THE GEORGE WASHINGTON UNIVERSITY

WASHINGTON, DC

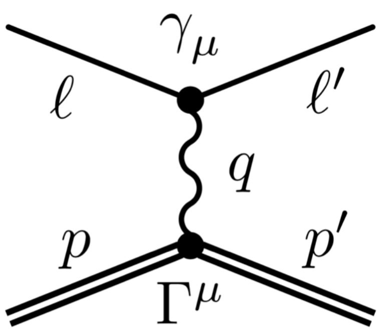
MUSE and Proton Radius Puzzle

Ievgen Lavrukhin

on behalf of the MUSE Collaboration

Introduction: Proton Radius

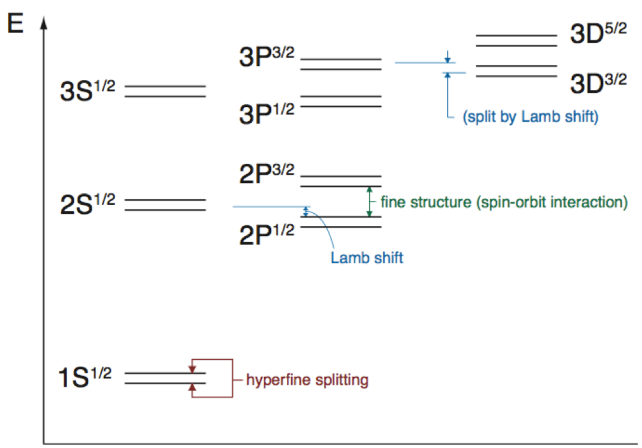
Lepton – Nucleon Scattering:



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

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

Hydrogen Spectroscopy:



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

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

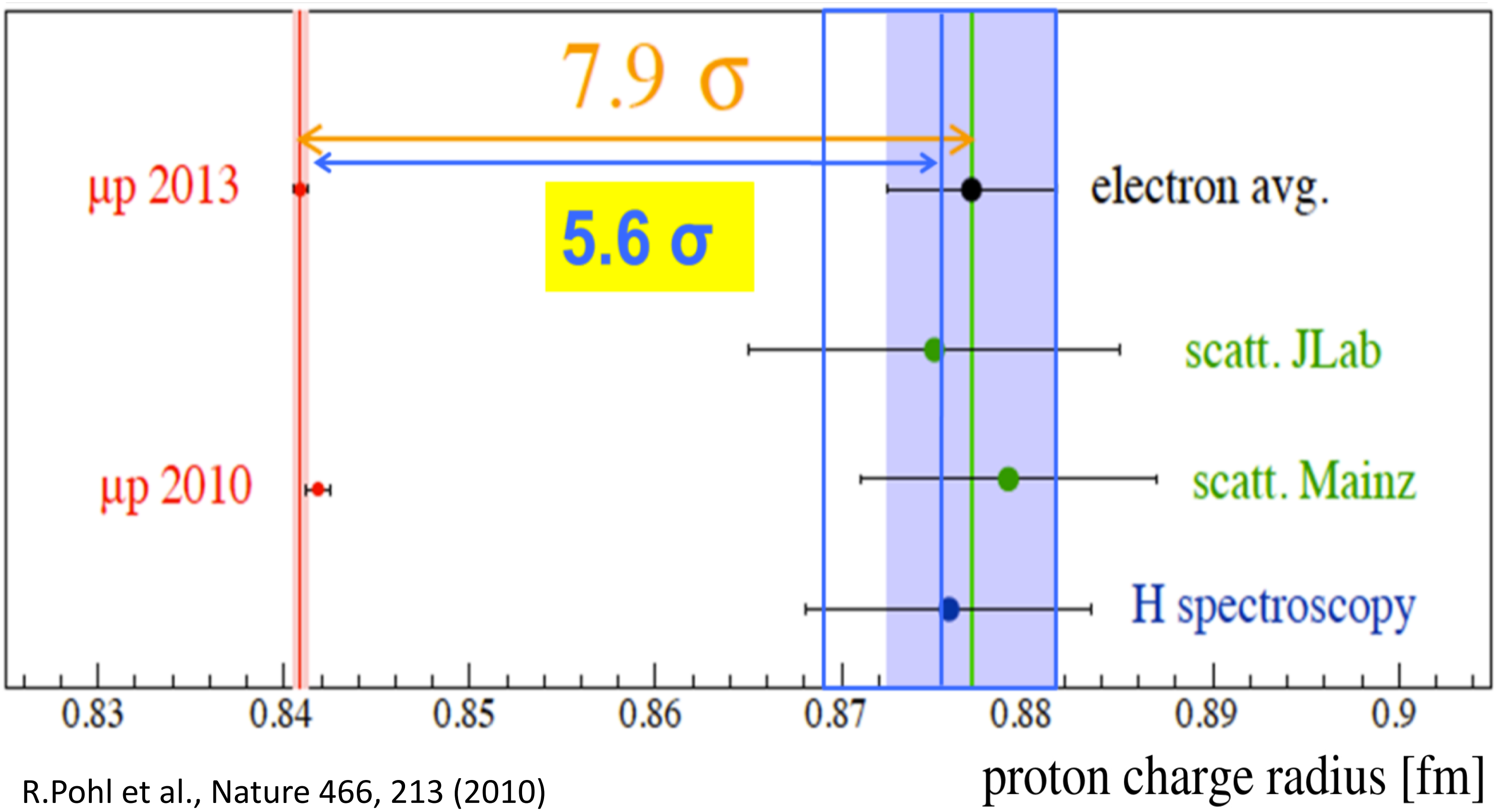
Point-like proton

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

Atomic wave function at origin

Introduction to Proton Radius Puzzle:

The Proton Radius Puzzle : Discrepancy between muonic hydrogen spectroscopy results and electron measurements. (First released → 2010)



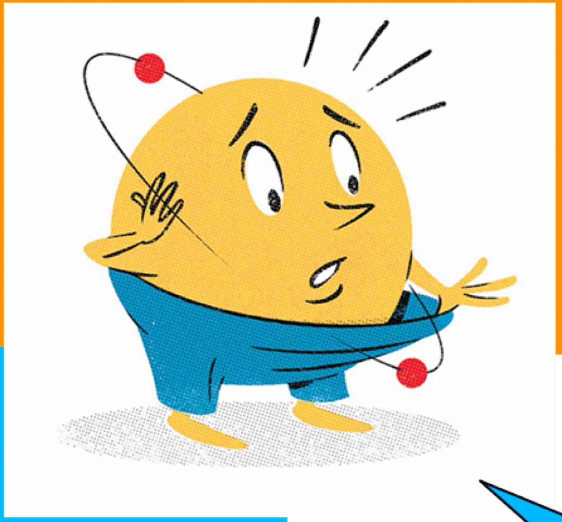
R.Pohl et al., Nature 466, 213 (2010)
A.Antognini et al., Science 339, 417 (2013)

Status of Proton Radius Puzzle (PRP):

Spectroscopy

Electronic hydrogen
0.8758 ± 0.0077

Muonic hydrogen
0.84087 ± 0.00039



Electron scattering
0.8751 ± 0.0061

Scattering

Muon scattering
???

Possible reasons of (PRP):

- The μ*p* (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.
- 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 μ*p* and *ep*
- Physics beyond Standard Model
  - ✓ μ and *e* Lepton universality violation.

Possible reasons of (PRP):

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MUSE will test this!

MUon Scattering Experiment (MUSE).

r_p (fm)	electrons	muons
spectroscopy	0.8758 ±0.0077	0.8409 ±0.0004
scattering	0.8770 ±0.0060	????

What MUSE proposes:

Simultaneous measurement of e^-p; μ^-p and e^+p; μ^+p elastic scattering reactions:

1. Simultaneous determination of the **Proton Radius in both *ep* and μ*p* scatterings**.
2. Direct comparison of *ep* and μ*p* scatterings at sub-percent level precision.
3. Extract **TPE effects** from the e^-p/e^+p and μ^-p/μ^+p ratios.
4. Test of Lepton universality.

MUSE Collaboration:

~63 MUSE collaborators from 24 institutions in 5 countries:

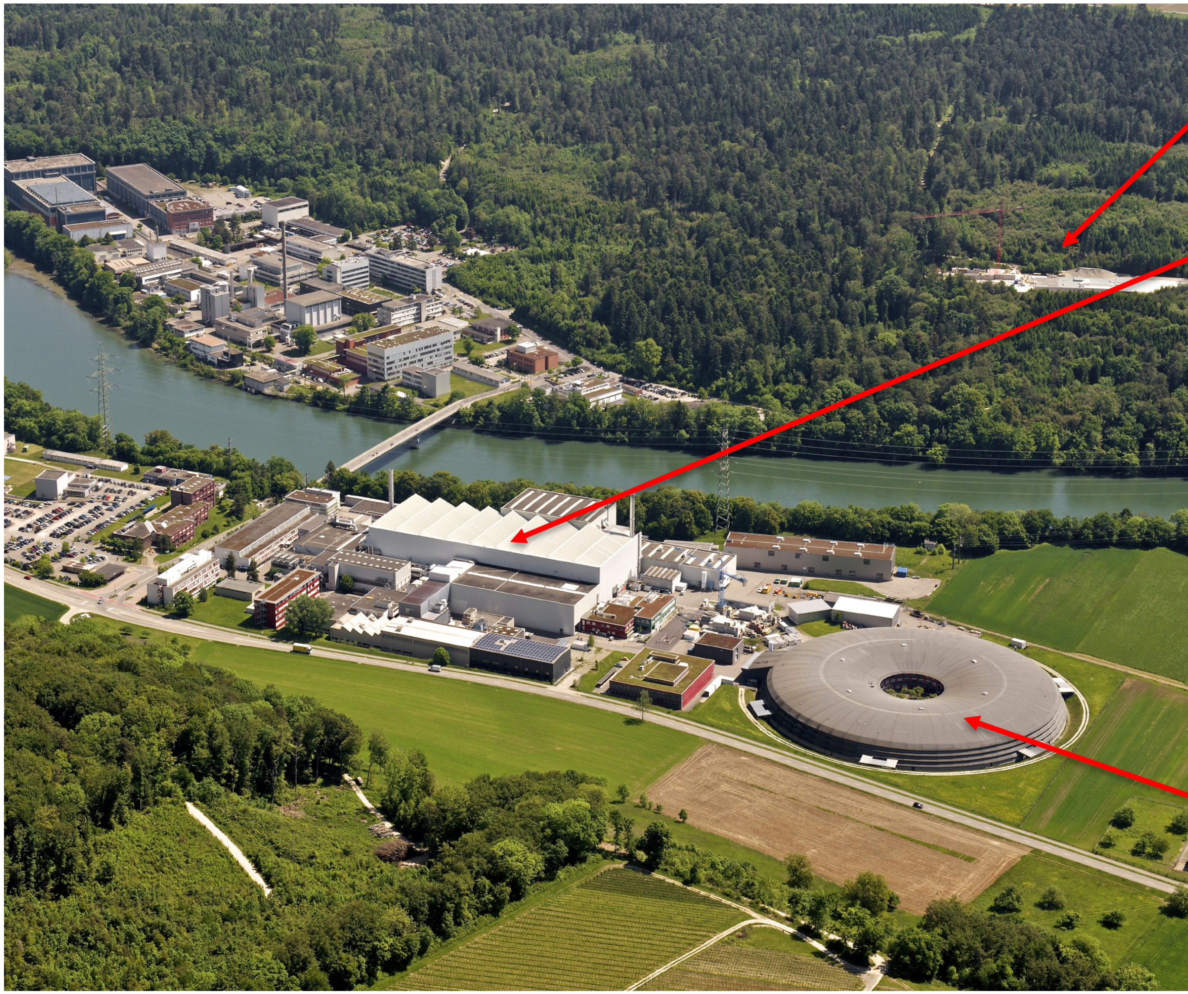
A. Afanasev[a], A. Akmal[b], J. Arrington[c], H. Atac[d], C. Ayerbe-Gayoso[e], F. Benmokhtar[f], N. Benmouna[b], N. Bern[b], J.C. Bernauer[g], E. Brash[h], W.J. Briscoe[a], T. Cao[i], D. Ciofi[a], E. Cline[j], D. Cohn[k], E.O. Cohen[l], C. Collicott[a], K. Deiters[m], J. Diefenbach[n], B. Dongwi[i], 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 Institute (PSI):



