Columbian College
of Arts & Sciences
THE GEORGE WASHINGTON UNIVERSITY

MUSE: muon proton scattering at PSI

E. J. Downie

on behalf of the

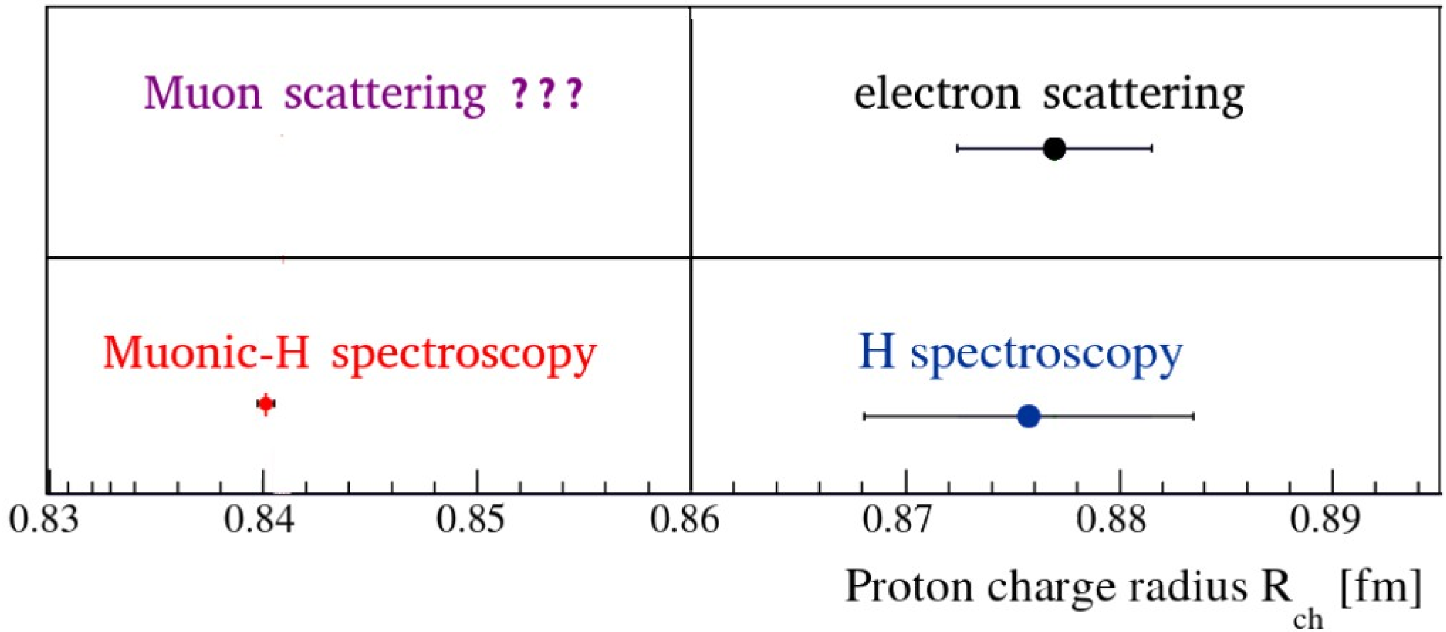
MUSE Collaboration

Award DE-SC0012485

Awards PHY-1614850,1714833

THE GEORGE WASHINGTON UNIVERSITY
WASHINGTON, DC

Why MUSE?



- Simultaneous measurement of e^+/μ^+ e^-/μ^- at beam momenta of 115, 153, 210 MeV/c in πM1 channel at PSI allows:
  - ➔ Determination of two photon effects
  - ➔ Test of lepton universality
  - ➔ Simultaneous determination of proton radius in both eP and μP scattering

MUSE Timeline

- 2011: Ron Gilman, Michael Kohl & Gerry Miller come up with 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)
- In between, many BVRs; reviews; test beams etc.
- Funded by NSF, NSF/BSF & DOE grants to:
  GW, Hampton, HUJI, Rutgers, TAU, Temple, U. Michigan, USC
- In-kind support from PSI (manpower, power supplies, equipment)
- Now: MUSE under construction @PSI
- Data taking: 6 months / year in 2019 & 2020

How many people do you need? - MUSE membership

Technical Design Report

for the

Paul Scherrer Institute Experiment R-12-01.1:
Studying the Proton "Radius" Puzzle with μp Elastic Scattering

June 1, 2017

The MUon Scattering Experiment collaboration (MUSE):

R. Gilman (Contact person),[1] E.J. Downie (Spokesperson),[2] G. Ron (Spokesperson),[3] S. Strauch (Spokesperson),[4] A. Afanasev,[2] A. Akmal,[5] J. Arrington,[6] H. Atac,[7] C. Ayerbe-Gayoso,[8] F. Benmokhtar,[9] N. Benmouna,[5] J. Bernauer,[10] A. Blomberg,[7] W. J. Briscoe,[2] D. Cioffi,[2] E. Cline,[1] D. Cohen,[3] E. O. Cohen,[11] C. Collicott,[12] K. Deiters,[13] J. Diefenbach,[12] B. Dongwi,[14] D. Ghosal,[15] A. Golossanov,[2] R. Gothe,[4] D. Higinbotham,[16] D. Hornidge,[17] Y. Ilieva,[4] N. Kalantarians,[14] M. Kohl,[14] B. Krusche,[15] G. Kumbartzki,[1] I. Lavrukhin,[2] L. Li,[4] J. Lichtenstadt,[11] W. Lin,[1] A. Liyanage,[14] W. Lorenzon,[18] K. E. Mesick,[19] Z.-E. Meziani,[7] P. Mohanmurthy,[10] P. Moran,[7] J. Nazeer,[14] E. Piasetzsky,[11] R. Ransome,[1] R. Raymond,[18] D. Reggiani,[13] P.E. Reimer,[6] A. Richter,[20] T. Rostomyan,[1] P. Roy,[18] A. Sarty,[21] Y. Shamai,[22] N. Sparveris,[7] N. Steinberg,[18] I. Strakovsky,[2] V. Sulkosky,[23] A.S. Tadepalli,[1] and M. Taragin[24]

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[2] *George Washington University, Washington, DC, USA*
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[4] *University of South Carolina, Columbia, South Carolina, USA*
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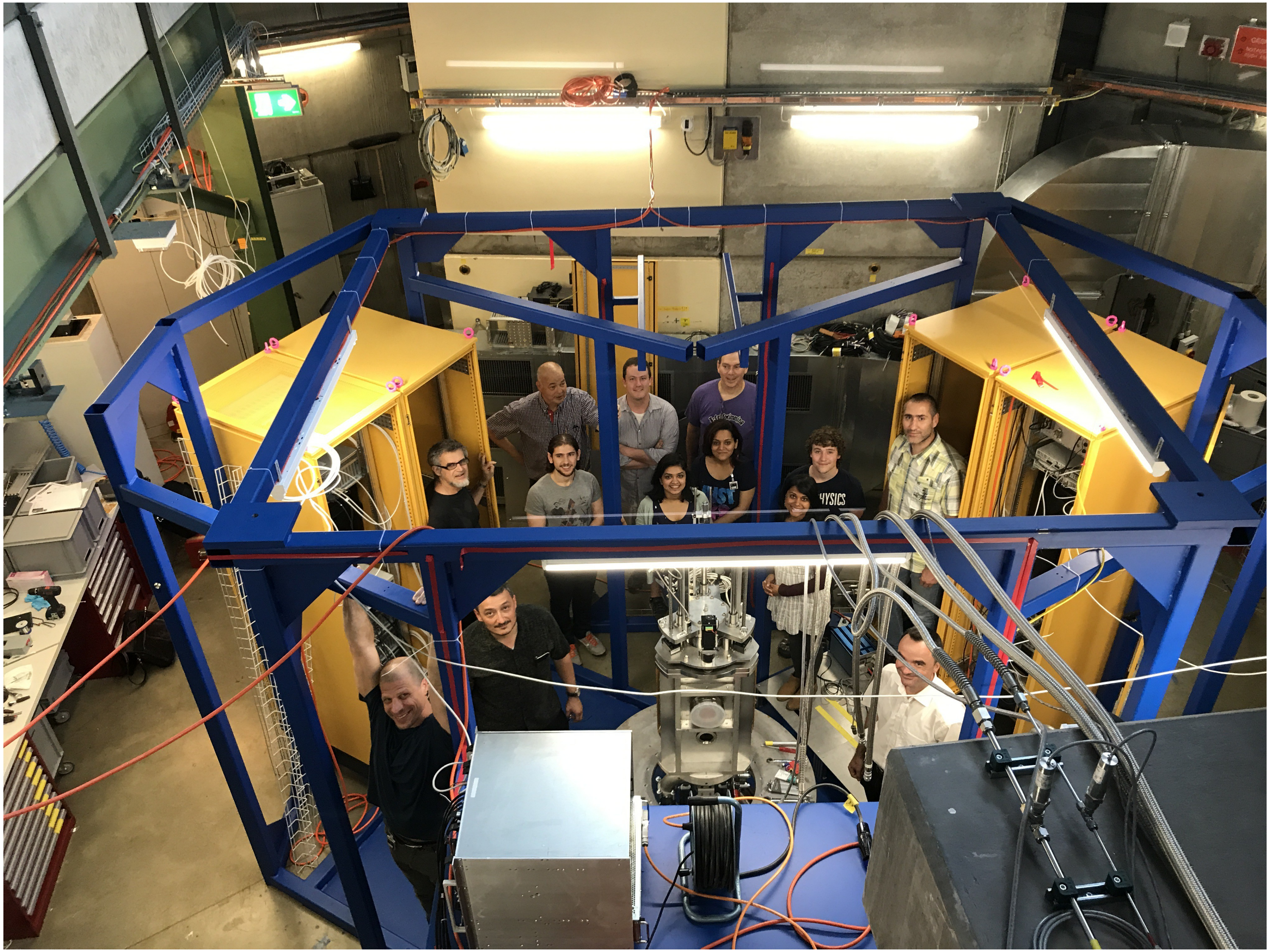
[6] *Argonne National Lab, Argonne, IL, USA*
[7] *Temple University, Philadelphia, Pennsylvania, USA*
[8] *College of William & Mary, Williamsburg, Virginia, USA*
[9] *Duquesne University, Pittsburgh, PA, USA*
[10] *Massachusetts Institute of Technology, Cambridge, Massachusetts, USA*
[11] *Tel Aviv University, Tel Aviv, Israel*
[12] *Johannes Gutenberg-Universität, Mainz, Germany*
[13] *Paul Scherrer Institut, CH-5232 Villigen, Switzerland*
[14] *Hampton University, Hampton, Virginia, USA*
[15] *University of Basel, Switzerland*
[16] *Jefferson Lab, Newport News, Viginia, USA*
[17] *Mount Alison University, New Brunswick, Canada*
[18] *University of Michigan, Ann Arbor, Michigan, USA*
[19] *Los Alamos National Laboratory, Los Alamos, NM, USA*
[20] *Technical University of Darmstadt, Darmstadt, Germany*
[21] *St. Mary's University, Halifax, Nova Scotia, Canada*
[22] *Soreq Nuclear Research Center, Israel*
[23] *University of Virginia, Charlottesville, Virginia, USA*
[24] *Weizmann Institute, Rehovot, Israel*

- ~60 MUSE collaborators from 24 institutions in 5 countries
- Funded by 5 agencies
- Technical Design Report:

  arXiv:1709.09753 [physics.ins-det]

How many people do you need? - MUSE membership



Paul Scherrer Institute πM1 Beam

- 590 MeV proton beam, 2.2mA, 1.3 MW beam, 50.6 MHz RF frequency
- World's most powerful proton beam
  - ➔ Secondary $e^{\pm}$, $\mu^{\pm}$, $\pi^{\pm}$ in piM1 beamline
- Separate out particle species by timing relative to beam RF
- Cut as many pions as possible, trigger on $e^{\pm}$, $\mu^{\pm}$

MUSE Experiment

$\theta \approx 20^o - 100^o$

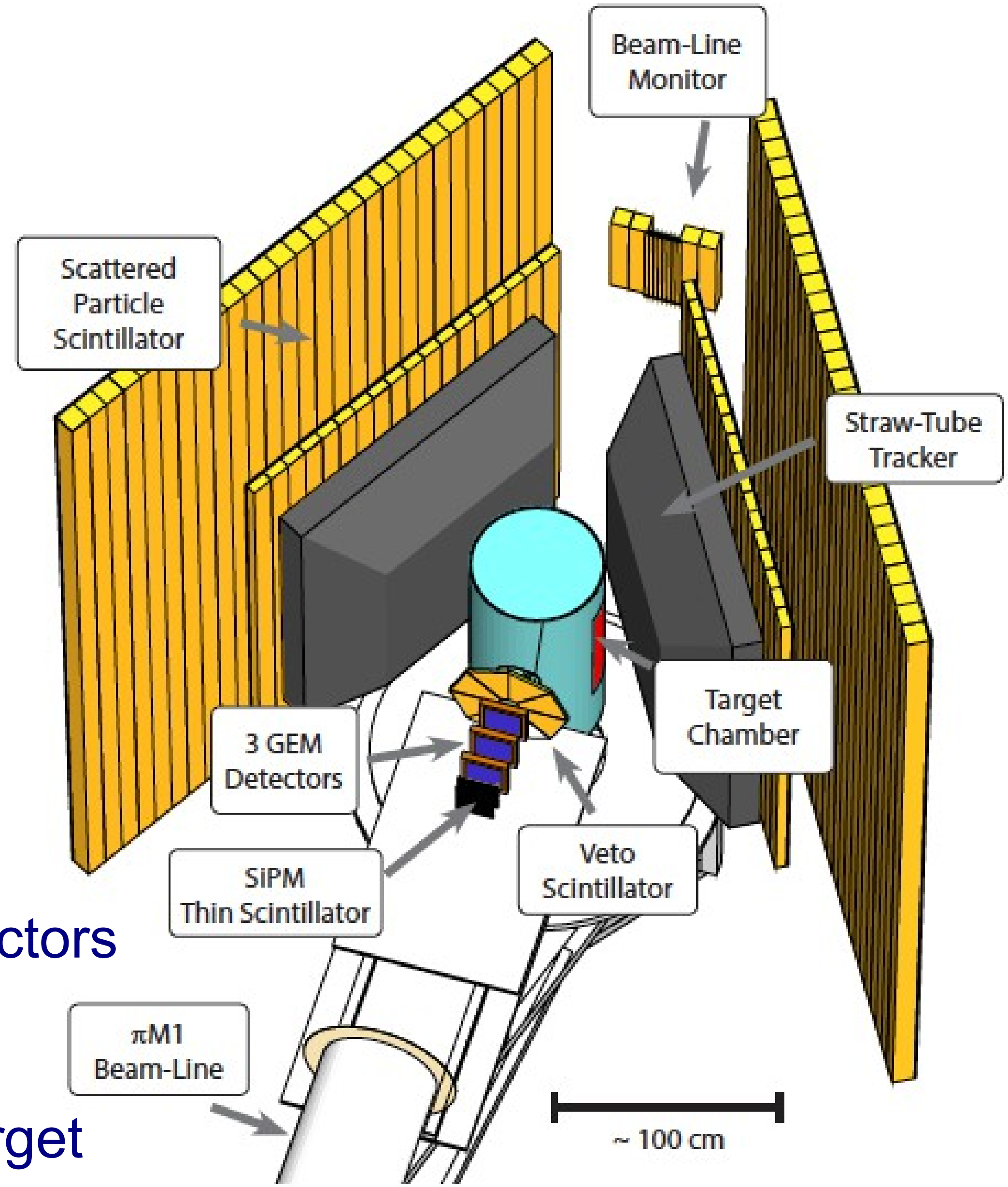
$Q^2 \approx 0.002$ - 0.07 GeV^2

3.3 MHz total beam flux

≈ 2-15% μ's

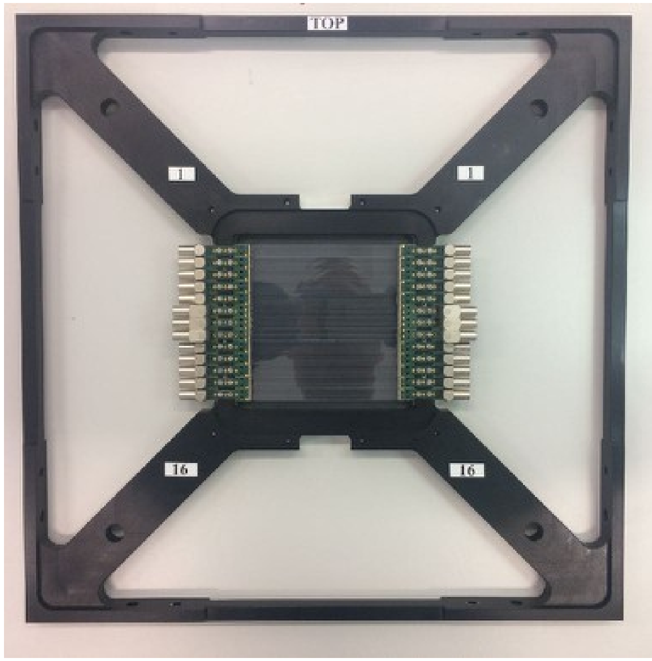
≈ 10-98% e's

≈ 0-80% π's



- Low beam flux
  - ➔ Large angle, non-magnetic detectors
- Secondary beam
  - ➔ Tracking of beam particles to target
- Mixed beam
  - ➔ Identification of beam particle in trigger

