The MUSE Experiment: Studying the Proton Radius Puzzle with μp elastic scattering

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Rutgers University

NUFACT2014
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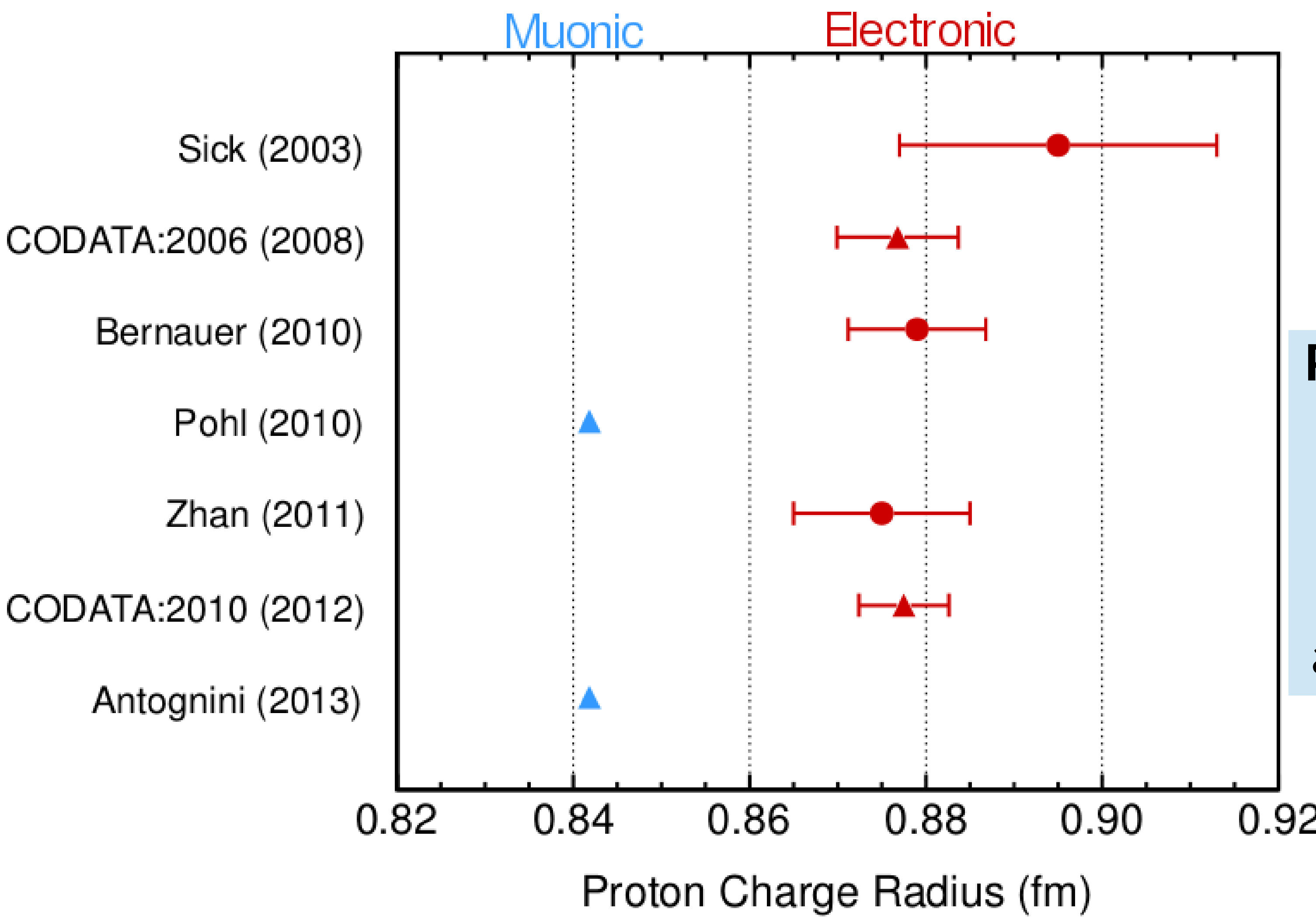
Glasgow, Scotland

Outline

- What is the proton radius puzzle
- How the proton radius is measured
- The MUSE contribution to a solution
- Experiment details and expected impact
- Summary

Review

Recent history of proton charge radius determinations:



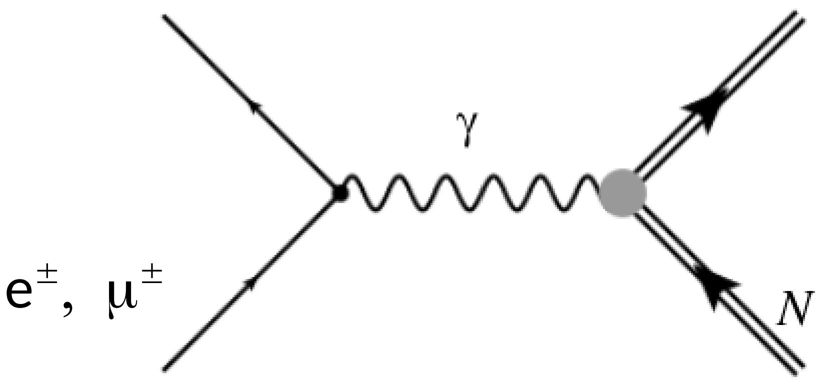
- ● **Scattering**
- ▲ **Spectroscopy**

Proton Radius Puzzle:
7.9σ discrepancy between the more precise muonic-H spectroscopy results and electronic results.

Muonic: ~0.84 fm   Electronic: ~0.88 fm

Lepton Scattering

Lepton scattering from a nucleon:



Vertex currents:

$$J_e^\mu = -e\overline{u}_e\gamma^\mu u_e$$

$$J_N^\mu = \overline{\psi}_N\left[F_1(Q^2)\gamma^\mu + F_2(Q^2)\frac{i\sigma^{\mu\nu}q_\nu}{2M_N}\right]\psi_N$$

F_1, F_2 are the Dirac and Pauli form factors

Sach's form factors:

$$\begin{aligned} G_E(Q^2) &= F_1(Q^2) - \tau F_2(Q^2) \\ G_M(Q^2) &= F_1(Q^2) + F_2(Q^2) \end{aligned}$$

Fourier transform (in the Breit frame) gives spatial charge and magnetization distributions

Derivative in $Q^2 \to 0$ limit:

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

$$\langle r_M^2 \rangle = -6\frac{dG_M^p(Q^2)/\mu_p}{dQ^2}\bigg|_{Q^2\to 0}$$

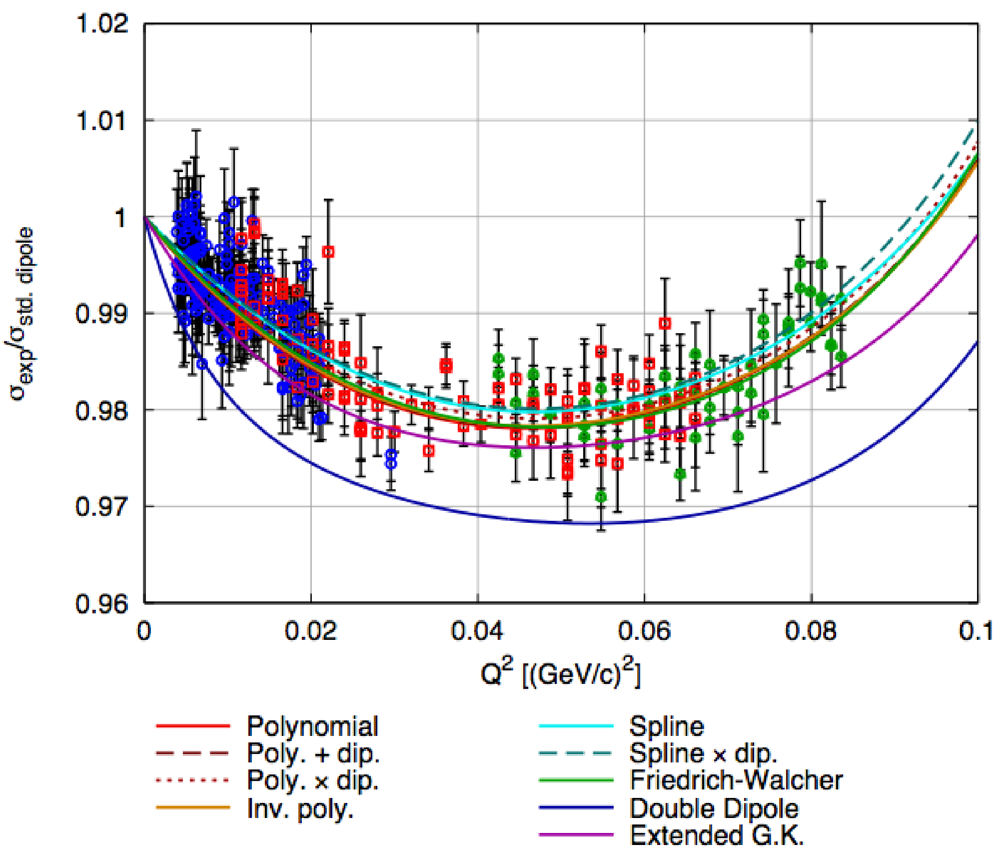
Expect identical result from ep and μp scattering

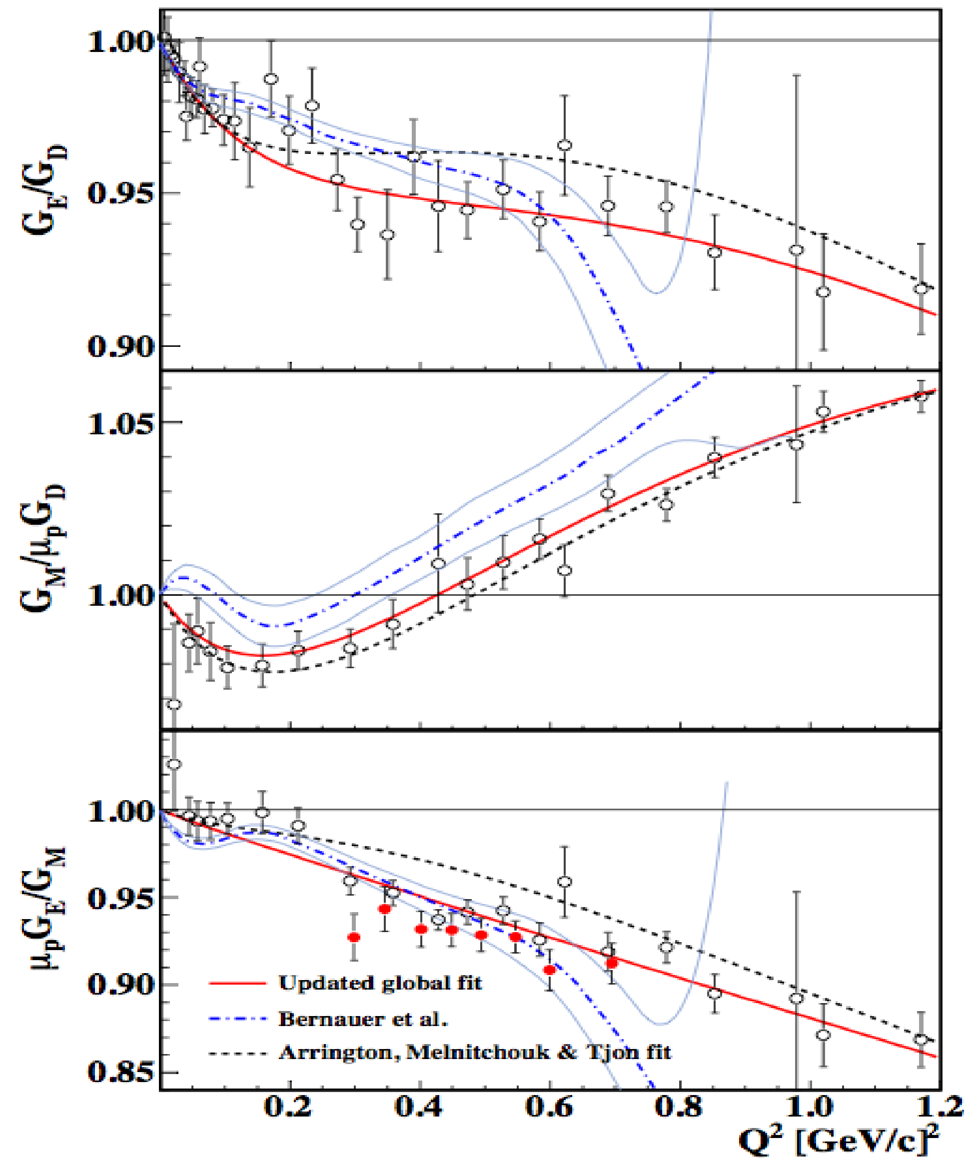
Elastic ep Scattering

Mainz A1: Bernauer *et al.* (2010)