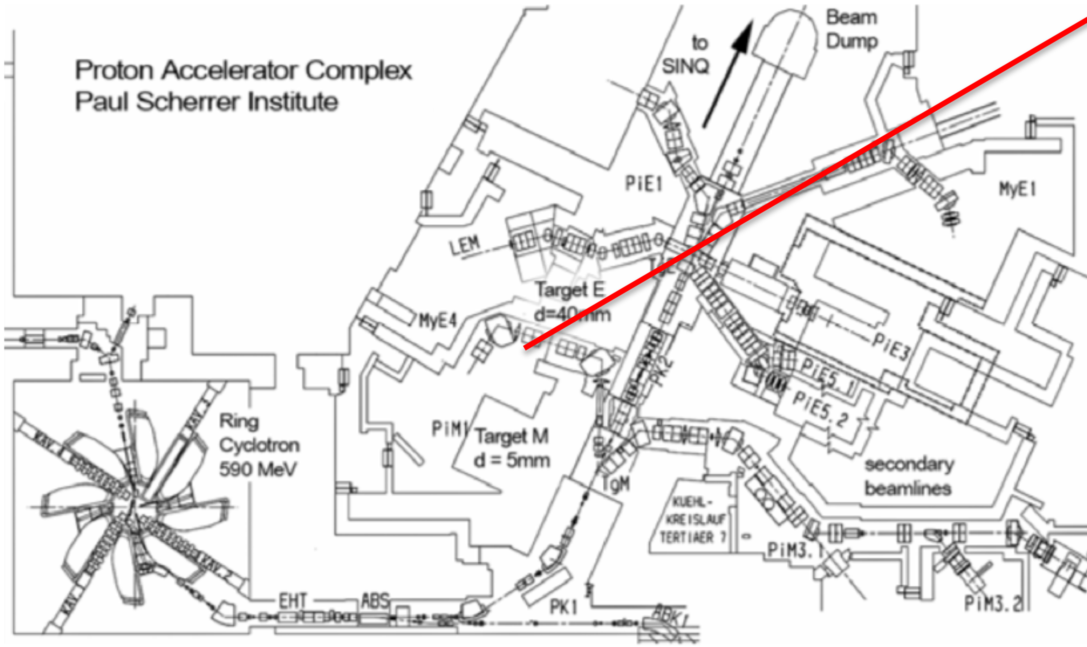
X-ray laser: SwissFEL

Proton accelerator: World's most powerful 590 MeV Proton beam (2.2 mA, 1.3 MW beam, 50.6 MHz RF frequency)

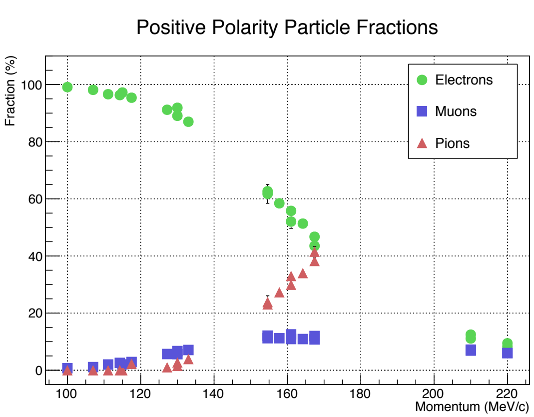
- $e^{\pm}$,$\mu^{\pm}$,$\pi^{\pm}$ in Secondary beam-lines

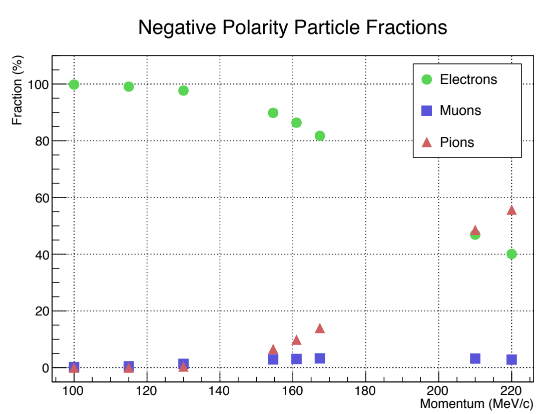
Synchrotron: Swiss Light Source (SLS), with 2.4 GeV photons

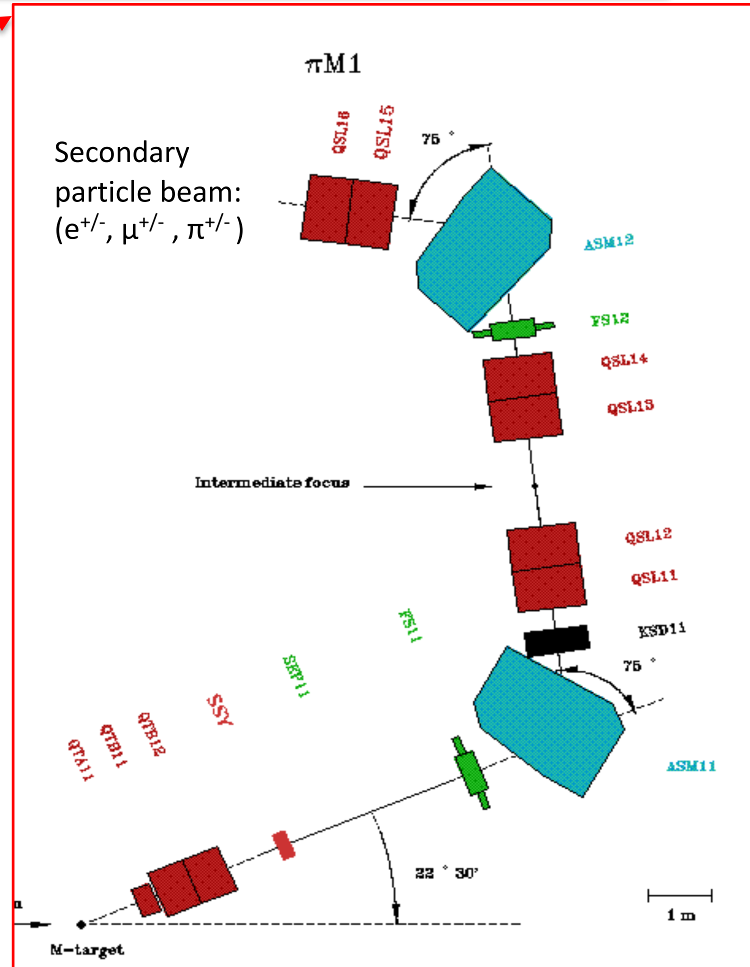
MUSE: PiM1 Beam line.



https://accelconf.web.cern.ch/accelconf/c07/PAPERS/157.pdf

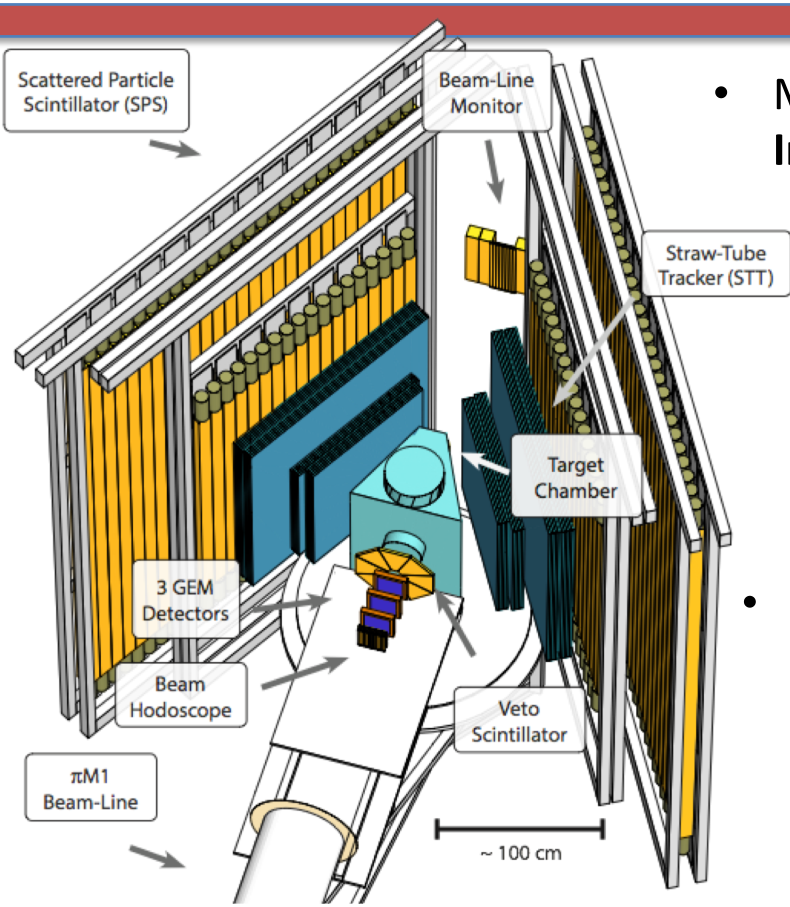






Momentum rage: 100-500 MeV/c
Momentum resolution: 0.1 %

MUSE: Detector Setup.

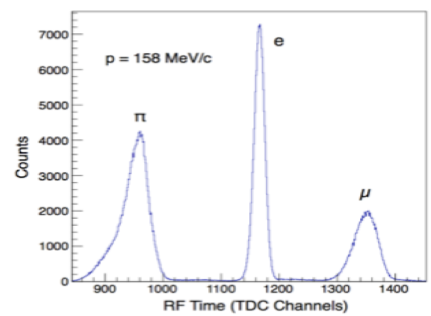


MUSE detector setup.

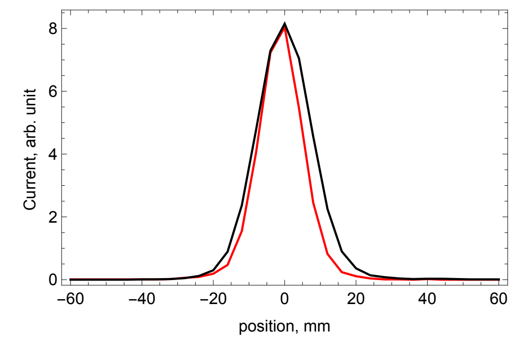
Parameter	Value
Beam momenta, GeV/c	0.115, 0.153, 0.210
Scattering angle range	20^o - 100^o
Q^2 range for electrons, GeV^2	0.0016 - 0.0820
Q^2 range for muons, GeV^2	0.0016 - 0.0799

- Mixed Secondary Particle beam at piM1, **Paul Scherer Institute (PSI), Switzerland.**

Beam particle time separation



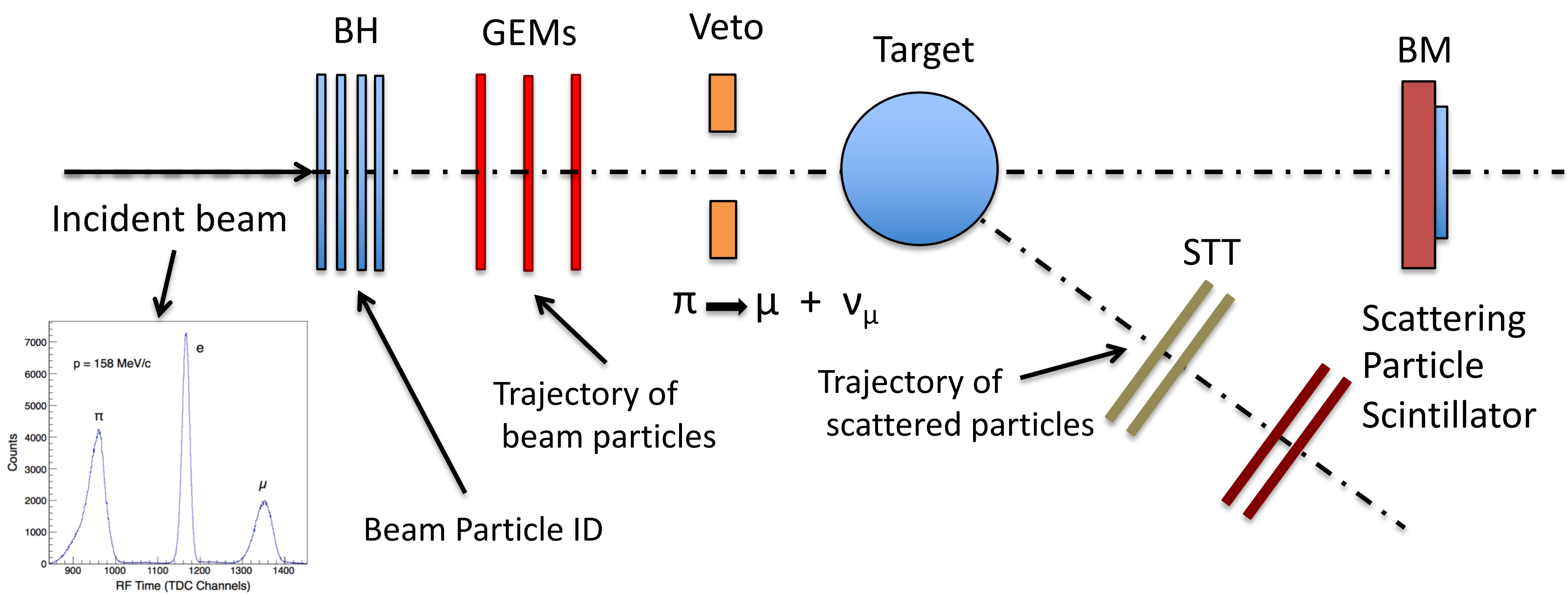
Beam dispersion.