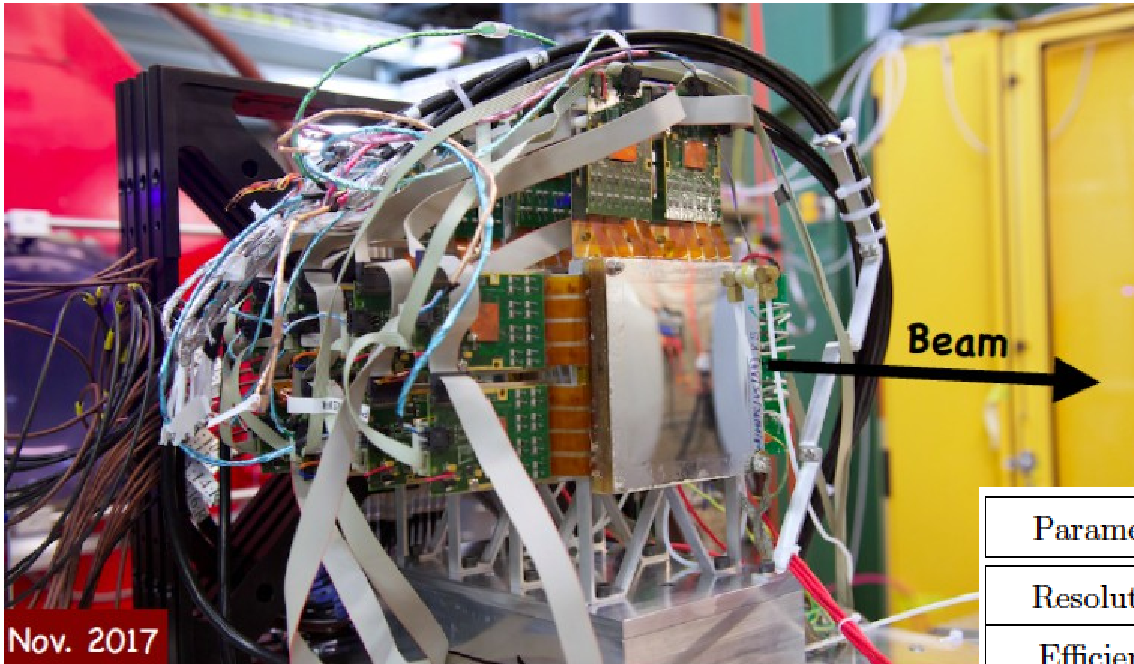
SiPM Detector (TAU, Rutgers, PSI)



Parameter	Performance Requirement	Achieved
Time Resolution	<100 ps / plane	✓ 80 ps
Efficiency	99%	✓ 99.8%
Positioning	≈1 mm, ≈1 mr	not attempted; easy – calibrated by data
Rate Capability	3.3 MHz / plane	✓ >10 MHz / plane

- Provides timing vs. beam RF for trigger PID, precise offline analysis
- Distinguishes muon scattering and decay using Δt with SPS
- Thin (2mm) BC-404 read out by Hamamatsu S13360-3075PE SiPMs
- 16 per plane, double ended readout, 2-4 planes depending on beam
- Extensively prototyped, exceeds requirements
- Completely built at PSI

GEM Chambers (Hampton)

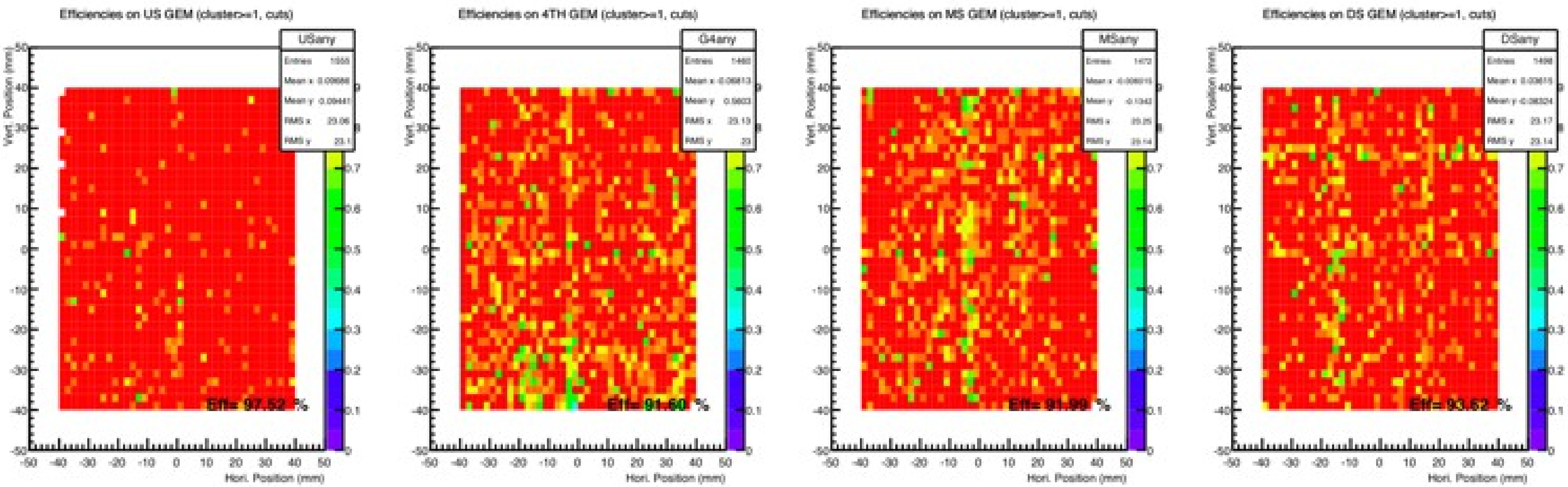


Parameter	Performance Requirement	Achieved
Resolution	100 μm / element	✓ 70 μm
Efficiency	98%	✓ 98%
Positioning	≈0.1 mm, ≈0.2 mr	not attempted; easy
Rate Capability	3.3 MHz / plane	✓ 5 MHz
Readout Speed	2 kHz / 20% deadtime	1 kHz / 100% deadtime

- Set of 3 10cm x 10cm GEM detectors built for & run in OLYMPUS
- Incident track angle to ~0.5 mr intrinsic; <5 mr multiple scattering
- Third GEM to reject ghost tracks
- Fourth element added for test beams to determine efficiencies etc.

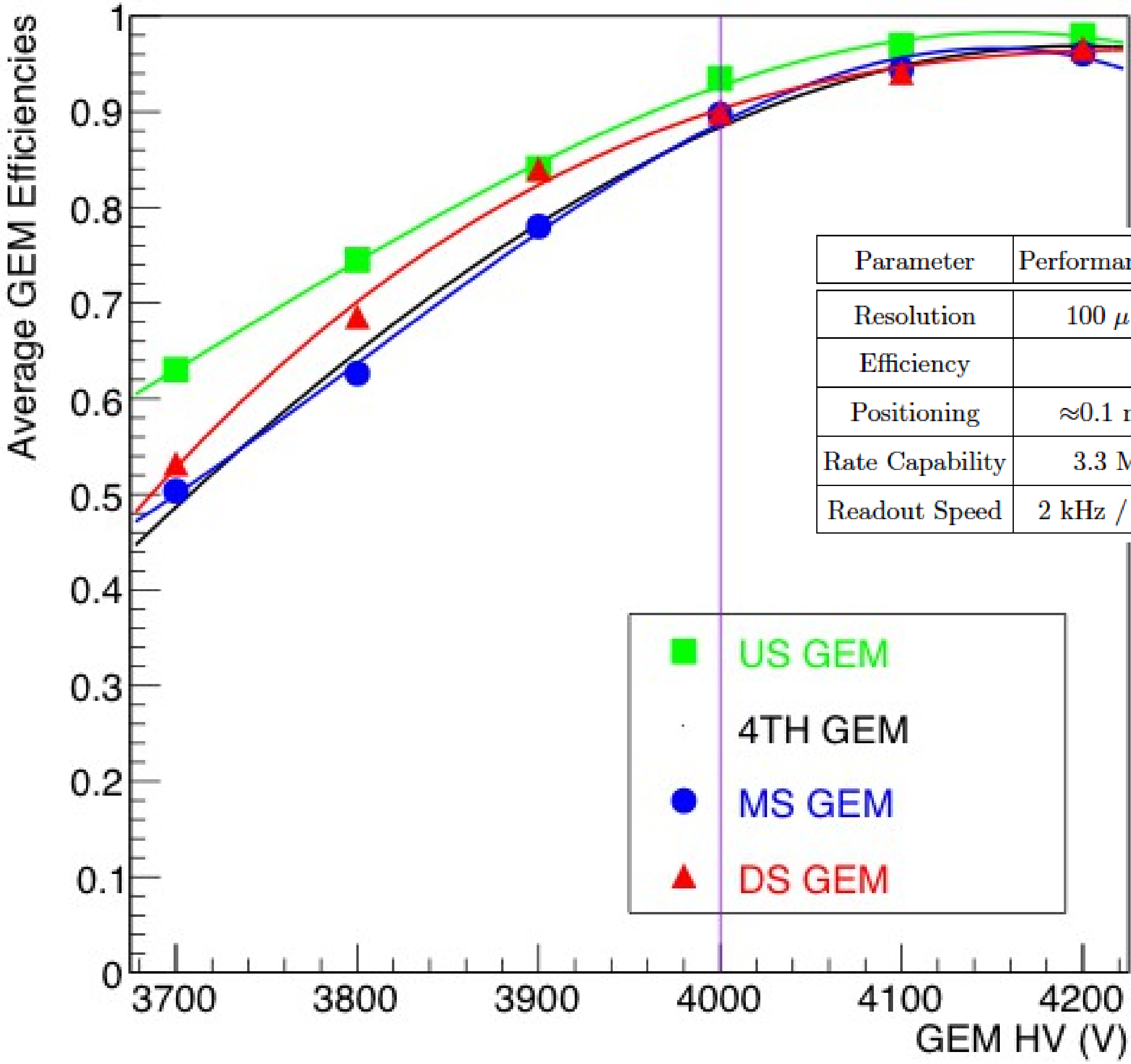
GEM Chambers (Hampton)

Parameter	Performance Requirement	Achieved
Resolution	100 μm / element	✓ 70 μm
Efficiency	98%	✓ 98%
Positioning	$\approx$0.1 mm, $\approx$0.2 mr	not attempted; easy
Rate Capability	3.3 MHz / plane	✓ 5 MHz
Readout Speed	2 kHz / 20% deadtime	1 kHz / 100% deadtime



- **De-focused** beam (quadrupoles off)
- Events with 1 cluster in each of 3 GEMs for candidate track
- Project track onto fourth GEM element –
  evaluate whether there was a cluster within +-10mm in X and Y
- Obtain efficiency map for each GEM element

GEM Chambers (Hampton)

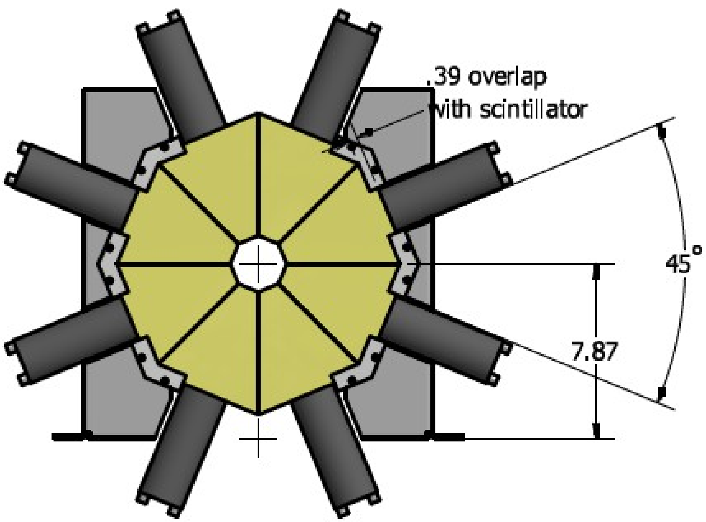


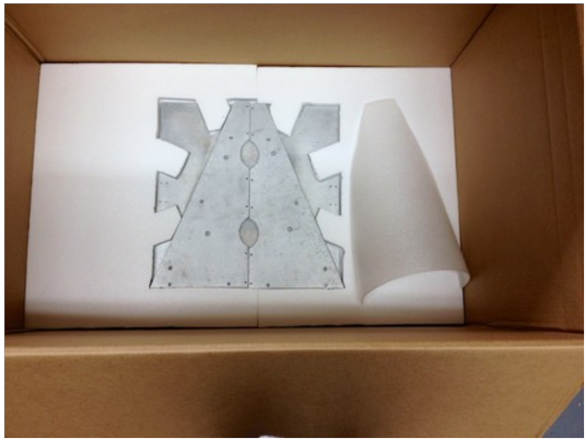
Parameter	Performance Requirement	Achieved
Resolution	100 μm / element	✓ 70 μm
Efficiency	98%	✓ 98%
Positioning	≈0.1 mm, ≈0.2 mr	not attempted; easy
Rate Capability	3.3 MHz / plane	✓ 5 MHz
Readout Speed	2 kHz / 20% deadtime	1 kHz / 100% deadtime

Veto Detector (USC)

- Annular 8-element veto detector surrounding target entrance window
- Eliminate upstream scattering & beam decays
- Completed and arrived at PSI on July 2

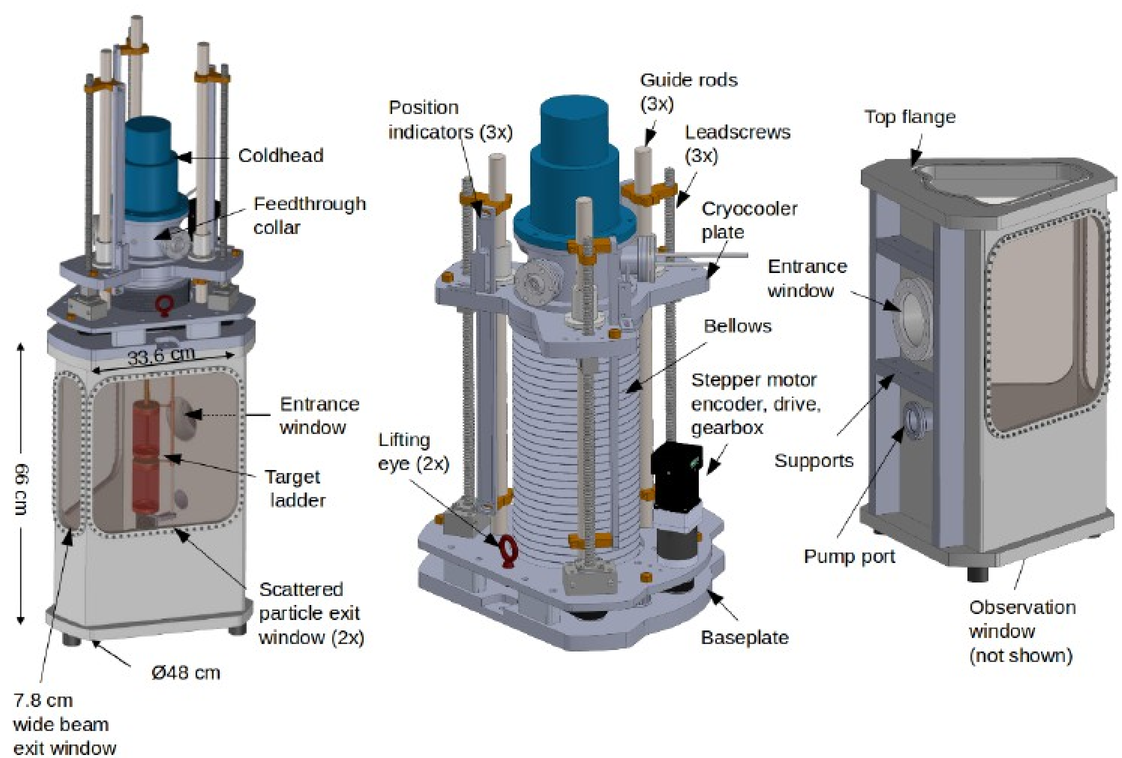
Parameter	Performance Requirement	Achieved
Time Resolution	1 ns / plane	not attempted; easy
Efficiency	99%	not attempted; easy
Positioning	$\approx$1 mm, $\approx$1 mr	not attempted; easy
Rate Capability	1 MHz / plane	not attempted; easy





Liquid Hydrogen Target (U.Mich.)

