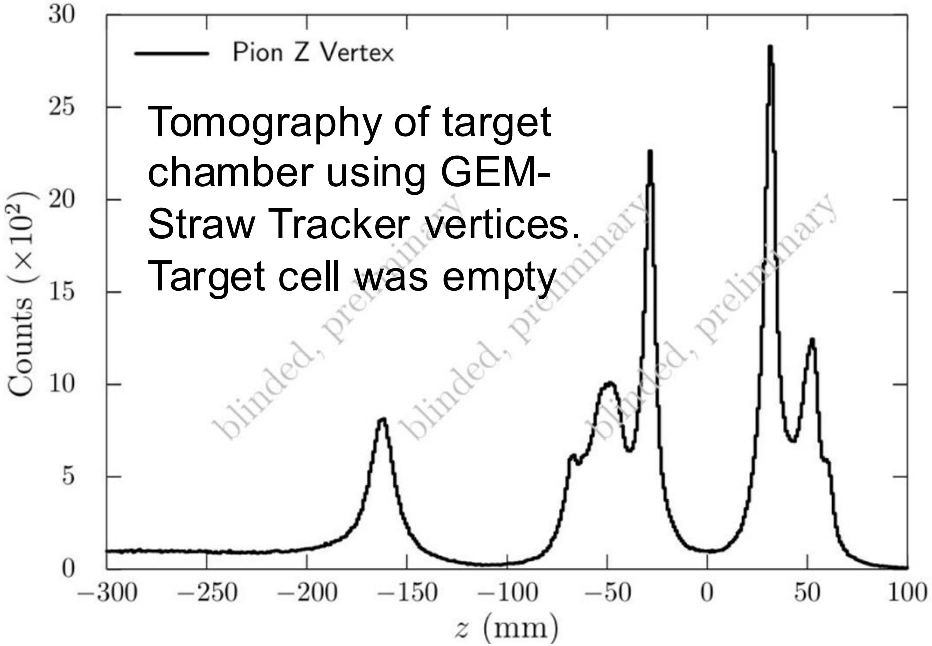
- Excellent ToF resolution $\sigma_{\Delta T} = \sqrt{\sigma_A^2 + \sigma_B^2} = 122$ ps
  - $\sigma_T = \frac{1}{\sqrt{2}} 122 \approx 86$ ps

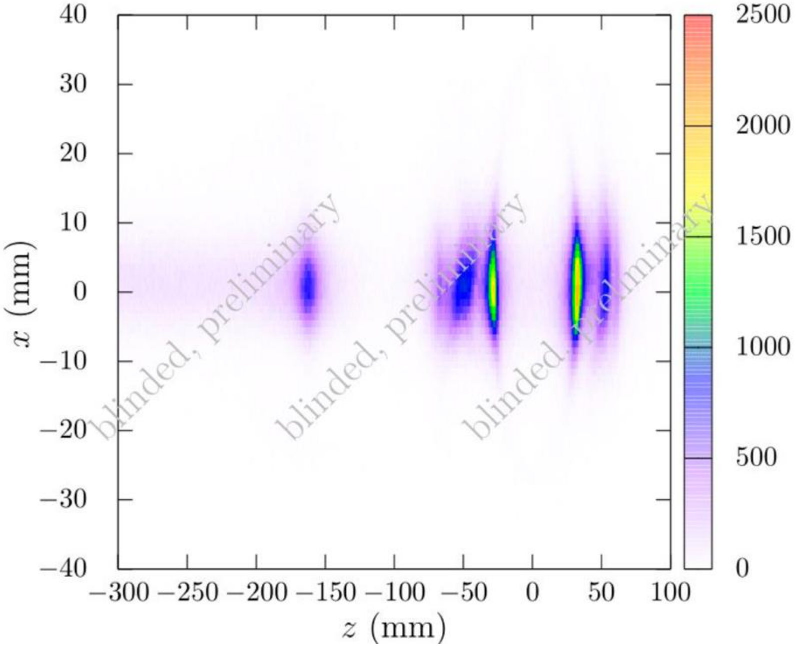
DETECTOR PERFORMANCE: TRACKING



Two tracking sub detectors:

- 4 GEMs track incoming beam
- 2 sets of x and y Straw Tube Trackers on each arm
  — 5 planes of straws in each direction (x, y)





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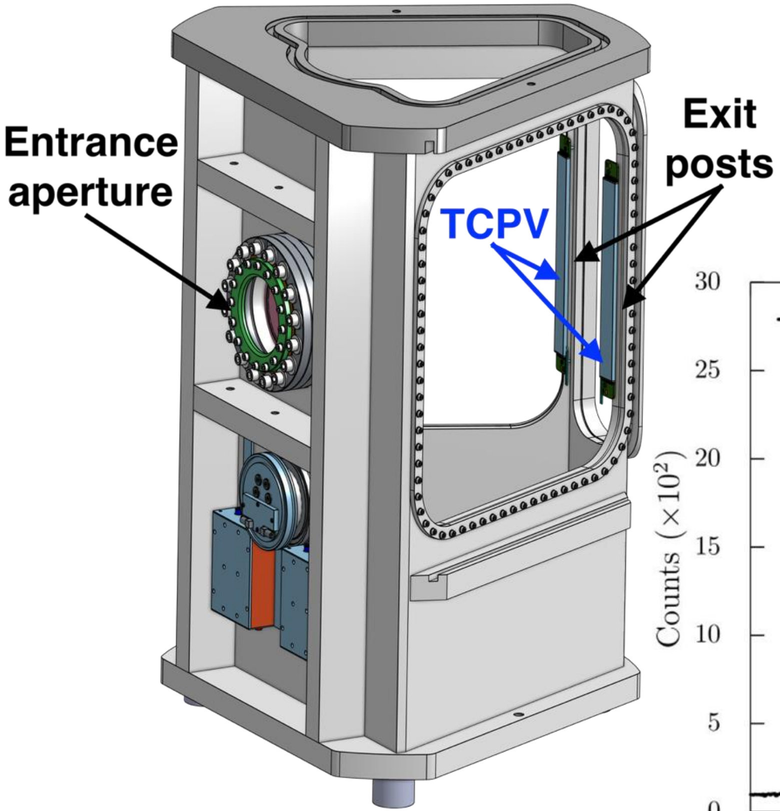
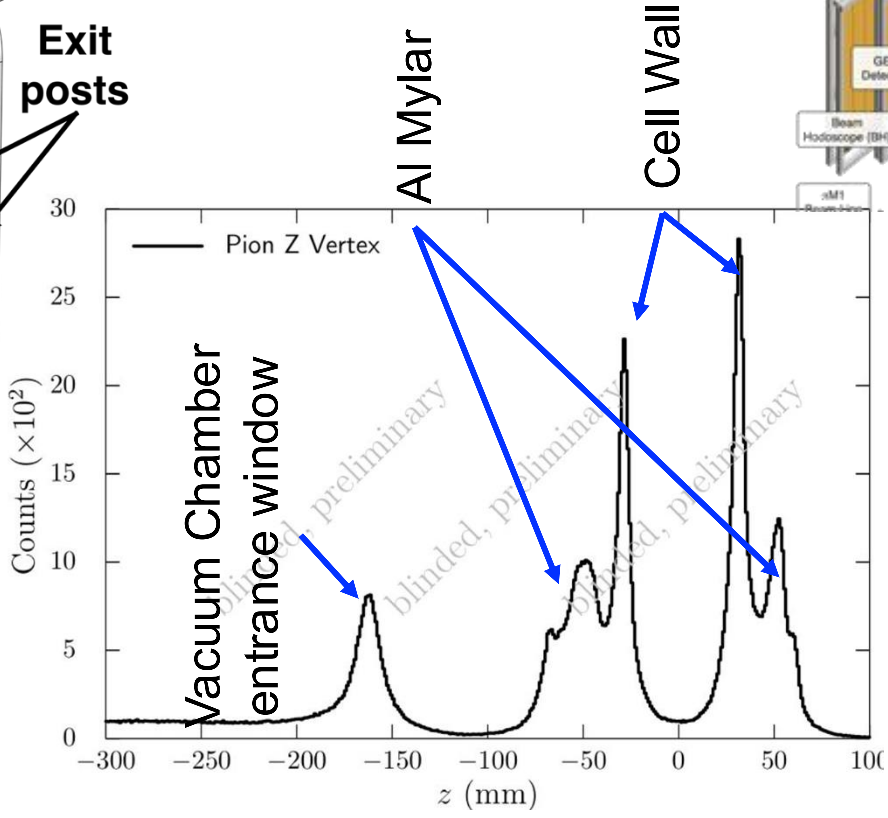
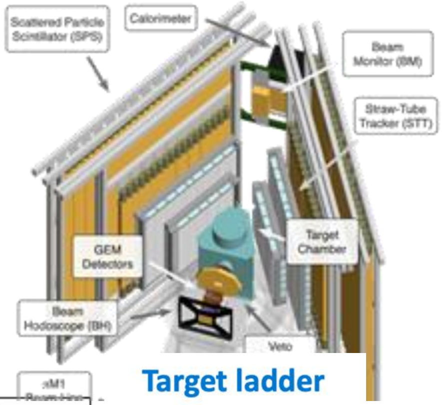


