Columbian College
of Arts & Sciences
THE GEORGE WASHINGTON UNIVERSITY

The MUSE experiment:
addressing the proton radius puzzle via elastic muon scattering

E. J. Downie

on behalf of the
MUSE Collaboration

THE GEORGE WASHINGTON UNIVERSITY
WASHINGTON, DC

Outline

- Why muon scattering?
- Hasn't it already been done?
- Possible explanations
- The MUSE experiment
- Conclusions

Cosmonaut Breaks Longstanding Space Record

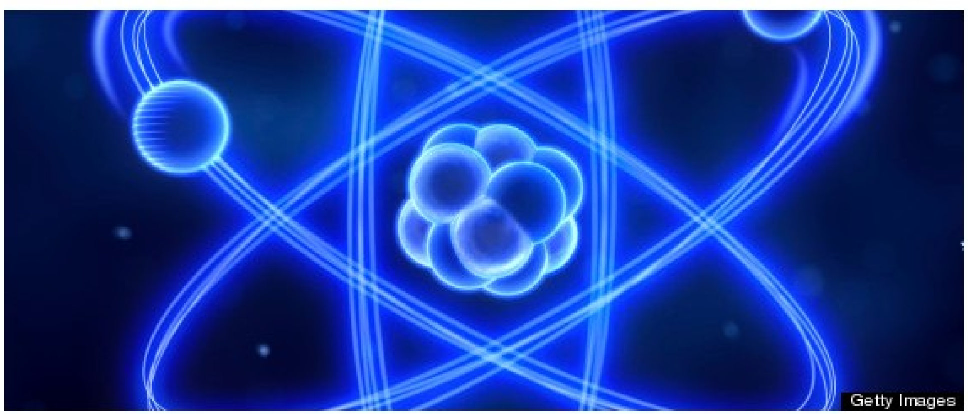
More In Science: WATCH: Horsehead Nebula... Magnetic Putty Explained... Va. Rocket Launch!...

Monarch's Misshapen Bones May Have Led To Torture-Like Treatment

Proton Size Smaller Than Physicists Thought, Puzzling New Measurements Suggest

Posted: 04/14/2013 10:16 am EDT

Like 343 people like this. Be the first of your friends.



Getty Images

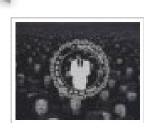
159 share | 235 tweet | 12 +1 | 23 email | 318 comment

GET SCIENCE ALERTS: Enter email SIGN UP

FOLLOW: Video, American Physical Society, Electrons, Physicists, Physics, Proton, Proton Measurements, Proton Mystery, Proton Size, Shrinking Proton, Science News

By: Stephanie Pappas, LiveScience Senior Writer

- The crash-dieting proton is famous!
- Not just interesting:
  - → Tests our theoretical understanding of proton
  - → Radius of proton is dominant uncertainty in many QED processes



Anonymous Calls For Internet Blackout To Protest CISPA

Like 13k

Report: Miranda Rights Won't

Why Muon Scattering?

r_p(fm)	ep	μp
atom	0.877±0.007	0.841±0.0004
scattering	0.875±0.006	**?**

- Muon results inconsistent with electron results
- To date no high-quality muon scattering measurements performed

Why do the muon and electron give different proton radii?

- **Assuming** the experimental results are not bad, what are viable theoretical explanations of the Radius Puzzle?
- Novel Beyond Standard Model Physics: Pospelov, Yavin, Carlson, ...: the electron is measuring an EM radius, the muon measures an (EM+BSM) radius
- Novel Hadronic Physics: G. Miller: currently unconstrained correction in proton polarizibility affects μ, but not e (effect$\propto m_l^4$)
- Basically everything else suggested has been ruled out - missing atomic physics, structures in form factors, anomalous 3rd Zemach radius, (cf. Michael Distler)
- See Trento Workshop on PRP for more details:

  http://www.mpq.mpg.de/~rnp/wiki/pmwiki.php/Main/WorkshopTrento

How do we Resolve the Radius Puzzle

- New data needed to test that the e and μ are really different, and the implications of novel BSM and hadronic physics
  - **BSM:** scattering modified for Q^2 up to m^2_{BSM} (typically expected to be MeV to 10s of MeV), enhanced parity violation
  - **Hadronic:** enhanced 2γ exchange effects
- Experiments include:
  - Redoing atomic hydrogen
  - Light muonic atoms for radius comparison in heavier systems
  - Redoing electron scattering at lower Q^2
  - **Muon scattering!**

How do we Resolve the Radius Puzzle

- New data needed to test that the e and μ are really different, and the implications of novel BSM and hadronic physics
  - **BSM:** scattering modified for Q^2 up to m^2_{BSM} (typically expected to be MeV to 10s of MeV), enhanced parity violation
  - **Hadronic:** enhanced 2γ exchange effects
- Experiments include:
  - Redoing atomic hydrogen
  - Light muonic atoms for radius comparison in heavier systems **CREMA**
  - Redoing electron scattering at lower Q^2 **Jlab & Mainz**
  - **Muon scattering!**

How do we Resolve the Radius Puzzle

- New data needed to test that the e and μ are really different, and the implications of novel BSM and hadronic physics
  - ➔ **BSM:** scattering modified for Q^2 up to m^2_{BSM} (typically expected to be MeV to 10s of MeV), enhanced parity violation
  - ➔ **Hadronic:** enhanced 2γ exchange effects

MUSE tests these

- Experiments include:
  - ➔ Redoing atomic hydrogen
  - ➔ Light muonic atoms for radius comparison in heavier systems **CREMA**
  - ➔ Redoing electron scattering at lower Q^2 **Jlab & Mainz**
  - ➔ **Muon scattering!**

Why Muon Scattering?

r_p(fm)	ep	μp
atom	0.877±0.007	0.841±0.0004
scattering	0.875±0.006	?

- Muon results inconsistent with electron results
- To date no high-quality muon scattering measurements performed
- Why not?

Why Muon Scattering?

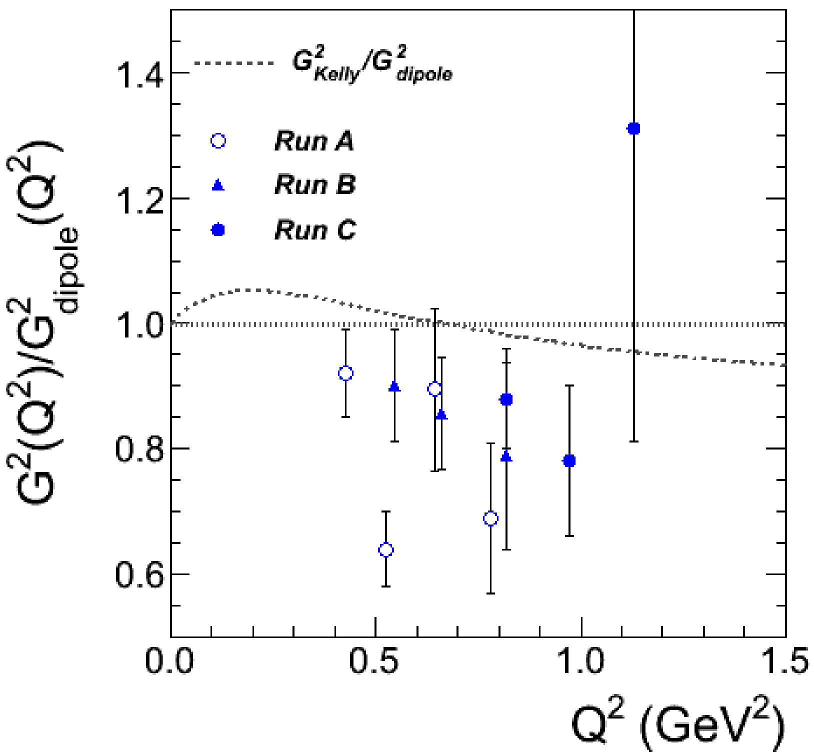
	e	μ
Stable?	yes	no
Primary / secondary	primary	secondary
Emmitance	small	large
Intensity	10^{15}/s	$10^5 – 10^6$/s
Backgrounds	-	**e, π**

- Muon beams are not electron beams!

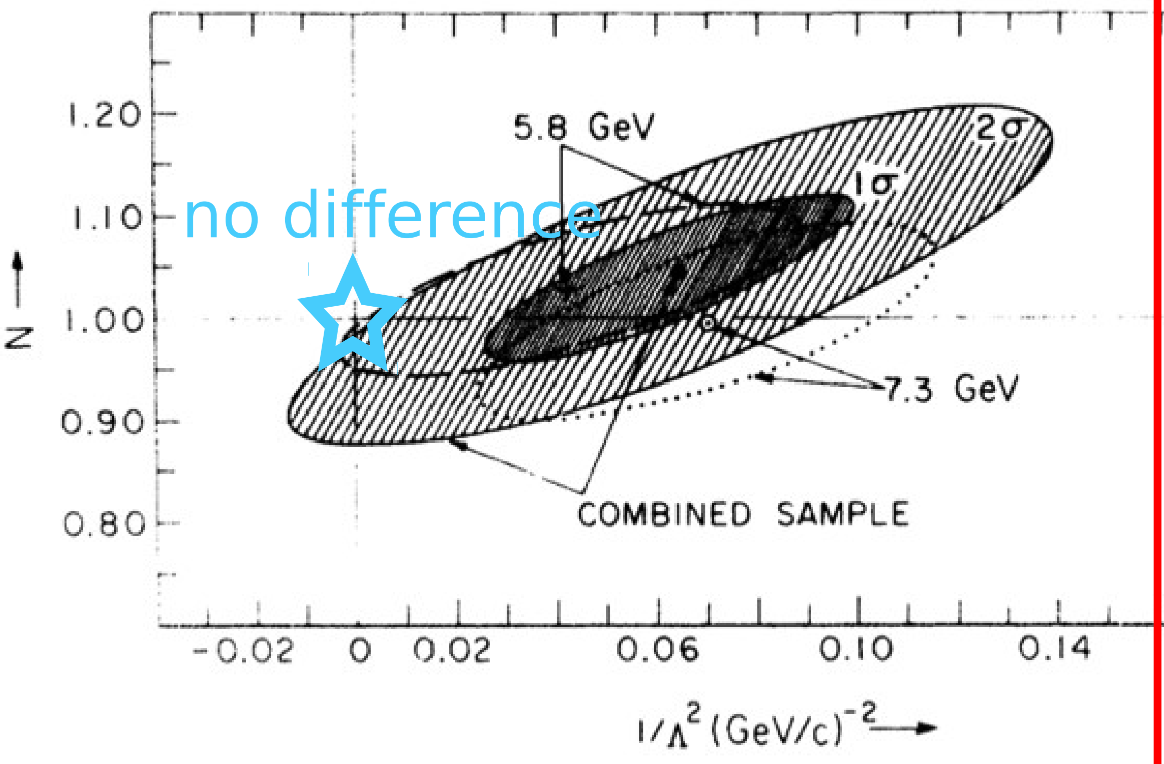
Previous e-μ Scattering Comparisons

- 1970's & 80's several scattering ep & μp tests
- Supported universality at 10% level
- Insufficient precision to test proton radius issues

Ellsworth et al.: form factors from elastic μp



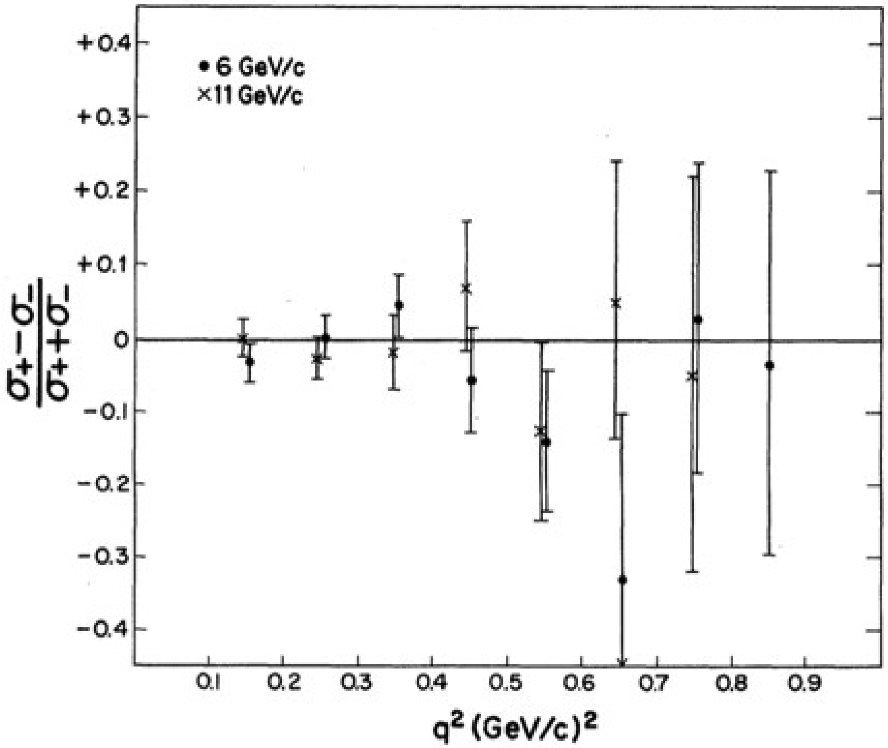
Kostoulas et al. parameterization of μp vs. ep elastic differences

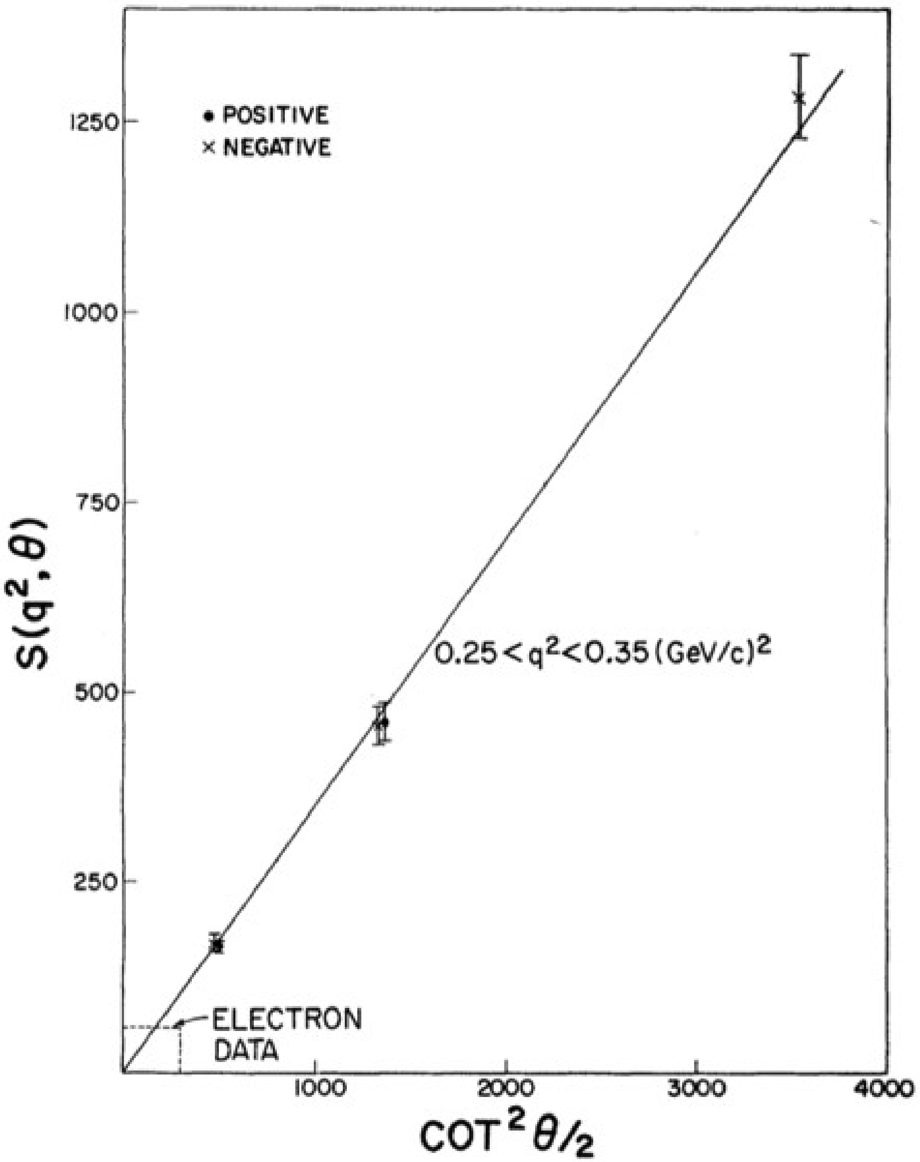


Entenberg et al DIS: $\sigma_{\mu p}/\sigma_{ep} \approx 1.0 \pm 0.04$ (±8.6% systematics)

Two-photon exchange tests in μp elastics

- Camilleri et al. PRL 23: No evidence for two-photon exchange effects, but very poor constraints by modern standards.



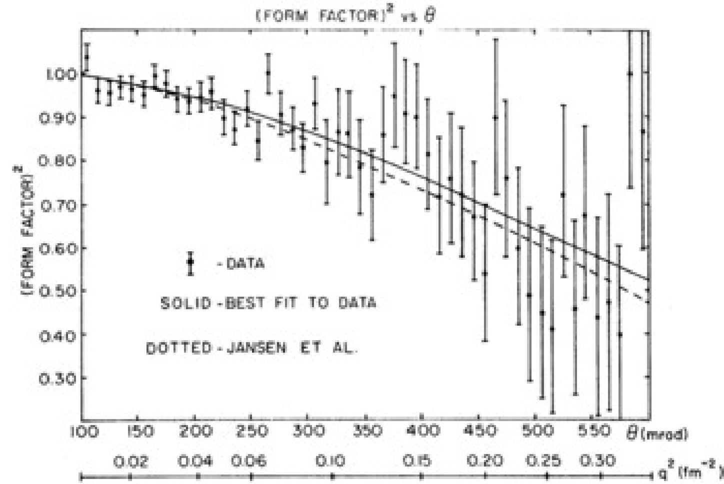


No difference between μ^+p and μ^-p elastic scattering

Rosenbluth plot is linear.