- Construction by U.Mich., PSI, CREARE
- Assembled at PSI
- Multiple successful cool-downs with Ne
- Hydrogen exhaust system constructed
- Safety review scheduled for Wed 22nd Aug.



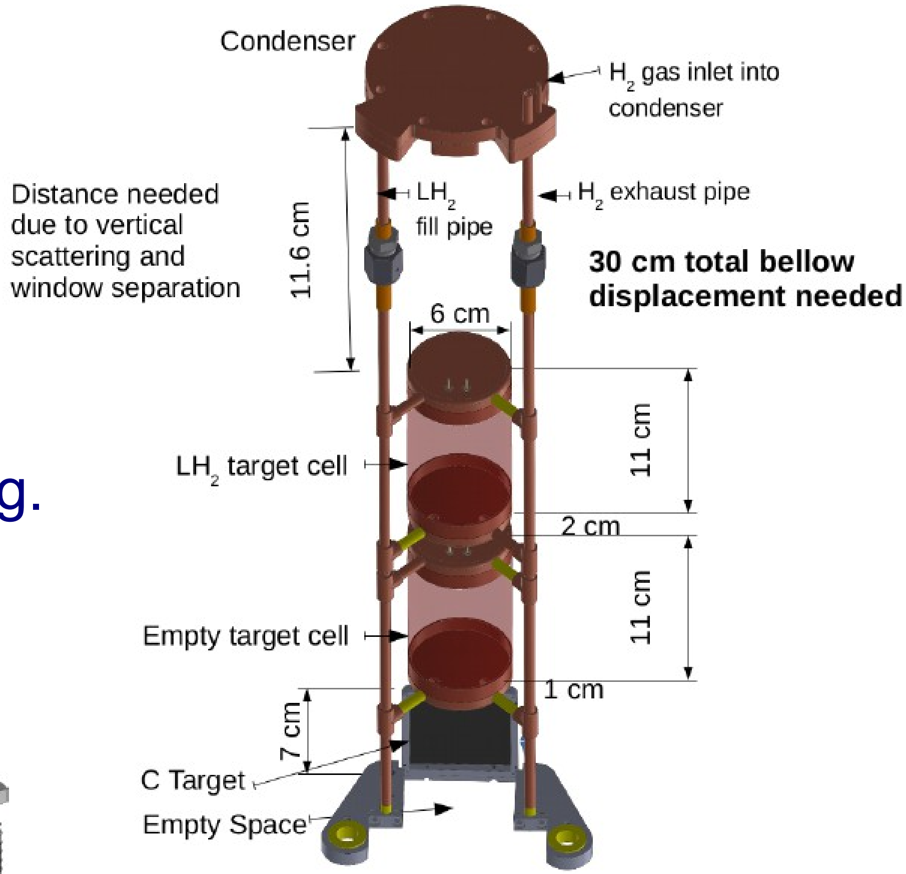
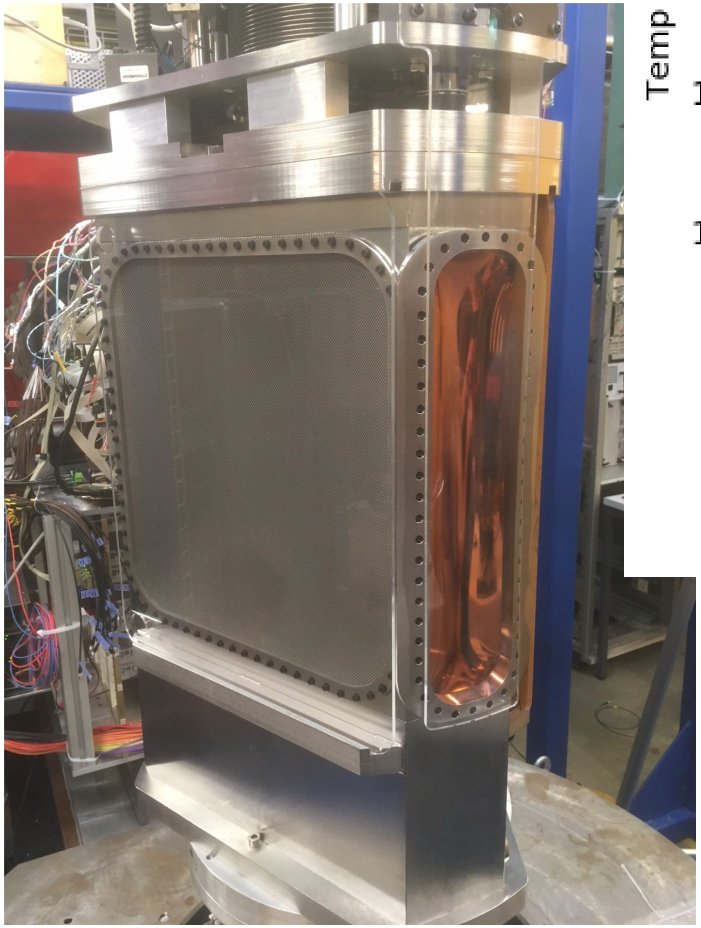
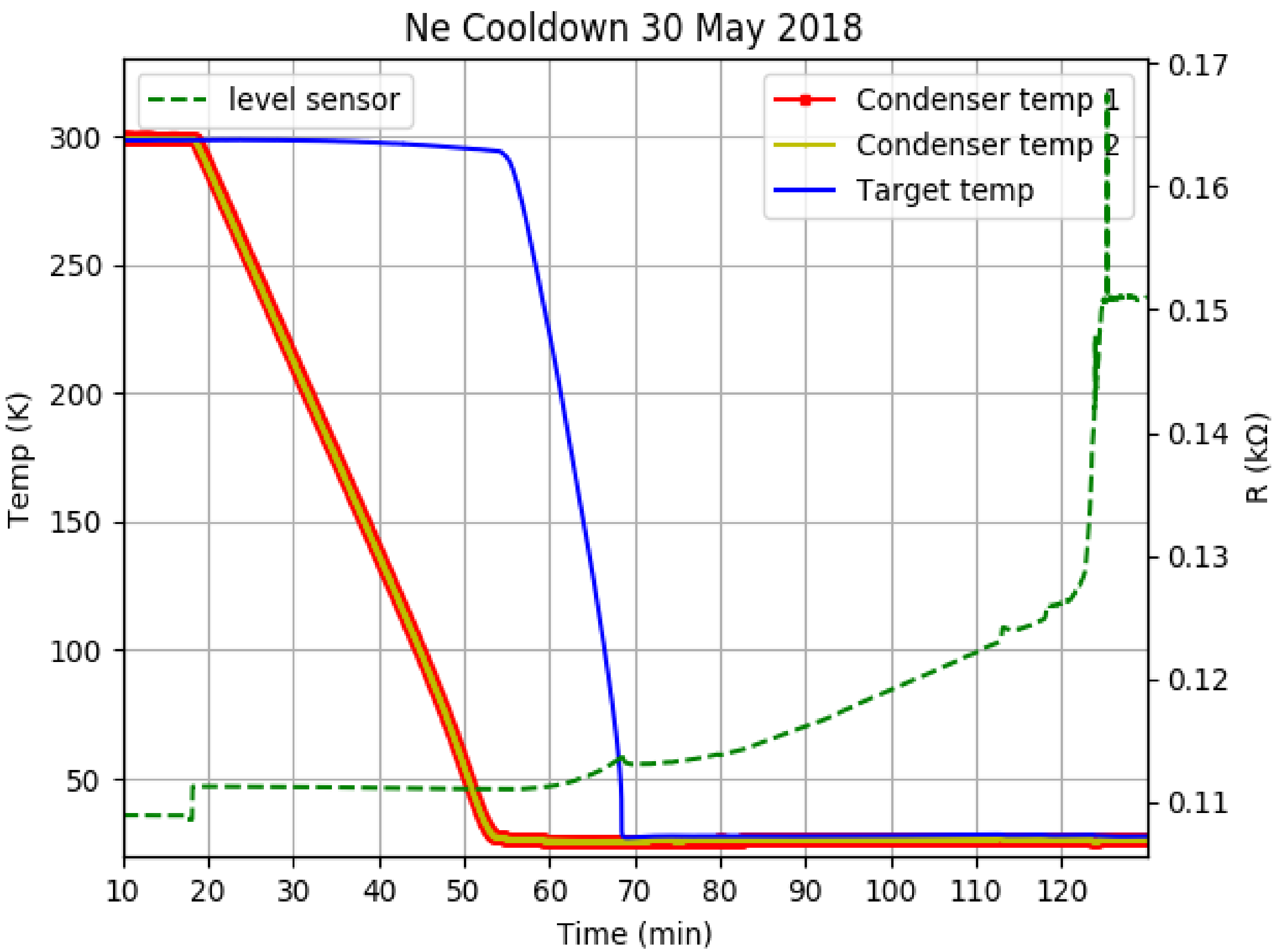


FIG. 21. A schematic view of the target ladder.

Liquid Hydrogen Target (U.Mich.)

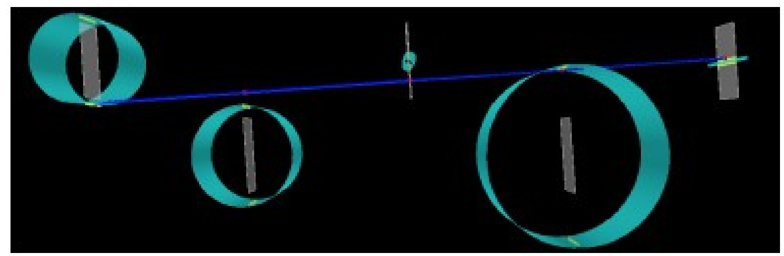
- Ne cool-down curves
- Target in place
- Tight fit!





Straw Tube Tracker (HUJI, Temple)

Parameter	Performance Requirement	Achieved
Position Resolution	150 μm	✓ <120 μm
Efficiency	99.8% tracking	$\approx$ 99% in prototype; moderate
Positioning	$\approx$0.1 mm, 0.2 mr in θ	not attempted; moderate
Positioning	$\approx$0.5 mr pitch, yaw, roll	not attempted; moderate
Positioning	50 μm wire spacing	not attempted; moderate
Rate Capability	0.5 MHz	not attempted; easy

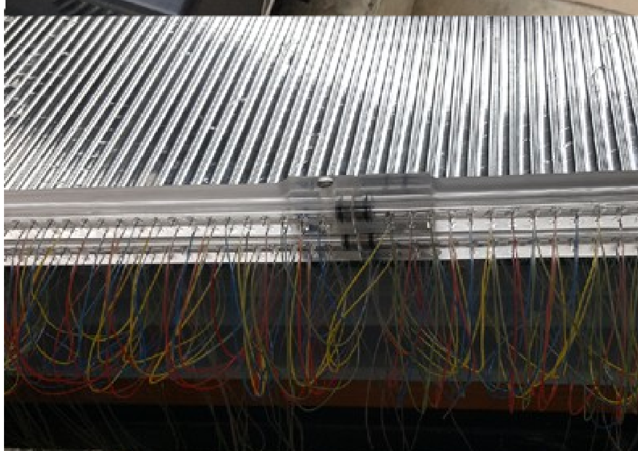


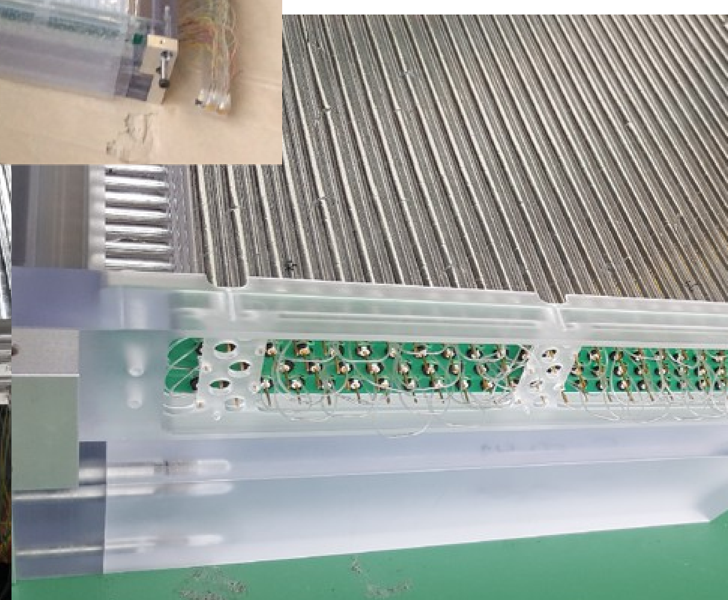
- Based on PANDA straw tube tracker design
- 2 chambers with 5 planes each in x and y, 2850 straws

Chamber	Distance (cm)	Active Area (cm^2)	Number of Straws per Chamber
Front	30	60×55	575
Back	45	90×80	850

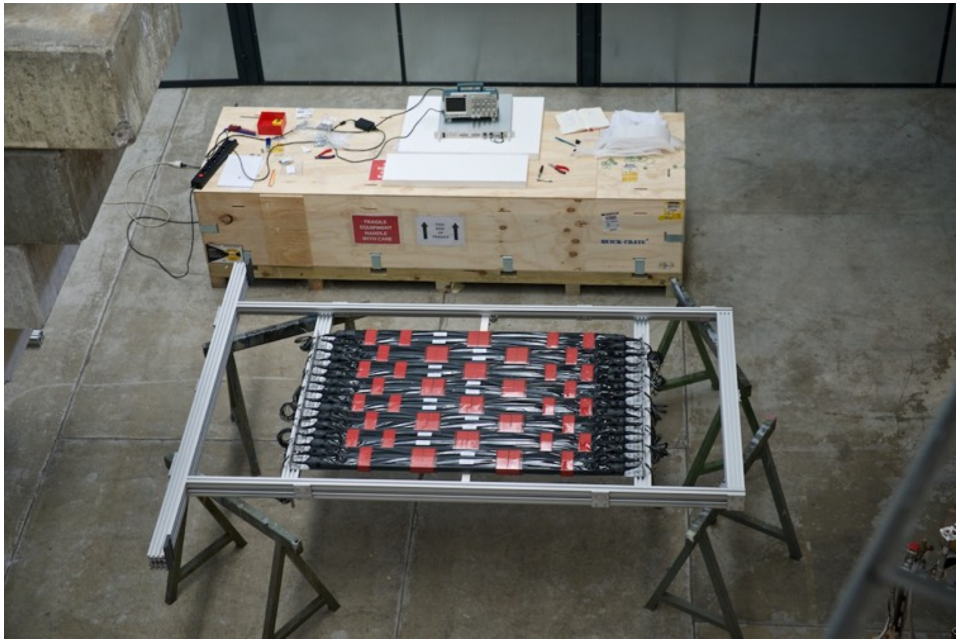
Straw Tube Tracker (HUJI, Temple)

