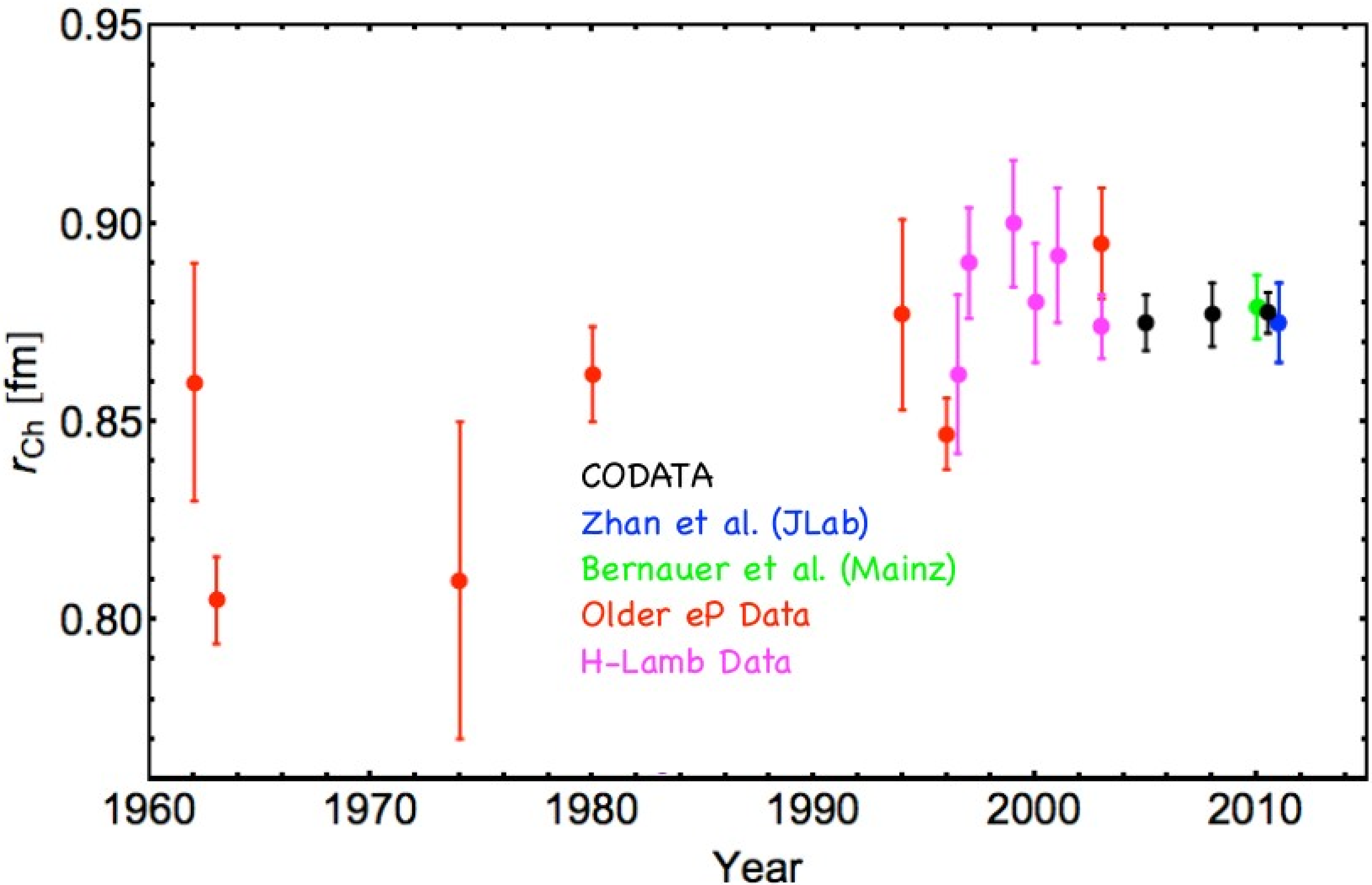
Proton Charge Radius Review and the MUSE Experiment at PSI

Katherine Mesick for the MUSE Collaboration
Rutgers University

Hall A/C Collaboration Meeting
June 5-6, 2014

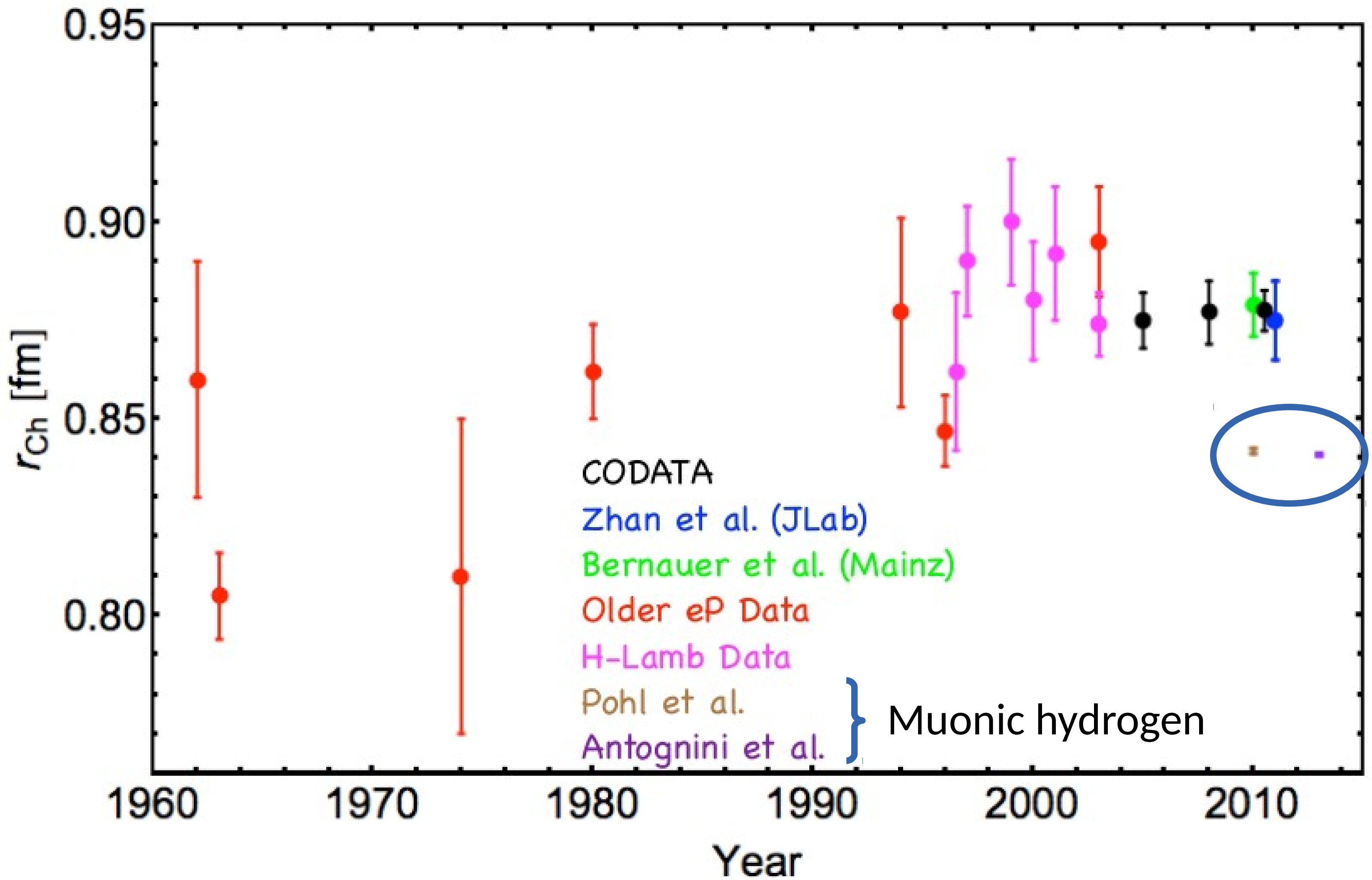
Review

History of Proton Charge Radius Measurements:



Review

History of Proton Charge Radius Measurements:

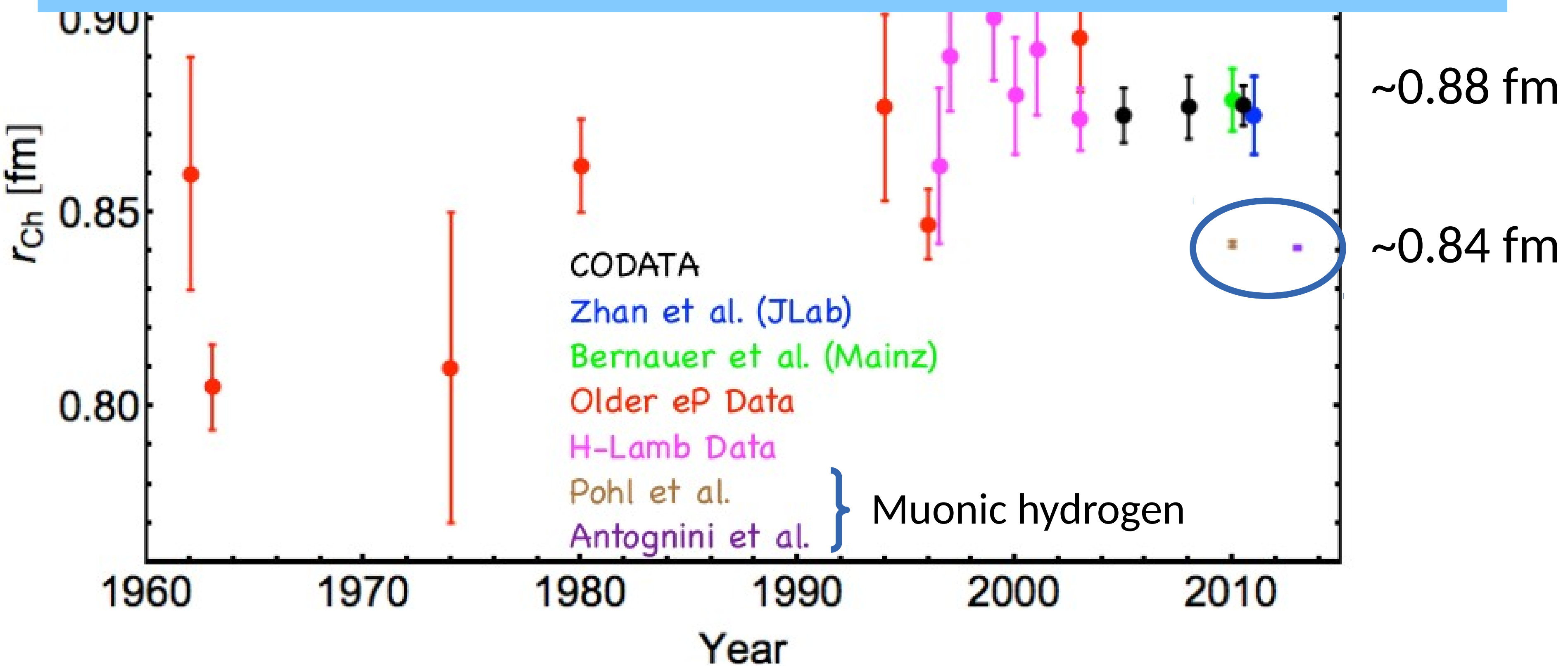


Review

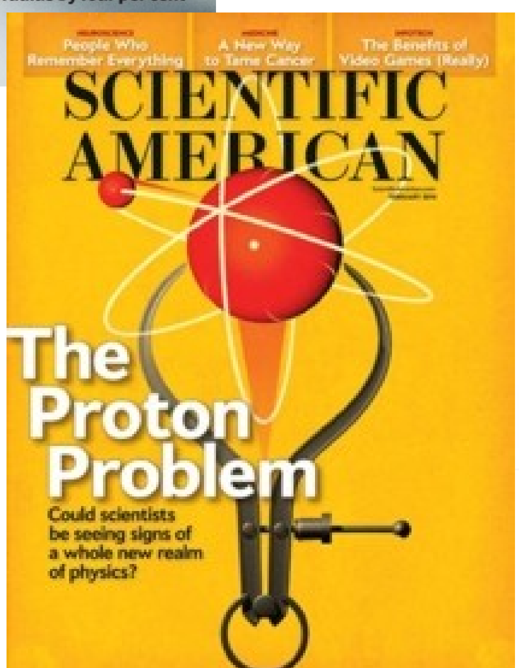
History of Proton Charge Radius Measurements:

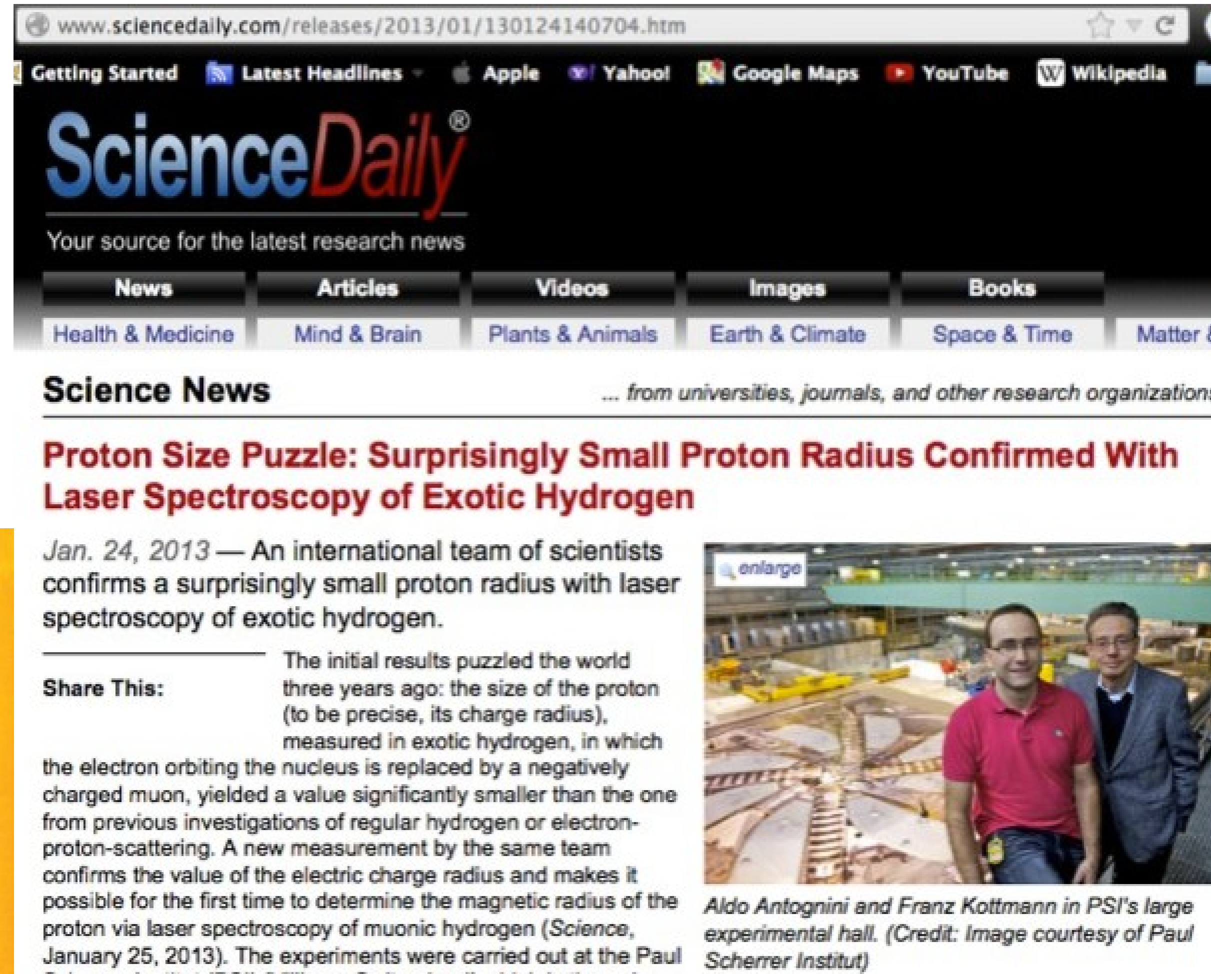
Proton Radius Puzzle: 7σ disagreement between more precise muonic hydrogen spectroscopy results and electron measurements

Currently no generally accepted solution to this puzzle!