C Radius and e-μ Universality

- ^{12}C radius determined with eC scattering and μC atoms agree
  - ➔ Offermann et al. eC: 2.478 ± 0.009 fm
  - ➔ Schaller et al. μC X rays: 2.4715 ± 0.016 fm
  - ➔ Ruckstuhl et al. μC X rays: 2.483 ± 0.002 fm
  - ➔ Sanford et al. μC elastic: 2.32 $^{+0.13}_{-0.18}$ fm



- Perhaps carbon is right, e's and μ's are the same.

- Perhaps hydrogen is right, e's and μ's are different.

- Perhaps both are right - opposite effects for proton and neutron cancel with carbon.

- But perhaps the carbon radius is insensitive to the nucleon radius, and μd or μHe would be a better choice?

- Also: A. Antognini et al: Muonic H + eH/D isotope shift ➪ r_d = 2.12771(22) fm vs. 2.130(10) fm from ed scattering.

MUSE Experiment

r_p(fm)	ep	μp
atom	0.877±0.007	0.841±0.0004
scattering	0.875±0.006	?

- 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

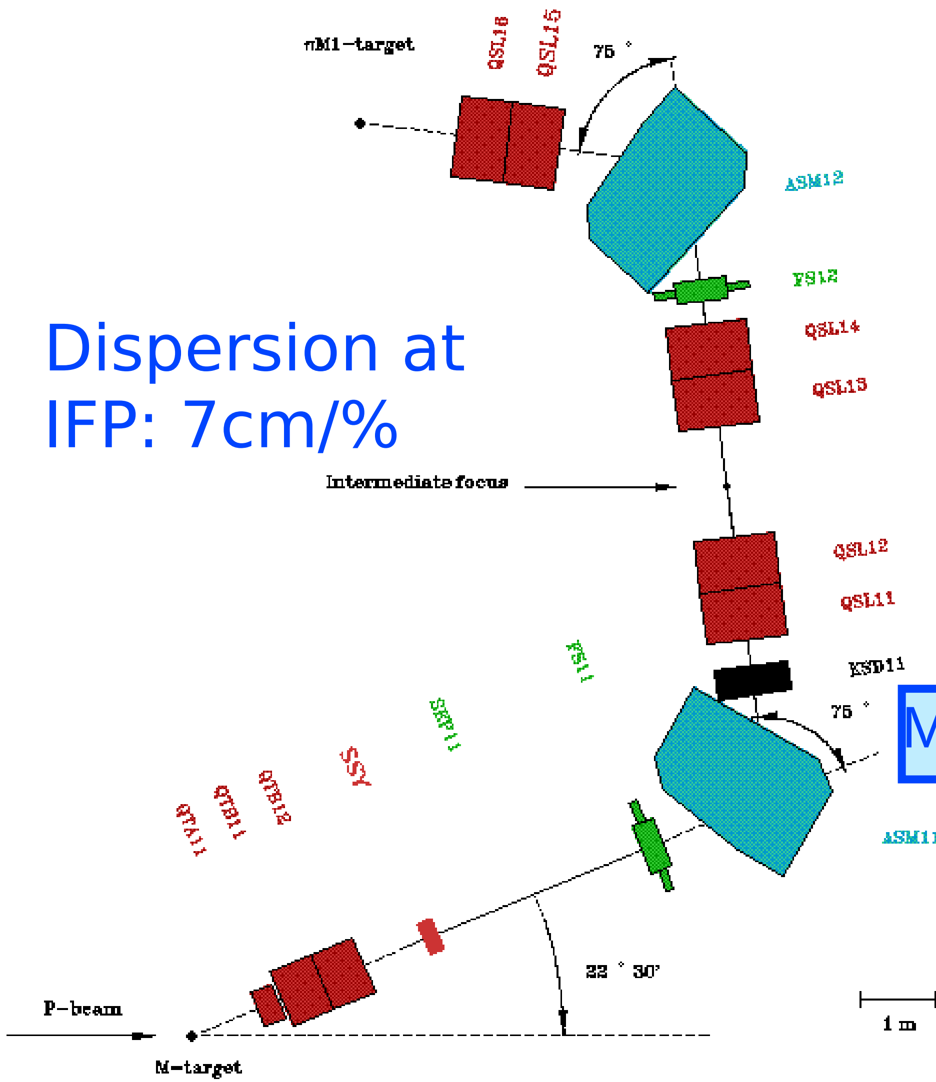
➔ Test of Lepton Universality

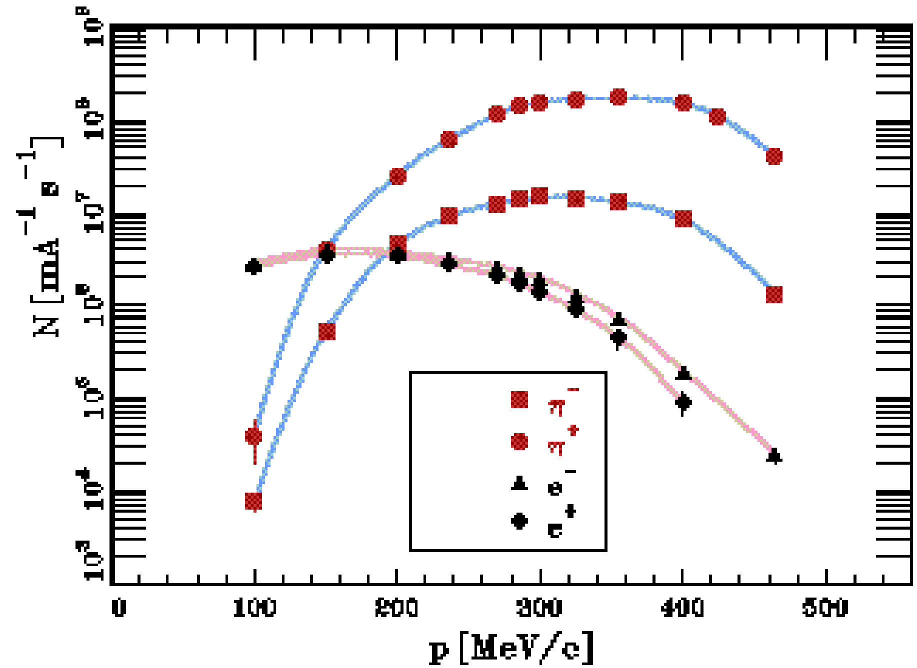
➔ Simultaneous determination of proton radius in both eP and μP scattering

Nominal PSI πM1 Channel Characteristics

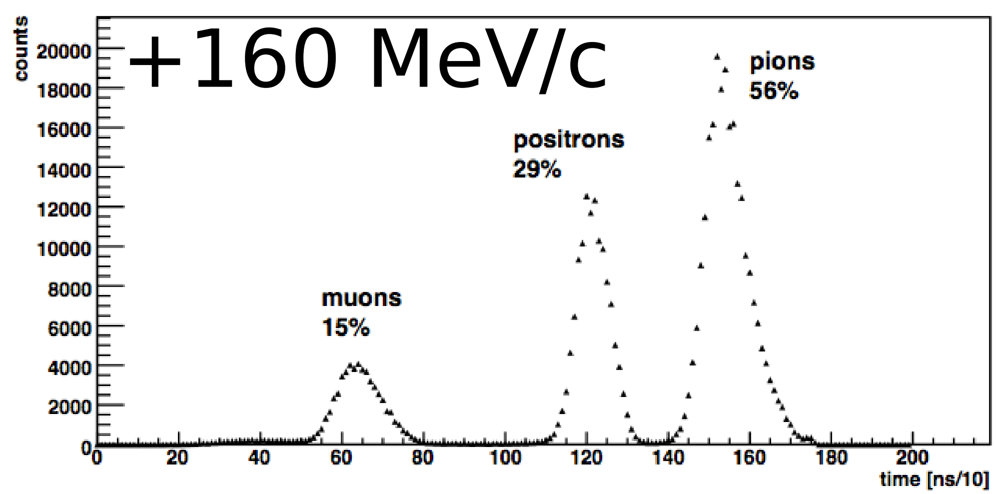
≈100 - 500 MeV/c mixed beam of μ's + e's + π's

Dispersion at IFP: 7cm/%





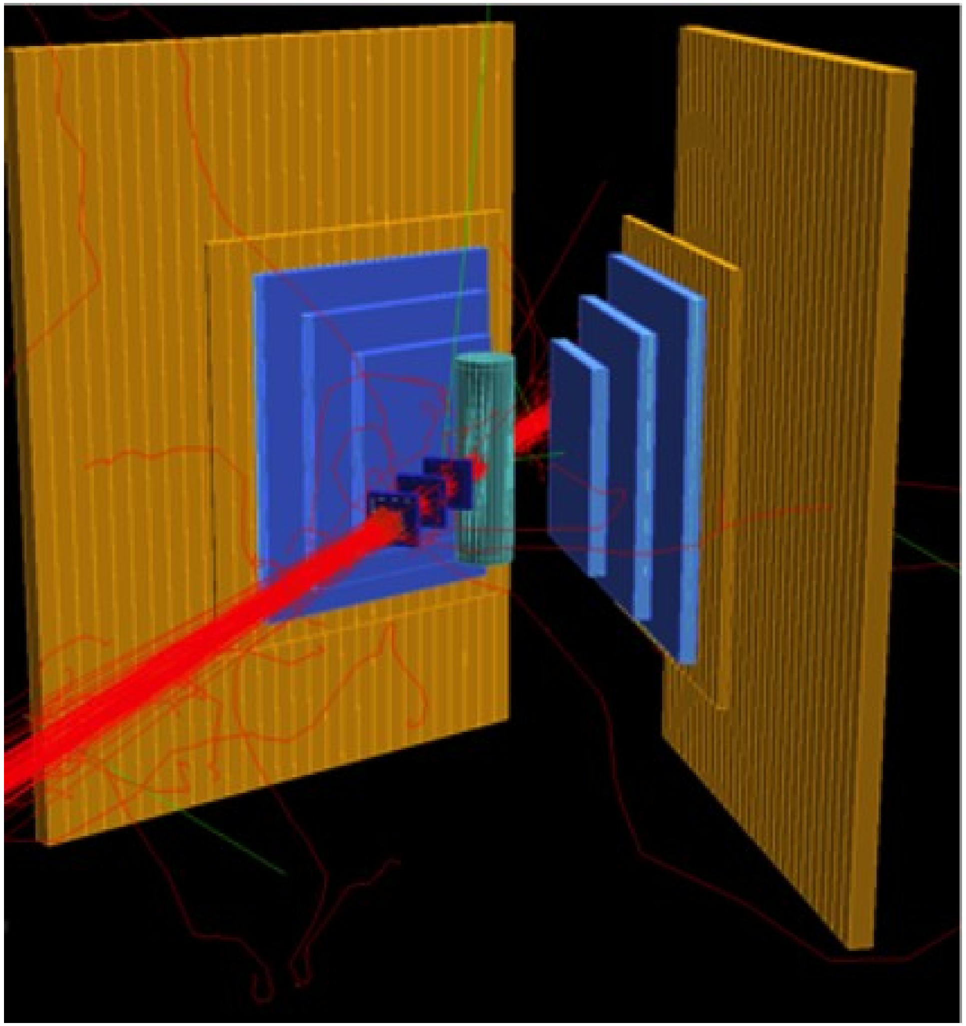
Momentum acceptance: 3% resolution: 0.1%



Beam spot (nominal): 1.5 cm X x 1 cm Y, 35 mr X' x 75 mr Y'

Spots from 0.7x0.9 cm^2 up to 16x10 cm^2, Δp/p from 0.1-3.0%, used previously.

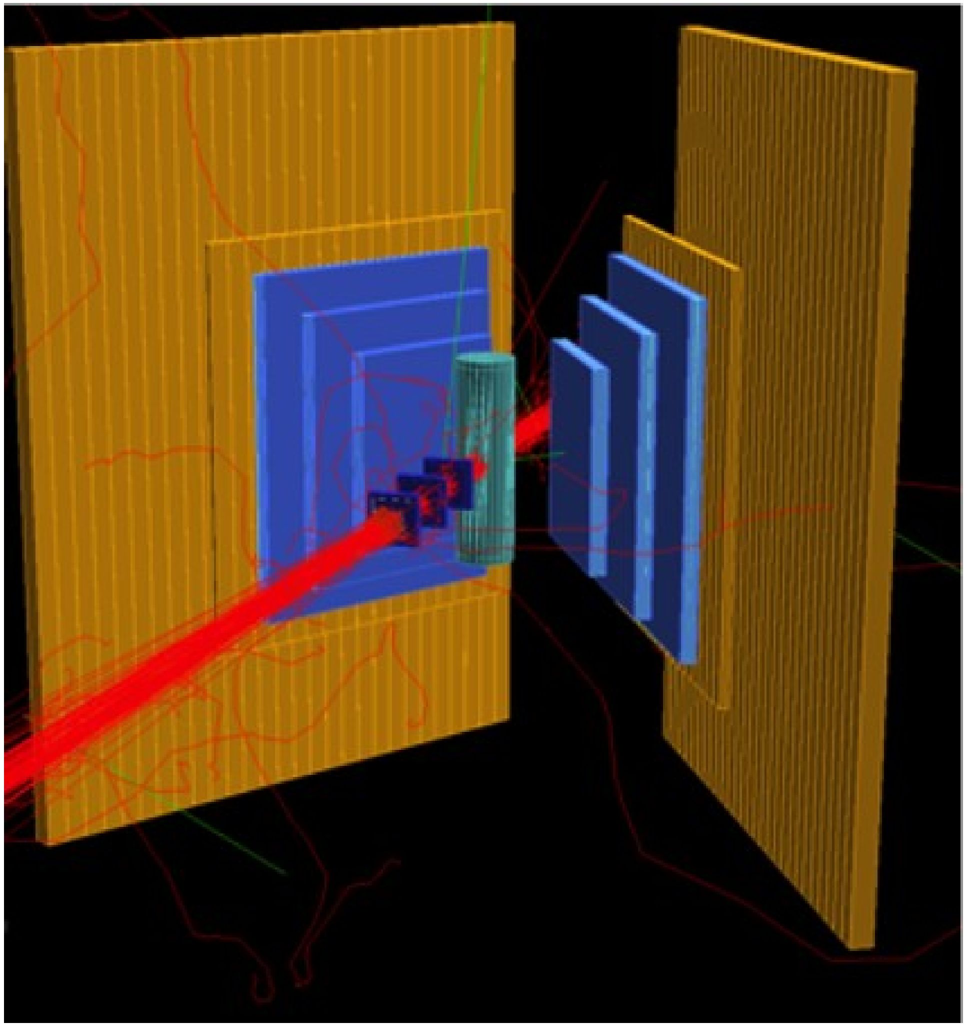
MUSE Experiment

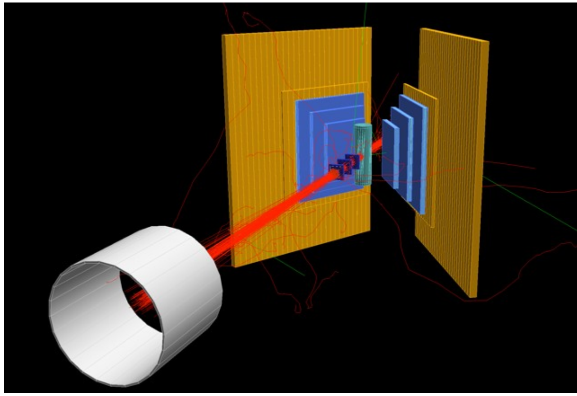


- Low beam flux. → Large angle, non-magnetic detectors.
- Secondary beam. → Tracking of beam particles to target.
- Mixed beam. → Identification of beam particle in trigger.

MUSE Experiment

- PSI πM1 channel
- ≈115, 153, 210 MeV/c mixed beams of $e^{\pm}$, $\mu^{\pm}$ and $\pi^{\pm}$
- FPGA trigger with beam PID
- $\theta \approx 20^{o} - 100^{o}$
- $Q^2 \approx 0.002 - 0.07$ GeV^2
- About 5 MHz total beam flux, ≈2-15% μ's, 10-98% e's, 0-80% π's
- Beam monitored with SciFi, ``quartz'' Cerenkov, GEMs
- Scattered particles detected with straw chambers and scintillators





SciFi Beam Detectors (Tel Aviv)

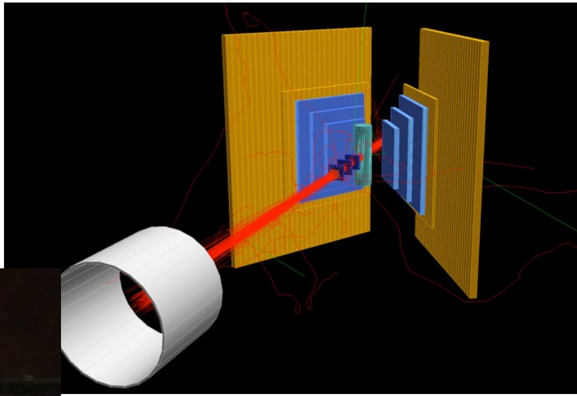
At target

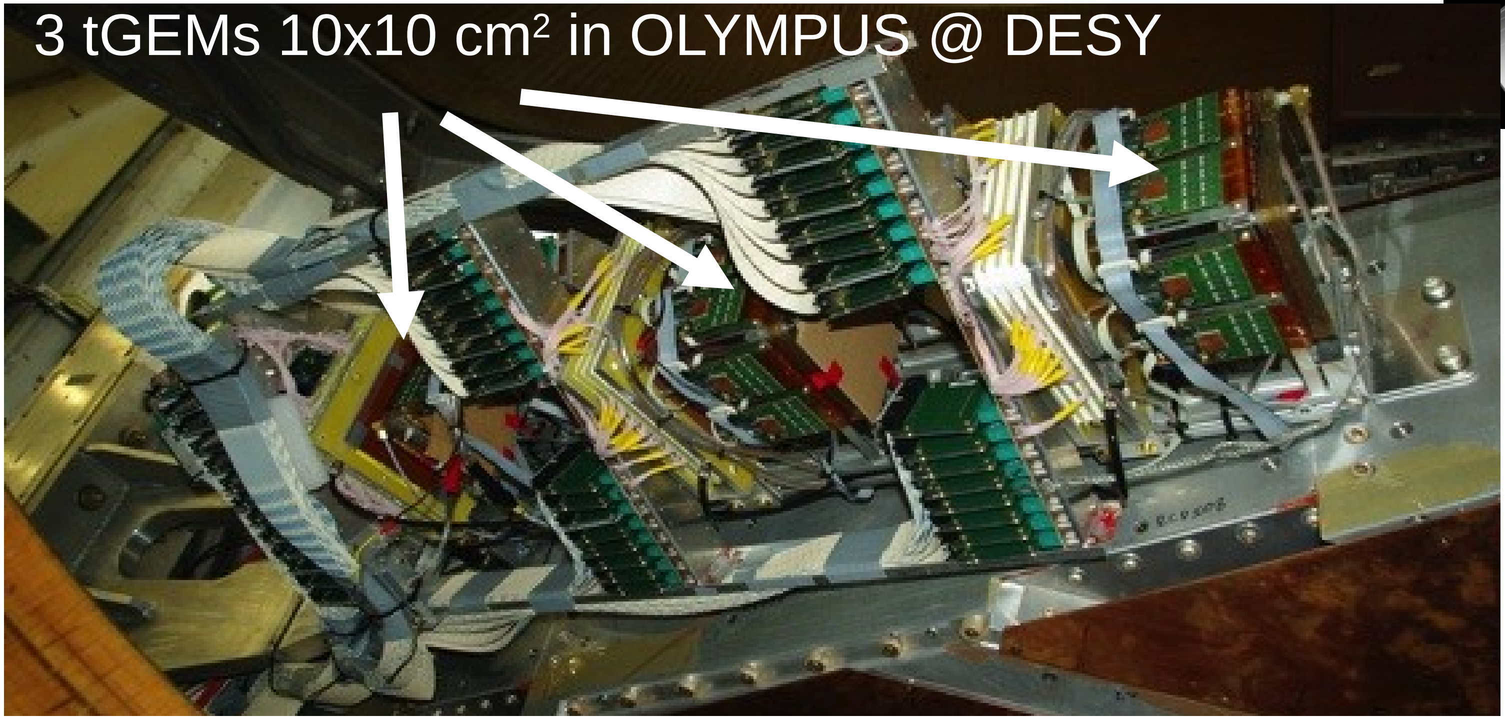
- Timing (~1ns σ in hardware) for PID in combination with beam RF
- Beam flux normalisations for absolute cross sections & triggering
- Position & time for correlations with GEMS
- TOF between counters for PID

Properties

- 2mm fibres, double-ended maPMT readout. UVY orientations for target detector with ≈ 120 fibres & 8 cm active area

GEM Chambers
(Hampton U.)