- Switched to PASTTREC readout
- Allows operation to design parameters
- 3 chambers / 4 completed
- Final chamber under construction
- STT electronics “critical path”





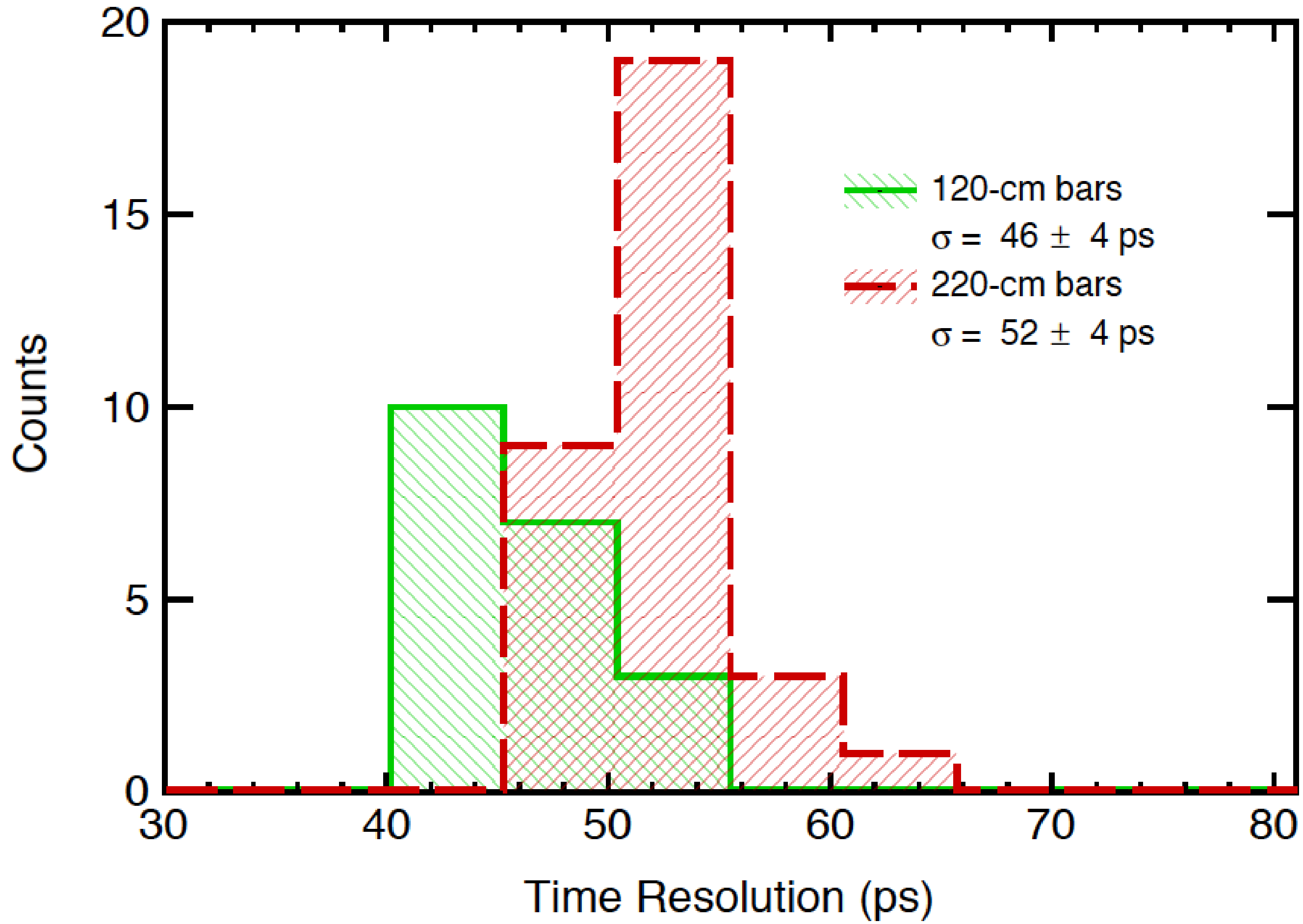
Scattered Particle Scintilators & Beam Monitor (USC)



- Two planes on each side of beam, all four planes complete
- 92 bars, double-ended readout
- 55 ps achieved

Parameter	Performance Requirement	Achieved
Time Resolution	≈60 ps / plane	✓ 55 ps
Efficiency	99%, ≪ 1% paddle to paddle uncertainty	✓ 99%, paddle to paddle not attempted, moderate
Positioning	≈1 mm, ≈1 mr	not attempted; easy
Rate Capability	0.5 MHz / paddle	✓ 1 MHz

Scattered Particle Scintilators & Beam Monitor (USC)



Parameter	Performance Requirement	Achieved
Time Resolution	≈60 ps / plane	✓ 55 ps
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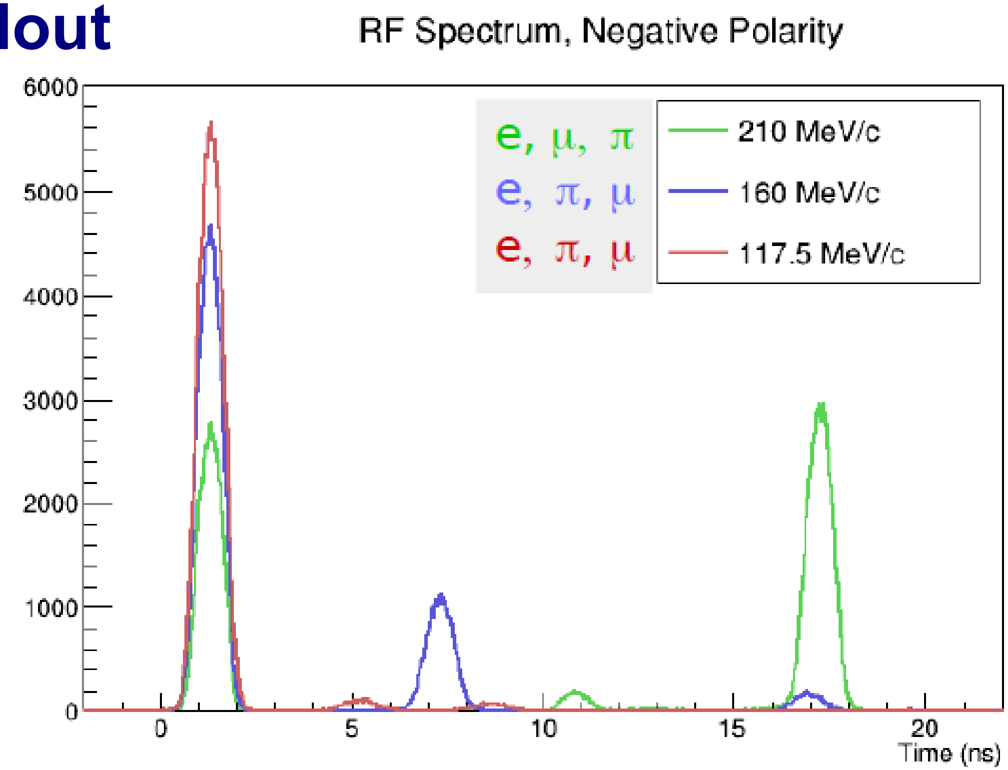
Positioning	≈1 mm, ≈1 mr	not attempted; easy
Rate Capability	0.5 MHz / paddle	✓ 1 MHz

Readout



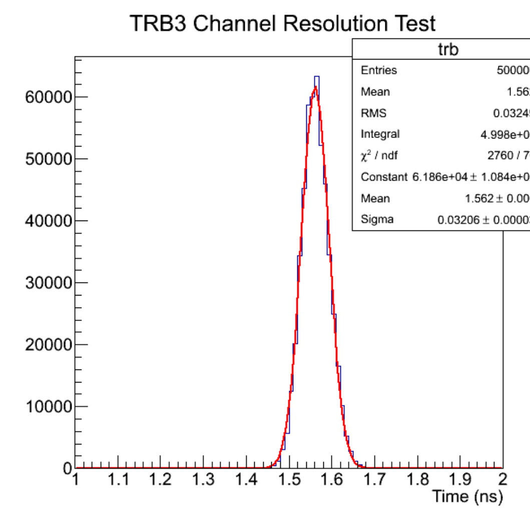
Measured timing differences from 2014 PSI test beam time

DAQ system (GWU & Montgomery College)

- 3000 TDC, 500 ADC channels
- TRB3-based read-out
- Mesytec MQDC-32 ADCs mostly for timing correction

Trigger (Rutgers)

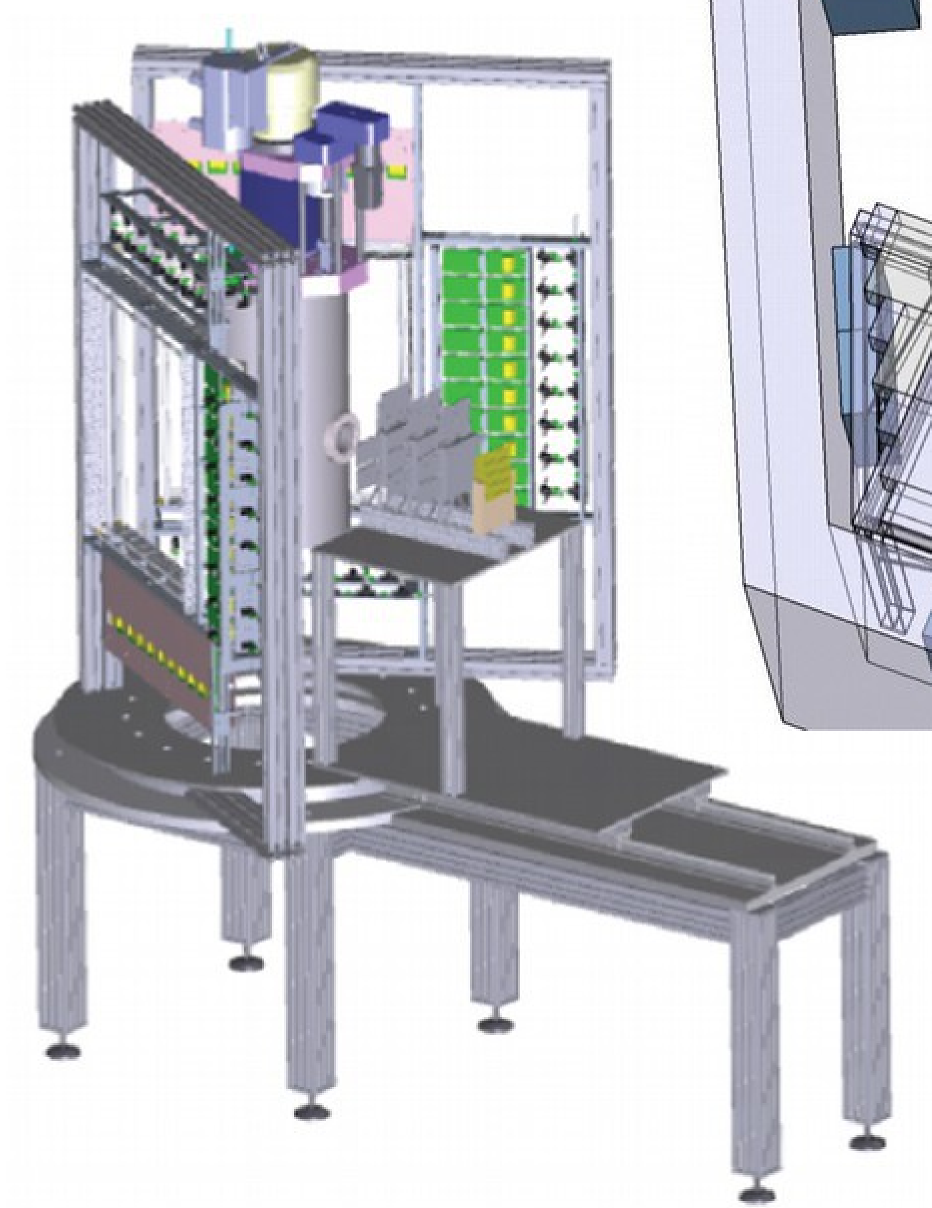
- TRB3 FPGA-based, accept $e^{\pm}$, $\mu^{\pm}$, reject $\pi^{\pm}$
- SiPM PID && Scattered Particle (LUT) && NOT(veto)
- PID determined by time between RF pulse and SiPM

