The Proton Radius Puzzle and MUSE

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Physics
Experiment
Outlook

Supported in part by the US National Science Foundation grants 1306126, 1441380, 1506160

What is the Proton Radius? Why measure it?

The proton has many radii.
Each radius is defined by the slope of a form factor.

$$\mathbf{r_p^2} \equiv -6\frac{\mathbf{dG_E}}{\mathbf{dQ^2}}\Big|_{\mathbf{Q^2=0}}$$

Nuclear physics:
Fundamental property of the nucleon.
Used in understanding nuclei.
Used to test nucleon theory.

Atomic physics:
Used in determination of fundamental constants.
Highly correlated with Rydberg constant.
A leading uncertainty in tests of QED and possible novel physics.

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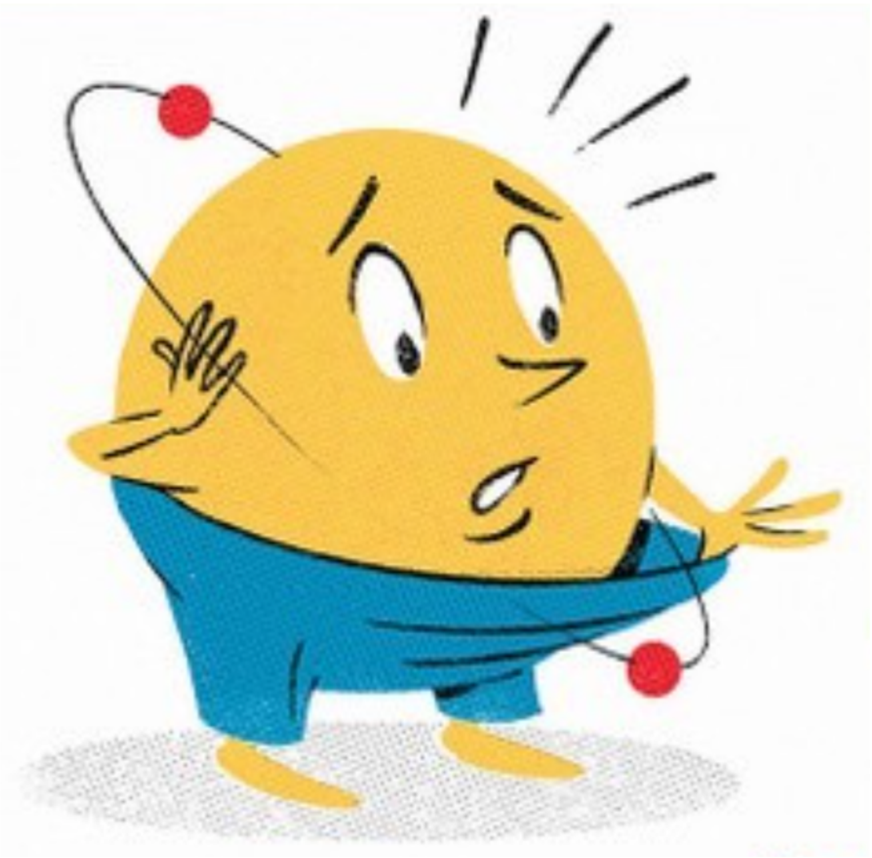


Nuclear physics:
Fundamental property of the nucleon.
Used in understanding nuclei.
Used to test nucleon theory.

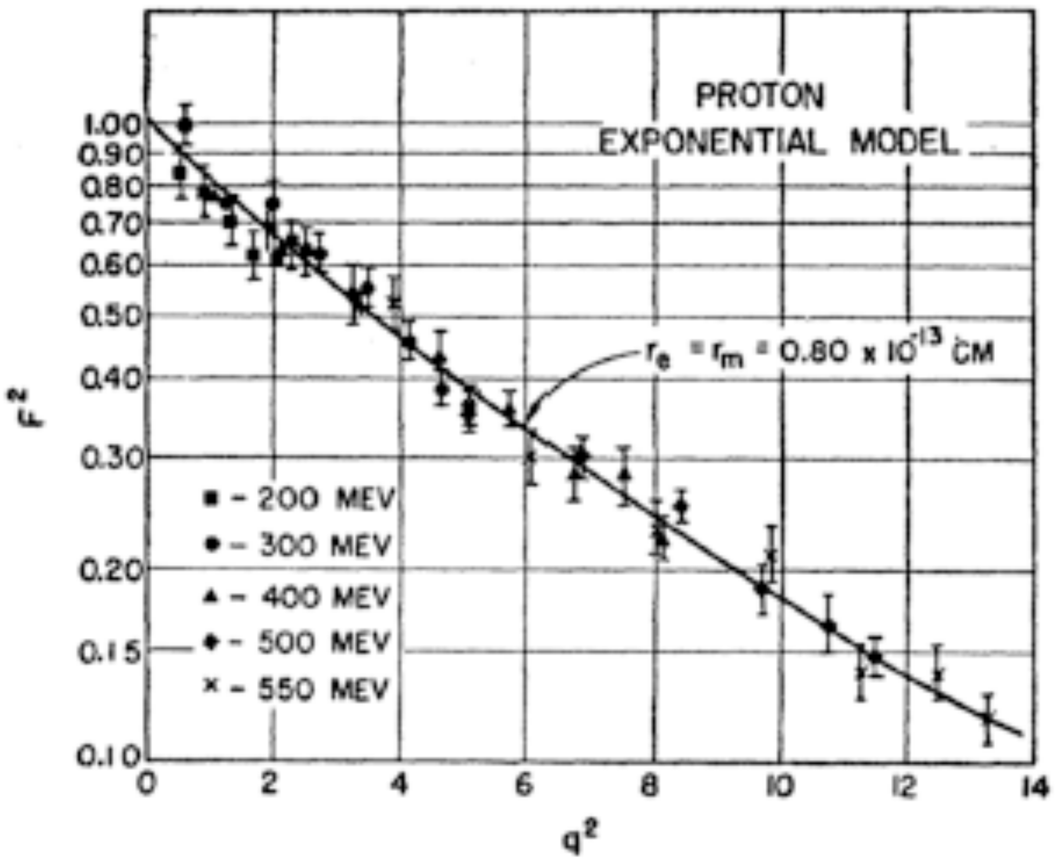
Not a leading issue in the EM community. Ingo Sick deserves much of the credit for advances in this area.

Atomic physics:
Used in determination of fundamental constants.
Highly correlated with Rydberg constant.
A leading uncertainty in tests of QED and possible novel physics.

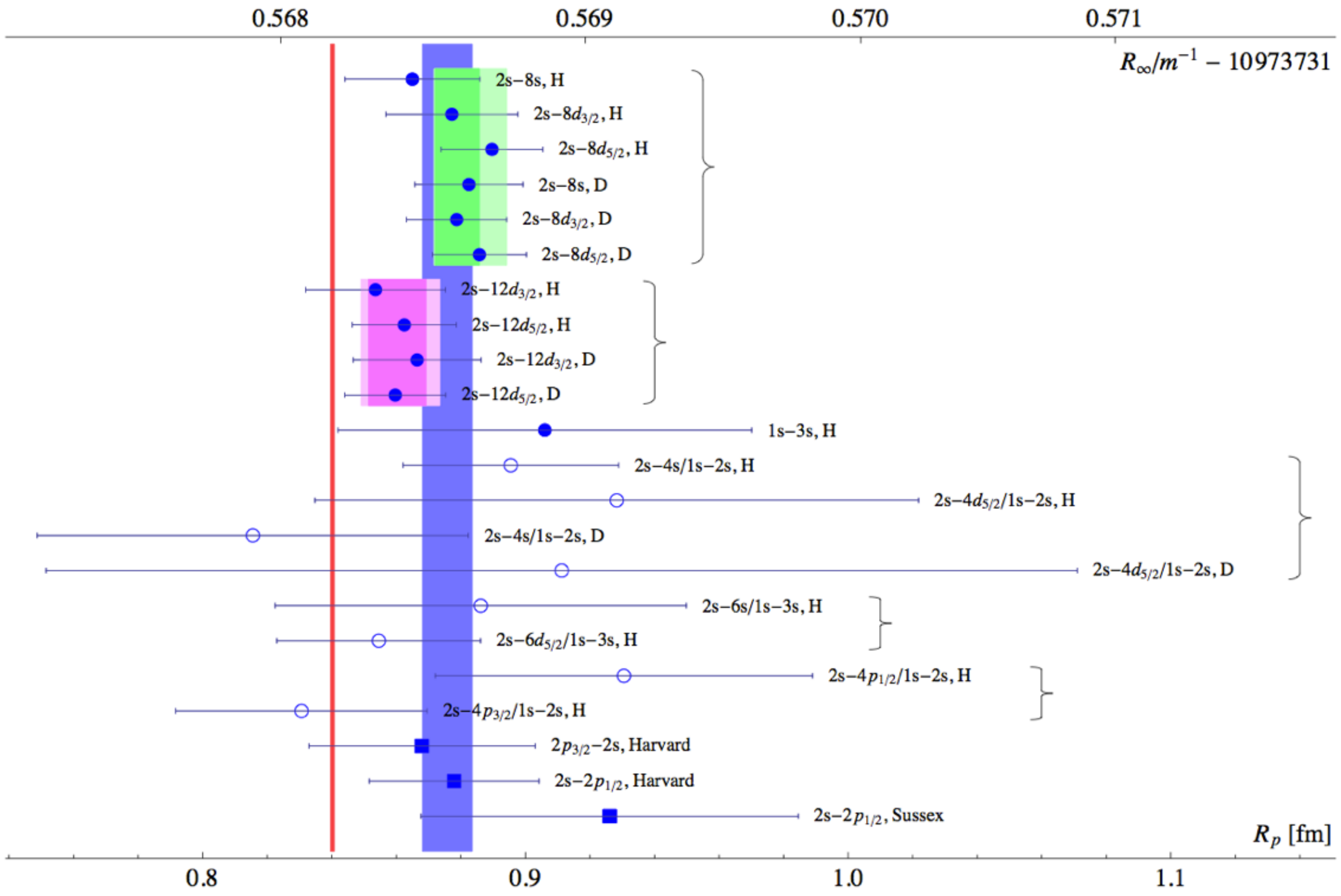
Many Years of Effort Determining r_p

Chambers and Hofstadter, Phys Rev 103, 14 (1956)

Measure the slope of the form factor

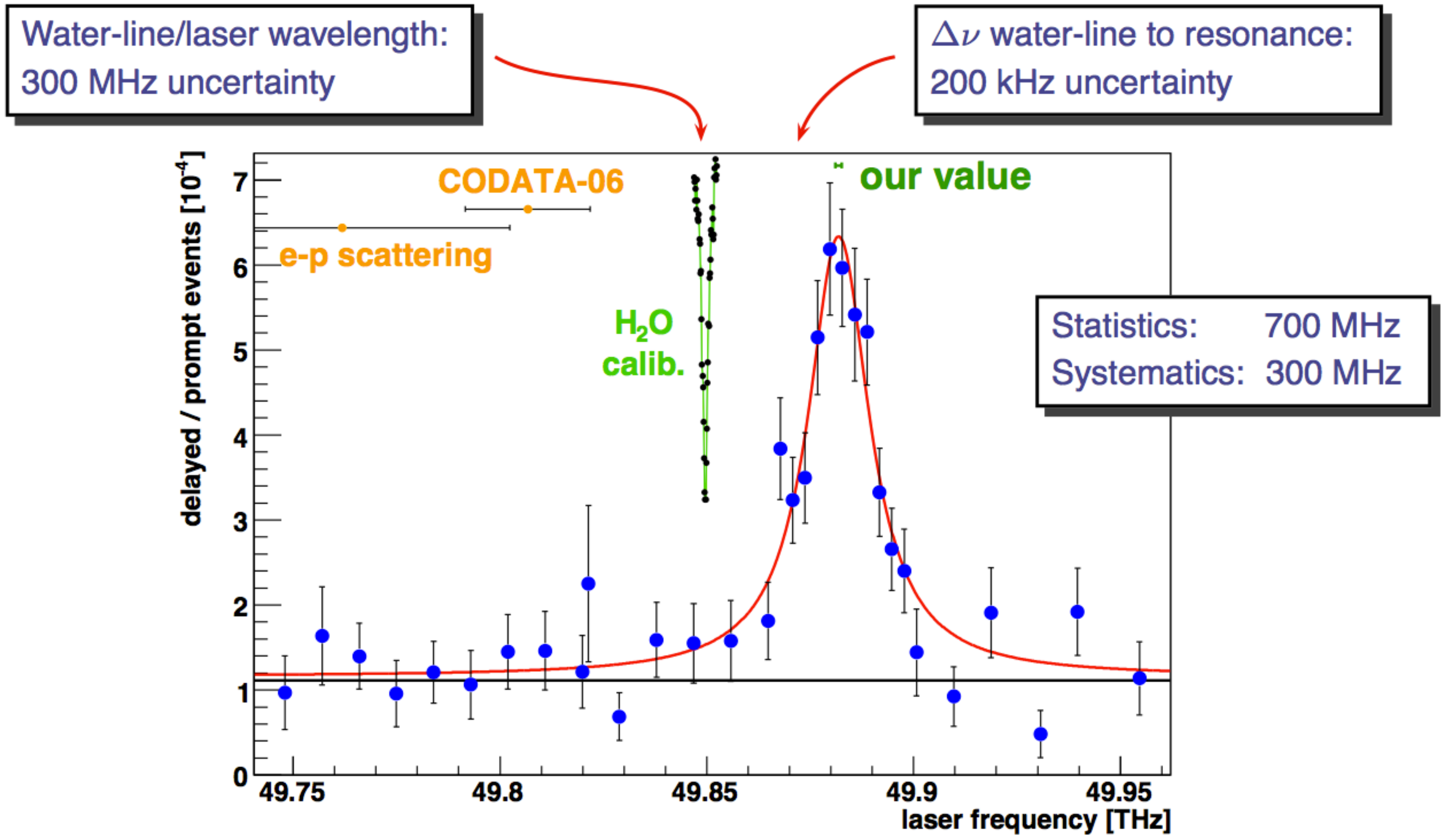


Karshenboim, arXiv:1410.7951



Many Years of Effort Determining r_p

R. Pohl et al., Nature (2010)
Measure a transition frequency that is affected by the proton size.



Water-line/laser wavelength:
300 MHz uncertainty

$\Delta\nu$ water-line to resonance:
200 kHz uncertainty

Statistics: 700 MHz
Systematics: 300 MHz

Possible Interesting New Physics

So a lot of attention

(But possible boring experimental issues.)

SCIENTIFIC AMERICAN

ScientificAmerican.com
FEBRUARY 2014

The Proton Problem

Could scientists be seeing signs o
a whole new real
of physics?

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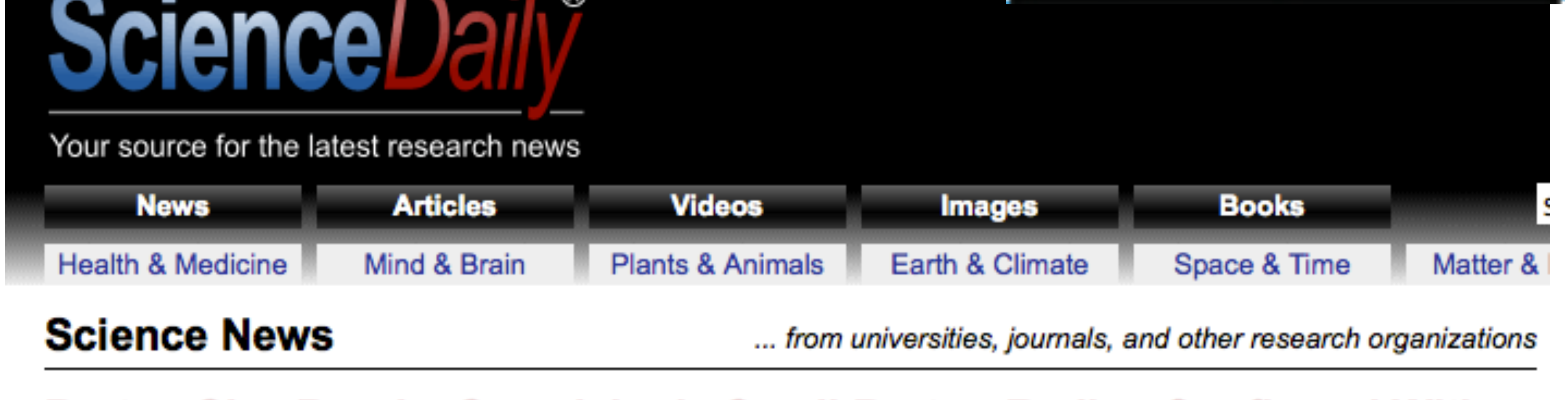
Scientific American cover story, by R Pohl and J Bernauer

NewScientist

TINY PARTICLE BIG PROBLEM

EVOLUTION IN MINIATURE



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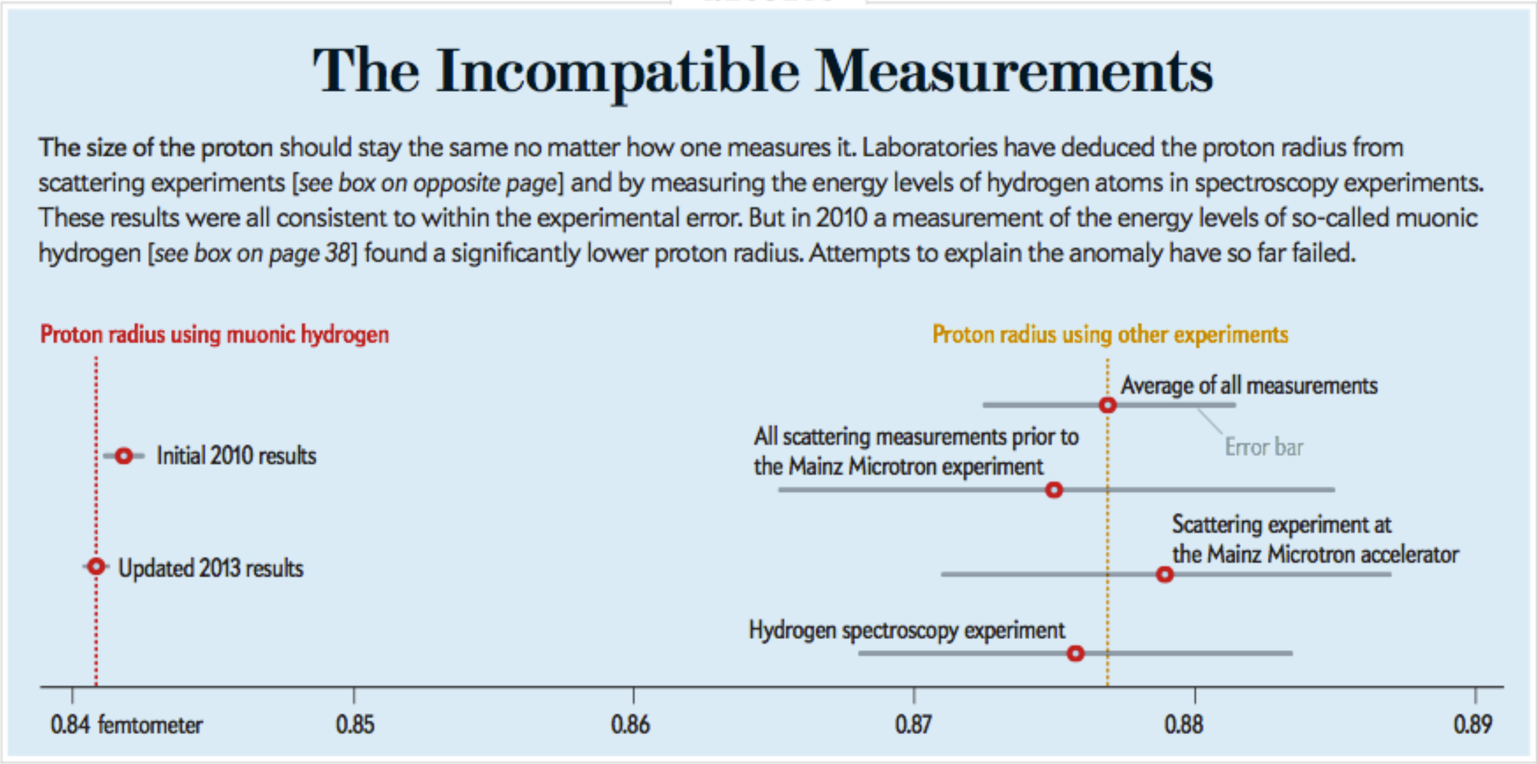
Proton Size Puzzle: Surprisingly Small Proton Radius Confirmed With

Aldo Antognini and Franz Kottmann in PSI's large experimental hall. (Credit: Image courtesy of Paul Scherrer Institut)



RESULTS

The Incompatible Measurements

The size of the proton should stay the same no matter how one measures it. Laboratories have deduced the proton radius from scattering experiments [*see box on opposite page*] and by measuring the energy levels of hydrogen atoms in spectroscopy experiments. These results were all consistent to within the experimental error. But in 2010 a measurement of the energy levels of so-called muonic hydrogen [*see box on page 38*] found a significantly lower proton radius. Attempts to explain the anomaly have so far failed.

The proton radius puzzle

r_p (fm)	atom	scattering
electron	0.8779 ± 0.0094 (Pohl analysis)	0.879 ± 0.008 (Bernauer 2010) 0.875 ± 0.009 (Zhan 2011)
muon	0.84087 ± 0.00039 (Antognini 2013)	?

CODATA 2010: 0.8775 ± 0.0051 – 7.2σ difference

Either radii from some experiments are wrong, or there is some interesting physics

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Still a puzzle in 2016. Why?

It takes a long time to set up new experiments.

The proton radius puzzle

r_p (fm)	atom	scattering
electron	Garching 2S-4P, …	Mainz initial state radiation JLab PRAD, …
muon	heavier light nuclei	MUSE

CODATA 2010: 0.8775 ± 0.0051 – 7.2σ difference

Still a puzzle in 2016. Why?

It takes a long time to set up new experiments.

Trento Proton Radius Puzzle Workshop

Still a puzzle in 2016.

What is MUSE?

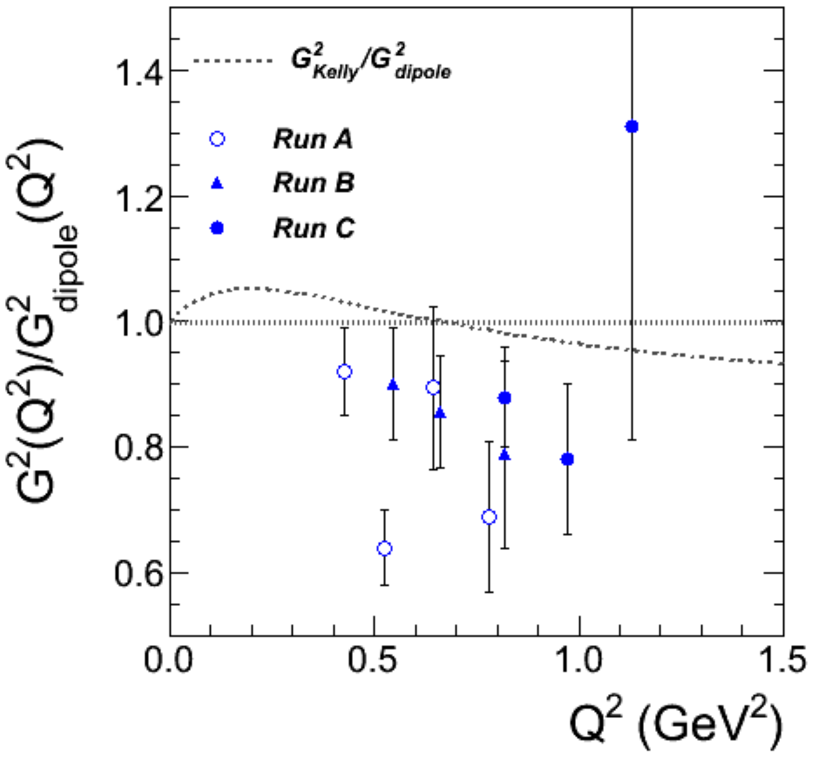
Simultaneous measurement of muon-proton AND electron-proton elastic scattering in the PSI PiM1 beam line.

Measurement with both beam polarities.