Jlab E08-007 Zhan *et al.* (2011)

1400 points covering Q^2 ~ 0.004 – 1 GeV^2, point-to-point cross section uncertainties 0.4%





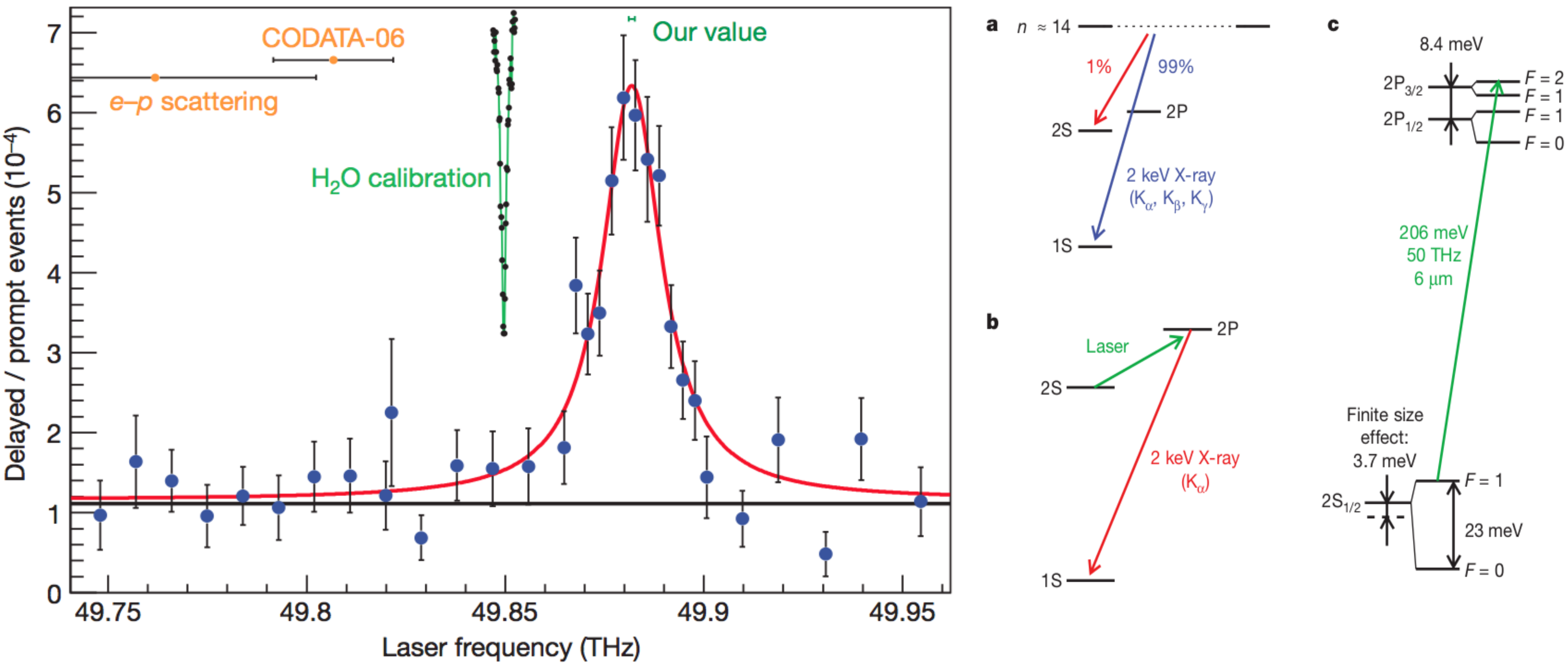
Global Fit: $r_p = 0.877 \pm 0.006$ fm

Muonic Hydrogen

Measure 2S → 2P Lamb Shift [Pohl *et al.*, Nature 466, 213-217 (2010)]

$$\Delta\tilde{E} = 209.9779(49) - 5.2262\, r_p^2 + 0.0347\, r_p^3 \text{ meV}$$

r_p = 0.84184 ± 0.00067 fm

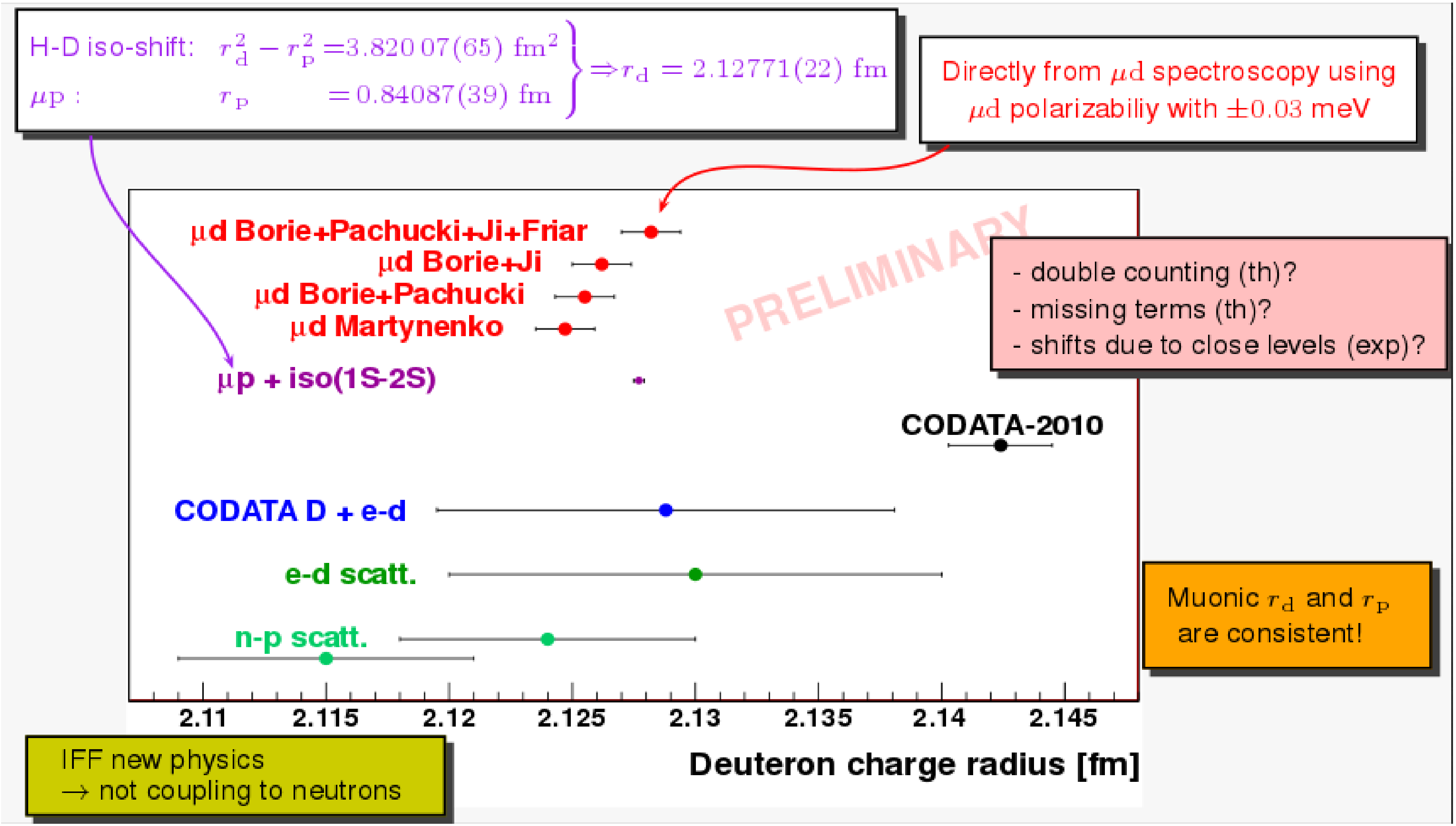


Reconfirmed in 2S → 2P Lamb + 2S-HFS
[A. Antognini *et al.*, Science 339, 417 (2013)]

r_p = 0.84087±0.00039 fm

New: Heavier Muonic Systems

PRELIMINARY: Deuteron charge radius (slide from A. Antognini)



VERY PRELIMINARY: muonic ^{4}He and e-^{4}He scattering radii consistent

Possible Explanations

- Experimental issues…
  - μH is wrong: 3-body effects, theory uncertainties
    - Seems unlikey, known theory corrections small
  - ep scattering is wrong: underestimated uncertainties, bad radius extractions, two-photon exchange, …
- New physics…
  - Lepton non-universality
  - New force / particle (dark photon?)
  - enhanced two-photon exchange for μp
  - Non-perturbative e+e- sea
  - ??
  - Note: many current theories ruled out / constrained by ^{4}He results
- No explanation with majority support in community
- **Need More Data!**

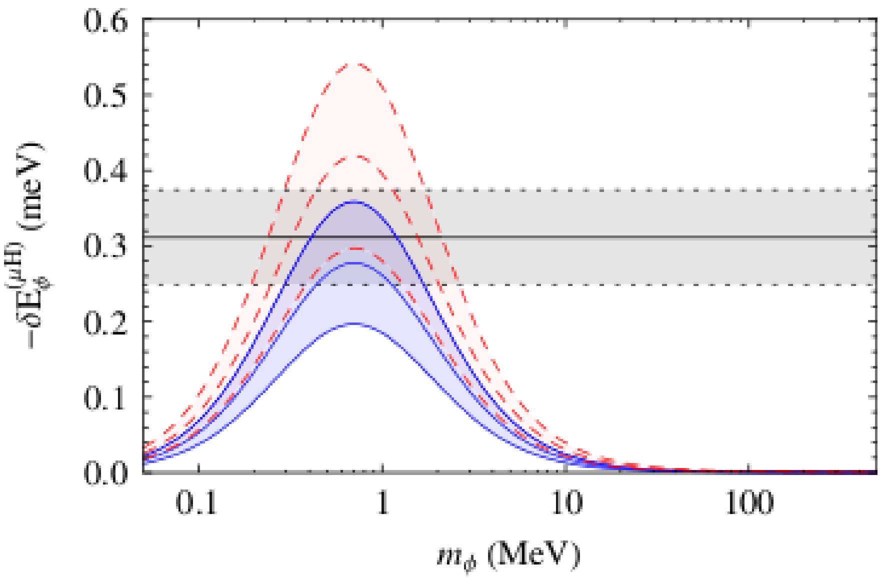
Theory examples

Dark Photon:

New force with few MeV mass particle coupling to μ and p (not e)

Consistent with muon g-2

Tucker-Smith and Yavin,
PRD **83**, 101702(R) (2011)

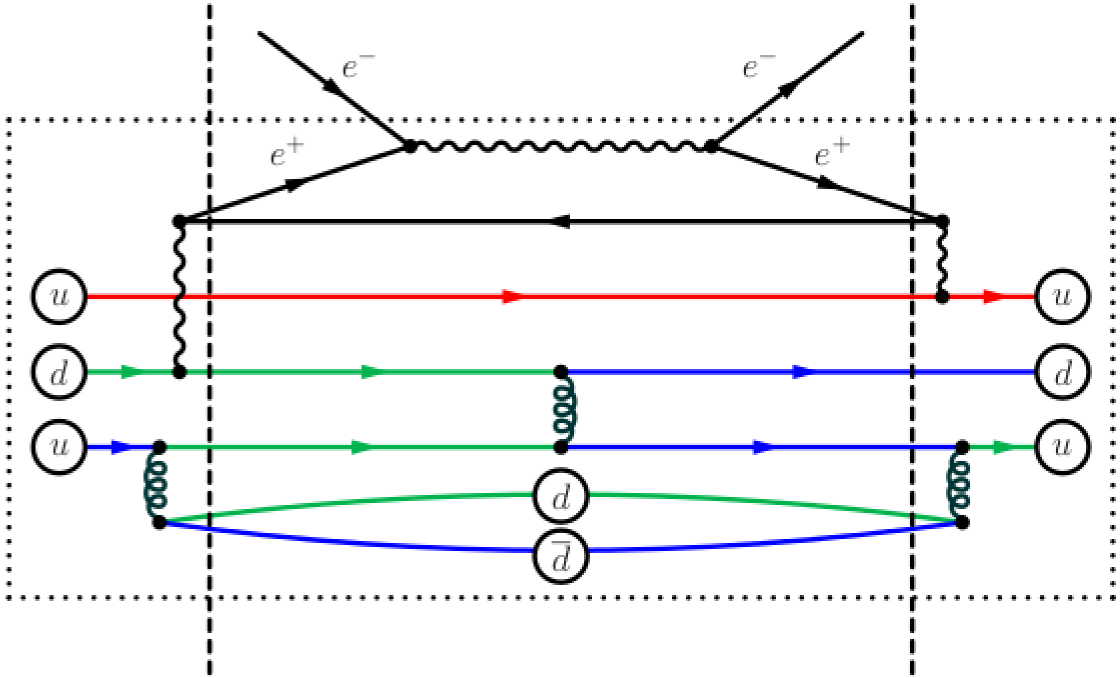


Non-perturbative sea:

~10e-7 light e+e- sea pairs per valence quark

electrons measure a larger proton size

Jentschura, PRA **88**, 062514 (2013)



What to do?

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

New data needed:

test are e and μ really different?

- Test implications for
  - BSM: modified scattering probability for Q^2 up to m^2_{BSM}, enhanced parity violation
  - Hadronic: enhanced two-photon exchange
- Experiments include:
  - Redoing atomic hydrogen,
  - Light muonic atoms
  - Redoing electron scattering at lower Q^2
  - Muon proton Elastic Scattering
  - Muon Scattering on Nuclei
  - Kaon Decays

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Possible next gen.

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  - BSM: modified scattering probability for Q^2 up to m^2_{BSM}, enhanced parity violation
  - Hadronic: enhanced two-photon exchange
- Experiments include:
  - Redoing atomic hydrogen, **YORK**
  - Light muonic atoms **CREMA (μD, μHe)**
  - Redoing electron scattering at lower Q^2 **JLab (ep) & Mainz (ep, eD)**
  - **Muon proton Elastic Scattering**
  - Muon Scattering on Nuclei
  - Kaon Decays **TREK (J-PARC)**

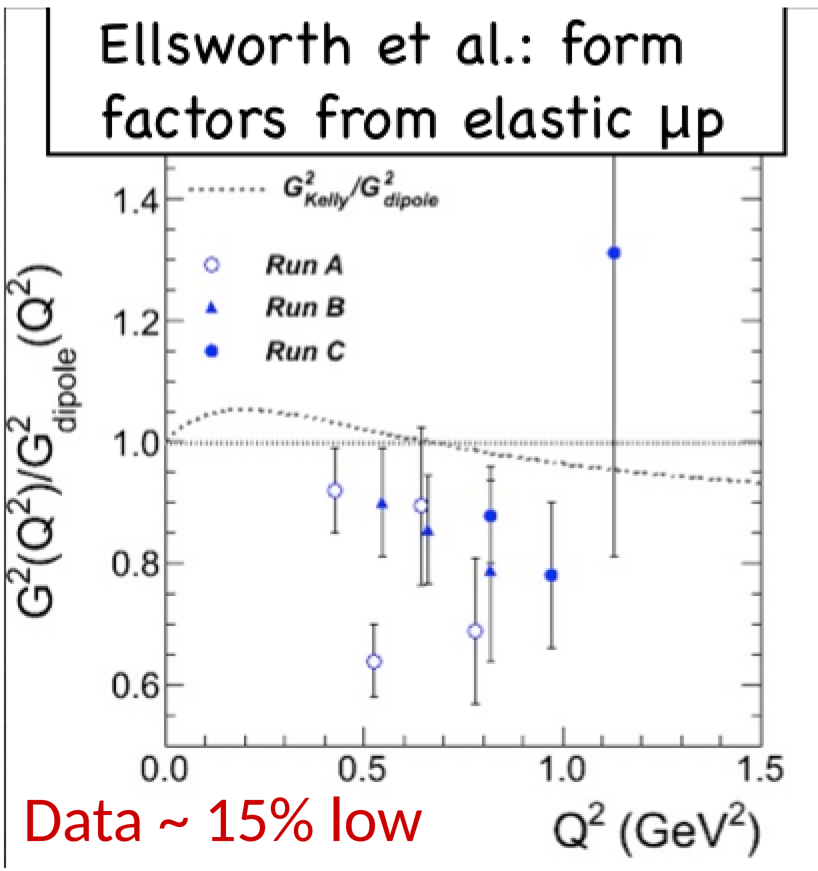
MUSE tests these

Possible next gen.

e-μ Universality

1970s-1980s: experiments tested e-μ universality to ~10% level

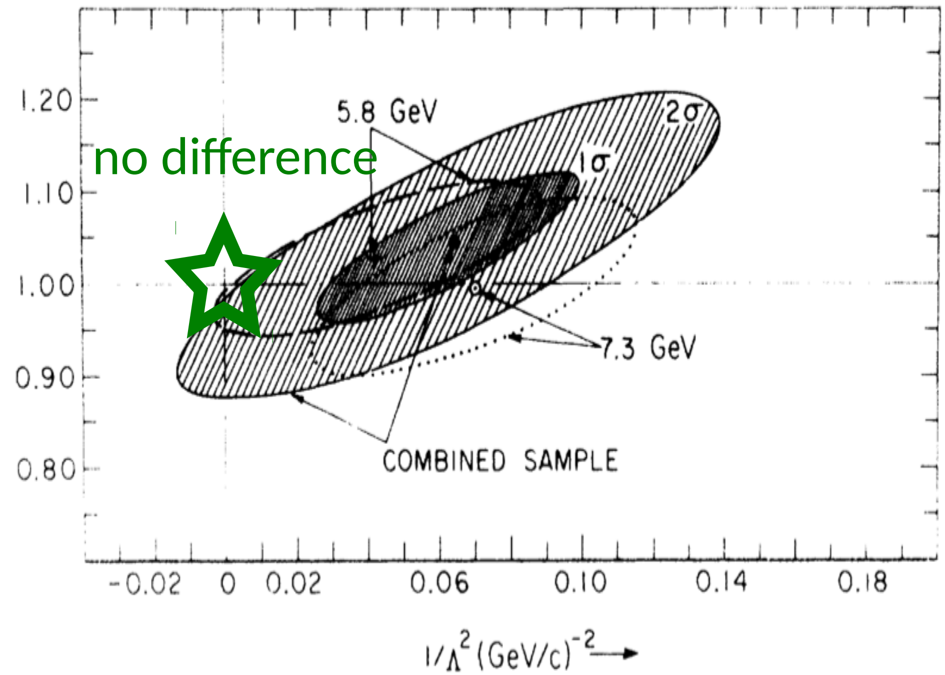
Elastic μp scattering: Ellsworth et al (1968)



Data ~ 15% low

Elastic μp scattering: Kostoulas et al (1974)

$$N \propto \frac{G_{\mu p}}{G_{ep}}$$



DIS μp scattering: (A. Entenberg et al (1974))

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

e-C, and μ-C are in agreement

Constraints not very good!

Also no evidence for TPE effects

MUon Scattering Experiment (MUSE)at PSI

Use the world's most powerful separated $e/\mu/\pi$ beam to directly test if μp and ep scattering are different:

- Measure to higher precision than previously done, in the low Q^2 region for sensitivity to the radius
- Measure both $\mu^{\pm}p$ and $e^{\pm}p$ cross sections, directly compare ratios for e/μ and μ^{+}/μ^{-}, e^{+}/e^{-} (TPE) for reduced systematics and robust result
- Multiple beam momenta for overlapping datasets
- If radii different by 4%, FF slope different by 8%, xsec slope by 16%

Cross Section Experiment

$d\sigma/d\Omega(Q^2) = N_{counts} / (\Delta\Omega \times N_{beam} \times (x\rho)_{target} \times \text{corrections} \times \varepsilon)$

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

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

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

following Preedom & Tegen, PRC36, 2466 (1987)

We cannot measure absolute cross sections well enough

Do a relative measurement with 0.4% (0.6%) systematic error for μ (e)