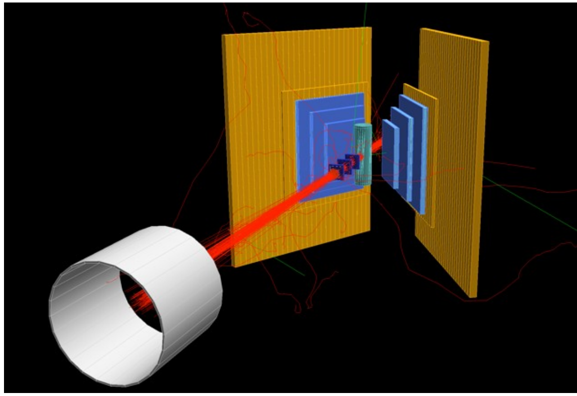


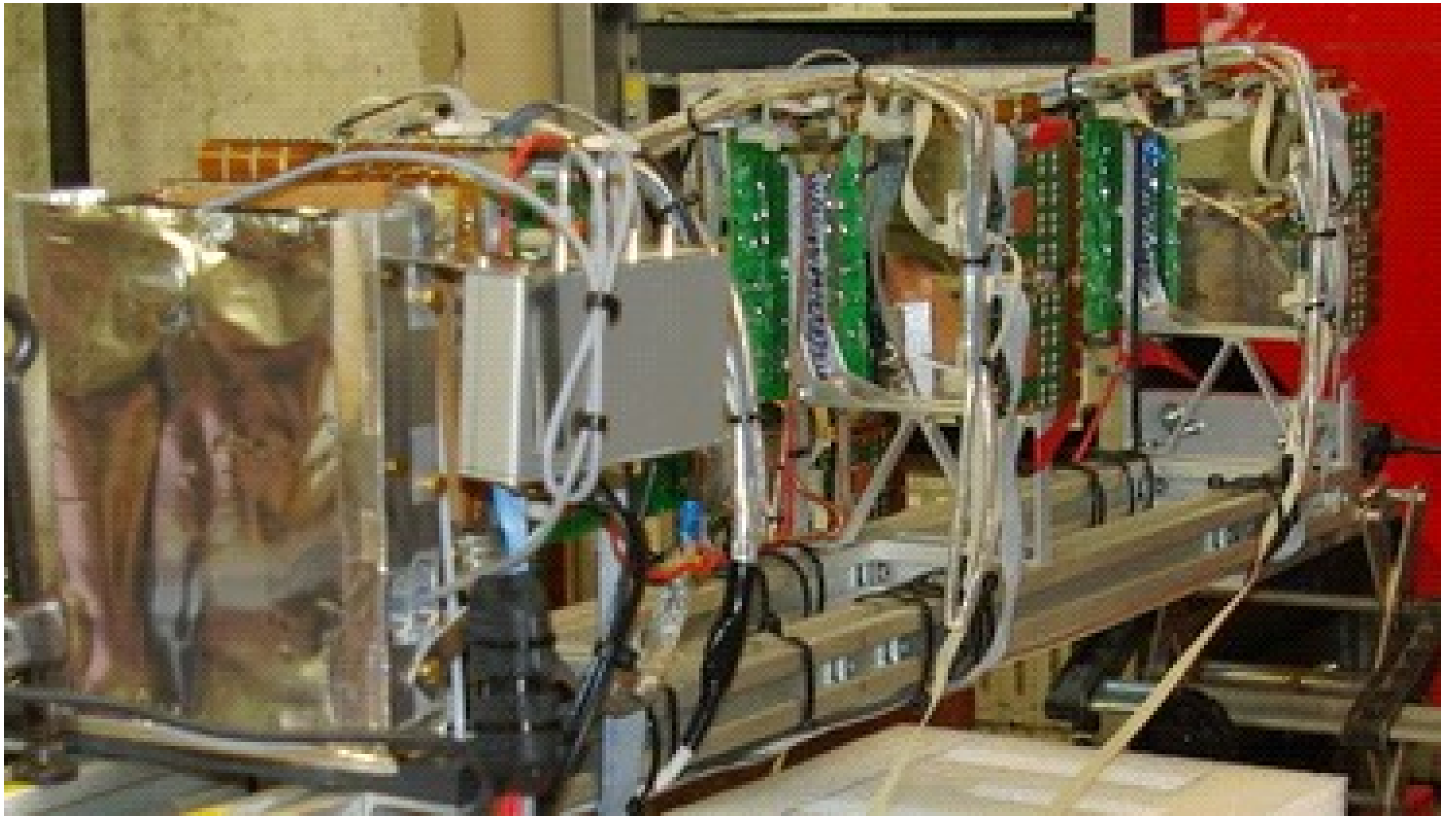
- Determine trajectory for scattering angle & Q^2
- Third GEM to reject ghosts
- GEMS from DESY OLYMPUS experiment
- At PSI
- Need work to speed up readout algorithm


GEMS OF OLYMPUS
Gems of Olympus 33 players online
GEMS OF OLYMPUS
Start Game
How to Play
Extras
More Games
Connected to Olympus 2
Player49135
EN

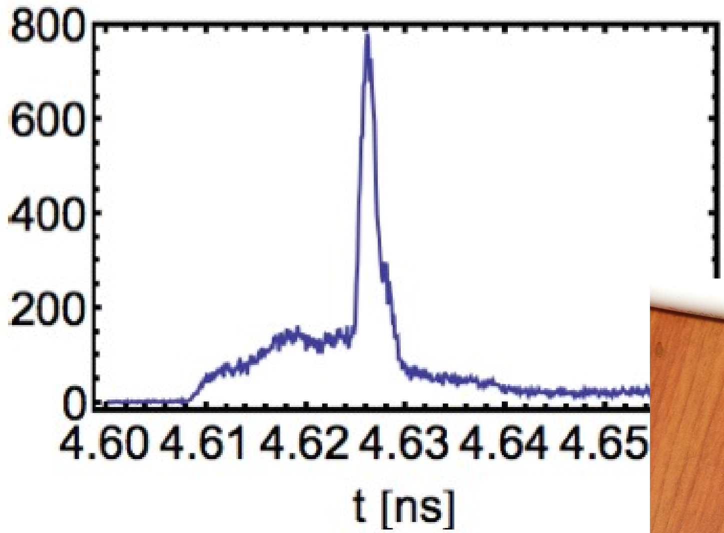
1000
Log in or register
Name
aleguu
Gem Collector
1269
athena13127
Cloud Catcher
1220
babcia99
Gem Guardian
1322
beija-flores
Oracle
1839
bruno5503
Harvest Honors 4183 | 0
qplay 8Ball 1014 | 0
Sevenventure 811 | 0
qplay Domino 586 | 0
Crystical 1657 | 0
Bubble Machine 869 | 0
Cold Fusion 601 | 0
Magical Solitaire 560 | 0
Pyramid Solitaire.. 1201 | 0
5-Dice 822 | 0
Backgammon 588 | 0
More qplay Games

GEM Chambers
(Hampton U.)

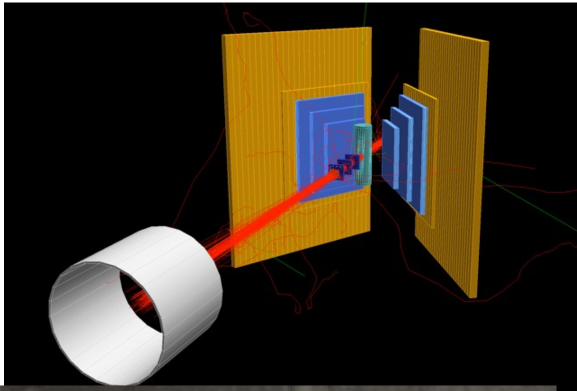


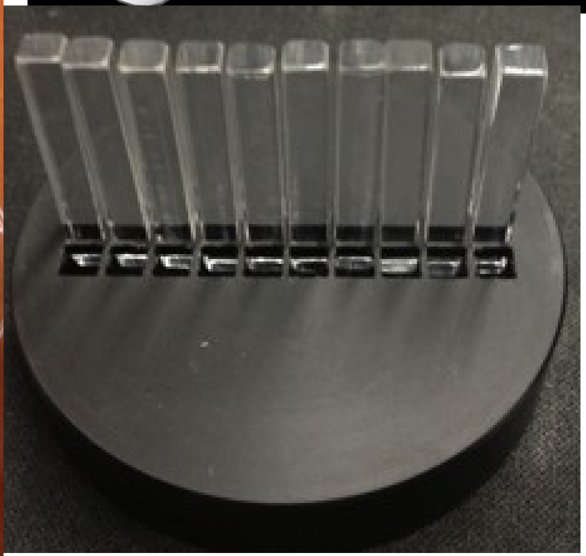


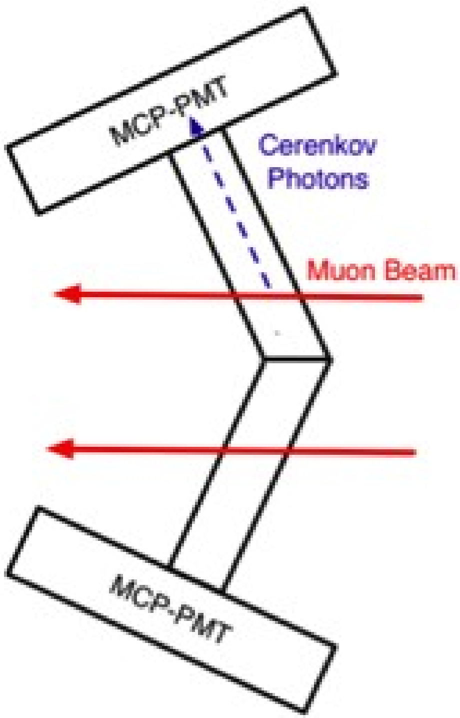
- Determine trajectory for scattering angle & Q^2
- Third GEM to reject ghosts
- GEMS from DESY OLYMPUS experiment
- At PSI
- Need work to speed up readout algorithm



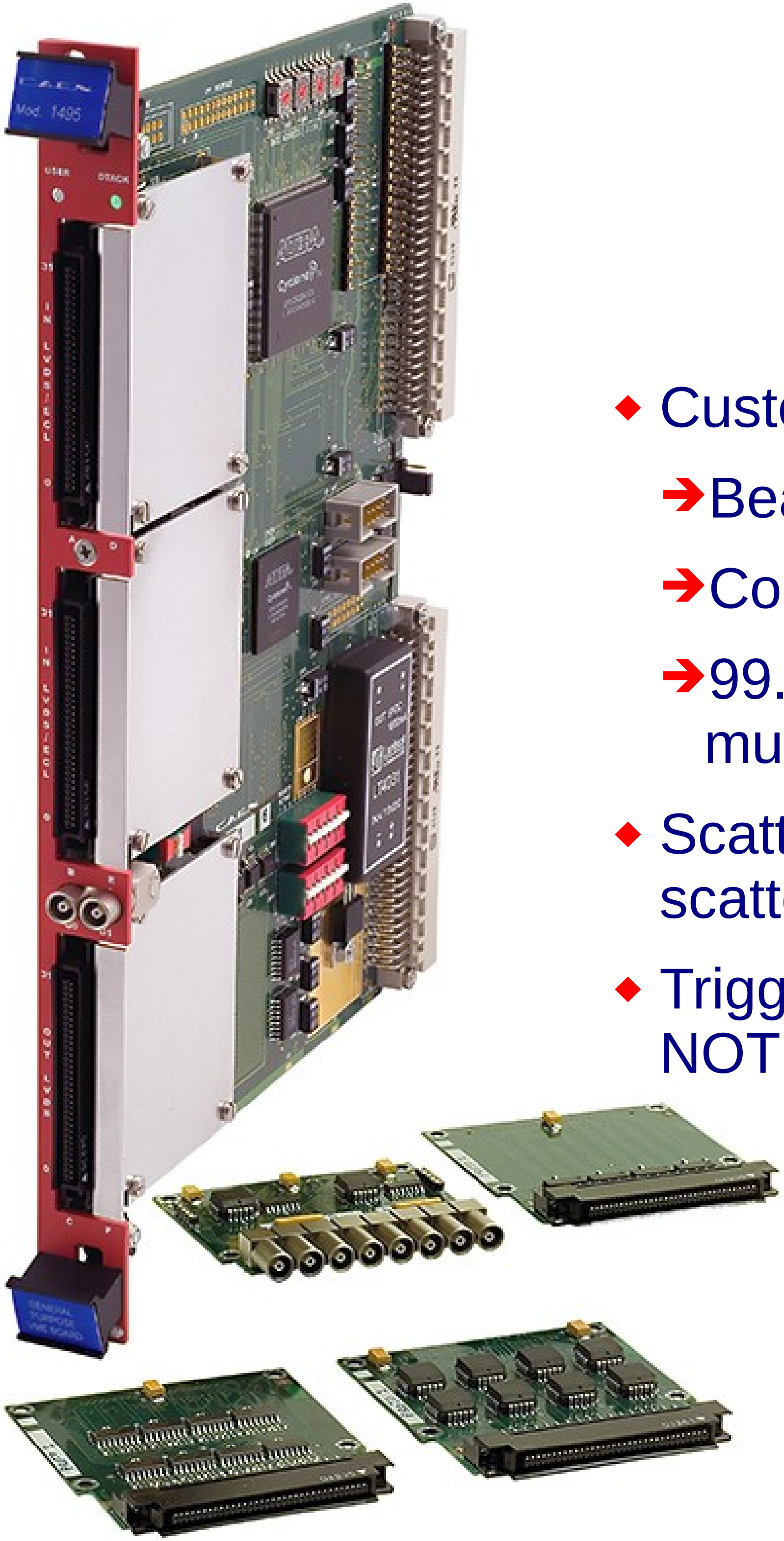
Quartz Cerenkov (Rutgers / HUJI)



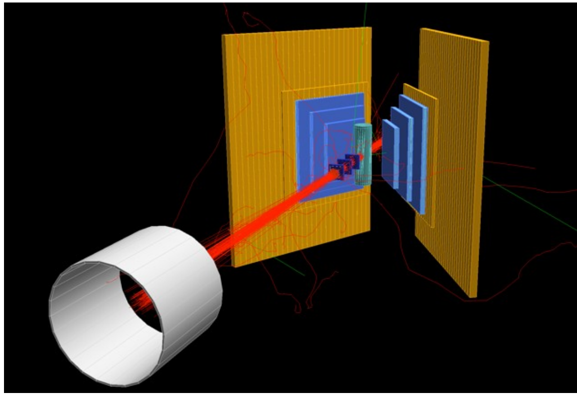




- Improved timing at target region
- Better RF time PID in analysis stage
- Muon decay event rejection
- Quartz Cherenkov Albrow et al. (FNAL) 10ps resolution
- Quartz at Cerenkov angle
- MUSE fewer photons ≈100ps (≈50ps after corrections)

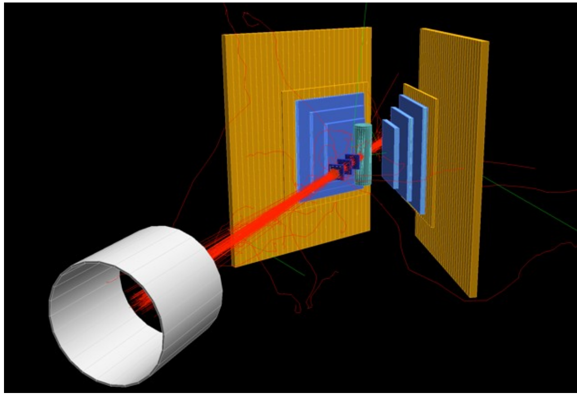


FPGAs
(Rutgers U.)