- Precise timing of incident and scattered particles.

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

MUSE: Trigger.

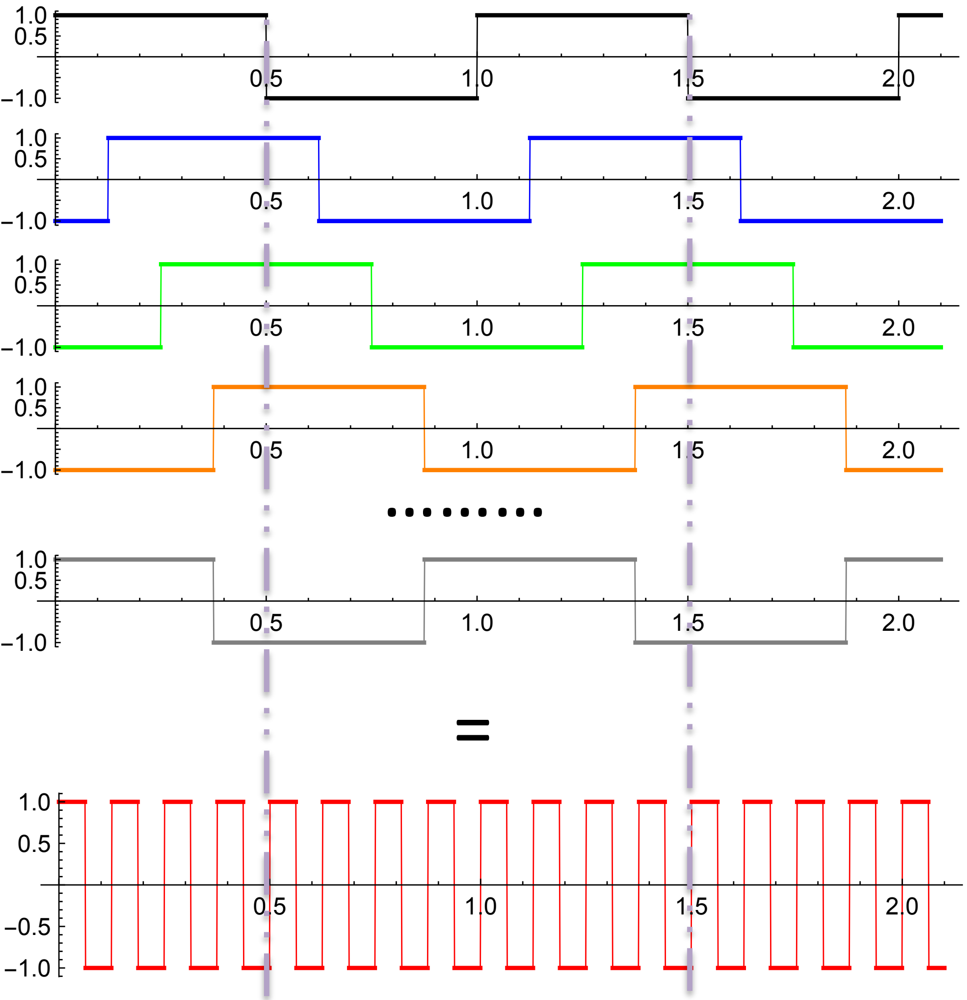


Trigger Logic:

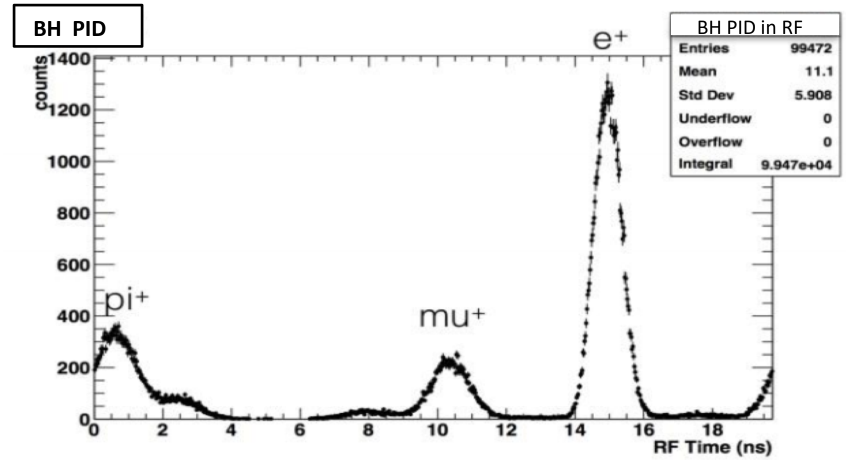
$$\underbrace{(e \text{ OR } \mu) \text{ AND } (\text{no } \pi)}_{\textbf{PID} \text{ is the Hardest Part}} \text{ AND } (\text{scatter}) \text{ AND } (\text{no veto})$$

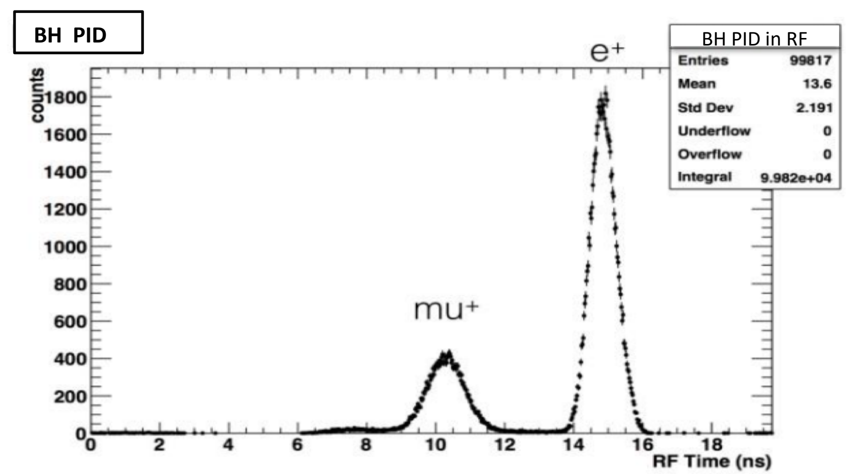
MUSE: Trigger (PID)

50.6 MHz RF signal from Accelerator:



400 MHz Clock for PID (16 bins)





Requirements for BH:

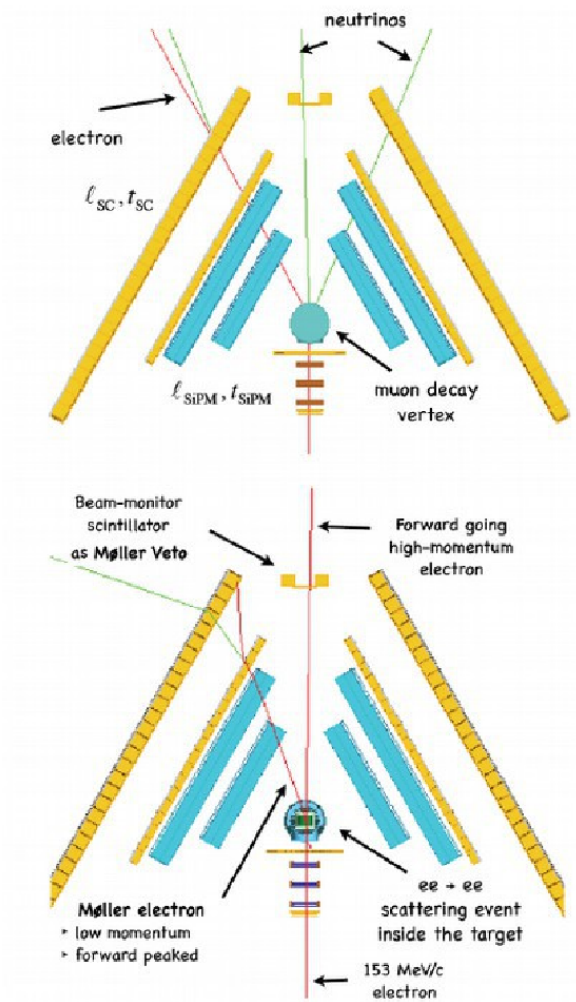
≤ 150 ps rms beam line timing for PID

MUSE: Trigger (Scattering Event)

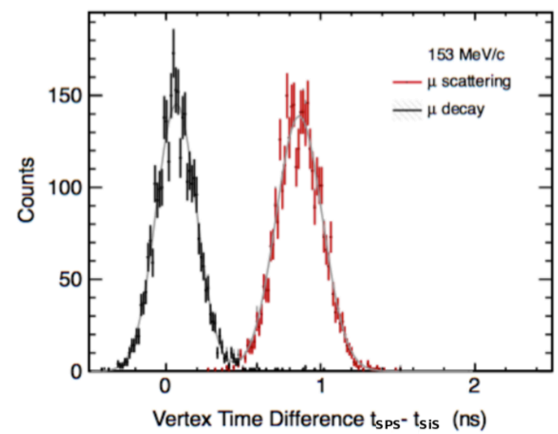
Front	Exact Back	3	2	1	Back	1	2	3
0	2.00		0.00	1.00	2.00	3.00	4.00	5.00
1	3.35	0.00	1.00	2.00	3.00	4.00	5.00	6.00
2	4.71	2.00	3.00	4.00	5.00	6.00	7.00	8.00
3	6.06	3.00	4.00	5.00	6.00	7.00	8.00	9.00
4	7.41	4.00	5.00	6.00	7.00	8.00	9.00	10.00
5	8.76	6.00	7.00	8.00	9.00	10.00	11.00	12.00
6	10.12	7.00	8.00	9.00	10.00	11.00	12.00	13.00
7	11.47	8.00	9.00	10.00	11.00	12.00	13.00	14.00
8	12.82	10.00	11.00	12.00	13.00	14.00	15.00	16.00
9	14.18	11.00	12.00	13.00	14.00	15.00	16.00	17.00
10	15.53	13.00	14.00	15.00	16.00	17.00	18.00	19.00
11	16.88	14.00	15.00	16.00	17.00	18.00	19.00	20.00
12	18.24	15.00	16.00	17.00	18.00	19.00	20.00	21.00
13	19.59	17.00	18.00	19.00	20.00	21.00	22.00	23.00
14	20.94	18.00	19.00	20.00	21.00	22.00	23.00	24.00
15	22.29	19.00	20.00	21.00	22.00	23.00	24.00	25.00
16	23.65	21.00	22.00	23.00	24.00	25.00	26.00	27.00
17	25.00	22.00	23.00	24.00	25.00	26.00	27.00	
			3 or 4	5 or 6				
		Anything >0.2 and <0.8 is defined as in the middle						

MUSE: Muon Decay and Moeller

Simulation for 153 MeV/c beam:



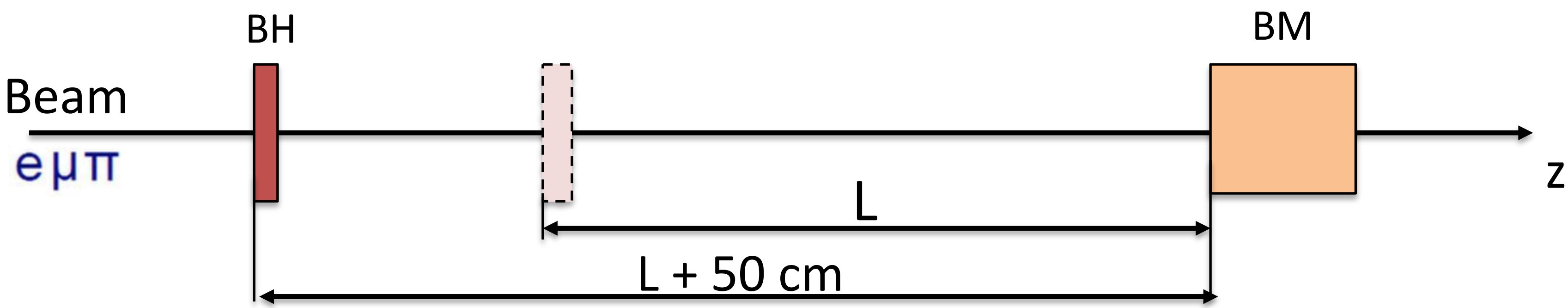
Muon Decays in flight can be removed with TOF measurements:



Requirements:
≤ 100 ps rms TOF for reaction ID

Moeller/Bhabba events can be effectively suppressed with BM acting as a Moeller-VETO

TOF Beam Momentum Measurement



The relativistic momentum is given by:

$$p = \frac{m\,v}{\sqrt{1 - {v^2}/{c^2}}} \Longrightarrow \boxed{t = \frac{L}{v}}$$

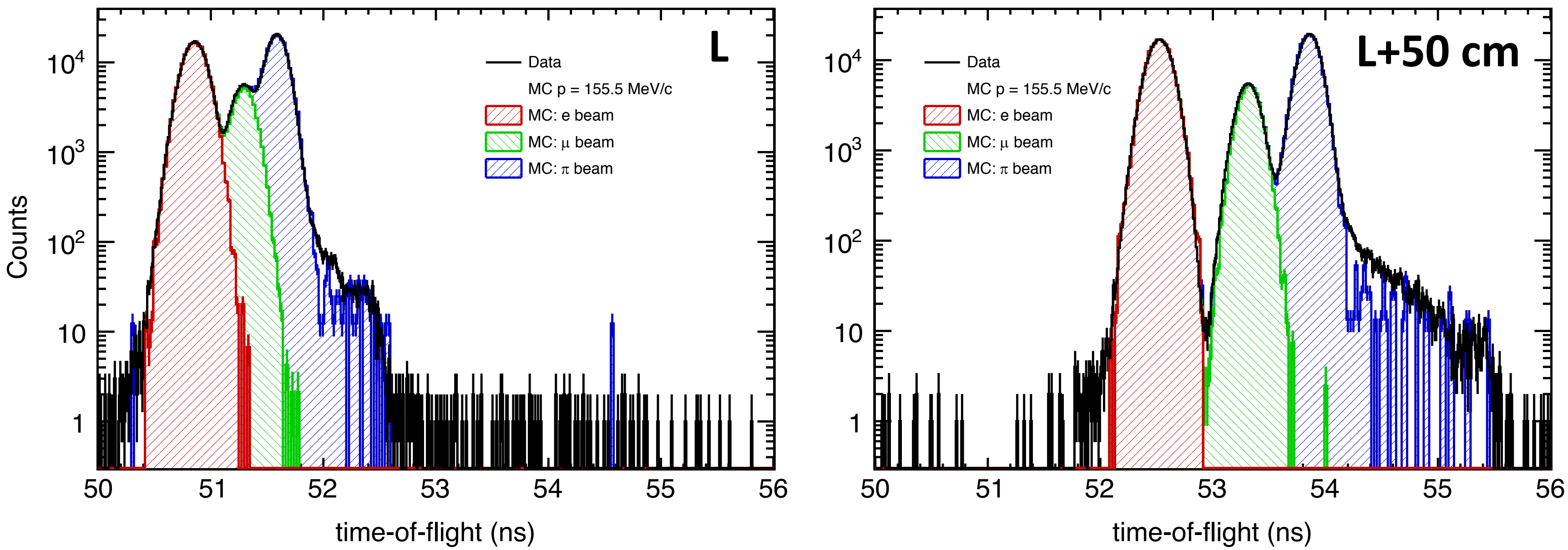
We can determine momentum of **muons** and **pions** from time of flight (TOF) distribution between two fixed detectors.

This method doesn't work for relativistic electrons!

TOF Beam Momentum Measurement

2 TOF measurements with 50 cm difference in detector spacing, compared to Geant4

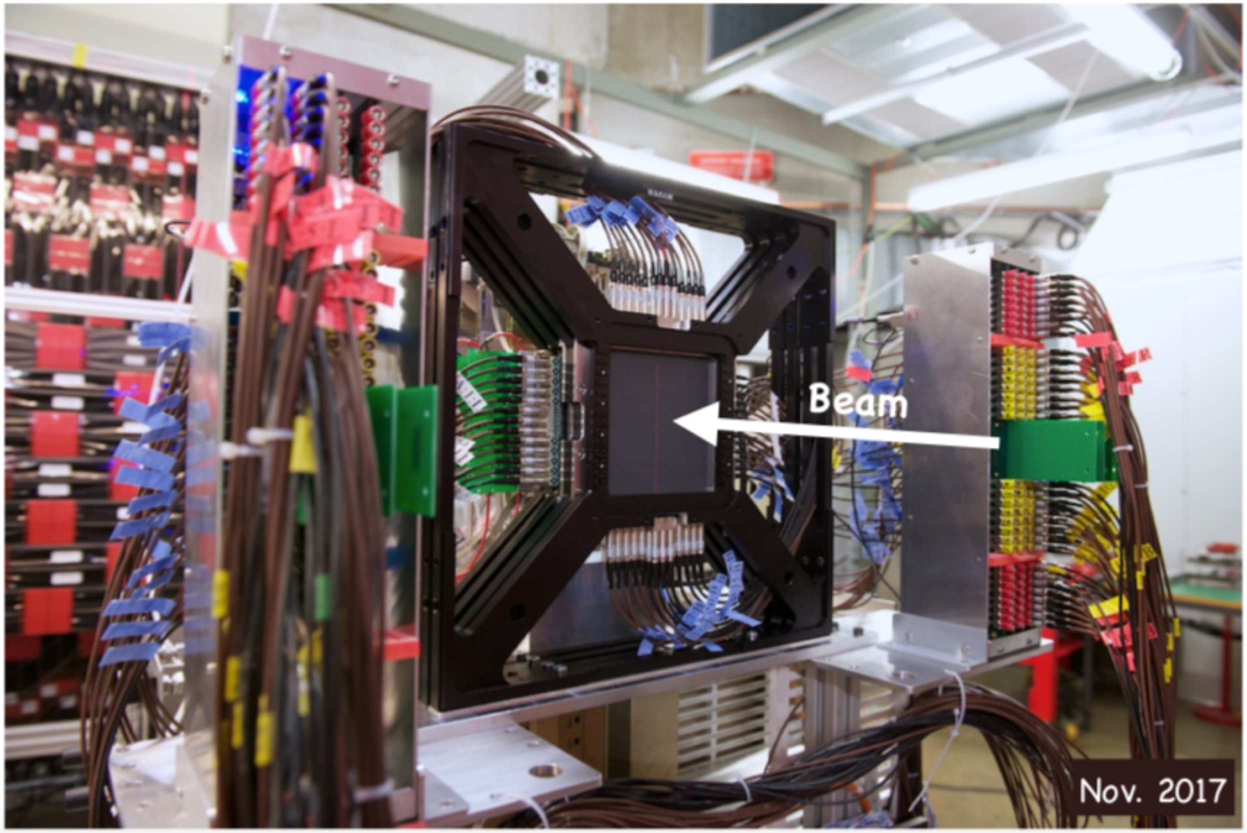
(Horizontal scale has arbitrary offset)

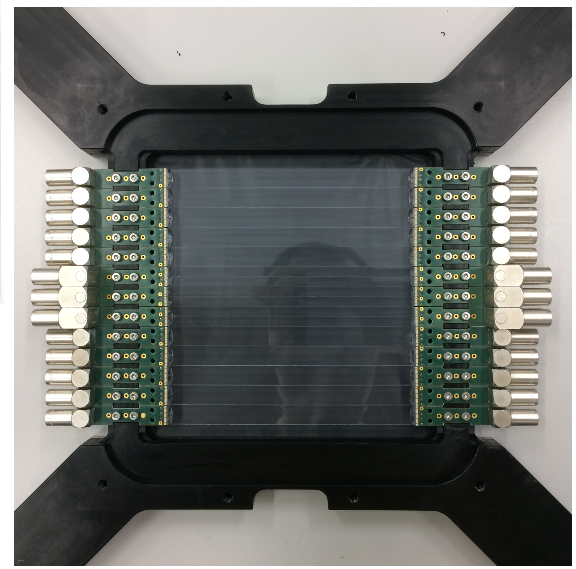


Preliminary data analysis determine $p_\pi(p_\mu)$ to 0.2%(0.3%)

MUSE: Beam Hodoscope (PID)

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	106 ps
#12	64 ps
#13	68 ps
#14	70 ps
#15	61 ps
#16	61 ps



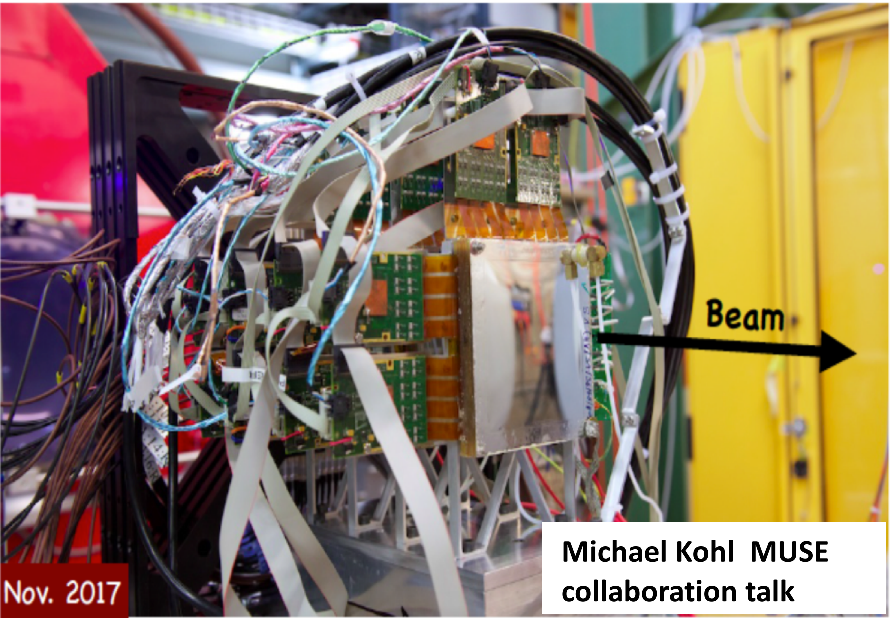


Requirements:

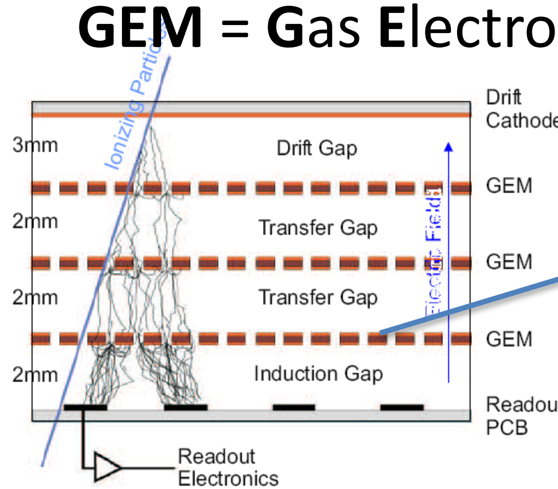
$\sigma_T \leq 150ps$; $\varepsilon \geq 99\%$

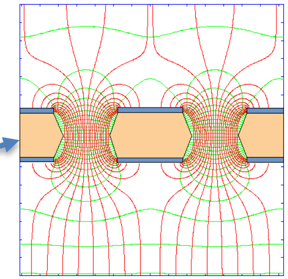
Meet requirements!

MUSE: GEM



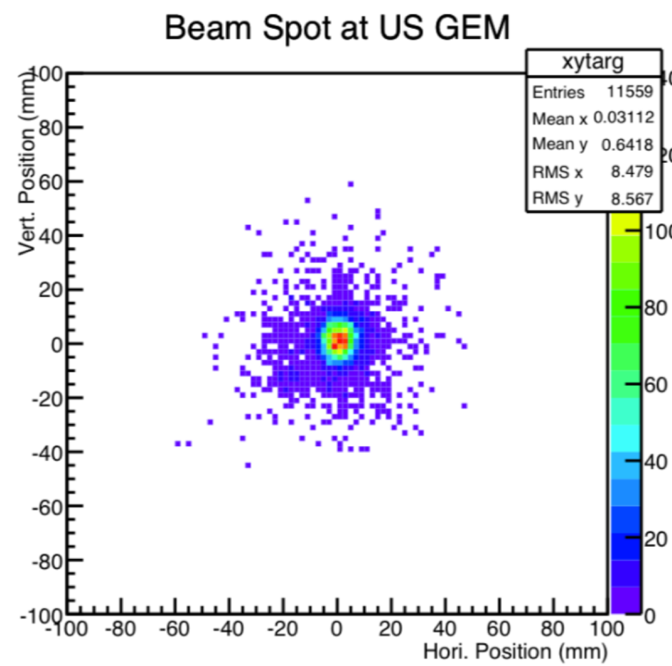
GEM = **G**as **E**lectron **M**ultiplier





- **70 µm** (100 µm) spatial resolution
- ε = **97 – 99%** (98.0%)

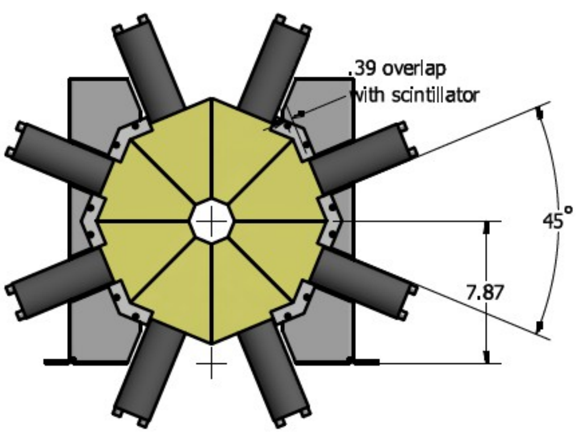
Meet requirements!