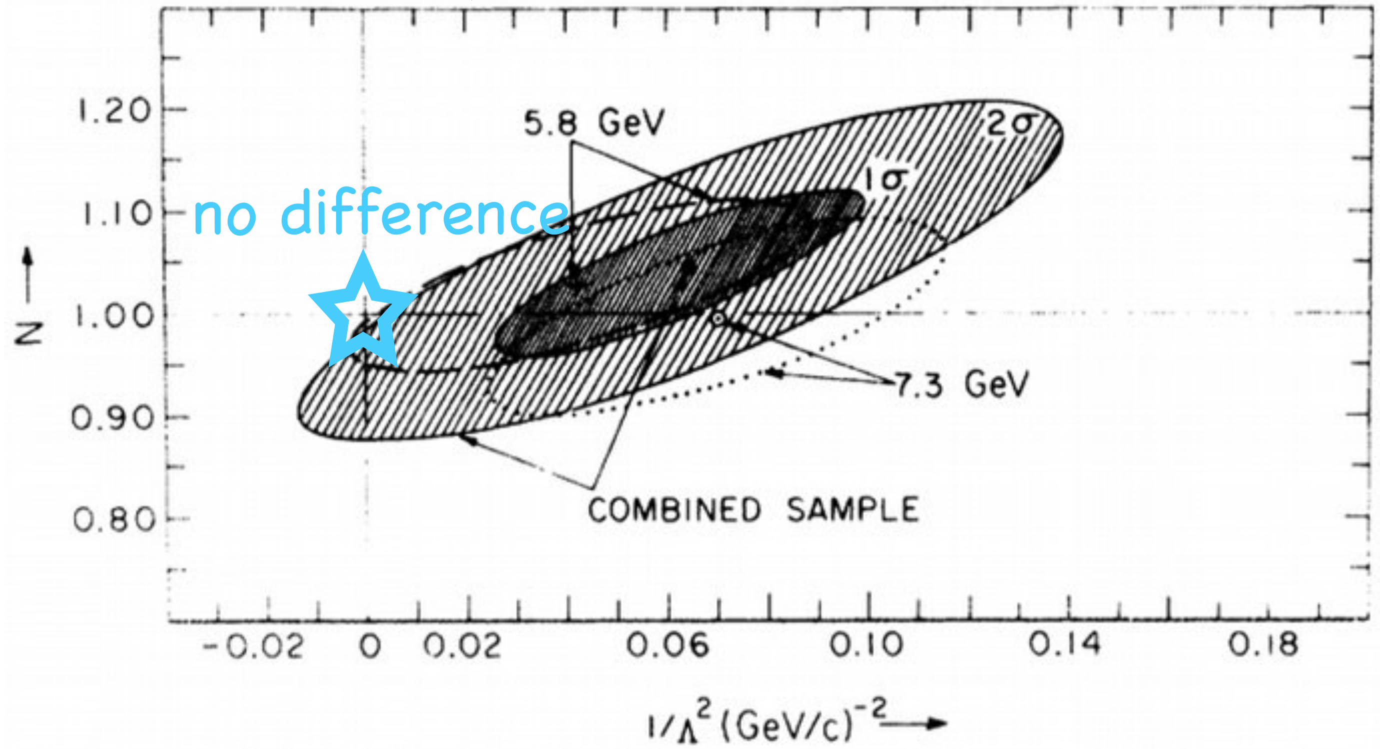
Determine cross section, form factors, two-photon exchange, very precise muon vs electron radius difference, and moderately precise radius

Muon Scattering has been done before but not well

Ellsworth et al. Phys. Rev. 165 (1968): form factors from elastic μp



Kostoulas et al. PRL 32 (1974) parameterization of μp vs. ep elastic differences



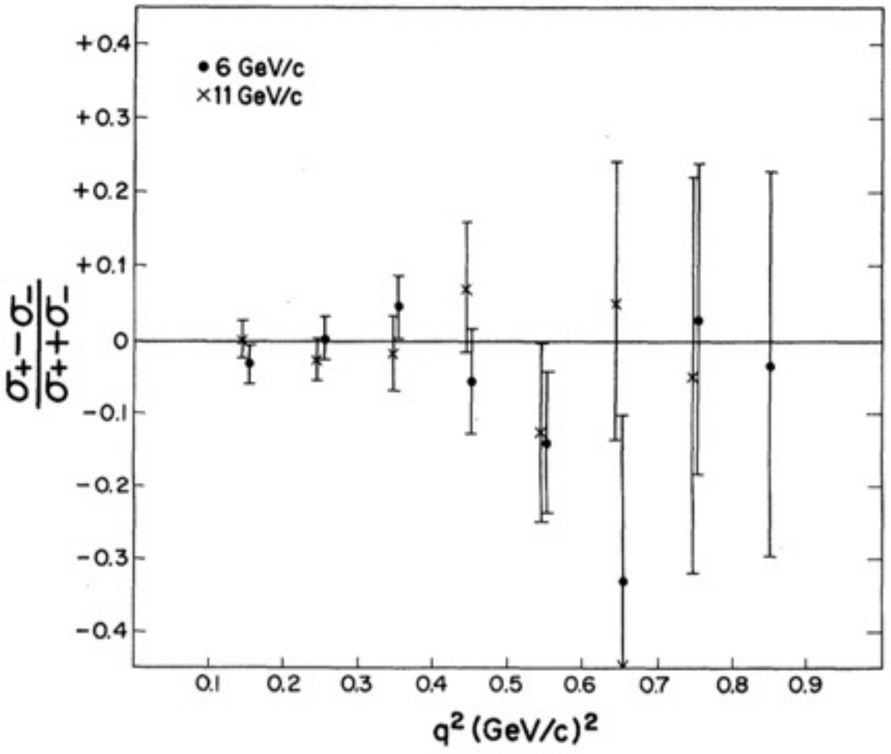
no difference

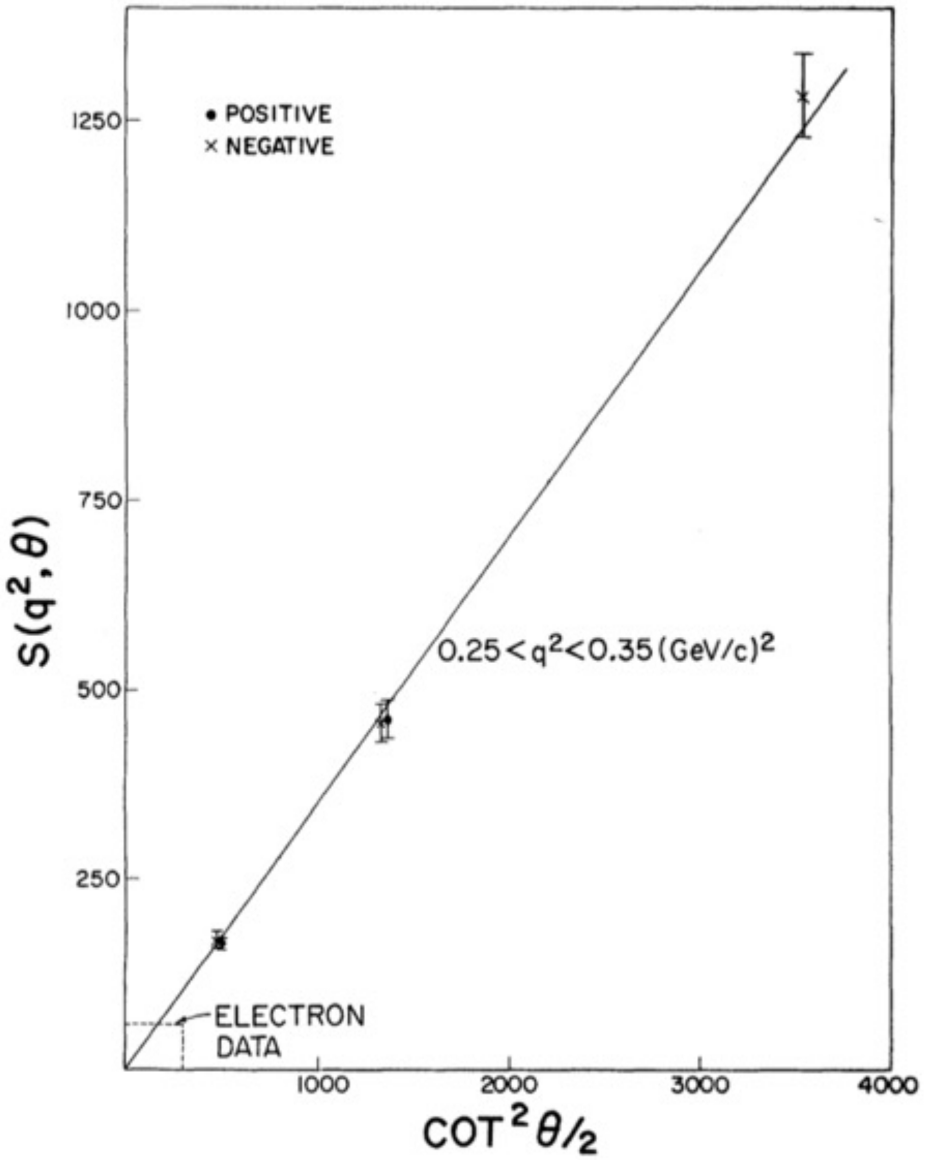
Entenberg et al. PRL 32 (1974) DIS:

$\sigma_{\mu p}/\sigma_{ep} \approx 1.0 \pm 0.04$ (8.6% systematics)

Two-Photon Exchange in Muon Scattering Explored, Imprecisely

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





And there was an attempt to determine r_p with muon scattering

Edward Berliner Ph.D. thesis, Nevis Laboratory, 1980:
$r_p = 1.13 \pm 0.21$ fm

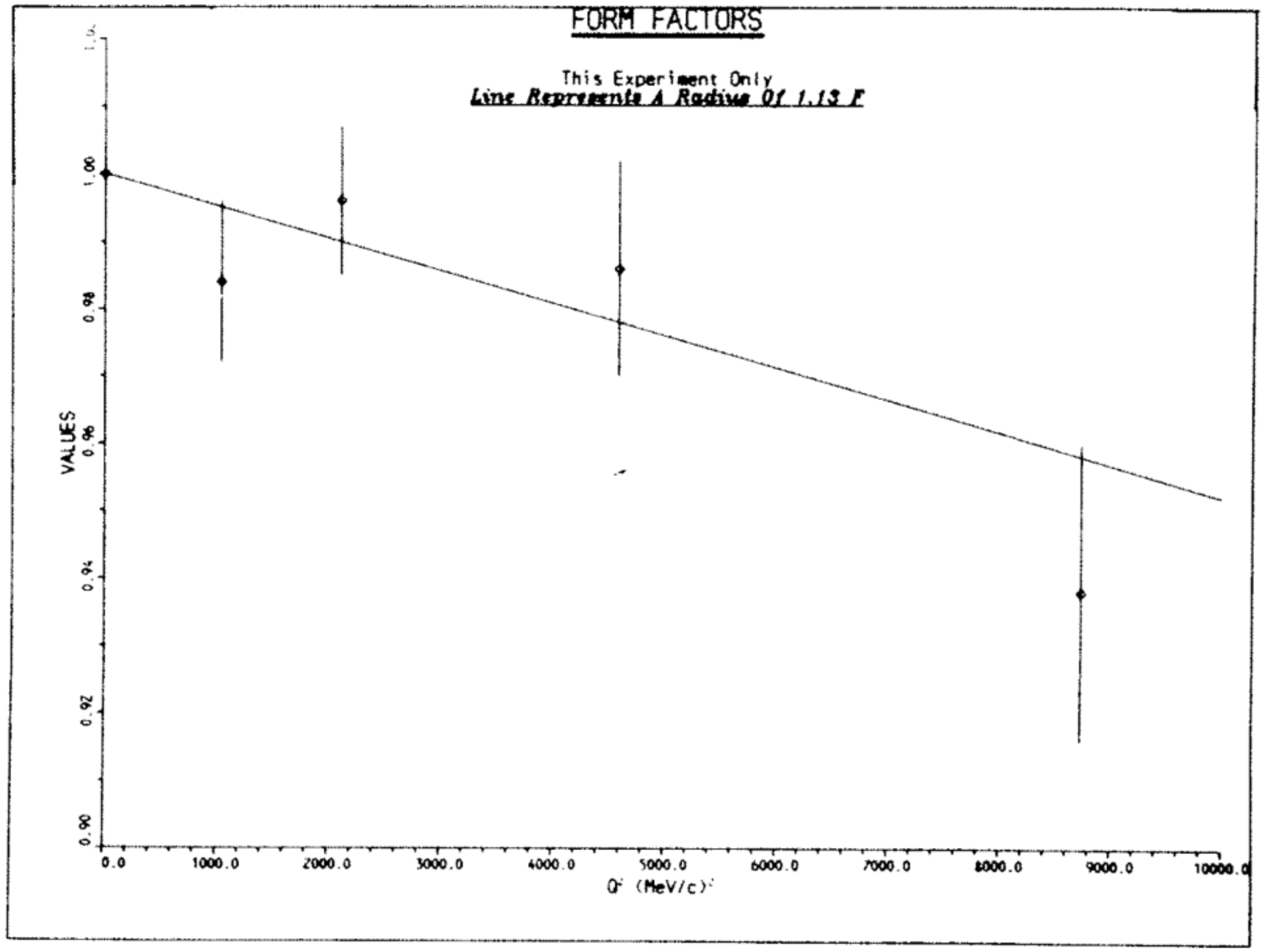


FIG. 41

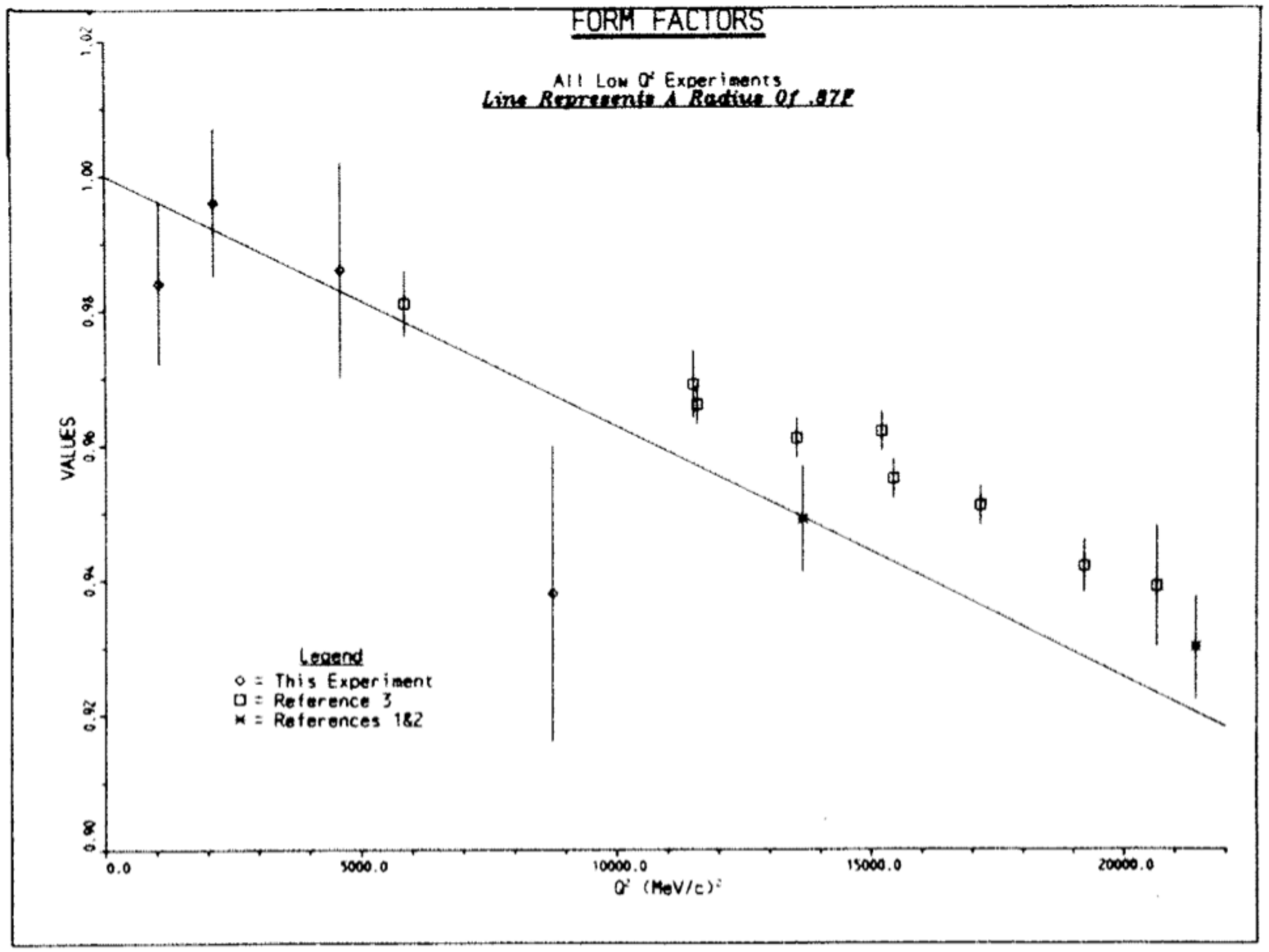
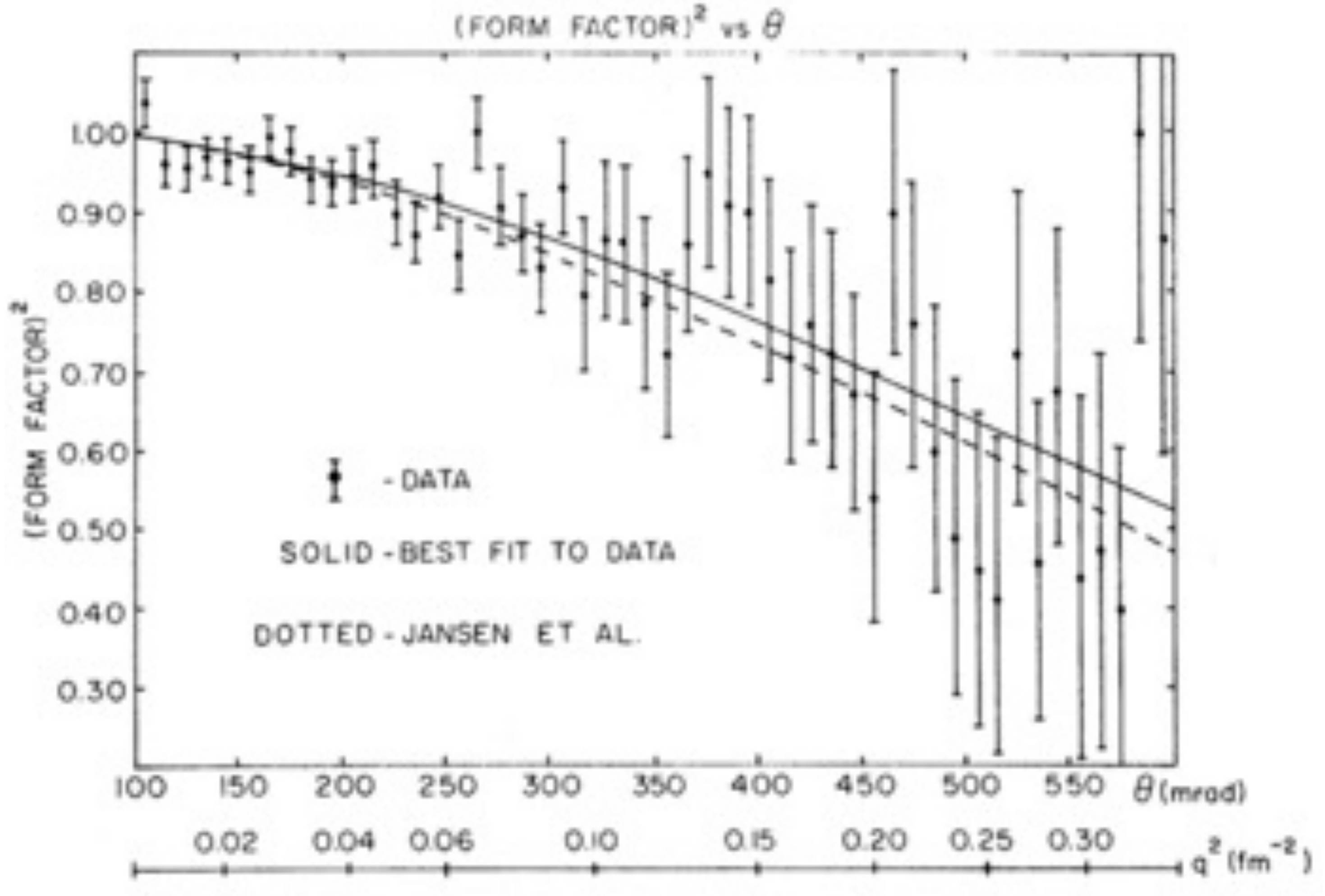


FIG. 42

Best muon scattering is on ^{12}C



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

What is MUSE?

590 MeV, 50.6 MHz proton beam.

PiM1: 100 - 450 MeV/c secondary $e^\pm$, $\mu^\pm$, $\pi^\pm$ beam.

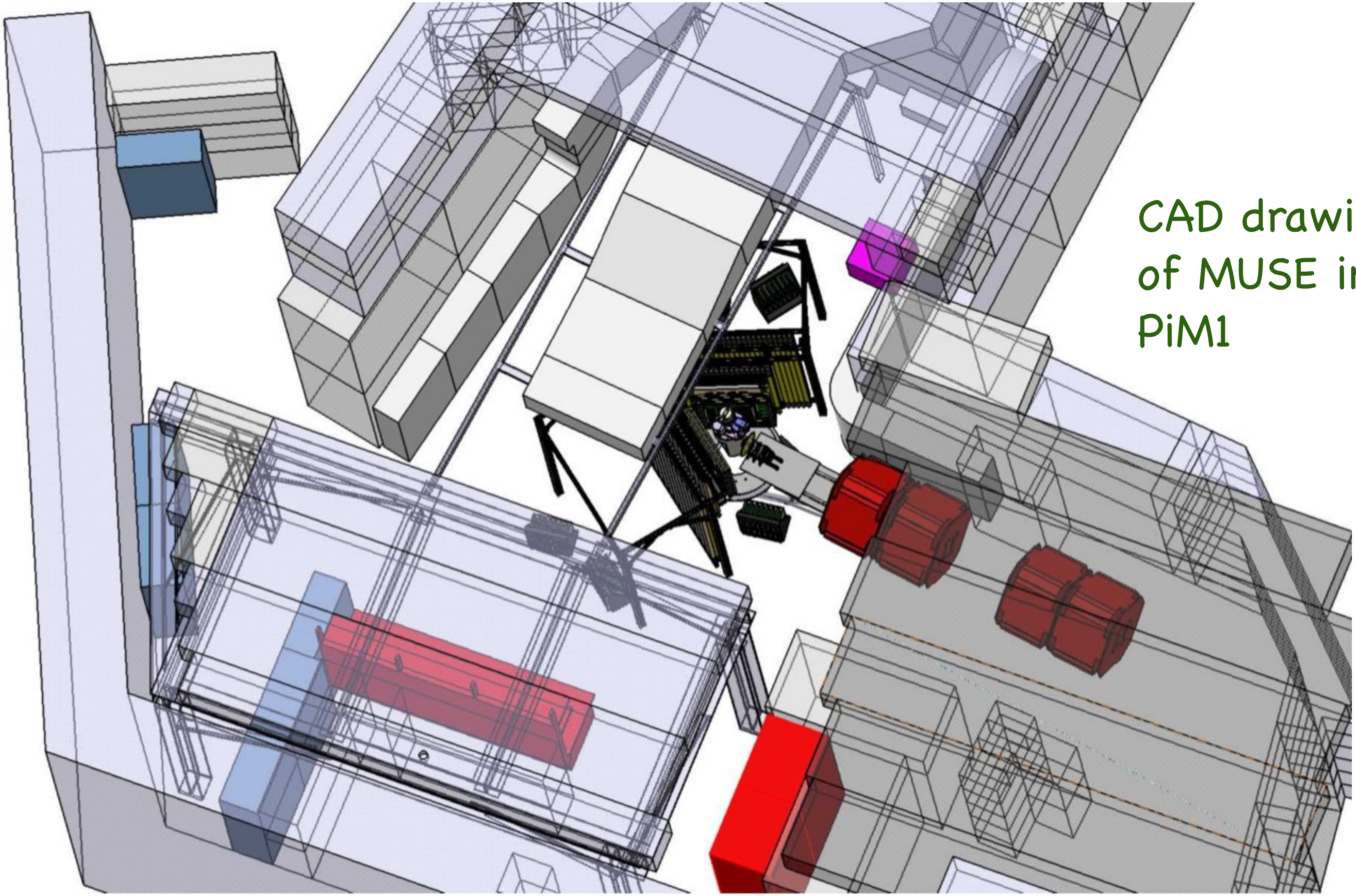
We use 115, 153, and 210 MeV/c, providing ≈2-15% μ's, 10-98% e's, 0-80% π's.

Identify beam particles through RF timing.

Trigger on e's and μ's.

Limit beam flux to 5 MHz.

What is MUSE?

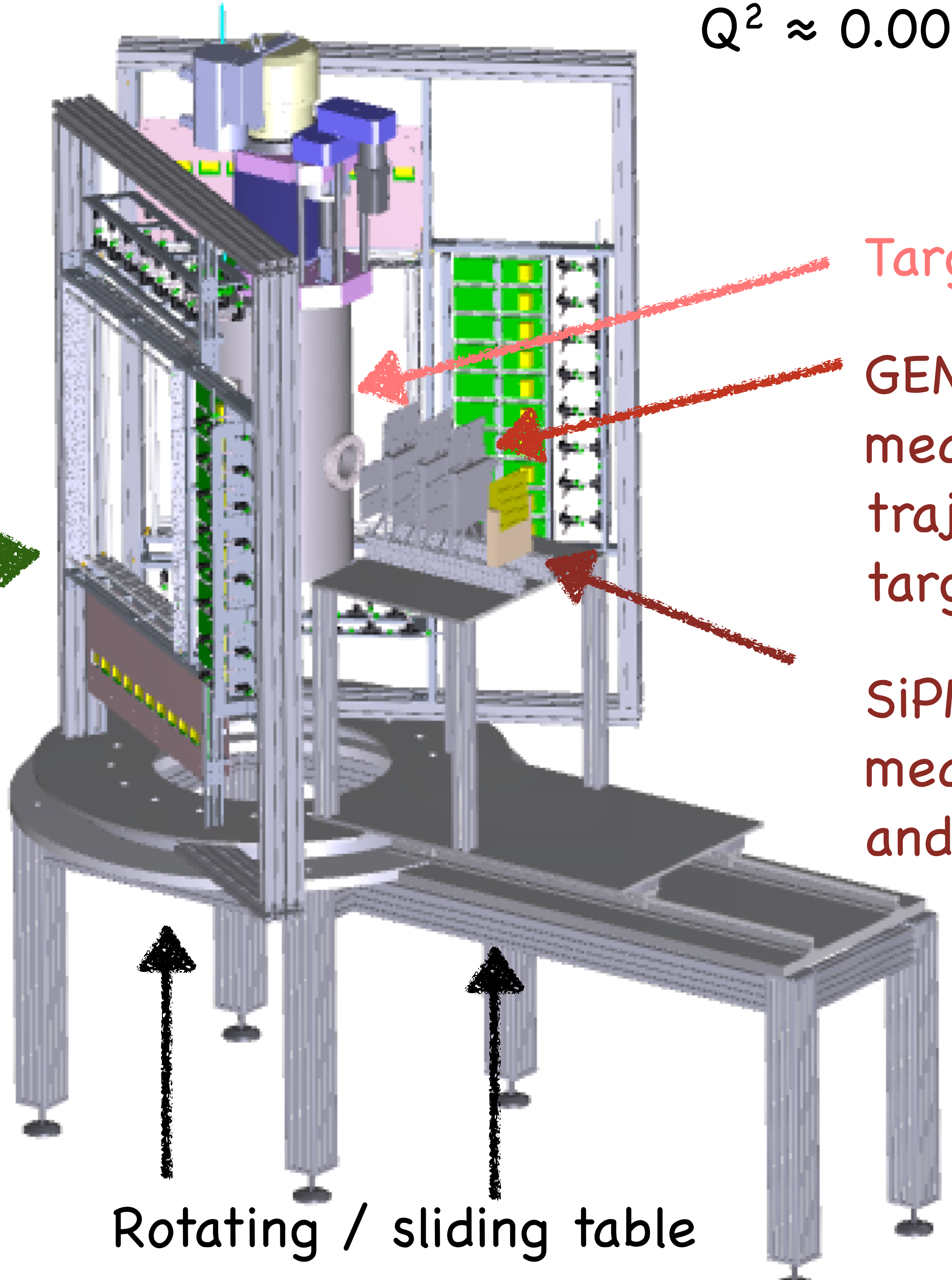


CAD drawing of MUSE in PiM1

What is MUSE?