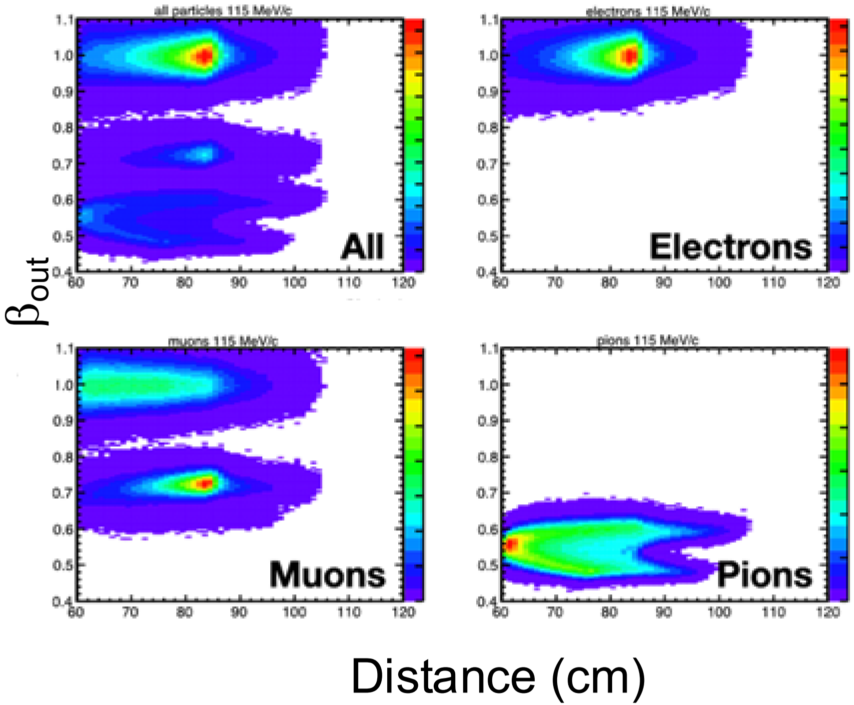




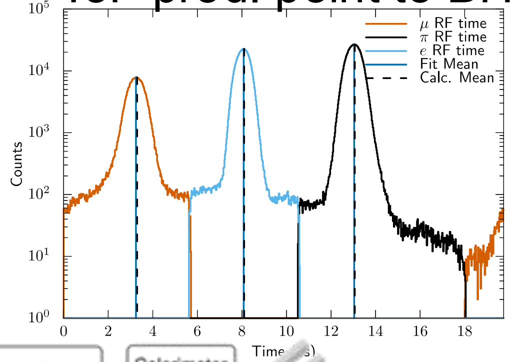
Target ladder

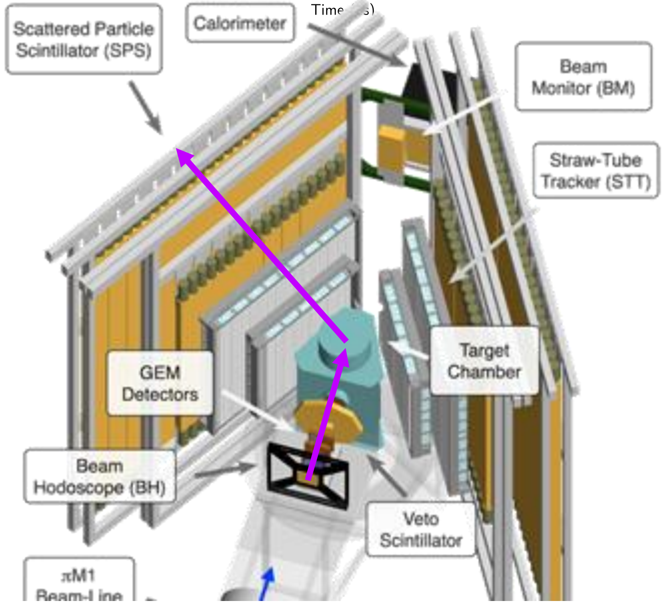
PARTICLE IDENTIFICATION BY β_{OUT} VS PATH LENGTH

