STATUS OF THE MUSE EXPERIMENT

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New Trends in High-Energy Physics
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Odessa, Ukraine

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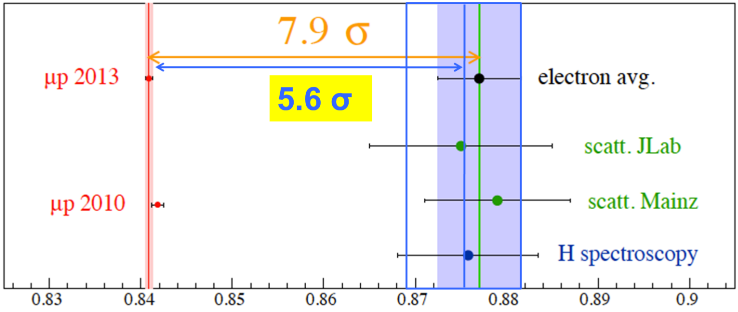
1614938 (MUSE Collaborative research) and 1614456

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

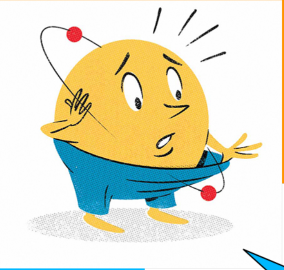
- The μp (spectroscopy) result is wrong
  Discussion about theory and extracting the proton radius from muonic Lamb shift measurement
- The *ep* (spectroscopy) results are wrong
  Accuracy of individual Lamb shift measurements?
  Rydberg constant could be off by 5σ
- The *ep* (scattering) results are 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 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

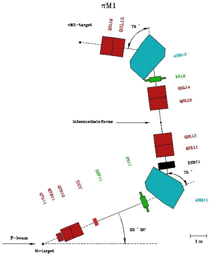
- Technical Design Report: arXiv:1709.09753 [physics.ins-det]

[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

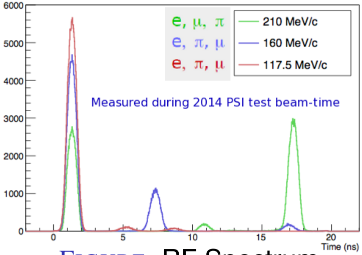


Figure: RF Spectrum

$\pi M1$ 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

ERROR ESTIMATIONS

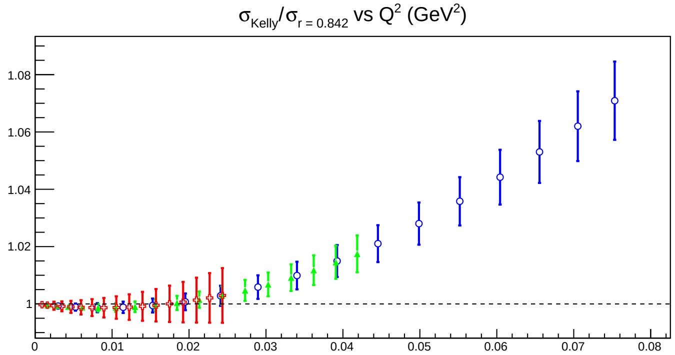
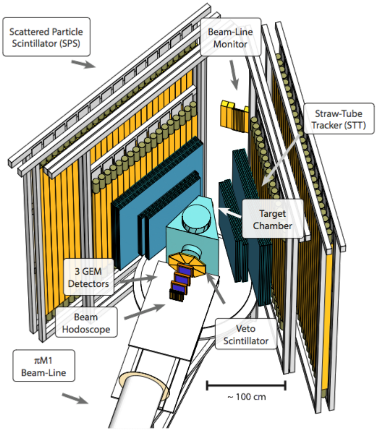


FIGURE: Estimated statistical uncertainties for $\mu^+ p$ elastic scattering cross sections, after background subtraction, and including experimental inefficiencies. Each point corresponds to a 5° bin in scattering angle.