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

$Q^2 \approx 0.002 - 0.08\ \mathrm{GeV}^2$



Target

GEM chambers measure trajectory into target

SiPM scintillators measure RF time and start TOF

Straw tube tracker

Not shown:
veto scintillator
downstream beam monitor,
scintillator trigger walls

Rotating / sliding table

Why not a small acceptance magnetic spectrometer?
And beam line detectors???

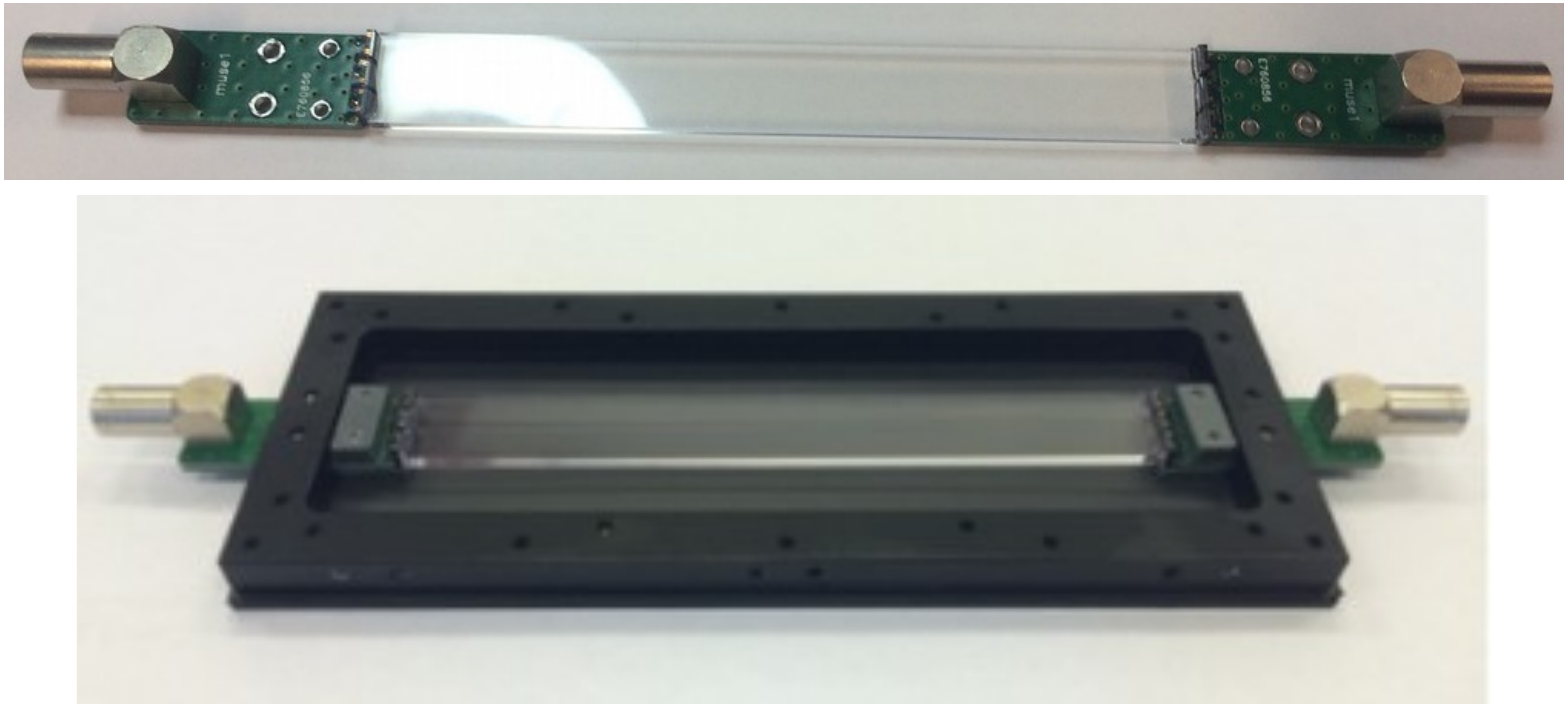
Small beam flux - MHz of particles, 10^{-9} of JLab or MAMI - severely limits Q^2 range without large acceptance detectors.

Mixed unstable beam with large divergence requires beam line detectors to identify incoming particle and trajectory.

Systematic uncertainty limits from knowledge of scattering angle, beam momentum, multiple scattering, solid angle

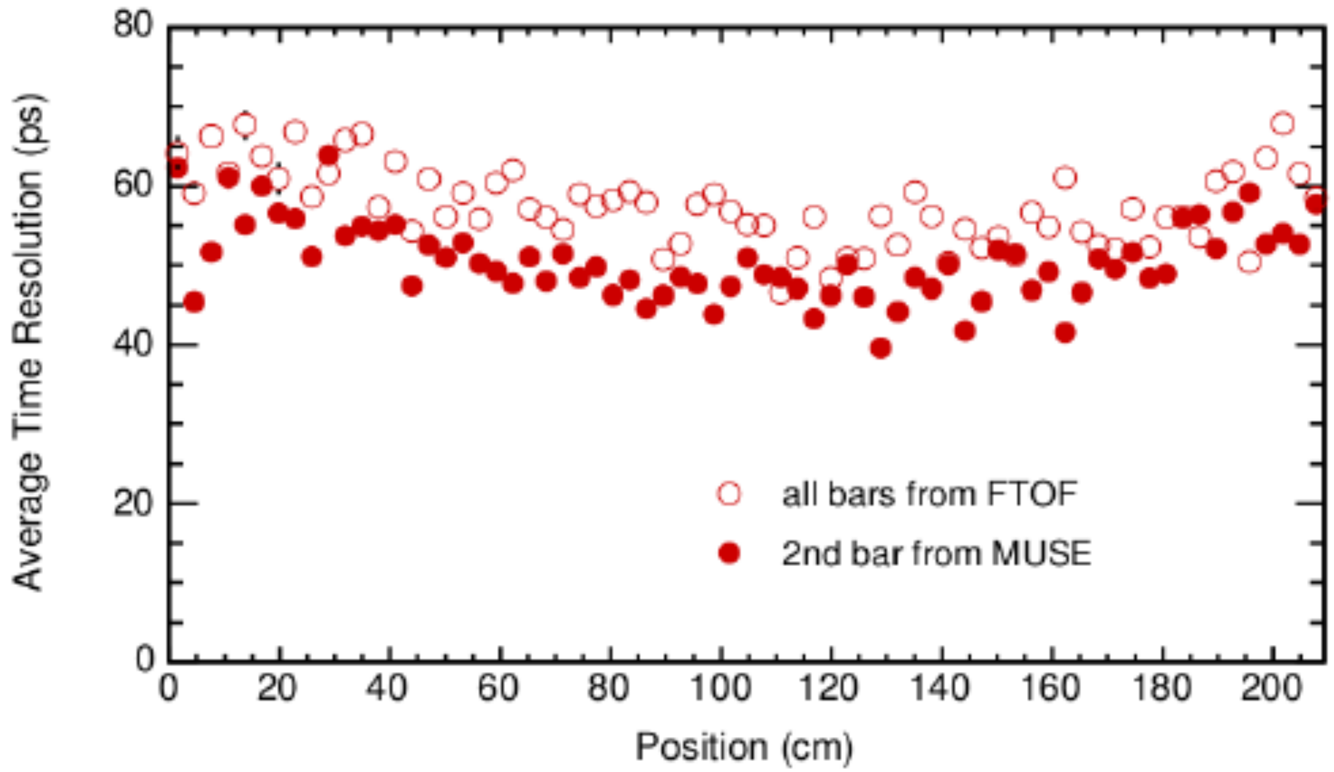
Large acceptance magnets (e.g., CLAS) generally generate imprecise cross sections.

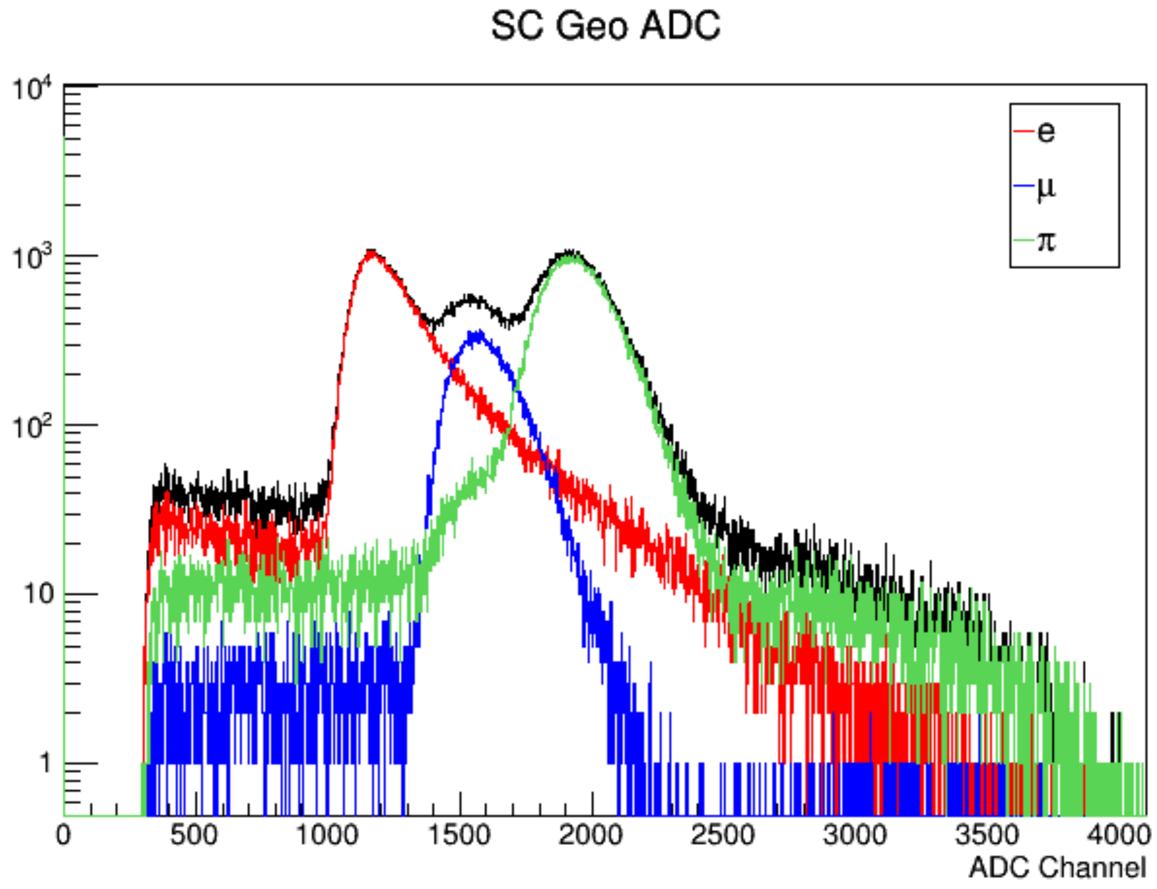
SiPM Scintillators



Silicon Photomultipliers by Hamamatsu, AdvanSiD, and others.
Base configuration: 10 cm x 5 mm x 2 mm EJ204, Hamamatsu S13360-3050PE SiPM, amplified signal to CFD.
Varied material, size, SiPM, "HV", threshold
Have obtained 99.9 ± 0.1 % efficiency with 53 ps paddle resolution.
Working with Alexey Stoykov (PSI).

Scintillators

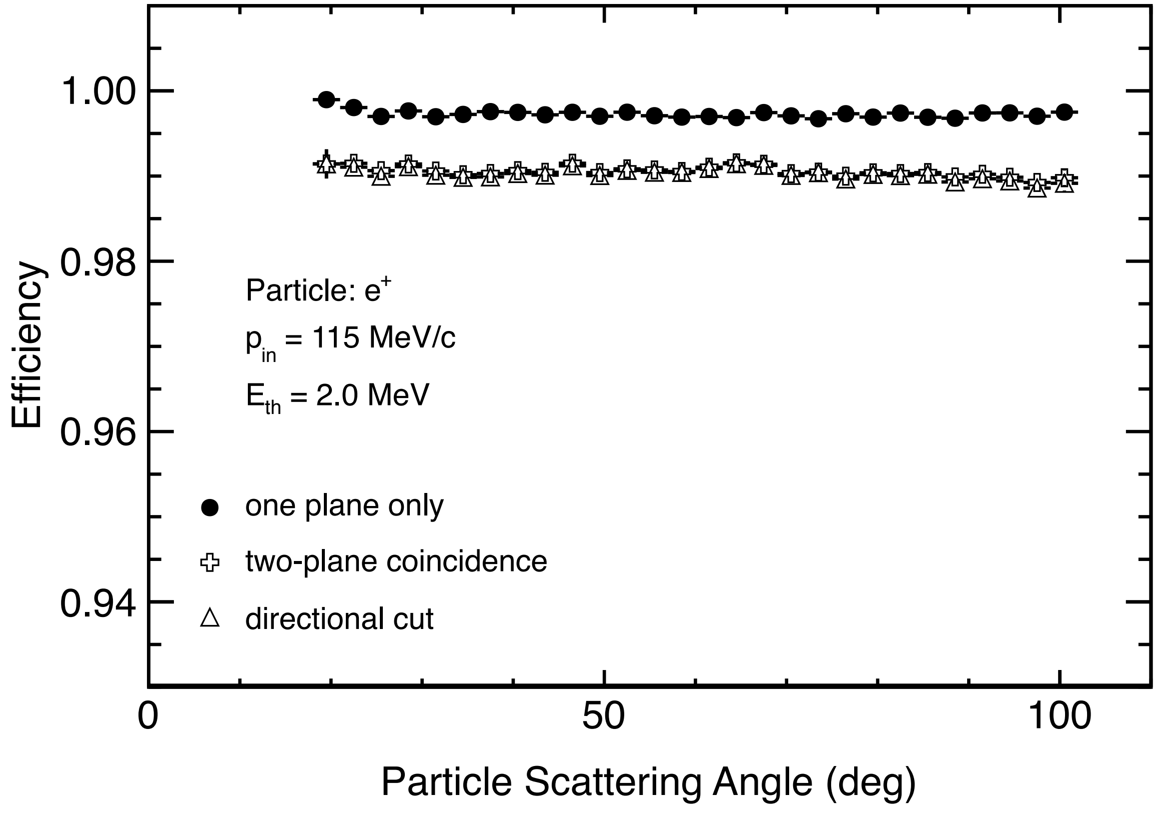




Based on CLAS-12 FTOF design: Hamamatsu R13435 PMT reading out BC404 scintillator

Two walls: $3 \times 6 \times 160$ cm^3, $6 \times 6 \times 220$ cm^3

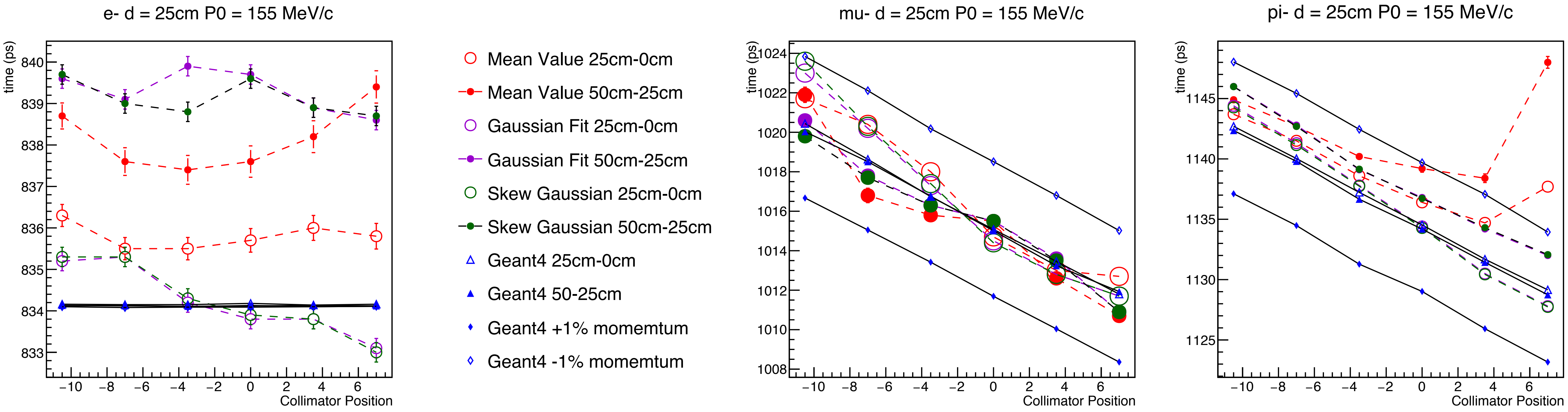
3+3 paddles at PSI for testing



Time of Flight

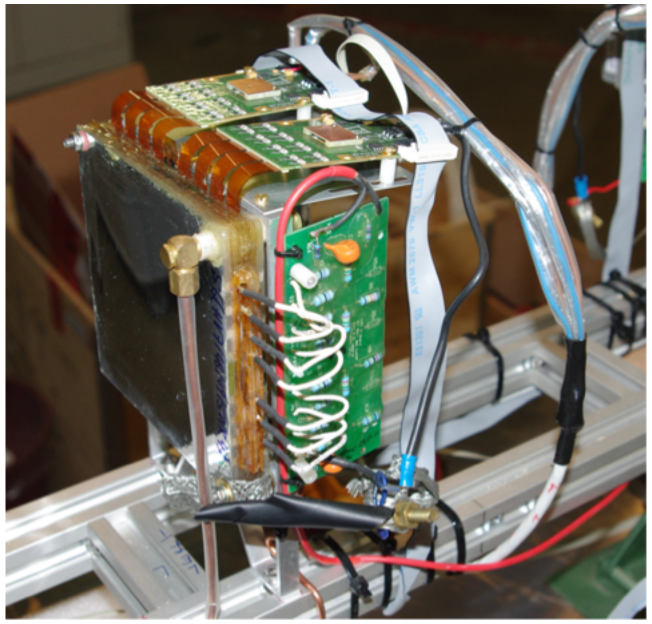
Time-of-flight analysis from December test run. Used precision table (50-cm travel) to make precise TOF difference measurements for precisely known path-length changes.

1. Electron peaks about 100 ps rms.
2. Muon and pion peaks about 90 ps rms.
3. Extracted peak positions with several fit functions.
4. Run into problems at the few ps level. (!) Many potential problems at this level.

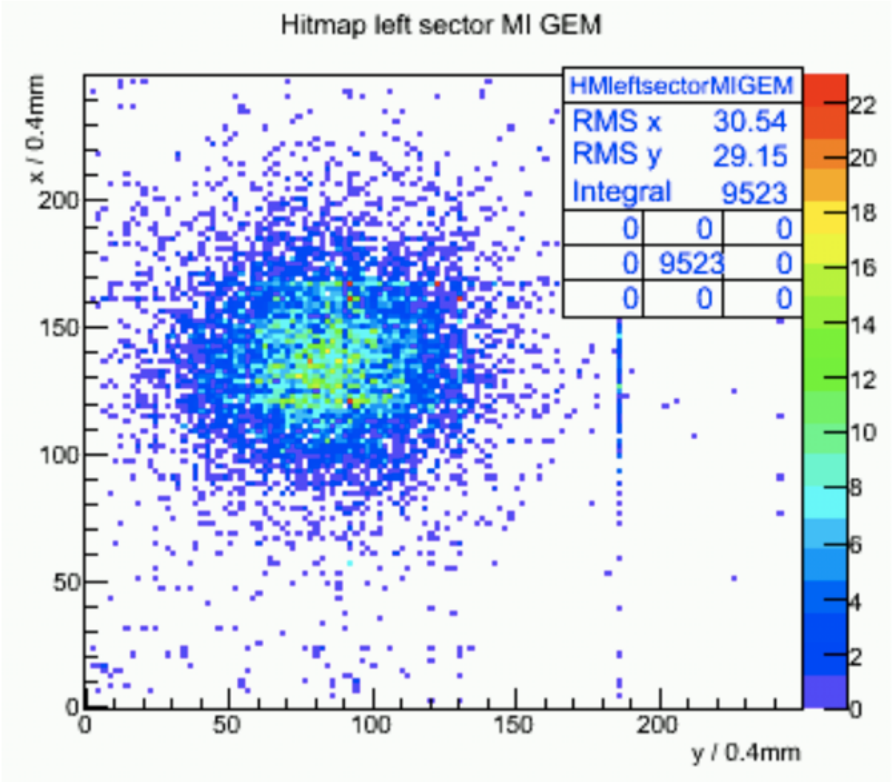


GEMs

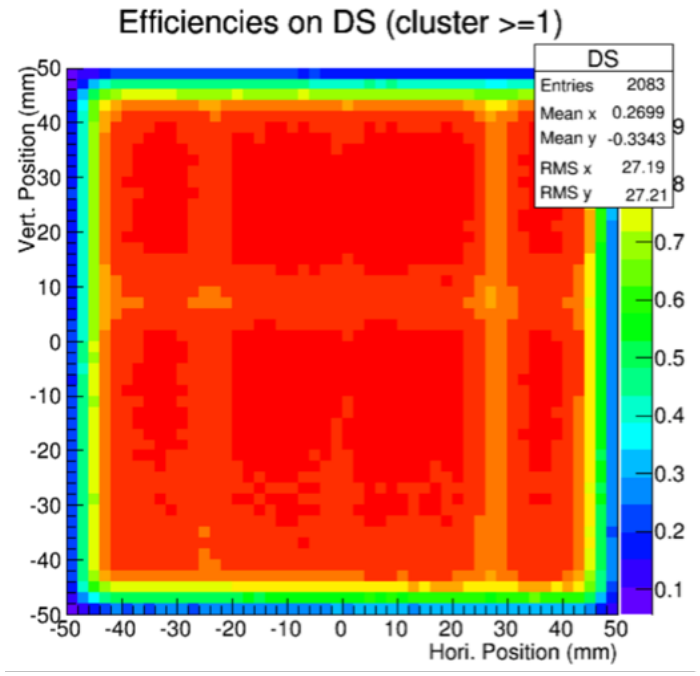
Used to track beam particles into the target



