Status of the MUSE experiment

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Correlations in Partonic and Hadronic Interactions 2018
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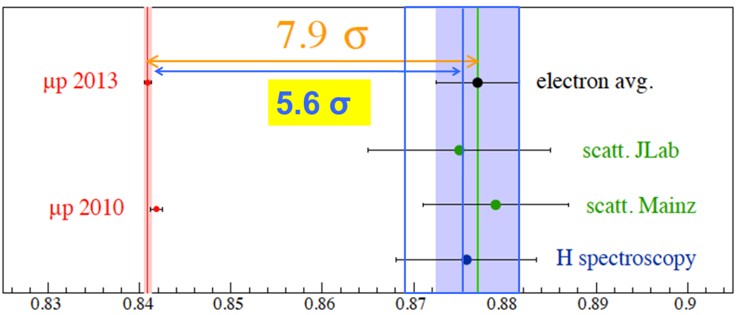
1614938 (MUSE Collaborative research) and 1614456

Proton Radius puzzle

The proton radius puzzle = Reduced size of the proton obtained with Muonic Hydrogen Spectroscopy (First released → 2010)

The proton rms charge radius measured with

electrons: 0.8751 ± 0.0061 fm **(CODATA2014)**
muons: 0.84087 ± 0.00039 fm



R. Pohl et al., Nature 466, 213 (2010)
A. Antognini et al., Science 339, 417 (2013)

Possible reasons

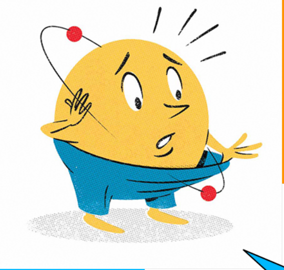
- **The μp (spectroscopy) result is wrong**
  Discussion about theory and extracting the proton radius from muonic Lamb shift measurement
- **The *ep* (spectroscopy) results are wrong**
  Accuracy of individual Lamb shift measurements?
  Rydberg constant could be off by 5σ
- **The *ep* (scattering) results are wrong**
  Fit procedures not good enough
  Q^2 not low enough, structures in the form factors
- **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*
- **Physics beyond Standard Model differentiating μ and *e***
  Lepton universality violation, light massive gauge boson
  Constrains on new physics: e.g. from Kaon decays

Status of the Proton Radius puzzle

Spectroscopy

Electronic hydrogen
0.8758 ± 0.0077

Muonic hydrogen
0.84087 ± 0.00039



Electron scattering
0.8751 ± 0.0061

Scattering

Muon scattering
???

MUSE TIME-LINE

- 2011: Ron Gilman & Michael Kohl came up with an idea
- 2012: MUSE presented to PSI BVR 43, and every BVR thereafter
- 2014: Conditional physics approval from PSI
- 2014: First R & D funding from NSF & DOE
- 2016: Full construction funding from NSF (award Sep. 15th)
- 2018:August: Installation and dress rehearsal at PSI
- 2018:December: MUSE → First Scattering Data
- 2019-2020: Data taking: 6 months / year
- 2020-2022: Data Analysis and Publications.

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

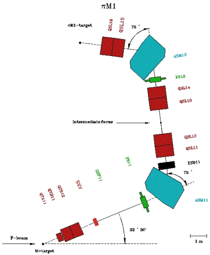
- Technical Design Report: arXiv:1709.09753 [physics.ins-det]

[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

- X-ray laser: SwissFEL
- Synchrotron: Swiss Light Source (SLS), with 2.4 GeV photons
- Proton accelerator: World's most powerful 590 MeV Proton beam (2.2 mA, 1.3 MW beam, 50.6 MHz RF frequency)
  1. $e^{\pm}, \mu^{\pm}, \pi^{\pm}$ in Secondary beam-lines
  2. Particle species are separated by timing relative to beam RF

$\pi M1$ Experimental Area



Beam Momenta (Gev/c)	0.115; 0.153; 0.210
Q^2 range for Electrons (Gev^2)	0.0016 – 0.0820
Q^2 range for Muons (Gev^2)	0.0016 – 0.0799

P, MeV/c	Polarity	e, %	μ, %	π, %
115	+	96.7	2.1	0.9
153	+	63.0	12.0	25.0
210	+	12.1	8.0	79.9
115	-	98.5	0.9	0.6
153	-	89.9	3.2	6.8
210	-	47.0	4.0	49.0

FIGURE: Beam composition

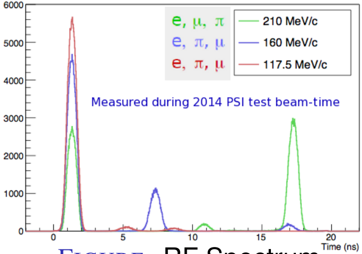


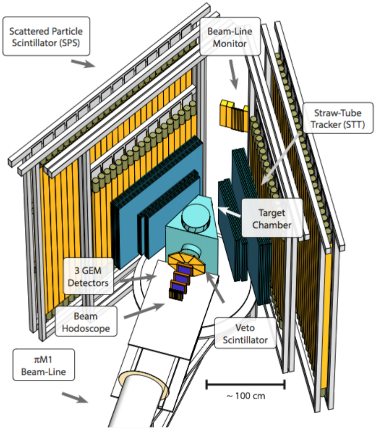
FIGURE: RF Spectrum

$\pi M1$ and MUSE

R_p (fm)	Electrons	Muons
Spectroscopy	0.8758 ± 0.0077	0.8409 ± 0.0004
Scattering	0.8751 ± 0.0061	???