Simulation of ToF from BH to SPS

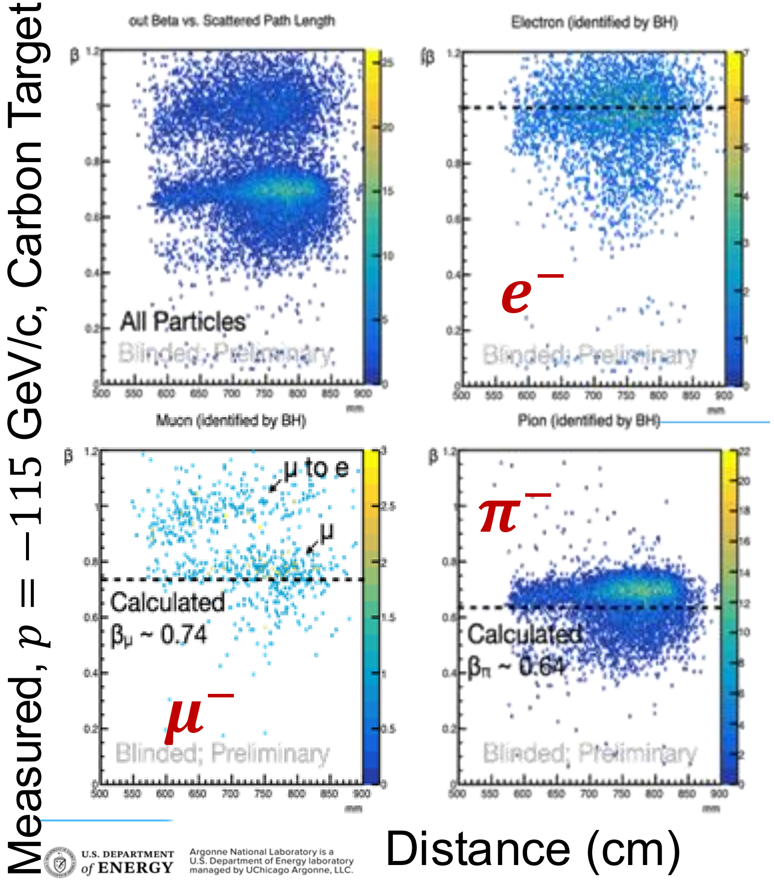


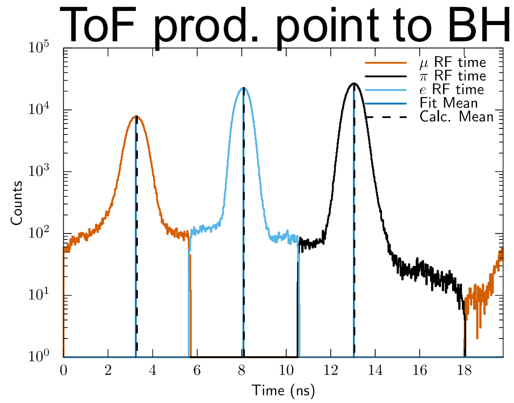
ToF prod. point to BH





Particle Identification by β_{OUT} vs Path Length



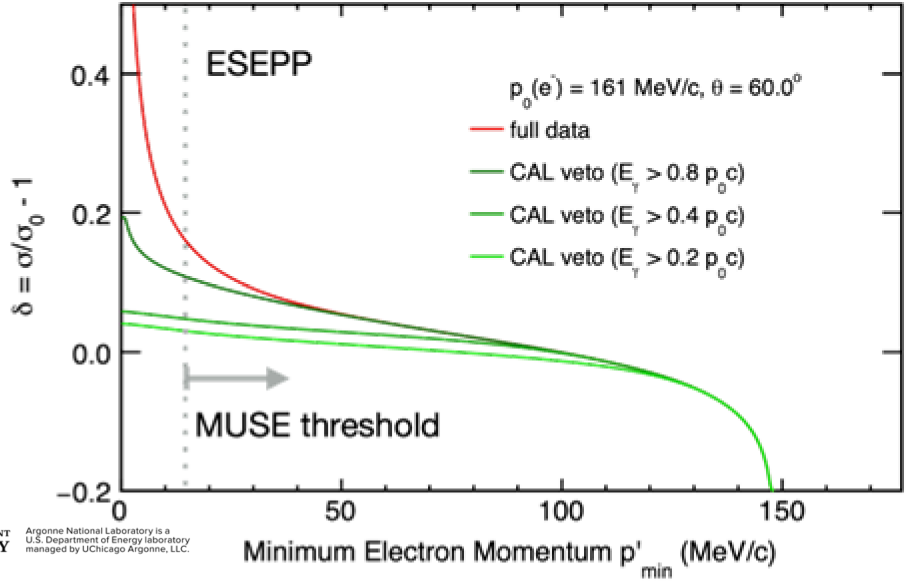


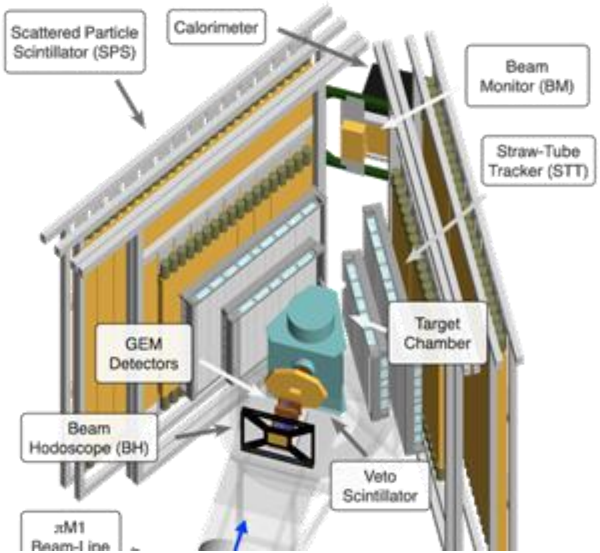
- $\beta_{\text{electron}} \stackrel{\text{def}}{=} 1$
- β_μ and β_π both larger than expected.
  - Possible time walk correction due to pulse height differences