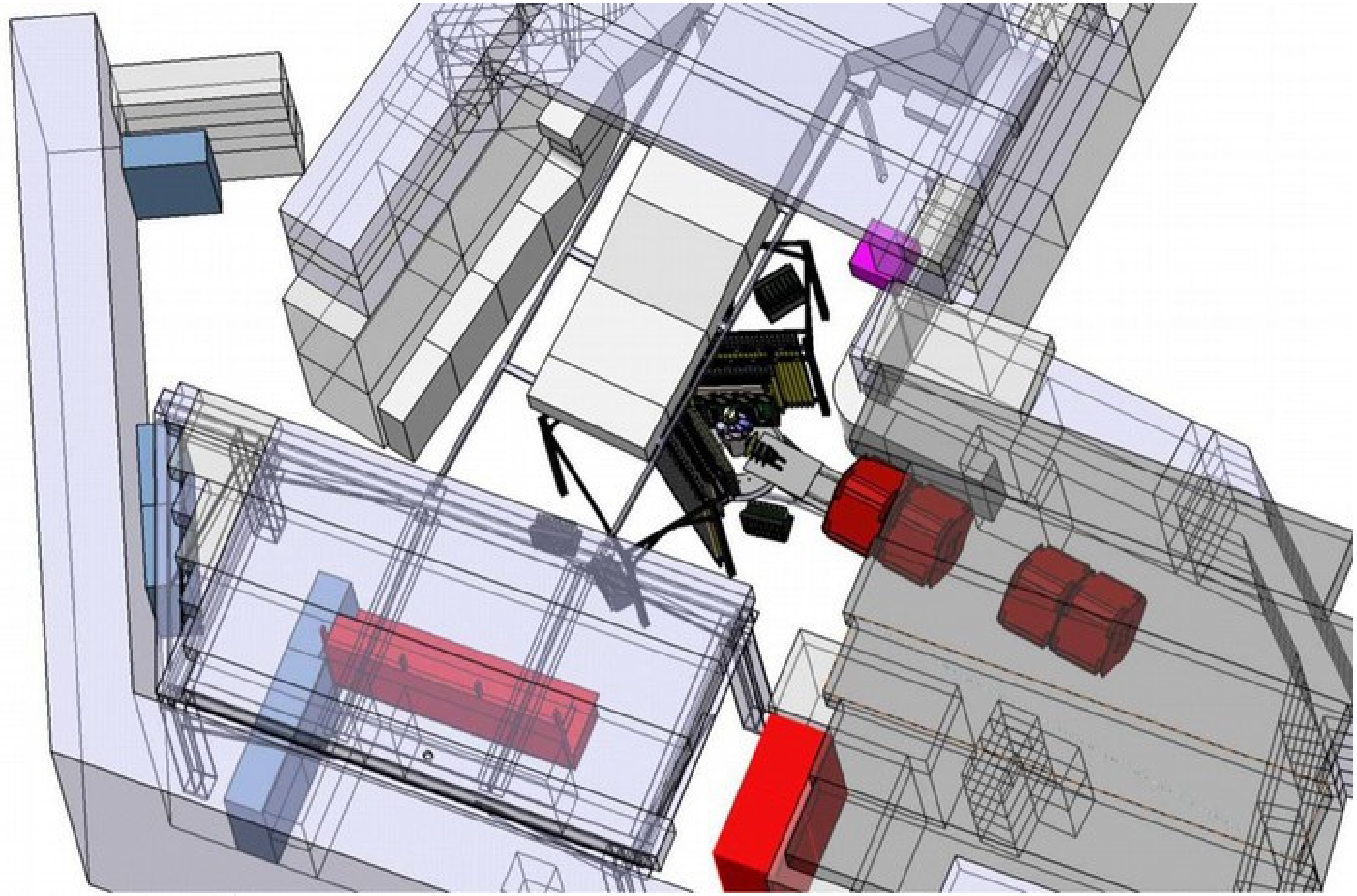


Relative timing test,

σ = 32 ps

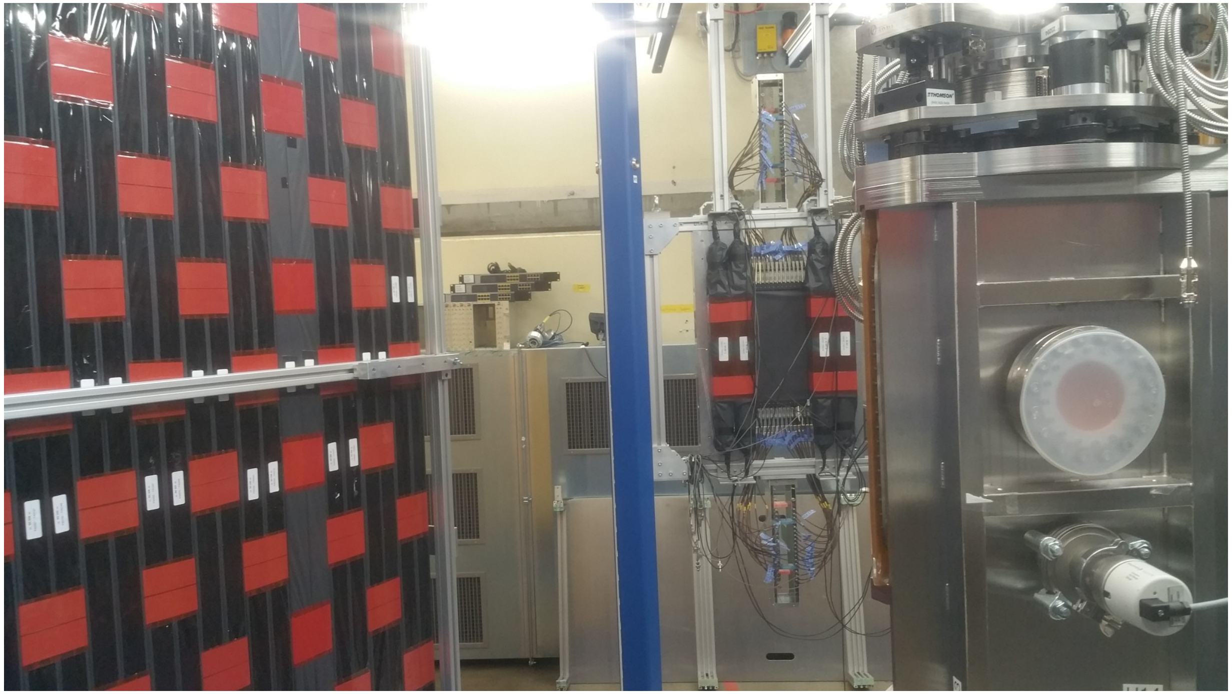
Mechanical Assembly (ANL & PSI)





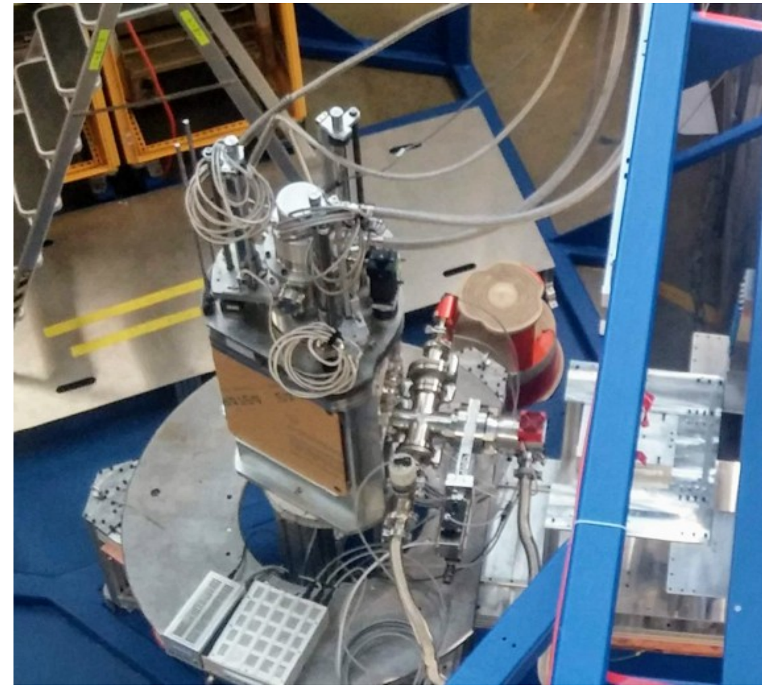
- Rotating table
- Retractable beam tracker
- Dedicated alignment procedures

Mechanical Assembly (ANL & PSI)

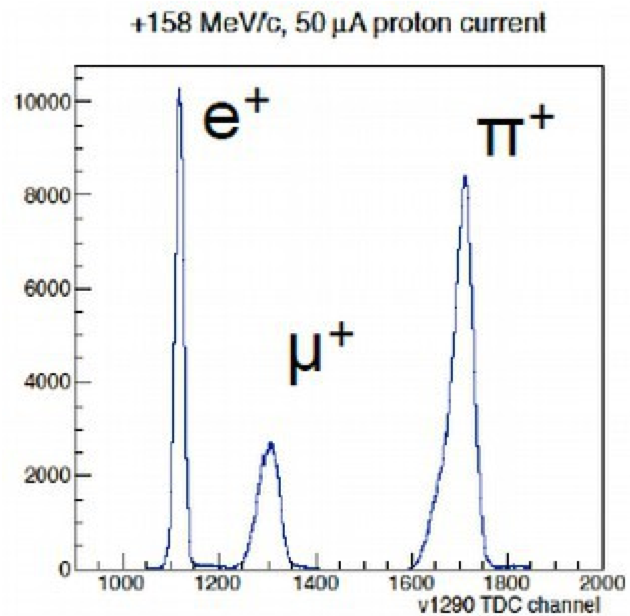


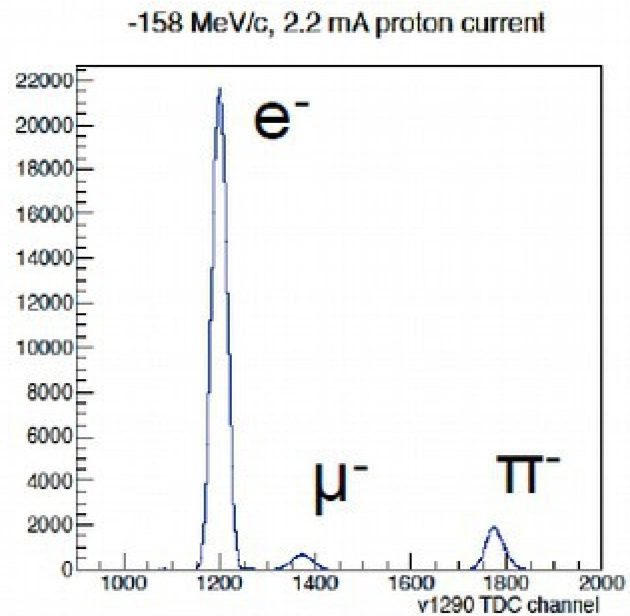
- Detectors mostly assembled
- Installation underway
- Alignment is critical

Mechanical Assembly (ANL & PSI)



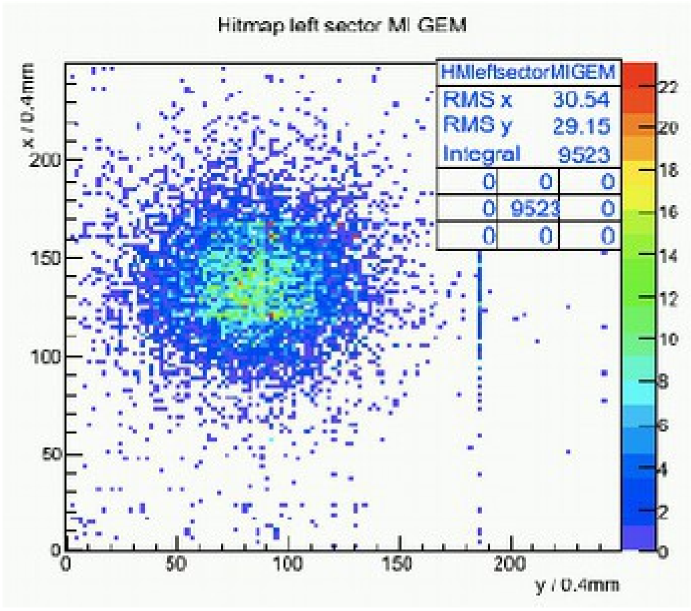
First Beam Tests

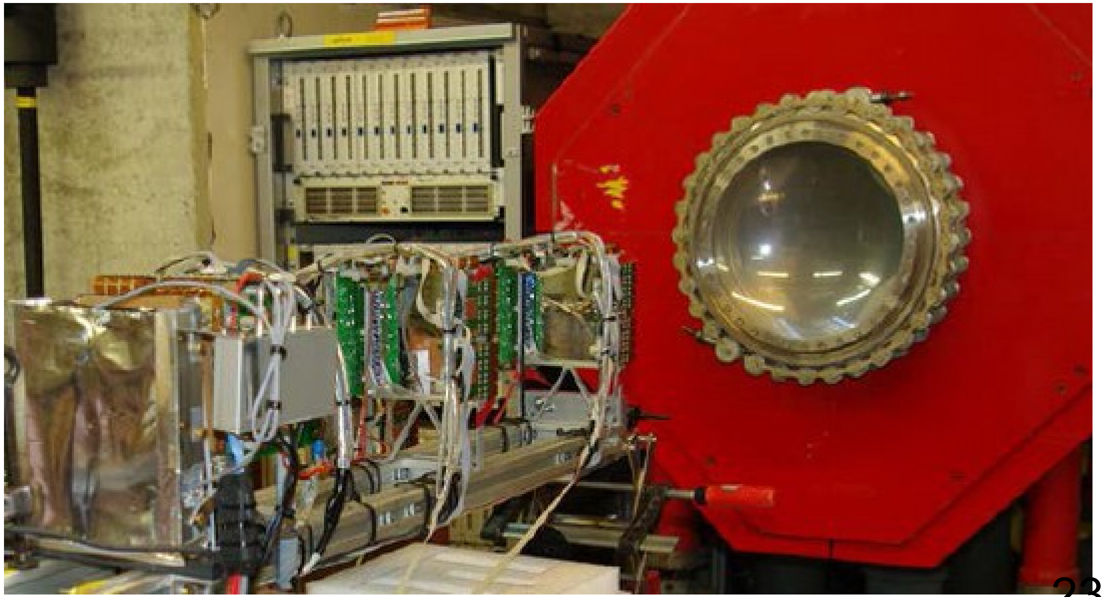




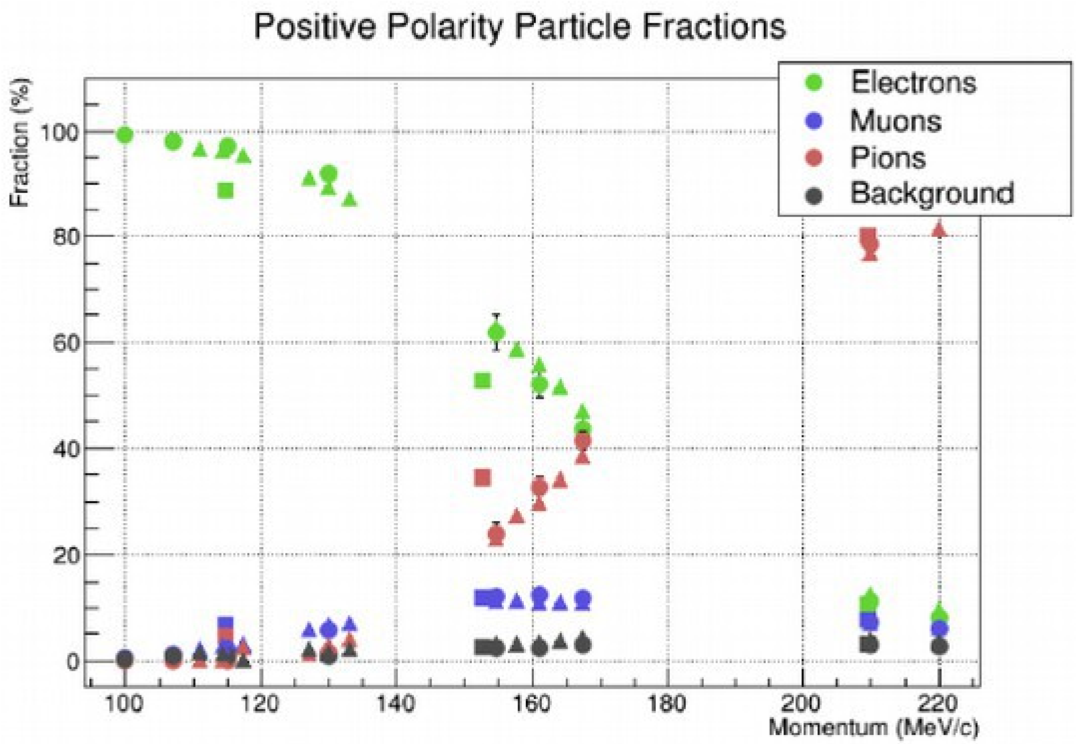
Time of flight relative to RF time (Fall 2012)