- Simultaneous measurement of $e^- p$; $\mu^- p$ and $e^+ p$; $\mu^+ p$ elastic scattering reactions at 3 different beam momenta: 115 MeV/c, 153 MeV/c, 210 MeV/c in $\pi M1$ area at PSI:
  1. Simultaneous determination of the Proton Radius in both ep and μp scatterings
  2. Direct comparison of ep and μp scatterings at sub-percent level precision
  3. Test of Lepton universality
  4. Determination of TPE effects

DETECTOR SETUP

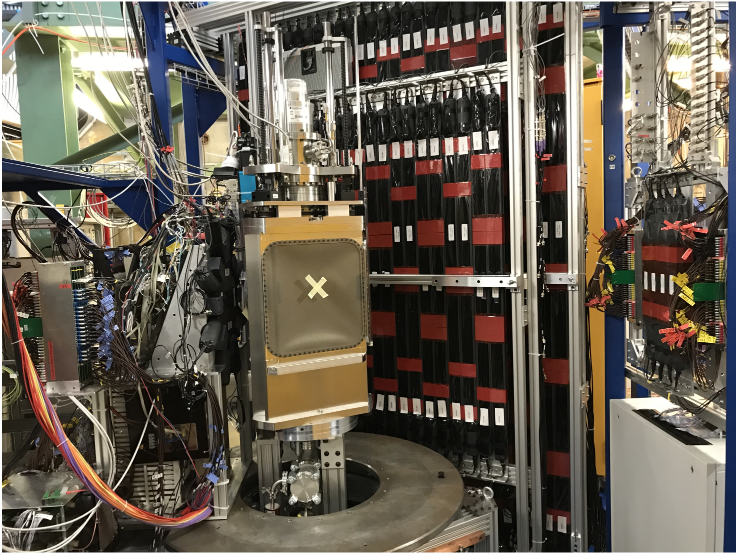


Measure $e^{\pm}p$ and $\mu^{\pm}p$ elastic scattering

$$p = 115, 153, 210 MeV/c$$
$$Q^2 = 0.002 - 0.07 (GeV/c)^2$$
$$\Theta = 20^\circ - 100^\circ$$

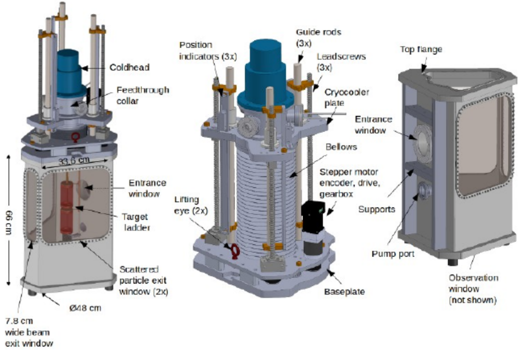
- Liquid hydrogen target
- TIMING: Beam-Hodoscope planes (BH) + Scattered Particle Scintillators (SPS) + Beam Monitor (BM)
  1. TOF for scattered and unscattered particles, for reaction ID
     $\sigma_T \leq 100 ps$; $\epsilon \geq 99\%$
  2. PID of Beam-line particles
     $\sigma_T \leq 150 ps$; $\epsilon \geq 99\%$
  3. Beam Momentum determination
- TRACKING: GEMs + Veto + Straw-Tube Tracker (STT) or BM

Detector Setup



Liquid Hydrogen Target

- Construction by U.Mich., PSI, CREARE
- Assembled at PSI
- Multiple successful cool-downs with Ne
- Hydrogen exhaust system constructed
- Safety review passed (PSI; Aug.2018)



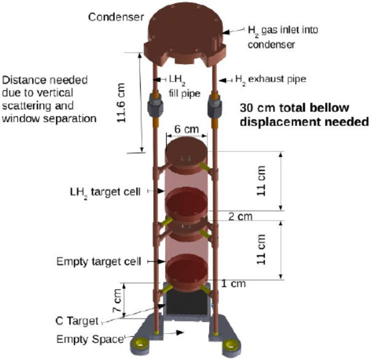
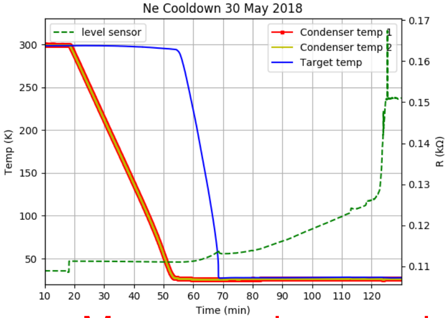
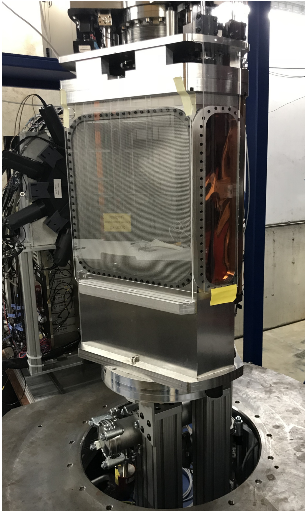


FIG. 21. A schematic view of the target ladder.

Liquid Hydrogen Target

Parameter	Requirements	Achieved
Liquid Hydrogen	Maintain filled cell at $T \approx 19k$ and $P \sim 1$ atm	November 2018, moderate
Cool-down time	< 3 days	✓ < 2 hours!
Beam Entrance	Window $> 6cm$	✓ Easy
Exit Windows	$20^\circ < \theta < 100^\circ$; $\phi = 0^\circ \pm 45^\circ$ at $\theta = 60^\circ$ beam up-down and left-right symmetry	✓ ✓ ✓ ✓

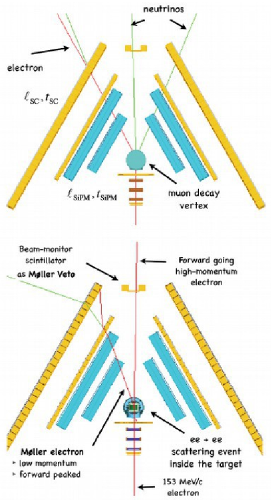




- Meets requirements!