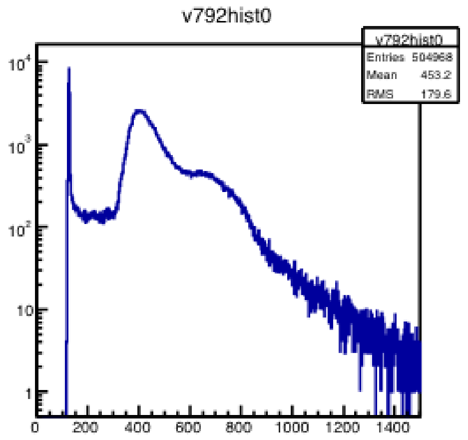


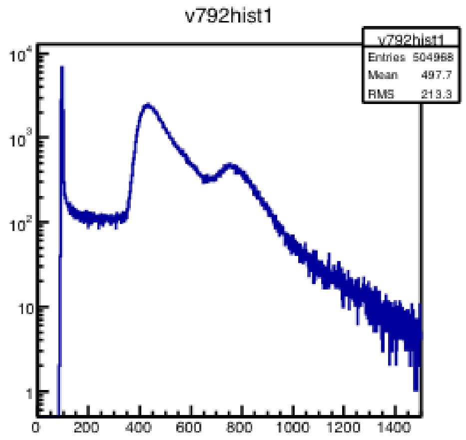
- Custom beam PID FPGA
  - ➔Beam Cerenkov & RF signals → PID
  - ➔Count particle types & reject pions
  - ➔99.9% efficient to reject pions or ID electrons & muons @ 153 / 210 MeV (from simulation)
- Scattered particle FPGA – CAEN v1495 to identify scattered particle hit patterns in scintillators
- Trigger FPGA: beam PID + scattered particle + NOT(veto) = trigger

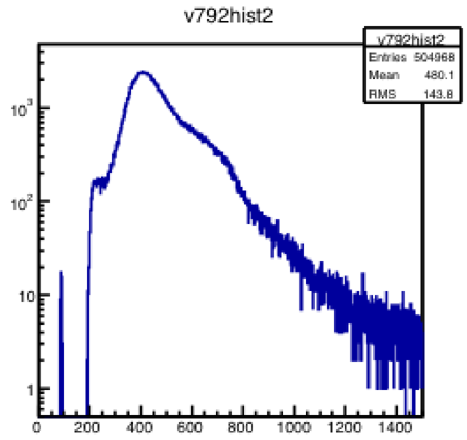
Beam Scintillators
(U. So. Carolina)

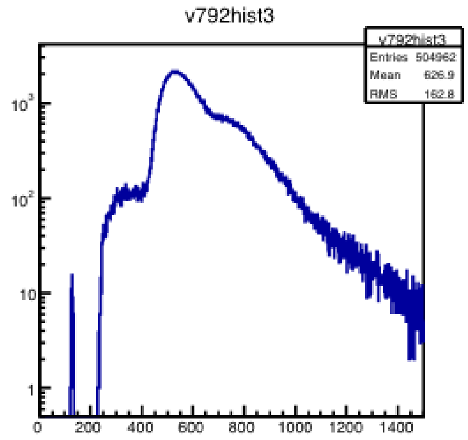


- Parasitic monitor of random, non-triggering beam particles
  - Same design as for CLAS 12
  - Test run data verified simulations
  - So. Carolina scintillator spectra:





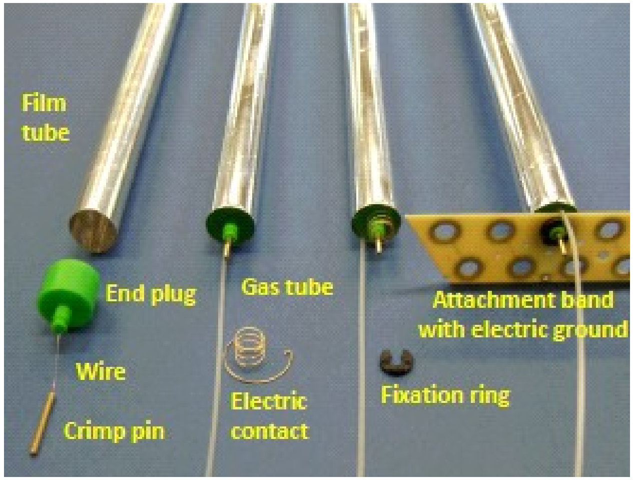


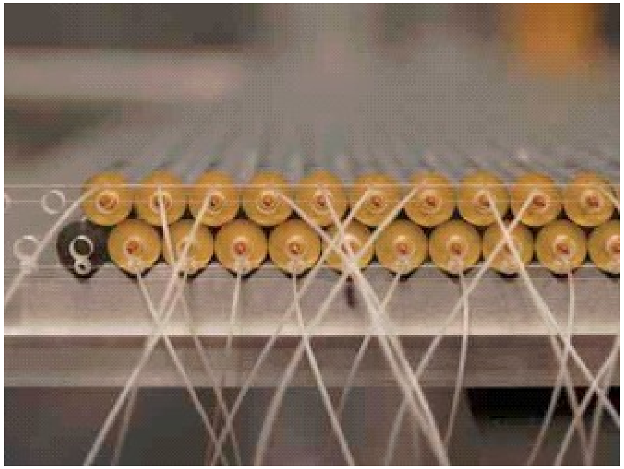


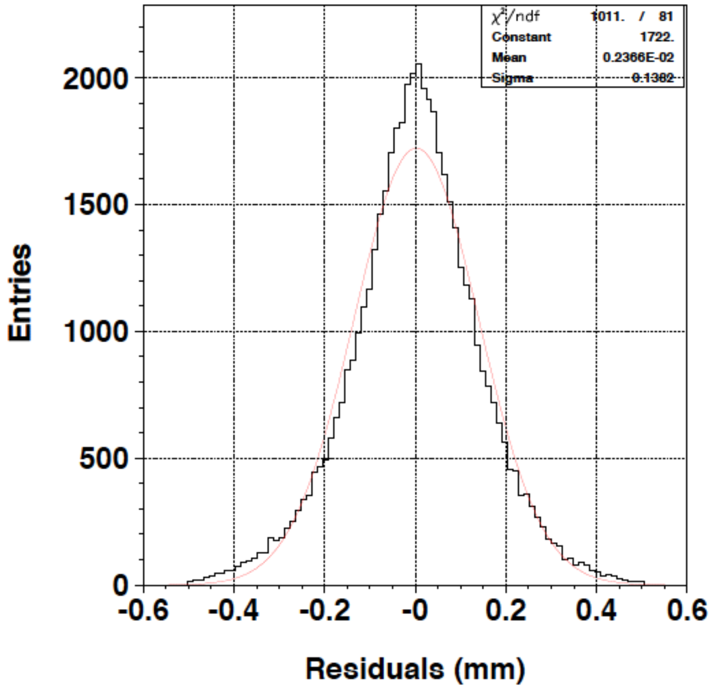
Scintillators not in trigger

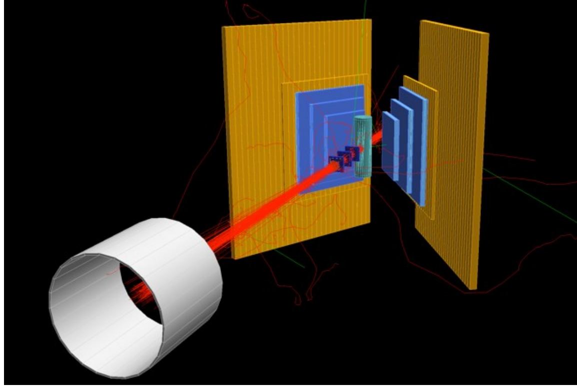
Scintillators in trigger (some pulser pedestals)

Straw Tube Tracker (HUJI)



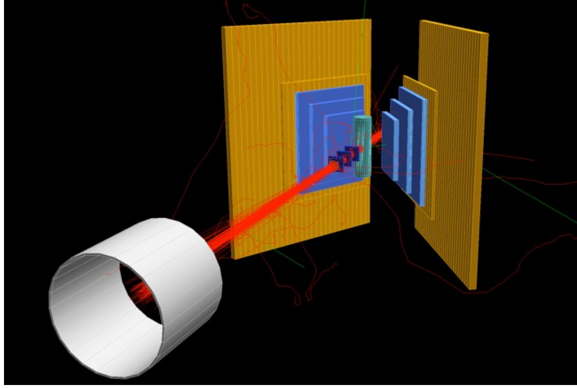


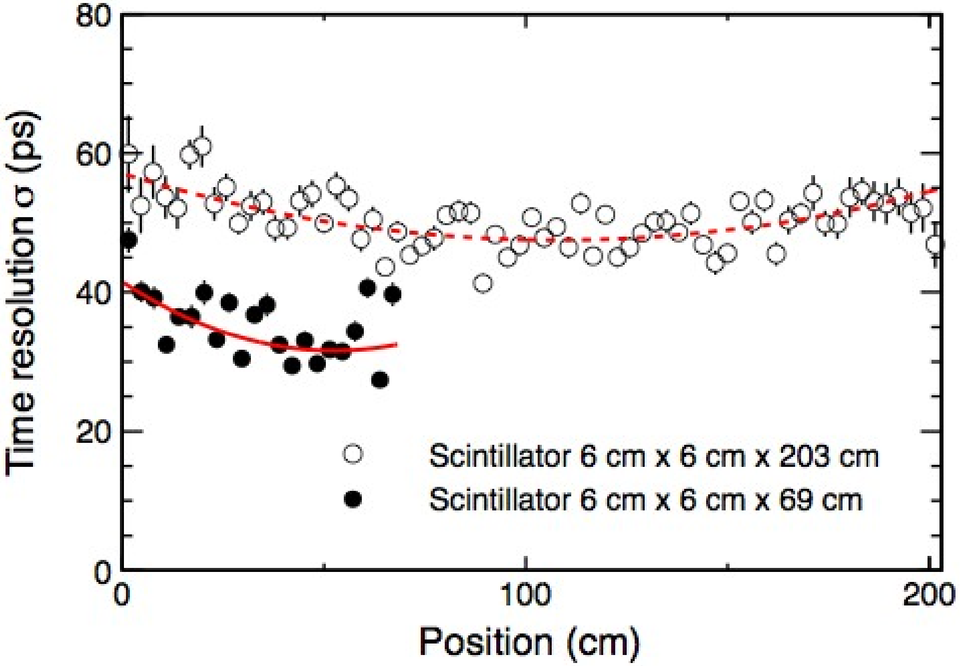




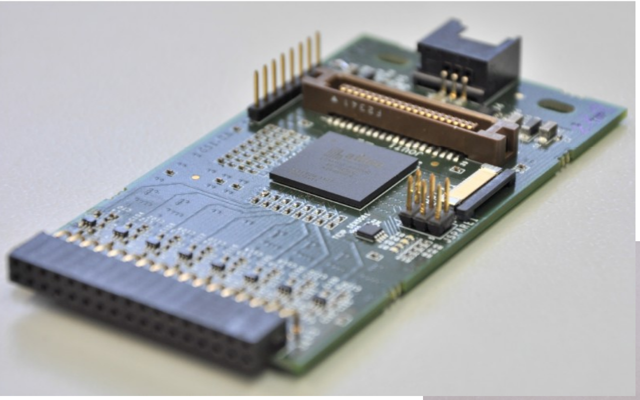
- Determine scattered particle trajectories with high efficiency and resolution
  - Copy of PANDA STTs – 140μm resolution achieved
  - Thin-walled, over-pressured (2 bar) straws
  - Directly coupled to PADIWA boards
  - Two chambers per side, ten planes per chamber
  - Calibrated relative to GEMs by rotating into beam

Scintillators
(U. So. Carolina)

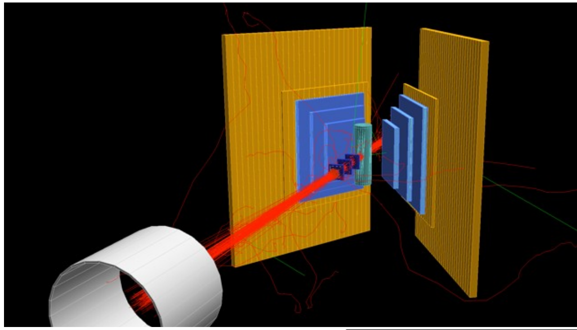


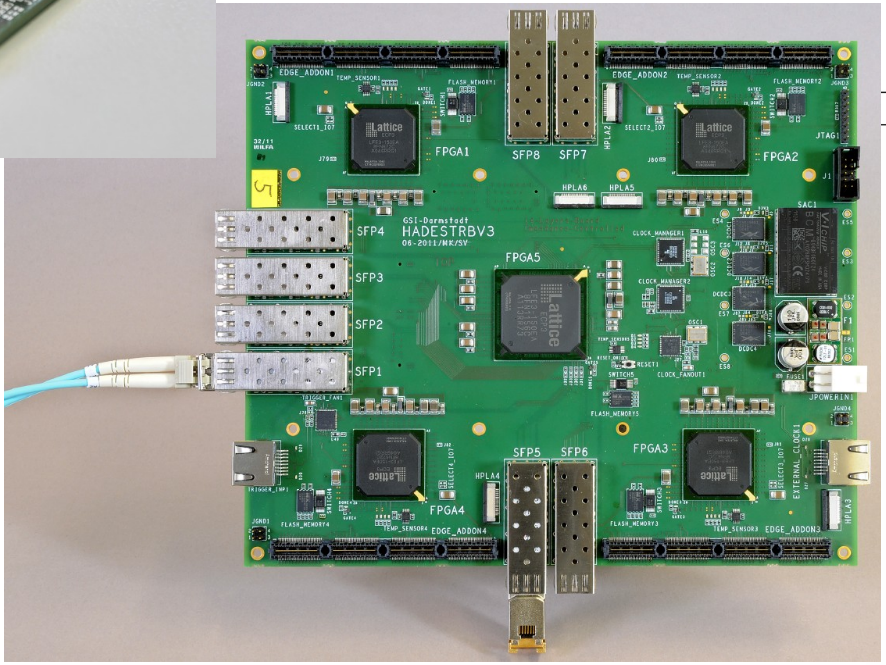


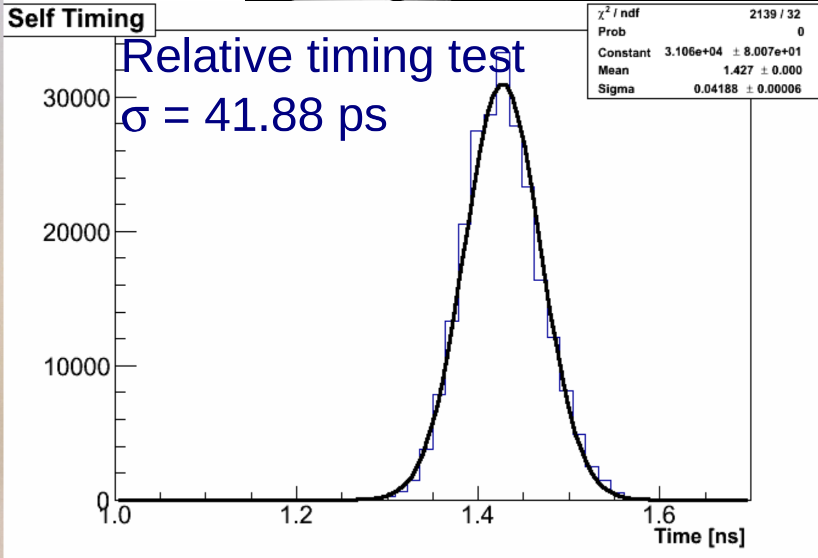
- Detect scattering particles depositing few MeV in each of two planes
- High precision timing for PID & rejection of electons from muon decay
- JLab CLAS12 design
- Front: 17 paddles, 6cm wide x 2cm thick x 103cm long, 50cm from target
- Rear: 27 paddles, 6cm wide x 6cm thick x 163cm long, 73cm from target
- Resolution: ≈40ps front, ≈50ps rear



Data Acquisition System (GW)







- TRB3s custom - designed by Michael Traxler (GSI)
- Timing from TRB3 boards, with PADIWAs as discriminator
- Precise, cost-effective, high channel density
- PADIWA customizable for each detector
- Excellent support from Michael Traxler (GSI)
- Analog signal to CAEN v792(N) for walk correction
- Custom splitters where necessary

MUSE μp Scattering at PSI

- μp and ep comparison:
- BSM physics could lead to different FF and radii although the effect in scattering experiments could go away once $Q^2 > m^2_{new}$
- Measure both $\mu^{\pm}p$ and $e^{\pm}p$ for 2γ exchange
- Proton polarizability effect enhances 2γ exchange
- MUSE is in the low Q^2 region, 0.002 - 0.07 GeV^2, (similar to Mainz and JLab experiments) for sensitivity to radius
- A variety of 2nd generation experiments (lower Q^2, $\mu^{\pm}n$, higher Q^2, PV, "heavy" nuclei ...) are already being considered.