DETECTOR SETUP



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

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

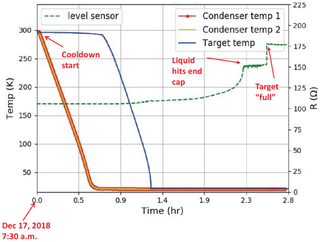
- Liquid hydrogen target
- TIMING: Beam-Hodoscope planes (BH) + Scattered Particle Scintillators (SPS) + Beam Monitor (BM)
  1. TOF for scattered and unscattered particles, for reaction ID

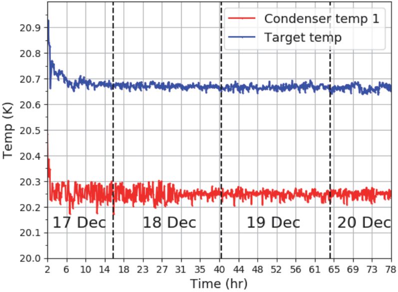
     $\sigma_T \leq 100ps;\ \epsilon \geq 99\%$
  2. PID of Beam-line particles

     $\sigma_T \leq 150ps;\ \epsilon \geq 99\%$
  3. Beam Momentum determination
- TRACKING: GEMs + Straw-Tube Tracker (STT) or BM

Liquid Hydrogen Target

- Construction by U.Mich., PSI, CREARE
- Safety review passed (PSI; Aug.2018)

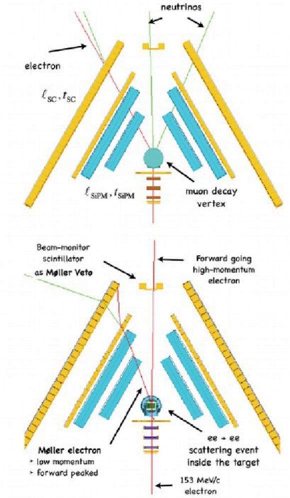




- Meets requirements!

Muon Decay and Moeller

Simulations (USC)

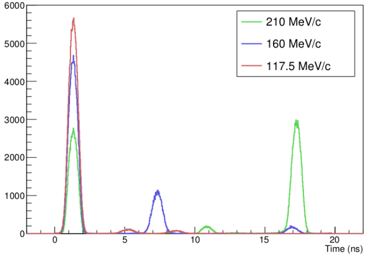


- Muon Decays in flight can be removed with TOF measurements
- Moeller/Bhabba events can be effectively suppressed with BM acting as a Moeller-VETO

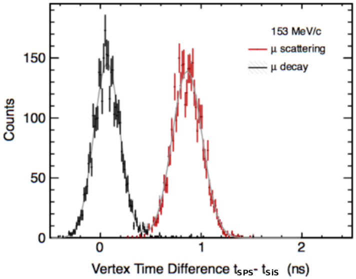
Key Requirements: Timing

- Beam-particle and reaction identification

DATA



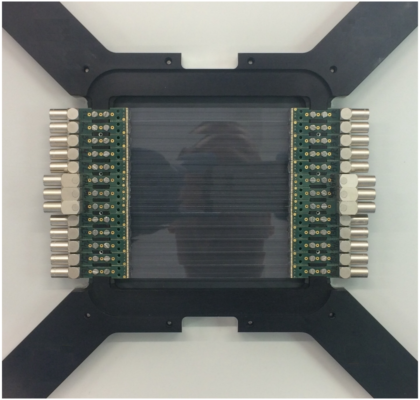
SIMULATION



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

Beam Hodoscope (BH) Planes

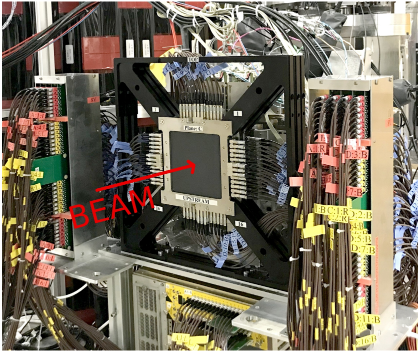
5 BH-Planes built
2 mm thick x 100 mm long x 4&8 mm wide BC404 +
+ Hamamatsu S13360-3075PE