Have 6 primary measurement settings x2 independent sets of detectors

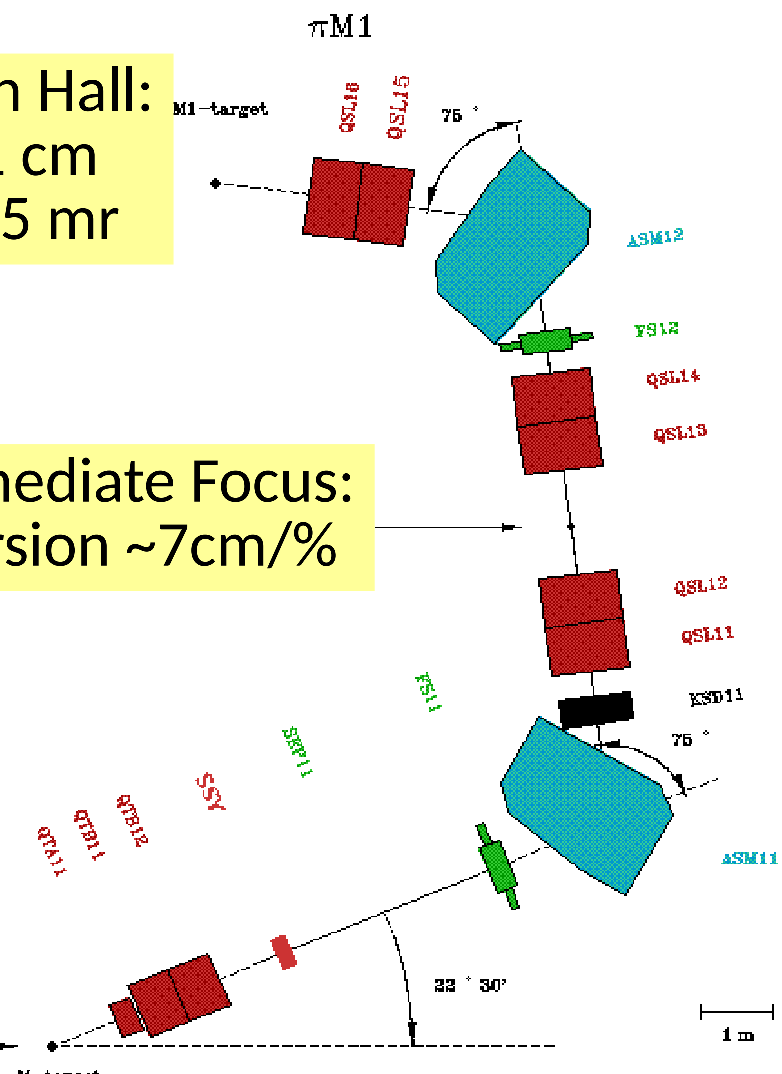
πM1 Channel at PSI

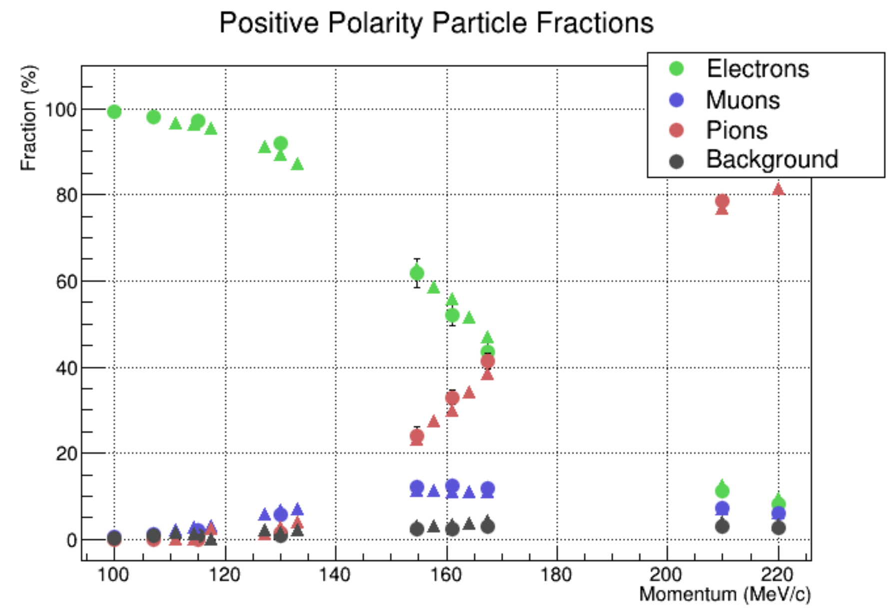
100-500 MeV/c mixed beam of e, μ, π

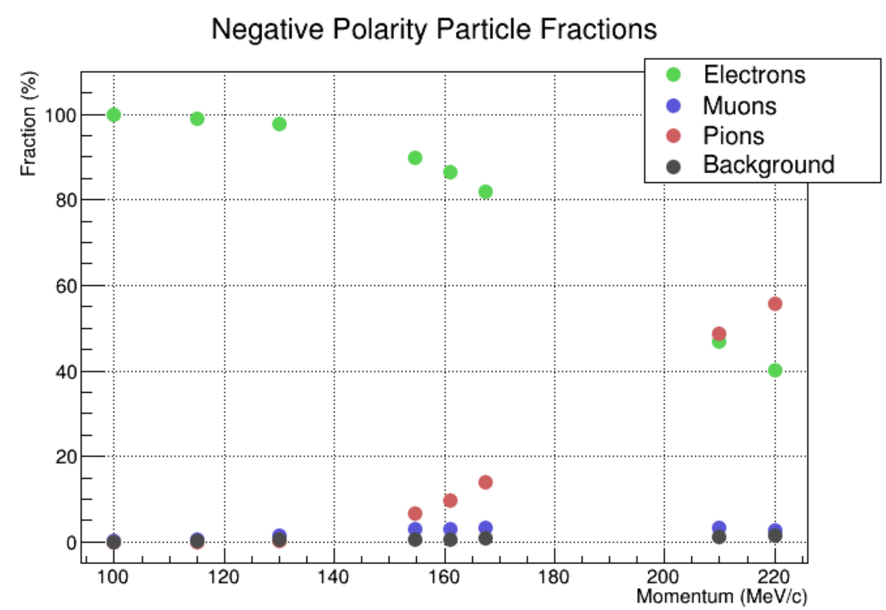
Beam spot in Hall:
~1.5 cm x 1 cm
~ 35 mr x 75 mr

Intermediate Focus:
Dispersion ~7cm/%

Production Target
50 MHz,
2.2 mA p







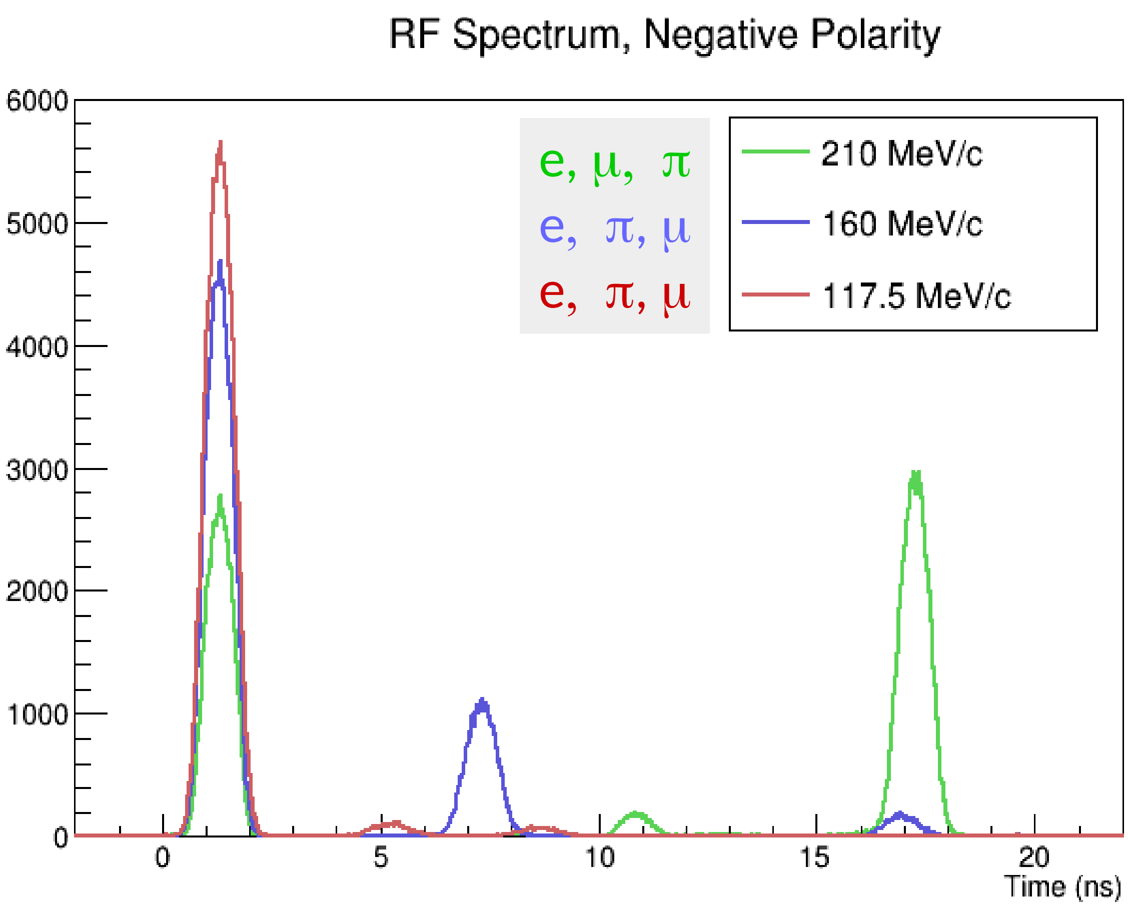
(MUSE beam test 6/2013)

Beam considerations

Particle timing separation at chosen momentum for PID

50 MHz RF → 20 ns between bunches

Select momentum with 2 – 4 ns separation: ~ 115, 153, 210 MeV/c



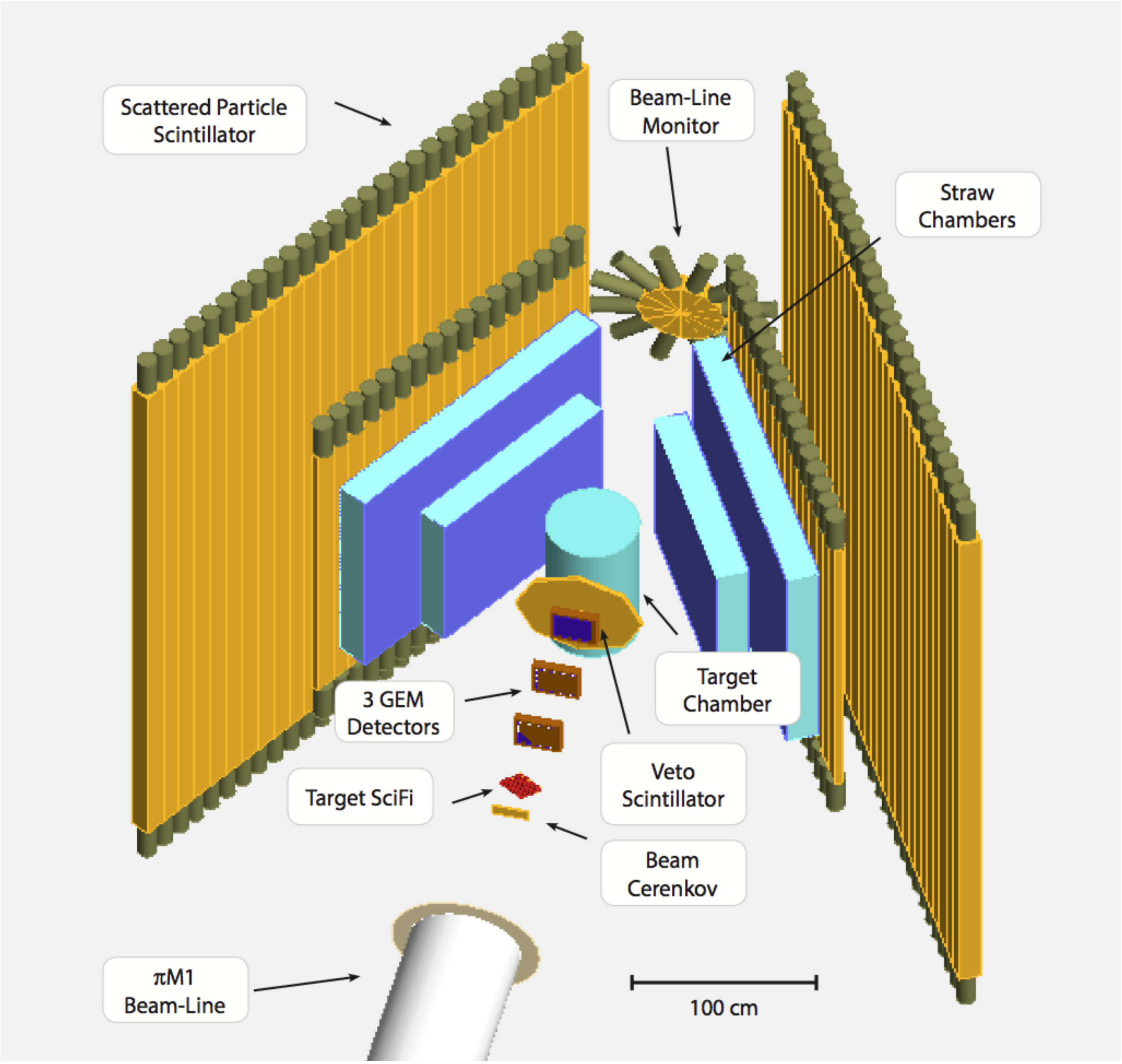
(MUSE beam test 6/2013)