Goals for Test Beam Times 2012 /13

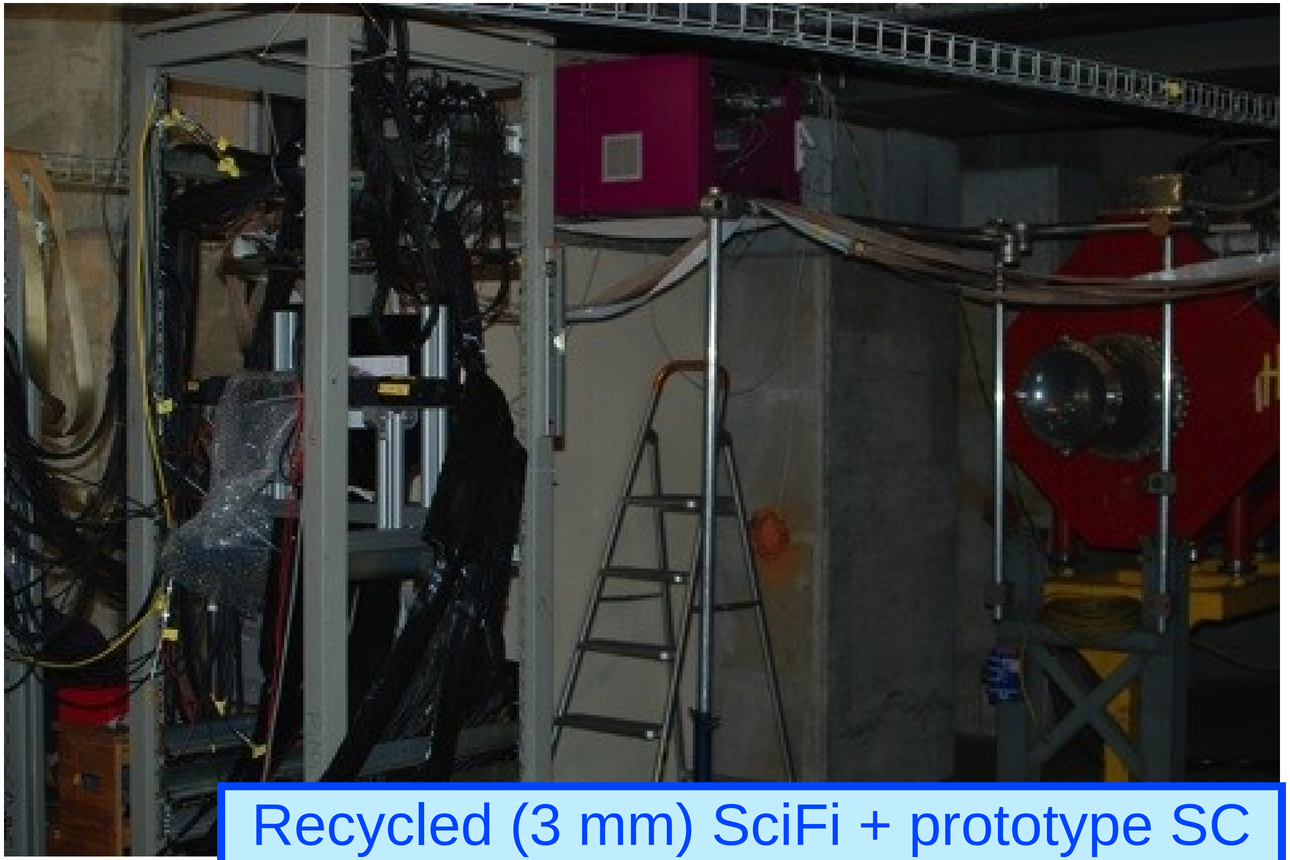
- Test beam times in Fall 2012, Summer 2013, December 2013
- Further test planed in June 2014
- Basic measurements at each beam momentum:
  - ➔ Determine RF time / particle type distributions
  - ➔ Determine beam size at target for each particle type and divergence
  - ➔ Determine beam distributions, dispersion and resolutions at Intermediate Focal Point (IFP) for each particle type
- Other measurements for constraints on simulations:
  - ➔ Look for protons in + polarity at IFP and see what we need to range them out (none found!)
  - ➔ Look at beam halo
  - ➔ Do mini scattering experiment

Fall 2012 Test Run

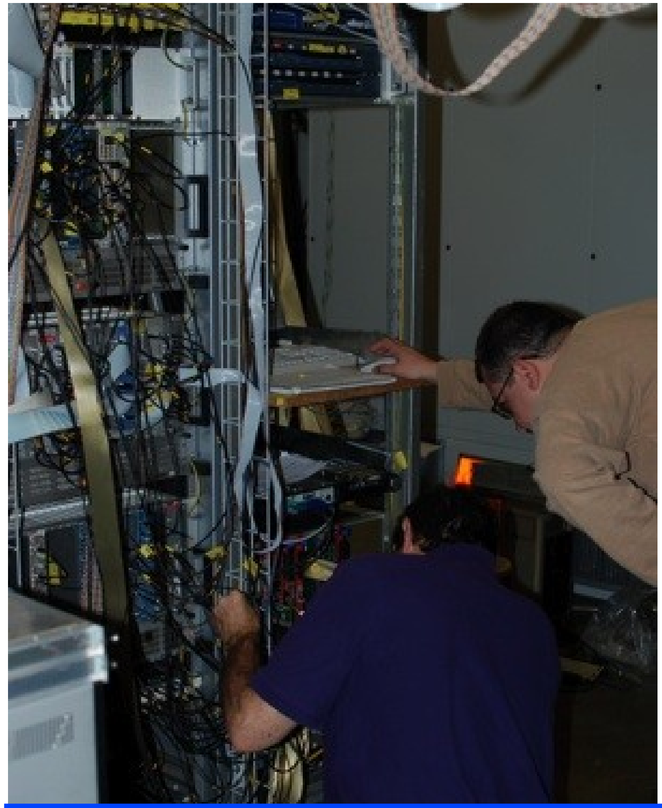
MUSE Test Run Report

The MUon proton Scattering Experiment collaboration (MUSE):

W.J. Briscoe,[1] K. Deiters,[2] E. Downie,[1] R. Gilman,[3] K.E. Myers,[3] E. Piasetzsky,[4] D. Reggiani,[2] P. Reimer,[5] G. Ron,[6] V. Sulkosky,[7] and M. Taragin[8]



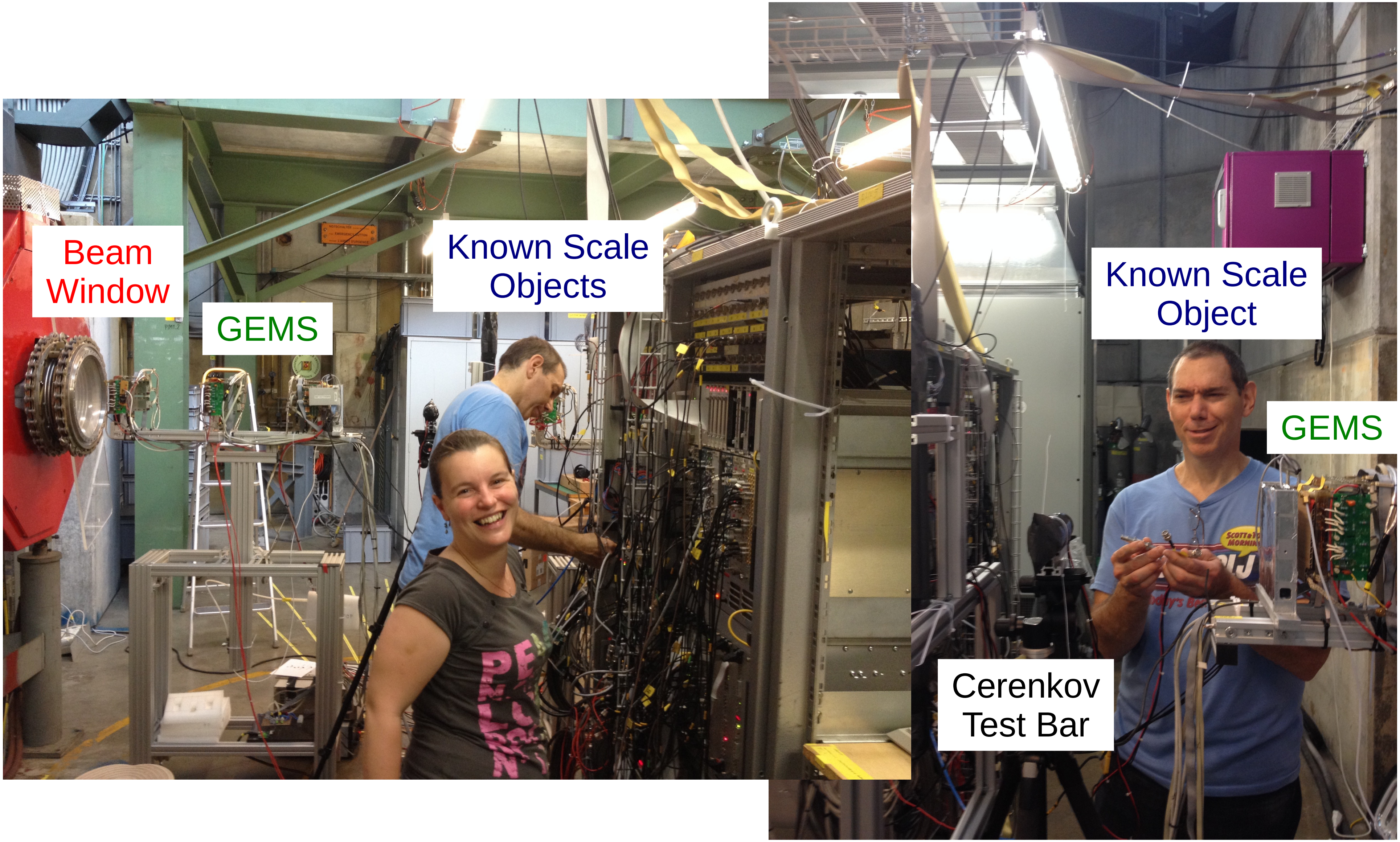
Recycled (3 mm) SciFi + prototype SC scintillators (5 cm x 5 cm)



NIM trigger, VME read out, working physicists

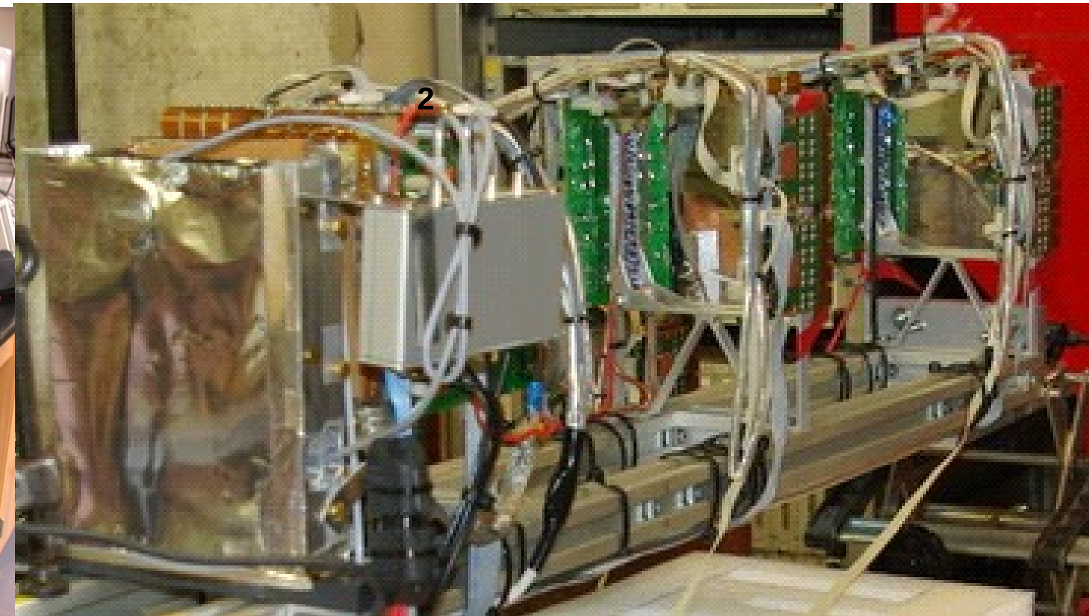
test run report on website:
http://www.physics.rutgers.edu/~rgilman/elasticmup