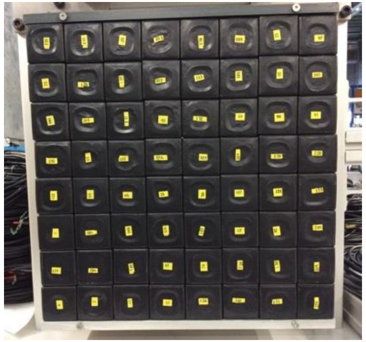
$$\left.\frac{dE}{dx}\right|_\pi \geq \left.\frac{dE}{dx}\right|_\mu \geq \left.\frac{dE}{dx}\right|_e$$

Radiative Corrections

- Strategy described in L. Li, S. Strauch, et al, *Eur. Phys. J. A* 60 (2024) 1, 8.
- Measure hard photon brems. with Calorimeter at 0°
  - On loan from A2 @ MAMI
  - W. Lin et al. To appear in NIM A, arXiv:2408.13380.







SUMMARY OF SYSTEMATIC UNCERTAINTIES IN MUSE

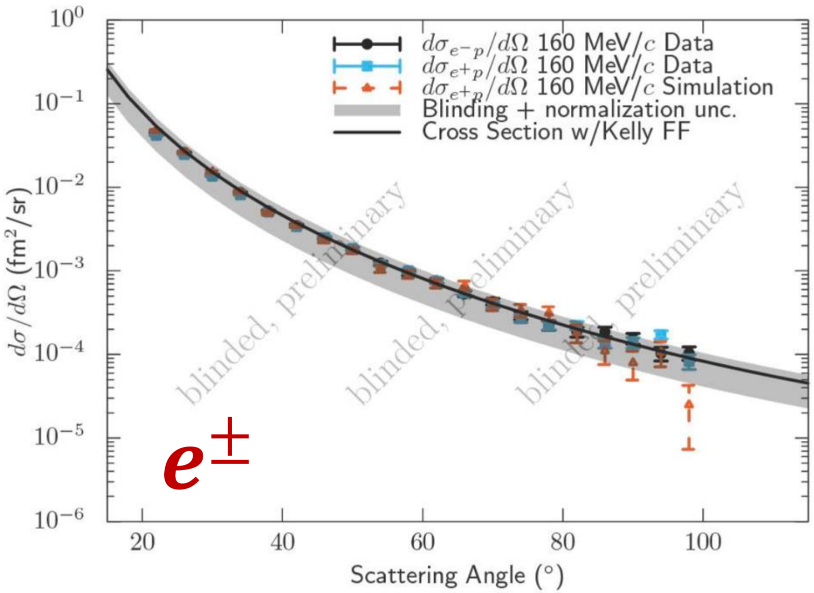
Table 1: Estimated MUSE relative systematic cross section uncertainties for the shape of angular distributions, the ratio of muon and electron scattering cross sections, and the ratio of + charge to − charge cross sections.