Existing GEM in MUSE test



Beam distribution measured by GEM

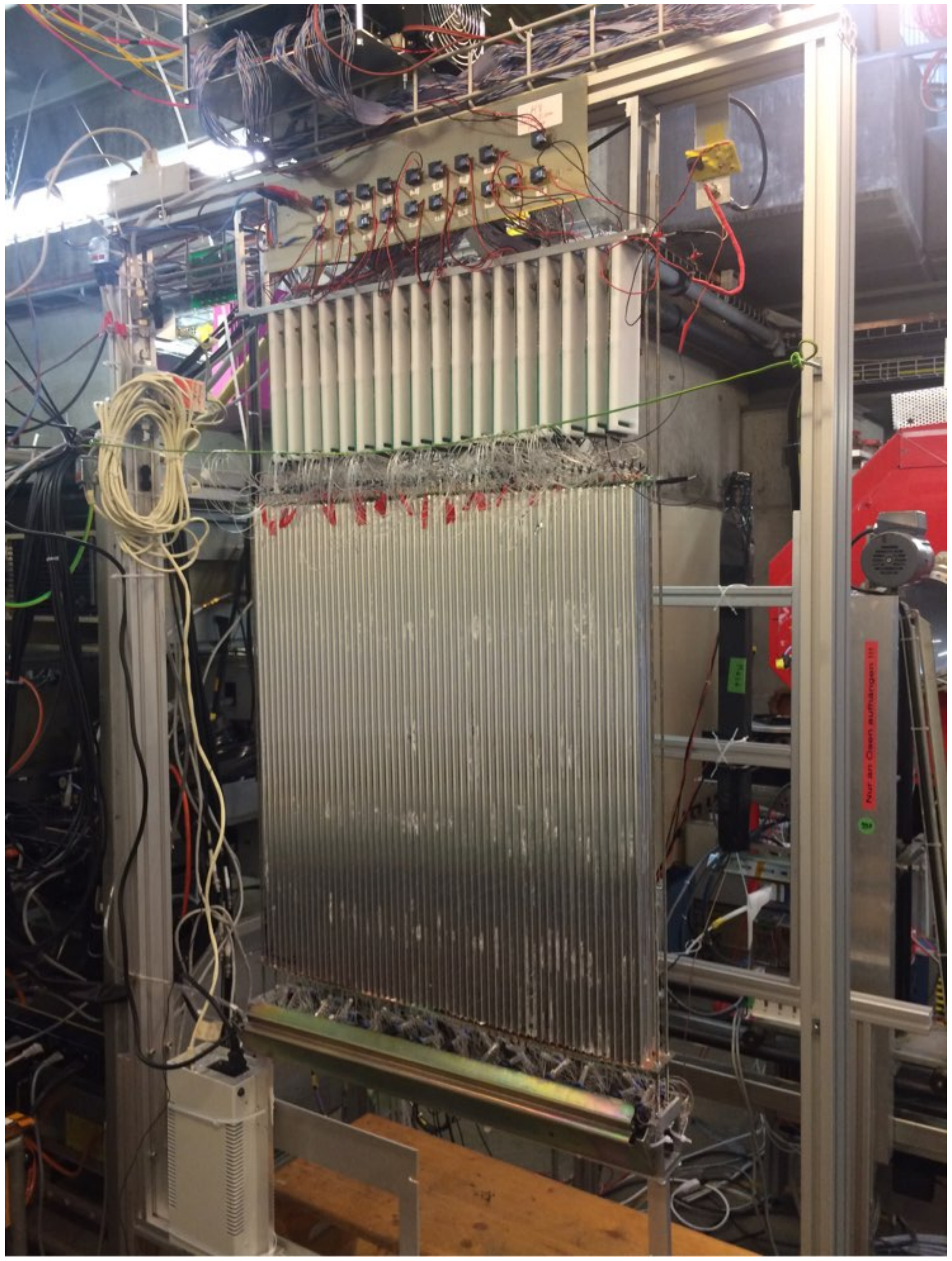


Measured efficiency map of a GEM

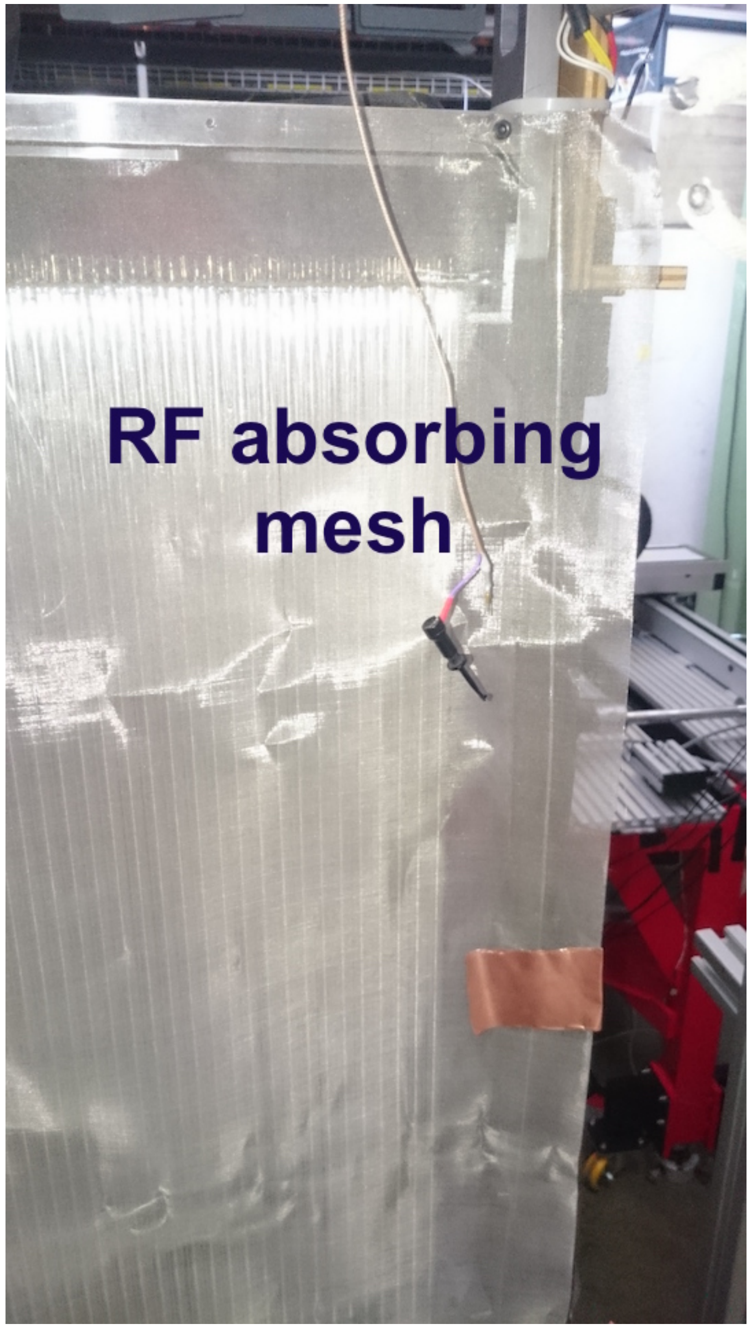
Using pre-existing OLYMPUS GEMs.
Upgrading DAQ rate capability.
(About 1 ms readout at OLYMPUS.)

Straw Tube Tracker

Used to track beam particles scattered from target.
Based on PANDA design.

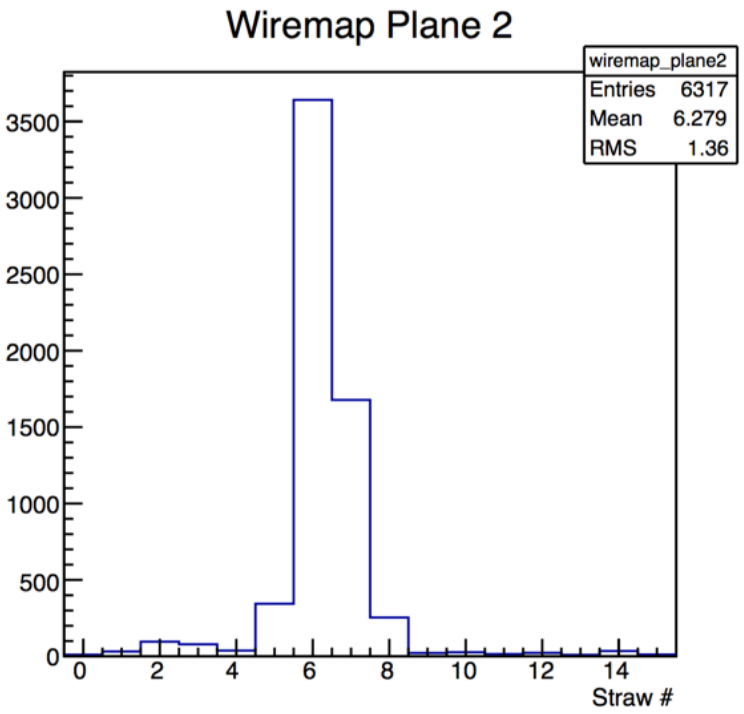


Initial STT at PiM1.

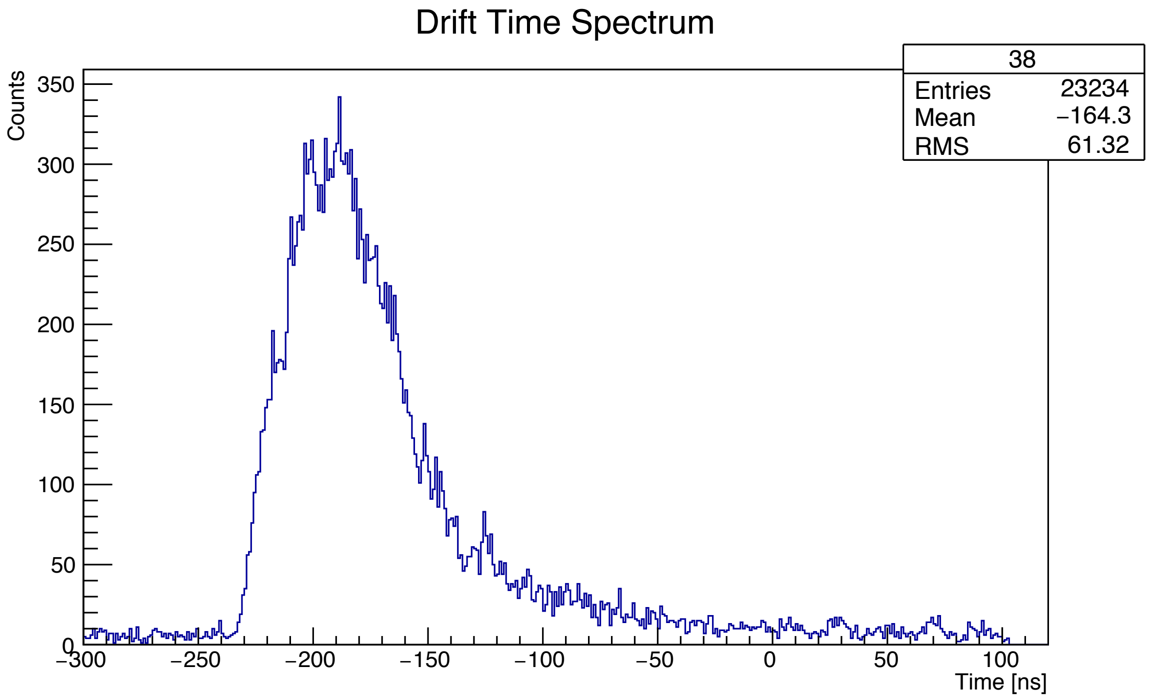


With noise reducing fabric.

Straw Tube Tracker Performance



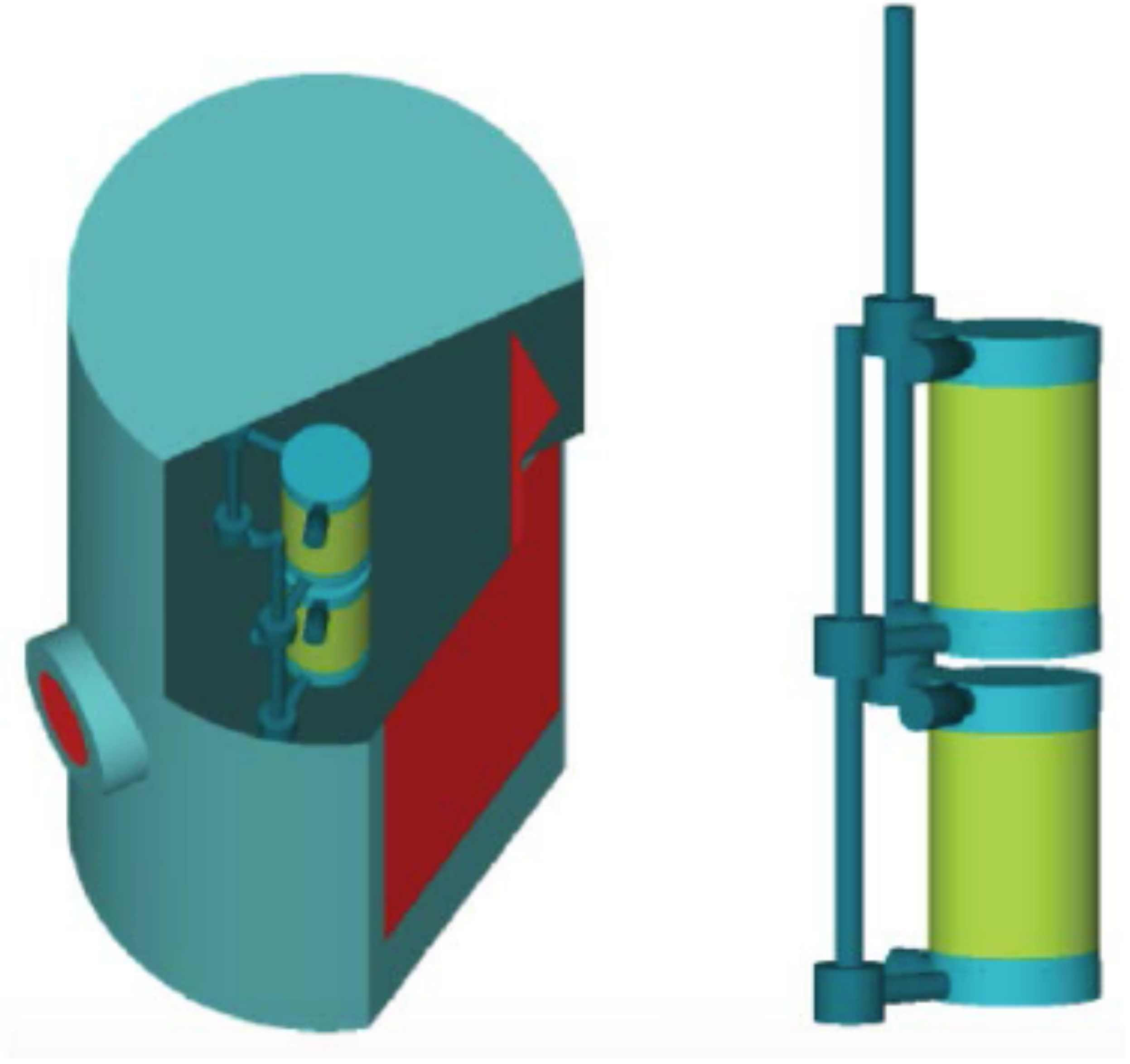
Wiremap showing the beam passing through plane 2, and some noise. Apparent beam width was determined by a 2-cm (2-straw) wide trigger paddle.



Straw 38 drift time spectrum. This is similar to the PANDA results, with a fast rise, slower fall, and long tail., but with a low level of background noise.

Cryotarget

Geant4 implementation of initial conceptual design of cryotarget.

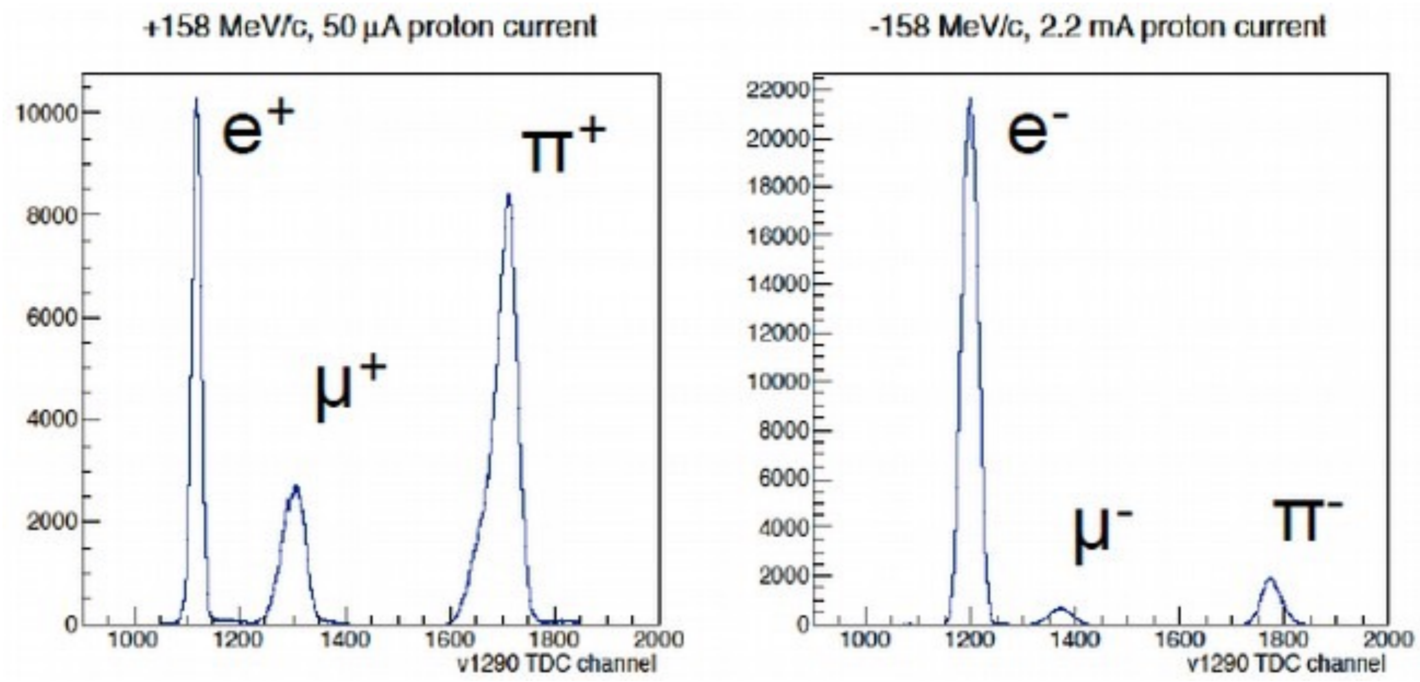


And more

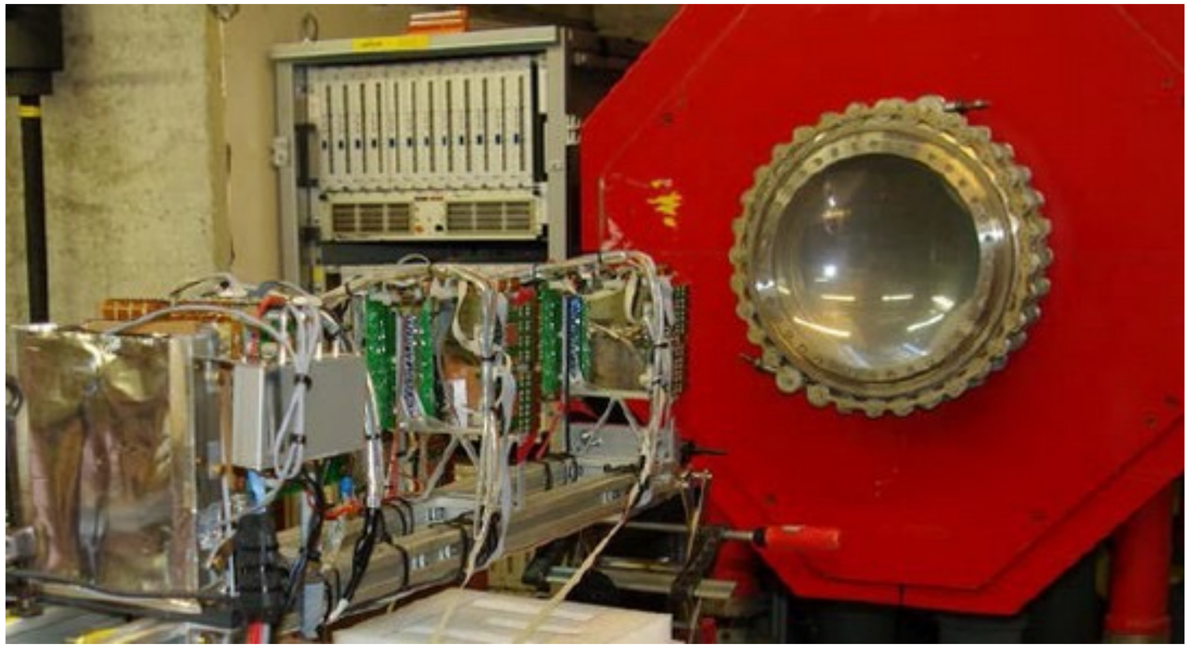
Beam Cerenkov
Electronics
Trigger
DAQ
...