In the news





Science News ... from universities, journals, and other research organizations

Proton Size Puzzle: Surprisingly Small Proton Radius Confirmed With Laser Spectroscopy of Exotic Hydrogen

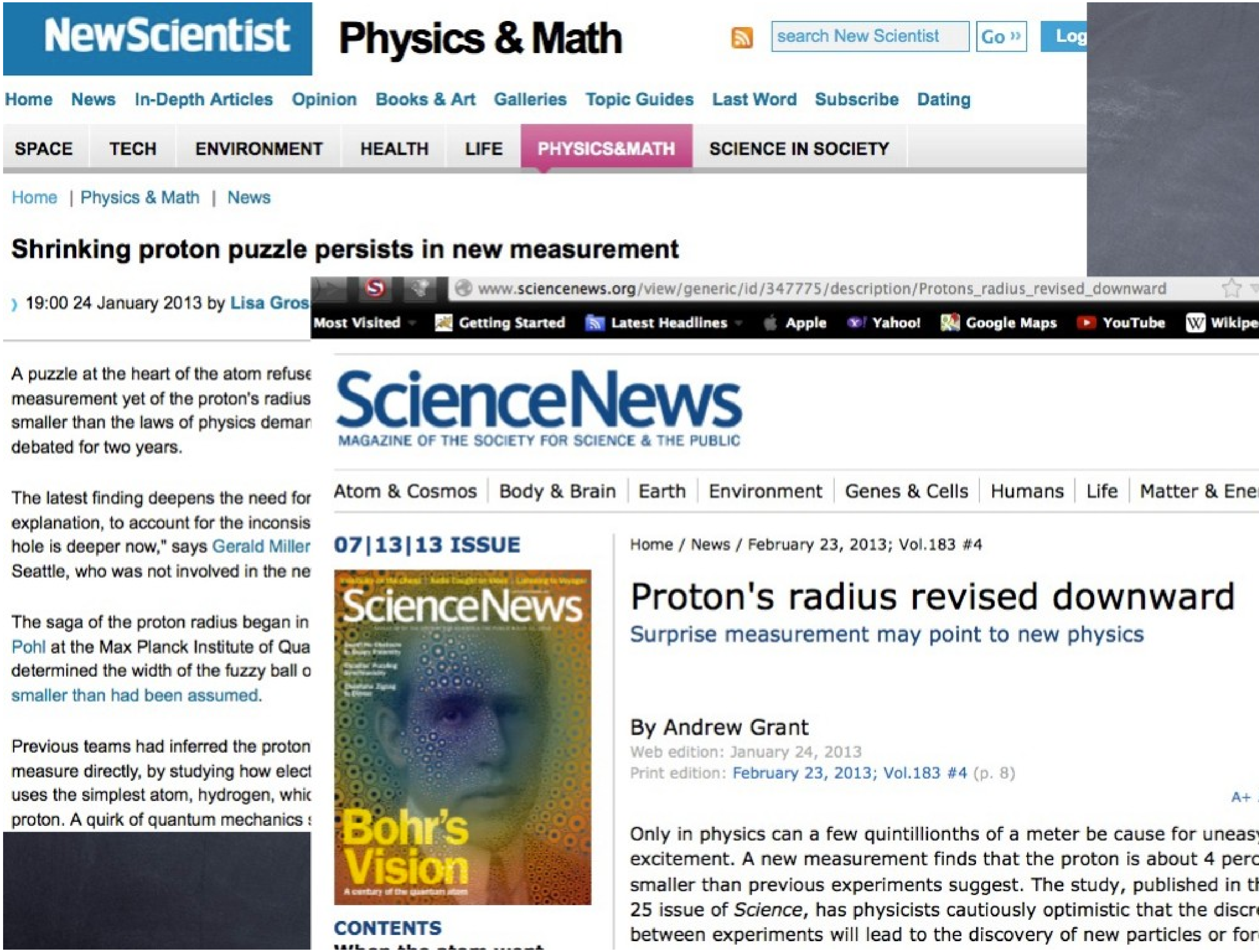
Jan. 24, 2013 — An international team of scientists confirms a surprisingly small proton radius with laser spectroscopy of exotic hydrogen.

Share This:

The initial results puzzled the world three years ago: the size of the proton (to be precise, its charge radius), measured in exotic hydrogen, in which the electron orbiting the nucleus is replaced by a negatively charged muon, yielded a value significantly smaller than the one from previous investigations of regular hydrogen or electron-proton-scattering. A new measurement by the same team confirms the value of the electric charge radius and makes it possible for the first time to determine the magnetic radius of the proton via laser spectroscopy of muonic hydrogen (*Science*, January 25, 2013). The experiments were carried out at the Paul Scherrer Institut (PSI) (Villigen, Switzerland) which is the only

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

In the news



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Shrinking proton puzzle persists in new measurement

19:00 24 January 2013 by Lisa Gros

A puzzle at the heart of the atom refuse
measurement yet of the proton's radius
smaller than the laws of physics deman
debated for two years.

The latest finding deepens the need for
explanation, to account for the inconsis
hole is deeper now," says Gerald Miller
Seattle, who was not involved in the ne

The saga of the proton radius began in
Pohl at the Max Planck Institute of Qua
determined the width of the fuzzy ball o
smaller than had been assumed.

Previous teams had inferred the proton
measure directly, by studying how elect
uses the simplest atom, hydrogen, whic
proton. A quirk of quantum mechanics

www.sciencenews.org/view/generic/id/347775/description/Protons_radius_revised_downward

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Proton's radius revised downward

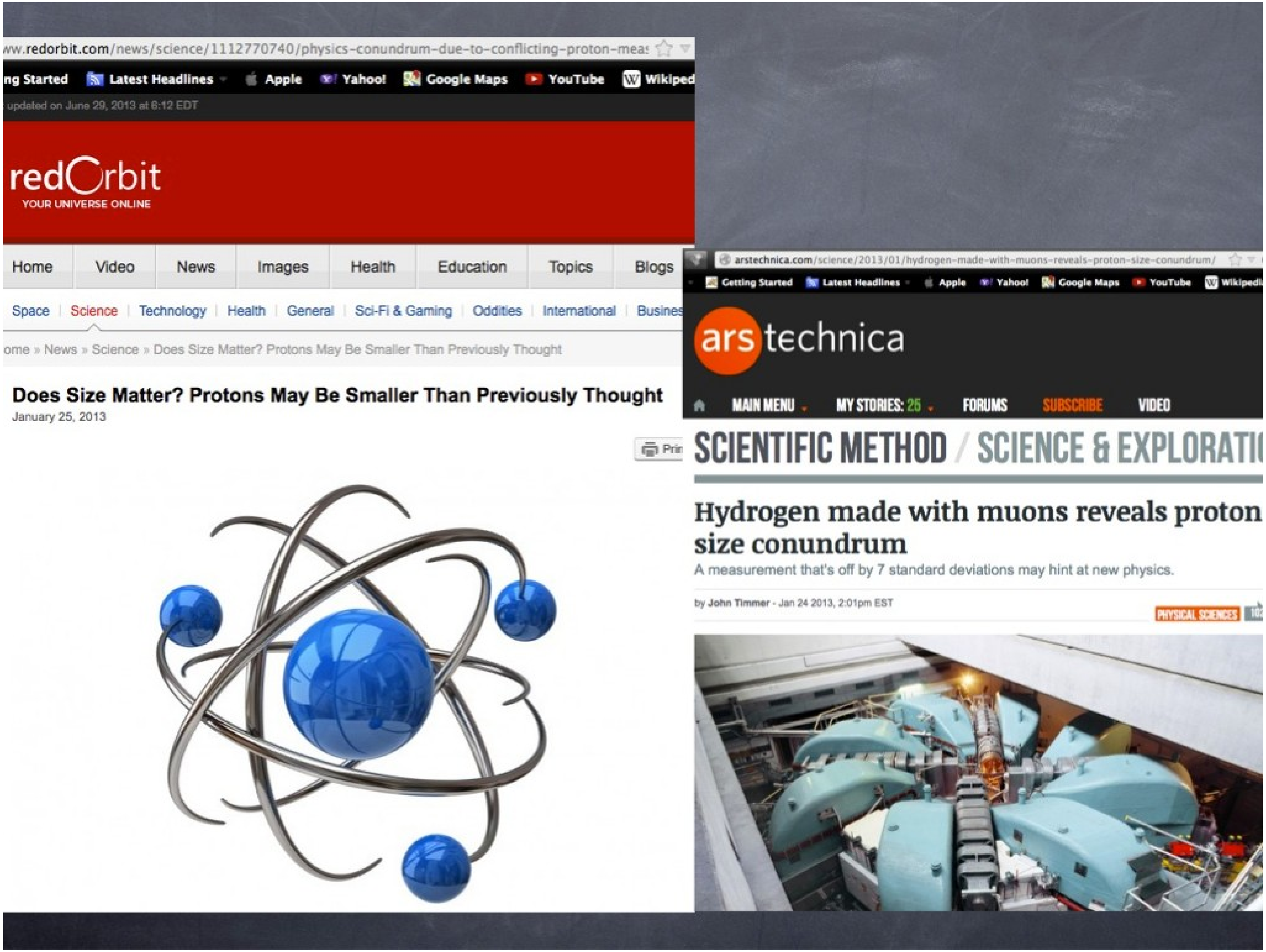
Surprise measurement may point to new physics

By Andrew Grant
Web edition: January 24, 2013
Print edition: February 23, 2013; Vol.183 #4 (p. 8)

A+ A-

Only in physics can a few quintillionths of a meter be cause for uneasy
excitement. A new measurement finds that the proton is about 4 perce
smaller than previous experiments suggest. The study, published in the
25 issue of *Science*, has physicists cautiously optimistic that the discre
between experiments will lead to the discovery of new particles or force

In the news



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Does Size Matter? Protons May Be Smaller Than Previously Thought
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SCIENTIFIC METHOD
Hydrogen made with muons reveals proton size conundrum
A measurement that's off by 7 standard deviations may hint at new physics.
by John Timmer - Jan 24 2013, 2:01pm EST

In the news

phys.org/news/2013-01-physicists-surprisingly-small-proton-radius.html

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Physicists confirm surprisingly s

Jan 24, 2013

International team of physicists confirms surprisingly small proton
spectroscopy of exotic hydrogen. The initial results puzzled the w
the size of the proton (to be precise, its charge radius), measured
which the electron orbiting the nucleus is replaced by a negatively
yielded a value significantly smaller than the one from previous in
hydrogen or electron-proton-scattering. A new measurement by th
the value of the electric charge radius and makes it possible for th
determine the magnetic radius of the proton via laser spectroscop

The experiments were carried out at the Paul Scherrer Institut (PS
Switzerland) which is the only research institute in the world provi
amount of muons. The international collaboration included the Ma
Quantum Optics (MPQ) in Garching near Munich, the Swiss Fede
Technology ETH Zurich, the University of Fribourg, the Institut für

www.huffingtonpost.com/2013/01/25/proton-radius-smaller-physicists-new-research_n_2549576.h

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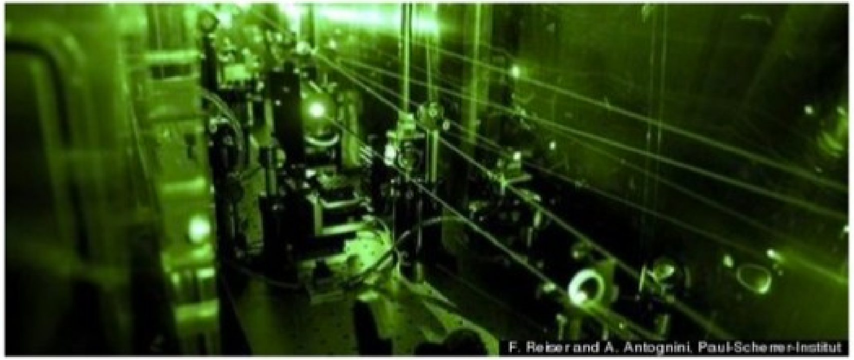
Proton Radius Is Smaller Than Physicists Had Thought, New Research Shows

Posted: 01/25/2013 8:20 am EST

Like · 242 people like this.



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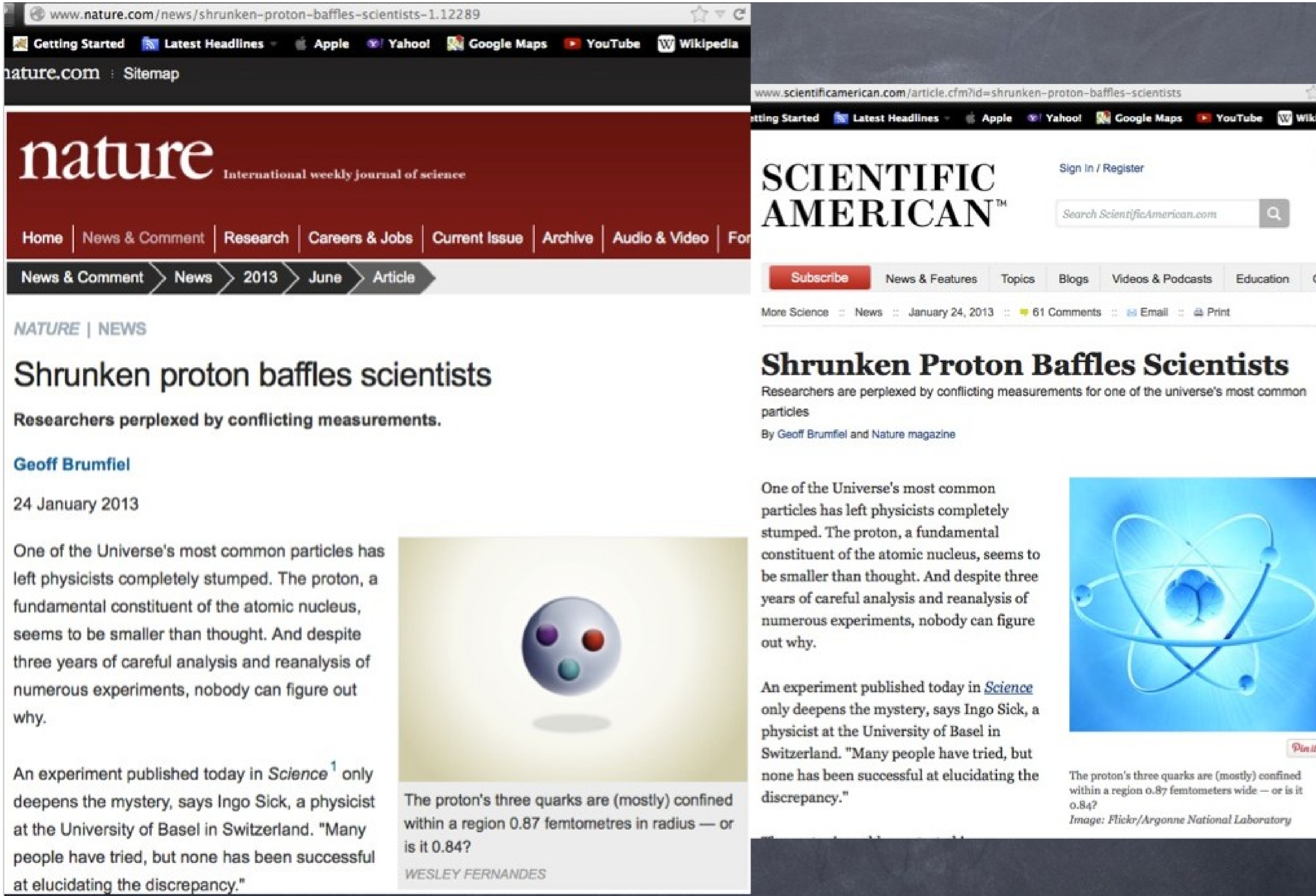
By: Jesse Emspak, LiveScience Contributor
Published: 01/24/2013 03:02 PM EST on LiveScience

How many protons can dance on the head of a pin? The answer is nowhere near as straightforward as one may think — and it might offer new insights into one of the most well-tested theories in physics.

In the news



www.nature.com/news/shrunken-proton-baffles-scientists-1.12289

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News & Comment > News > 2013 > June > Article

NATURE | NEWS

Shrunken proton baffles scientists

Researchers perplexed by conflicting measurements.

Geoff Brumfiel

24 January 2013

One of the Universe's most common particles has left physicists completely stumped. The proton, a fundamental constituent of the atomic nucleus, seems to be smaller than thought. And despite three years of careful analysis and reanalysis of numerous experiments, nobody can figure out why.

An experiment published today in *Science*[1] only deepens the mystery, says Ingo Sick, a physicist at the University of Basel in Switzerland. "Many people have tried, but none has been successful at elucidating the discrepancy."

The proton's three quarks are (mostly) confined within a region 0.87 femtometres in radius — or is it 0.84?