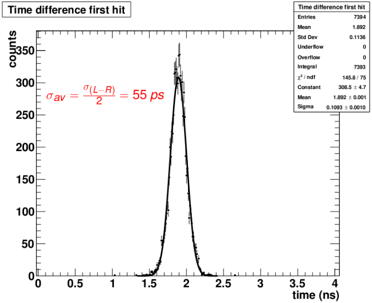


BH Planes

- Extensively prototyped
- 5 BH-Planes built at PSI
- Exceed requirements!

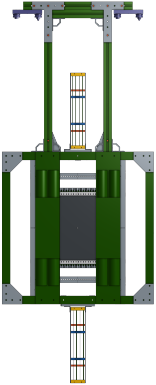
Parameter	Requirements	Achieved
Time Resolution	$< 100 ps/$ plane	✓ $80 ps$
Efficiency	$\geq 99\%$	✓ 99.8%
Positioning	$\approx 1 mm, \approx 1 mr$	✓ easy by calibration
Rate Capability	3.3 MHz / plane	✓ >10 MHz / plane

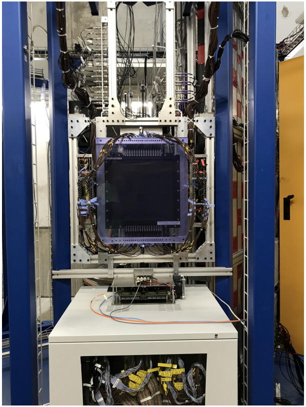




BEAM MONITOR (BM)

- 3 mm x 12 mm x 300 mm BC404 + S13360-3075PE
- 6 mm shifted 2 planes: 16 paddles per plane + 4 front bars
- All paddles: $\sigma_T < 100ps$ (Best: $\sigma_T = 59ps$);$\epsilon \geq 99.9\%$

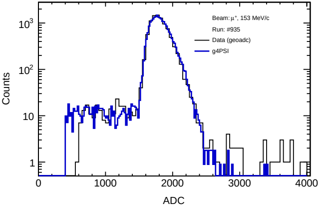


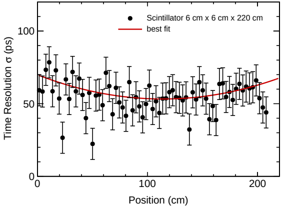


Meets requirements!

SCATTERED PARTICLE SCINTILLATOR (SPS)

- Based on CLAS12 FTOF12 system, built at USC
- 2 planes on each side of beam, all 4 walls complete
- 92 bars, double-ended readout





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

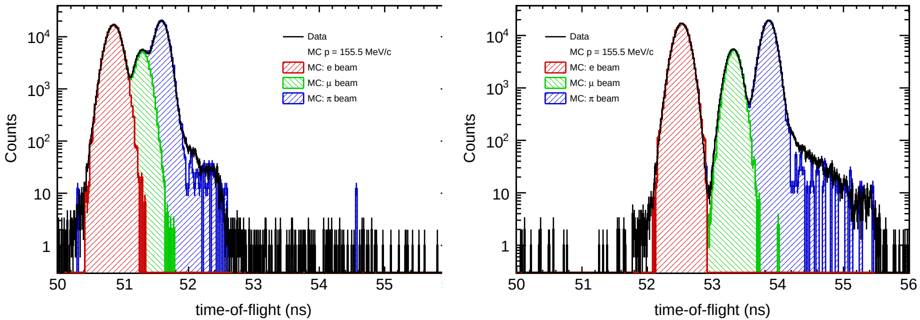
- 220 cm BC404 bars: $\sigma_{av.} = 52ps \pm 4ps$
- 120 cm BC404 bars: $\sigma_{av.} = 46ps \pm 4ps$