Muon Decay and Moeller

Simulations (USC)

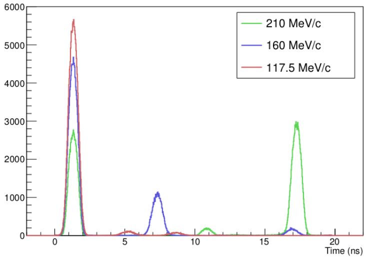


- Muon Decays in flight can be removed with TOF measurements
- Moeller/Bhabba events can be effectively suppressed with BM acting as a Moeller-VETO

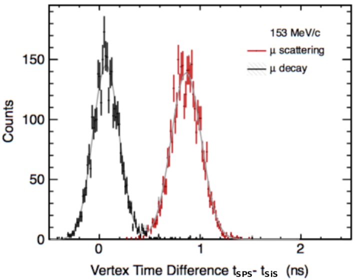
KEY REQUIREMENTS: TIMING

- Beam-particle and reaction identification

DATA

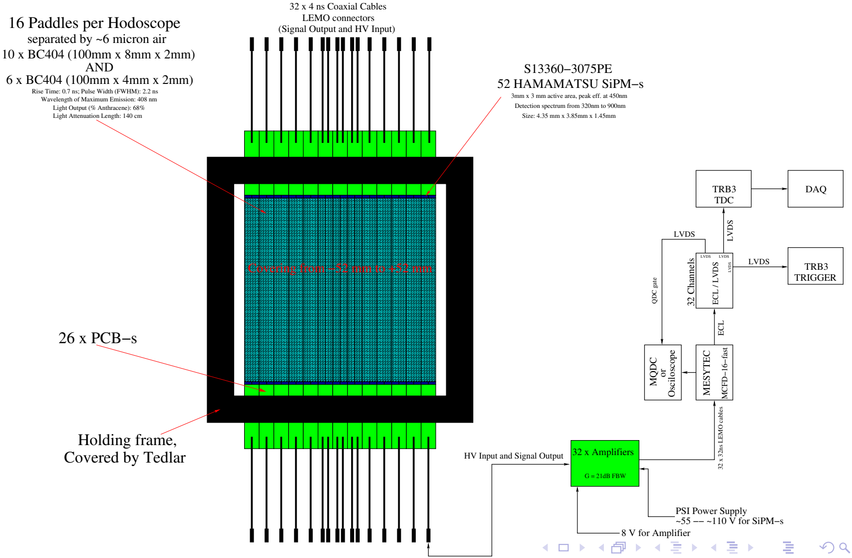


SIMULATION



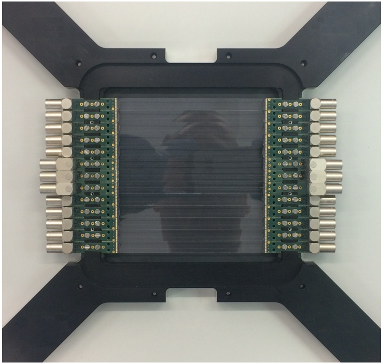
- 150 ps rms beam line timing for PID
- $\leq$ 100 ps rms TOF for reaction ID

BH FINAL DESIGN



BH Planes

4 BH-Planes successfully tested
2 mm thick x 100 mm long x 4&8 mm wide BC404 +
+ Hamamatsu S13360-3075PE



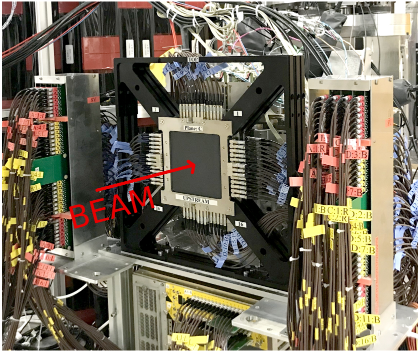
Paddle	Paddle Time Resolution
#1	65 ps
#2	66 ps
#3	62 ps
#4	77 ps
#5	68 ps
#6	95 ps
#7	97 ps
#8	97 ps
#9	91 ps
#10	95 ps
#11	96 ps
#12	64 ps
#13	68 ps
#14	70 ps
#15	61 ps
#16	61 ps

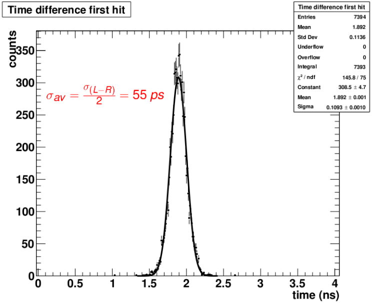
Meets requirements!