WESLEY FERNANDES

www.scientificamerican.com/article.cfm?id=shrunken-proton-baffles-scientists

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Shrunken Proton Baffles Scientists

Researchers are perplexed by conflicting measurements for one of the universe's most common particles

By Geoff Brumfiel and Nature magazine

One of the Universe's most common particles has left physicists completely stumped. The proton, a fundamental constituent of the atomic nucleus, seems to be smaller than thought. And despite three years of careful analysis and reanalysis of numerous experiments, nobody can figure out why.

An experiment published today in *Science* only deepens the mystery, says Ingo Sick, a physicist at the University of Basel in Switzerland. "Many people have tried, but none has been successful at elucidating the discrepancy."

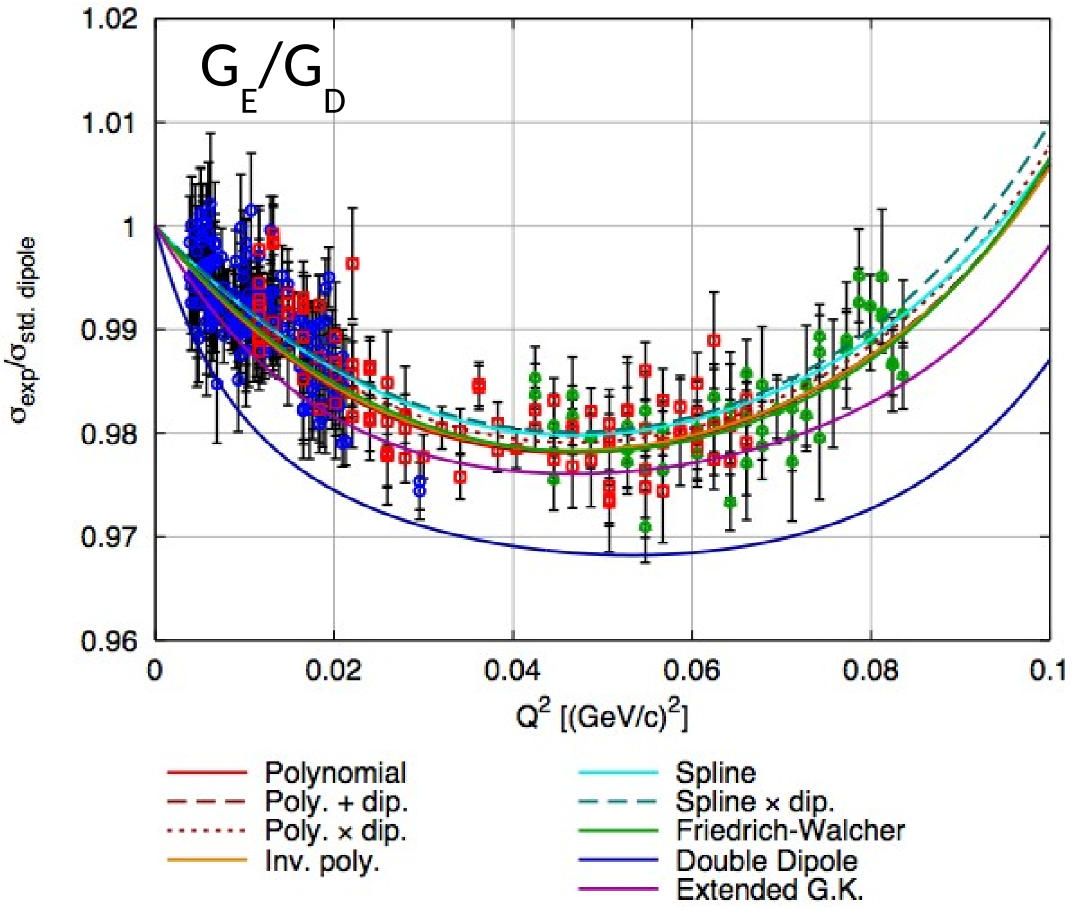
Pin it

The proton's three quarks are (mostly) confined within a region 0.87 femtometers wide — or is it 0.84?
Image: Flickr/Argonne National Laboratory

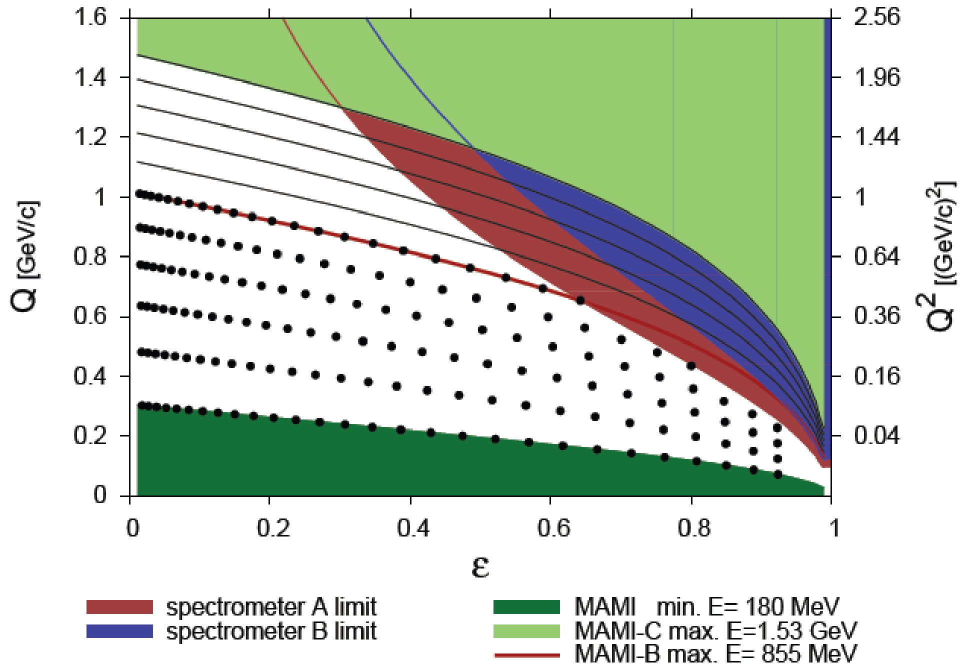
Elastic ep Scattering

Radius extracted from slope of the form factor at $Q^2 = 0$:

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



Bernauer *et al.* (2010)



1400 points covering $Q^2 \sim 0.004$ – 1 GeV^{2,} point-to-point cross section uncertainties 0.4%

Studied multiple fit forms

Precise extractions

$r_E = 0.879 \pm 0.008$ fm

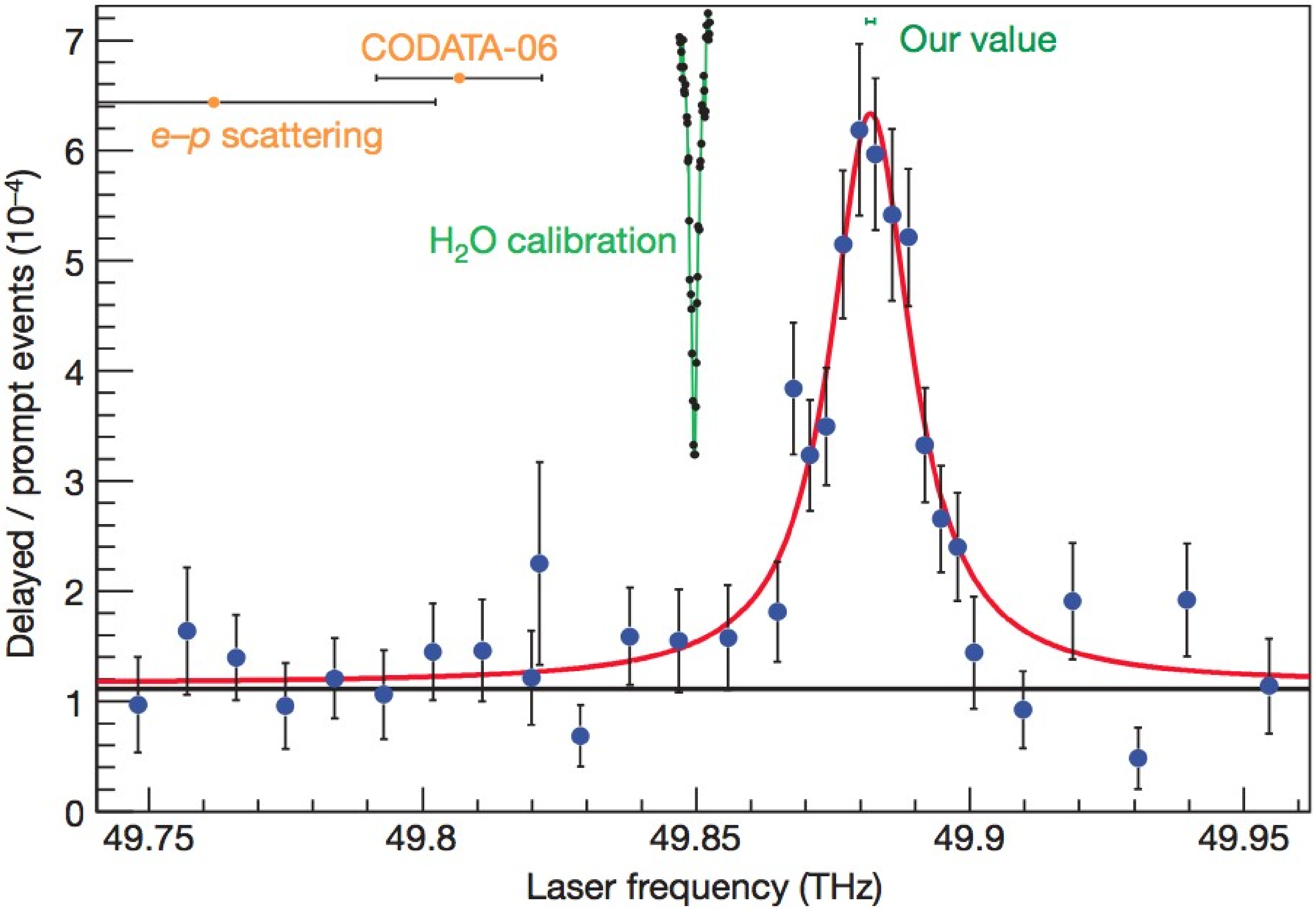
$r_M = 0.777 \pm 0.017$ fm

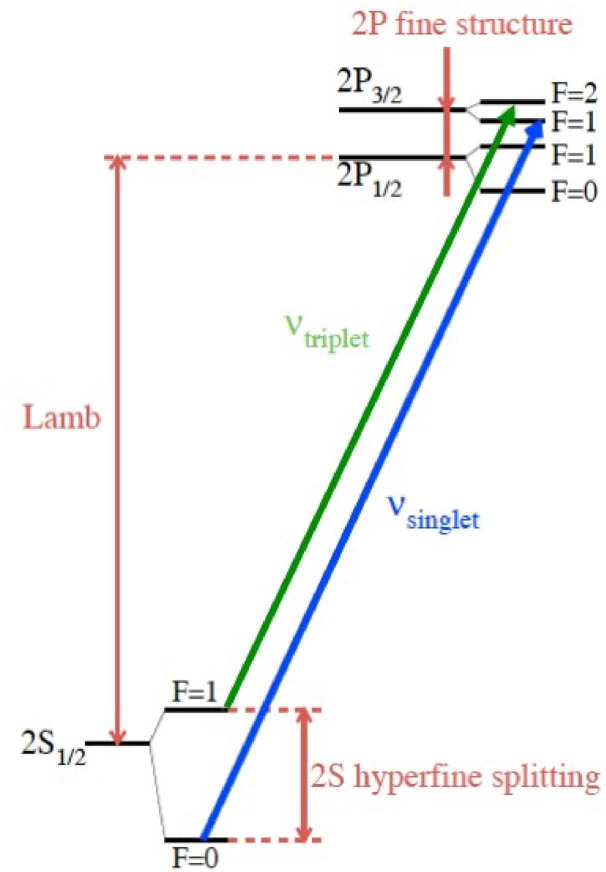
Muonic Hydrogen

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

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

$r_p = 0.84184 \pm 0.00067$ fm





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

$r_p = 0.84087 \pm 0.00039$ fm

PDG Summary

Most measurements of the radius of the proton involve electron-proton interactions, and most of the more recent values agree with one another. The most precise of these is rp = 0.879(8) fm (BERNAUER 2010). The CODATA 10 value (MOHR 2012), obtained from the electronic results, is 0.8775(51). However, a measurement using muonic hydrogen finds rp = 0.84087(39) fm (ANTOGNINI 2013), which is 13 times more precise and seven standard deviations (using the CODATA 10 error) from the electronic results.

...

Until the difference between the ep and μp values is understood, it does not make sense to average the values together. For the present, we give both values.

It is up to workers in this field to solve this puzzle.

Possible Explanations

- Experimental issues…
  - μp is wrong: 3-body effects, …
  - ep is wrong: underestimated uncertainties, bad radius extractions, …
- New physics…
  - Beyond Standard Model: lepton non-universality, new force / particle (dark photon?), many theories exist! (see next slide)
  - Novel Hadronic Physics: proton polarizability correction (m_l^4) leading to enhanced two-photon exchange for μp
- Many bad theories ruled out…
  - Structure in form factor, quantum gravity, oscillating protons, frame dependence, large 3rd Zemach moment, measuring different things
- No explanation with majority support in community
- Need More Data!

Dark Photons and the PRP

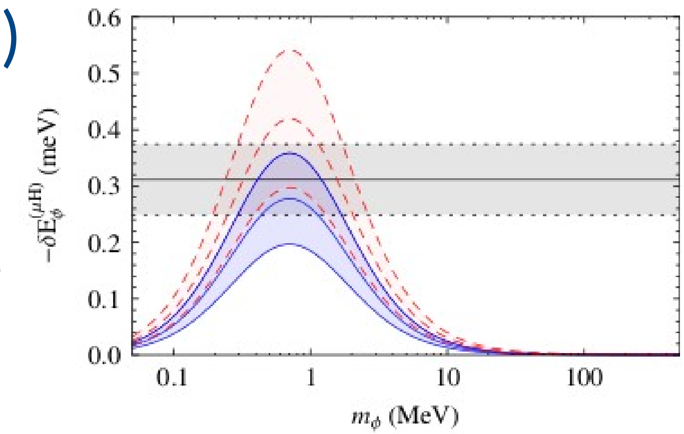
Examples that can solve the PRP and are consistent with muon g-2…

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

new force with few MeV mass particle coupling

to μ and p (not e)

predicts similar effect for μD, larger effect for μHe



Batell, McKeen, and Pospelov, PRL **107**, 011803 (2011)

New e/μ differentiating U(1) force, <100 MeV gauge boson,

predicts enhanced parity violation in μp scattering, order 10e-4

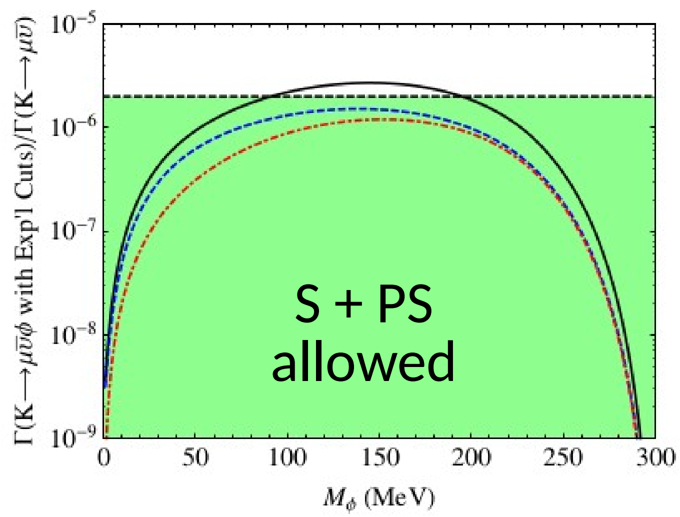
Carlson and Rislow, PRD **86**, 035013 (2012)