- 2-plane coincidence $\epsilon \geq 99.5\%$ for all particles, except for e^+ ($\epsilon \sim 99.0\%$)

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

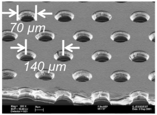
- **GEM = Gas Electron Multiplier**

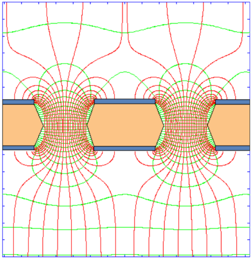
  introduced by F. Sauli in mid 90's, F. Sauli et al., NIMA 386 (1997) 531

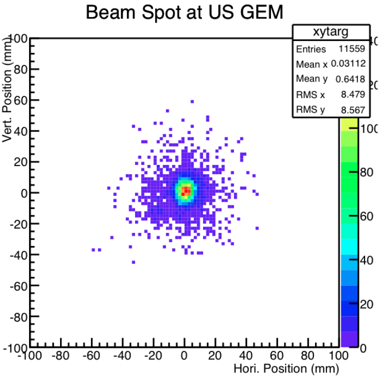
- **Copper layer-sandwiched Kapton foil (Apical) with chemically etched micro-hole pattern**

- **Supply ~400V across foil, immersed in Ar:CO_2 (70:30)**

⇨ gas amplification in the holes



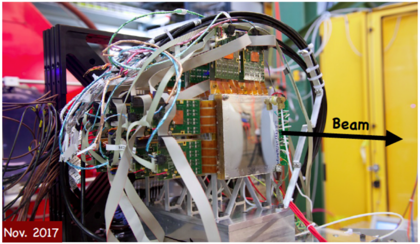




TRACKING DETECTORS: GEMS

- 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)

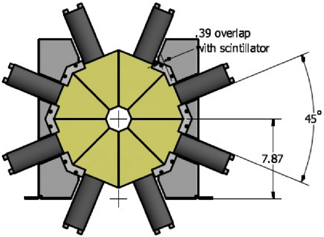


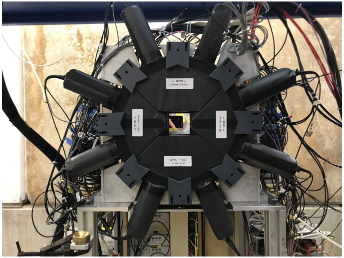
Parameter	Requirements	Achieved
Spatial Resolution	100μm/ element	✓ 70μm
Efficiency	98%	✓ $>$ 98%
Positioning	$\approx 0.1 mm$, $\approx 0.2 mr$	Not attempted; easy
Rate Capability	3.3 MHz / plane	✓ 5 MHz / plane
Readout Speed	3 kHz	2 kHz; Will be achieved with New VME crates

Meets requirements!

VETO DETECTOR (UNI. SOUTH CAROLINA)

- Annular 8-element VETO detector, surrounding target entrance window
- Eliminate upstream scattering and beam decays
- $\sigma_T \leq$ 200 ps (Goal was: 1 ns); $\epsilon >$ 99.0%





Meets requirements!

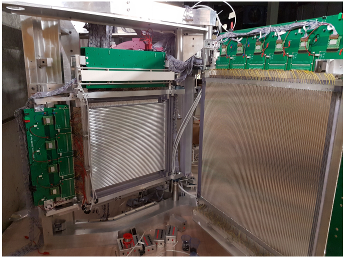
Straw Tube Tracker (STT)