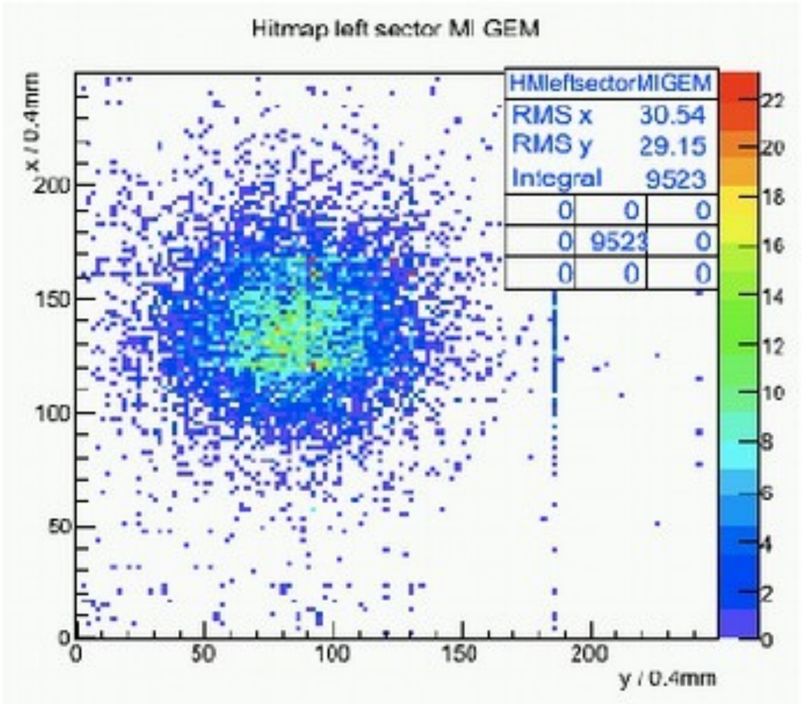
Beamline

Time of flight relative to RF time - Fall 2012

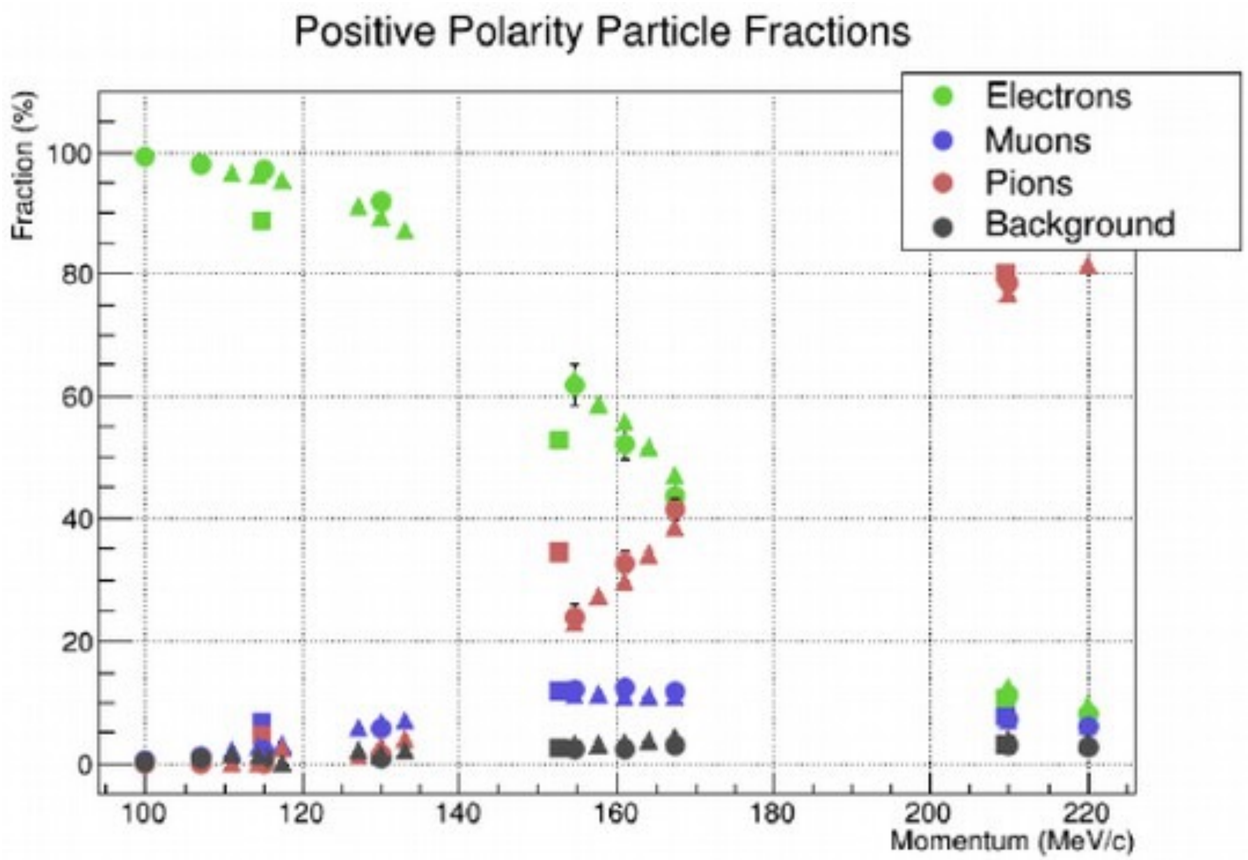


Beam spot with GEM - May 23, 2013



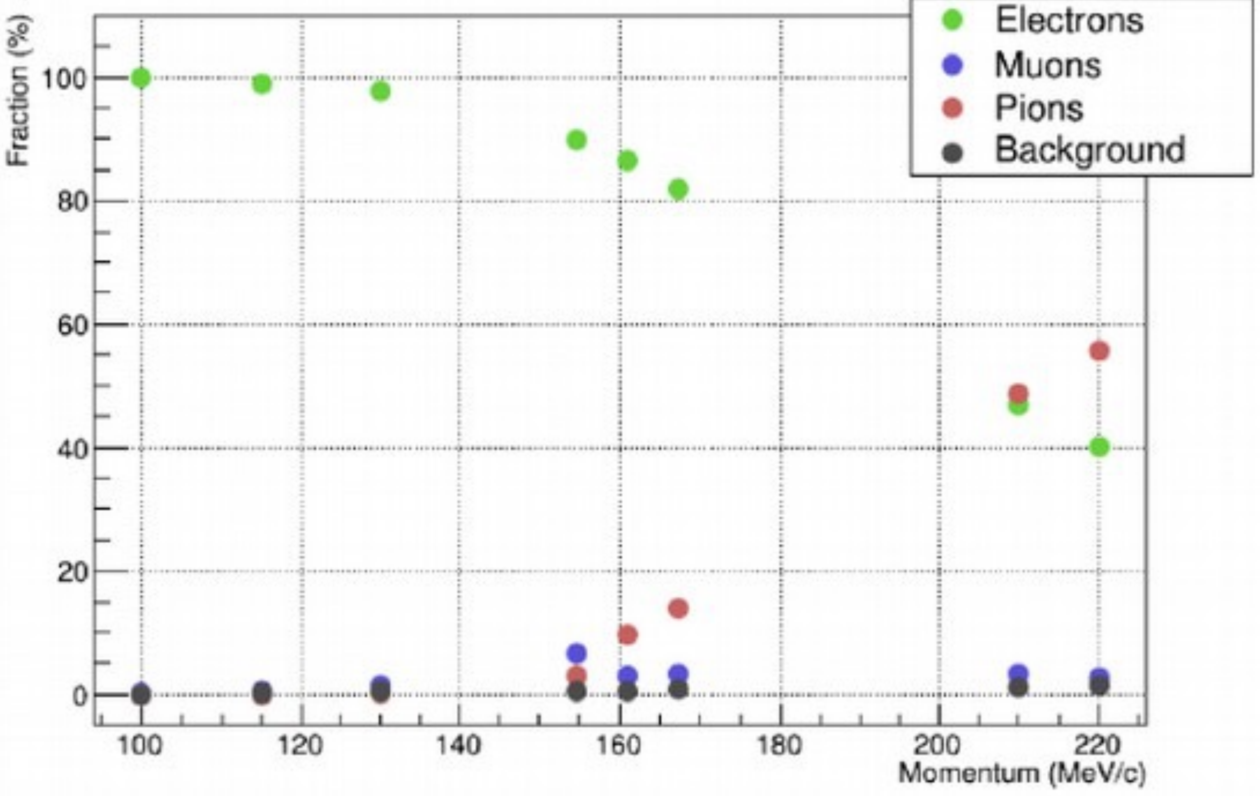


Beamline

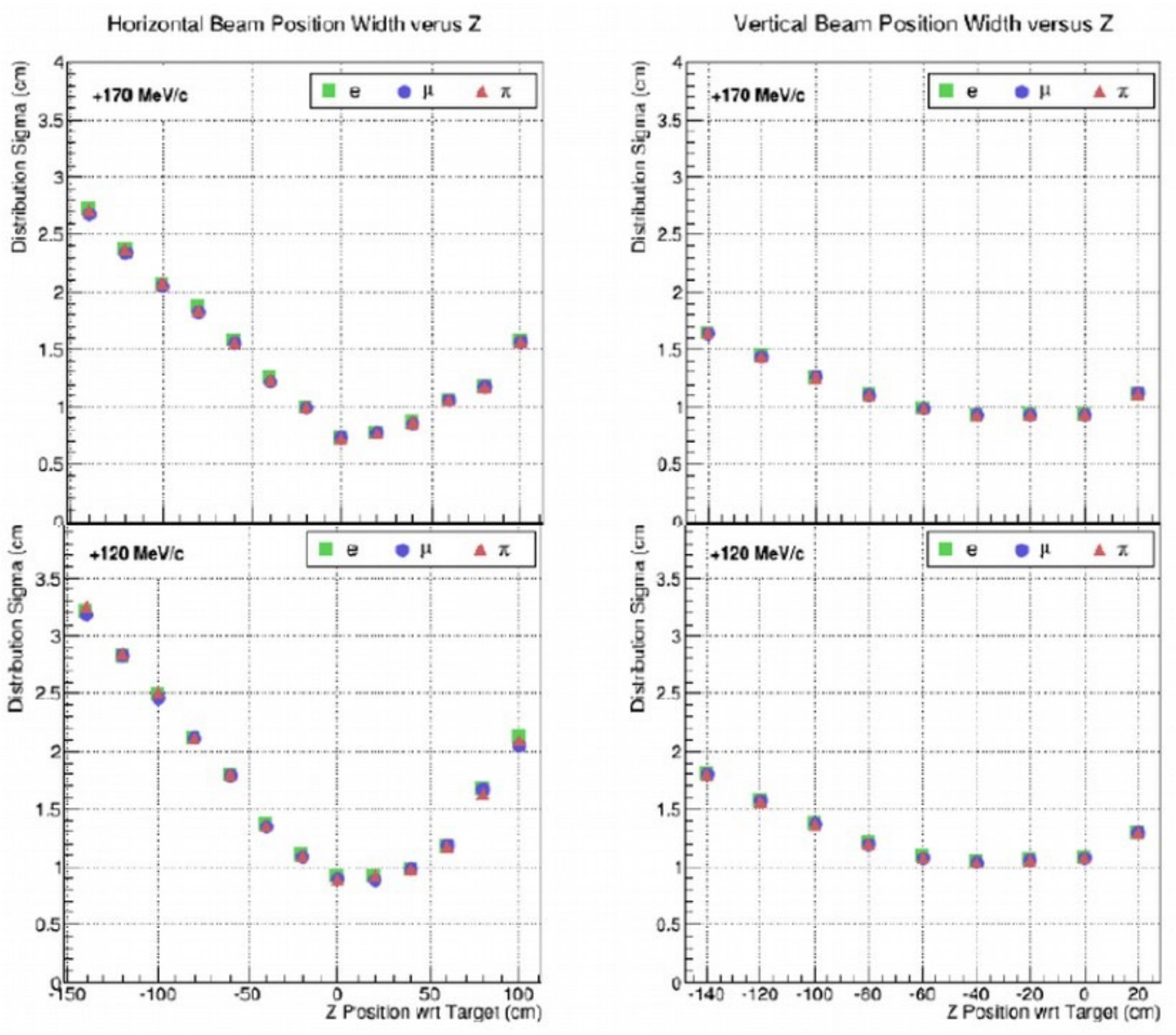


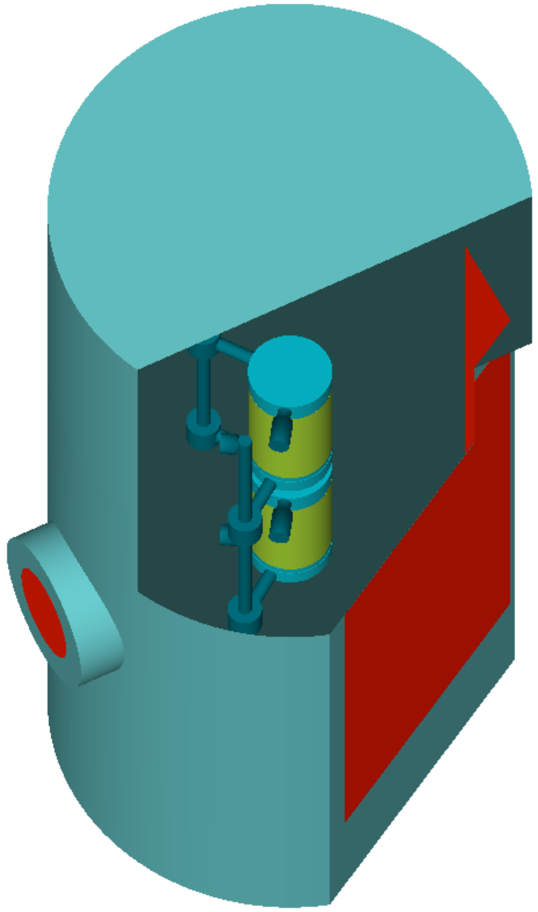
Beam composition vs. momentum – December, 2013

Negative Polarity Particle Fractions



3D Beam Tomography

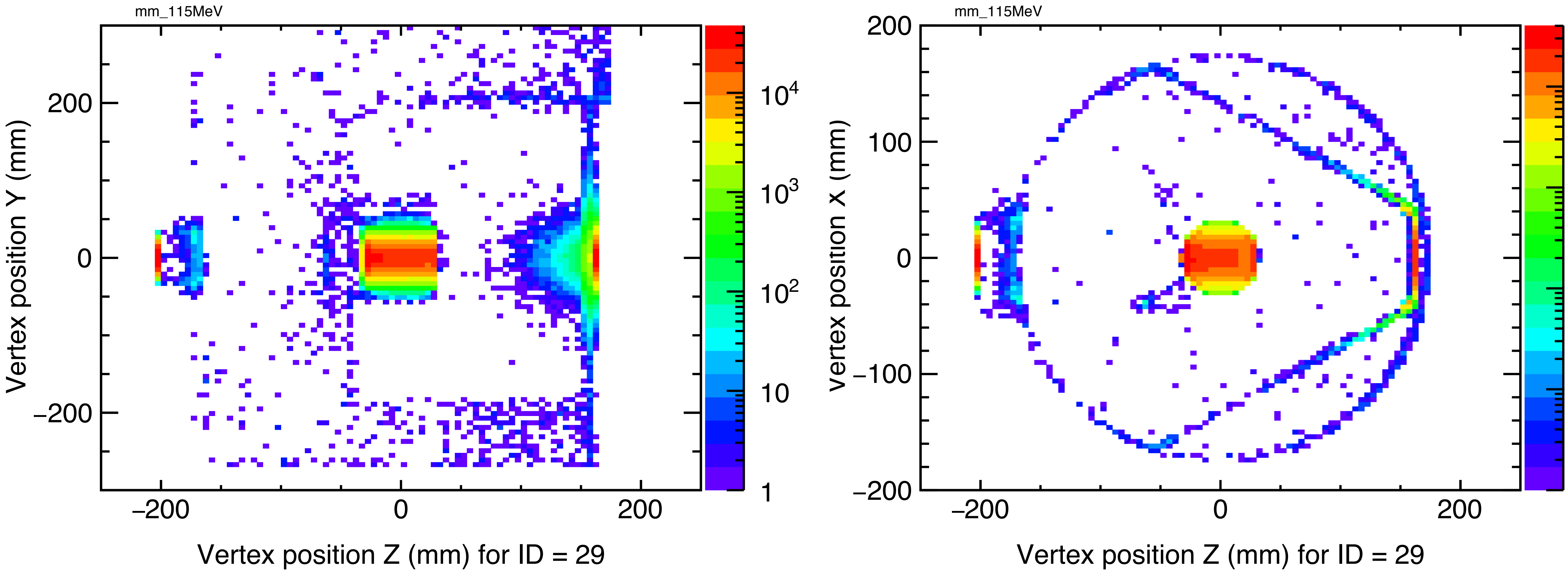




Simulations (USC)

1. The latest conceptual design of the scattering chamber and target cells was implemented and studied.

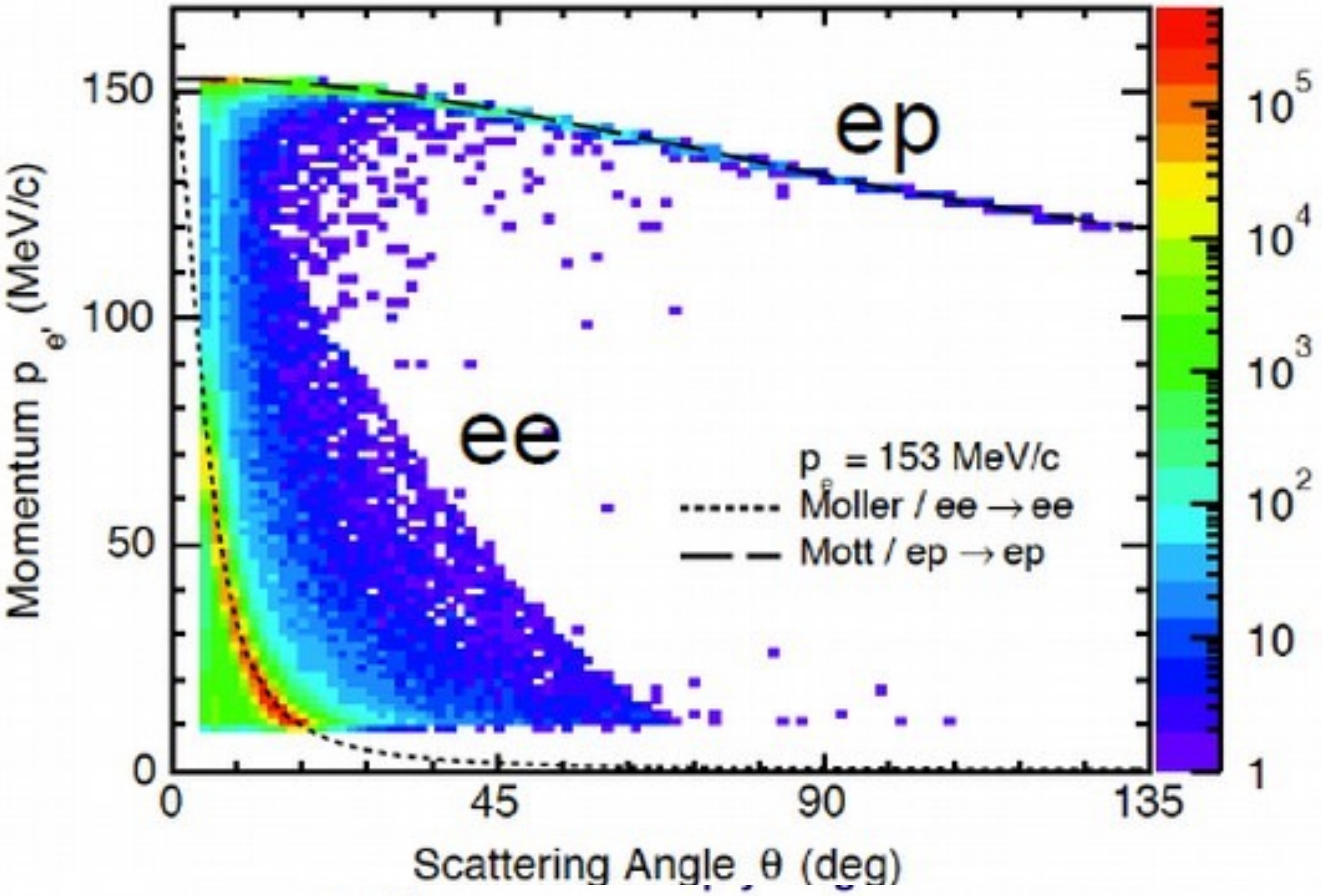
115 MeV/c μ^-p

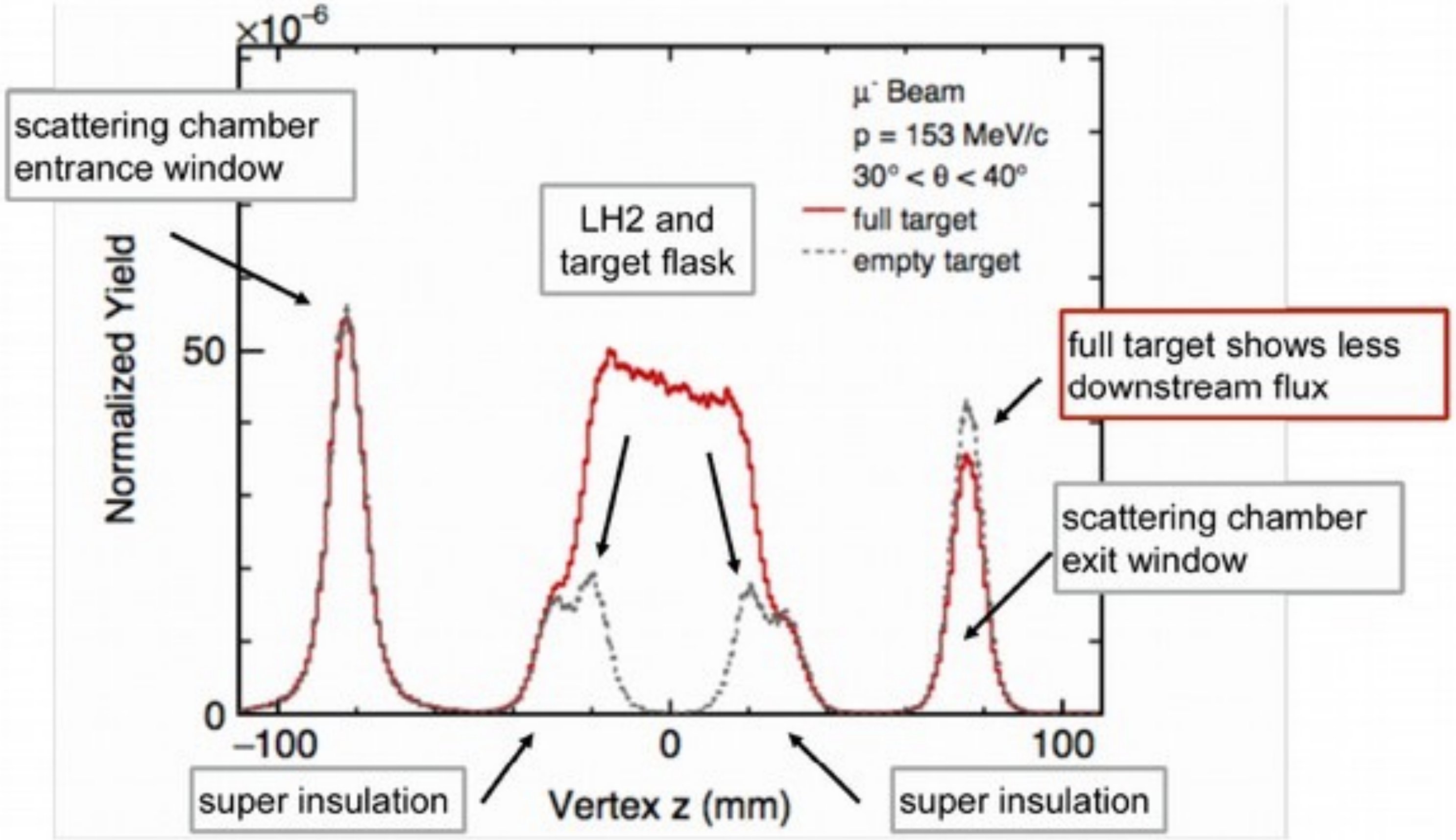


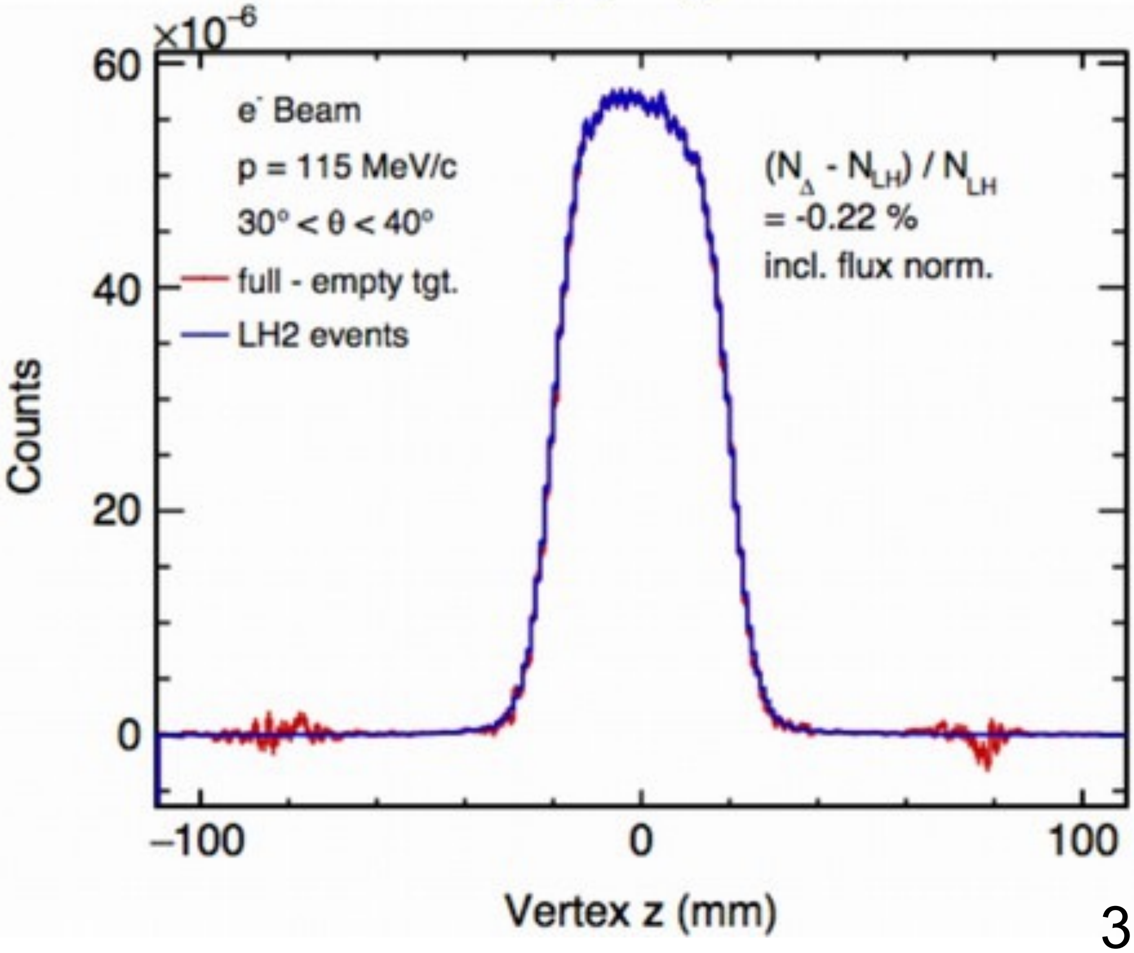
scattered particles with > 10 MeV/c at >10°, no veto signal

Simulations (USC)

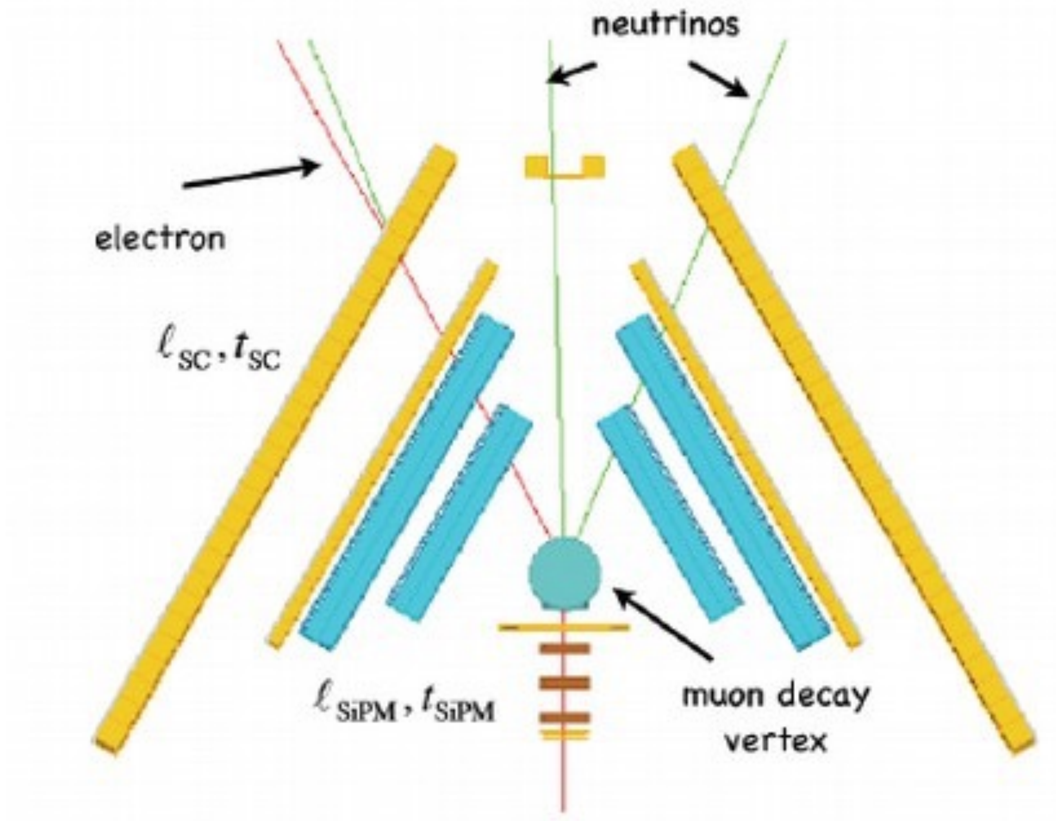
- Particle vertex and scattering angle reconstruction meet MUSE requirements
- Background from target walls and windows can be cleanly eliminated or subtracted
- Simulations verified by test data

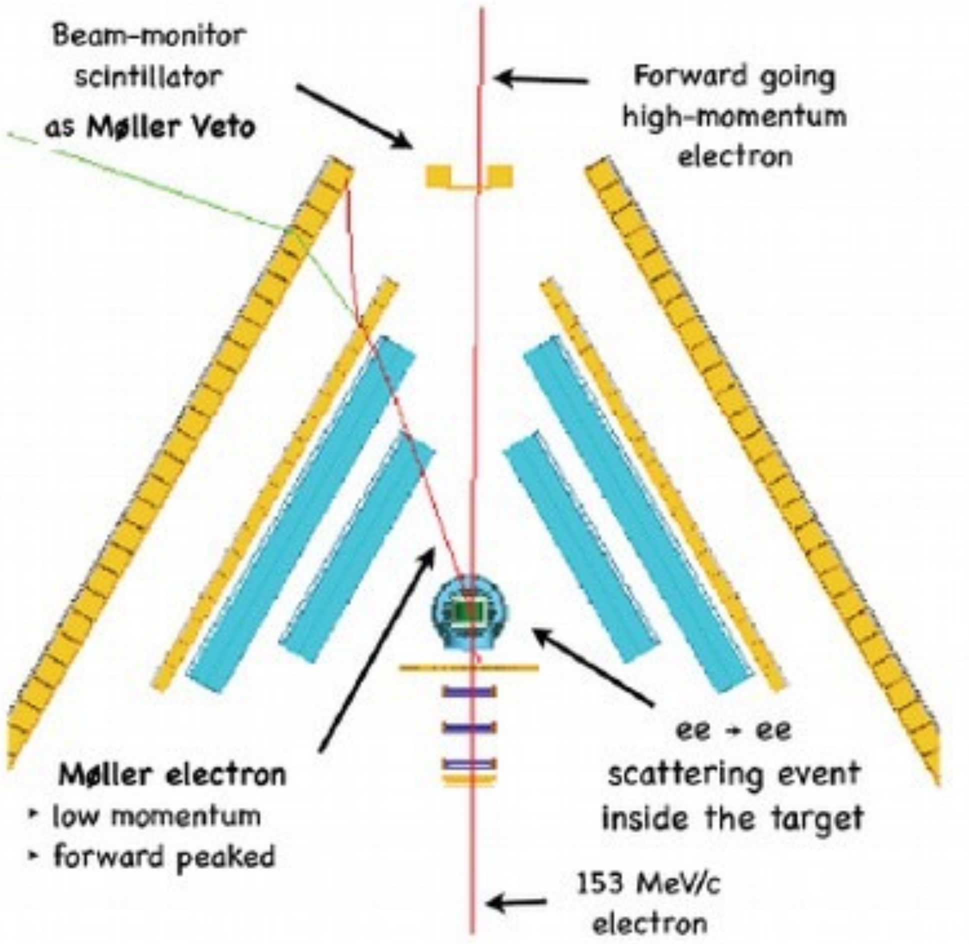






Simulations (USC)