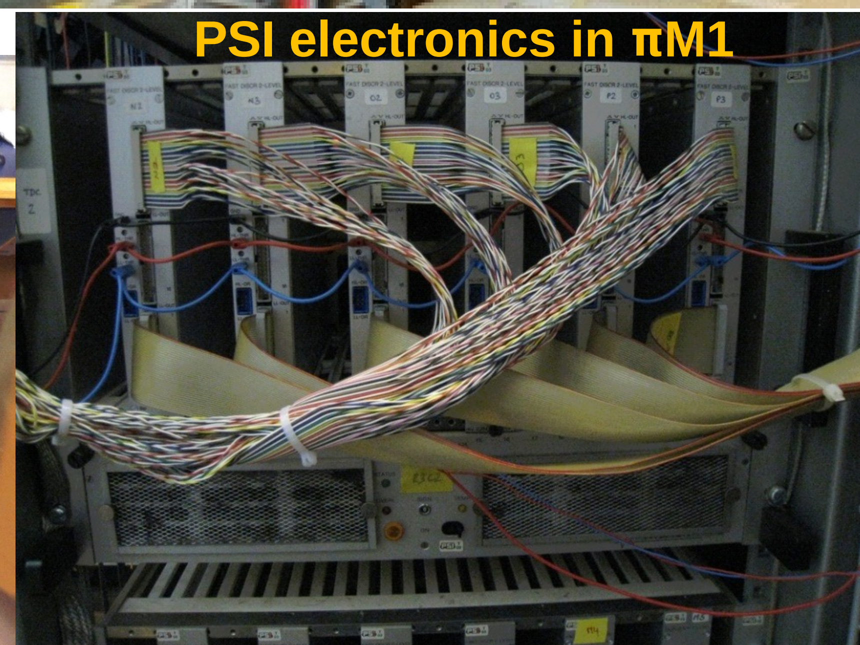
Summer 2013 Test Run

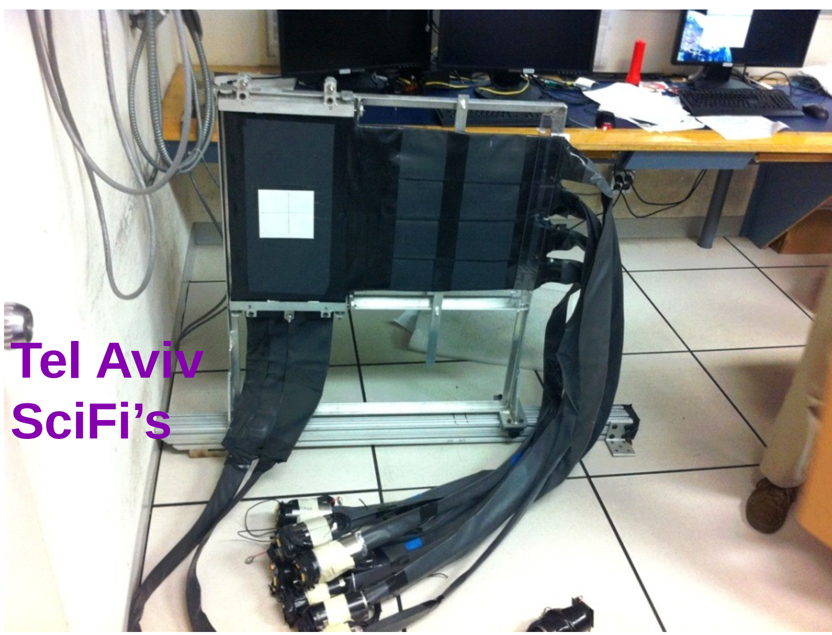


Test Run Equipment

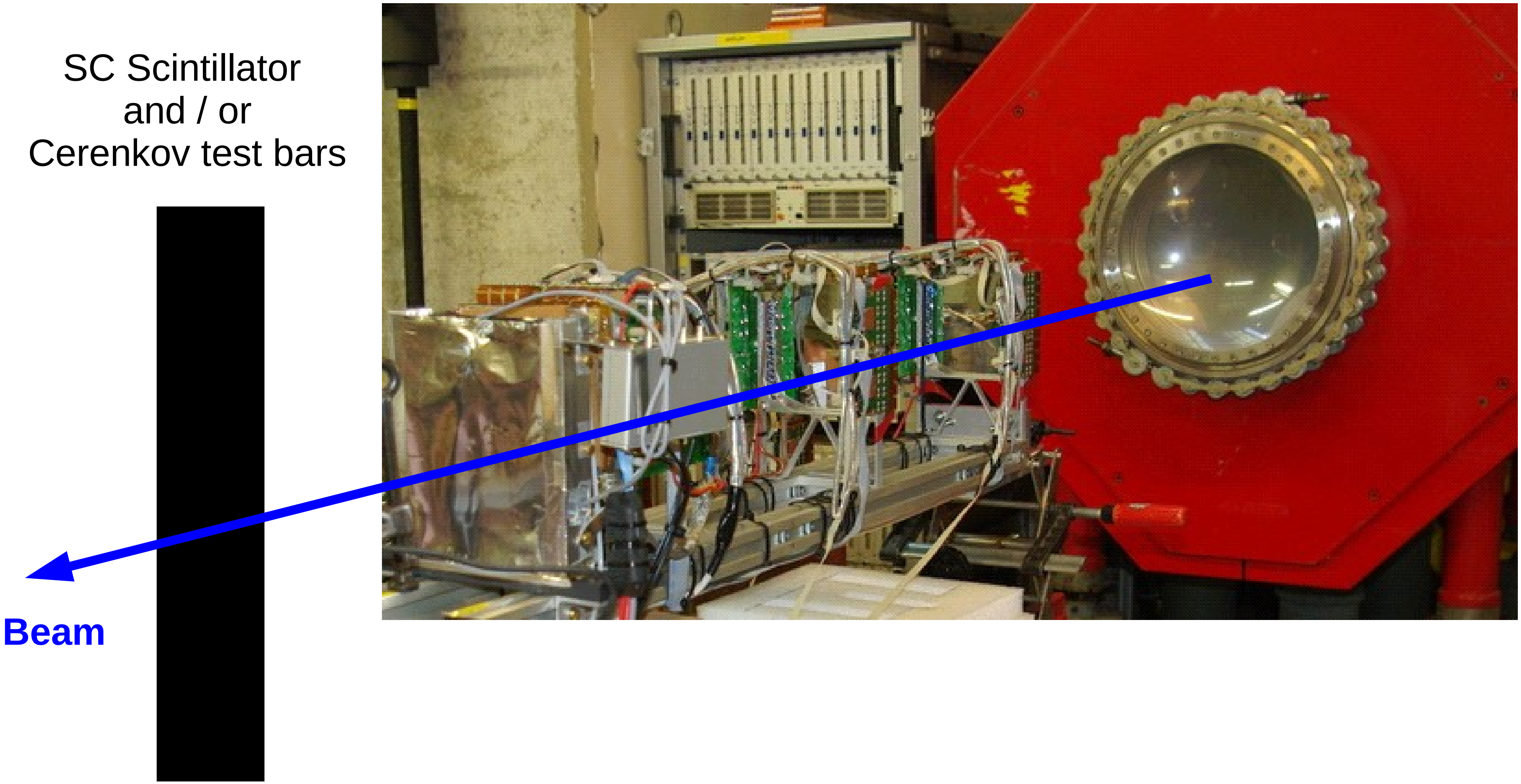
3 10 x 10cm^2 GEMs from OLYMPUS @ DESY



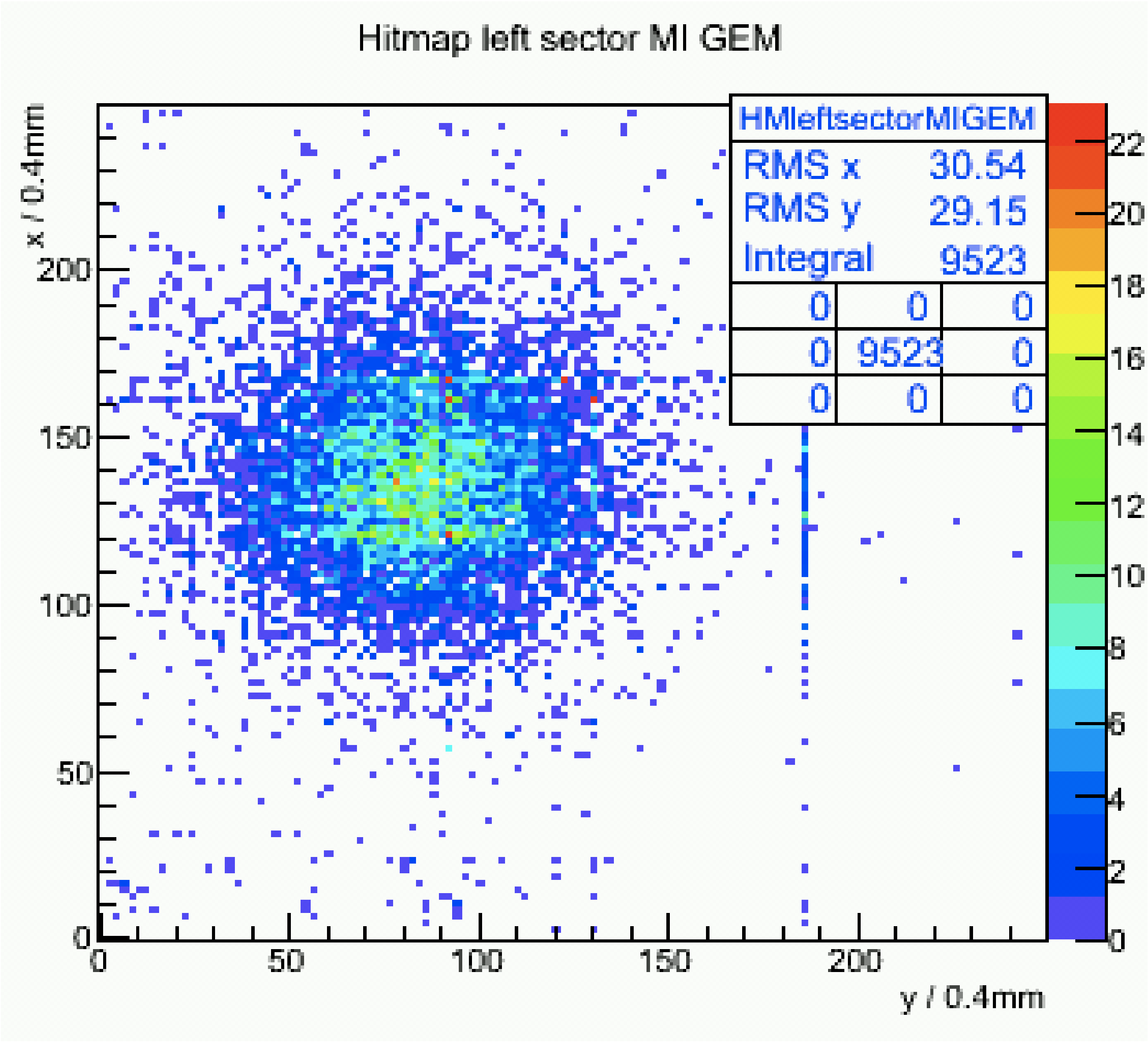




Test Run Setup

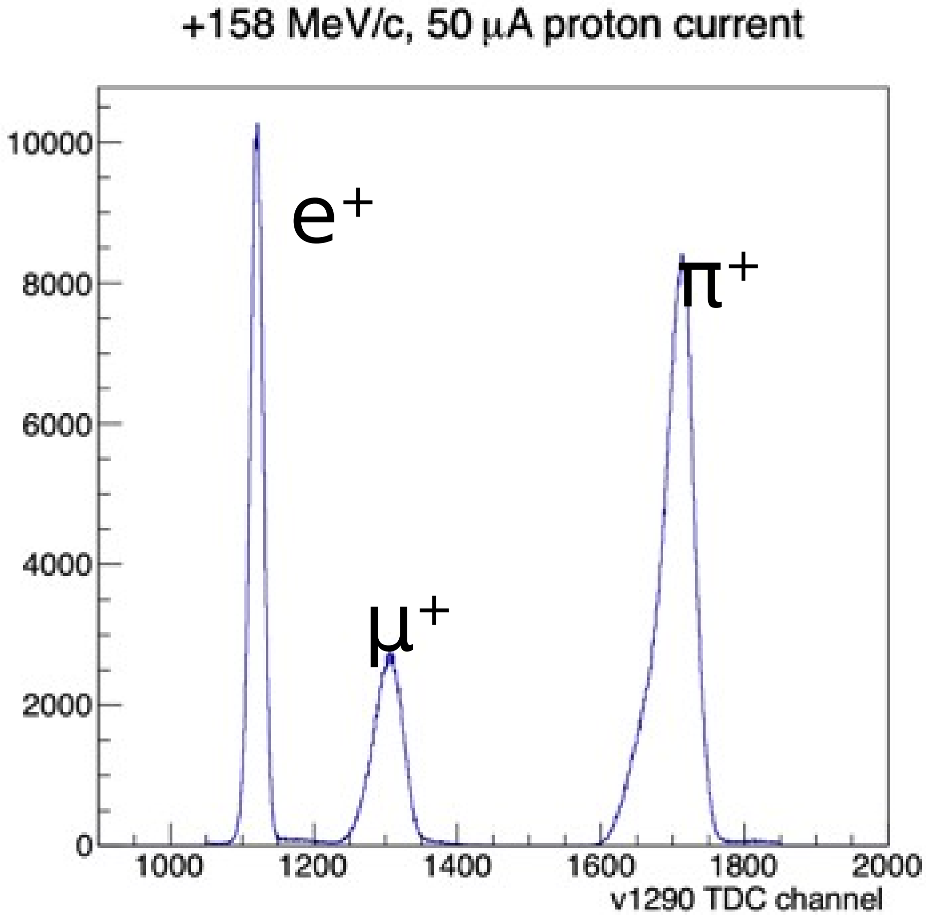


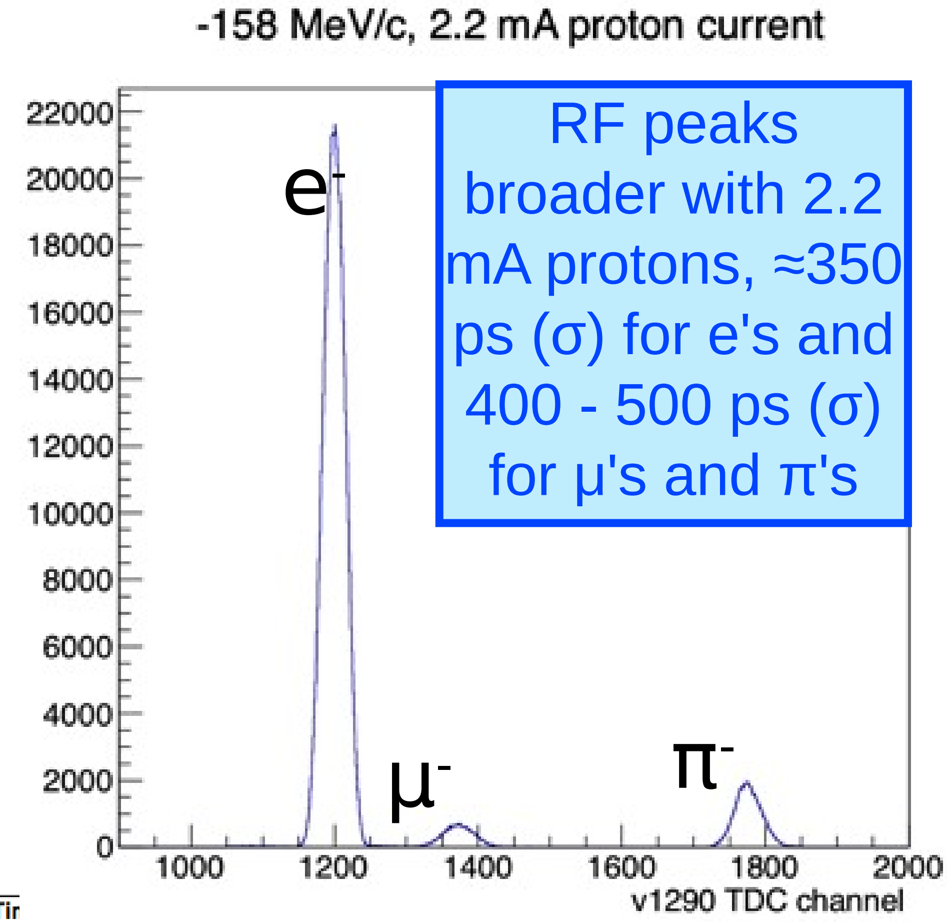
Beam Profile From GEMS



- Nice circular beam-spot
- Mostly within 2cm, tails out to 4cm
- Converging at 40mrad angle

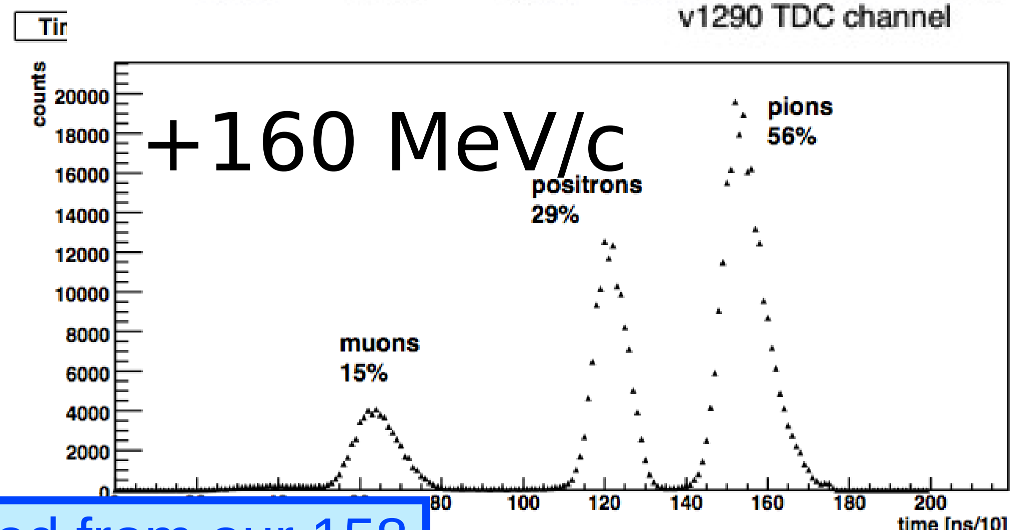
πM1 Channel - RF time in target region





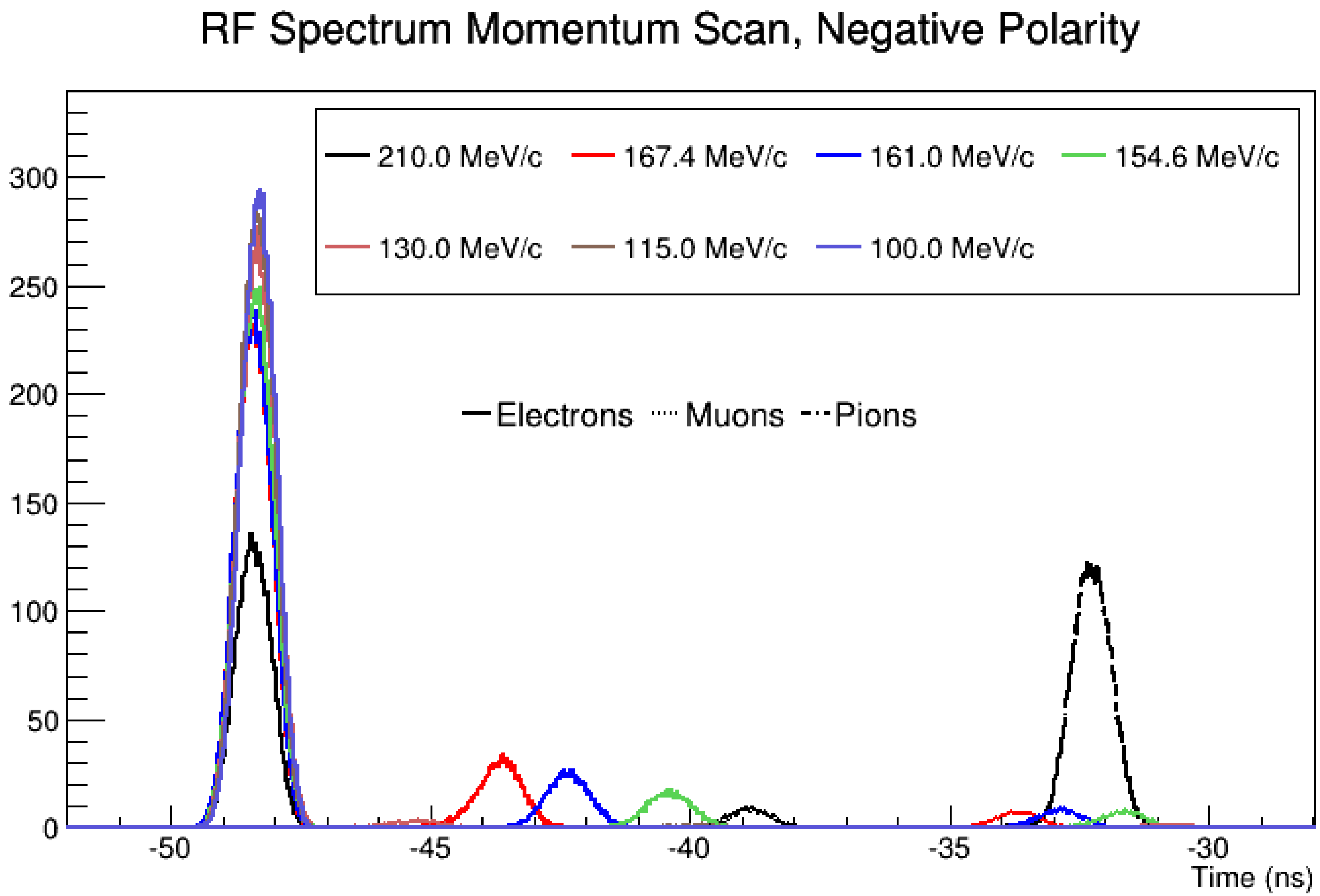
RF peaks broader with 2.2 mA protons, ≈350 ps (σ) for e's and 400 - 500 ps (σ) for μ's and π's

Obtained RF time spectra for several momenta from ≈110 to 225 MeV/c, and used these to determine relative particle fluxes