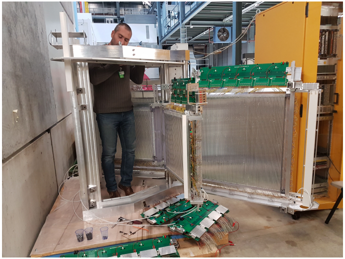
- Based on PANDA STT-design
- Built at HUJI, Temple
- 2 chambers, 5 planes each in x and y
- In total 2850 Straws
- Before: Readout $\rightarrow$ PADIWA/TRB3
- New Readout $\rightarrow$ PASTTREC/TRB3

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 all planes are ready, wire mapping in process



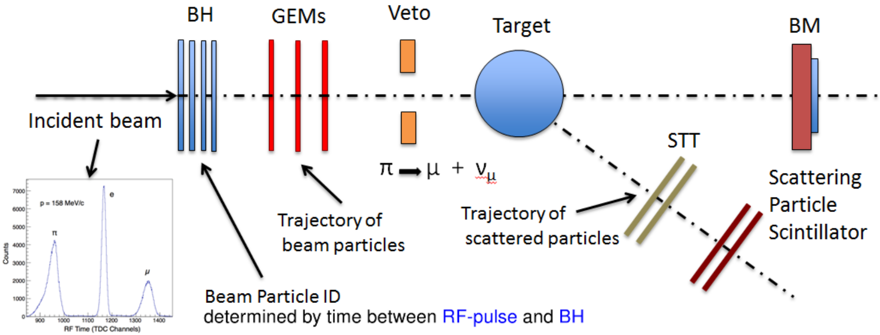


Summary of detectors

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)



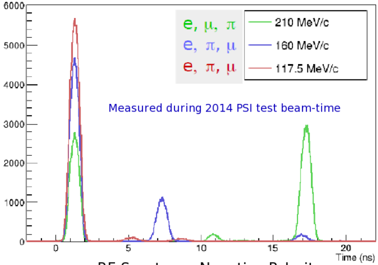
Trigger Logic: TRB3 FPGA-based:

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

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

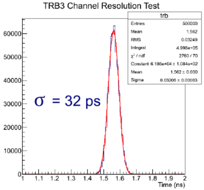
PID is the Hardest Part

MUSE DAQ (GWU & Montgomery College)



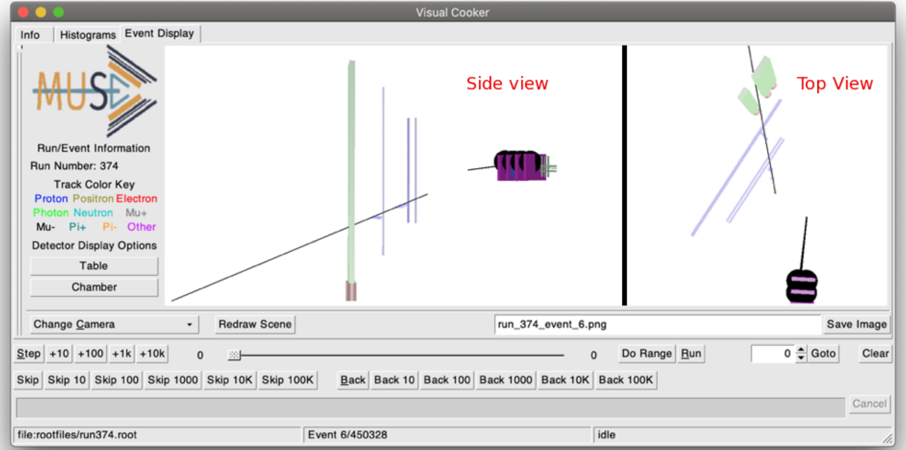
RF Spectrum, Negative Polarity

- 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

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

MUSE

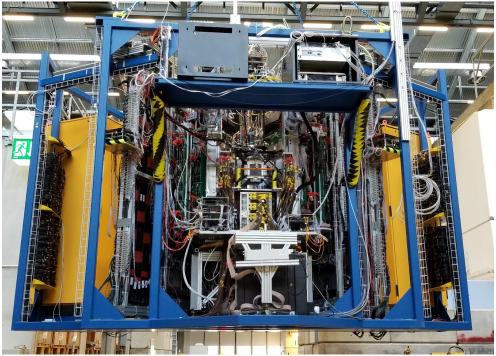
MUSE suited to verify 5.6σ effect (CODATA 2014) with even higher significance:

- 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)

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 $\rightarrow$ First Scattering Data
- 2019-2020: Data taking: 6 months / year
- 2020-2022: Data Analysis and Publications.