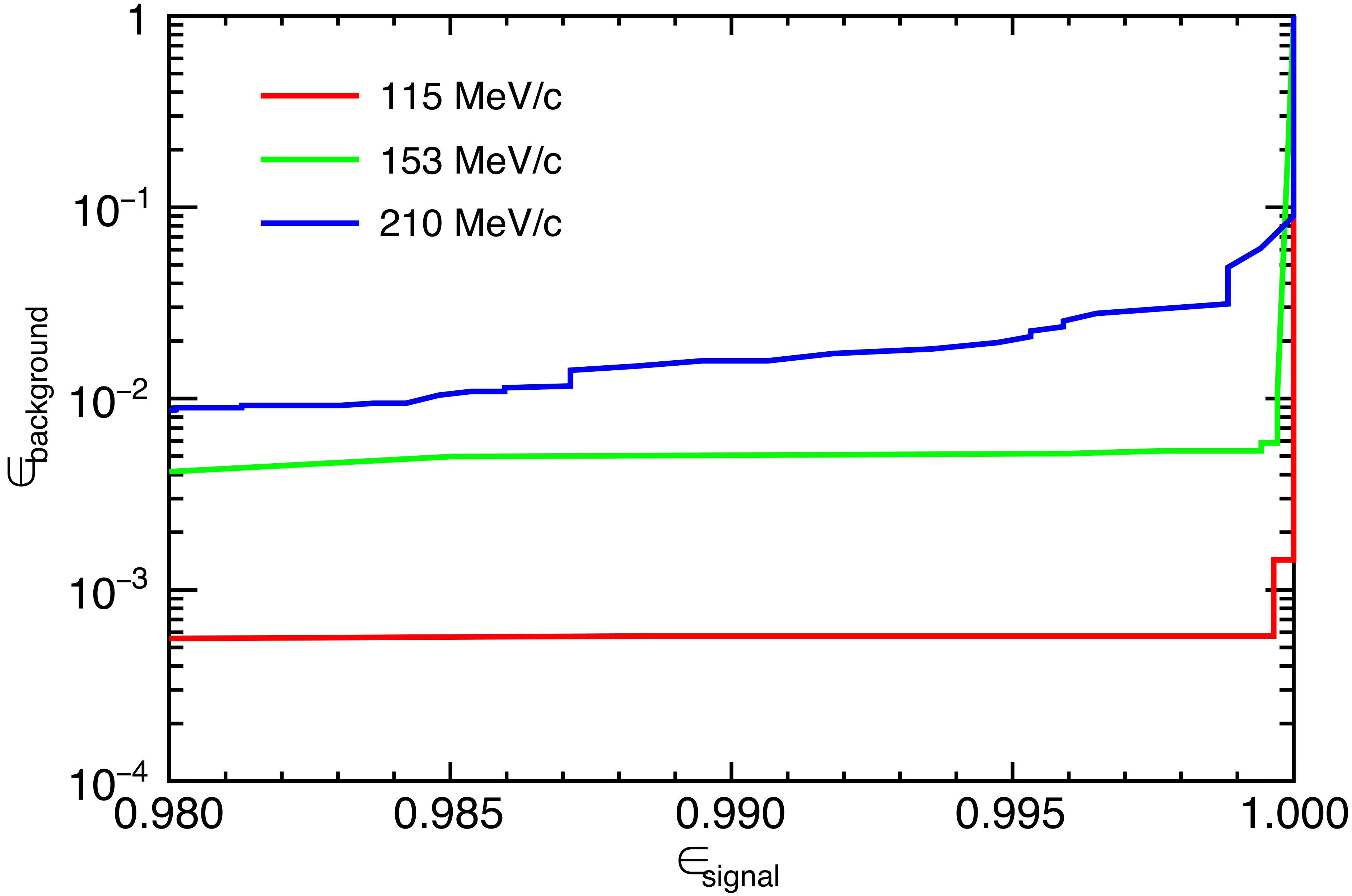


- Muon decays in flight can be removed with time-of-flight measurements

- Moeller/Bhabba events generally do not trigger the DAQ; those that do can be suppressed with veto from the beamline monitor detector

Simulations (USC)

Simulation of efficiency for including muon decay background vs. including muon elastic scattering, with reactions identified by neural net



The Cross Section

$$\left[\frac{d\sigma}{d\Omega}\right] = \left[\frac{d\sigma}{d\Omega}\right]_{ns} \times \left[\frac{G_E^2(Q^2)+\tau G_M^2(Q^2)}{1+\tau} + \left(2\tau - \frac{m^2}{M^2}\right) G_M^2(Q^2)\frac{\eta}{1-\eta}\right]$$

$$\left[\frac{d\sigma}{d\Omega}\right]_{ns} = \frac{\alpha^2}{4E^2}\frac{1-\eta}{\eta^2}\frac{1/d}{\left[1+\frac{2Ed}{M}\sin^2\frac{\theta}{2}+\frac{E}{M}(1-d)\right]}$$

$$\tau = Q^2/4m^2$$

following Preedom & Tegen, PRC36, 2466 (1987)

$$\eta = Q^2/4EE'$$

$$d = \frac{\left[1-\frac{m^2}{E^2}\right]^{1/2}}{\left[1-\frac{m^2}{E'^2}\right]^{1/2}}$$

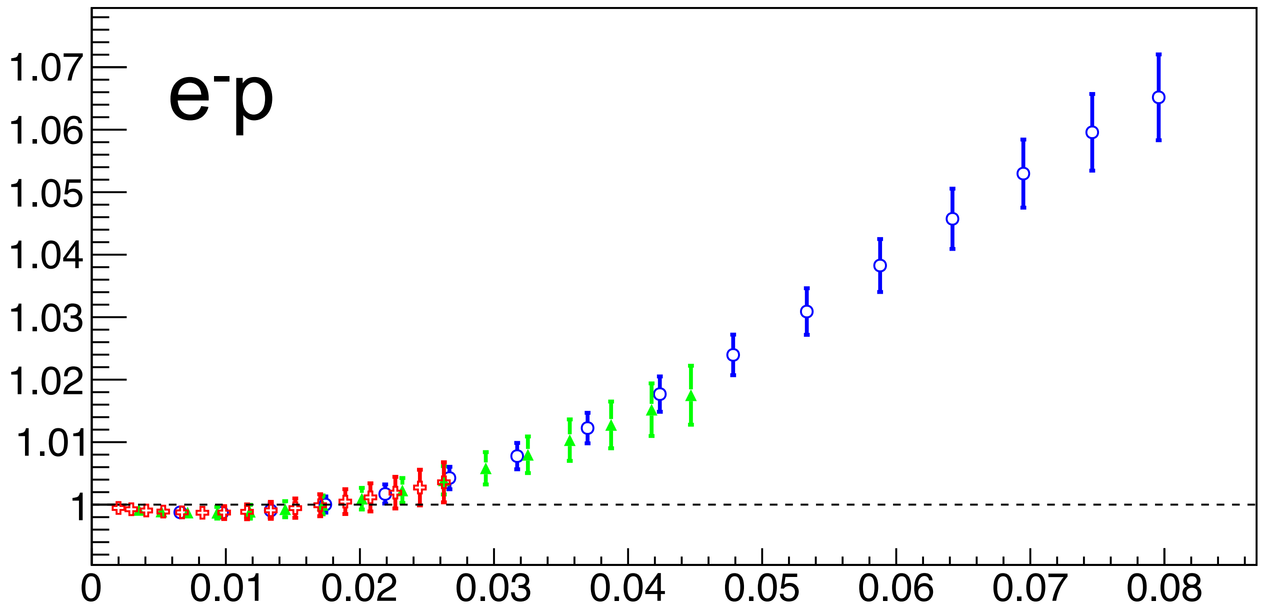
115 MeV/c

153 MeV/c

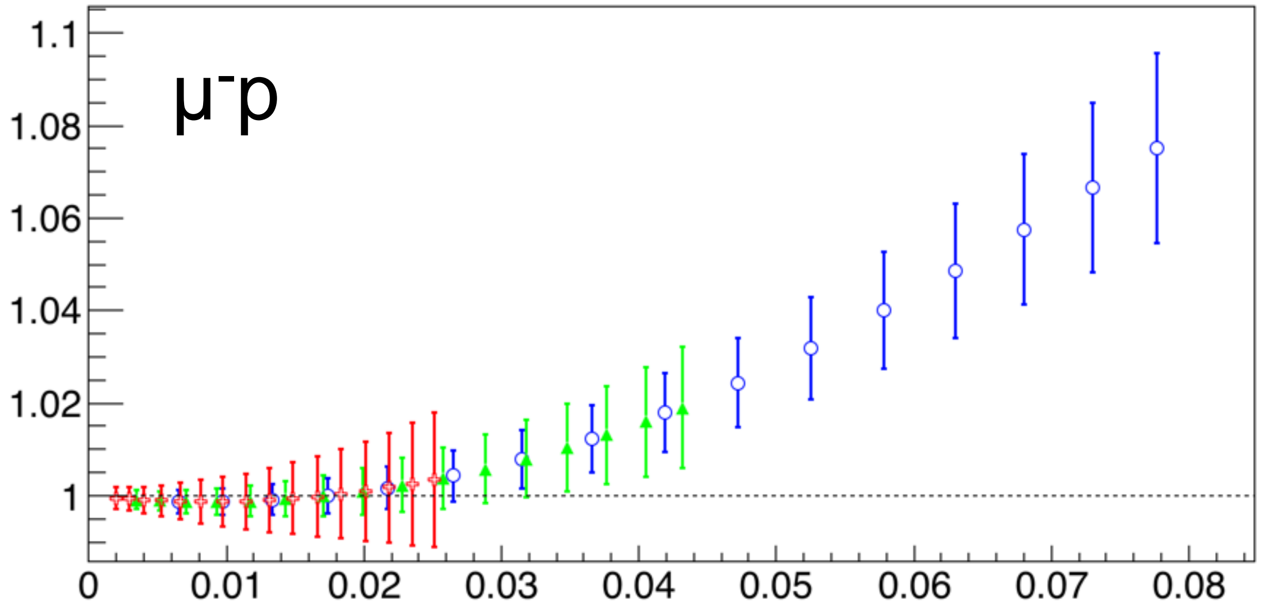
210 MeV/c

Statistical Results

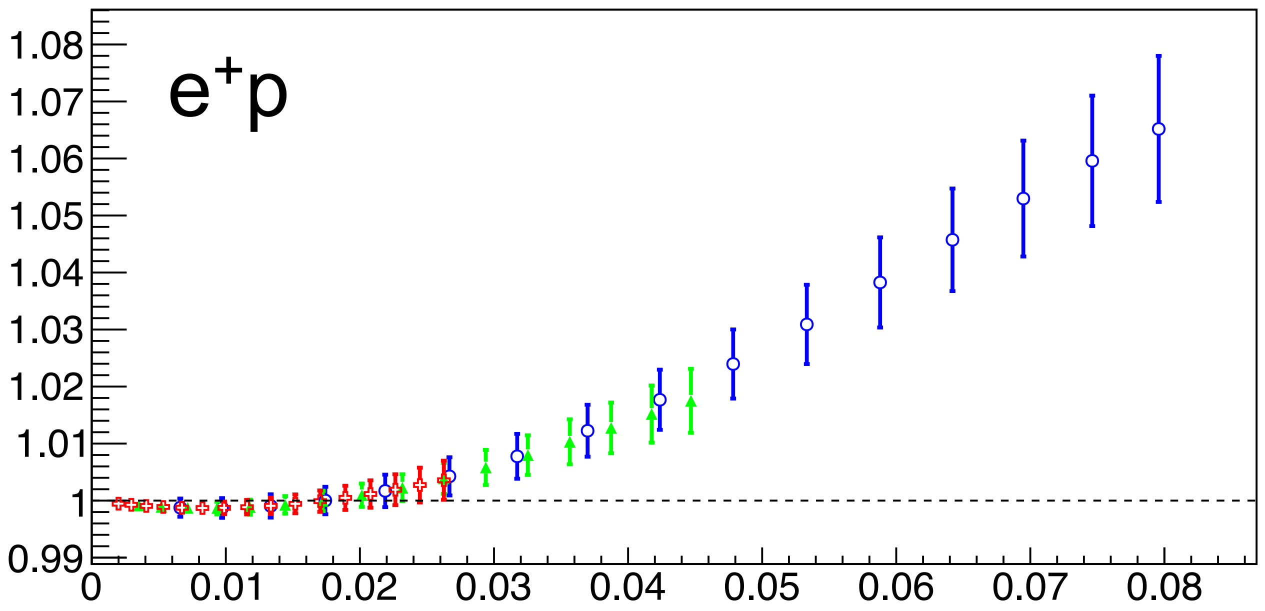
$\sigma_{Kelly}/\sigma_{r=0.842}$ vs Q^2 (GeV^2) e^-p



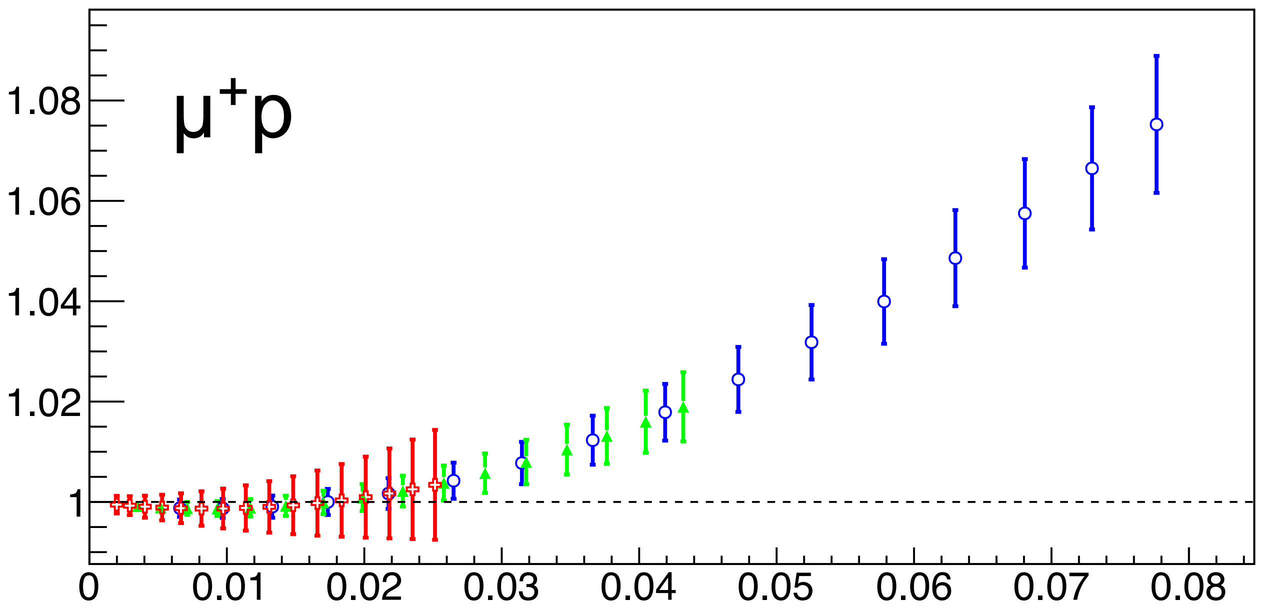
$\sigma_{Kelly}/\sigma_{r=0.842}$ vs Q^2 (GeV^2) μ^-p



$\sigma_{Kelly}/\sigma_{r=0.842}$ vs Q^2 (GeV^2) e^+p



$\sigma_{Kelly}/\sigma_{r=0.842}$ vs Q^2 (GeV^2) μ^+p



Relative Systematic Uncertainties List

These are relative (point-to-point within data set) uncertainties for ep or μp - uncertainties that change the angular distribution shape.

$d\sigma/d\Omega(Q^2)$ = counts / ($\Delta\Omega$ x N_{beam} x N_{target}/area x Corrections x Efficiencies)

1. Efficiencies
    1. SiPM ≈0%
    2. GEMs - detection & tracking efficiency ≈0%
    3. veto ≈0%*
    4. straw tubes ≈0%
    5. scintillators 0.1%
    6. monitor ≈0%*
    7. electronics / trigger 0%^
    8. detector stability ≈0%^
2. Solid angle $\Delta\Omega$ 0.1%
3. N_{beam} ≈0%
4. N_{target}/area ≈0%
5. Corrections
    1. θ offset 0.2% max
    2. Mult scat 0.15% max
    3. Target interactions 0%
    4. Energy offset 0.1%
    5. Radiative corrections 0.5% for e, 0.1% for μ
    6. Mass / kinematics 0.15%
6. Background subtraction
    1. Muon decay in flight 0.1%
    2. Target walls 0.3%
    3. Pion induced events 0%
    4. Beam PID mis-ID 0.1%
    5. Cuts 0%*

* small, from initial Geant4 studies

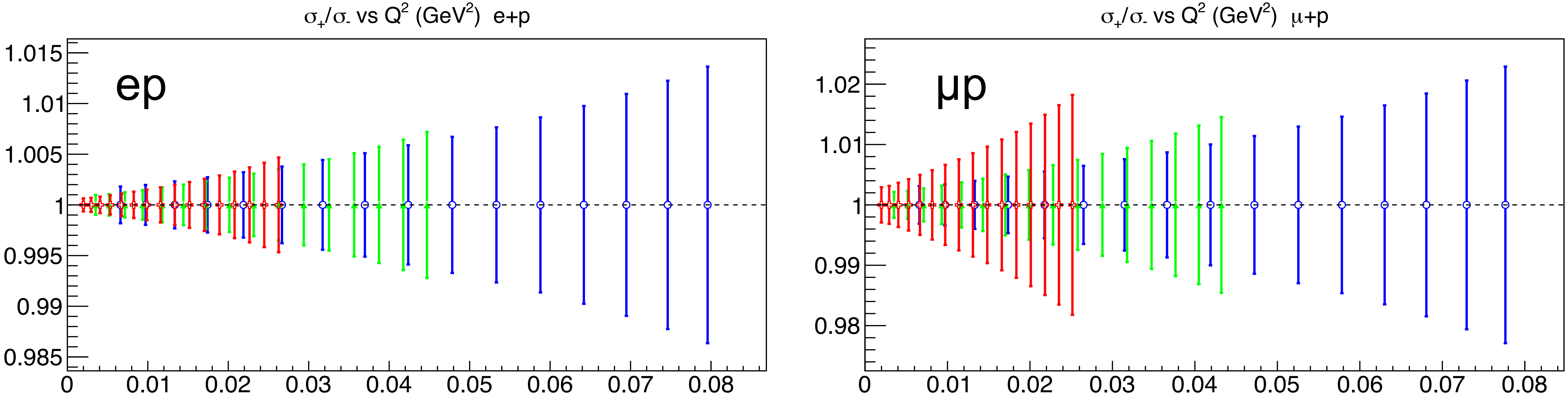
^ need to prove in practice

115 MeV/c

153 MeV/c

210 MeV/c

Statistical Results



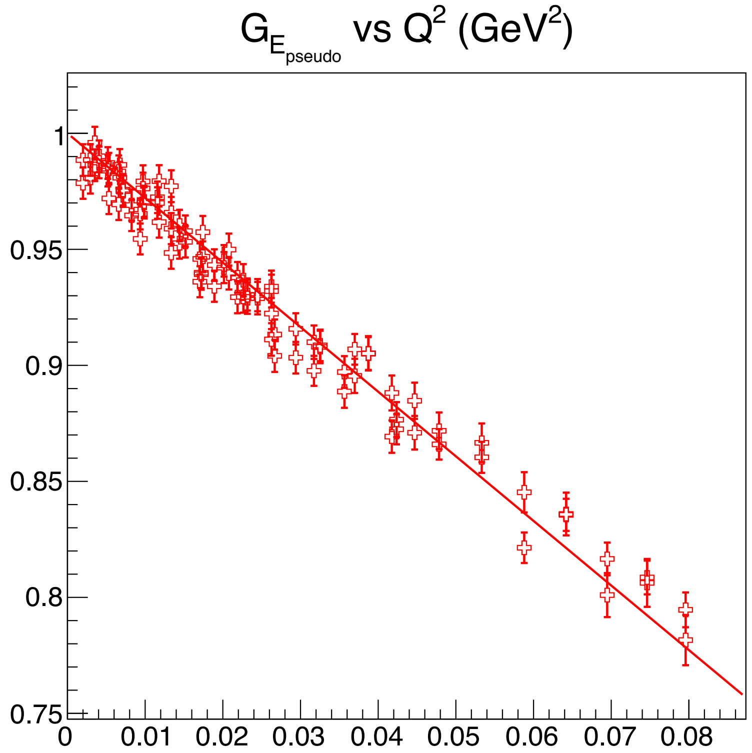
Systematics for ep ≈ 0.2%

Systematics for μp ≈ 0.2%

Conventional theoretical estimate: 1% TPE.

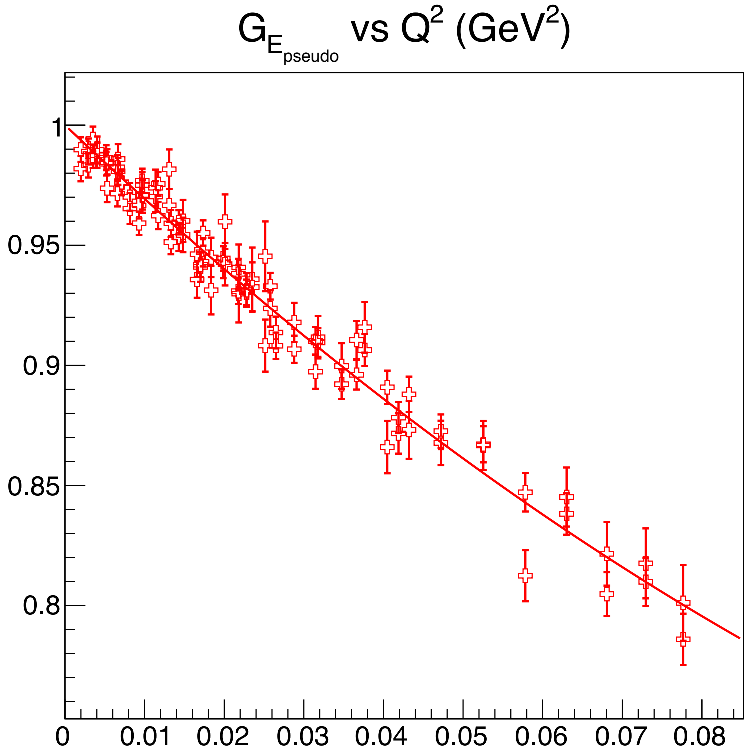
Radius Extractions

A problem with many (often poor) solutions



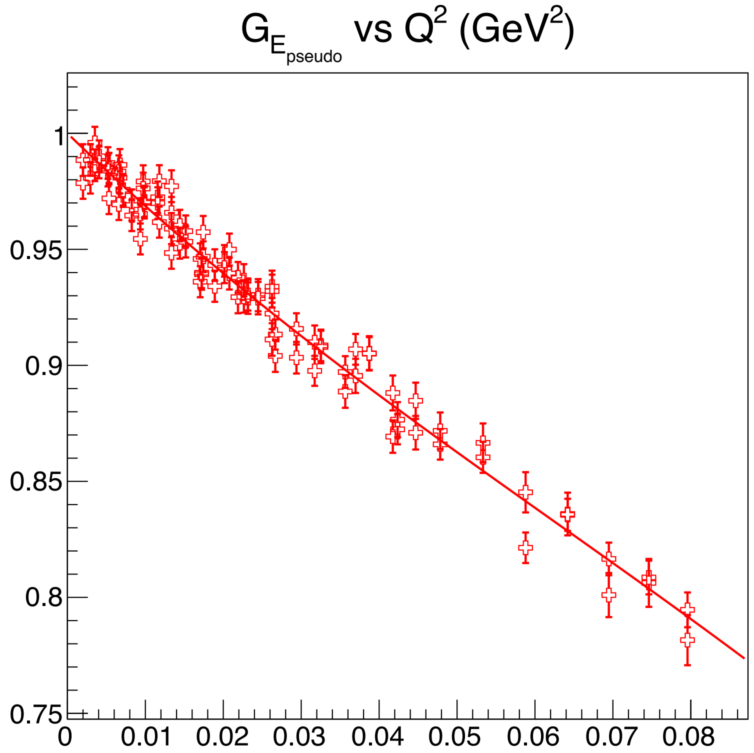
ep 1st order

Bad χ^2



μp 2nd order

Just right!



ep 3rd order

Big uncertainties

Our data range more or less limits us to 2 parameter fits.

And all the consequent issues.

How to Compare μp vs ep?

- Truncation error (offset) cancels for μp and ep, since they have (about) the same Q^2 range.
- Best statistical uncertainties for 1st-order fit, so…

Generating fit / analyzing fit	ep offset (fm)	ep uncertainty (fm)	μp offset (fm)	μp uncertainty (fm)	truncation offset difference
Kelly / polynomial	-0.0527	0.0034	-0.0505	0.0027	-0.0022
Arrington / polynomial	-0.0369	0.0035	-0.0355	0.0028	-0.0014
Bernauer / polynomial	-0.0725	0.0034	-0.0696	0.0027	-0.0029
Dipole / polynomial	-0.0384	0.0036	-0.0367	0.0029	-0.0017
Kelly / inv. polynomial	0.0080	0.0042	0.0074	0.0033	0.0007
Arrington /inv. polynomial	0.0189	0.0043	0.0178	0.0034	0.0012
Bernauer / inv. polynomial	-0.0101	0.0042	-0.0101	0.0033	-0.0001
Dipole / inv. polynomial	0.0134	0.0044	0.0125	0.0035	0.0009

How to Compare μp vs ep?