Limit beam flux to 5 MHz at target with collimator at IFP

Momentum (MeV/c)	e Flux (MHz)	μ Flux (MHz)	π Flux (MHz)
+115	4.85	0.10	0.05
+153	3.15	0.60	1.25
+210	0.60	0.40	4.00
−115	4.93	0.05	0.03
−153	4.50	0.16	0.34
−210	2.35	0.20	2.45

Experiment Setup

Detector Overview in Simulation



- **Measure ep and μp cross sections**

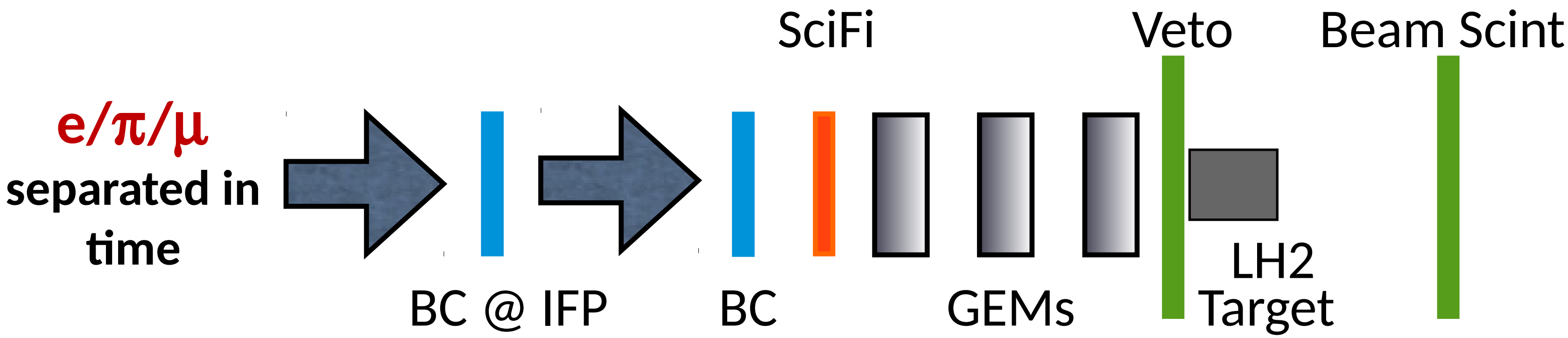
  p = 115, 158, and 210 MeV/c
  $\theta = 20^{\circ} - 100^{\circ}$
  $Q^2 = 0.002 - 0.07\ \mathrm{GeV}^2$
  $\varepsilon = 0.256 - 0.94$

- **Measure both + and – polarity**

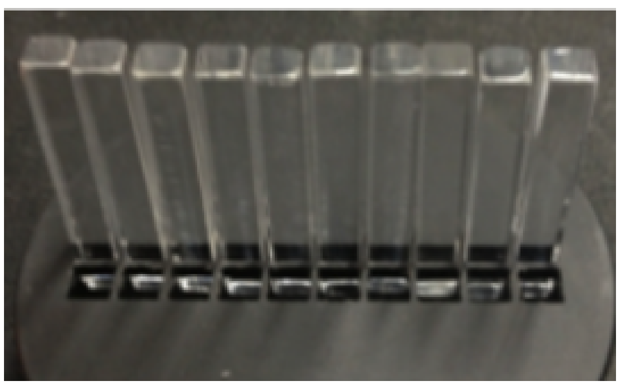
- **Challenges include**

  Need high pion rejection efficiency
  Good particle ID
  Precise timing

Beamline Instrumentation



Sapphire Beam Cerenkov
(Rutgers/HUJI)

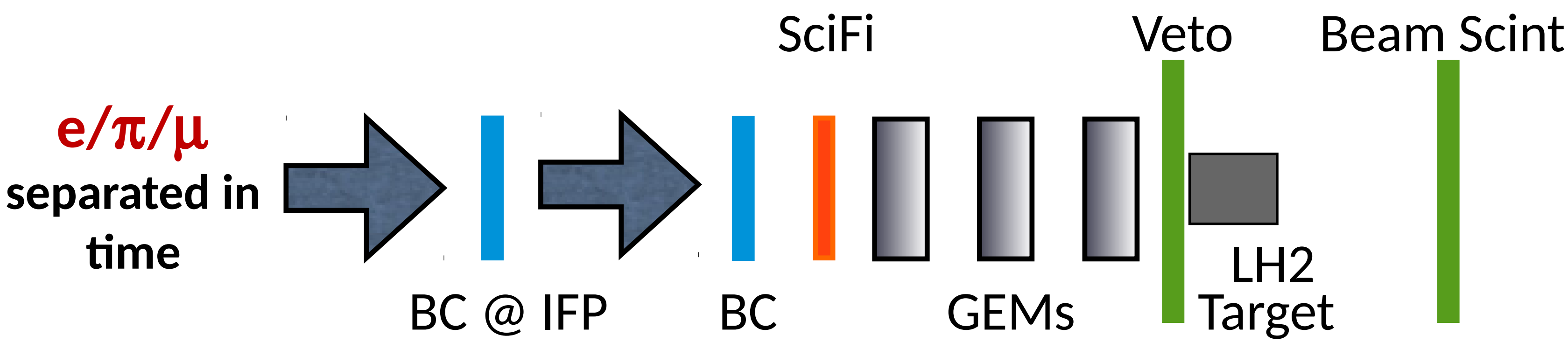


<100 ps resolution at analysis level:
- Precise TOF, particle ID
- Muon decay event rejection
- Use at IFP (high neutron rate)

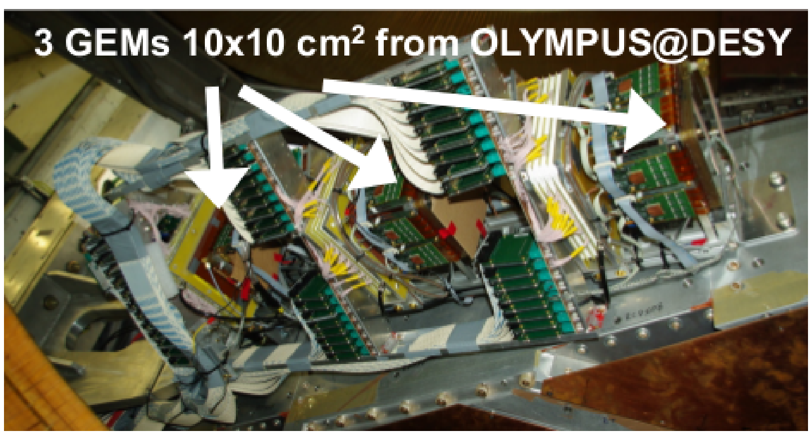
Scintillating Fiber Array
(Tel Aviv)

2 mm fibers, double-ended maPMT
- 1 ns timing for trigger PID
- beam flux normalization
- position & time correlations with GEMs

Beamline Instrumentation



GEMs (Hampton)

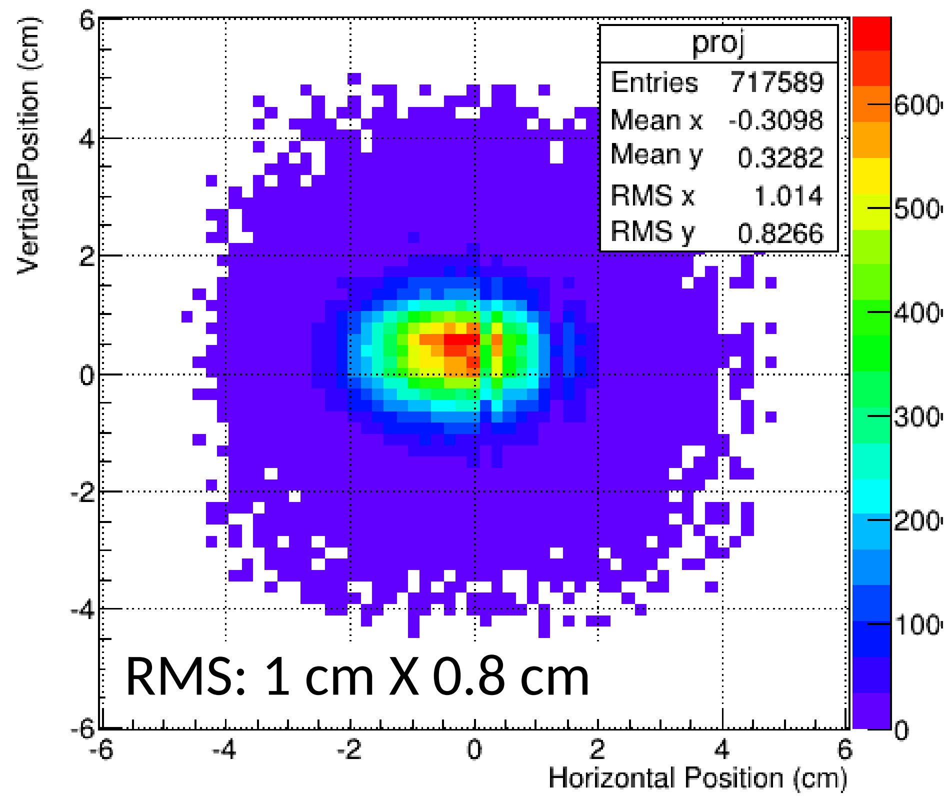


Determine incident angle to 0.5 mr

Third GEM to reject ghost tracks

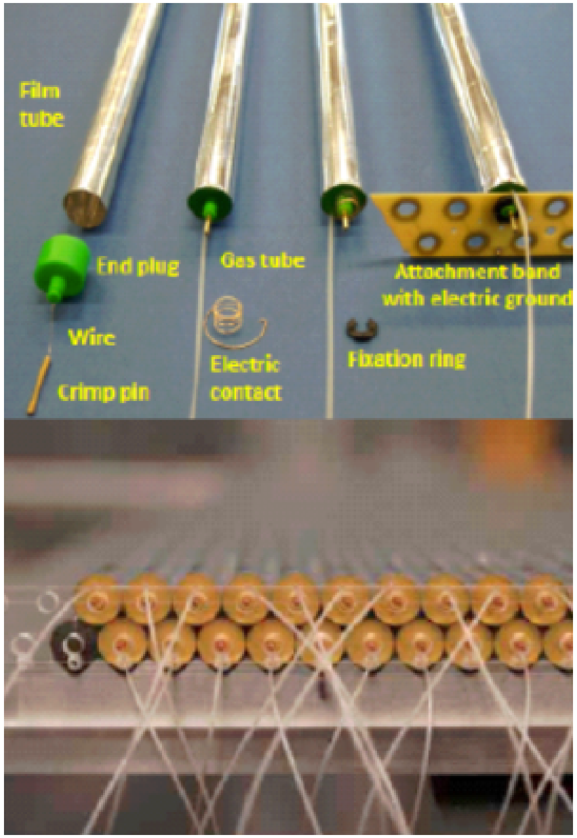
Existing from OLYMPUS, moved to PSI

Beam spot measured with GEM



(MUSE beam test 6/2014)