Two new particles couple to μ and not e

scalar + pseudoscalar or

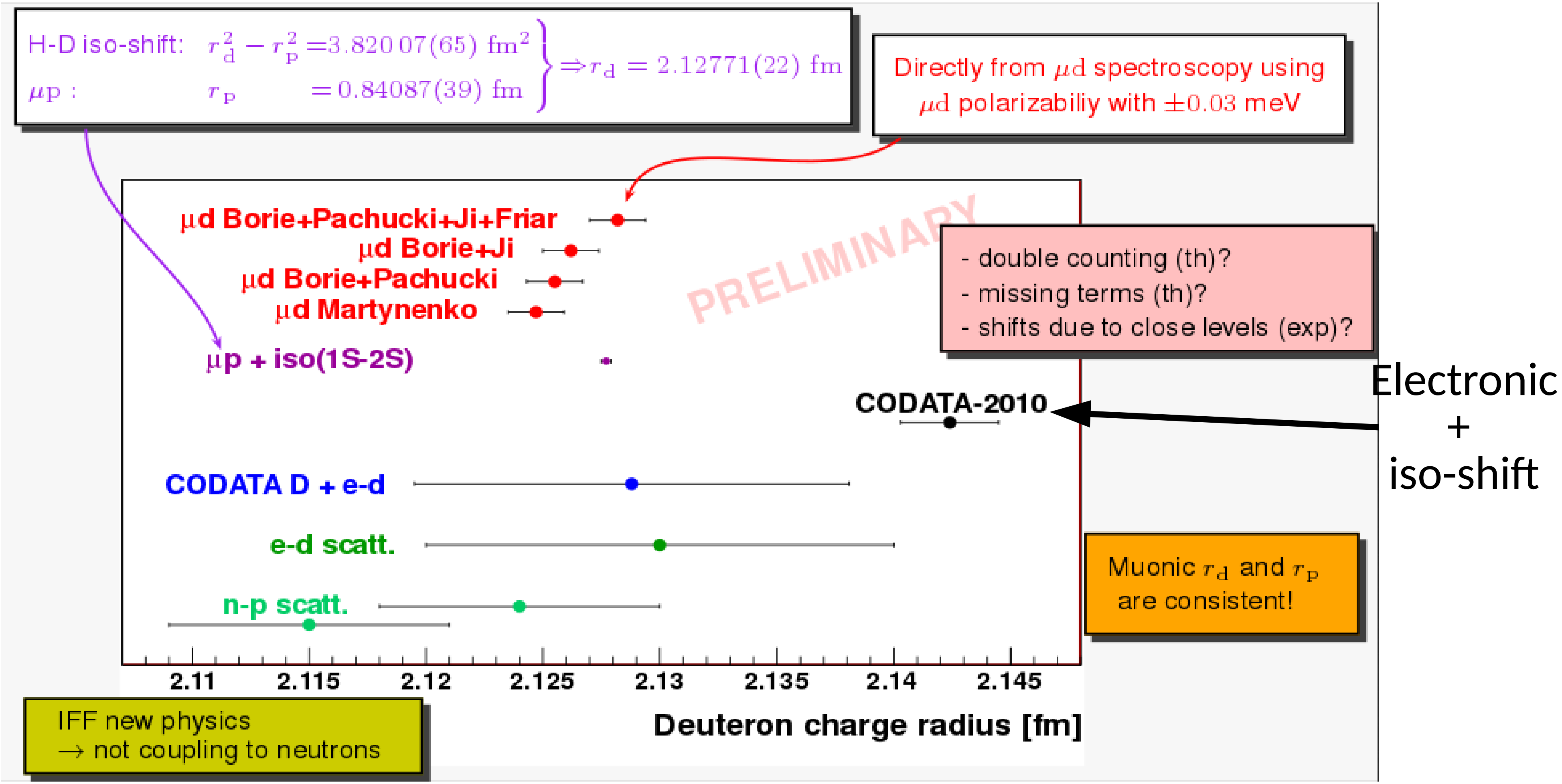
vector + axial vector

Constraints on allowed masses from Kaon decays



New: Heavier Muonic Systems

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

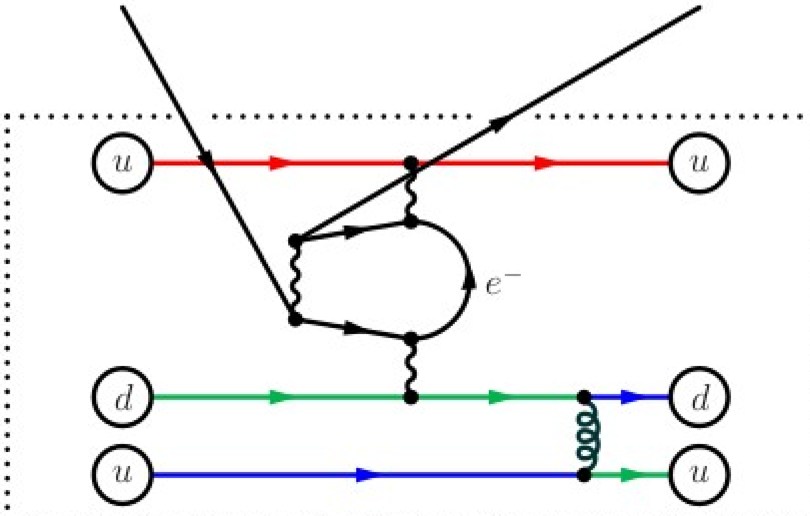


PRELIMINARY: muonic He and e-He scattering are consistent

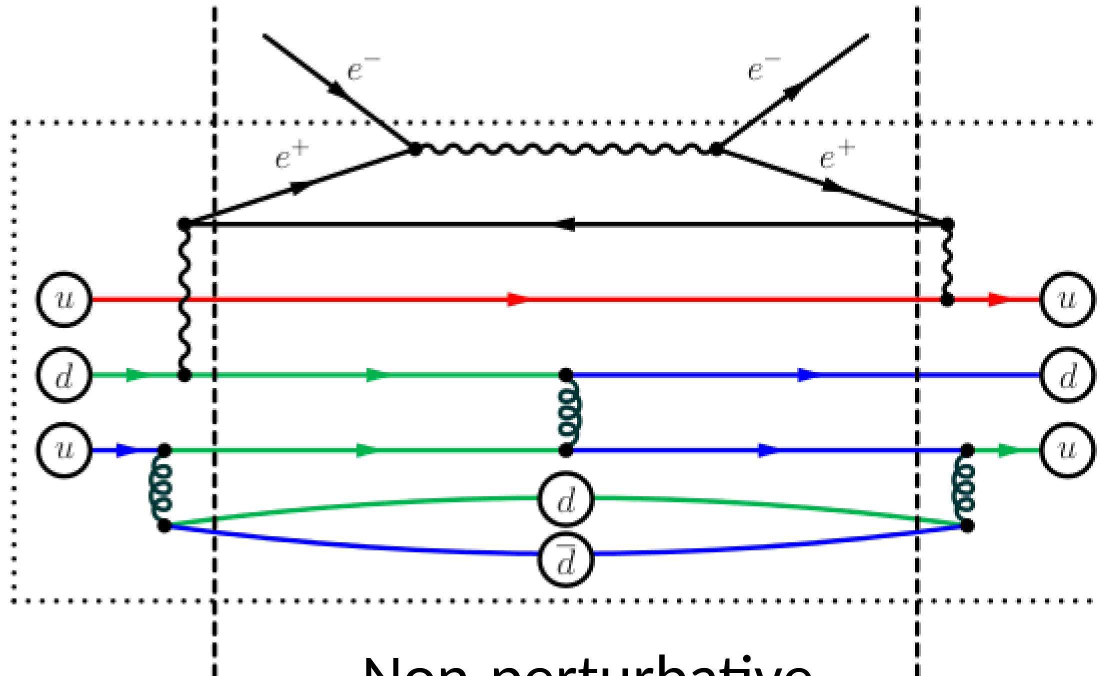
These limit theory models! Excludes Pospelov, limit NP with new particles to m < 1.5 MeV under certain assumptions (Carlson)

A Recent Nucleon Sea Idea

Jentschura, PRA **88**, 062514 (2013): Non-universality due to e+e- sea



Perterbative



Non-perturbative

- **Pertubative**: scattered electron coupling to electronic vacuum polarization, part of radiative correction to proton polarizability – too small
- **Non-perturbative**: ~10e-7 light e+e- sea pairs per valence quark, electrons measure a larger proton size
- **Controversial**, but not ruled out

What to do?

- New data needed to test that the e and μ are really different, and the implications of novel BSM and hadronic physics
  - 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 for radius comparison in heavier systems
  - Redoing electron scattering at lower Q^2
  - Muon proton Scattering
  - Muon Scattering on Nuclei
  - Kaon Decays

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MUSE tests these

Possible next gen.

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  - Hadronic: enhanced two-photon exchange
- Experiments include:
  - Redoing atomic hydrogen
  - Light muonic atoms for radius comparison in heavier systems **CREMA (μD, μHe)**
  - Redoing electron scattering at lower Q^2 **JLab (ep) & Mainz (ep, eD)**
  - Muon proton Scattering
  - Muon Scattering on Nuclei
  - Kaon Decays **TREK (J-PARC)**

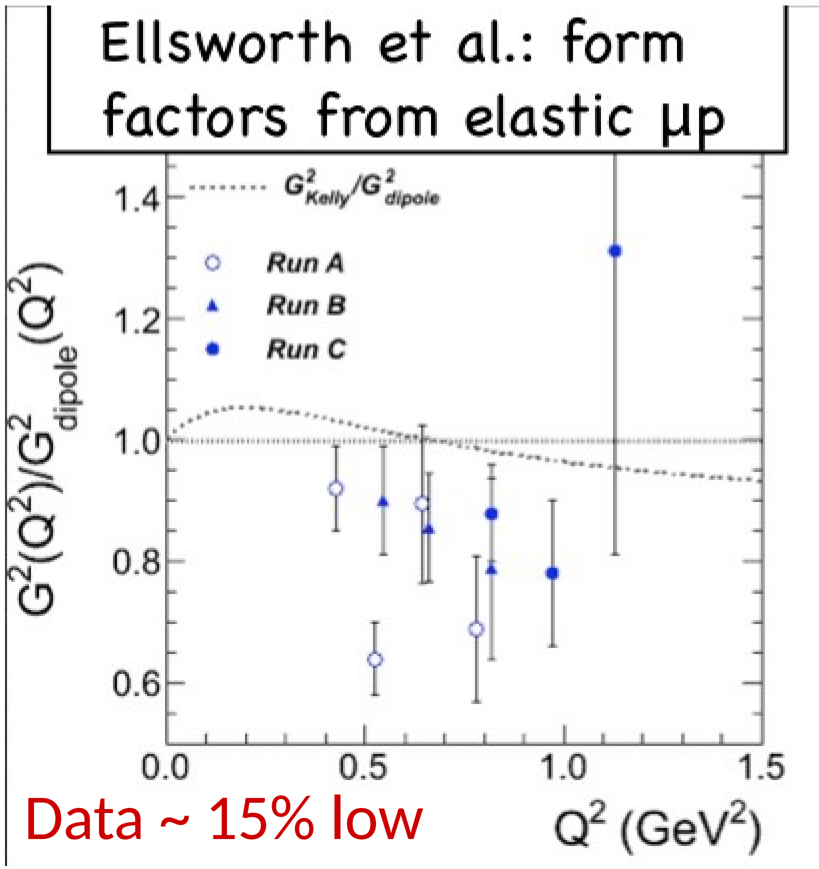
MUSE tests these

Possible next gen.

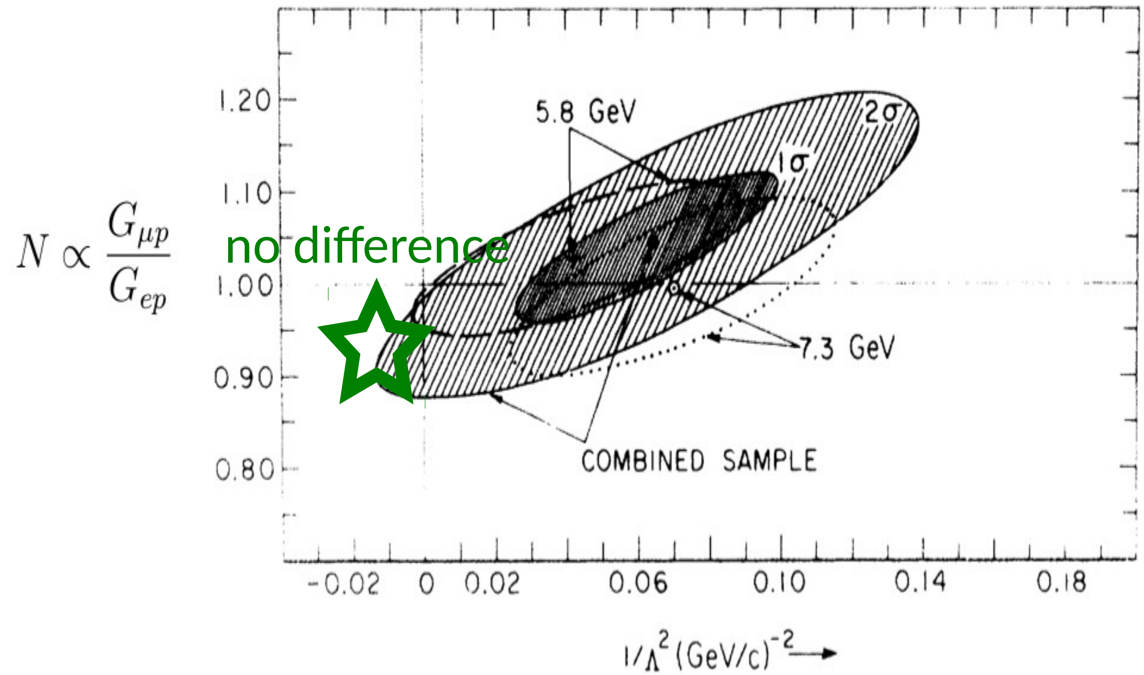
e-μ Universality

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

Elastic μp scattering: Ellsworth et al (1968)



Elastic μp scattering: Kostoulas et al (1974)



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

Also no evidence for TPE effects

e-μ Universality

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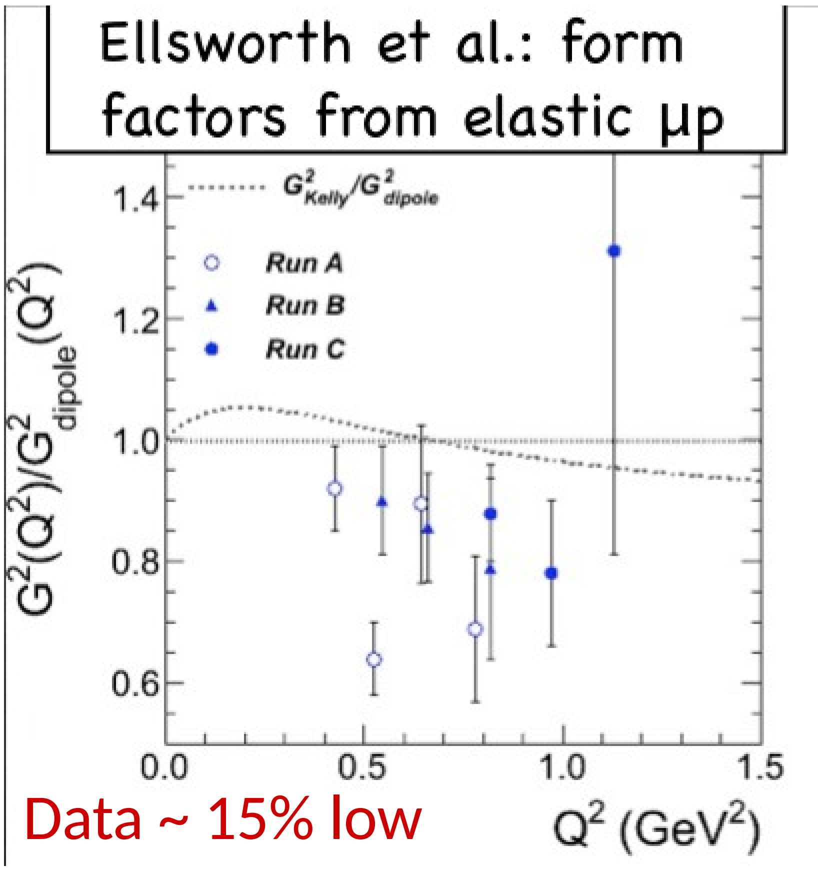
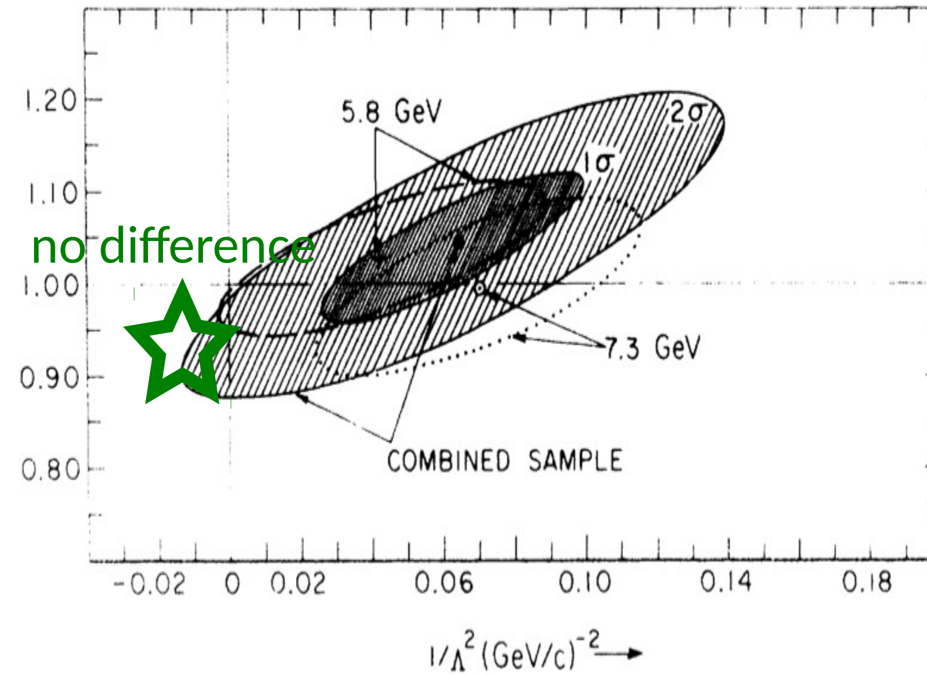


Elastic μp scattering: Kostoulas et al (1974)

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



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

e-C, and μ-C are in agreement

Also no evidence for TPE effects

Constraints not very good!