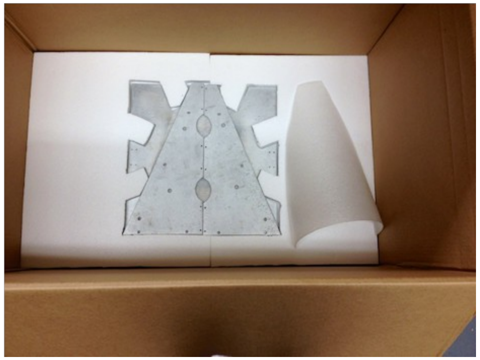


MUSE: Veto

- Eliminate upstream scattering & beam decays
- Completed and arrived at PSI on July 2

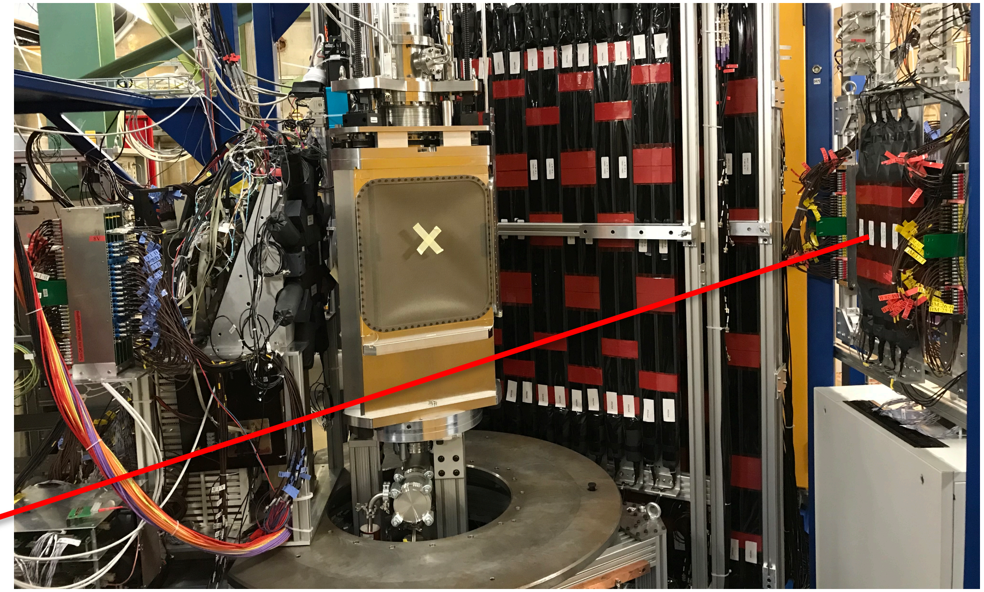
Parameter	Performance Requirement	Achieved
Time Resolution	1 ns / plane	not attempted; easy
Efficiency	99%	not attempted; easy
Positioning	≈1 mm, ≈1 mr	not attempted; easy
Rate Capability	1 MHz / plane	not attempted; easy





Taken from Professor Downie talk: https://indico.mitp.uni-mainz.de/event/132/contribution/37/material/slides/0.pdf

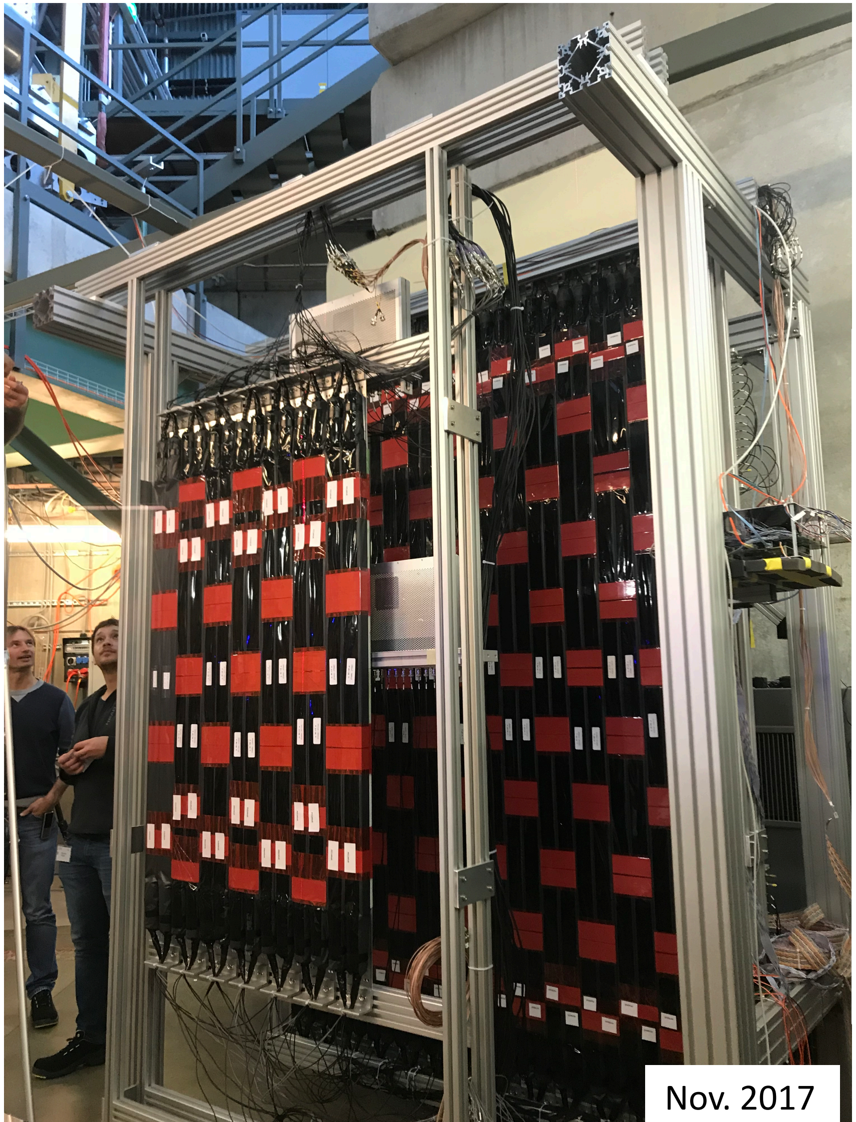
MUSE: Beam Monitor



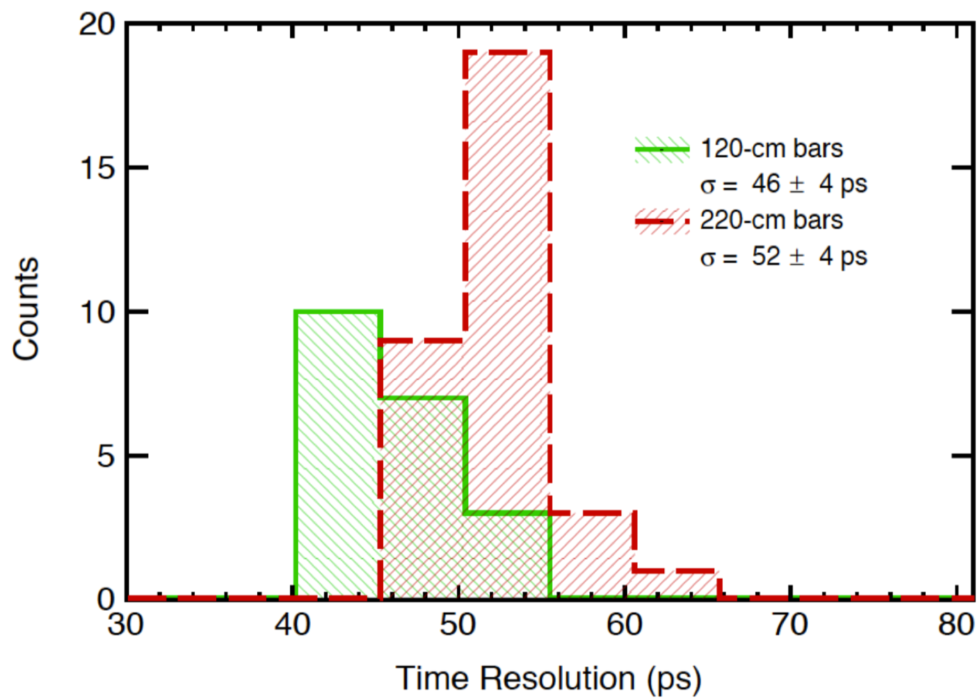
- 3 BM prototypes successfully tested:
  3 mm thick x 300 mm long x 12 mm wide
  BC404 + S13360-3075PE; S13360-3050PE; AdvanSiD
- Best result: S13360-3075PE:
  $\sigma_T = 59ps$; $\varepsilon \geq 99.9\%$

Meet requirements!

MUSE: SPS (TOF and scattering event)

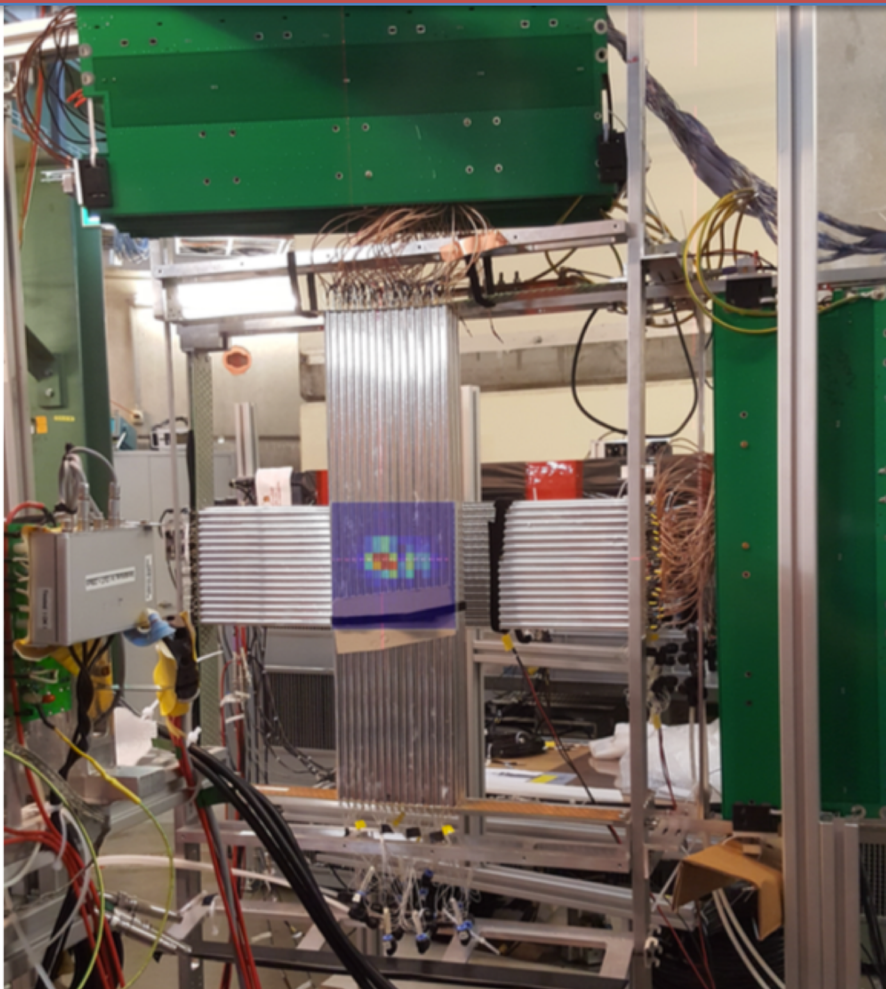


Parameter	Performance Requirement	Achieved
Time Resolution	≈60 ps / plane	✓ 55 ps
Efficiency	99%, ≪ 1% paddle to paddle uncertainty	✓ 99%, paddle to paddle not attempted, moderate
Positioning	≈1 mm, ≈1 mr	not attempted; easy
Rate Capability	0.5 MHz / paddle	✓ 1 MHz



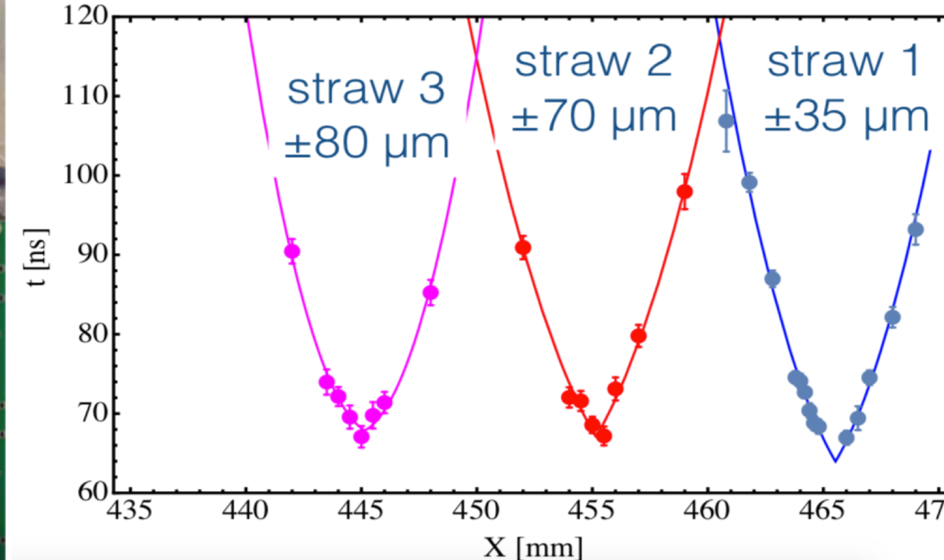
Meet requirements!