Beam spot with GEM – May 23, 2013

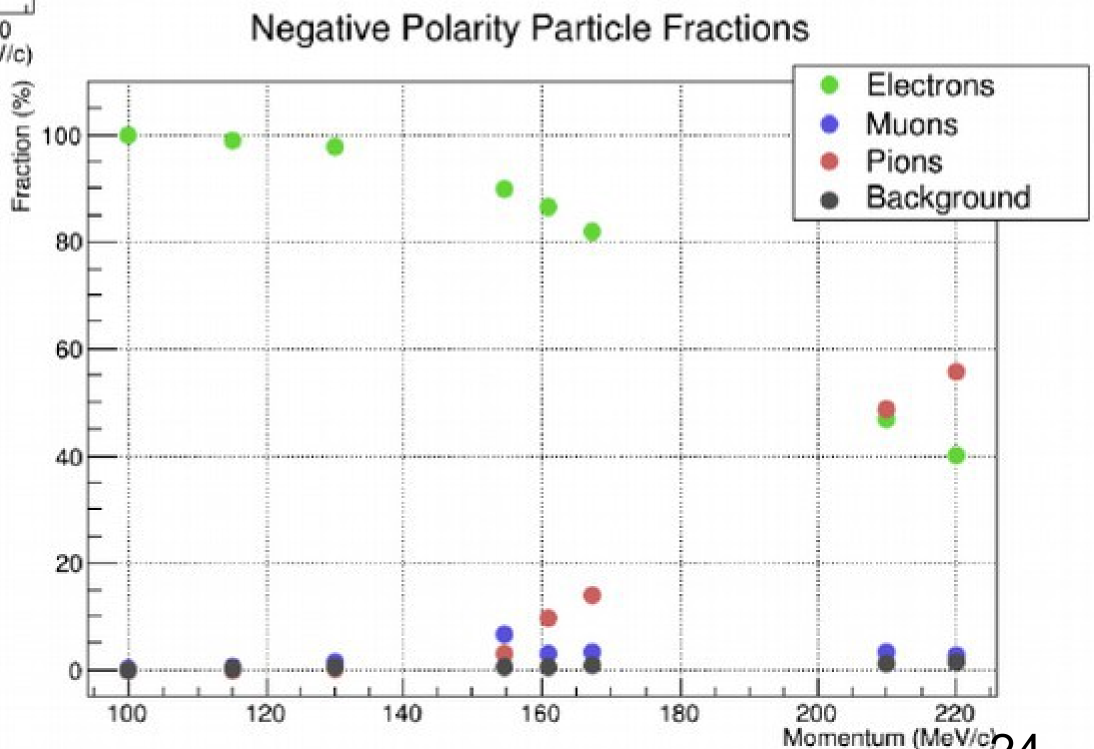




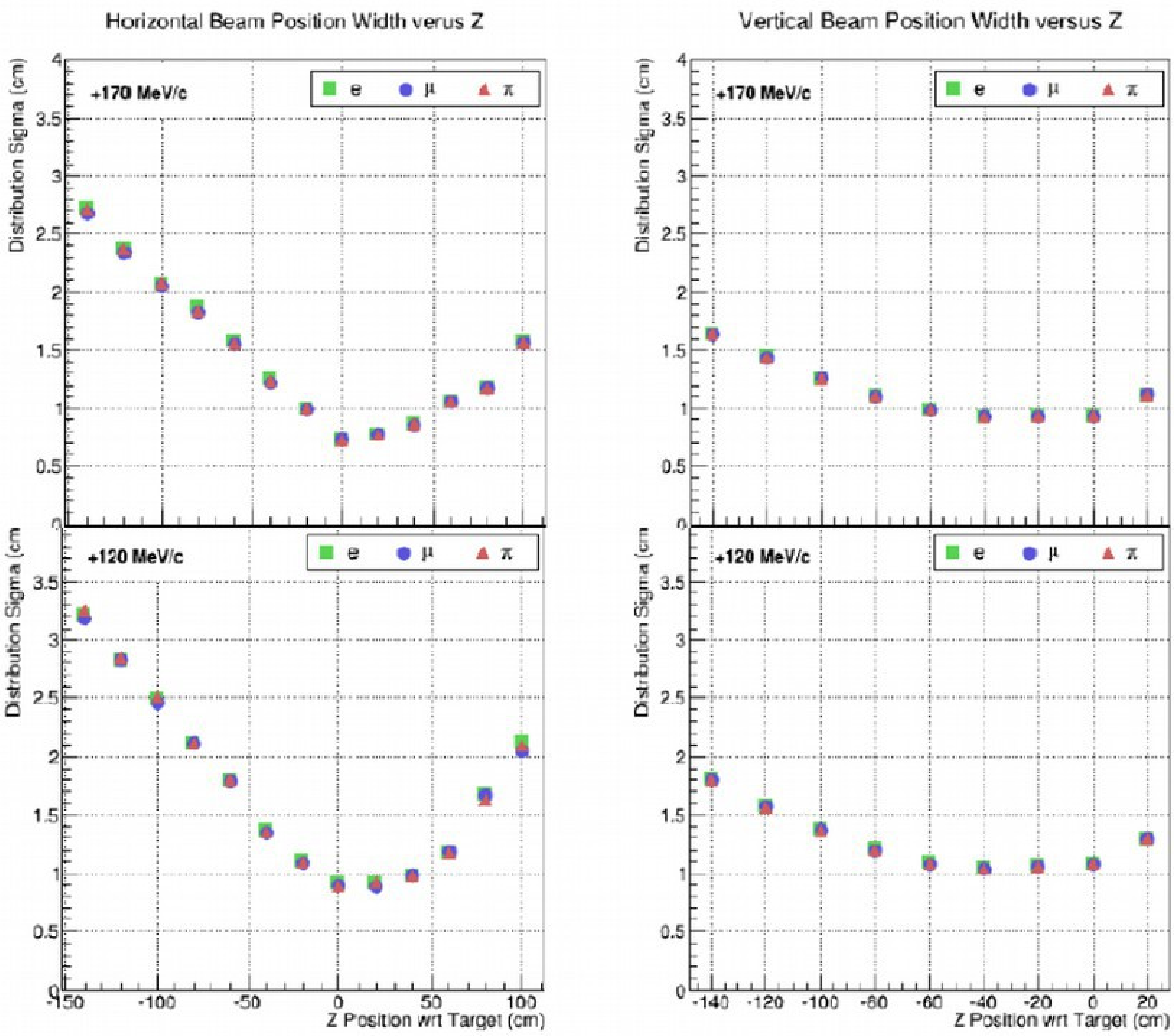
Composition of the πM1 secondary beam



Beam test results from December 2013

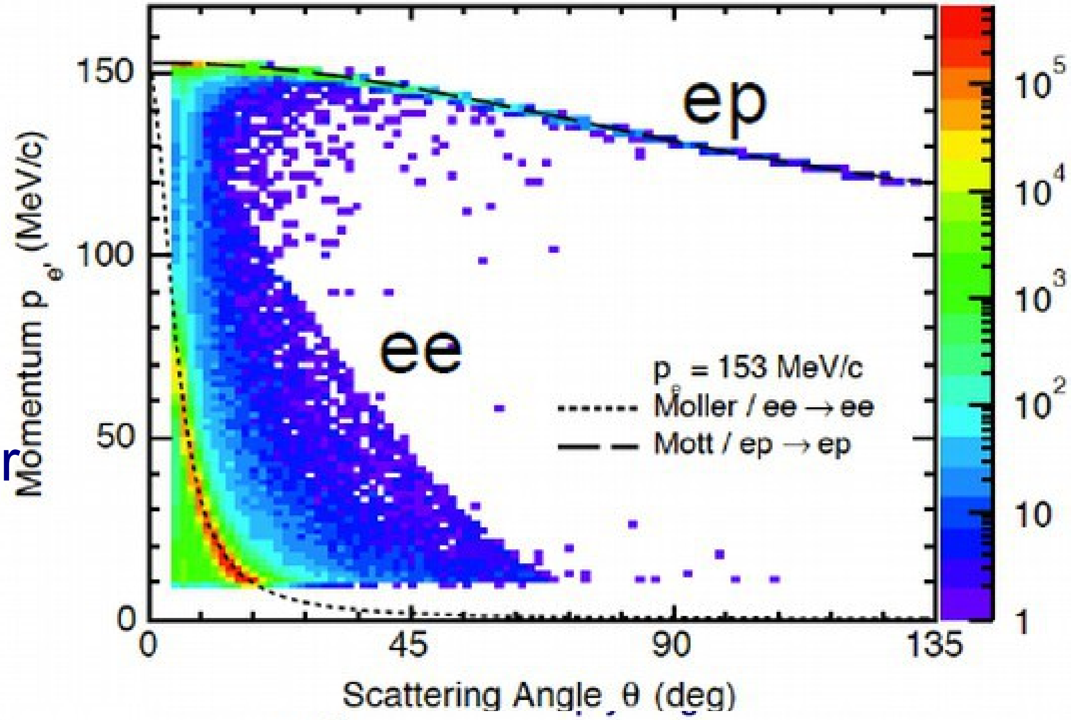


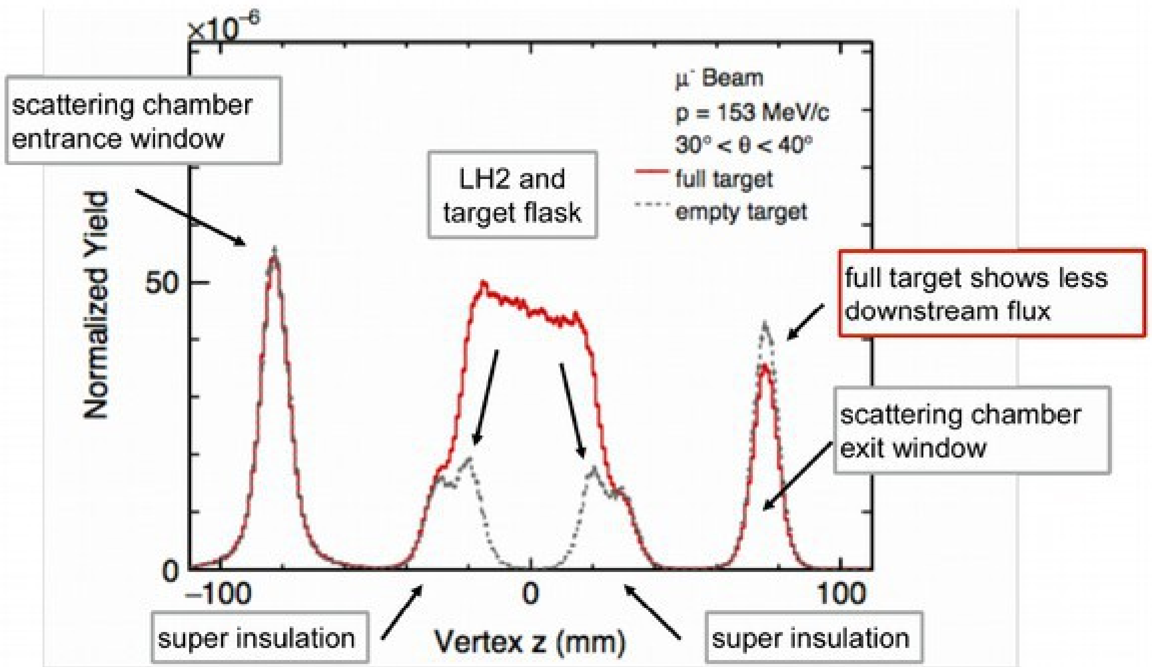
3D Beam Tomography

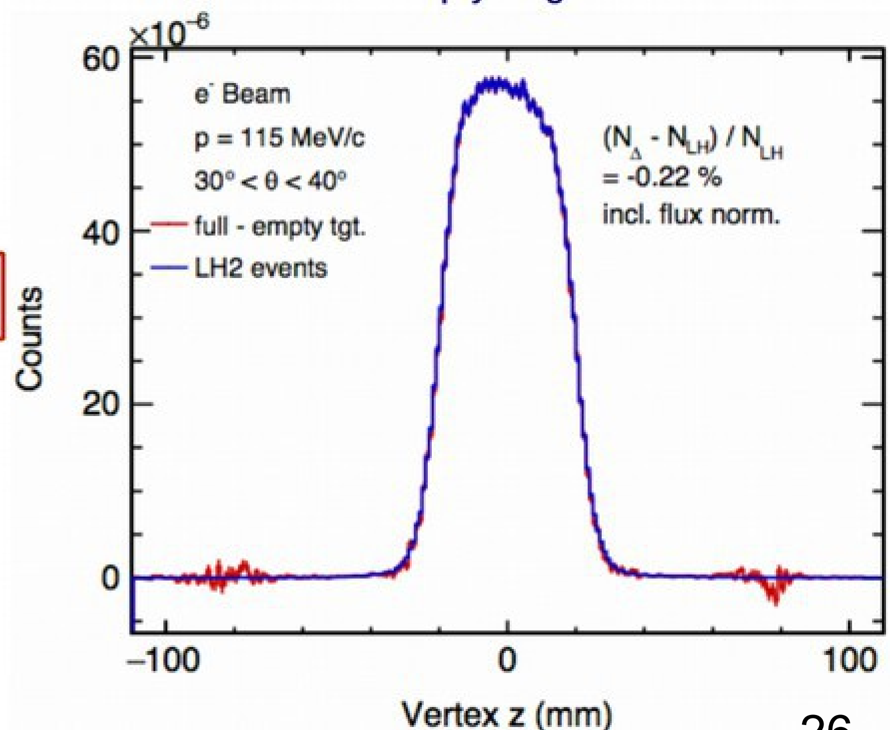


Simulations (USC & U. Mich)

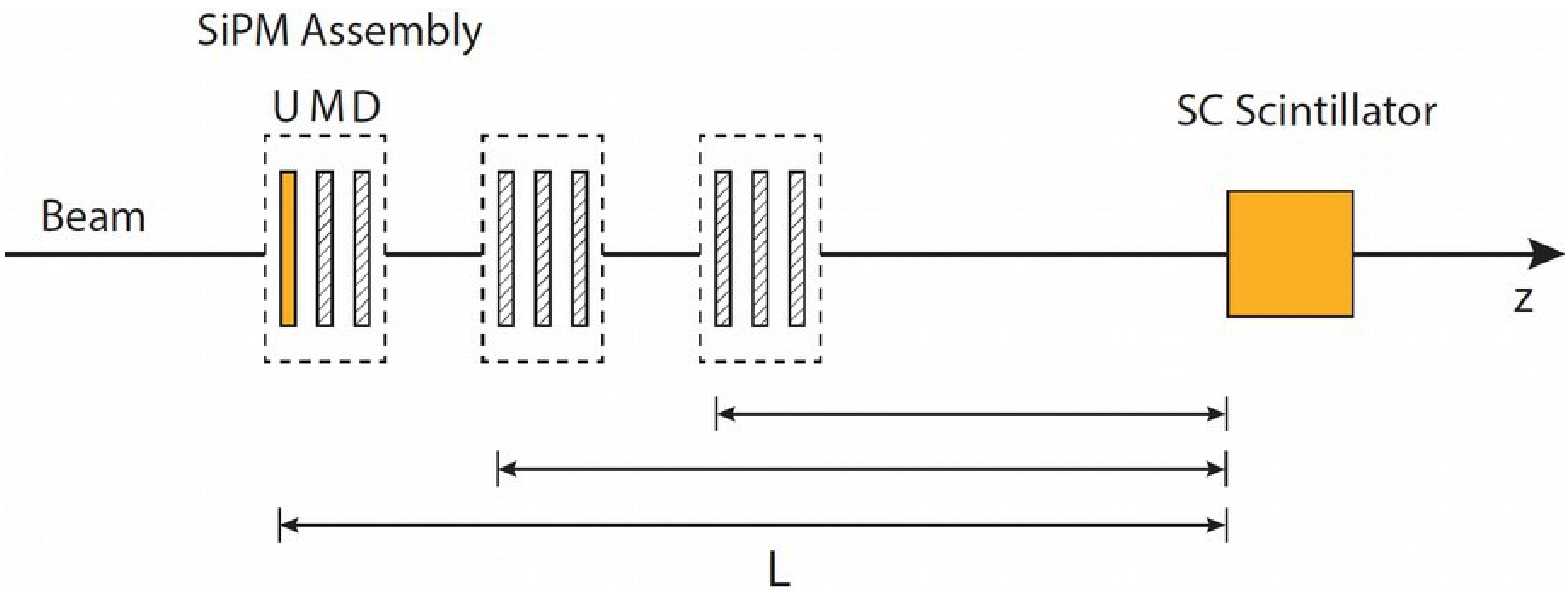
- Particle vertex and scattering angle reconstruction meet MUSE requirements
- Background from target walls and windows can be cleanly eliminated or subtracted
- Simulations verified by test data