MUSE: μp scattering

Why μp elastic scattering?

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

MUSE:

→ First competitive μp measurement

→ simultaneous e and μ for direct comparison

→ will also measure TPE for e and μ

MUSE: μp scattering

Why μp elastic scattering?

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MUSE:

→ First competitive μp measurement

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→ will also measure TPE for e and μ

Challenges: secondary muon beam!

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

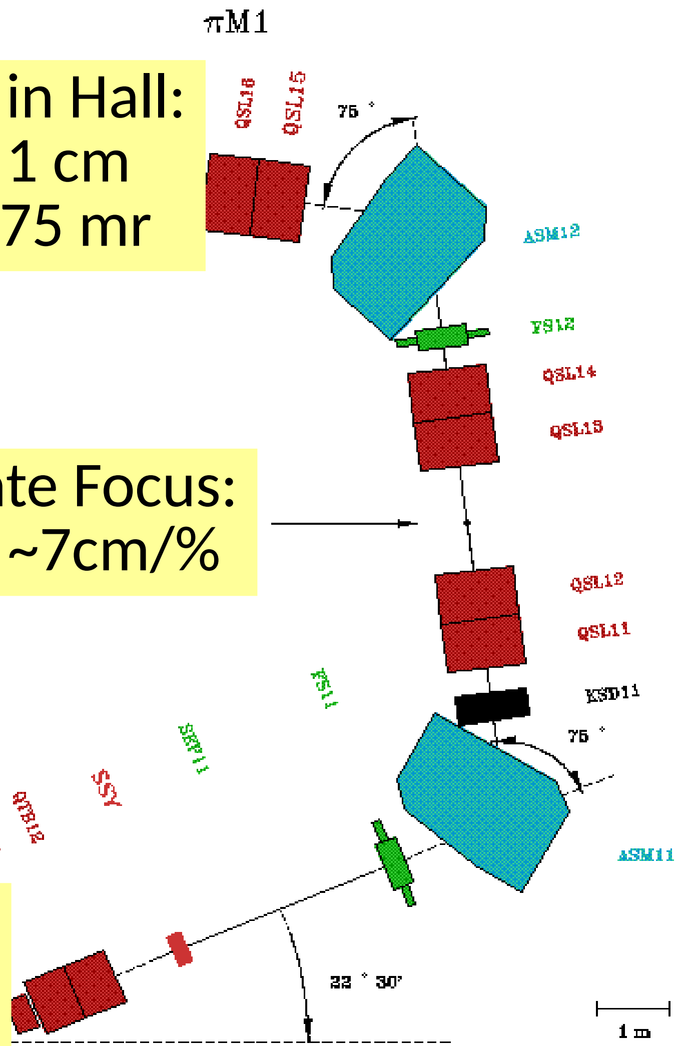
πM1 Channel at PSI

100-500 MeV/c mixed beam of e, μ, π

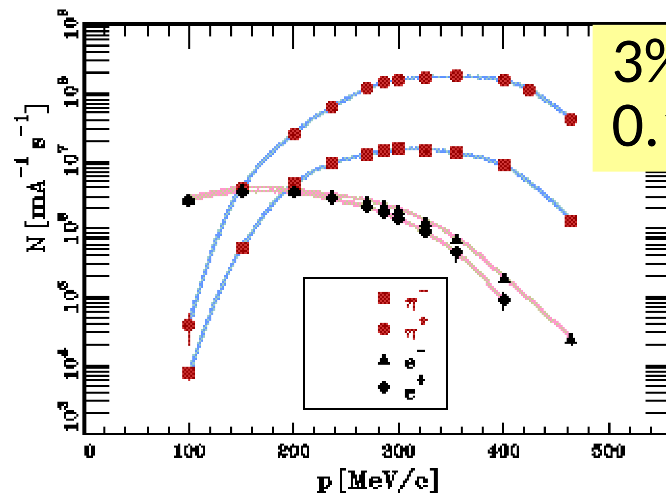
Beam spot in Hall:
~1.5 cm x 1 cm
~ 35 mr x 75 mr

Intermediate Focus:
Dispersion ~7cm/%

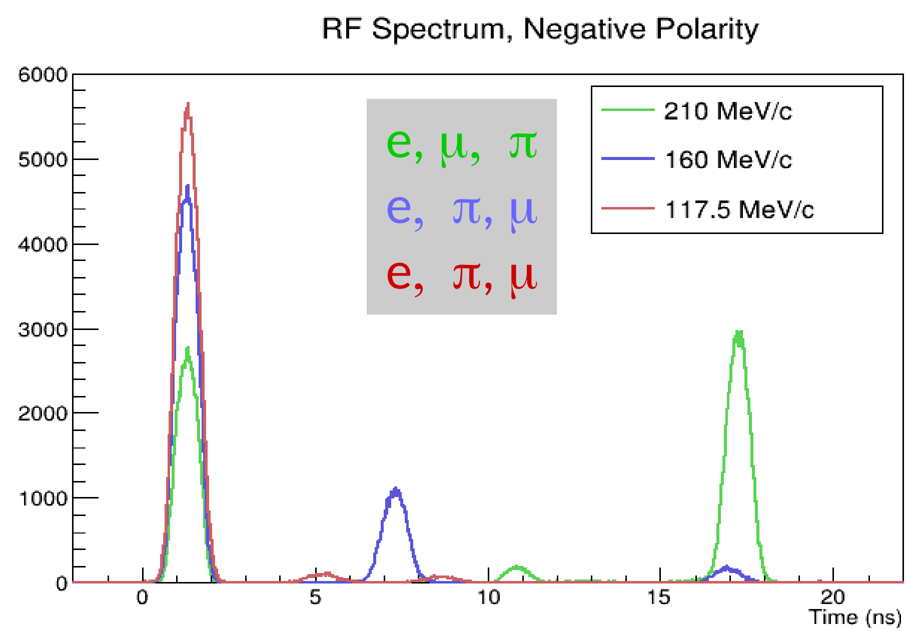
Production Target
50 MHz p



3% momentum
0.1% resolution

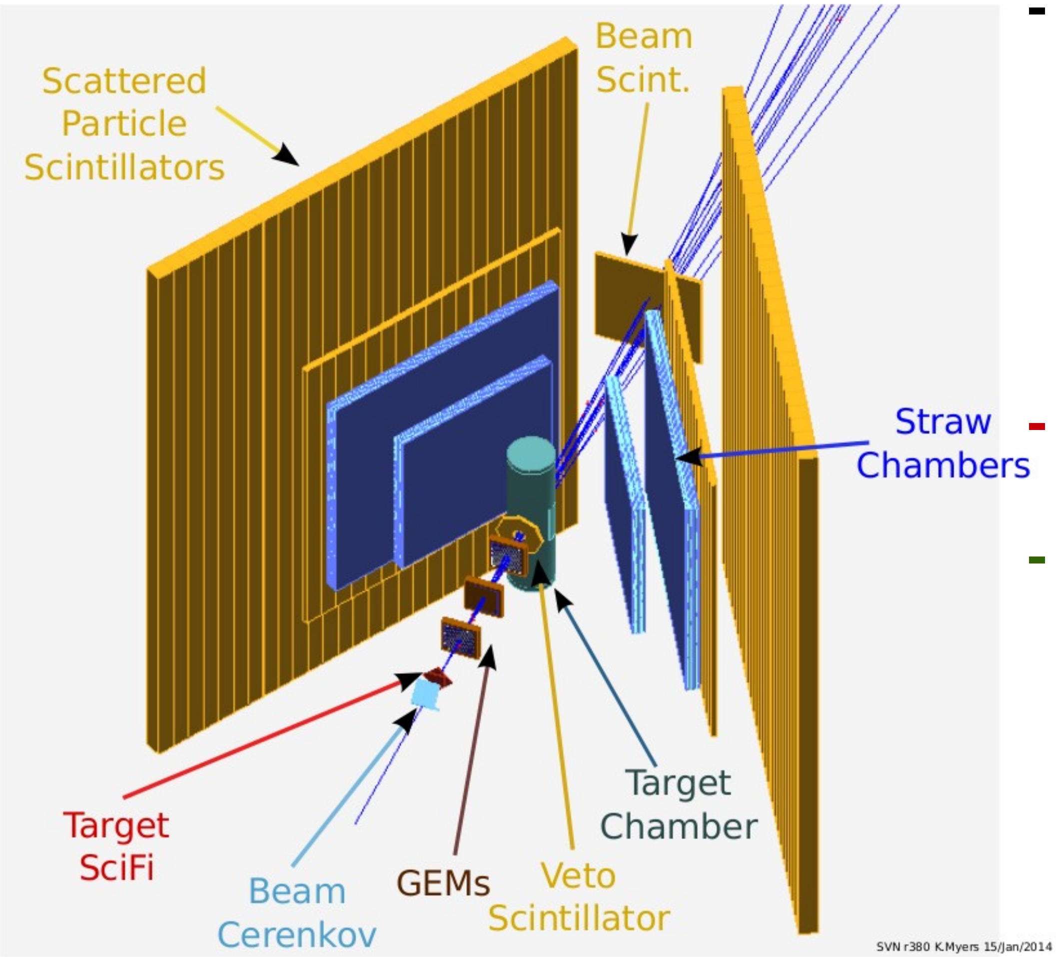


Timing separation at chosen momentum



Experiment Setup

Detector Overview in Simulation



- **Measure ep and μp cross sections**

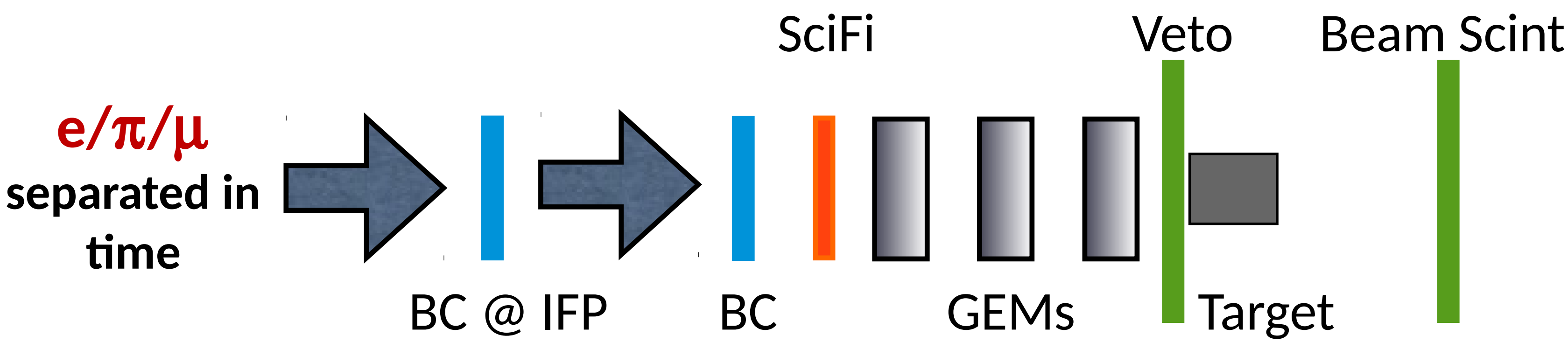
  p = 115, 158, and 210 MeV/c
  $\theta = 20^\circ - 100^\circ$
  $Q^2 = 0.002 - 0.07\ GeV^2$

- **Measure both + and – polarity**

- **Challenges**
  - Beam flux 5 MHz, DAQ rate 2 kHz, only order 1-10 Hz elastic events!
  - Require high pion rejection efficiency and good particle ID
  - Moller and muon decay from target need background subtraction

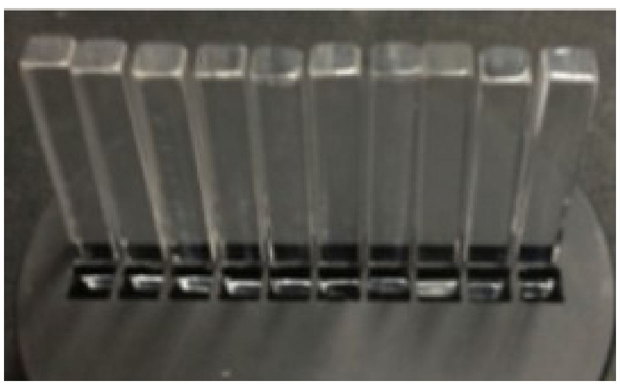
- TOF for PID, momentum determination
- Measure tracks before and after target
- Downstream beam scint. to monitor stability

Beamline Instrumentation



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

Sapphire Beam Cerenkov (Rutgers/HUJI)



Better timing at analysis level
Muon decay rejection, TOF, momentum determination
50 ps resolution expected

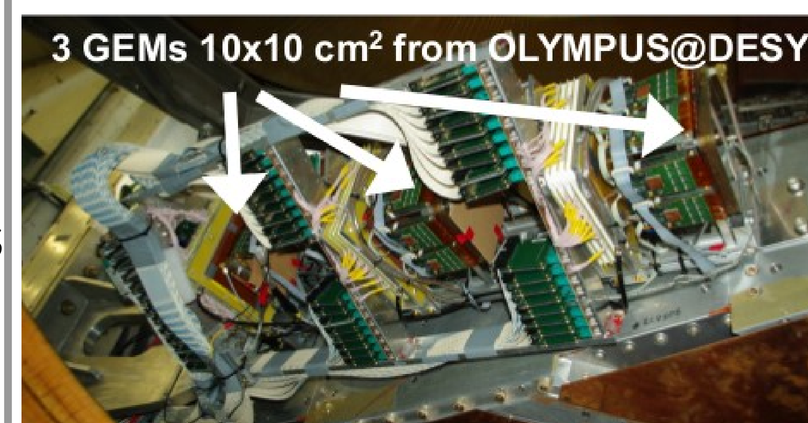
Scintillating Fiber Array (Tel Aviv)

GEMs (Hampton)