MUSE: STT

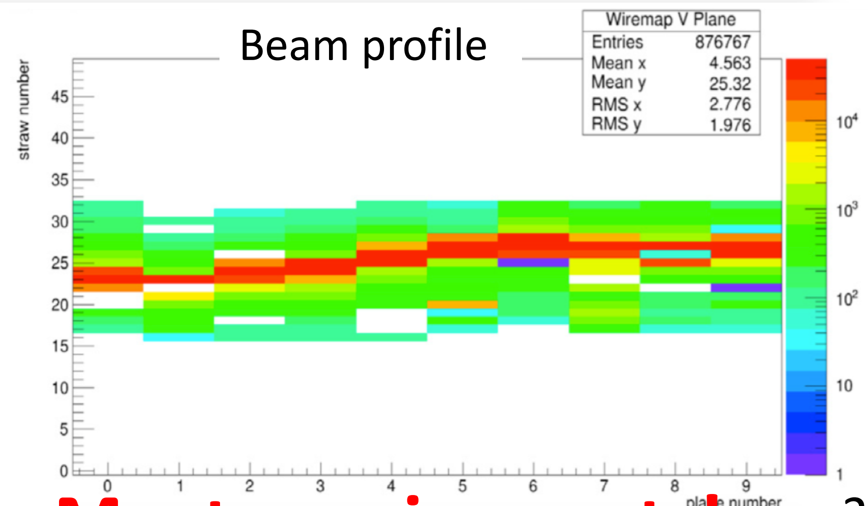


- ~ 3000 Straws
- 150µm spatial resolution
- ~ 99.9% tracking efficiency

Position resolution



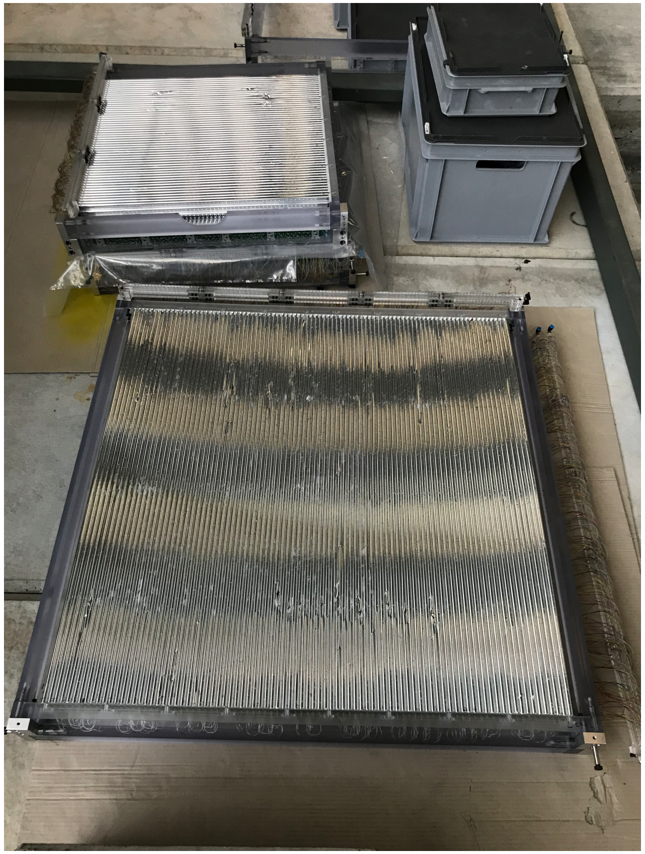
Beam profile



Meet requirements!

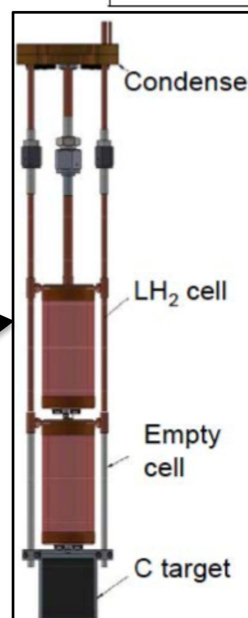
MUSE: STT

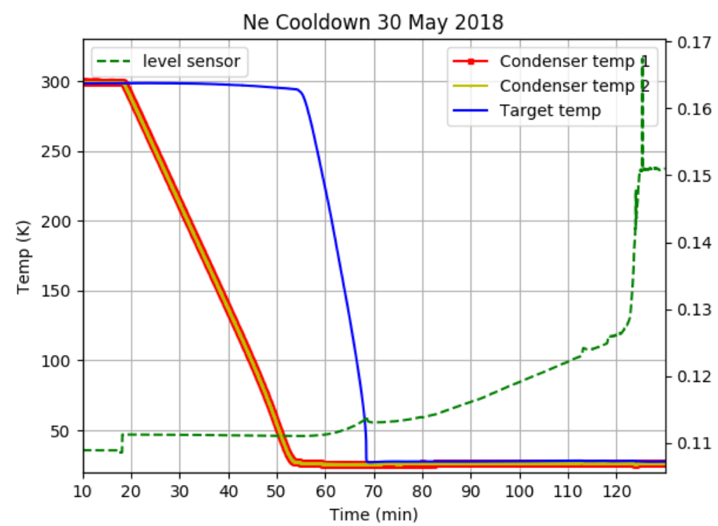
- STT Frame is ready.
- Straws production will be done in middle of October 2018.
- Detector will be ready for December 2018 beamtime.



MUSE: Target

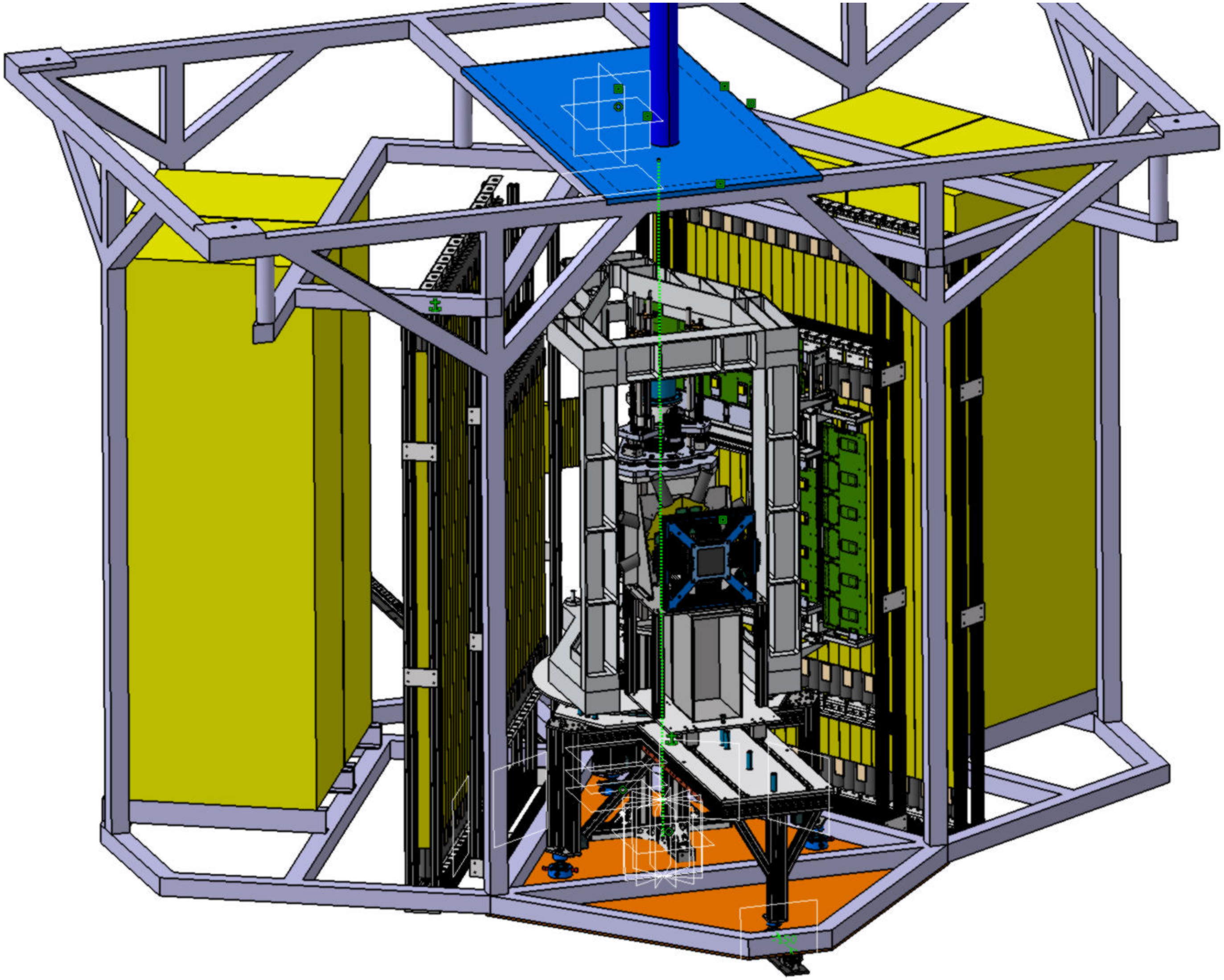
Parameter	Performance Requirement	Achieved?
Liquid hydrogen	maintain liquid hydrogen-filled cell at T≈19 k and P∼1 atm	not attempted; moderate
Cool down time	$<$ 3 days	✓ achieved; $<$ 2 hours!
Beam entrance window	>6 cm	✓ achieved; easy
Exit window(s) (One continuous or two symmetric on beam left and beam right)	$20^\circ < \theta < 100^\circ$; $\phi = 0^\circ \pm 45^\circ$ at $\theta = 60^\circ$ beam up-down and beam left-right symmetry	✓ achieved; challenging