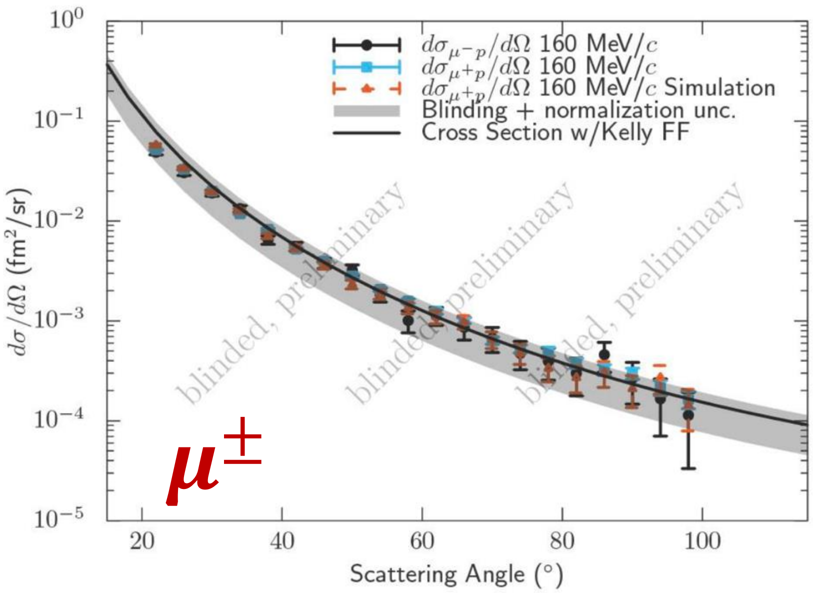
Uncertainty	angular distribution (%)	μ/e (%)	$+/-$ (%)
Detector efficiencies	0.1	0.1	0.1
Solid angle	0.1	small	small
Luminosity	small	small	small
Scattering angle offset	0.2	small	small
Multiple scattering correction	0.15	small	small
Beam momentum offset	0.1	0.1	0.1
Radiative correction	0.1 (μ), 0.5 (e)	0.5	1γsmall
Magnetic contribution	0.15	small	small
Subtraction of μ decay from μp	0.1	0.1	small
Subtraction of target walls	0.3	small	small
Subtraction of pion-induced events	small	small	small
Beam PID / reaction misidentification	0.1	0.1	0.1
Subtraction of μ decay from ep	small	small	small