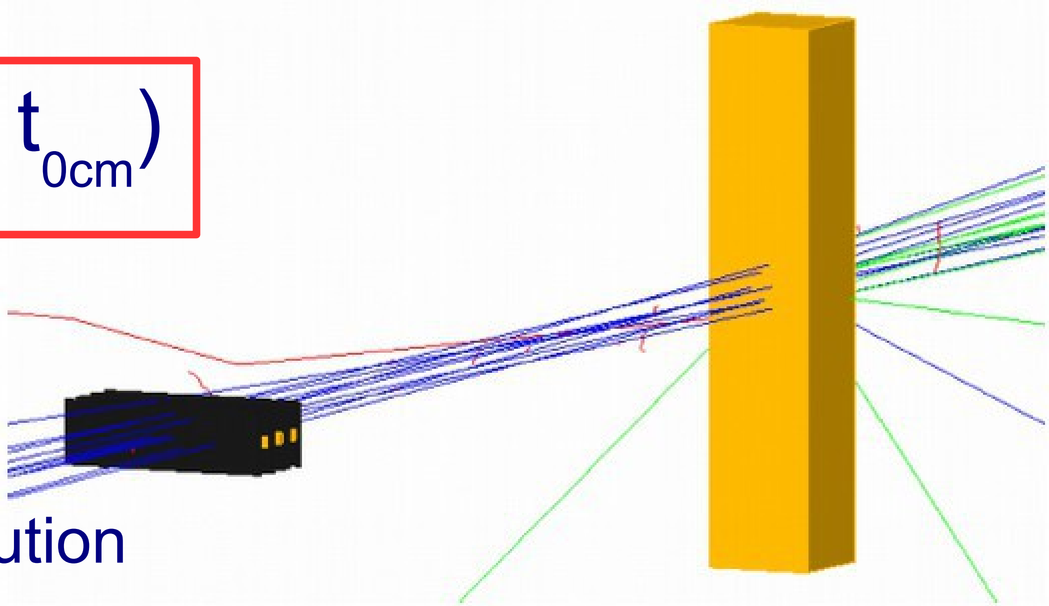
TOF Beam Momentum Measurement



$$t_{simulation} - t_{experiment} = \Delta(t_{Xcm} - t_{0cm})$$

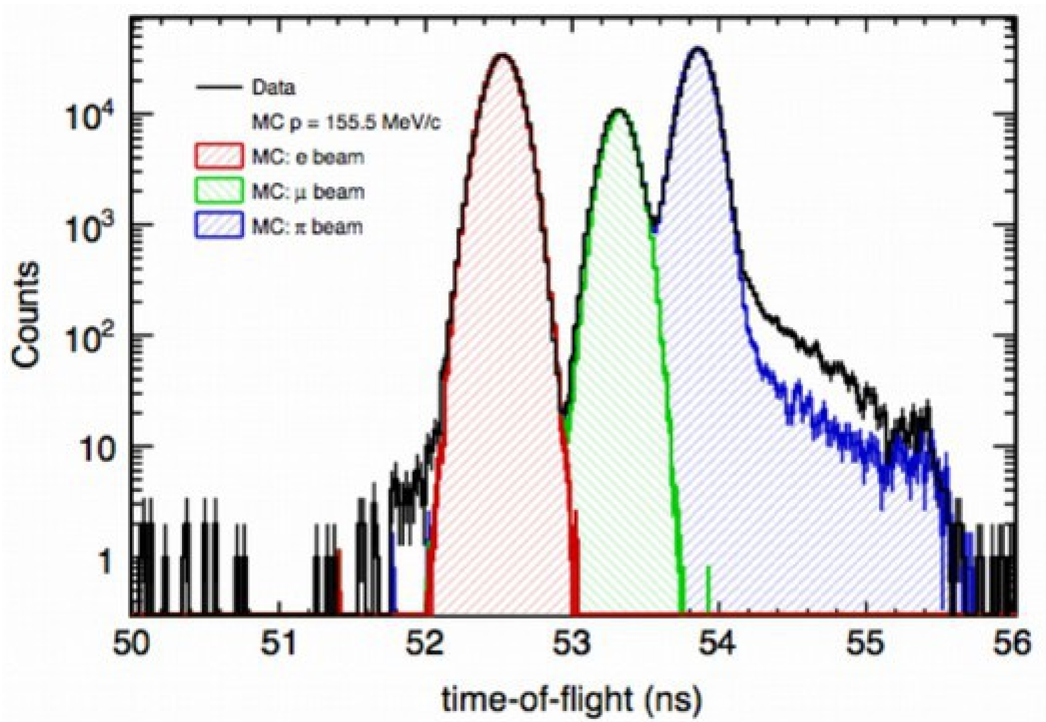
In the simulation

- ✔ Use realistic beam profile
- ✔ Match to experimental time resolution
- ✔ Match to experimental particle flux



TOF Beam Momentum Measurement

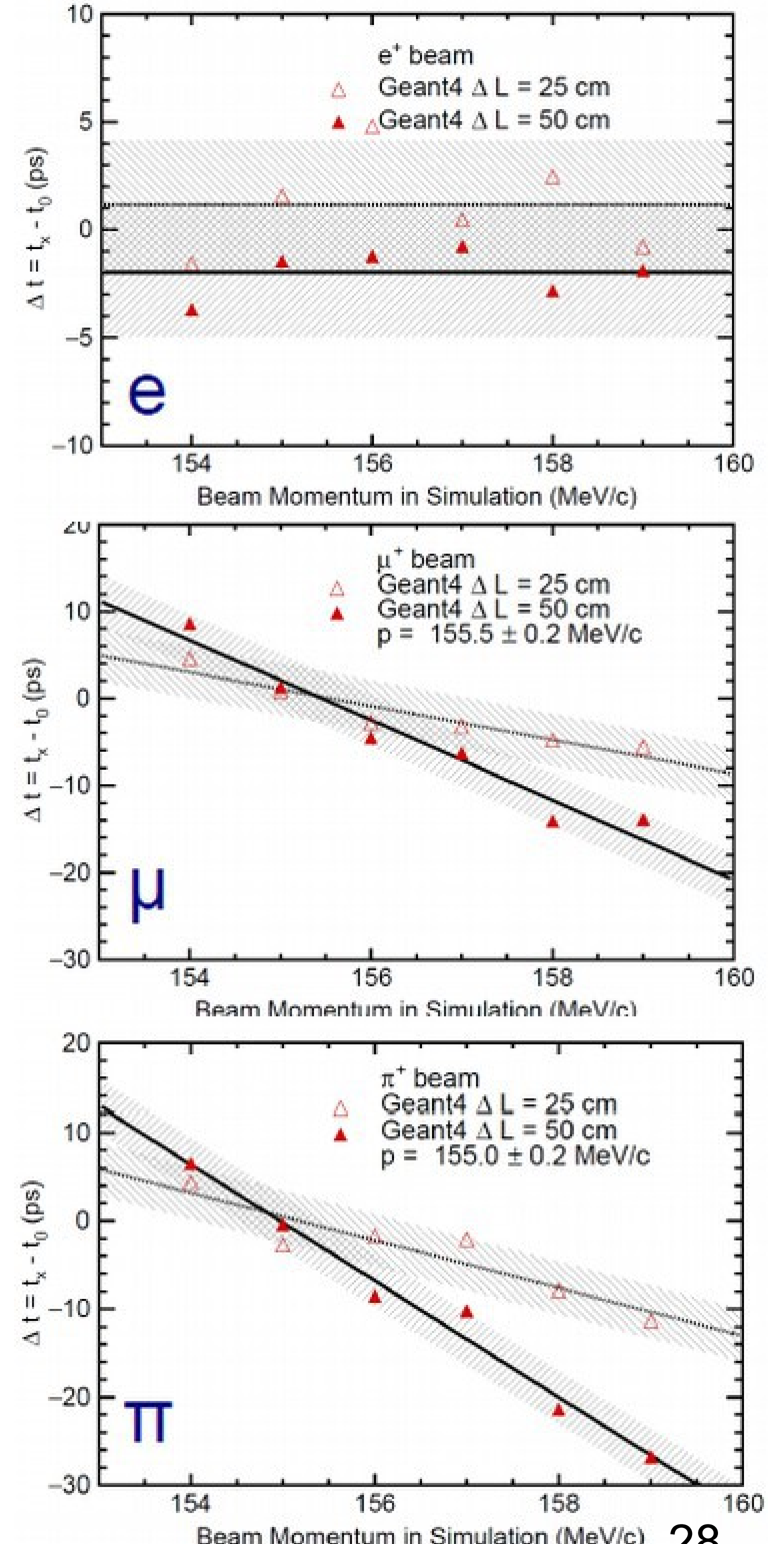
Consistent beam momenta were extracted from muon and pion spectra



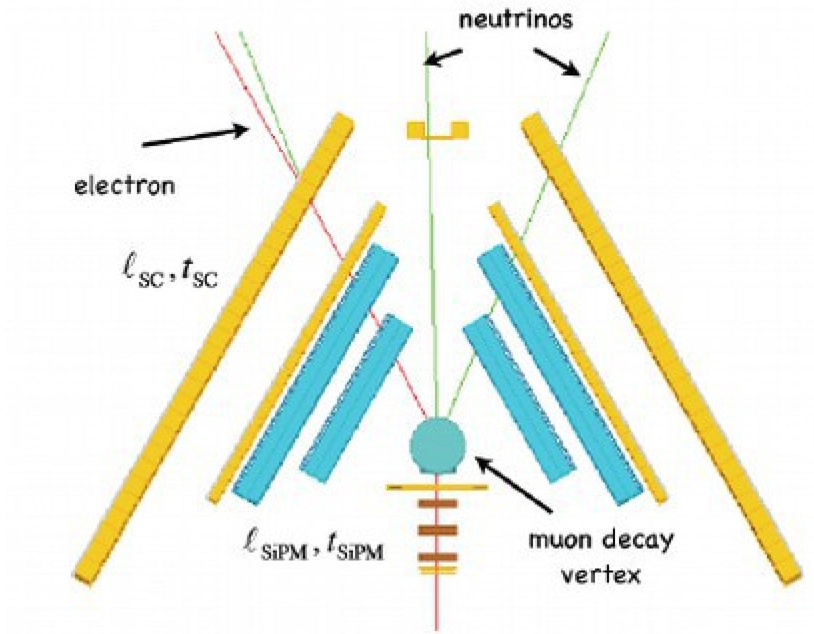
Good agreement between simulation and data, no evidence of beam tail from collimation

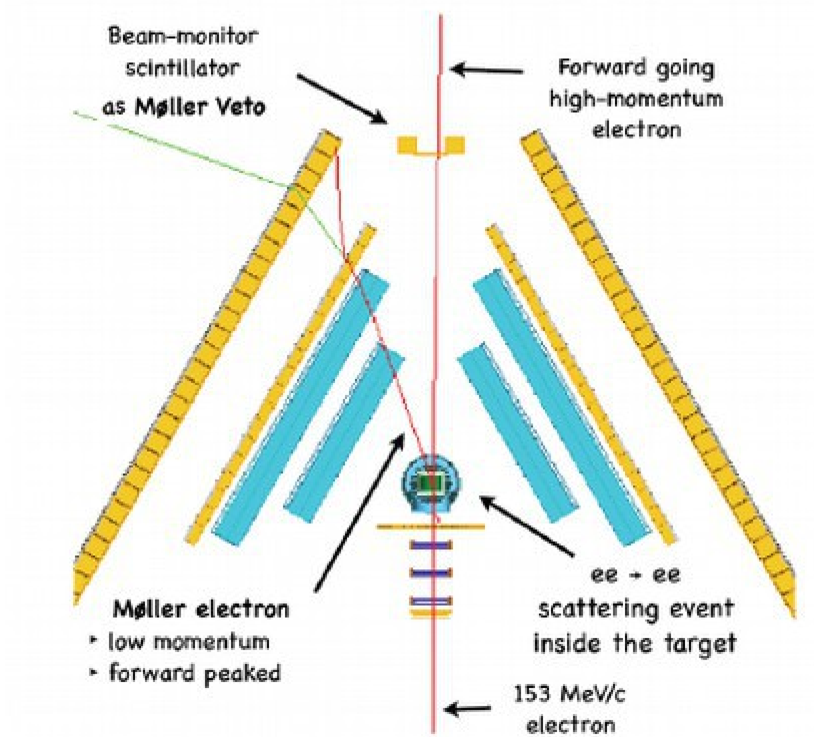
p(π) ≈ p(μ) with Δp / p < 0.3%

Preliminary results meet specifications

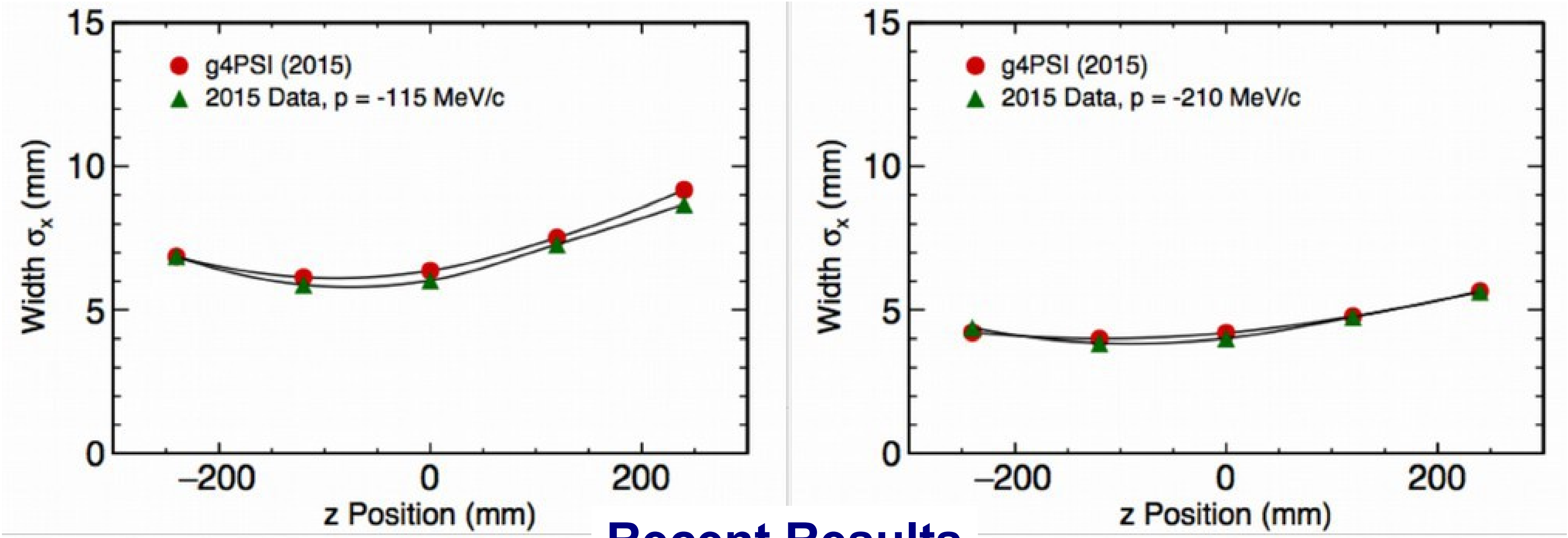


Simulations (USC)

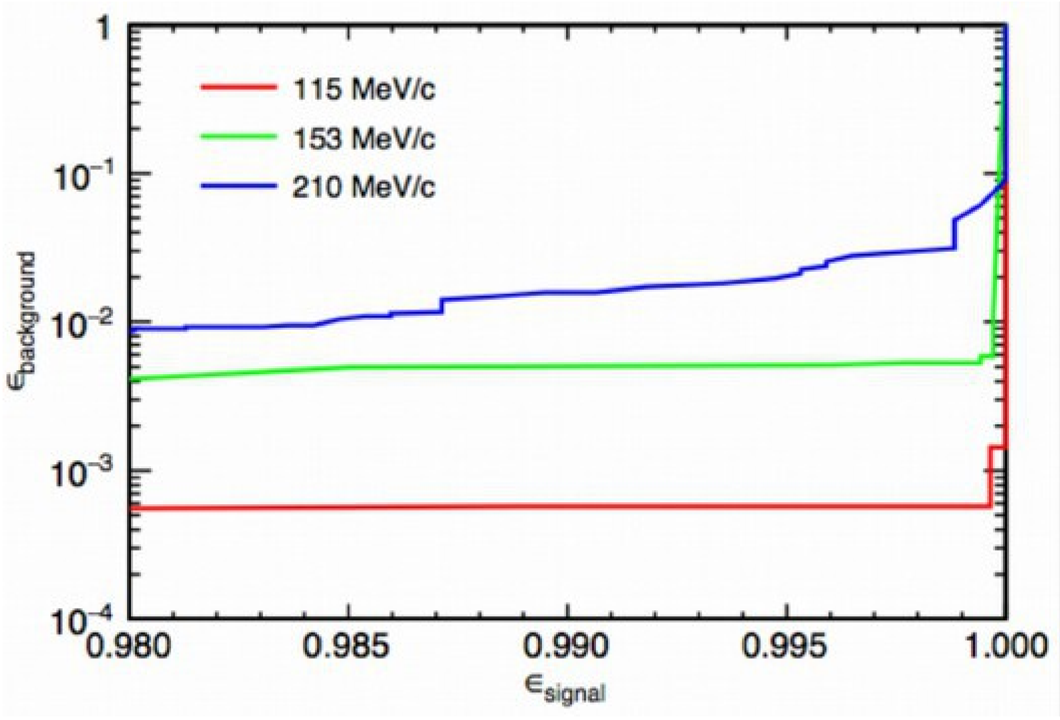




- Muon decays in flight can be removed with time-of-flight measurements
- Moeller/Bhabba events can be effectively suppressed with veto from the beamline monitor detector