SUMMARY



- NSF, DOE, BSF, PSI, Uni-Basel fundings received
- MUSE will be the first muon scattering measurement with the required precision to address the Proton Radius Puzzle!

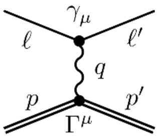
THANK YOU FOR YOUR ATTENTION!

Additional Slides

Additional Slides

PHYS. MOTIVATION: PROTON RADIUS

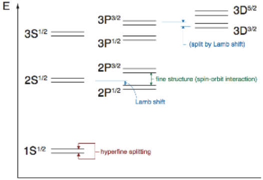
Lepton – Nucleon Scattering:



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

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

Hydrogen Spectroscopy:



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

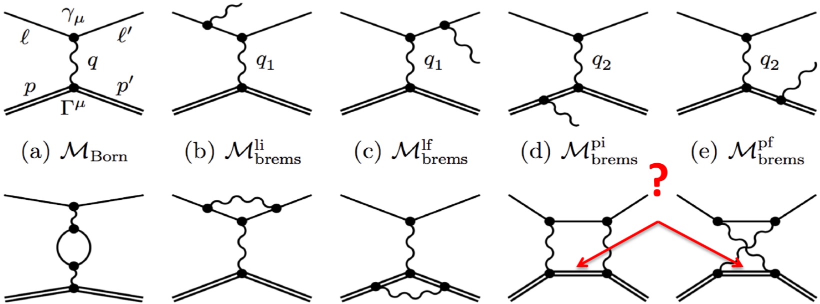
Point-like proton

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

Atomic wave function at origin

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

FEYNMAN DIAGRAMS (L AND NL ORDER)



(a) $\mathcal{M}_{\text{Born}}$ (b) $\mathcal{M}^{\text{li}}_{\text{brems}}$ (c) $\mathcal{M}^{\text{lf}}_{\text{brems}}$ (d) $\mathcal{M}^{\text{pi}}_{\text{brems}}$ (e) $\mathcal{M}^{\text{pf}}_{\text{brems}}$

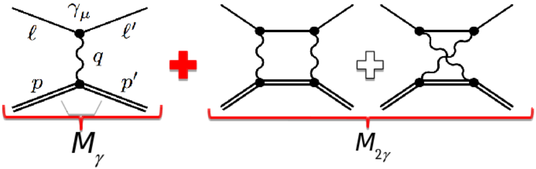
(f) $\mathcal{M}_{\text{vac}}$ (g) $\mathcal{M}^{\ell}_{\text{vert}}$ (h) $\mathcal{M}^{p}_{\text{vert}}$ (i) $\mathcal{M}_{\text{box}}$ (j) $\mathcal{M}_{\text{xbox}}$

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]

TPE CORRECTION

Two Photon Exchange **(TPE)** is the next-to-leading order correction that depends on nucleon structure:



$$\frac{d\sigma}{d\Omega}^{Born+TPE} = \left(\frac{\alpha}{4m_pQ^2}\frac{E'}{E}\right)^2 \left|M_\gamma + M_{2\gamma}\right|^2 = \left(\frac{\alpha}{4m_pQ^2}\frac{E'}{E}\right)^2 \left(\left|M_\gamma\right|^2 + 2\mathrm{Re}(M_\gamma^* M_{2\gamma}) + \left|M_{2\gamma}\right|^2\right)$$