- Truncation error (offset) cancels for μp and ep, since they have (about) the same Q^2 range.
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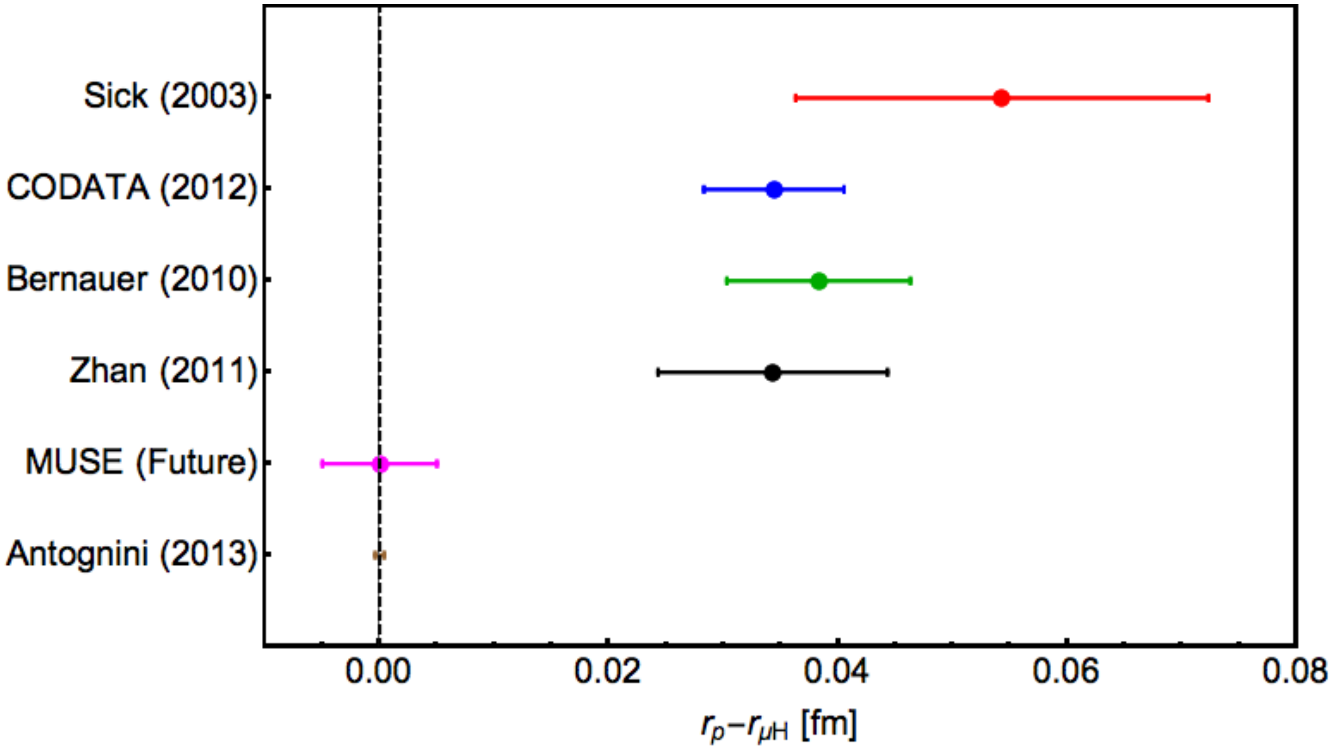
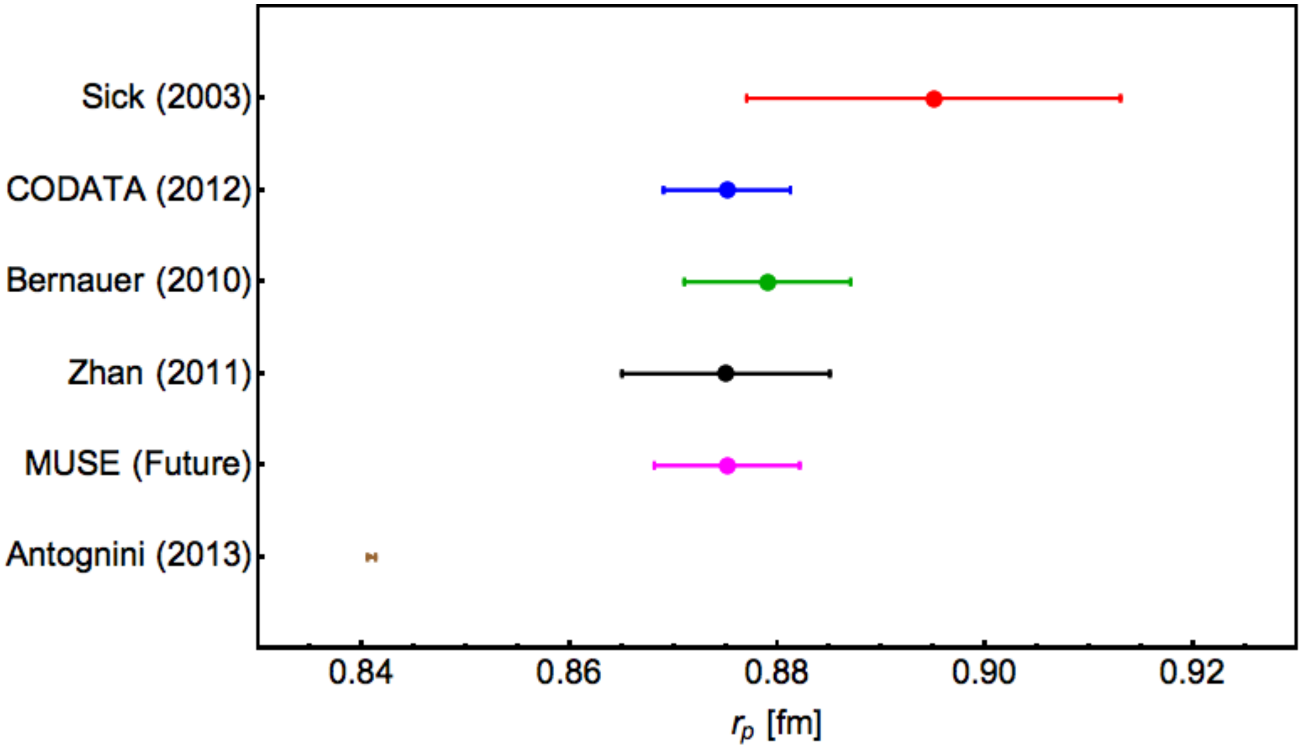
Generating fit / analyzing fit	ep offset (fm)	ep uncertainty (fm)	μp offset (fm)	μp uncertainty (fm)	truncation offset difference
Kelly / poly	-0.0527	0.0034	-0.0505	0.0027	-0.0022
Arri poly					014
Berr poly					029
Di poly					017
Kelly / inv. polynomial	0.0080	0.0042	0.0074	0.0033	0.0007
Arrington /inv. polynomial	0.0189	0.0043	0.0178	0.0034	0.0012
Bernauer / inv. polynomial	-0.0101	0.0042	-0.0101	0.0033	-0.0001
Dipole / inv. polynomial	0.0134	0.0044	0.0125	0.0035	0.0009

Conclusion:
Can compare μp to ep with 1st-order IP fits, statistical uncertainties about 0.005 fm and systematic uncertainties about 0.001 fm.

Summary Results



1^{st} order IP fit for check of consistency of r_{ep} and $r_{\mu p}$. Point arbitrarily put at $r_{ep} - r_{\mu p} = 0$.*



If $r_{ep} \approx r_{\mu p}$, average the two to determine what r_p is, using 2^{nd} order IP fit.

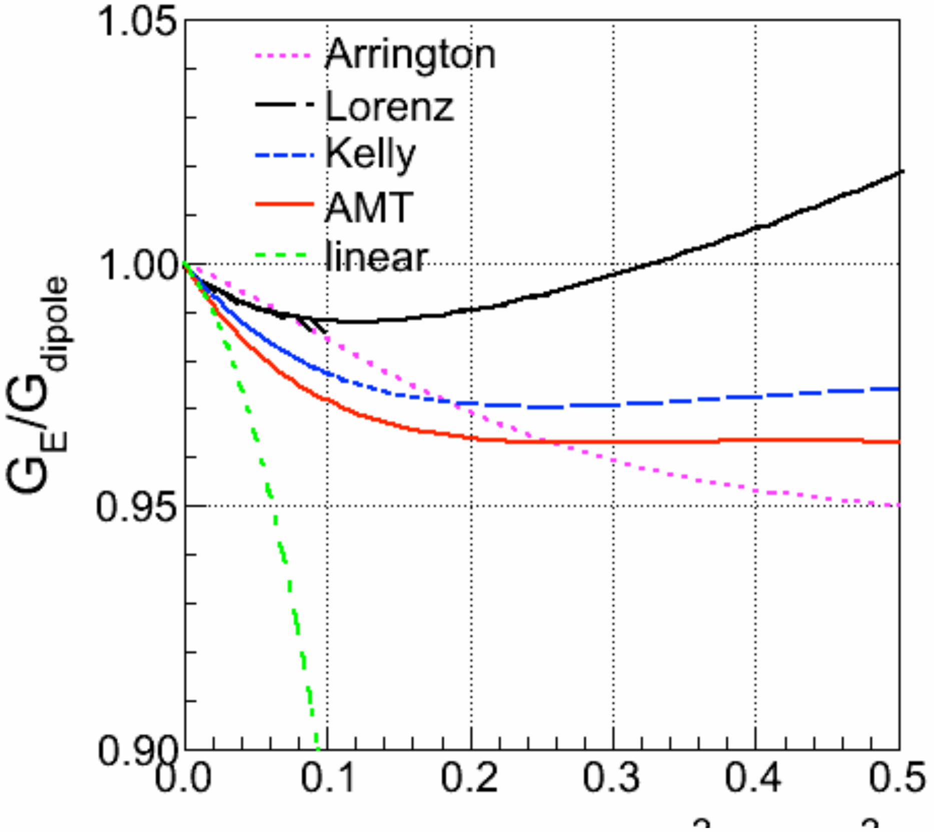
Point arbitrarily put at $r_p \approx 0.875$.

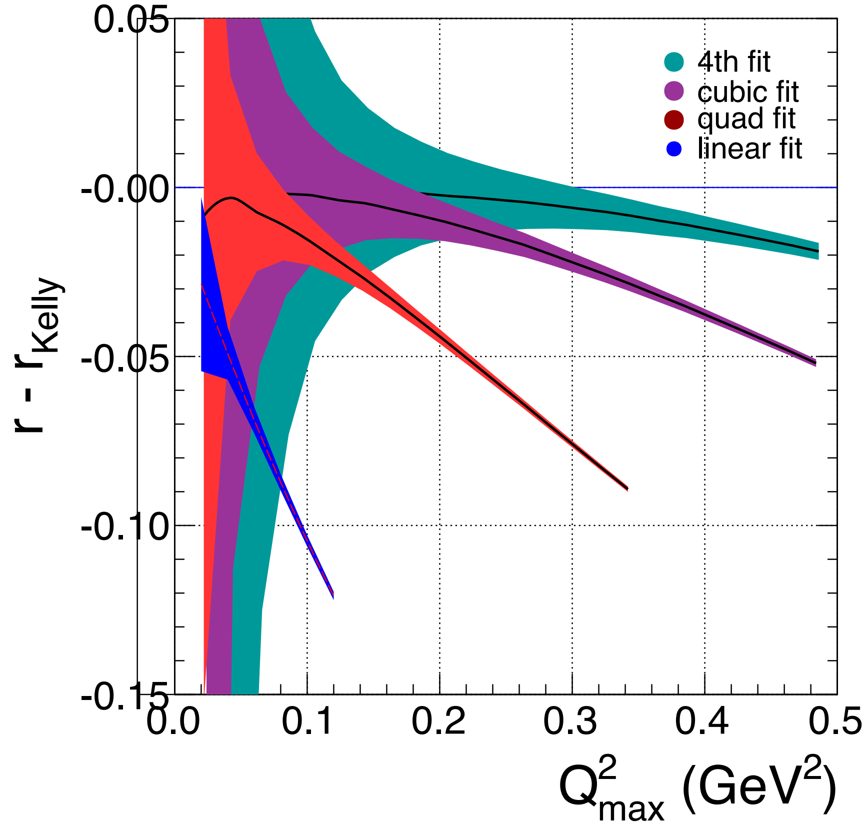
* Note: Difference in MUSE determined entirely by MUSE. Other differences are taken with respect to Antognini muonic hydrogen radius.

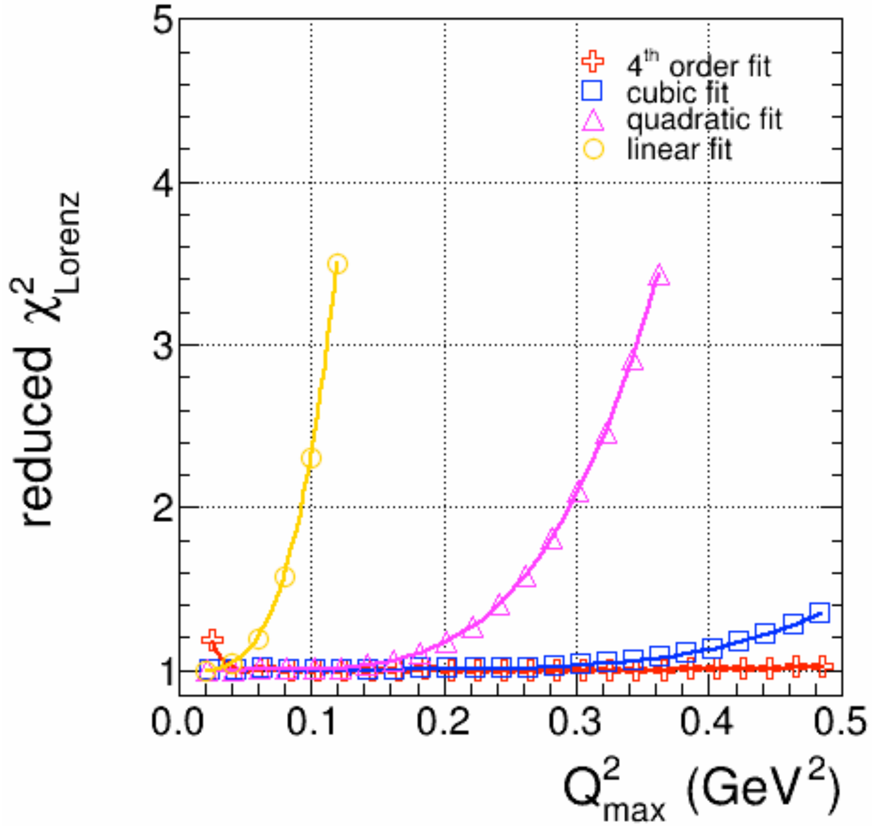
Truncation Errors

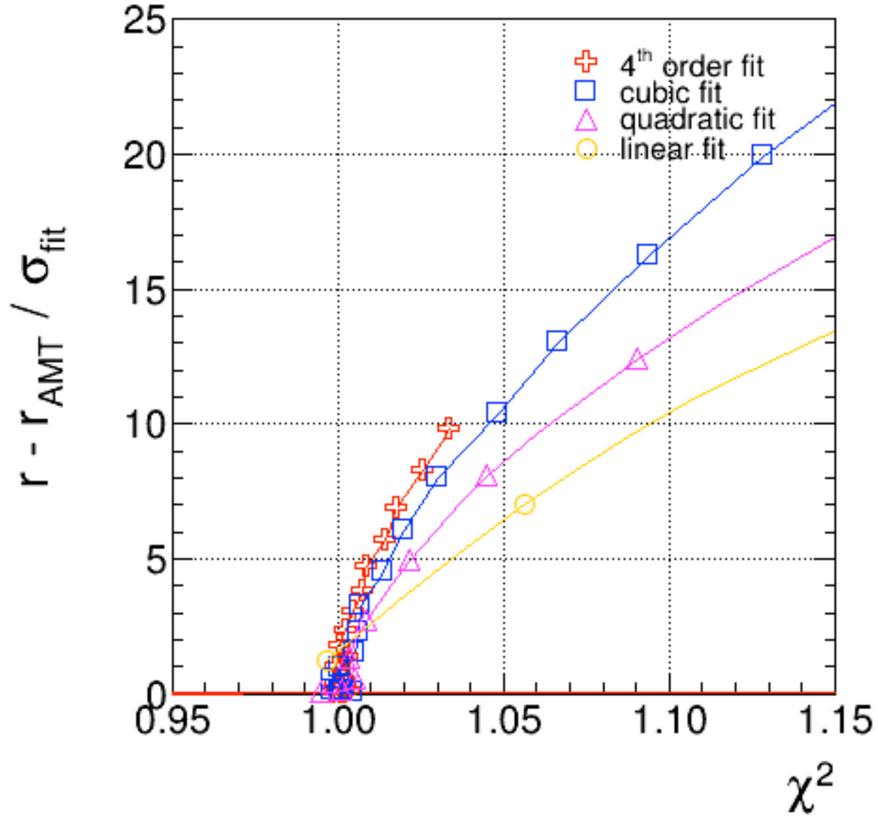
I. Sick: TE make polynomial fits unreliable

E. Kraus et al.: … and polynomial fits “always” underestimate the radius!









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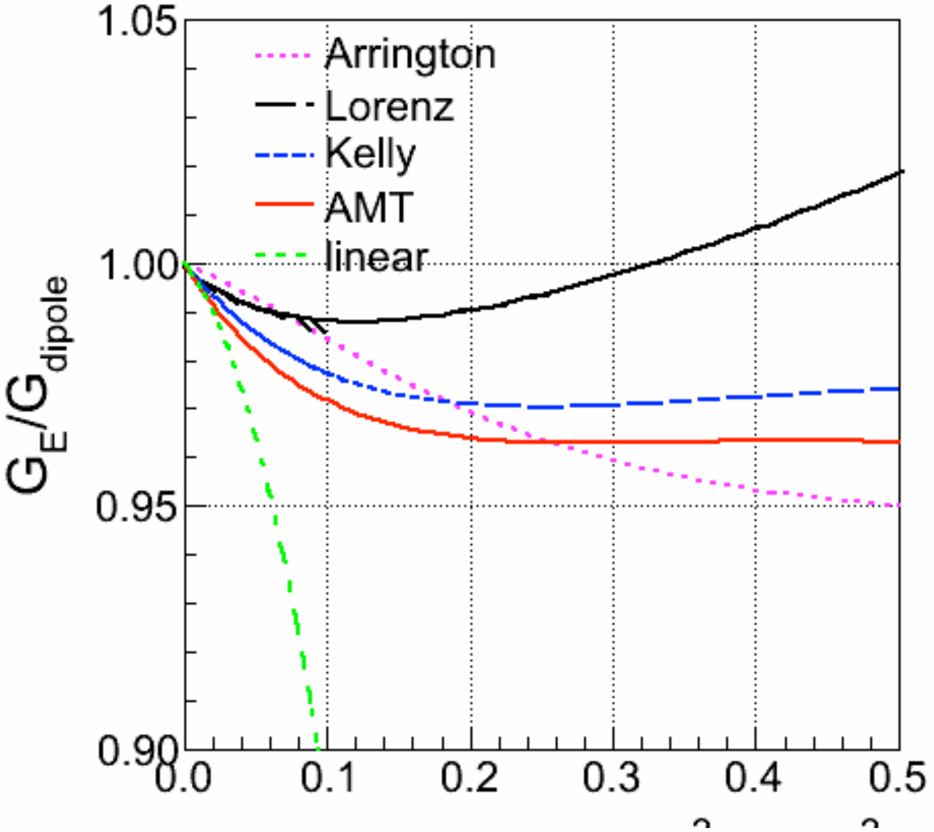
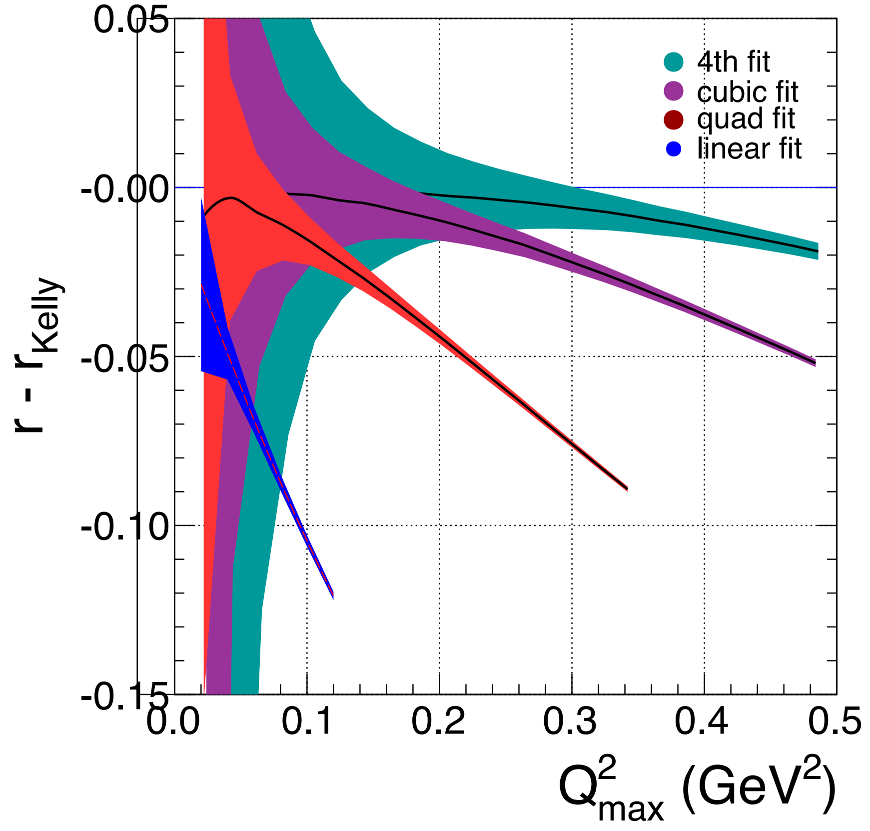
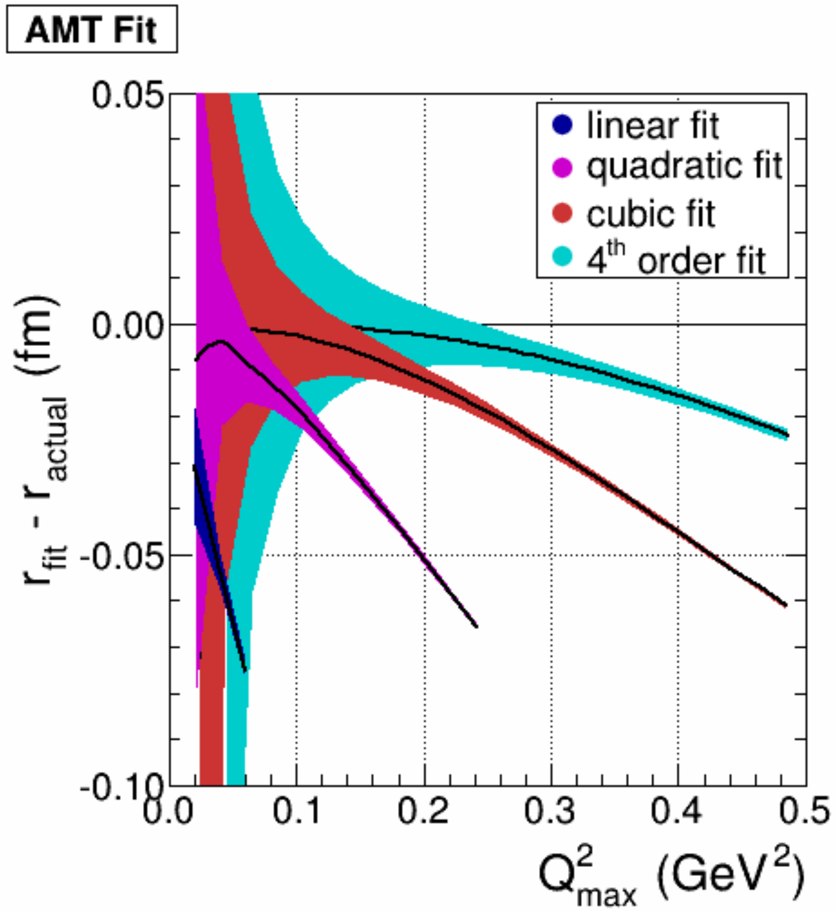
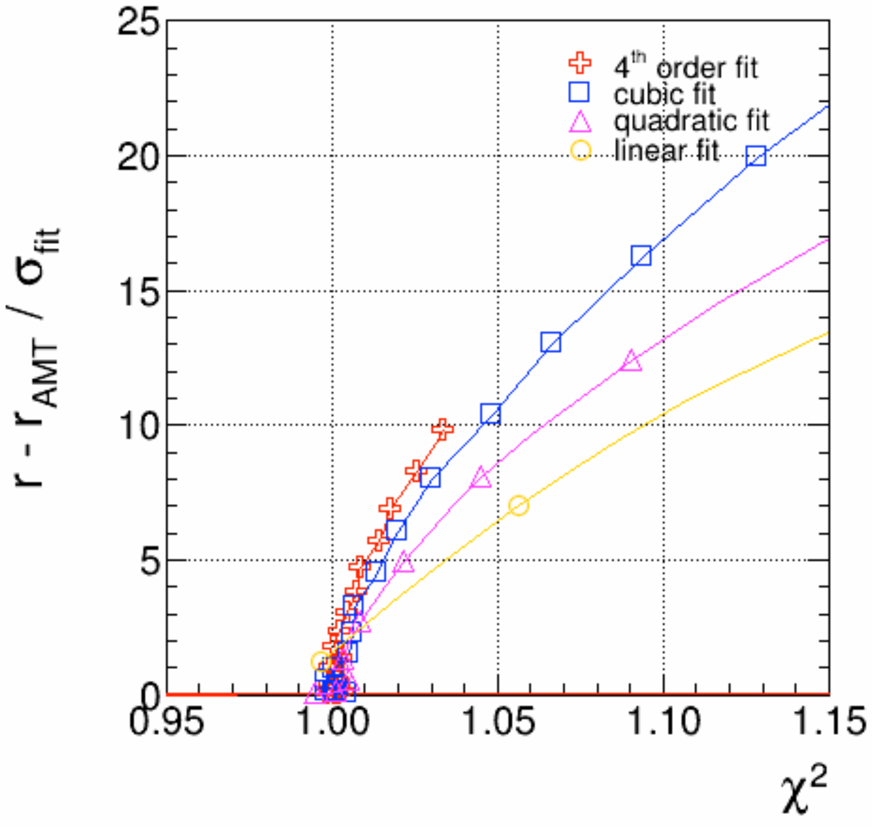








Experiment Status Summary

MUSE has either demonstrated or is within reach of meeting all technical specifications. We have measured beam properties, prototyped detectors, simulated the experiment, and studied systematics. And continue to refine the work.