Scattered Particle Detectors



Straw Tube Tracker (HUJI + Temple):

~3000 straws, 2 chambers each side of beam

Determine scattered particle trajectory to 140 μm

Directly coupled to fast readout boards

Calibrated relative to GEMs by rotating into beam

Fast scintillators (South Carolina):

~ 90 bars, 2 planes each side of the beam

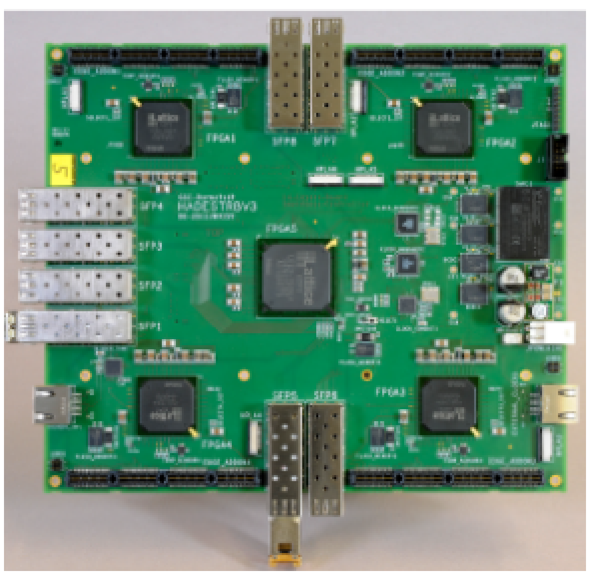
~100 (~200) cm long bars front (back) walls (thickness: 2 cm / 6 cm)

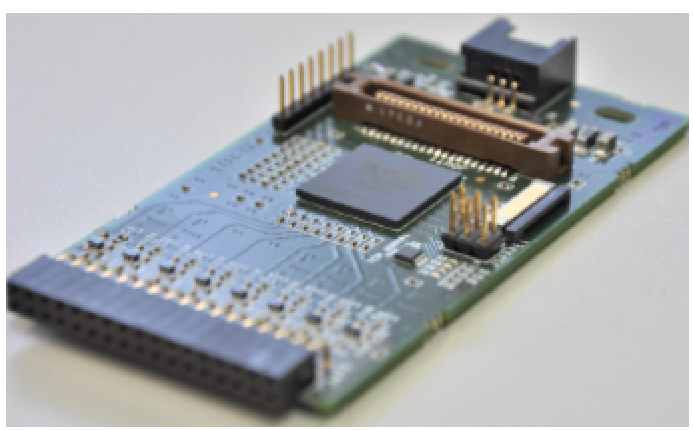
High-precision 40-50 ps timing, part of beam PID

DAQ & Trigger

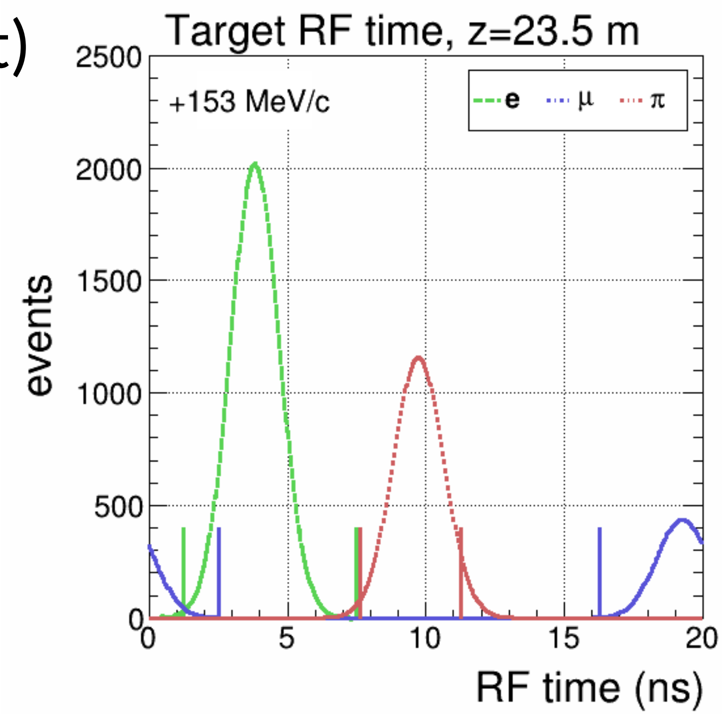
DAQ (GWU): Use custom TDCs – TRB3
- cost effective, 256 ch/board
- < 25 ps resolution (11 ps in GSI bench test)
- PADIWA for frontend amplifier/disc
- Scaler functionality on board
- 5 FPGAs/board

Use standard v792 QDCs for time-walk



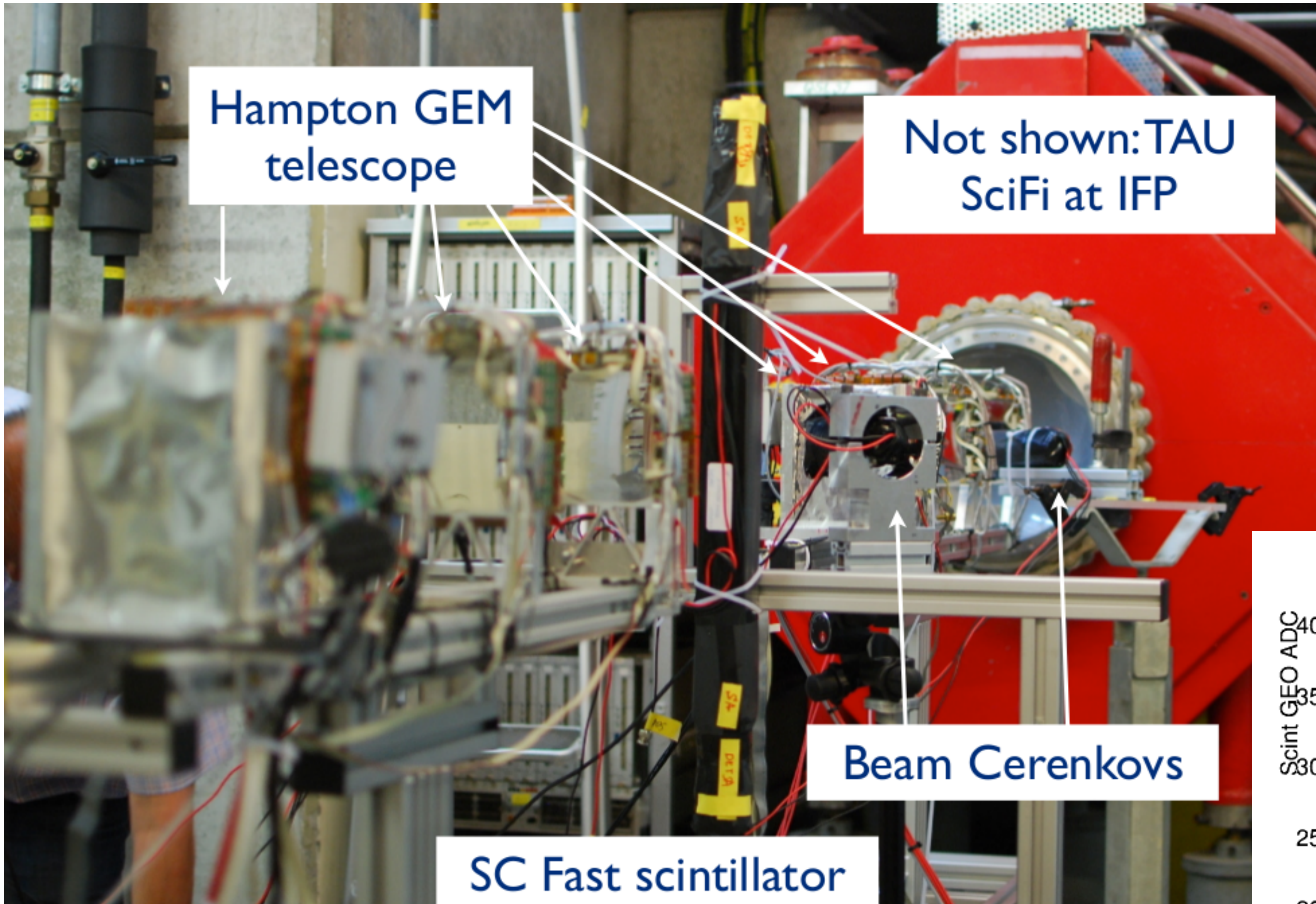


Trigger (Rutgers)



- Use FPGA from TRB3
- SciFi + BC + Beam RF determine beam PID
- Pion rejection >99.9%
- Trigger: beam PID + not VETO + scat. particle

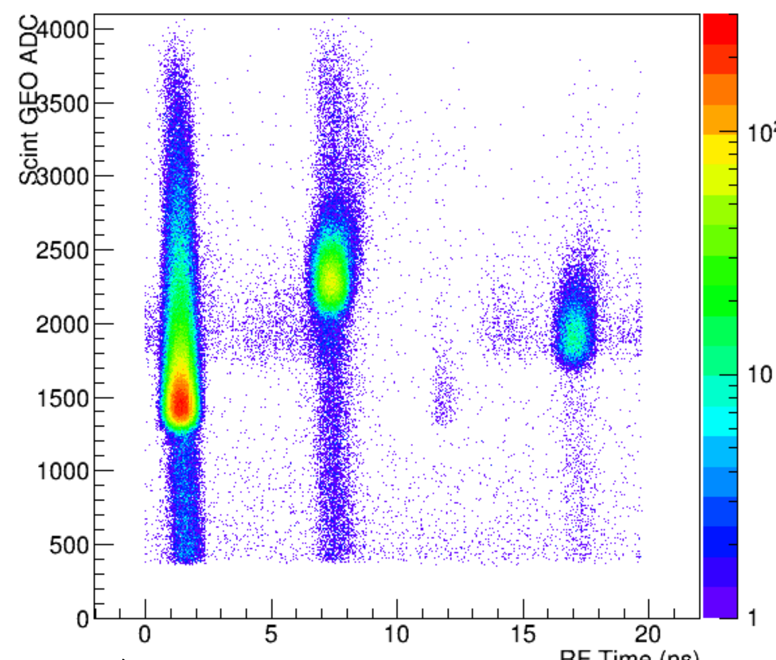
Beam test measurements



Test Measurements:

- Dec 2012
- June 2013
- Fall 2013
- June 2014
- Dec 2014 (planned)