BH Planes

- Extensively prototyped; exceeds requirements!
- Completely built at PSI

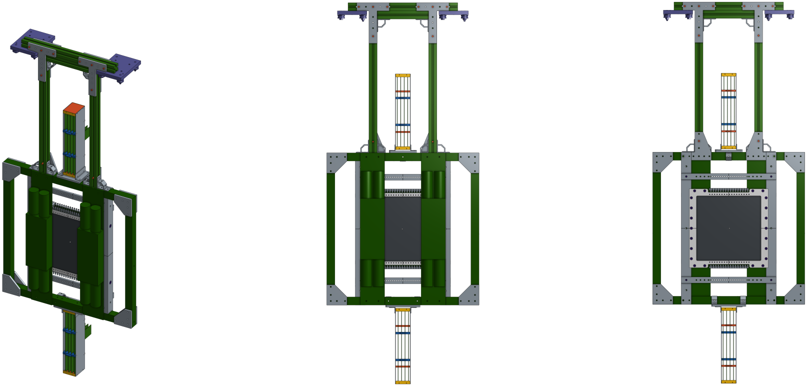
Parameter	Requirements	Achieved
Time Resolution	$< 100ps/$ plane	✓ $80ps$
Efficiency	$\geq$ 99%	✓ 99.8%
Positioning	$\approx 1mm, \approx 1mr$	✓ easy by calibration
Rate Capability	3.3 MHz / plane	✓ >10 MHz / plane





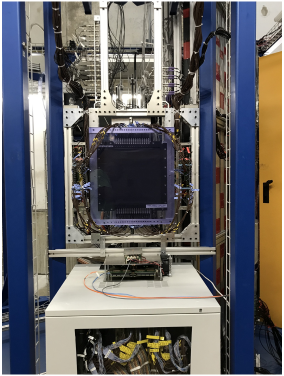
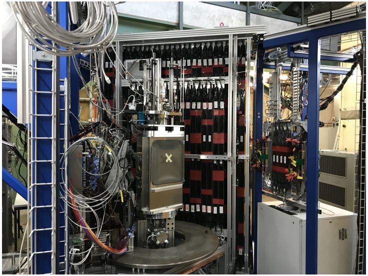
Beam Monitor (BM)

3 mm x 12 mm x 300 mm BC404 + S13360-3075PE



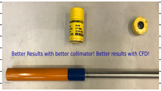
- Fully prototyped, designed and built at PSI by me
- 6 mm shifted 2 planes: 16 paddles per plane
- Completely Functional!

Beam Monitor

Beam Monitor: Test Results

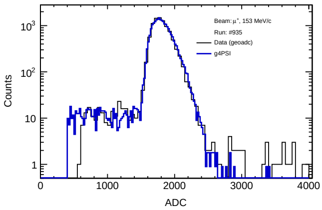
- 3 BM prototypes successfully tested:
  3 mm thick x 300 mm long x 12 mm wide BC404 +
  S13360-3075PE; S13360-3050PE; AdvanSiD
- Best result: S13360-3075PE: $\sigma_T = 59ps$; $\epsilon \geq 99.9\%$

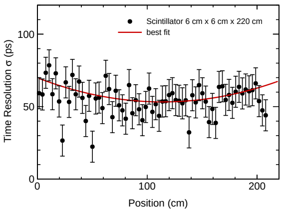
Paddle #	time diff., ps	Top		Bottom		HV, V	Comments
		Amplitude, mV	falling time, ns	Amplitude, mV	falling time, ns		Trigger = Top&Bottom, -50 mV threshold, AC coupled
1	173	1000	1.3	920	1.21	165.63	No CFD, with oscilloscope=Level discriminator with no walk correction
2	195	860	153	700	1.51	167.81	In all cases we used 10 cm long collimator with 10-12 mm in diameter
3	167	1090	1.33	870	1.27	165.72	
4	178	1070	1.44	830	1.42	165.09	
5	166	1115	1.3	870	1.25	165.76	
6	191	980	1.45	720	1.36	165.65	
7	167	1140	1.3	865	1.28	165.81	
8	193	890	1.5	650	1.49	166.01	
9	168	1190	1.27	935	1.18	165.87	
10	200	840	1.55	550	1.52	167.28	
11	169	1140	1.23	907	1.22	165.9	
12	197	900	1.48	500	1.49	166.62	
13	158	1160	1.28	940	1.17	165.96	We used 90-Sr as a sourse
14	205	665	1.51	454	1.47	166.86	
15	164	1160	1.3	973	1.15	166.08	Amplifies SN#009
16	209	550	1.52	390	1.5	166.72	Amplifies SN#010
17	166	780	1.5	715	1.4	166.12	Amplifies SN#011
18	170	1180	1.3	915	1.17	166.68	Amplifies SN#012
19	168	910	1.47	900	1.28	166.16	
20	197	790	1.52	550	1.52	167.01	
21	200	715	1.54	770	1.4	166.27	
22	174	1080	1.38	900	1.16	167.55	
23	191	790	1.51	840	1.4	166.38	
24	172	1170	1.29	860	1.2	166.83	
25	195	854	1.5	686	1.5	166.58	
26	167	1200	1.29	900	1.12	165.32	
27	197	795	1.46	846	1.36	166.62	
28	170	1150	1.27	900	1.09	165.41	
29	197	800	1.49	740	1.46	166.7	
30	190	1020	1.5	640	1.41	165.46	
31	165	1240	1.2	960	1.06	166.75	
32	177	1180	1.29	850	1.23	165.51	

- TESTED: Meets requirements!