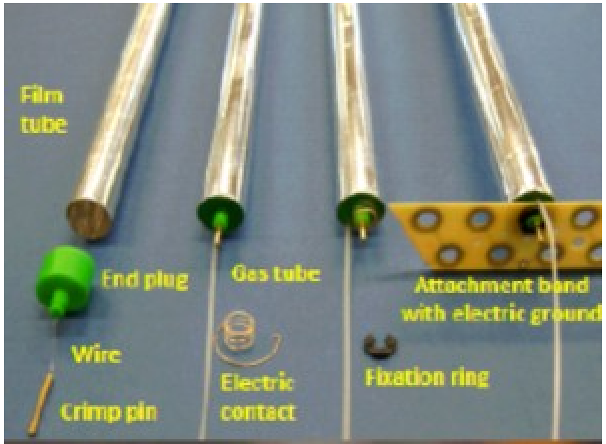
Determine angle incident to 0.5 mr

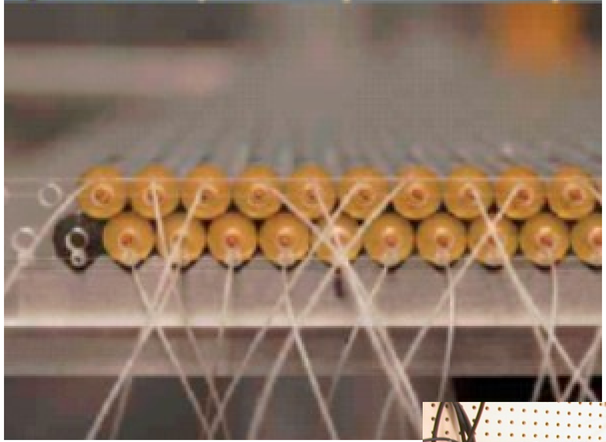
Third GEM to reject ghost tracks

Existing from OLYMPUS



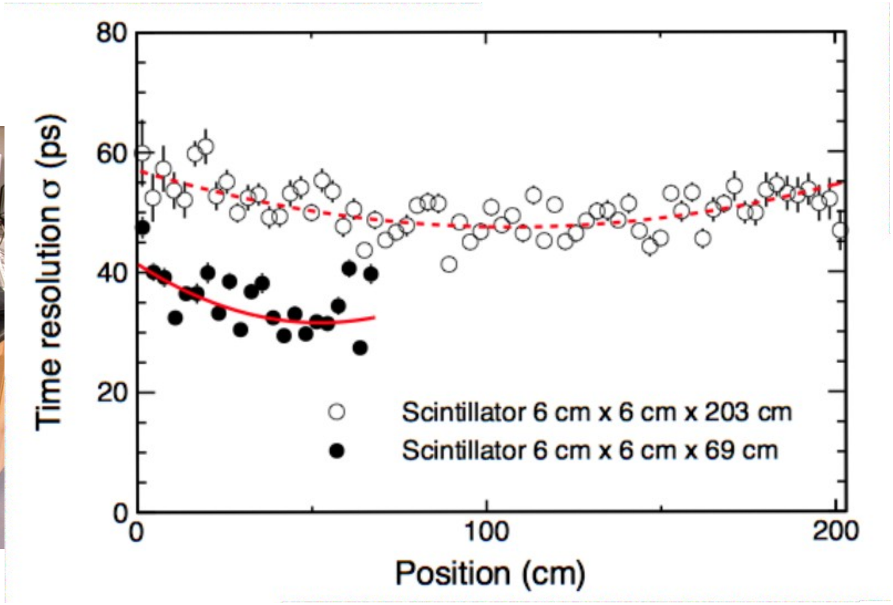
Scattered Particle Detectors





Straw Tube Tracker (HUJI + Temple):
~3000 straws, 2 chambers each side of beam,
determine scattered particle trajectory, 140 μm
Copy existing PANDA design
Calibrated relative to GEMs by rotating into beam

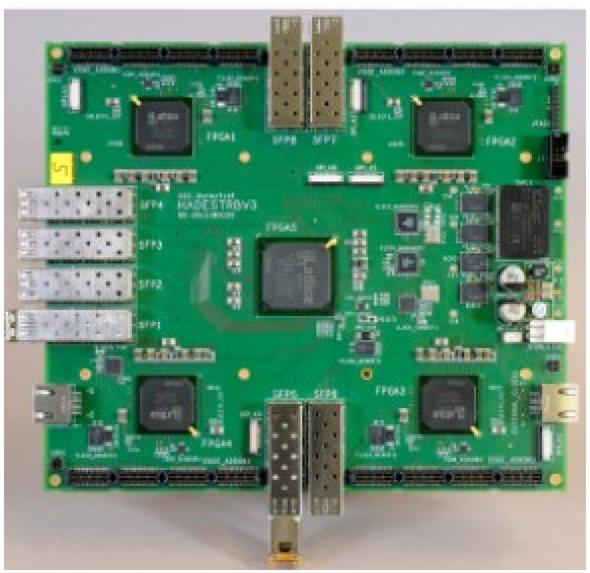
Fast scintillators (South Carolina):
~ 90 bars, 2 planes on each side of the beam
Copy CLAS12 design, 100 (200) cm long front (back)
High-precision 40-50 ps timing, part of beam PID

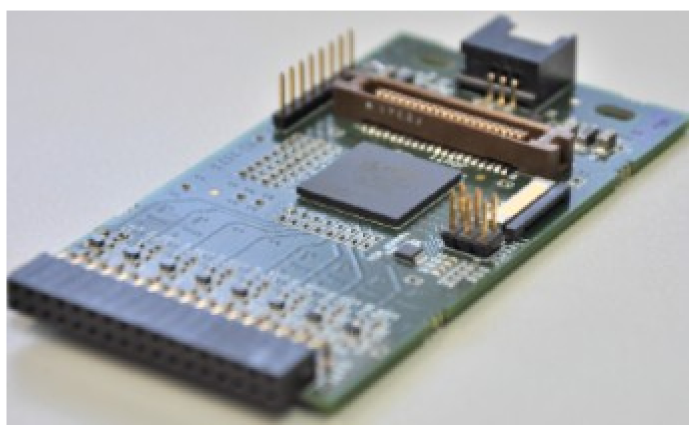


DAQ & Trigger

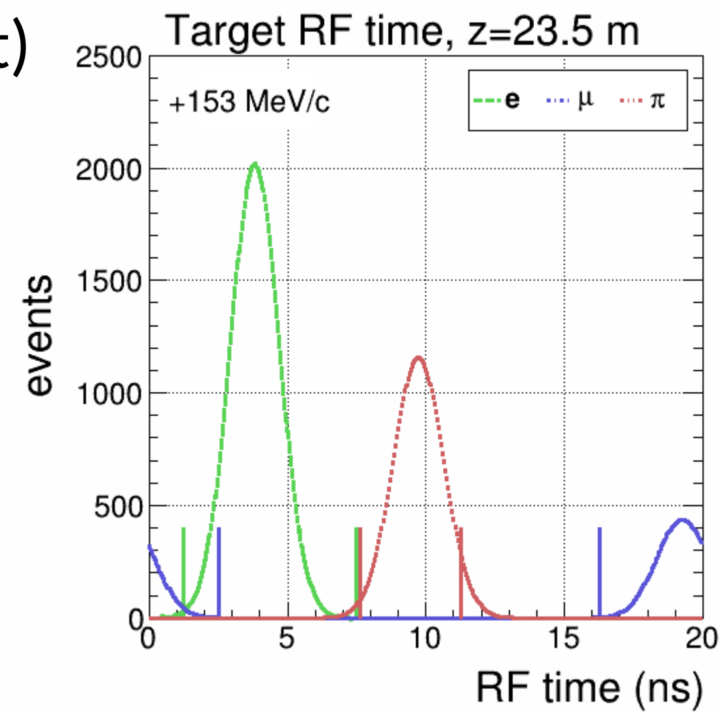
DAQ (GWU): Use custom TDCs – TRB3
- cost effective, 256 ch/board
- < 25 ps resolution (11 ps in GSI bench test)
- PADIWA for frontend amplifier/disc
- Scaler functionality on board
- 5 FPGAs/board

Use standard v792 ADCs for time-walk



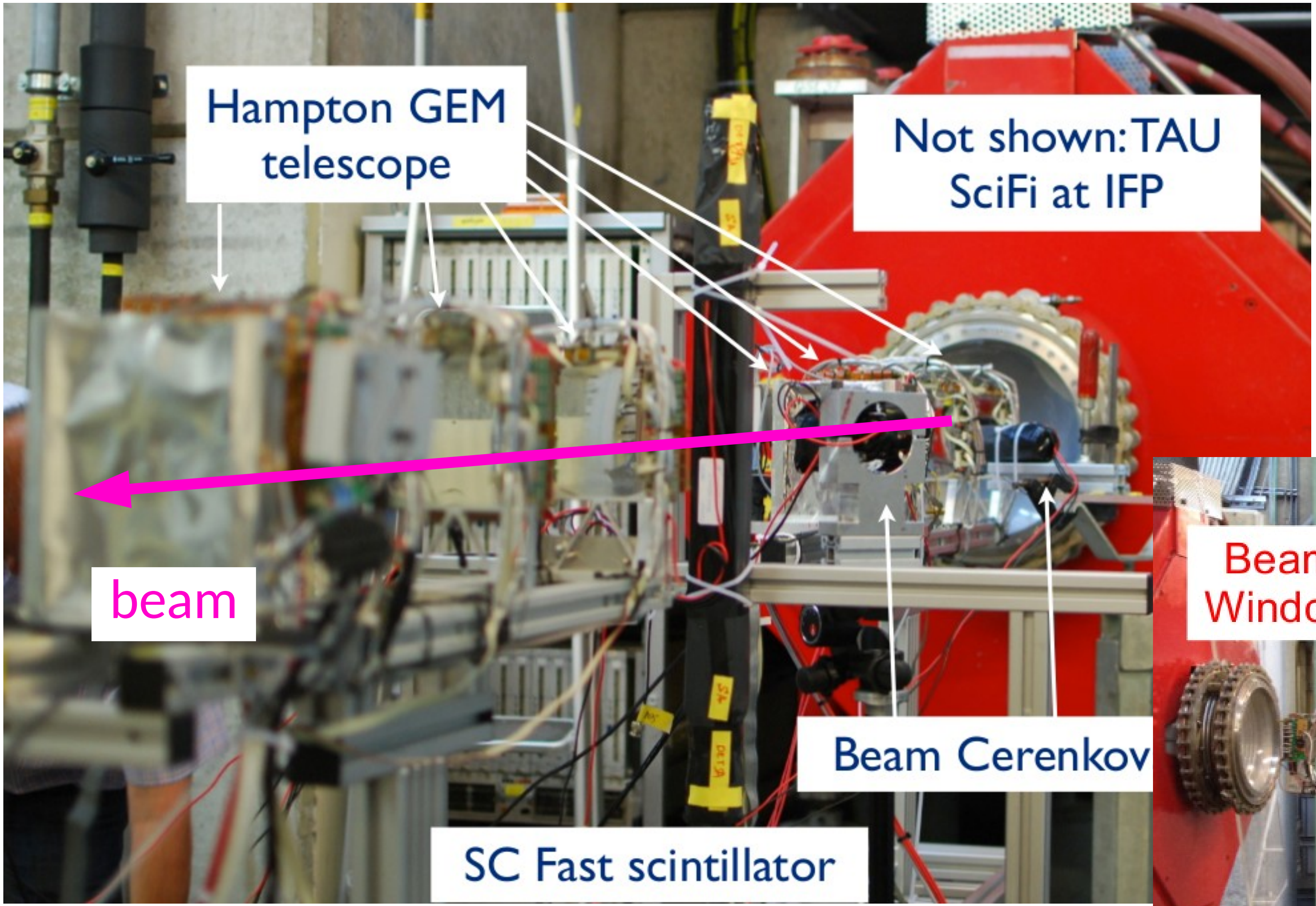


Trigger (Rutgers)

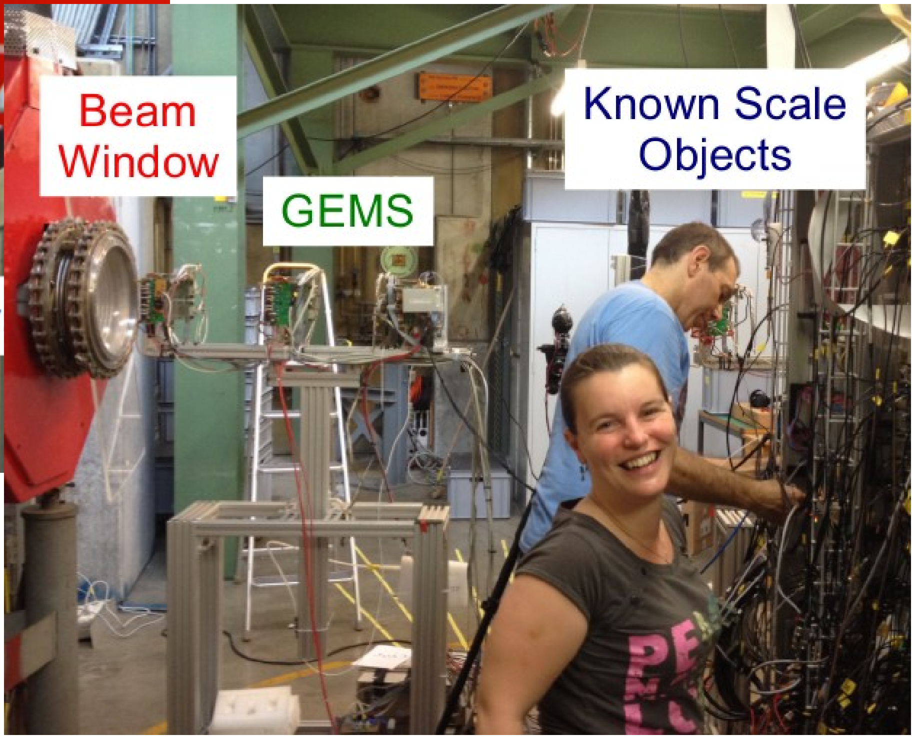


- Use FPGA from TRB3
- SciFi + BC + Beam RF determine beam PID
- Pion rejection >99.9%
- Trigger: beam PID + not VETO + scat. particle

Beam test measurements



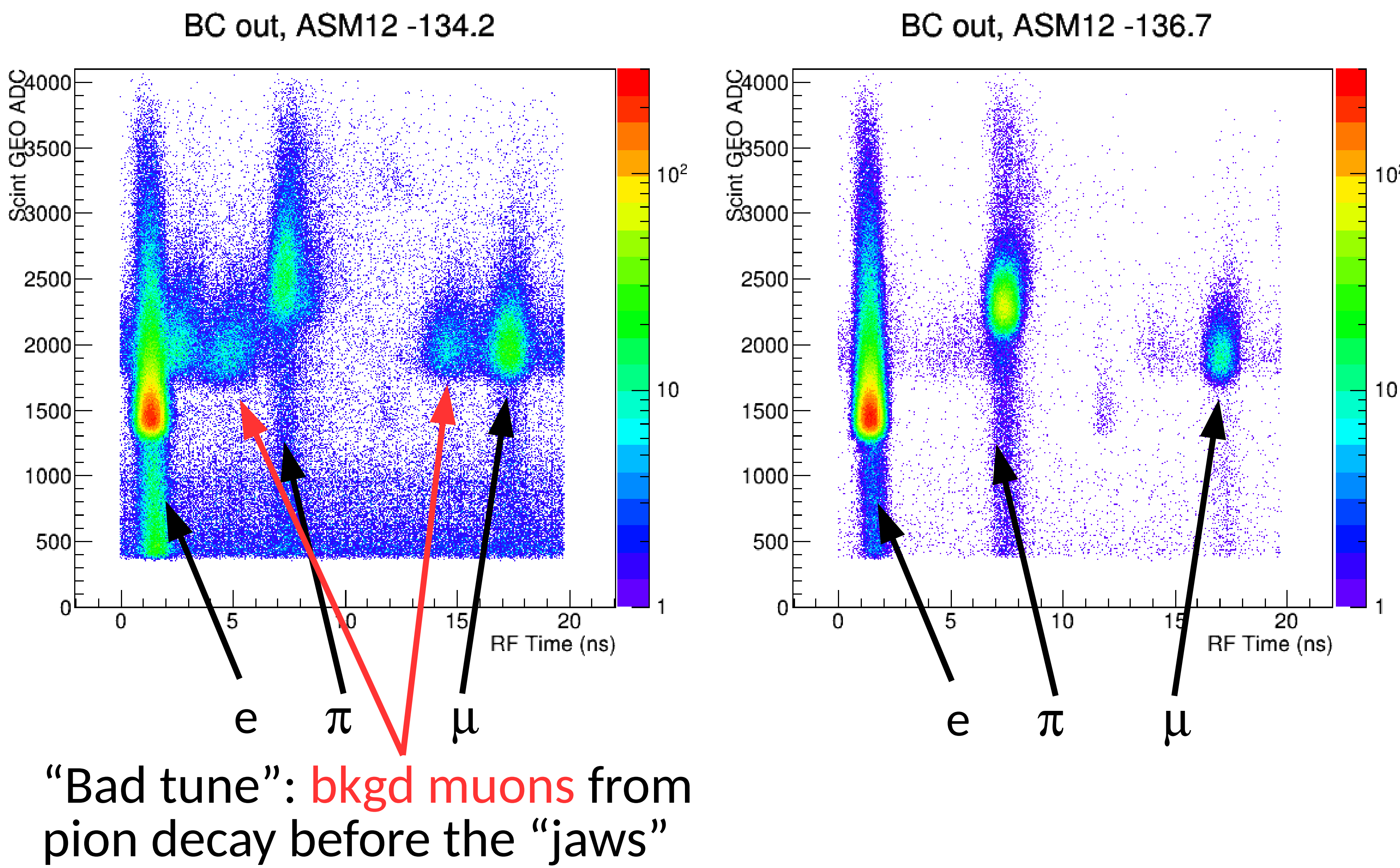
Test Measurements:
- Dec 2012
- June 2013
- Fall 2013
- June 2014
- Dec 2014 (planned)