Subtraction of ee from ep	small	small	small
TOTAL	0.5 (μ), 0.7 (e)	0.5	0.2

MUSE RUN PLAN

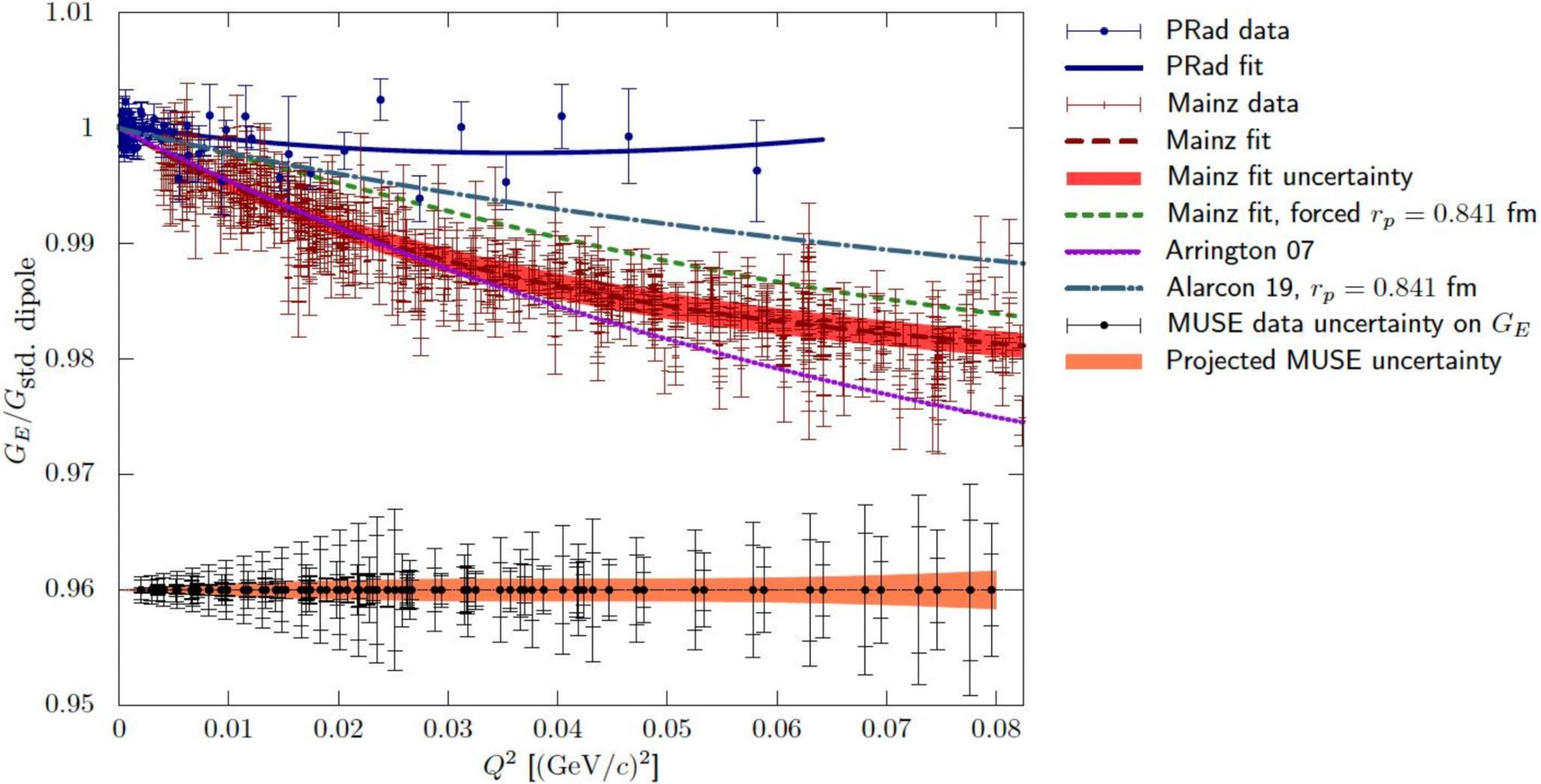
- **2021**: Worked on recovering from COVID-19
- **2022**: Completed 5 months of data taking
    - Took data in all experimental kinematics on LH_2
- **2023**: Completed 5 months of awarded beam time
- **2024**: Completed 5 months of awarded beam time
    - Collected ~75 % of expected total statistics
- **2025**: Now running 5 months of beam time to complete the data taking needed to achieve physics goals
    - Refining the analysis procedure
    - Detectors, target checked, refurbished and re-calibrated
    - Start of the beam time now