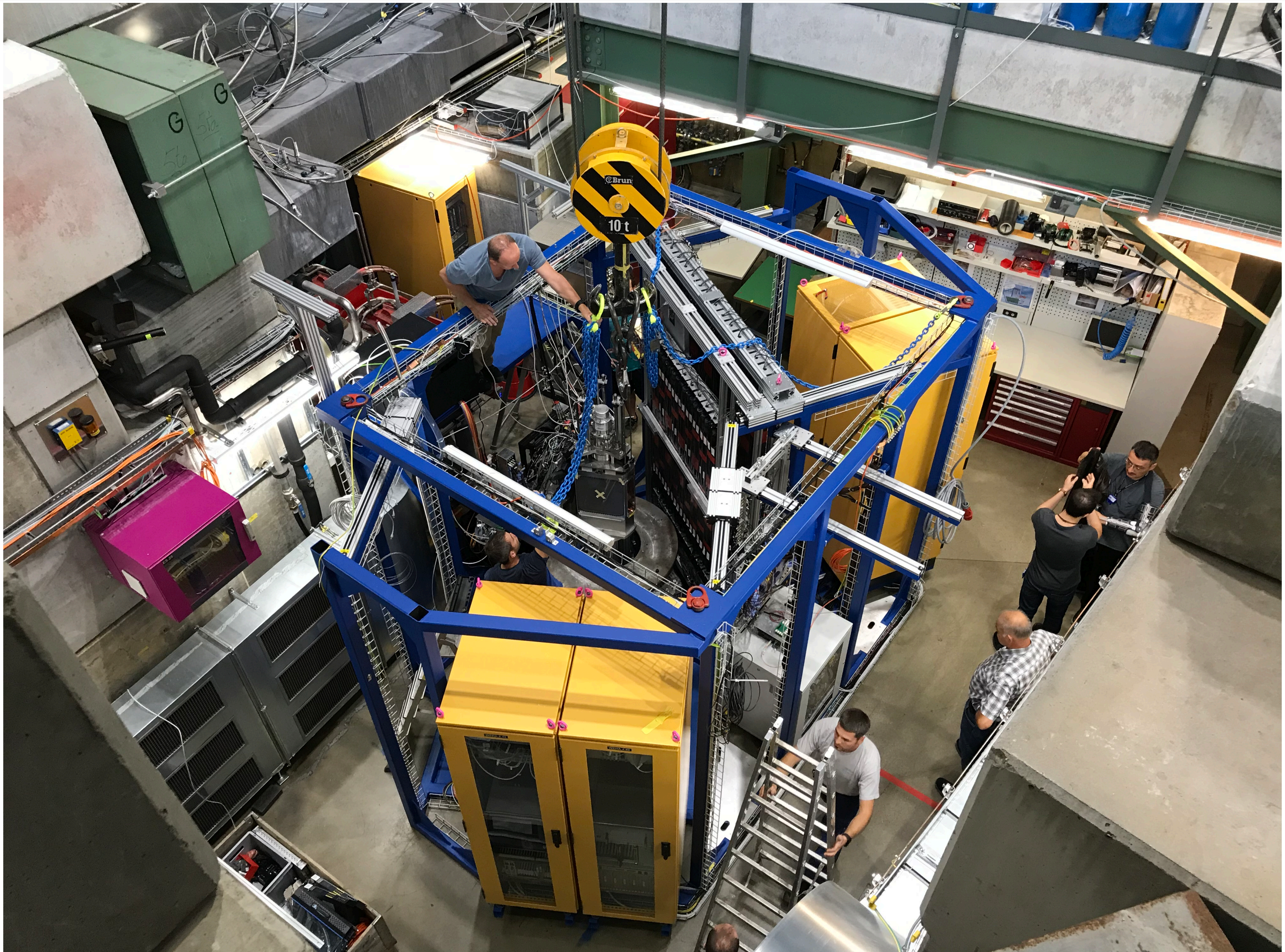


Meet requirements!

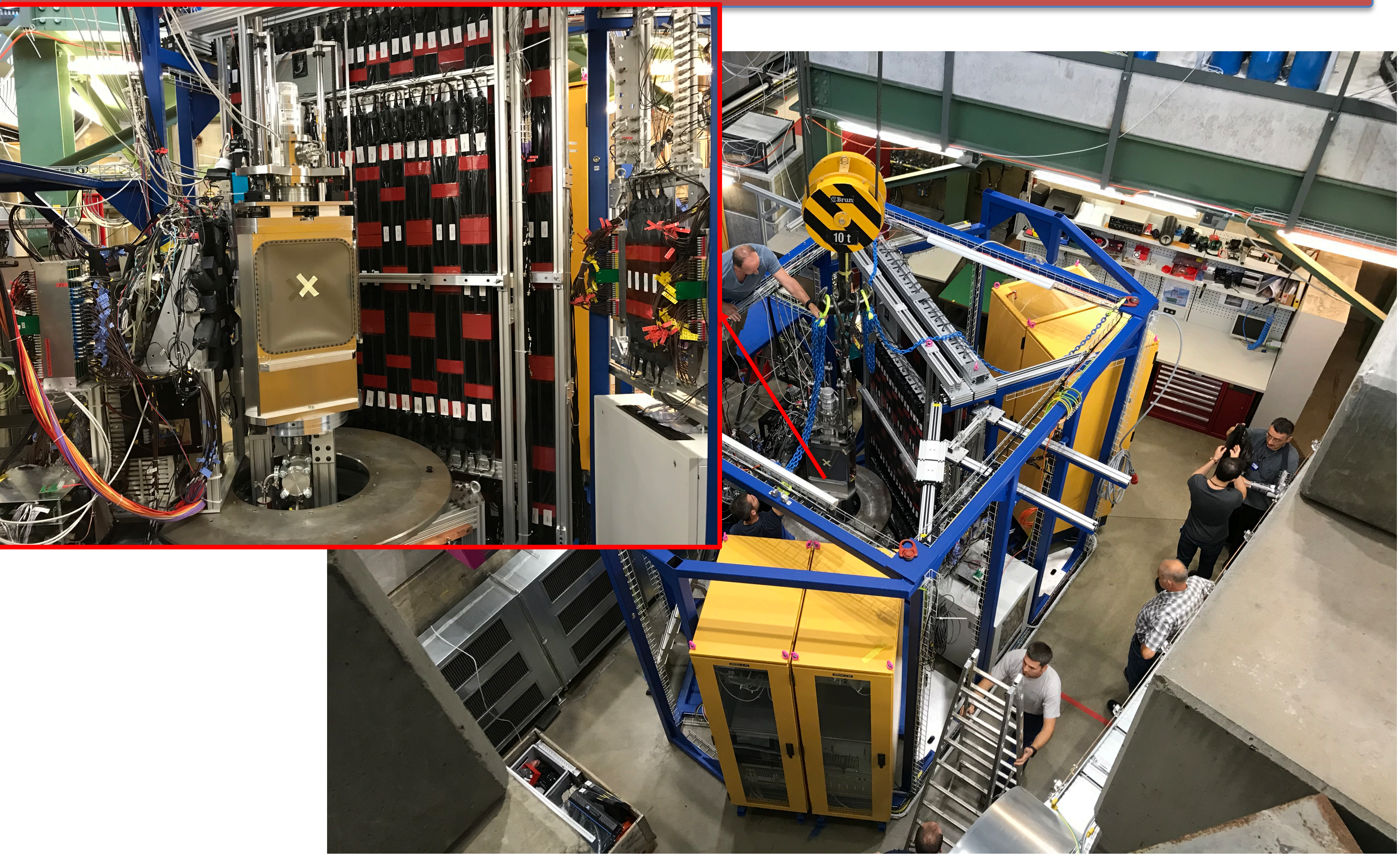
Platform Design



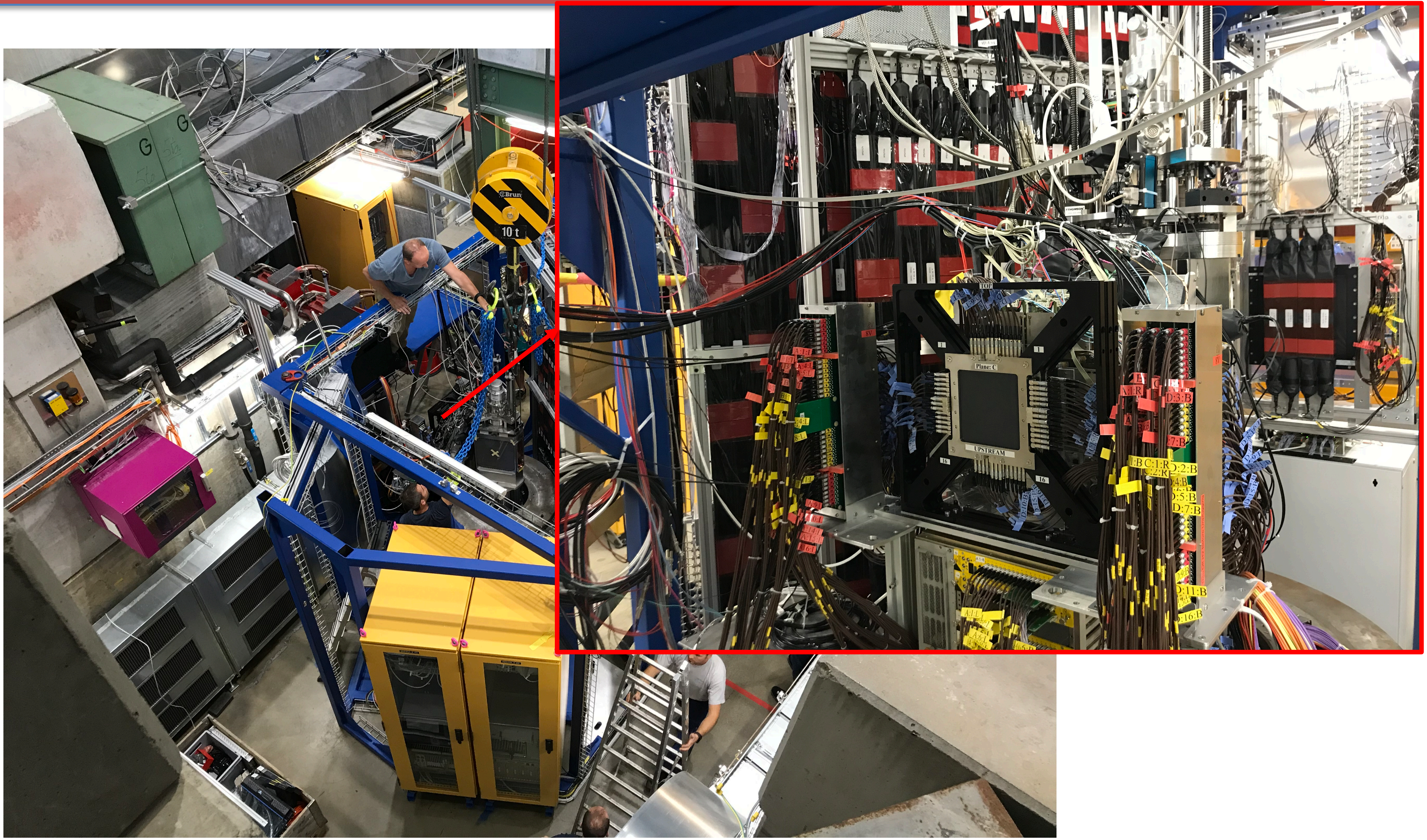
Detectors Assembly



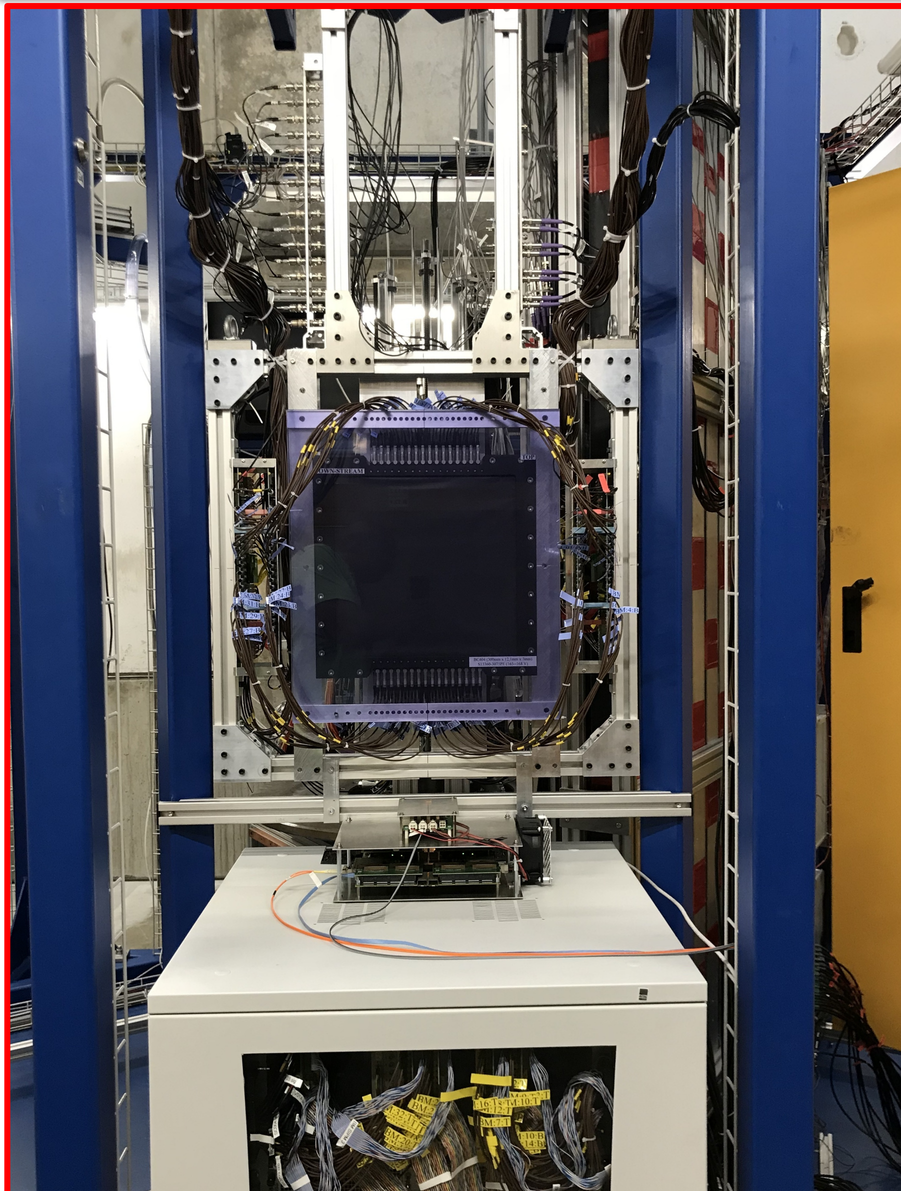
Detectors Assembly



Detectors Assembly



Detectors Assembly



MUSE: Detector Summary

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

Preliminary!