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

Beam test measurements

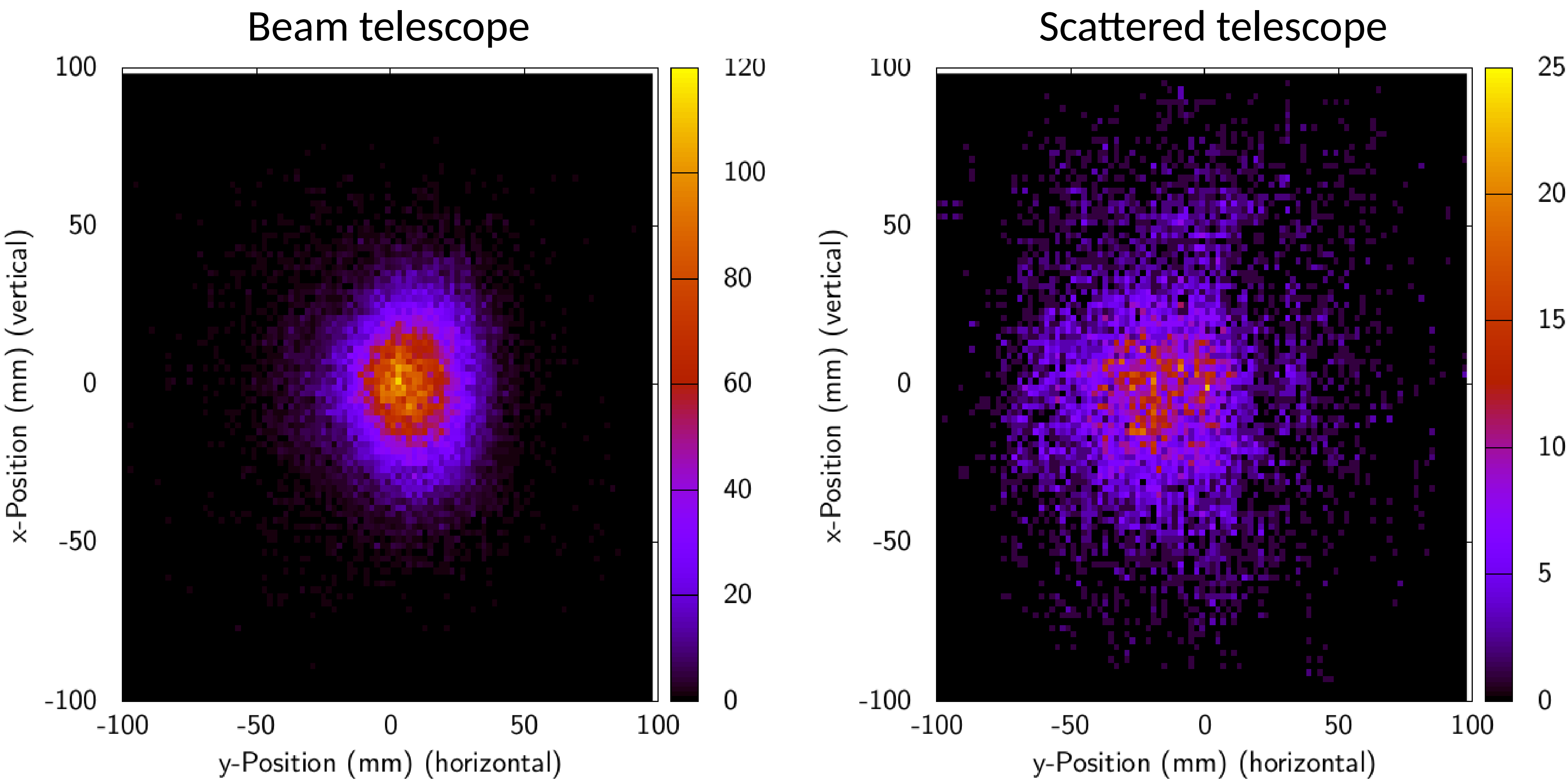
Studying the beam tune: ADC versus RF Time (total TOF over 23.5 m)



Beam test measurements

Mini Scattering Measurement – GEM tracks projected to target

Target IN

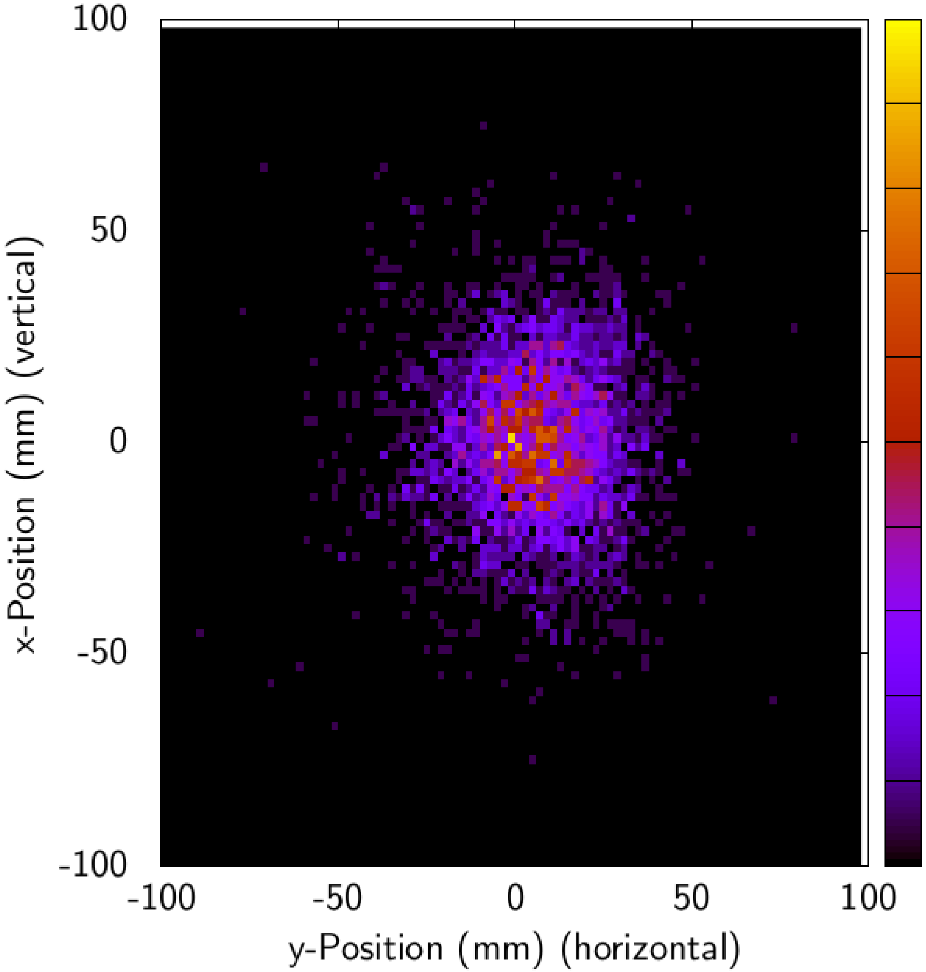


Beam test measurements

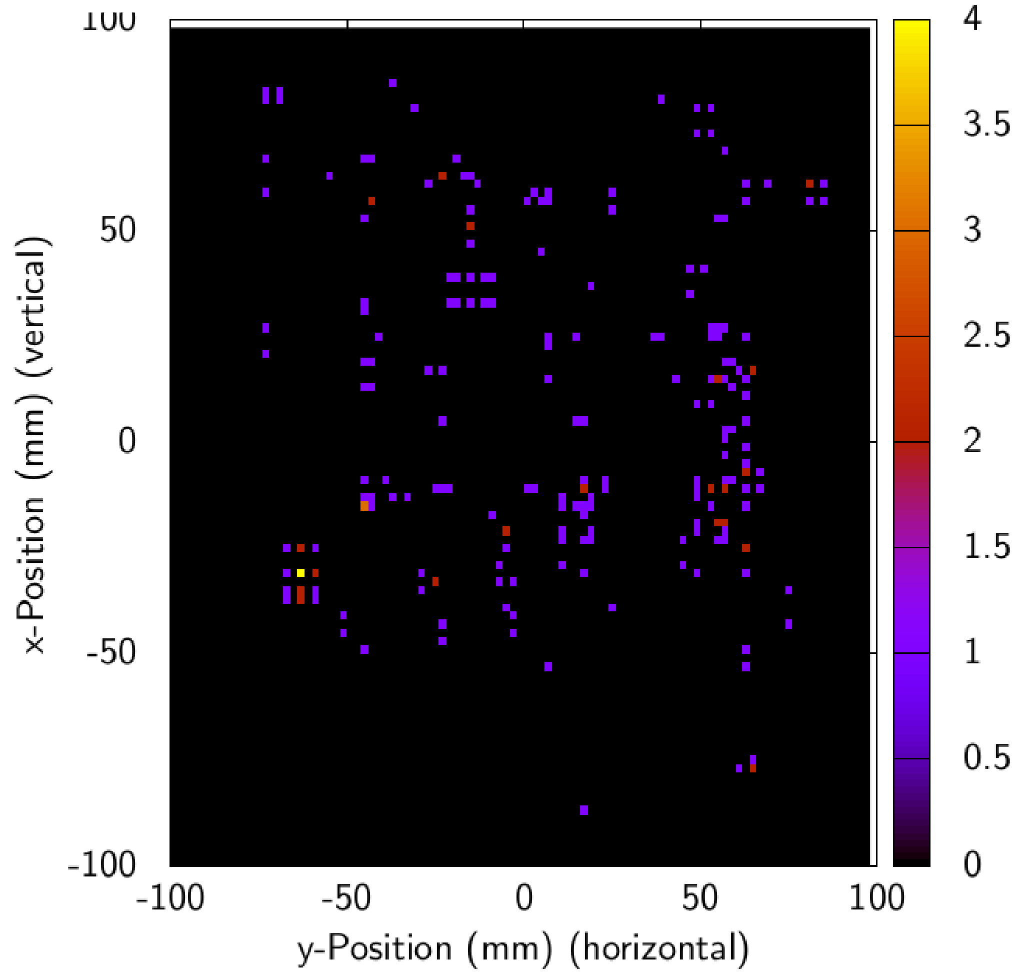
Mini Scattering Measurement – GEM tracks projected to target

Target OUT

Beam telescope



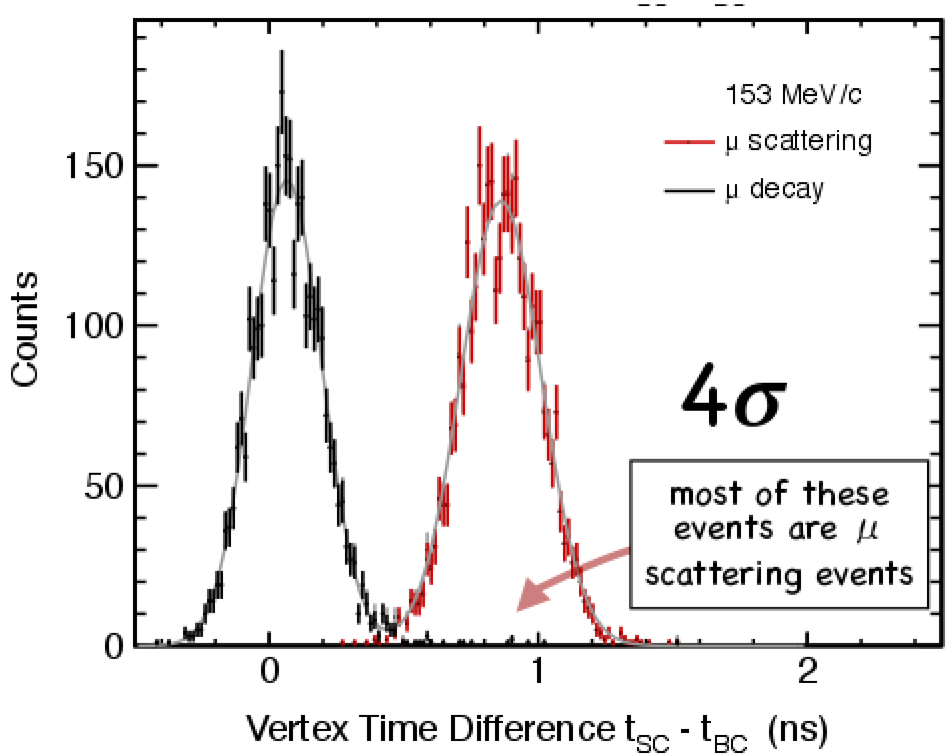
Scattered telescope



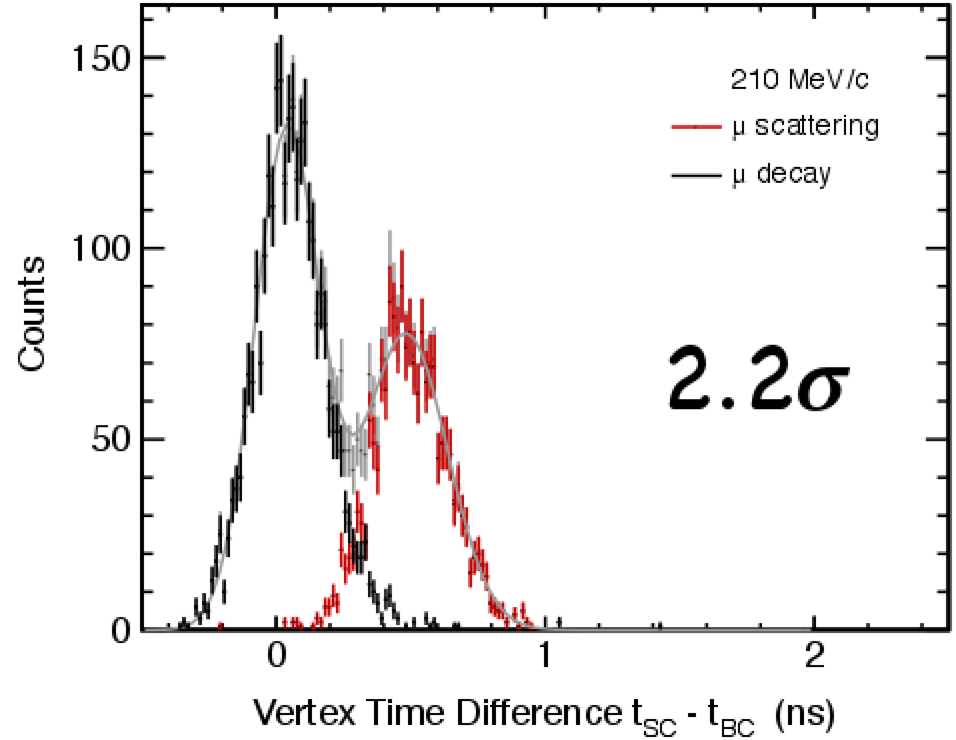
Decay Background Simulation

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

153 MeV/c



210 MeV/c



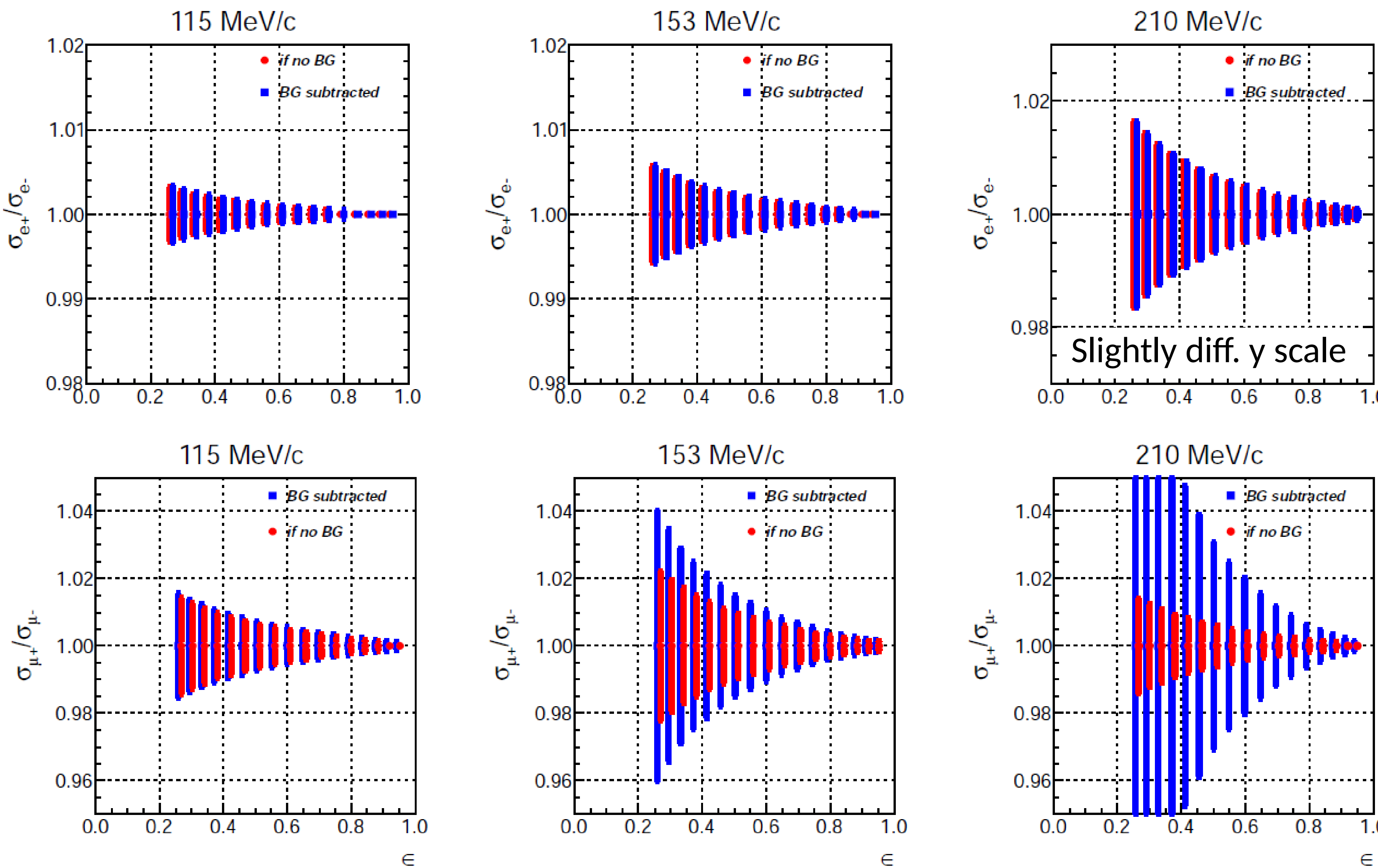
- Better (6σ) separation at 115 MeV/c
- Will also measure empty target for subtraction, can also calculate