0

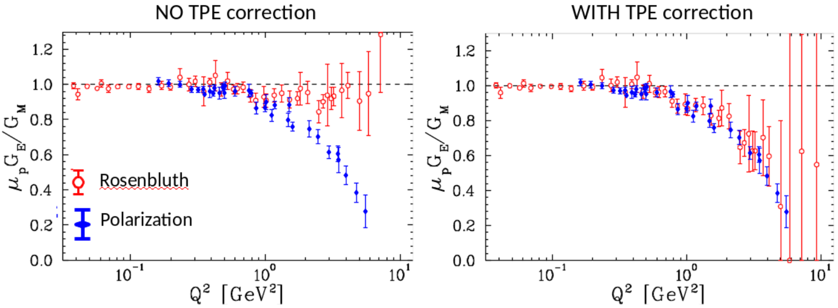
$$\frac{d\sigma}{d\Omega}^{Born+TPE} = \left(\frac{\alpha}{4m_pQ^2}\frac{E'}{E}\right)^2 \left|M_\gamma\right|^2 \left(1 + \frac{2\mathrm{Re}(M_\gamma^* M_{2\gamma})}{\left|M_\gamma\right|^2}\right) = \frac{d\sigma}{d\Omega}^{Born}\left(1+\delta_{2\gamma}\right); \quad \delta_{2\gamma} = \frac{2\mathrm{Re}(M_\gamma^* M_{2\gamma})}{\left|M_\gamma\right|^2}$$

TPE correction

Effect of the TPE correction

$$\frac{d\sigma}{d\Omega}^{Born+TPE} = \frac{d\sigma}{d\Omega}^{Born}\left(1+\delta^{TPE}\right) \Rightarrow \sigma_{red}^{Born+TPE} = \sigma_{red}^{Born}\left(1+\delta^{TPE}\right) = \tau F_M^2(Q^2) + \varepsilon F_E^2(Q^2)$$

$$F_M(Q^2) \rightarrow G_M(Q^2) \qquad F_E(Q^2) \rightarrow G_E(Q^2)$$



[*] J. Arrington, W. Melnitchouk and J. A. Tjon, Global analysis of proton elastic form factor data with two-photon exchange corrections, PhysRev C **76**, 035205 (2007)