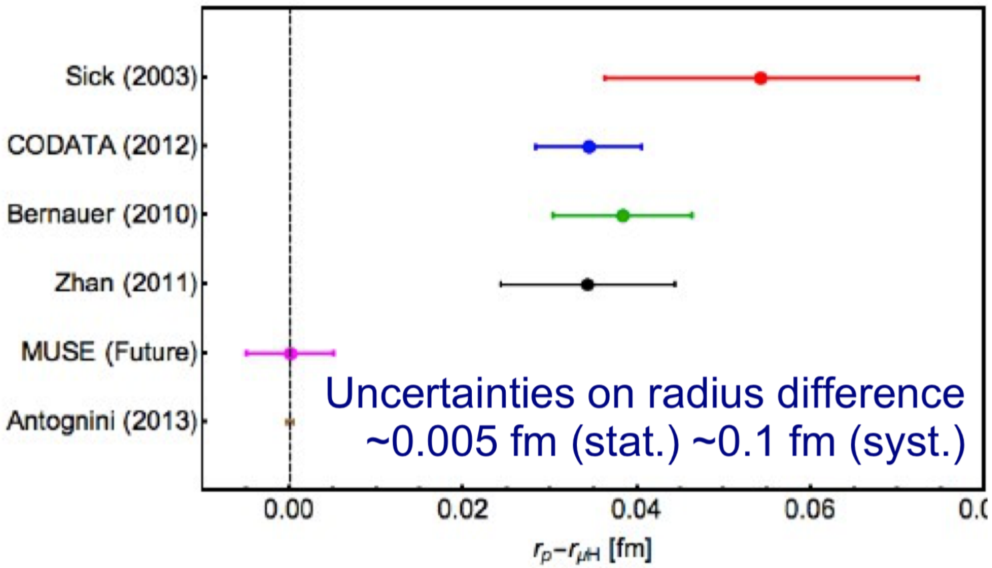
Meet all requirements!

Meanwhile, additional improvement and testing is in the progress!

MUSE: Expectations.

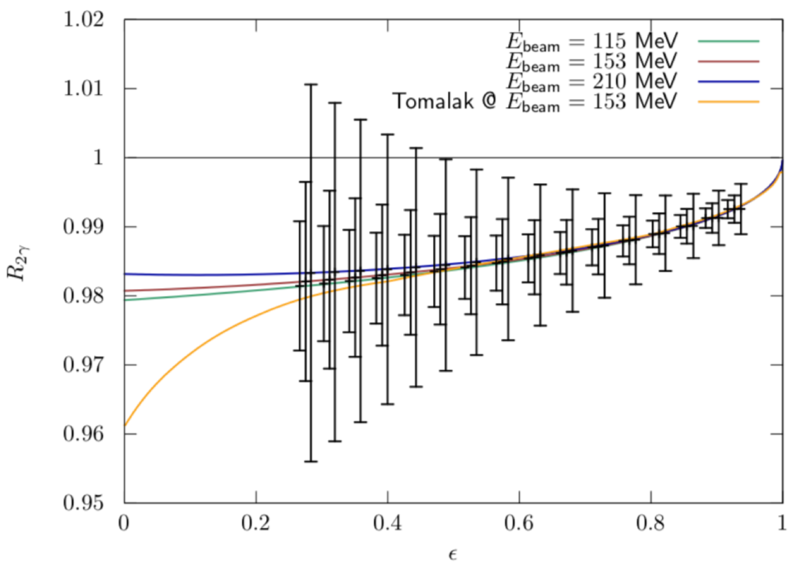
- Charge radius extraction limited by systematics, fit uncertainties.
- Many uncertainties are common to all extractions in the experiments, cancel in e+/e-, μ+/μ-, and μ/e comparisons.

Proton Radius difference:



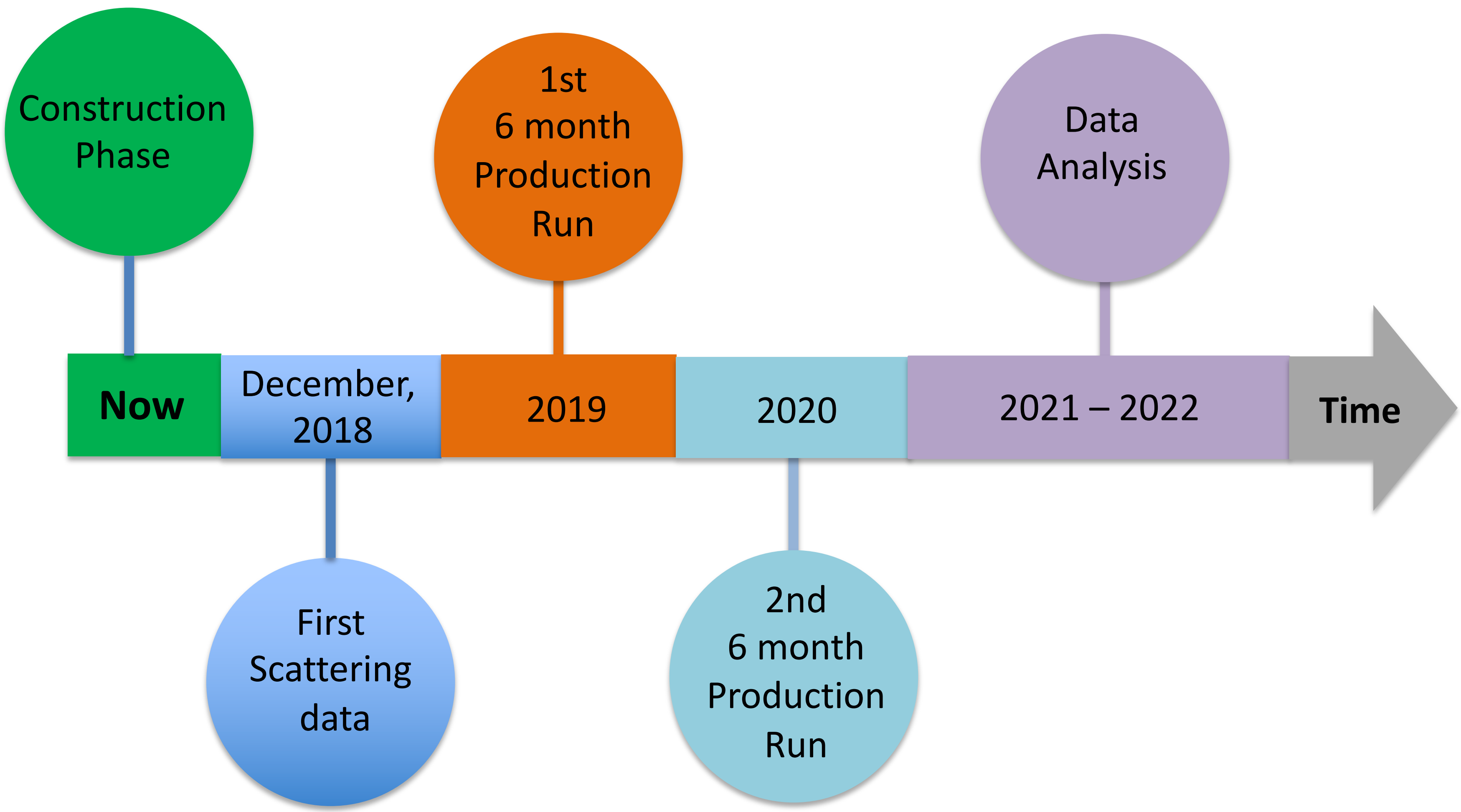
Taken from E. J. Downie talk: https://indico.mitp.uni-mainz.de/event/132/contribution/37/material/slides/0.pdf

Two-Photons Exchange (ep only):



Taken from Jan C. Bernauer talk: https://indico.mitp.uni-mainz.de/event/132/contribution/33/material/slides/0.pdf

Timeline:

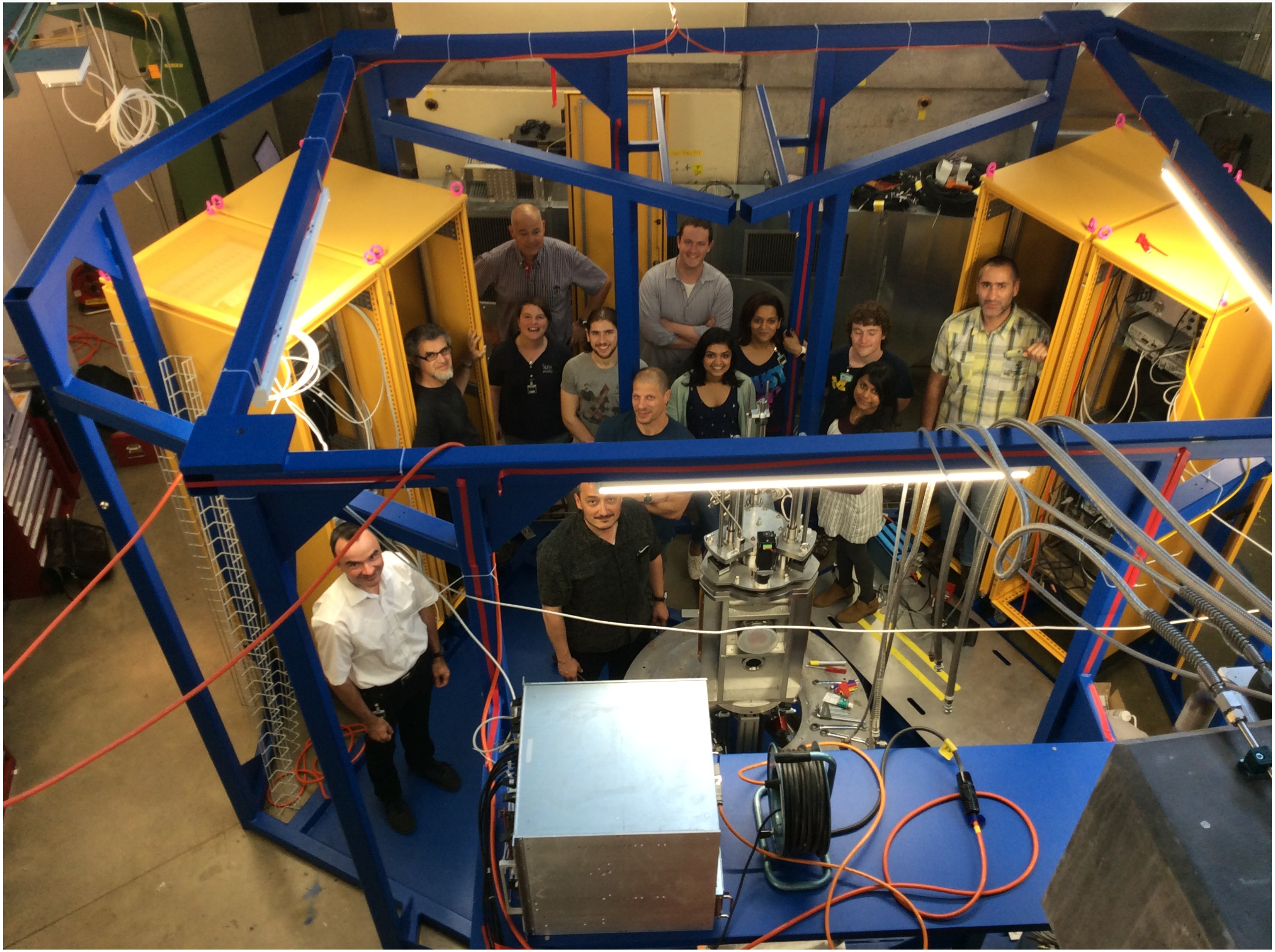

Construction Phase
1st 6 month Production Run
Data Analysis
Now
December, 2018
2019
2020
2021 – 2022
Time
First Scattering data
2nd 6 month Production Run

Acknowledgement:

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]

Acknowledgement:



Thank you for your attention!