Blinded, Very Preliminary 2023 Data



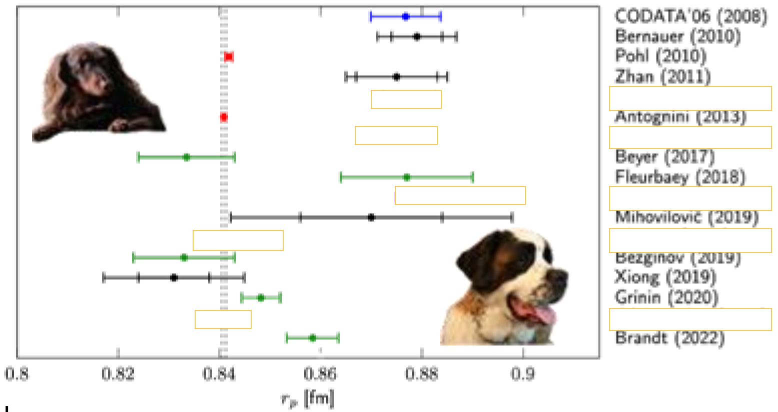


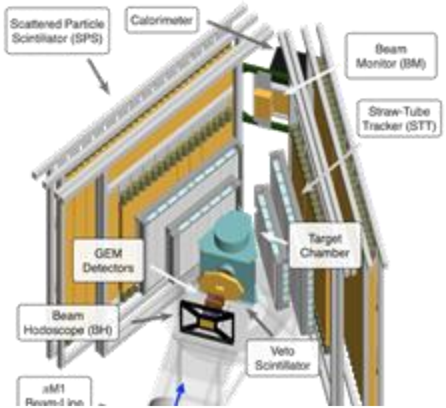
Expected Statistical Uncertainty



SUMMARY

- The value of the mean squared charge radius of the proton is to be determined





- MUSE:
  - — compare $\mu^{\pm}p$ and $e^{\pm}p$ elastic scattering
  - — apparatus is well understood
  - — Much of the data is already recorded