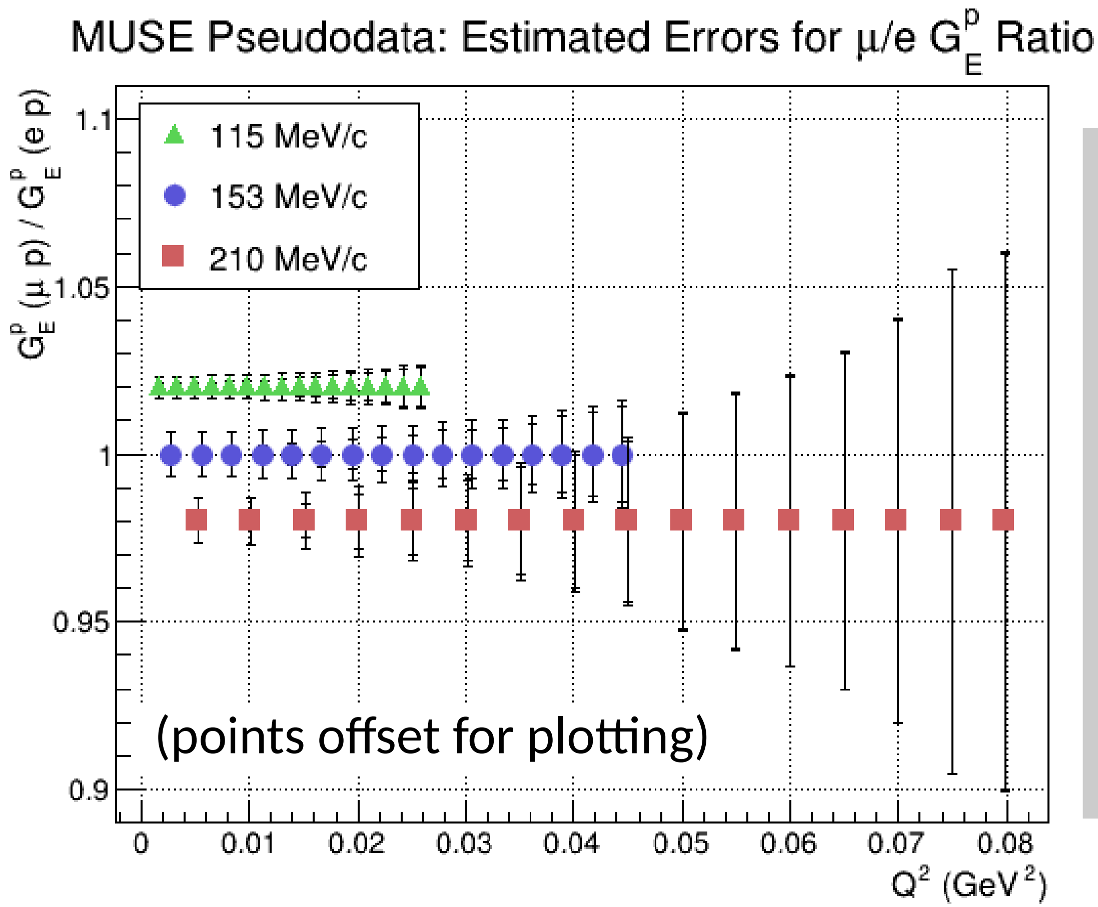
ADC vs. RF Time



(MUSE beam test 12/2013)

- Characterization of beam – RF distributions
- Determine beam size and divergence (GEMs)
- Study beam tune, backgrounds
- Measure timing resolution, characterize BC
- DAQ and software development

Expected Results



Relative Errors

Solid Angle	0.1%
Scintillator Efficiency	0.1%
Beam Mom. Sensitivity	0.1%
Angle Determination	0.1%
Magnetic Contributions	0.1%
Multiple Scattering	0.3%
Radiative Corrections – μ	0.1%
Radiative Corrections – e	0.5%

Conservative estimate of total uncertainty for the relative μ/e form factor comparison

Not optimized for time spent at the 3 individual settings

Total Relative Uncertainty in Cross Section*:

μ: 0.4%
e: 0.6%

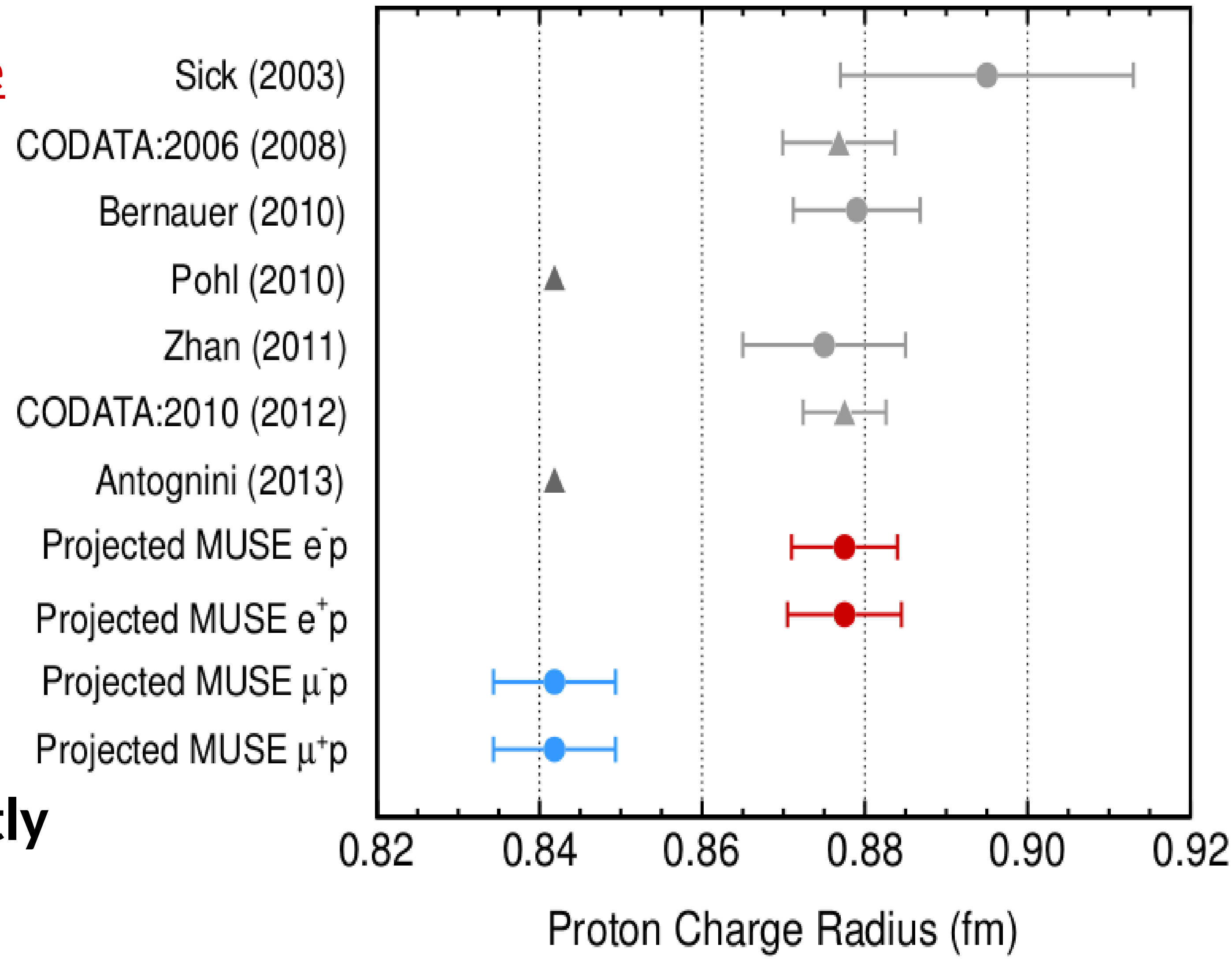
* Factor of two smaller for G_E

Some further partial cancellation in ratios

Expected Results

Fit form factors individually

Relative Radius Uncertainties



Sensitivity to difference in extracted radius:

δr = 0.009 fm (μ-e)

(Current discrepancy ~0.035 fm)

Tests discrepancy directly at same significance as current measurements

MUSE Timeline

- **Feb 2012:** First proposed to PSI PAC
- **July 2012:** PAC / PSI Technical Review
- **Fall 2012:** 1st beam test run at πM1
- **Jan 2013:** PAC / PSI Approval
- **June 2013:** 2nd beam test run at πM1
- **Fall 2013:** Funding requests
- **December 2013:** 3rd beam test run at πM1
- **Jan 2014:** 2nd PAC / PSI Review
- **March 2014:** NSF Review with DOE representation
- **June 2014:** 4th beam test run at πM1
- **Now:** R & D funding from NSF / DOE (~ $750k)
- **Dec 2014:** Next beam test runs at πM1
- **June 2015:** Advanced test run with some equipment
- **Nov 2016:** "Dress rehearsal" with full beamline detectors and 1 full spectrometer side
- **2017-18:** Two 6-month production runs

Summary

- The "proton radius puzzle" is a high profile issue, and is still unresolved 4 years later
- Explanation unclear, no general consensus
  - BSM? TPE? Experiment?
  - Many theories ruled out by recent muonic helium-4 results
- MUSE will uniquely:
  - simultaneously measure μp and ep scattering for direct comparison of radius with reduced systematics
  - Measure of e+/e- and μ+/μ– to test two-photon exchange
- R & D work is underway, planning for production running in 2017-18

MUSE Collaboration

The MUon 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] C. Ayerbe-Gayoso,[6] F. Benmokhtar,[7] J. Bernauer,[8] E. Brash,[9] W. J. Briscoe,[2] K. Deiters,[10] J. Diefenbach,[5] B. Dongwi,[5] L. El Fassi,[1] S. Gilad,[8] K. Gnanvo,[11] R. Gothe,[12] D. Higinbotham,[13] Y. Ilieva,[12] M. Jones,[13] M. Kohl,[5] G. Kumbartzki,[1] J. Lichtenstadt,[14] A. Liyanage,[5] N. Liyanage,[11] Z.-E. Meziani,[15] P. Monaghan,[5] K. E. Mesick,[1] C. Perdrisat,[6] E. Piasetzsky,[14] V. Punjabi,[16] R. Ransome,[1] D. Reggiani,[10] P.E. Reimer,[4] A. Richter,[17] A. Sarty,[18] Y. Shamai,[19] N. Sparveris,[15] S. Strauch,[12] V. Sulkosky,[20] A.S. Tadepalli,[1] M. Taragin,[21] and L. Weinstein[22]

~50 Collaborators from ~20 institutions

New Collaborators welcome! Thank You!

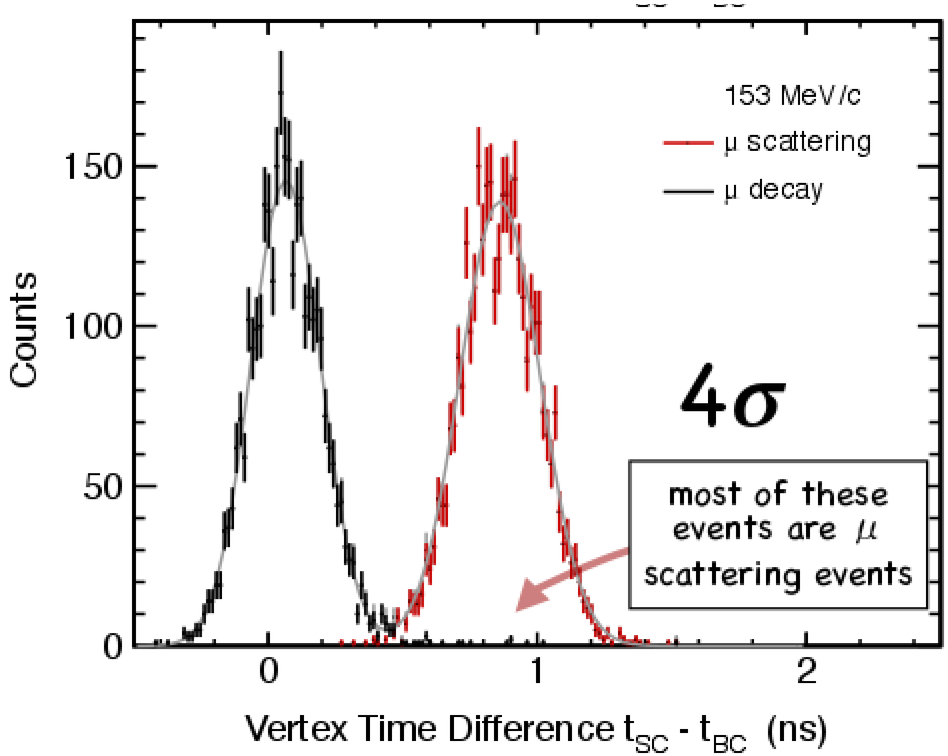
http://www.physics.rutgers.edu/~rgilman/elasticmup