Scattered Particle Scintillator (SPS)

- Copy of CLAS12 FTOF12 system, built at USC
- Engineering details of support being worked out



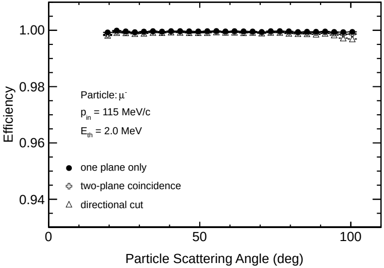


- Peak: particles going through the bar
- Low energy tail: particles going out the side of the bar

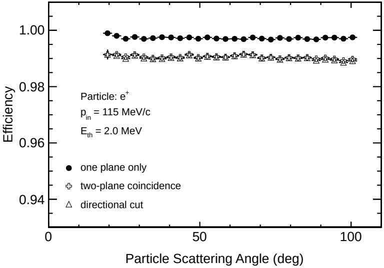
- 220 cm BC404 bars: $\sigma_{av.} = 52ps \pm 4ps$
- 120 cm BC404 bars: $\sigma_{av.} = 46ps \pm 4ps$

SPS: Simulations

2-plane coincidence $\epsilon \geq 99.5\%$ for all particles, except for e^+



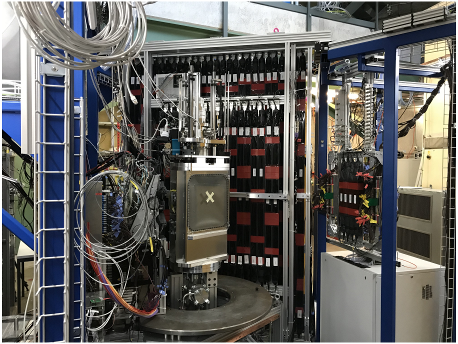
ϵ_{trig} vs Angle for μ^-



ϵ_{trig} vs Angle for e^+

SPS

- 2 planes on each side of beam, all 4 walls complete
- 92 bars, double-ended readout



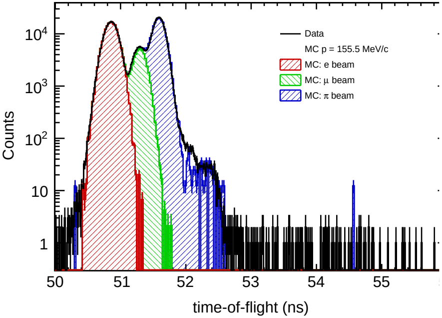
Parameter	Requirements	Achieved
Time Resolution	$\approx 60ps/$ plane	✓ $\leq 55ps$
Efficiency	$\geq 99\%$, $\ll 1\%$ paddle to paddle uncertainty	✓ $> 99\%$, paddle to paddle not attempted, moderate
Positioning	$\approx 1mm$, $\approx 1mr$	✓ easy
Rate Capability	0.5 MHz / plane	✓ >1 MHz / plane

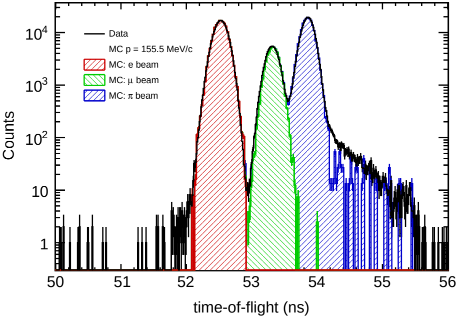
- Meets requirements!

TOF

2 TOF measurements (1 BH-Plane → SPS) with 50 cm difference in detector spacing, compared to Geant4

(Horizontal scale has arbitrary offset)





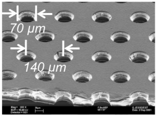
Preliminary data analysis determine $p_\pi(p_\mu)$ to 0.2%(0.3%)

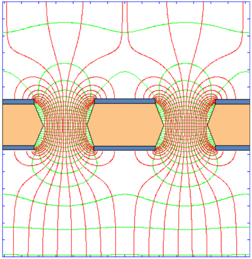
Meets requirements!

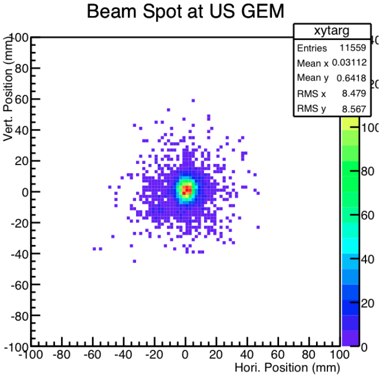
TRACKING DETECTORS: GEMS

- **GEM = Gas Electron Multiplier**
  introduced by F. Sauli in mid 90's, F. Sauli et al., NIMA 386 (1997) 531
- **Copper layer-sandwiched Kapton foil (Apical) with chemically etched micro-hole pattern**
- **Supply ~400V across foil, immersed in Ar:CO_2 (70:30)**

→ **gas amplification in the holes**



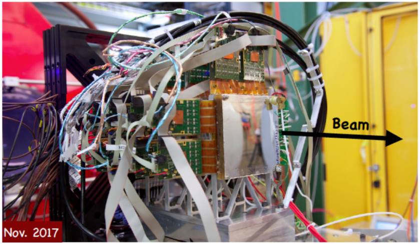




Tracking Detectors: GEMs

- Set of 3x 10cm x 10cm GEM detectors built for OLYMPUS
- Telescope gaps reduced to 8.5 cm
- Gas mixture: Ar:CO2 70:30
- APV cards arranged in-plane
- New digitizer module (MPD v4)

- 70 μm (100 μm) spatial resolution
- $\epsilon = 97 - 99\%$ (98.0%)
- Successful operation of New DAQ:
  1. Readout time 0.5 ms with new system (0.9 ms in 2015; Goal is: 0.15 ms)
  2. Up to 2 kHz, 32-bit block transfer (BLT) (Goal is to reach up to 3 kHz)



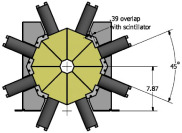
Parameter	Requirements	Achieved
Spatial Resolution	100μm/ element	✓ 70μm
Efficiency	98%	✓ $>$ 98%
Positioning	$\approx$ 0.1mm, $\approx$ 0.2mr	Not attempted; easy
Rate Capability	3.3 MHz / plane	✓ 5 MHz / plane
Readout Speed	3 kHz	2 kHz; Will be achieved with New VME crates

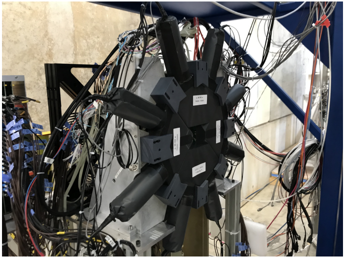
Meets requirements!