Recent Results



Top:

- Geant 4 sims tuned to match measured beam parameters

Left:

- Neural net separates muon scattering from muon decay reactions

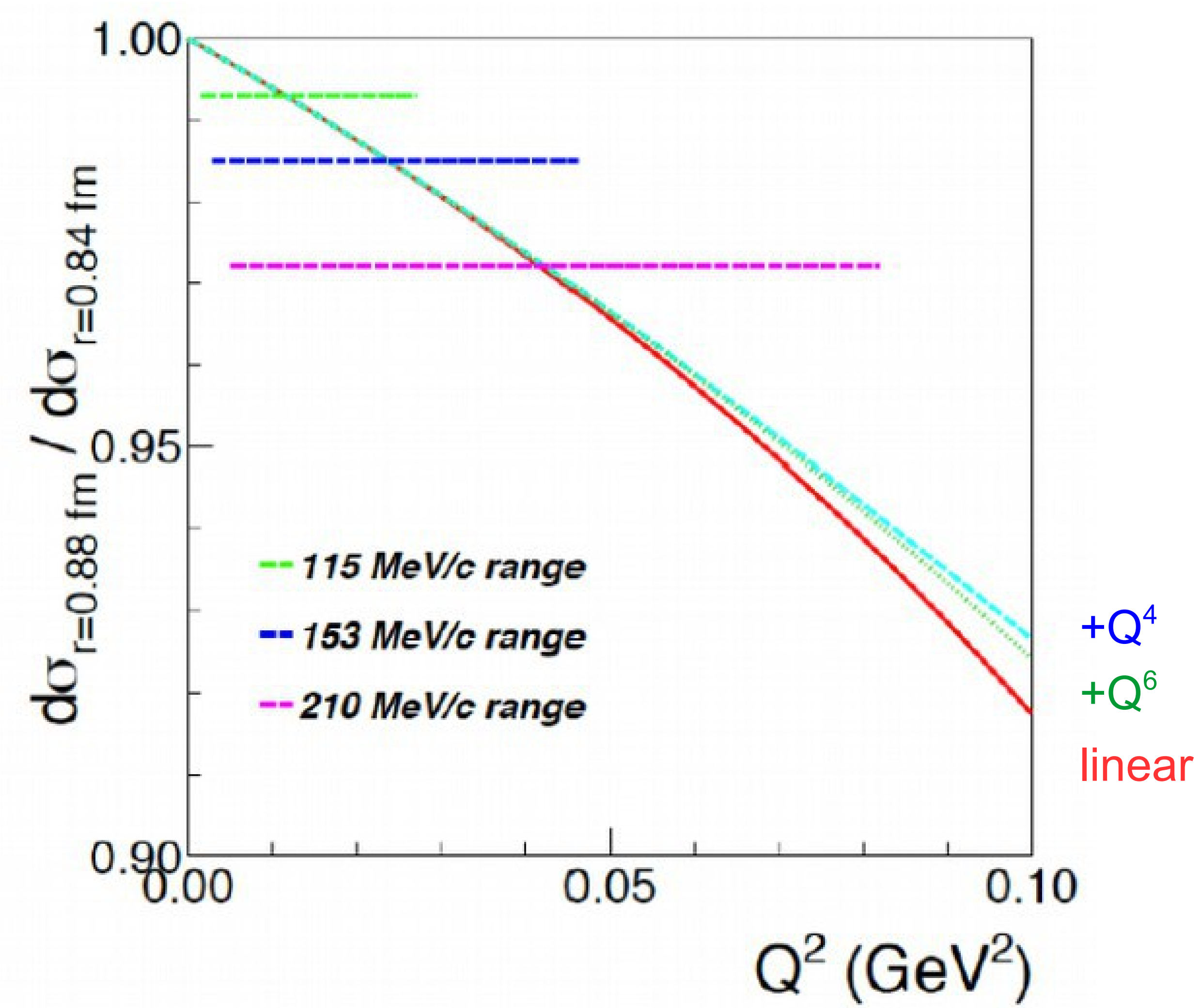
MUSE uncertainty budget

Scintillator efficiency	0.1%
Solid angle	0.1%
Beam momentum offset	0.1%
Theta offset	0.2%
Multiple scattering	0.15%
Muon decay in flight	0.1%
Radiative corrections	0.1% μ 0.5% e
Target wall subtraction	0.3%
Beam PID mis-ID	0.1%

- MUSE measuring relative cross sections
- Point-to-point uncertainties, most important
- Uncertainties mostly well controlled: largest from angle and radiative corrections.
- Have six settings and two independent detectors, consistency check
- Multiple calibration measurements / simulations planned

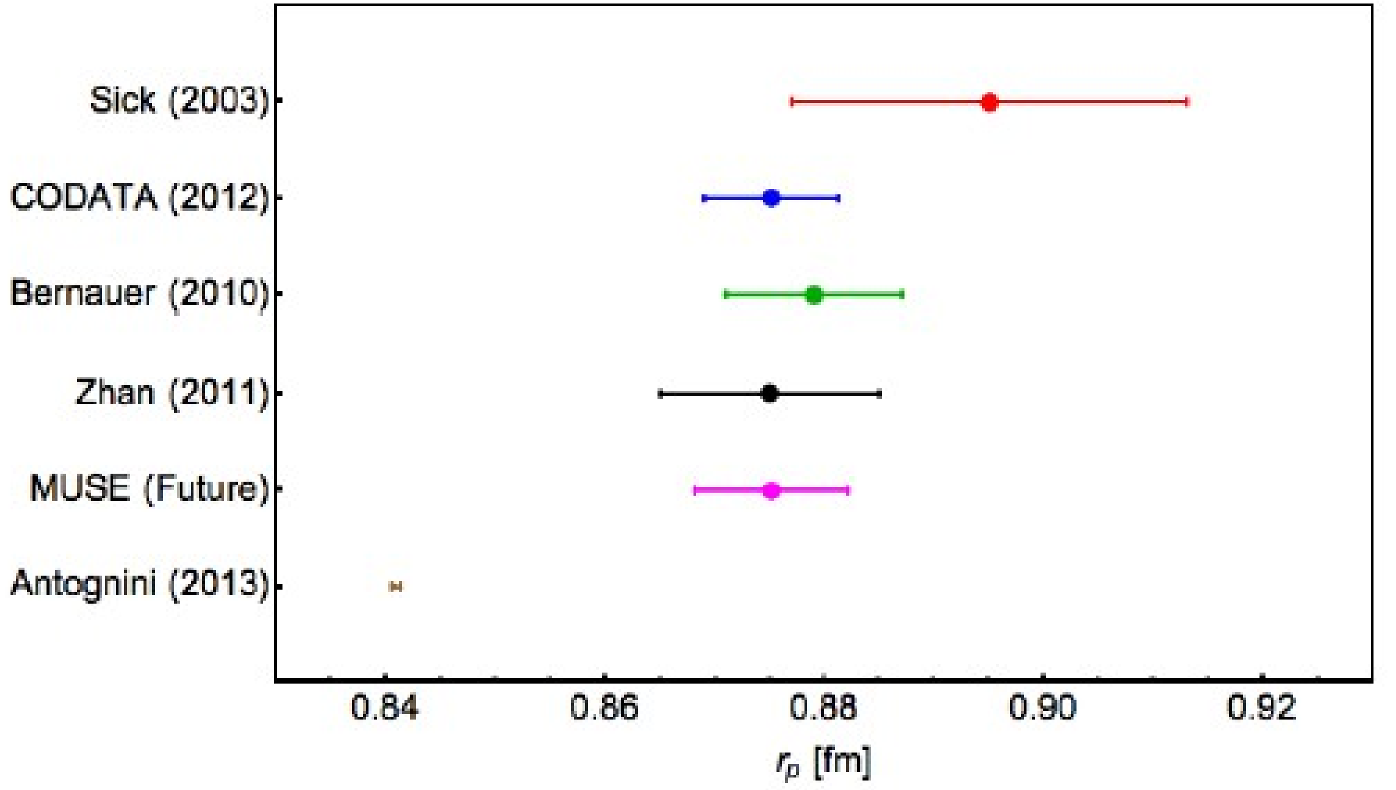
Projected sensitivity for MUSE

- Cross sections to < 1% stat. for backward μ, <<1% for forward e and μ, absolute 2%, point-to-point relative uncertainties to a few x 10^{-3}
- Individual radius extractions from $e^{\pm}$, $\mu^{\pm}$ each to 0.01 fm



Projected sensitivity for MUSE

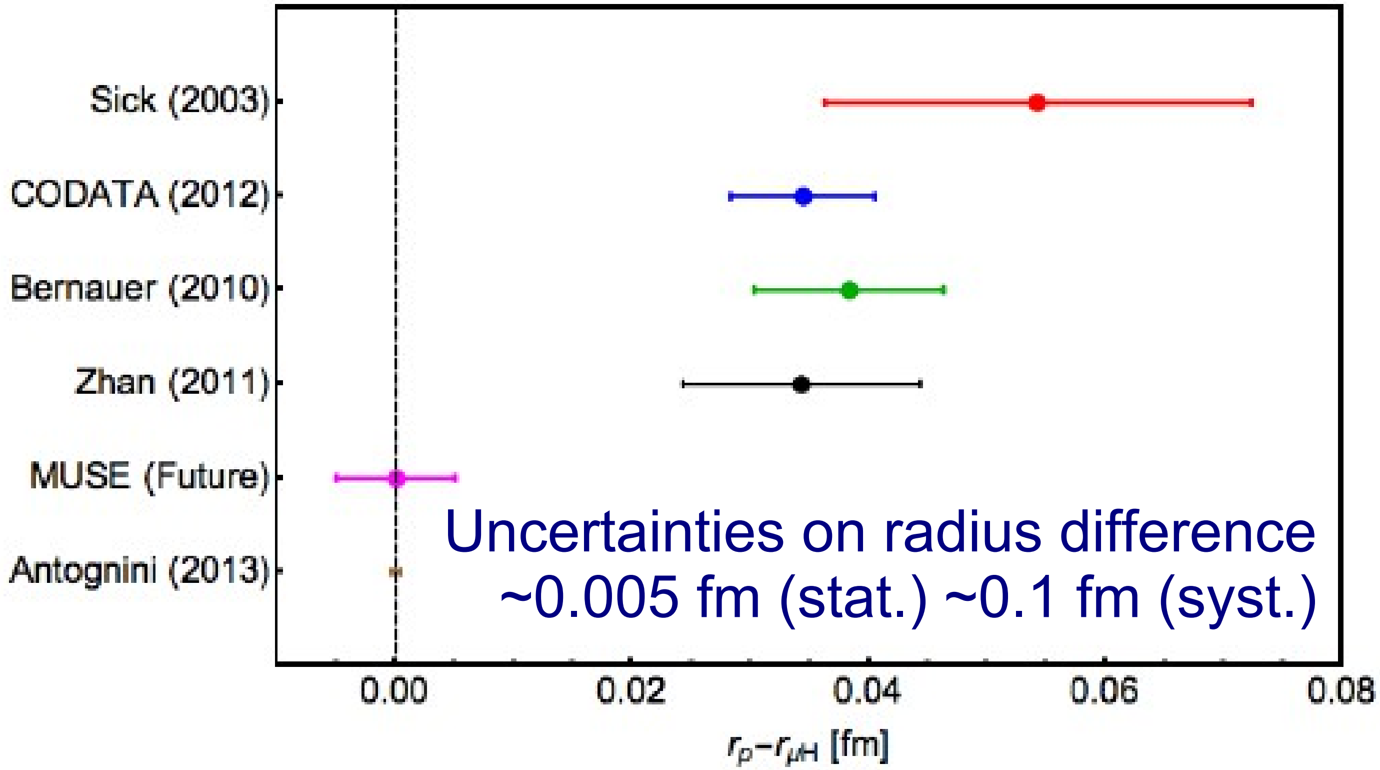
- Compare e± xsecs and μ± xsecs for TPE. Charge average to eliminate TPE to 0.01 fm
- From e/μ xsec ratios: extract e-μ radius difference with minimal truncation error to 0.005 fm
- If no difference, extract radius to 0.007 fm (2nd-order fit)



*Note: MUSE point arbitrarily put at r_p=0.875 fm

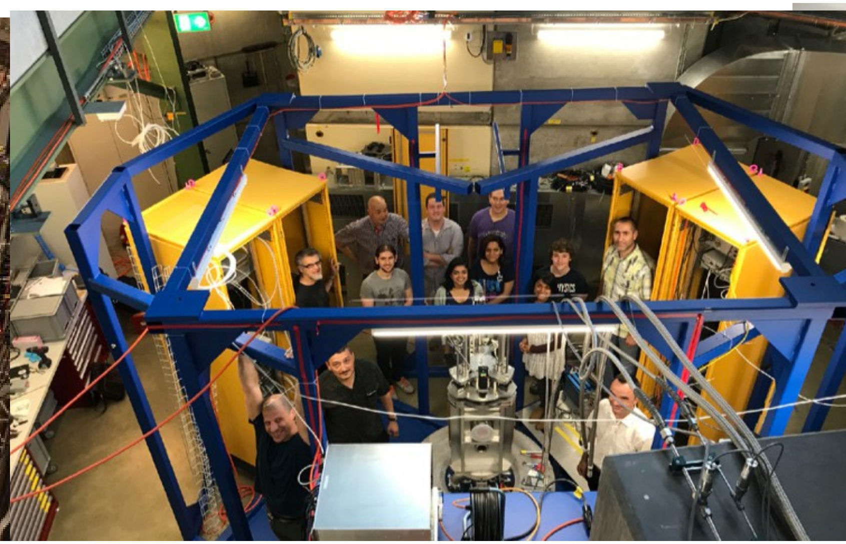
Projected sensitivity for MUSE

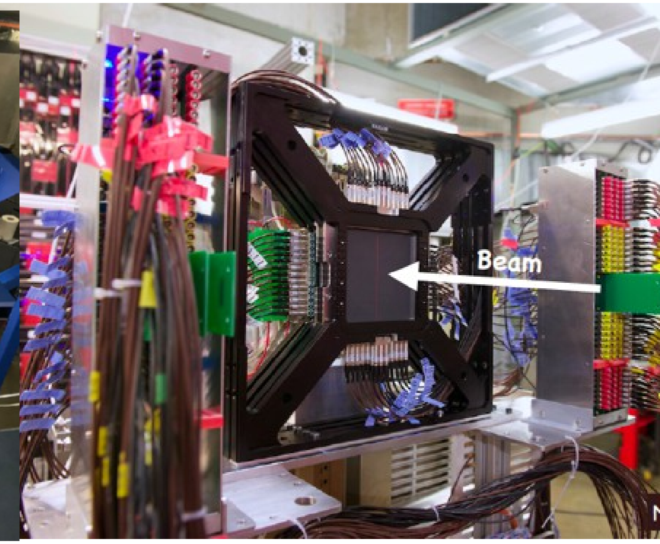
- Charge radius extraction limited by systematics, fit uncertainties
- Many uncertainties are common to all extractions in the experiments, cancel in e+/e-, μ+/μ-, and μ/e comparisons
- **MUSE suited to verify 5.6σ effect (CODATA 2014) with even higher significance**
- **$R_e - R_\mu = 0.034 \pm 0.006$ fm (5.6σ), MUSE: δr = 0.005 fm (~7σ)**



*Note: Difference in MUSE determined entirely by MUSE. Other differences are taken with respect to Antognini muonic hydrogen radius.

Conclusion





- Many efforts underway to explain the Proton Radius Puzzle!
- Since 1st MUSE proposal in February 2012, very many test beam times
- R & D from NSF, DOE, BSF; NSF construction funding (May '16) enables:
    - Funding & construction 2016–2018
    - Production running 2019–2020 (2 x 6 months)
- MUSE will be the first muon scattering measurement with the required precision to address the Proton Radius Puzzle!

Thank you!