Extras

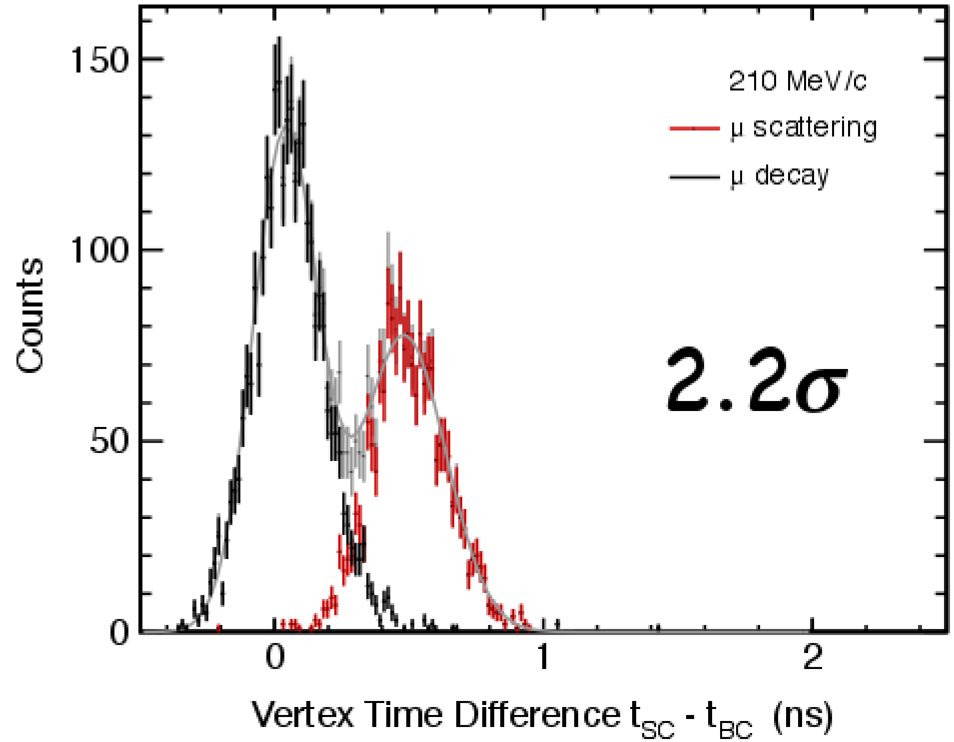
Decay Background Simulation

Geant4 simulation of muon decay event separation:
- TOF from Cerenkov to Scintillator

153 MeV/c



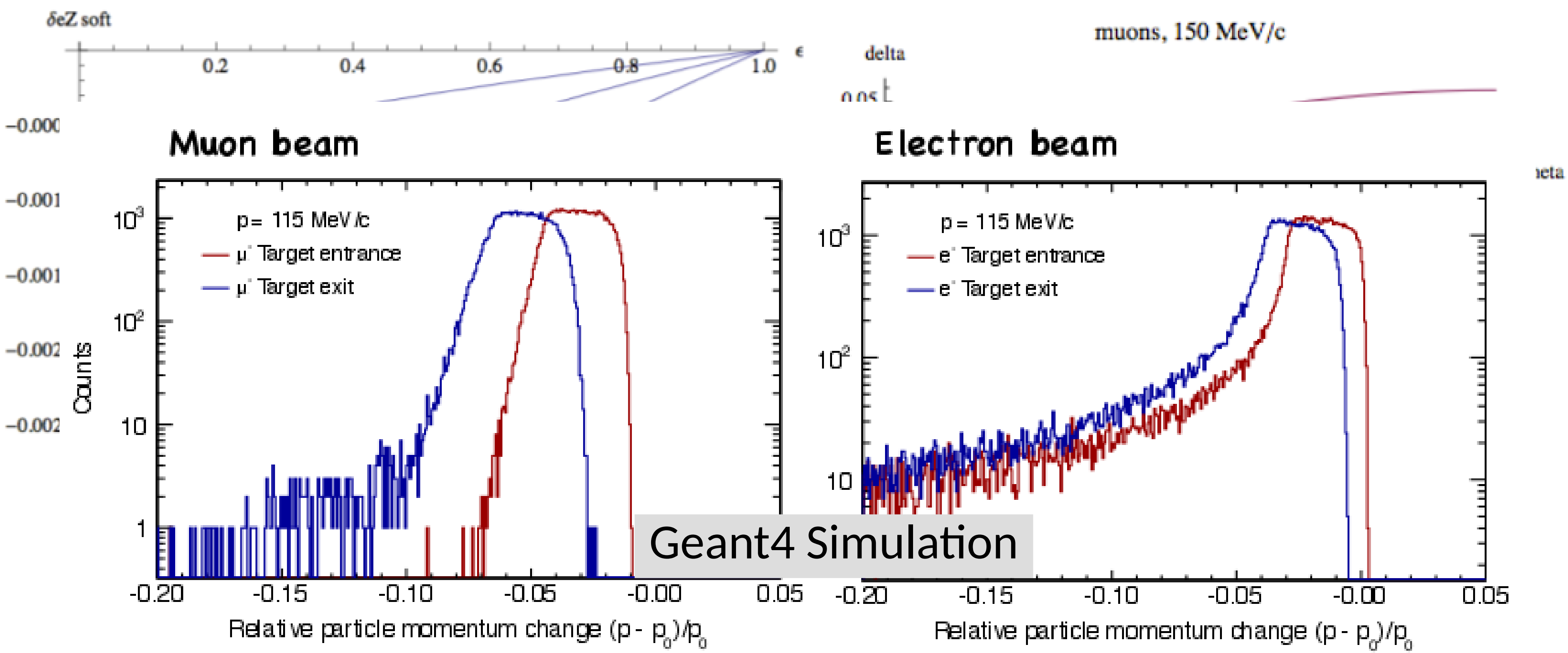
210 MeV/c



- Better (6σ) separation at 115 MeV/c
- Will also measure empty target for subtraction, can also calculate

Radiative Corrections / TPE

Effect ~ 3% for 100° at 210 MeV/c for muons, ~ 5 times larger for e
Uncertainties over an order of magnitude smaller
Standard codes exist – updated to avoid approximations



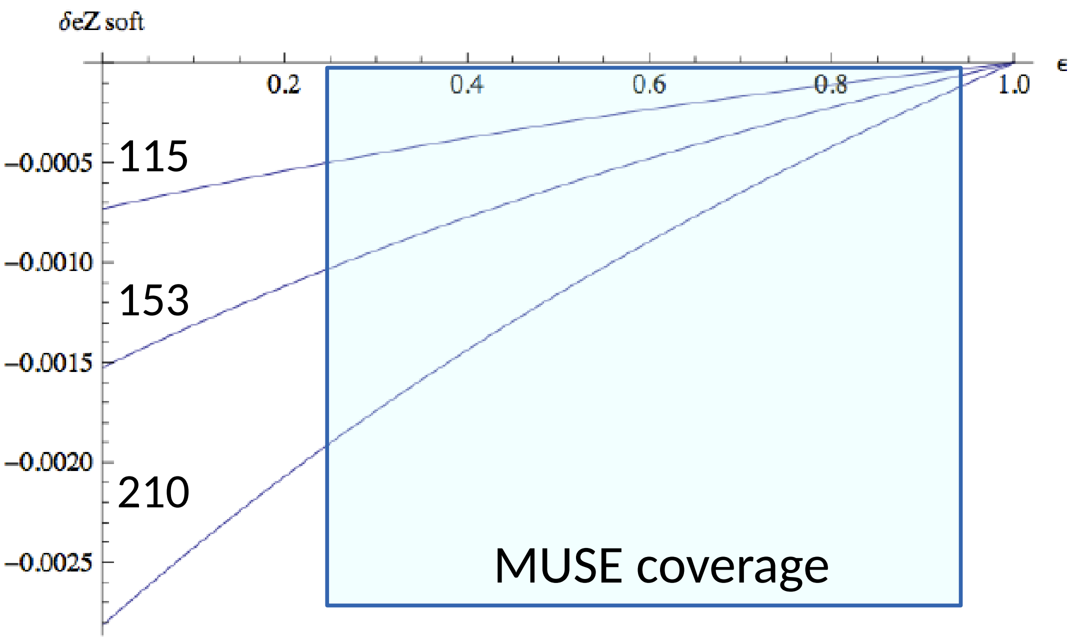
shown are for electrons; the muon calculations are very similar. Right: Muon radiative corrections at 150 MeV/c for MUSE. The blue (red) curve is the full (approximate) calculation.

Some Theoretical Corrections

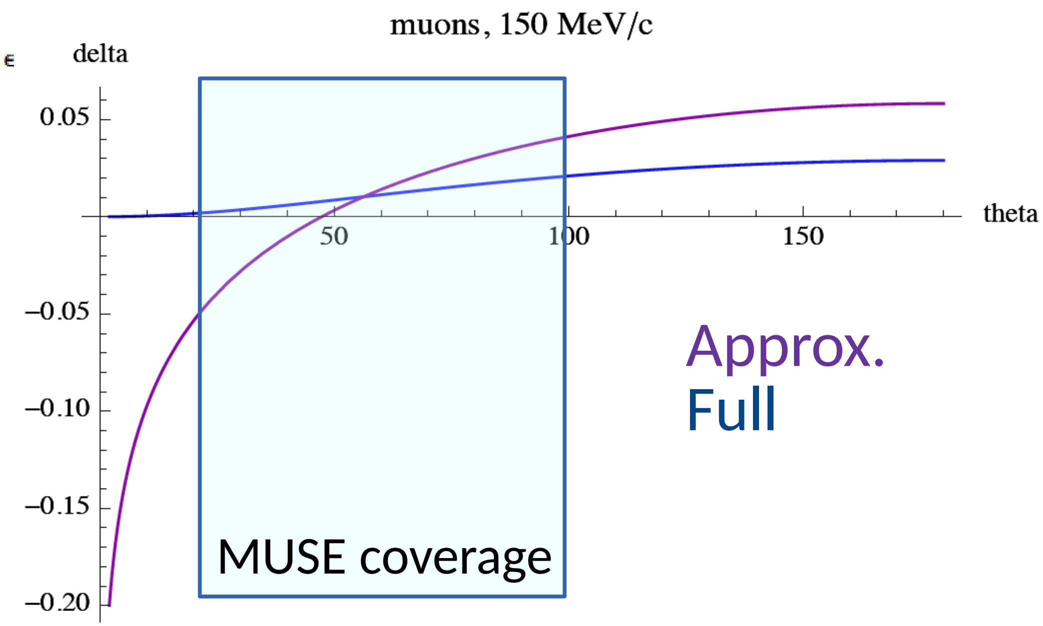
Soft TPE: <0.25% effect expected at MUSE kinematics, but we will measure any enhanced effects directly with our experiment!

Coulomb Corrections: Expected to be small, standard codes exist.

Radiative Corrections: Codes updated to remove approximations, effect ~ 3% for 100° at 210 MeV/c for muons, ~ 5 times larger for e. Contribution to the uncertainty over an order of magnitude smaller



Soft TPE Correction



Muon Radiative Correction

Calculations from A. Afanasev