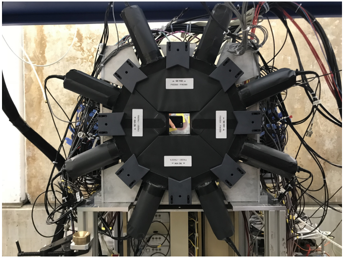
VETO DETECTOR (UNI. SOUTH CAROLINA)

- Annular 8-element VETO detector, surrounding target entrance window
- Eliminate upstream scattering and beam decays
- Arrived at PSI on July.2018 and is already installed in place

Parameter	Requirements	Achieved
Time Resolution	$1ns/$ element	✓ $\leq 200ps$
Efficiency	99%	✓ $> 99\%$
Positioning	$\approx 1mm, \approx 1mr$	✓ Achieved!
Rate Capability	1 MHz / element	✓ $\gg 1MHz/$ el.







Meets requirements!

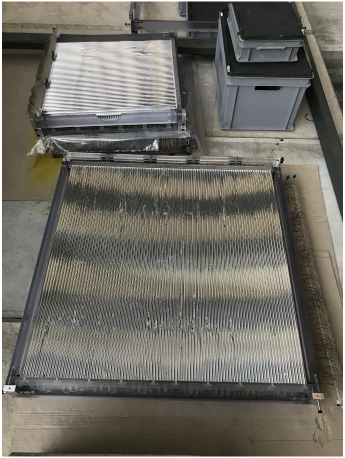
Straw Tube Tracker (STT)

- Based on PANDA STT-design
- Built at HUJI, Temple
- 2 chambers, 5 planes each in x and y
- In total 2850 Straws
- Before: Readout $\rightarrow$ PADIWA/TRB3
- New Readout $\rightarrow$ PASTTREC/TRB3

Parameter	Requirements	Achieved
Spatial Resolution	$150\mu m/$	✓ $< 120\mu m$
Efficiency	99.8% tracking	$\approx$ 99%; moderate
Positioning	$\approx 0.1mm$, $\approx 0.2mr$ in θ	Not attempted; moderate
Positioning	$50\mu m$ wire spacing	Not attempted; moderate
Rate Capability	0.5 MHz	Not attempted; easy

Straw Tube Tracker (STT)

- STT Frame and almost all planes are ready
- Final plane is being assembled in HUJI

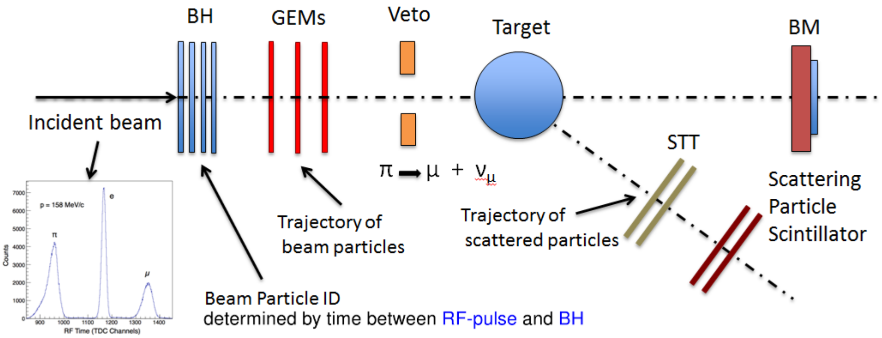


SUMMARY OF DETECTORS

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 (Rutgers)



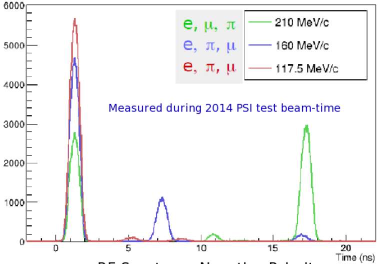
Trigger Logic: TRB3 FPGA-based:

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

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

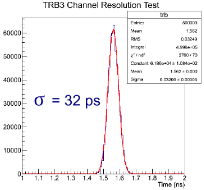
PID is the Hardest Part

MUSE DAQ (GWU & Montgomery College)



RF Spectrum, Negative Polarity

- 3000 TDC and 500 ADC channels
- MESYTEC MCFD-16-fast for Timing
- MESYTEC MQDC-32 mostly for timing correction and detector monitoring
- TRB3 FPGA-based Readout



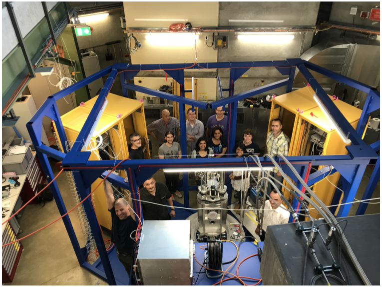
Relative timing test

MUSE

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

- Proton Charge radius extraction limited by systematics, fit uncertainties
- Uncertainties mostly well controlled: largest from angle and radiative corrections
- Many uncertainties are common to all extractions in the experiment and cancel in $(pe^+)/(pe^-)$, $(p\mu^+)/(p\mu^-)$ and $(p+e)/(p+\mu)$ comparisons
- Compare $p+e^\pm$ and $p+\mu^\pm$ Scattering Cross-sections for TPE. Charge average to determine TPE to 0.01 fm
- Individual radius extractions from $p+e^\pm$, $p+\mu^\pm$ each to 0.01 fm
- From $(p+e)/(p+\mu)$ 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)

Conclusion



- Many test beam-times since 1st MUSE proposal in February 2012
- NSF, DOE, BSF fundings received
- MUSE will be the first muon scattering measurement with the required precision to address the Proton Radius Puzzle!