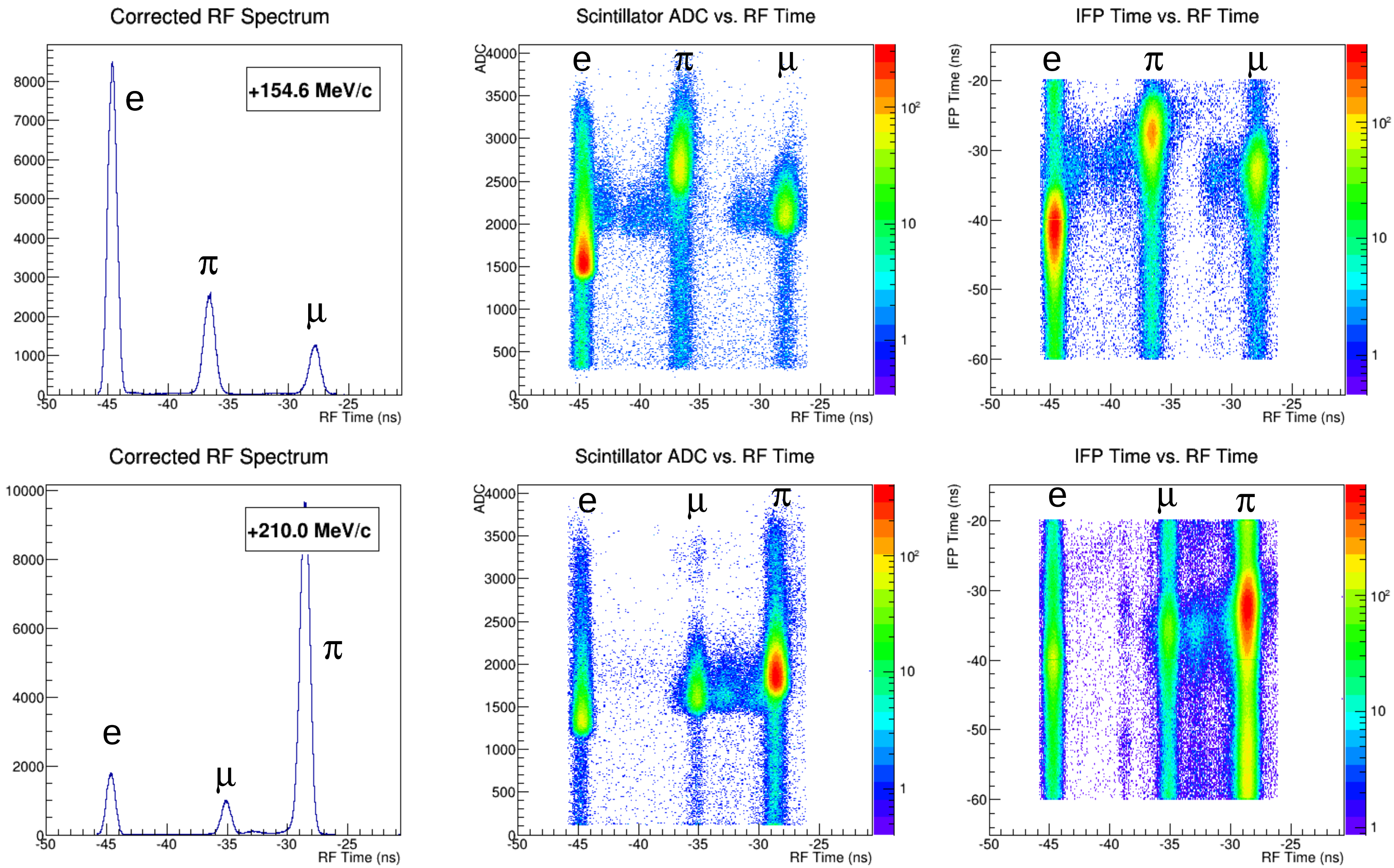


Old spectra, for comparison - 160 reversed from our 158

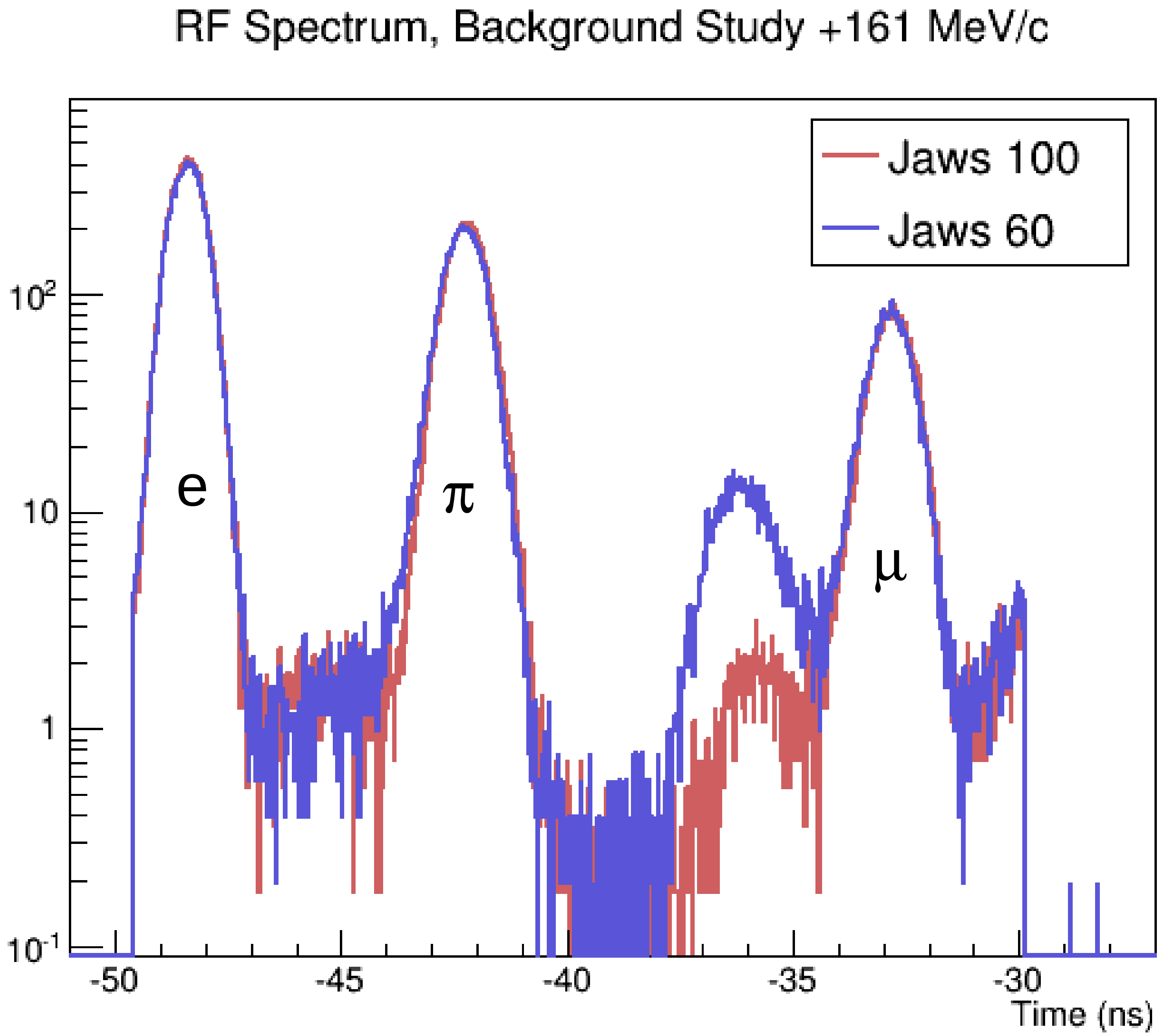
RF Spectra from Test Run



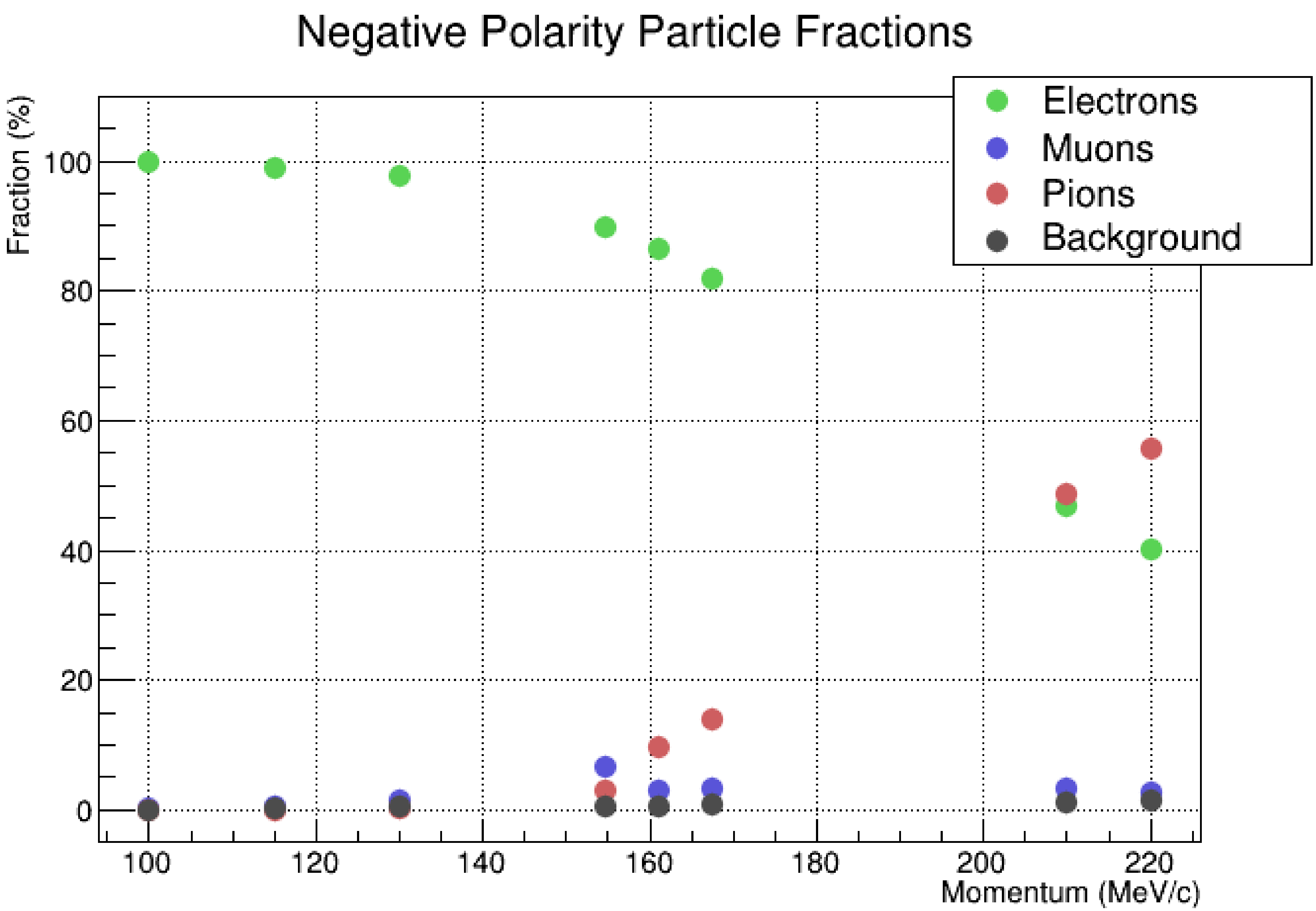
RF Time vs ADC Spectra



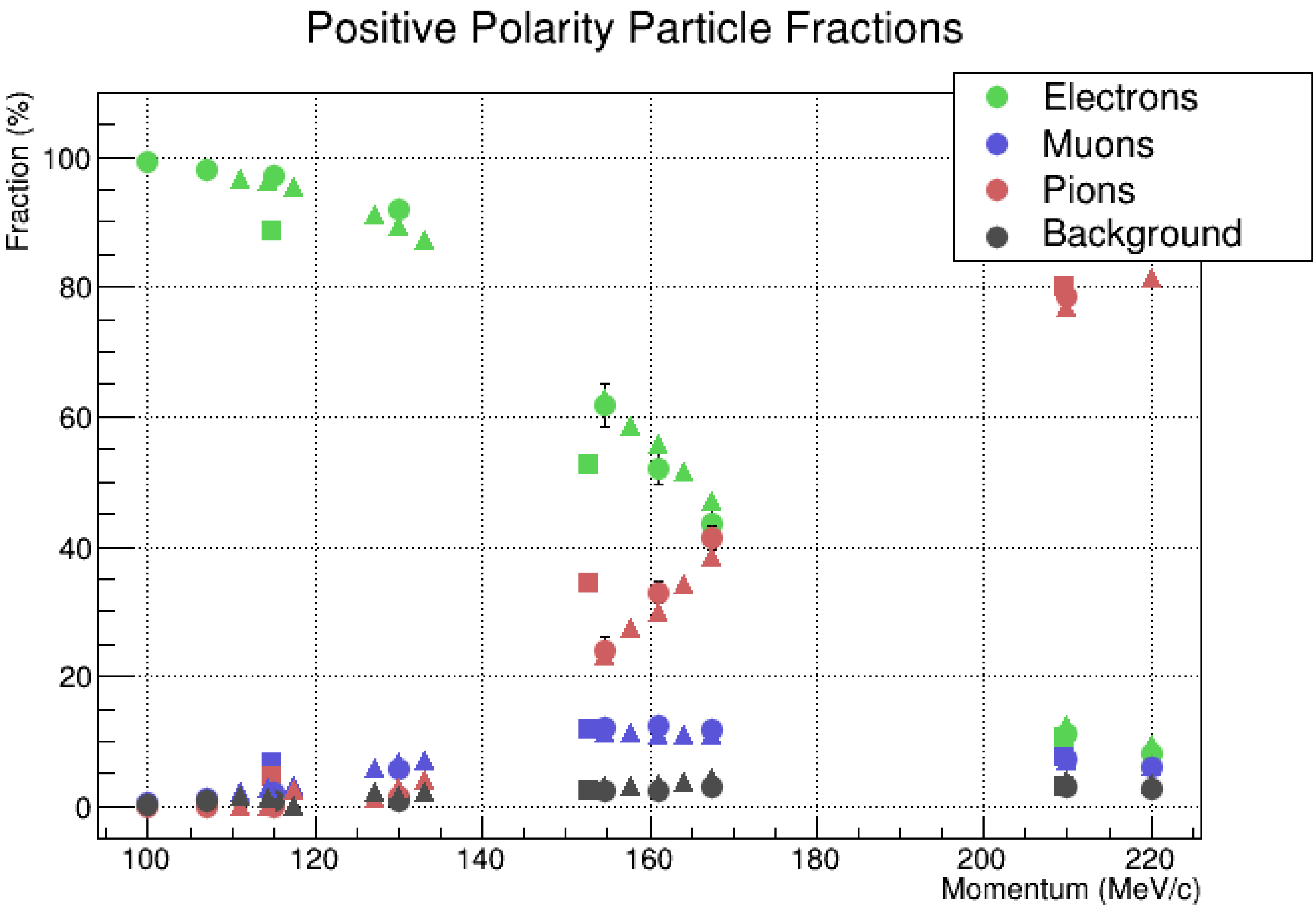
Jaws Create Backgrounds



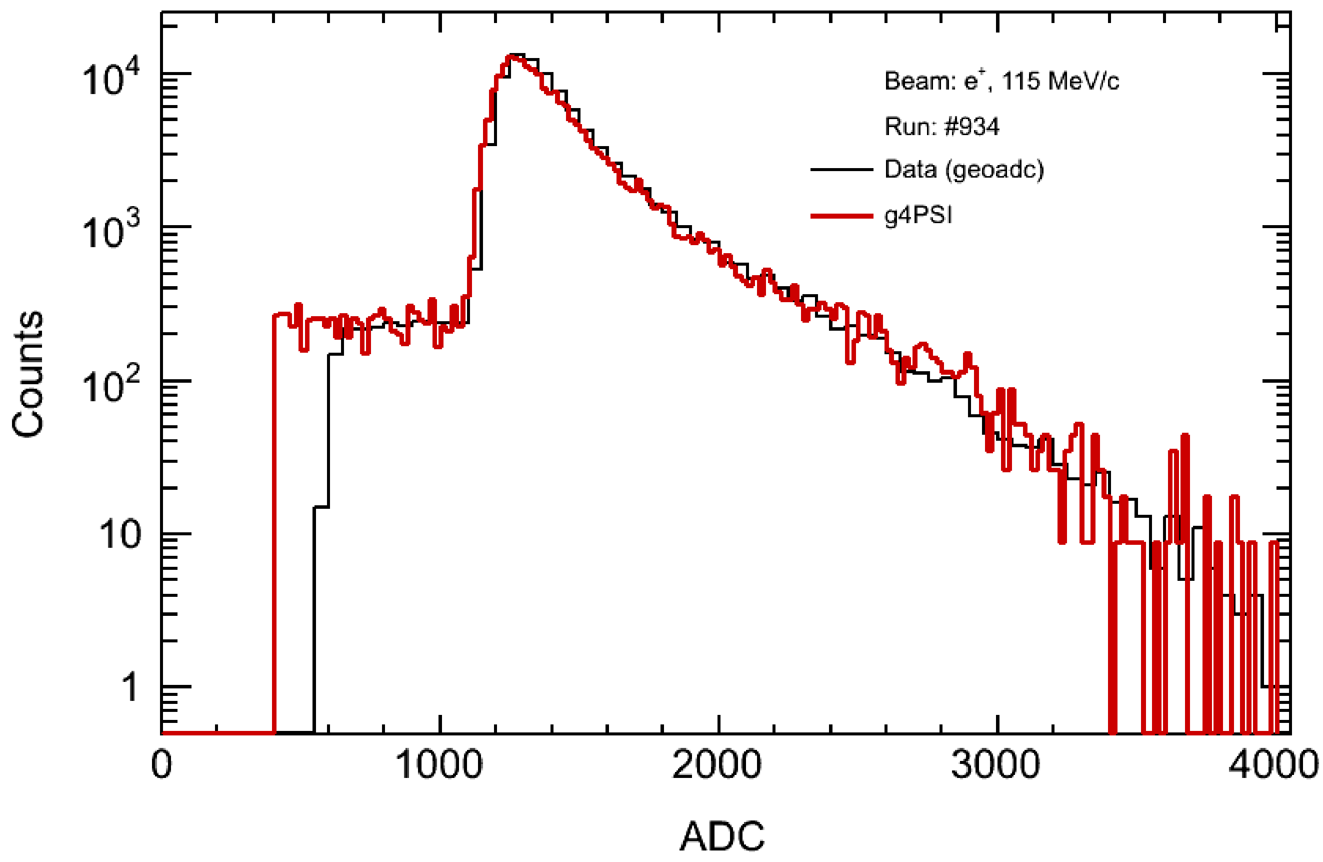
Fraction of Negative Particle Species



Fraction of Positive Particle Species



Comparison of Simulation to June 2013 Test Data



- Comparison of data to simulation
- Test data for 115 MeV
- Lots of simulation work still to be done!