PSI:

- Approved, but must pass technical-design-report review to be awarded significant beam time.

NSF:

- Has (with DOE) provided prototyping funds.
- MUSE passed technical and management reviews in February and May, 2016.
- NSF currently working on getting midscale^{++} funding – but now atomic hydrogen has led to questions.

Outlook

New results will be coming out from atomic and muonic hydrogen and PRAD in next 1-2 years

MUSE can (with funding) run in 2018-2019, and test

- lepton universality and possible new physics through cross sections, form factors and extracted radii, in a single experiment
- whether the radius is about 0.84 vs 0.88 fm
- extraction of the radius from scattering with a particle with reduced radiative corrections
- Two photon exchange, a long time issue in electron scattering, and the limiting issue (polarizibility) in muonic atom nuclear radius extractions

MUon proton Scattering Experiment - MUSE

- **55 MUSE collaborators from 24 institutions in 5 countries**

A. Afanasev, A. Akmal, J. Arrington, H. Atac, C. Ayerbe-Gayoso, F. Benmokhtar, N. Benmouna, J. Bernauer, A. Blomberg, E. Brash, W.J. Briscoe, *E. Cline*, *D. Cohen*, *E.O. Cohen*, C. Collicott, K. Deiters, J. Diefenbach, B. Dongwi, **E.J. Downie**, L. El Fassi, S. Gilad, R. Gilman, K. Gnanvo, R. Gothe, D. Higinbotham, Y. Ilieva, L. Li, M. Jones, N. Kalantarians, M. Kohl, G. Kumbartzki, *I. Lavrukhin*, J. Lichtenstadt, *W. Lin*, A. Liyanage, N. Liyanage, Z.-E. Meziani, P. Monaghan, K.E. Mesick, P. Moran, J. Nazeer, C. Perdrisat, E. Piasetzsky, V. Punjabi, R. Ransome, D. Reggiani, P.E. Reimer, A. Richter, **G. Ron**, T. Rostomyan, A. Sarty, Y. Shamai, N. Sparveris, **S. Strauch**, V. Sulkosky, A.S. Tadepalli, M. Taragin, and L. Weinstein

George Washington University, Montgomery College, Argonne National Lab, Temple University, College of William & Mary, Duquesne University, Massachusetts Institute of Technology, Christopher Newport University, Rutgers University, Hebrew University of Jerusalem,Tel Aviv University, Paul Scherrer Institut, Johannes Gutenberg-Universität, Hampton University, University of Virginia, University of South Carolina, Jefferson Lab, Los Alamos National Laboratory, Norfolk State University, Technical University of Darmstadt, St. Mary’s University, Soreq Nuclear Research Center, Weizmann Institute, Old Dominion University

Backup

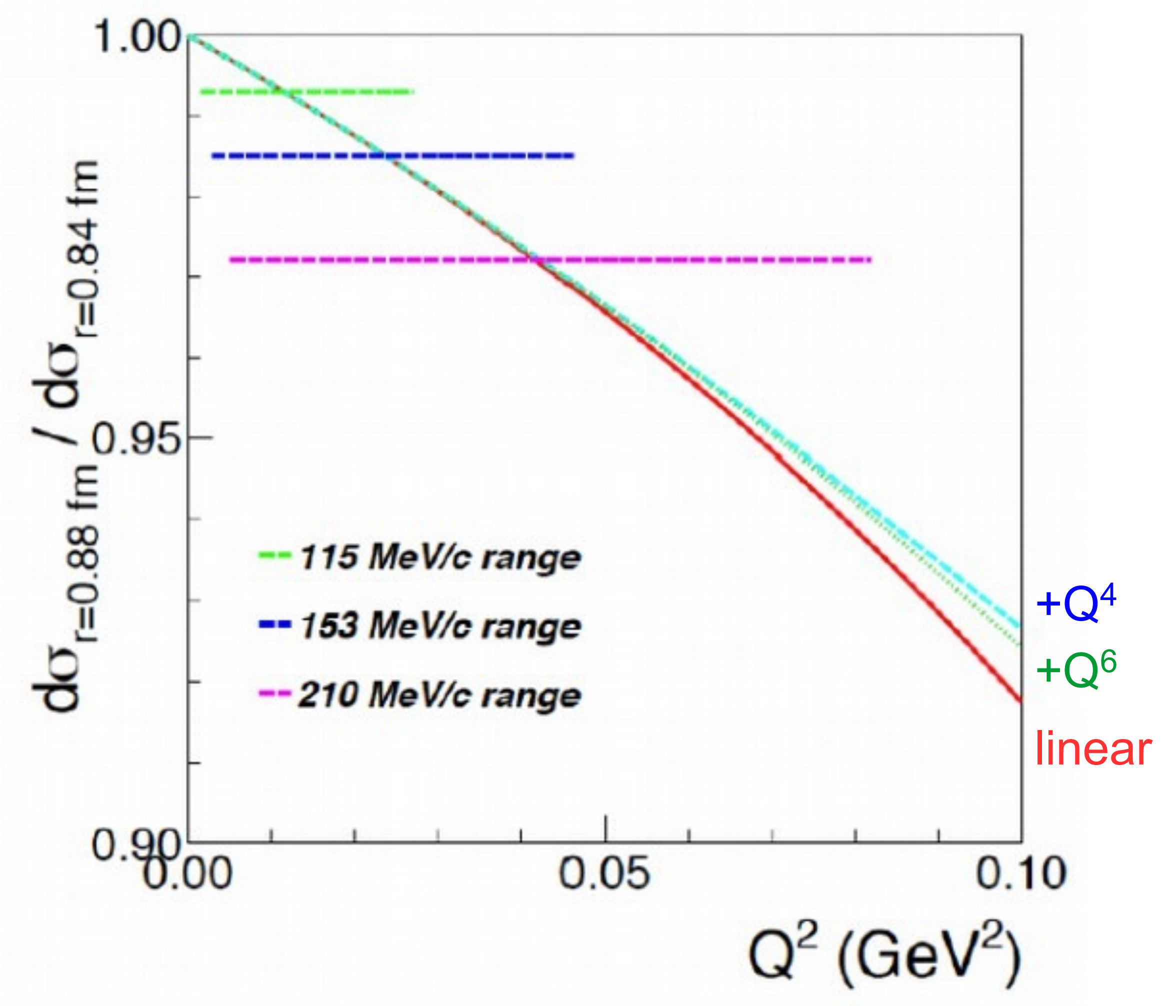
Note on Effects on Cross Section

Angle Dependence

$$\frac{d\sigma_R}{d\sigma_r} \approx \left[\frac{1 - Q^2R^2/6\ldots}{1 - Q^2r^2/6\ldots}\right]^2$$

The 0.88 vs 0.84 fm difference in radii leads to a ≈6% effect on the cross sections at our largest Q^2.

We want to keep systematic effects well below 0.01 fm, so well below a ≈1.5% variation in cross section vs angle.



JLab, Mainz plan to go to 10^{-4}.

Differences are small at low Q^2.

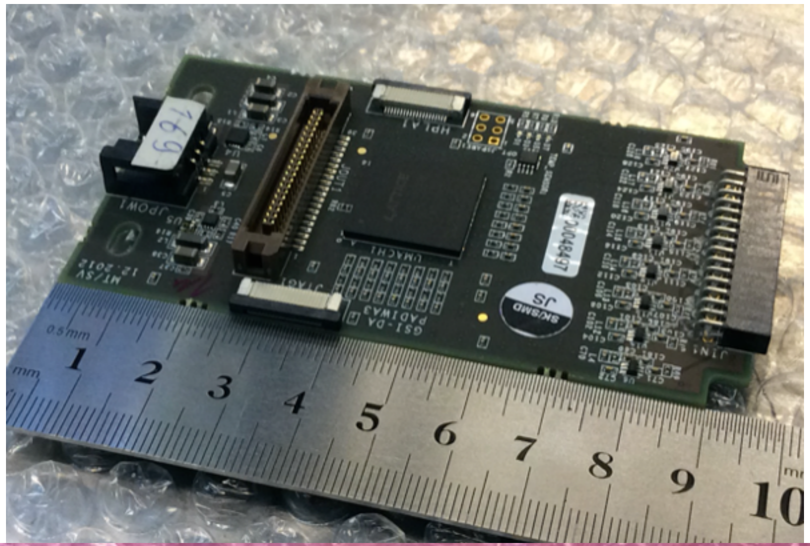
Electronics (GW)

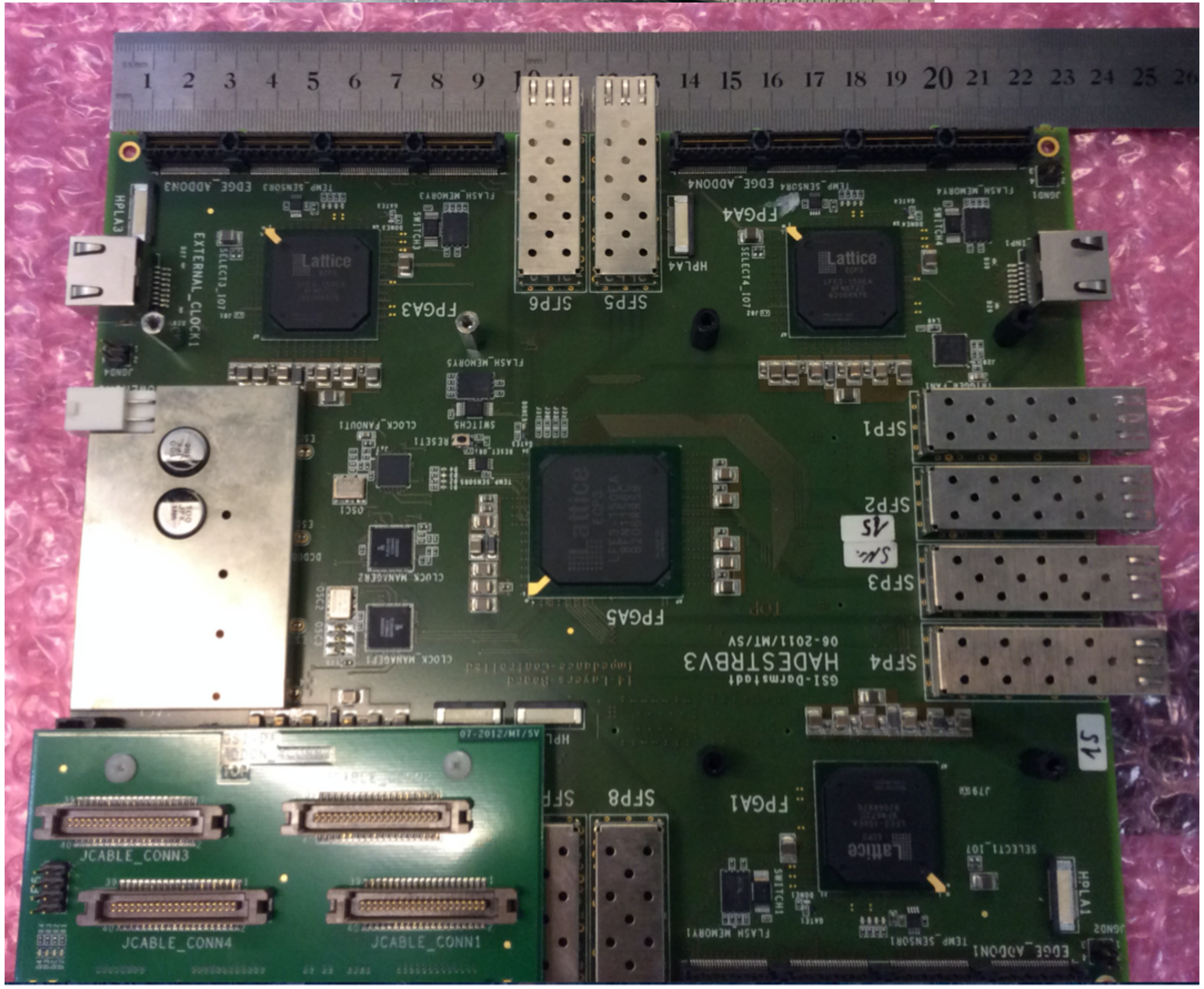
TRB3 for TDCs:
- around 10 ps resolution
- custom GSI board
- 192 channels/board
- AD with PADIWA level disc

VME QDCs for charge
- Improve level disc timing to CFD level
- MESYTEC - individual channel gates

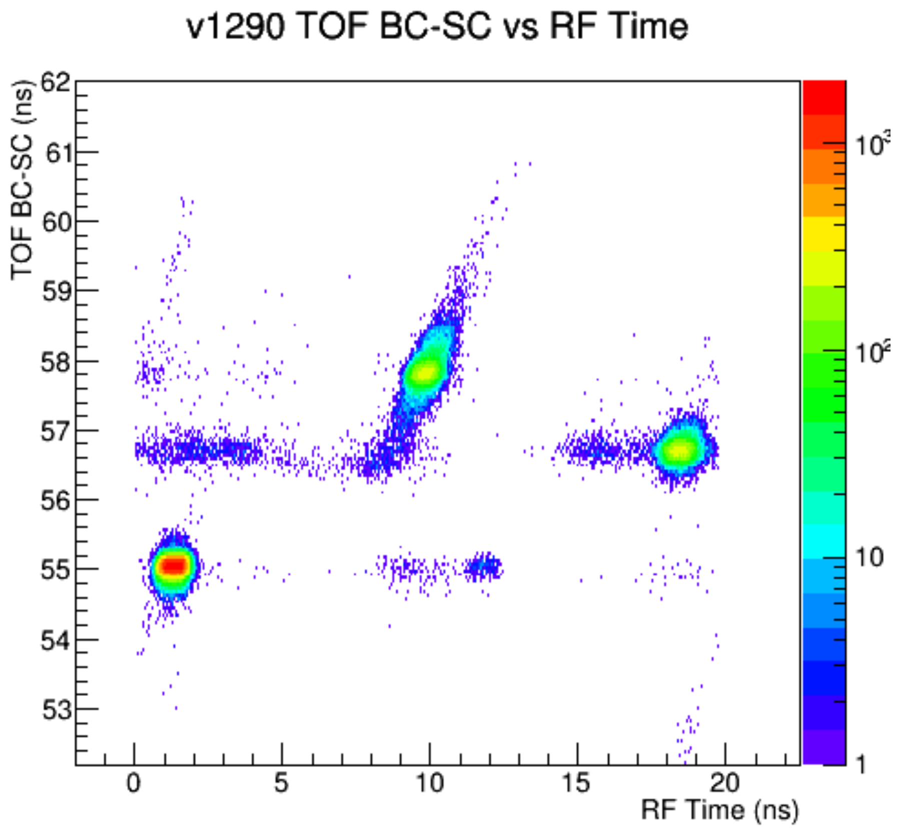
TRBs include 32-bit scalers

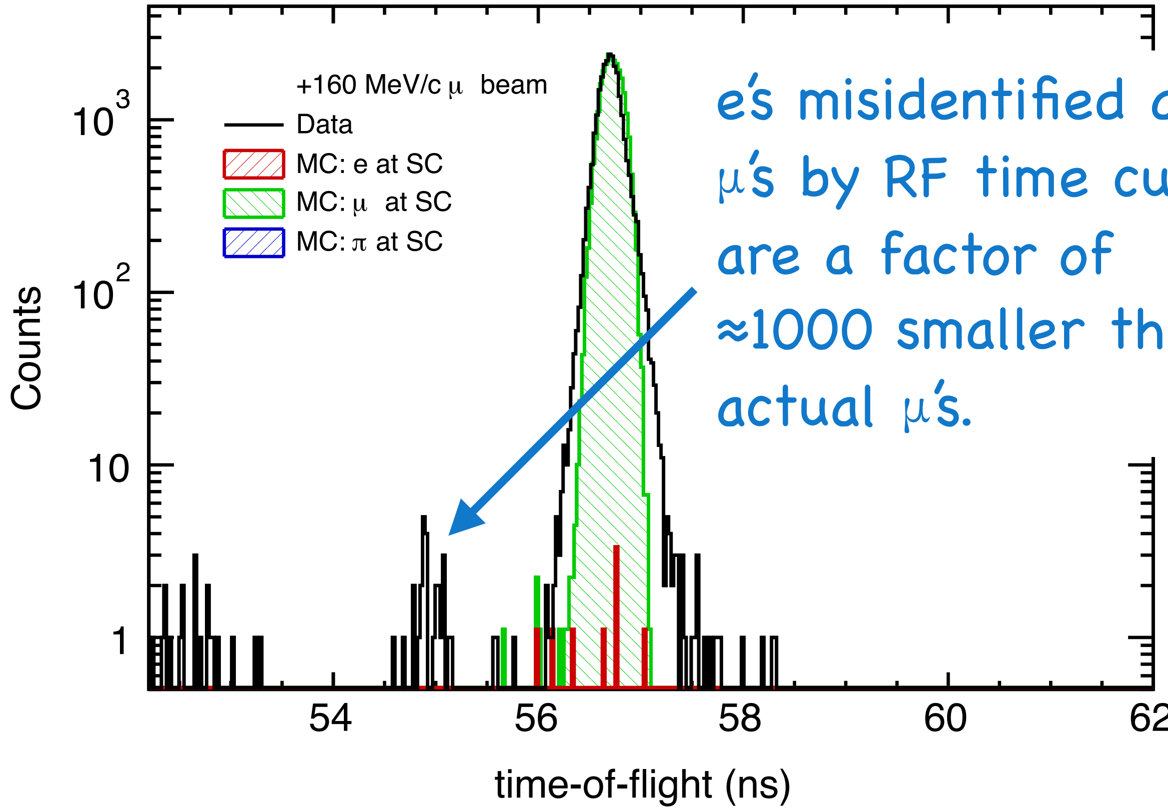
Trigger implemented on TRB FPGAs





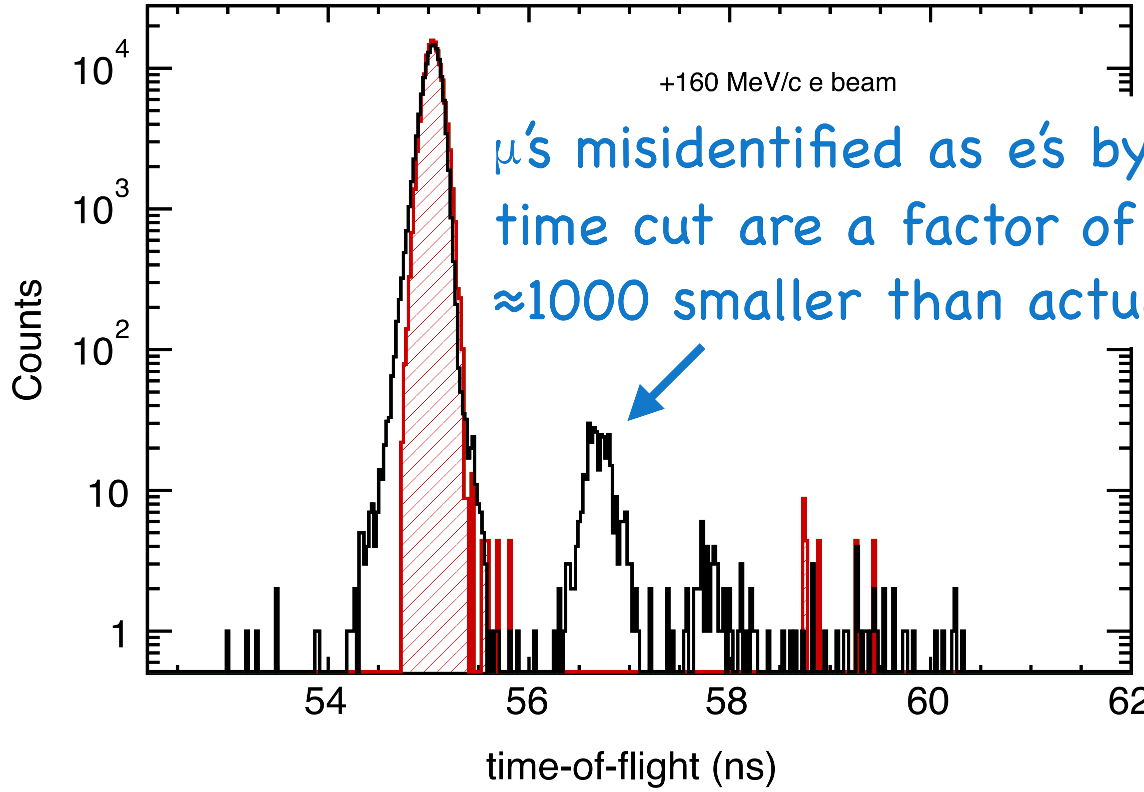
Beam Backgrounds





e's misidentified as μ's by RF time cut are a factor of ≈1000 smaller than actual μ's.

all test data vs Geant4



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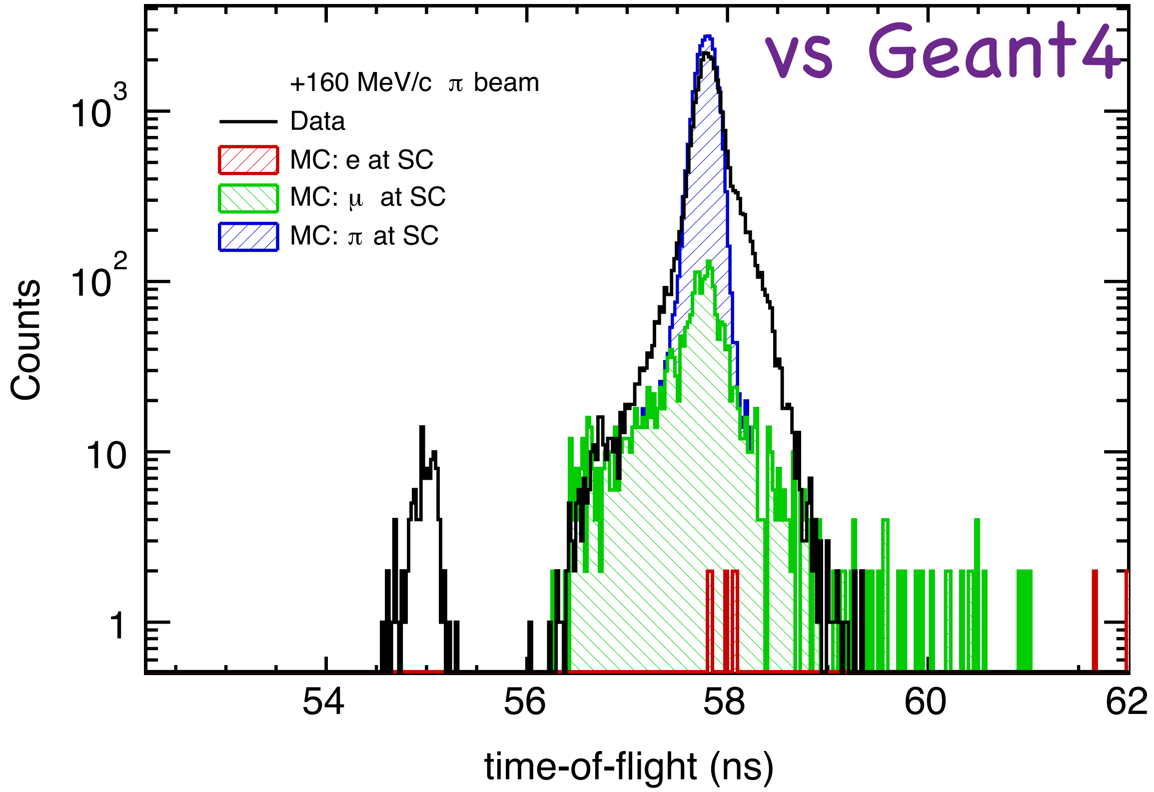

Detector Specifications needed to reach expected systematic uncertainties

Spec.	BC	SiPM	GEM	STT	Scint	Beam monitor
Time or position resolution	100 ps	100 ps (plane) for 80 ps TOF	100 μm/ GEM	150 μm/ plane → < 100 μm / STT	≈ 50 ps / 2 planes	150 ps
Positioning	≈1 mm	≈1 mm (calib. to GEMs)	defines coordinate system	0.1 mm	≈1 mm (calib. to STTs)	≈1 mm (calib. to GEMs)
Pitch / Yaw / Roll	insensitive, calib./ optim. pitch	insensitive	defines coordinate system	0.2 mr in θ, 0.5 mr for p/ y/r	≈1 mr	insensitive
efficiency (*stats only)	≈99%*	≈99%	98%*	>99% tracking	≈99%	≈99%*
Uniformity, stability	-	-	-	<0.1% eff. angle variation	<0.1% eff. angle variation	<10 ps time variation