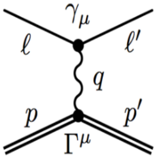
THANK YOU FOR YOUR ATTENTION!

Additional Slides

Additional Slides

Elastic ep Scattering

QED theory is perturbative! → Born (One Photon) Approximation!



Proton is **not** point-like particle:

→ Hadron current operator depends on electric and magnetic form factors:

$$\Gamma^\mu = \Gamma^\mu\left(G_E(Q^2), G_M(Q^2)\right)$$

Differential Cross Section is proportional to the scattering amplitude squared:

structure of proton

$$\frac{d\sigma}{d\Omega} = \left(\frac{\alpha}{4m_p Q^2}\frac{E'}{E}\right)^2 \left|M_\gamma\right|^2 = \frac{d\sigma}{d\Omega}_{Mott} \frac{\varepsilon G_E^2(Q^2) + \tau G_M^2(Q^2)}{\varepsilon(1+\tau)}$$

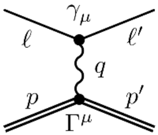
$$\frac{d\sigma}{d\Omega_{Mott}} = \frac{\alpha^2 E' \cos^2\frac{\theta}{2}}{4E^3 \sin^4\frac{\theta}{2}}$$

$$\tau = \frac{Q^2}{4m_p^2}$$

$$\epsilon = \left(1 + 2(1+\tau)\tan^2\frac{\theta}{2}\right)^{-1}$$

PHYS. MOTIVATION: PROTON RADIUS

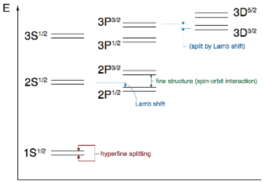
Lepton – Nucleon Scattering:



$$\frac{d\sigma}{d\Omega} = \frac{d\sigma}{d\Omega_{Mott}} \cdot \frac{\varepsilon \cdot G_E^2(Q^2) + \tau \cdot G_M^2(Q^2)}{\varepsilon(1+\tau)} \cdot \left(1 + \sum_{NL} \delta_{NL}\right)$$

$$\langle r_E^2 \rangle = -6 \frac{dG_E^p(Q^2)}{dQ^2}\bigg|_{Q^2 \to 0}$$

Hydrogen Spectroscopy:



$$E = -\frac{Ryd}{n^2} + \Delta E_{finite\_size} + \Delta E_{QED}$$

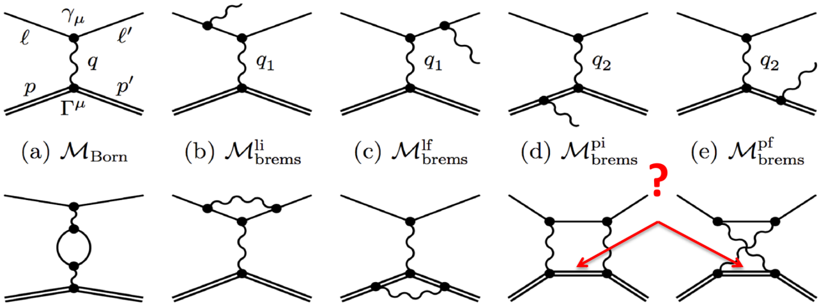
Point-like proton

$$\Delta E_{finite\_size} = \frac{2\pi\alpha}{3} r_E^2 |\Psi(0)|^2$$

Atomic wave function at origin

[Carl E. Carlson, The Proton Radius Puzzle. arXiv:1502.05314v1]

FEYNMAN DIAGRAMS (L AND NL ORDER)



(a) $\mathcal{M}_{\rm Born}$ (b) $\mathcal{M}^{\rm li}_{\rm brems}$ (c) $\mathcal{M}^{\rm lf}_{\rm brems}$ (d) $\mathcal{M}^{\rm pi}_{\rm brems}$ (e) $\mathcal{M}^{\rm pf}_{\rm brems}$
(f) $\mathcal{M}_{\rm vac}$ (g) $\mathcal{M}^{\ell}_{\rm vert}$ (h) $\mathcal{M}^{p}_{\rm vert}$ (i) $\mathcal{M}_{\rm box}$ (j) $\mathcal{M}_{\rm xbox}$

TPE is the largest theoretical uncertainty!