πM1 Channel – Particle Fluxes

- Limiting flux to 5 MHz total, by cutting the 3% momentum bite
  - Flux of electrons 1.4 – 35 times larger than flux of muons

P (MeV/c)	π (MHz)	μ (MHz)	e (MHz)	Momentum bite (%)
+115	0.43	0.43	4.0	1.8
+153	2.10	0.59	2.3	0.9
+210	4.1	0.39	0.54	0.2
-115	0.01	0.14	4.9	2.0
-153	0.55	0.17	4.3	1.3
-210	2.23	0.77	2.0	0.6

Beam Line Summary

- Good flux of μ's at target, much better flux of e's
- Beam properties independent of particle type
- Protons not an issue at our momenta
- Particles can be separated by ≈ns level RF timing at ≈115, 153, 210 MeV/c for our geometry
- Beam emittance requires event by event tracking into target with GEMs
- Time width of particles appears to be 450 ps (σ), except electrons appear to be ≈350 ps

➔ Necessitates high timing precision beam Cerenkov for rejection of μ decays

Next Few Years for MUSE

Feb 2012	First PAC presentation
July 2012	PAC / PSI Technical review
Fall 2012	1st test run in πM1 beamline
Jan 2013	PAC approval
Summer 2013	2nd test run in πM1 beamline
Fall 2013	Funding requests
Summer 2014	Money arrives? - start construction
Summer 2015	Start assembling equipment at PSI
Late 2015	Set up and have dress rehersal
2016 - 2017	2 6-month experiment production runs

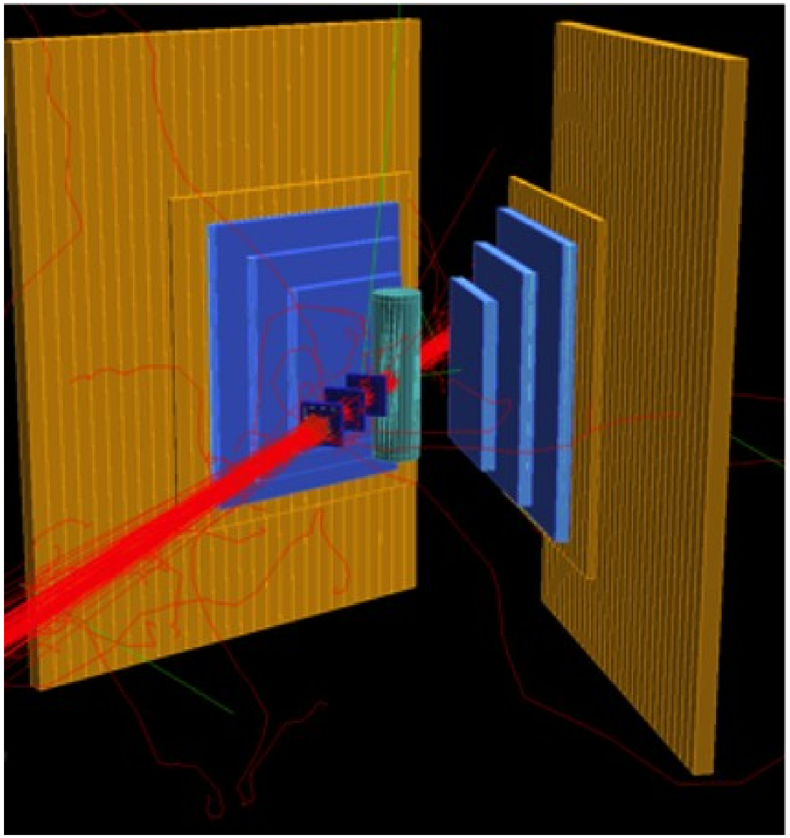
Next Few Years for MUSE

Feb 2012	First PAC presentation
July 2012	PAC / PSI Technical review
Fall 2012	1st test run in πM1 beamline
Jan 2013	PAC approval
Summer 2013	2nd test run in πM1 beamline
Fall 2013	Funding requests
Summer 2014	Money arrives? - start construction
Summer 2015	Start assembling equipment at PSI
Late 2015	Set up and have dress rehersal
2016 - 2017	2 6-month experiment production runs

Next Few Years for MUSE

Feb 2012	First PAC presentation
July 2012	PAC / PSI Technical review
Fall 2012	1st test run in πM1 beamline
Jan 2013	PAC approval
Summer 2013	2nd test run in πM1 beamline
Fall 2013	Funding requests
Summer 2014	Money arrives? - start construction
Summer 2015	Start assembling equipment at PSI
Late 2015	Set up and have dress rehersal
2016 - 2017	2 6-month experiment production runs

Reference Design

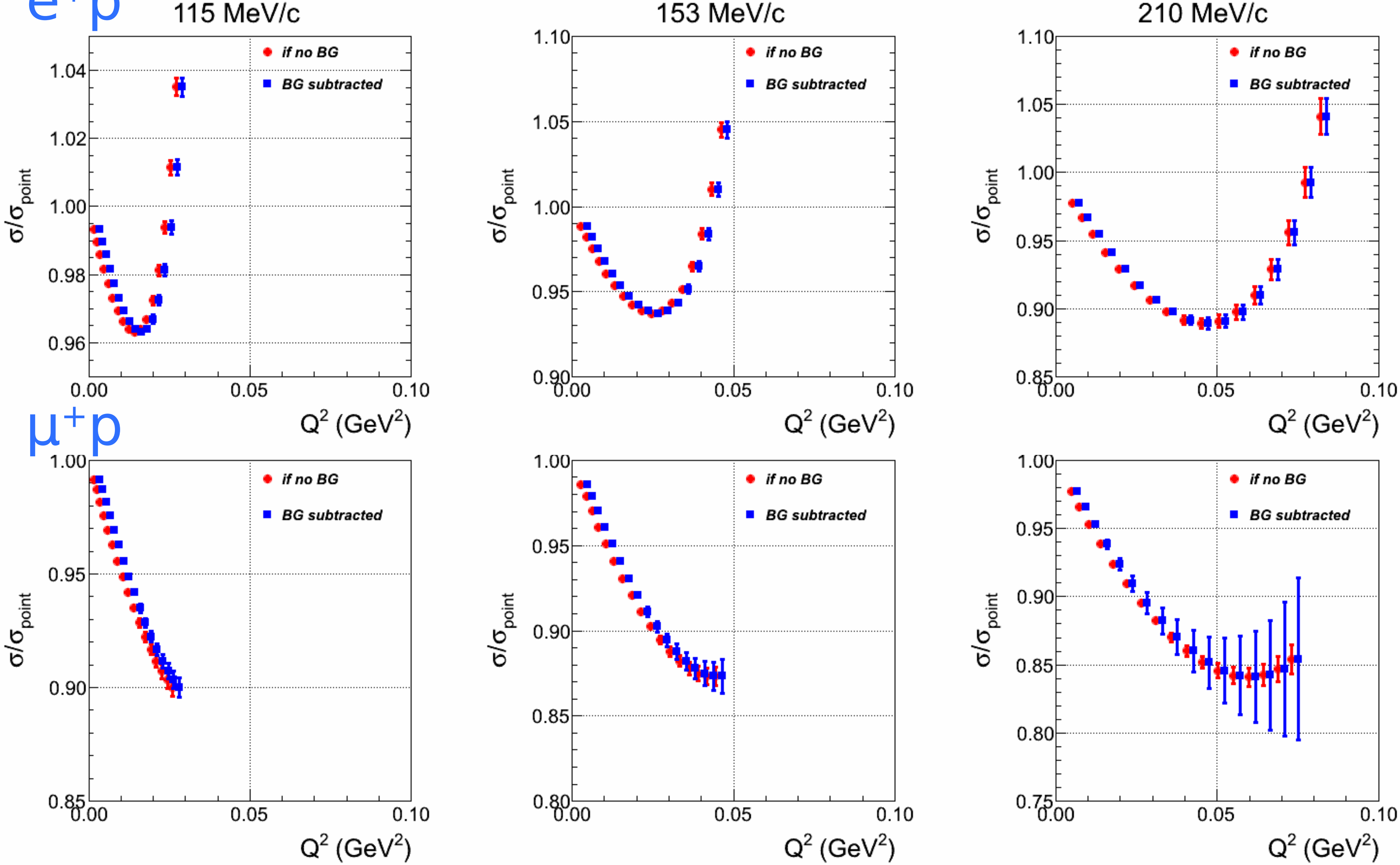


- Beam: IFP SciFi → target SciFi → Cerenkov → GEM → target → beam monitor scintillators
- STTs & scintillator walls for scattered particles
- Standard technology
- Geant4 estimates, target collimator bg. v. sensitive to beam distributions
- Custom FPGA trigger to record scattering events and reject π

New Equipment Summary

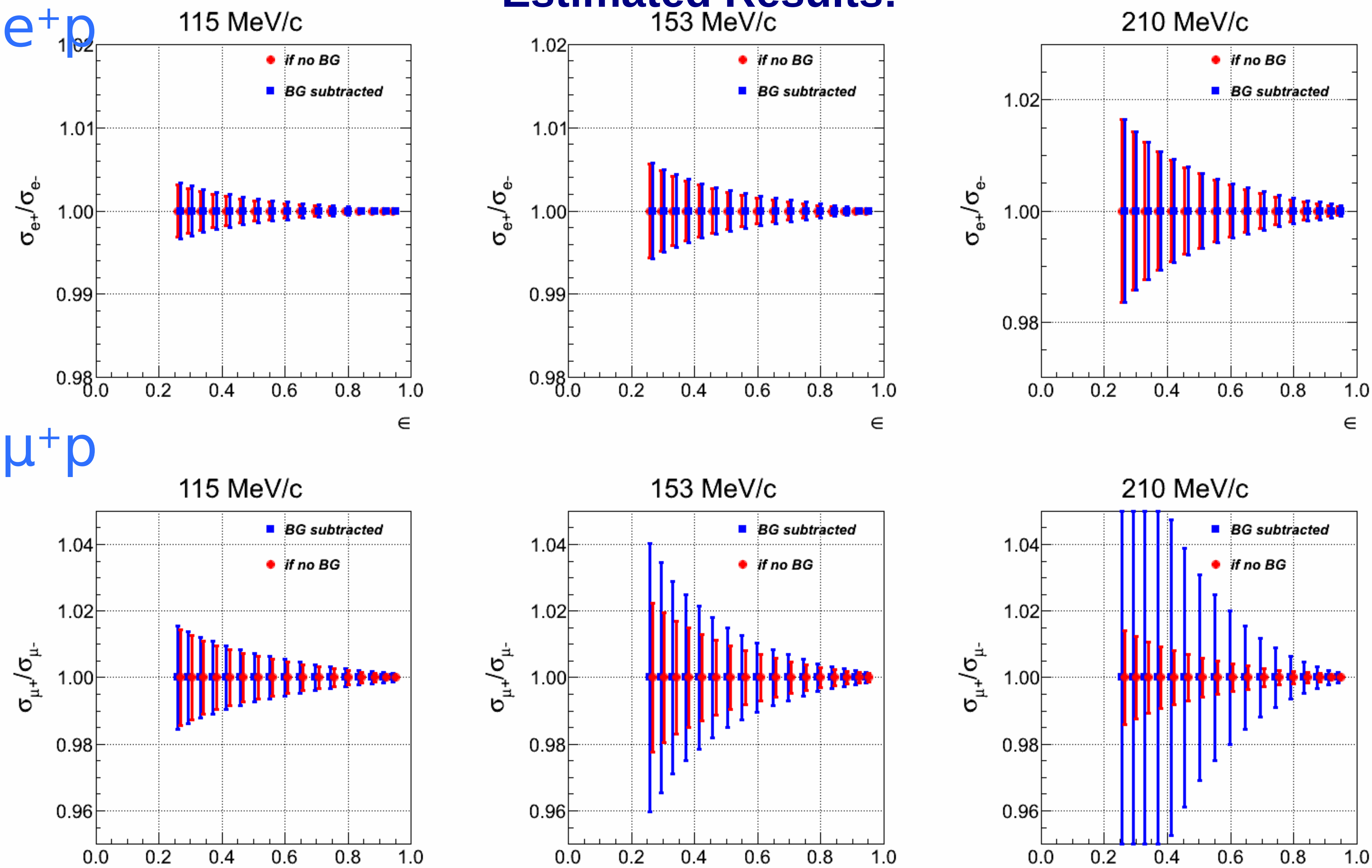
Detector	Who	Technology
Beam SciFi	Tel Aviv	conventional
GEMs	Hampton	detector exists
Quartz Cerenkov	Rutgers	prototyped
FPGAs	Rutgers	conventional
Target	GWU	conventional
Straw Tube Tracker	HUJI	Copy system developed for PANDA
Scintillators	SC	Copy existing system
DAQ	GWU	Conventional, except TRB3 prototyped

Estimated Results!



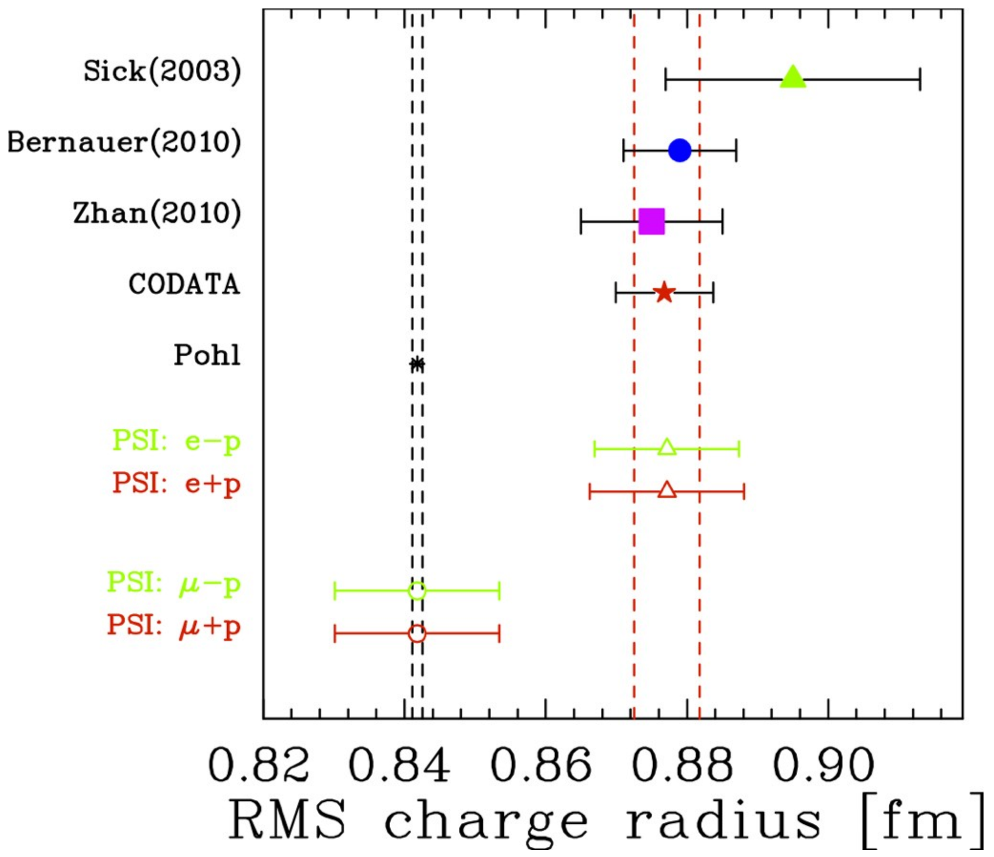
- Stat. uncertainties only, comparable sensitivity for ep & μp, as in spectroscopy
- 6 month run, equal time for each setting, $\theta_{scatter} = 20 - 100°$
- Uncertainties include endcap and μ decay subtractions

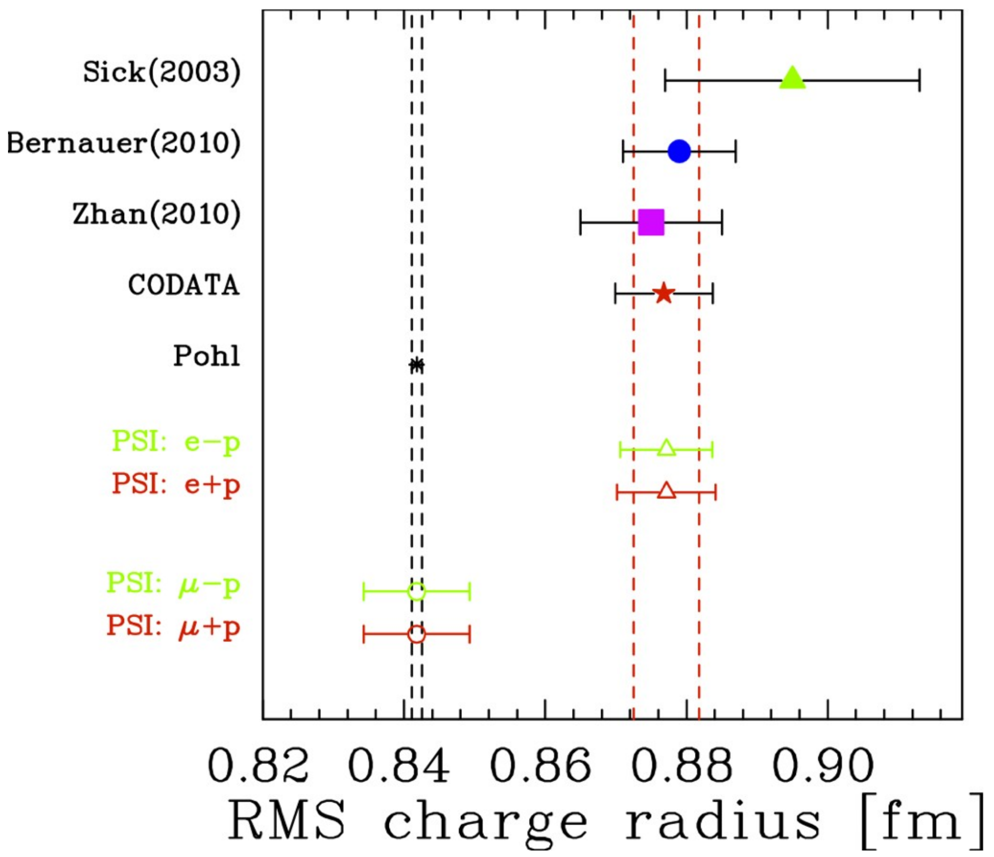
Estimated Results!



- Statistical uncertainties only, endcap BG mainly at ε near 1
- μ limited by μ decay rejection (conservatively estimated)
- $e^{+/-}$ mainly limited by radiative corrections, here 1γ cancels, prob. det. response

Physics





- Radius extraction from John Arrington
- Left: independent absolute extraction
- Right: extraction with only relative uncertainties

Outlook

- **The proton radius puzzle is a high-profile issue**
    - ➔ Explanation unclear
    - ➔ PSI MUSE tests interesting possibilities: Are μp and ep interactions different? If so, does it arise from 2γ exchange effects ($\mu^+ \neq \mu^-$) or BSM physics ($\mu^+ \approx \mu^- \neq e^-$)?
- Within 3-4 years (budgets willing) we should have new electron scattering results and start to see the muon scattering results, and possibly start to resolve the puzzle, perhaps seeing new physics!

MUSE Collaboration

The MUon proton Scattering Experiment collaboration (MUSE):

R. Gilman (Contact person),[1] E.J. Downie (Spokesperson),[2] G. Ron (Spokesperson),[3] A. Afanasev,[2] J. Arrington,[4] O. Ates,[5] F. Benmokhtar,[6] J. Bernauer,[7] E. Brash,[8] W. J. Briscoe,[2] K. Deiters,[9] J. Diefenbach,[5] C. Djalali,[10] B. Dongwi,[5] L. El Fassi,[1] S. Gilad,[7] K. Gnanvo,[11] R. Gothe,[12] K. Hafidi,[4] D. Higinbotham,[13] R. Holt,[4] Y. Ilieva,[12] H. Jiang,[12] M. Kohl,[5] G. Kumbartzki,[1] J. Lichtenstadt,[14] A. Liyanage,[5] N. Liyanage,[11] M. Meziane,[15] Z.-E. Meziani,[16] D. Middleton,[17] P. Monaghan,[5] K. E. Myers,[1] C. Perdrisat,[18] E. Piasetzsky,[14] V. Punjabi,[19] R. Ransome,[1] D. Reggiani,[9] P. Reimer,[4] A. Richter,[20] A. Sarty,[21] E. Schulte,[16] Y. Shamai,[22] N. Sparveris,[16] S. Strauch,[12] V. Sulkosky,[7] A.S. Tadepalli,[1] M. Taragin,[23] and L. Weinstein[24]

Thank you for your attention!