PHYS. MOTIVATION: TPE

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

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

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

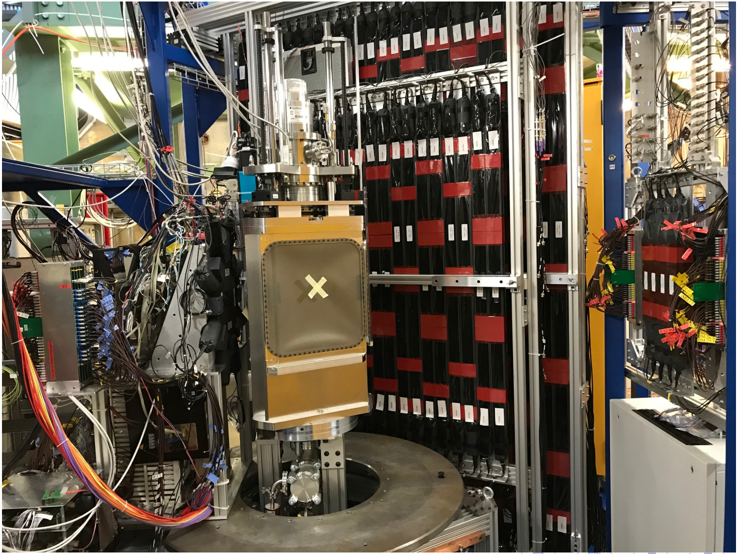
Charge independent: δ_{even}

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

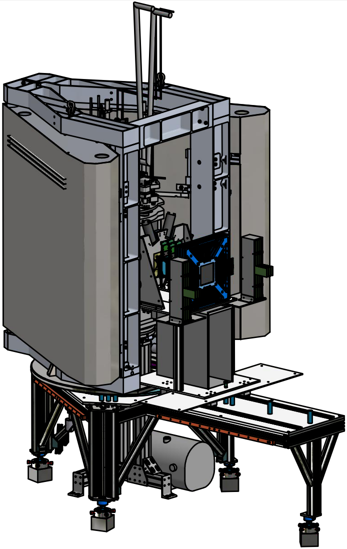
$$R = \frac{\sigma(e^+p)}{\sigma(e^-p)} = \frac{\left(1 - \delta_{2\gamma} - \delta_{brem} + \delta_{even}\right)}{\left(1 + \delta_{2\gamma} + \delta_{brem} + \delta_{even}\right)} \approx 1 - 2\frac{\delta_{2\gamma} + \delta_{brem}}{1 + \delta_{even}}$$

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

Detector Setup

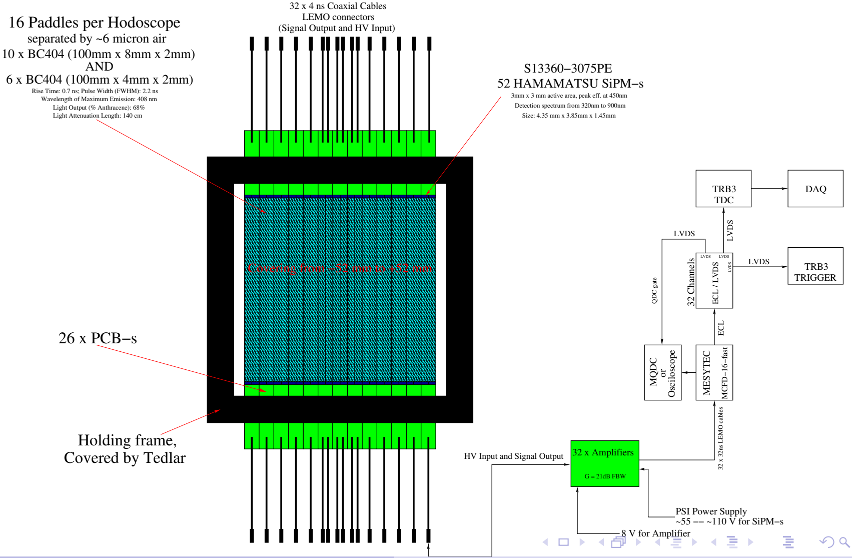


TABLE



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

BH FINAL DESIGN



Ham. S13360–3075PE Radiation tests results

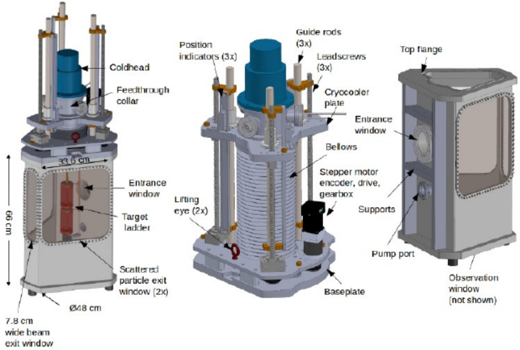
(100mm x 4mm x 2mm) BC422 + S13360-3075PE

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

Liquid Hydrogen Target

- Construction by U.Mich., PSI, CREARE
- Safety review passed (PSI; Aug.2018)



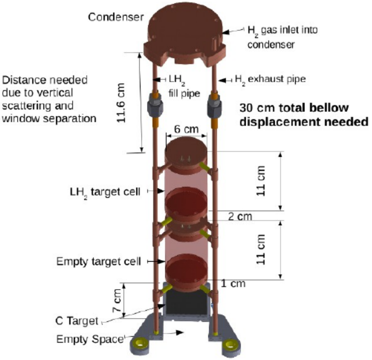


FIG. 21. A schematic view of the target ladder.