[A. V. Gramolin et al. A new event generator for the elastic scattering of charged leptons on protons. arXiv:1401.2959, 2014]

PHYS. MOTIVATION: TWO PHOTON EXCHANGE (TPE)

Differential *ep* cross section in next-to-leading order approximation:

$$\frac{d\sigma}{d\Omega}\left(e^{\pm}p\right) = \frac{d\sigma}{d\Omega}^{Born}\left(1 \pm \delta_{2\gamma} \pm \delta_{brem} + \delta_{even}\right)$$

Charge independent: δ_{even}

Charge dependent: $\pm \delta_{2\gamma} \pm \delta_{brem}$

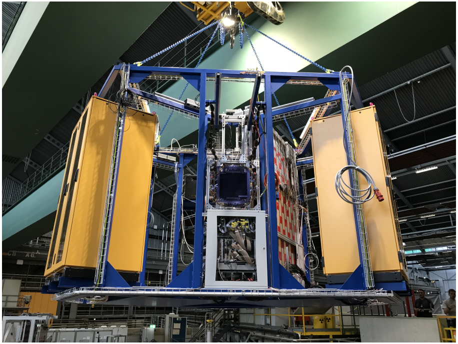
TPE contribution can be determined from the ratio of elastic $e^{+}p$ to $e^{-}p$ cross sections:

$$R = \frac{\sigma\left(e^{+}p\right)}{\sigma\left(e^{-}p\right)} = \frac{\left(1 - \delta_{2\gamma} - \delta_{brem} + \delta_{even}\right)}{\left(1 + \delta_{2\gamma} + \delta_{brem} + \delta_{even}\right)} \approx 1 - 2\frac{\delta_{2\gamma} + \delta_{brem}}{1 + \delta_{even}}$$

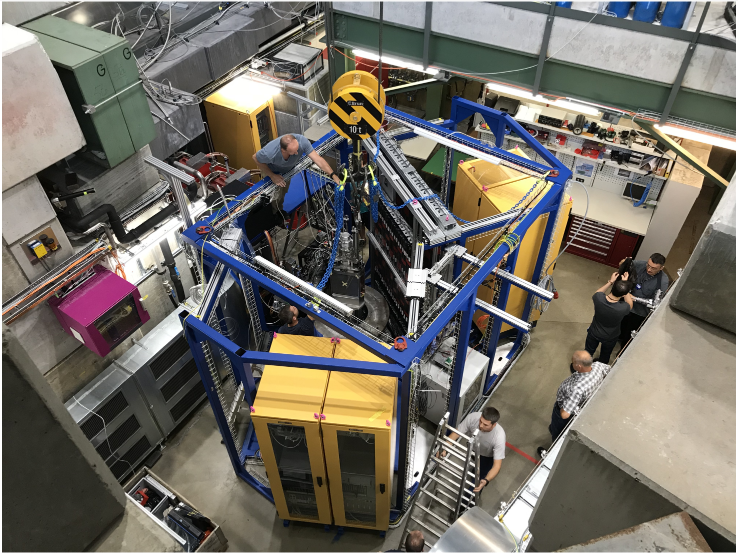
If we know δ_{even}, δ_{brem}, then we can find $\delta_{2\gamma}$!

$\pi M1$ Experimental Area

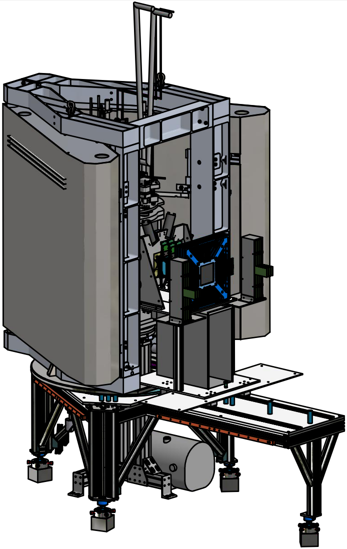
$\pi M1$: Moving In



$\pi M1$: MUSE IS IN

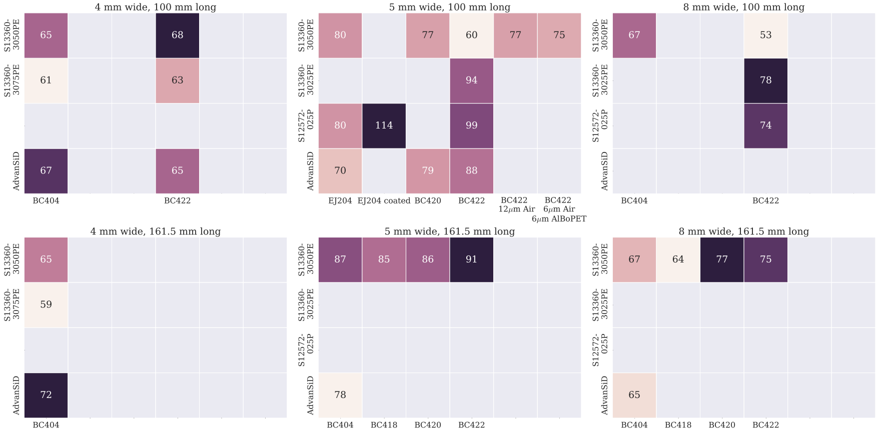


TABLE



- Rotating table
- Movable, with exact positions for TOF
- Retractable tracker
- Dedicated Alignment procedures are required

BH Prototyping



HAM. S13360–3075PE RADIATION TESTS RESULTS

(100mm x 4mm x 2mm) BC422 + S13360-3075PE

Irrad. time	V	I_{dark}	CFD	Eff.	RMS P. R.
0 h	55 V	$\sim 1\mu A$	20 mV	$99.1\% \pm 0.1\%$	63 ps
5 h	55 V	$\sim 140\mu A$	20 mV	$99.4\% \pm 0.1\%$	66 ps
10 h	55 V	$\sim 235\mu A$	20 mV	$99.4\% \pm 0.1\%$	72 ps
15 h	55 V	$\sim 287\mu A$	20 mV	$99.4\% \pm 0.1\%$	77 ps
15 h	56 V	$\sim 430\mu A$	20 mV	$99.2\% \pm 0.1\%$	75 ps
2 m. later	55 V	$\sim 153\mu A$			

* $\sim 46kHz$ on (2mm x 2mm) detector