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
- **Jan 2014:** 2nd PAC / PSI Review
- **March 2014:** NSF Review with DOE representation
- **Now:** R & D funding from NSF / DOE (amount tbd)
- **June & 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

Expected Results

Relative comparisons for e+/e- (top), mu+/mu- (bottom)

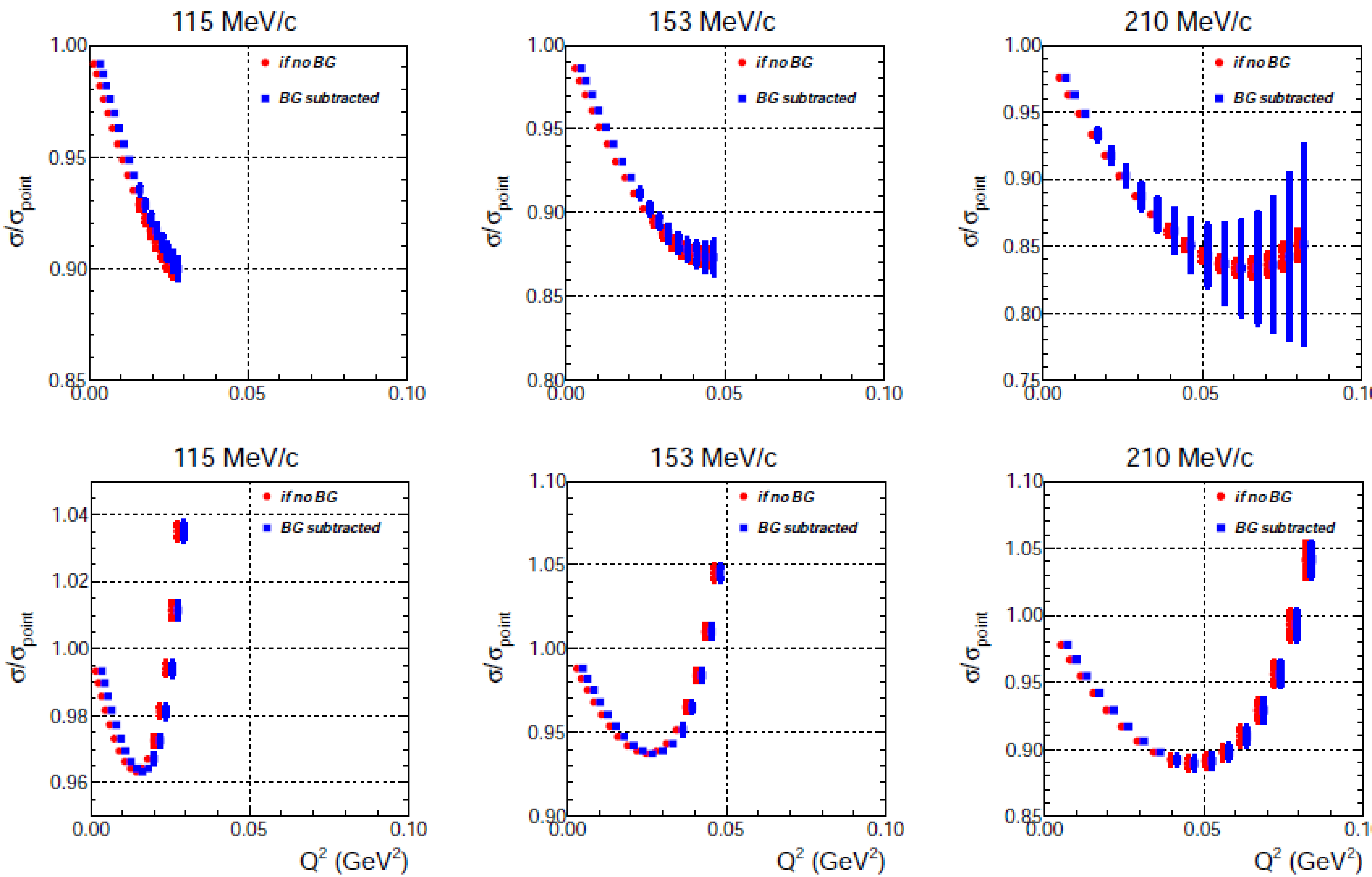


Stat. Errors only, but they dominate

Plotted versus epsilon -- virtual photon polarization

Expected Results

Cross Sections: μ^+p (top), e^+p (bottom) [Kelly FF's]



Offset in blue points for plotting

Statistical errors only

For electrons: Stat. errors well below 1%

For muons: Stat. errors below 1% for 115 and 153, above 1% at 210.

Expected Results

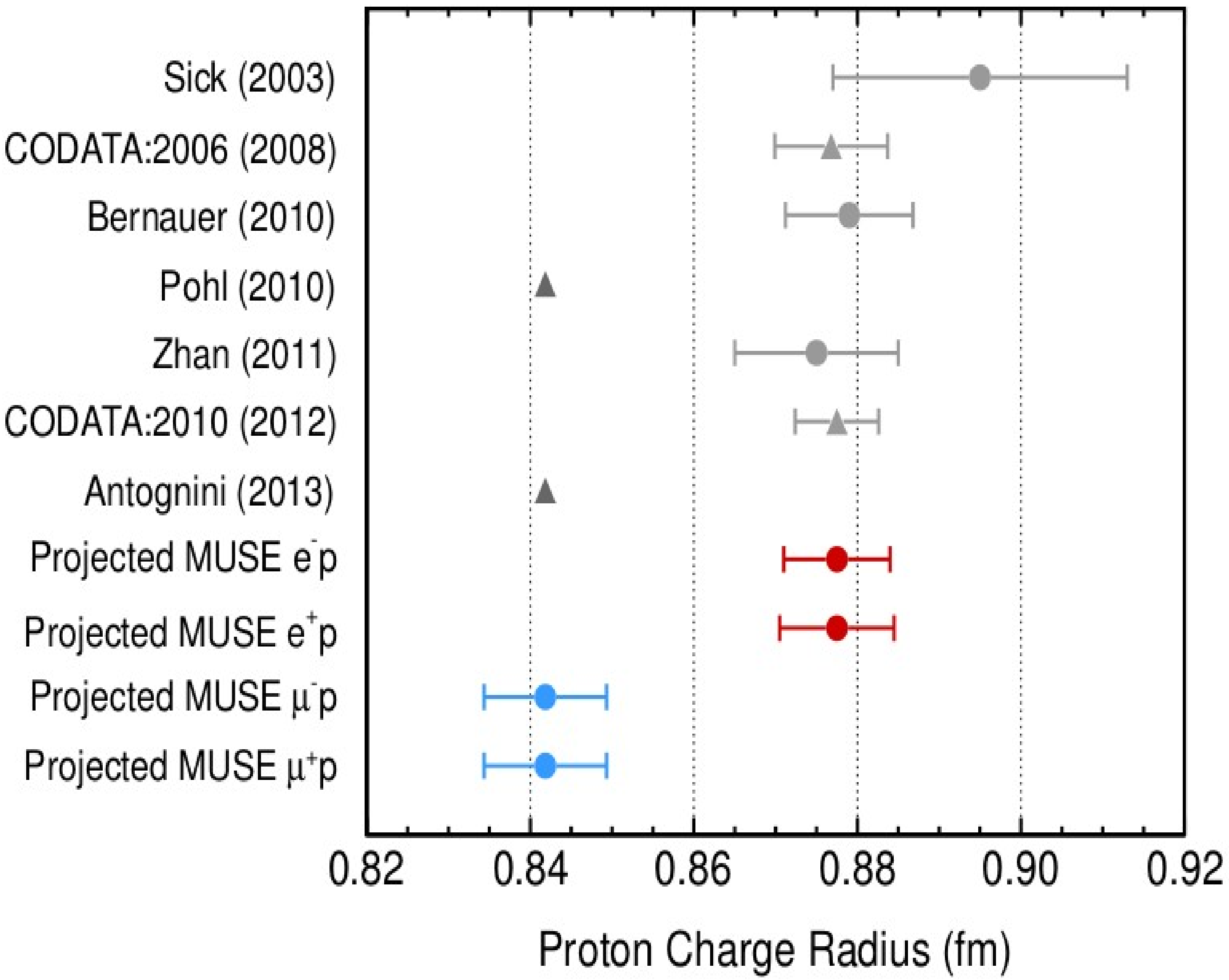
In Relative Comparison:
0.6% (0.3%) systematic uncertainty in CS (FF)

δr = 0.007 fm (μ)
δr = 0.006 fm (e)

δr = 0.009 fm (μ-e)

Current discrepancy ~0.035 fm -> ~4σ measurement

Relative Radius Uncertainties



Summary

- Proton Radius Puzzle is a high profile issue, and is still unresolved 4 years later
- Explanation unclear, not general consensus
  - BSM? TPE? Experiment?
- MUSE tests these
  - Simultaneous measurement of μ/e for direct comparison of radius with reduced systematics
  - Measure of e+/e- and μ+/μ– for TPE
- R & D work underway, planning for production running in 2017-18

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] 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. 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]

New Collaborators welcome! Thank You!

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

Extras

Equipment Summary

Detector	Who	Technology
Beam SciFi	Tel Aviv	conventional
GEMs	Hampton	detector exists
Sapphire Cerenkov	Rutgers	prototyped (Albrow et al)
FPGAs	Rutgers	conventional
Target	George Washington	conventional - very low power
Straw Tube Tracker	Hebrew U + Temple	copy existing system (PANDA)
scintillators	South Carolina	copy existing system
DAQ	George Washington	conventional, except TRB3

Expected Rates

Rate for detector arms combined, 5 MHz total beam flux

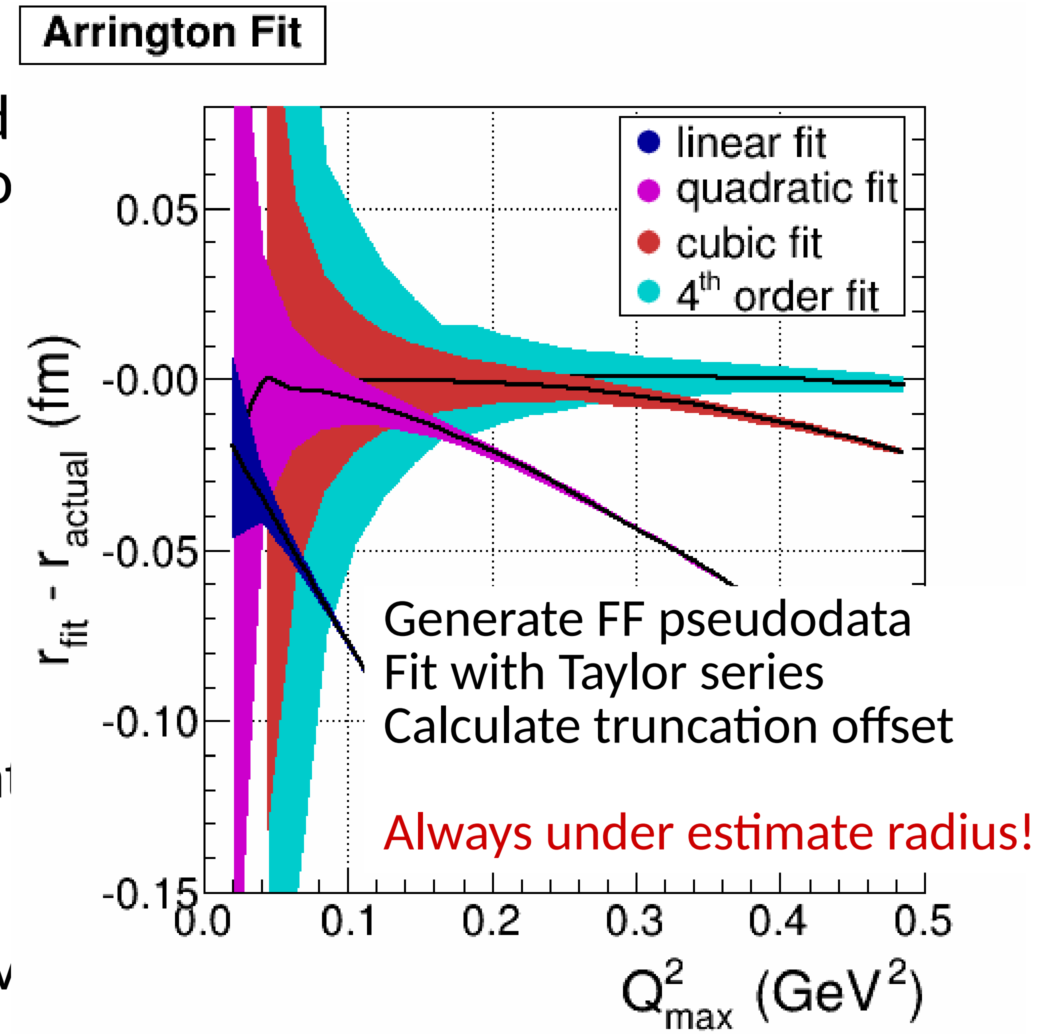
Momentum (MeV/c)	+115	+153	+210	-115	-153	-210
$\mu + p$ **elastic scattering**	**0.6**	**2.6**	**1.0**	**0.3**	**0.7**	**0.5**
μ+kapton elastic scattering	0.8	2.0	0.4	0.4	0.5	0.2
Geant4: μ singles	655	1.8k	1.3k	335	440	684
Geant4: μ triggers	57	241	111	29	61	56
$e + p$ **elastic scattering**	**54**	**20**	**1.9**	**55**	**28**	**7.5**
e+kapton elastic scattering	21	6.6	0.5	22	9.5	2.0
Geant4: e singles	139k	84.6k	16.4k	158k	134k	69.3k
Geant4: e triggers	3.0k	2.3k	635	3.6k	3.7k	2.7k
Geant4: π singles	12.7k	176k	227k	6.4k	48.0k	137k
Geant4: π triggers	1.8k	28.6k	33.8k	896	7.9k	20.4k
Geant4: π triggers + beam PID	15.2	277	6.8	7.3	76.3	4.1
Total singles rate	152.3k	262.2k	245.0k	164.9k	182.7k	206.9k
Total Geant4 triggers + beam PID	3.1k	2.9k	756	3.7k	3.9k	2.8k

Elastic ep Scattering

Scattering knowledge dominated by recent Bernauer *et al.* Mainz experiment, plus Jlab polarization data

Extracting a radius from the scattering d
Until recent, all analyses ignored most o

- Coulomb corrections
- Two-photon exchange
- Truncation offsets
- World data fits vs. radius fits
- Model dependence
- Treatment of systematic uncertaint
- Fits with unphysical poles
- Including time-like data to “improv

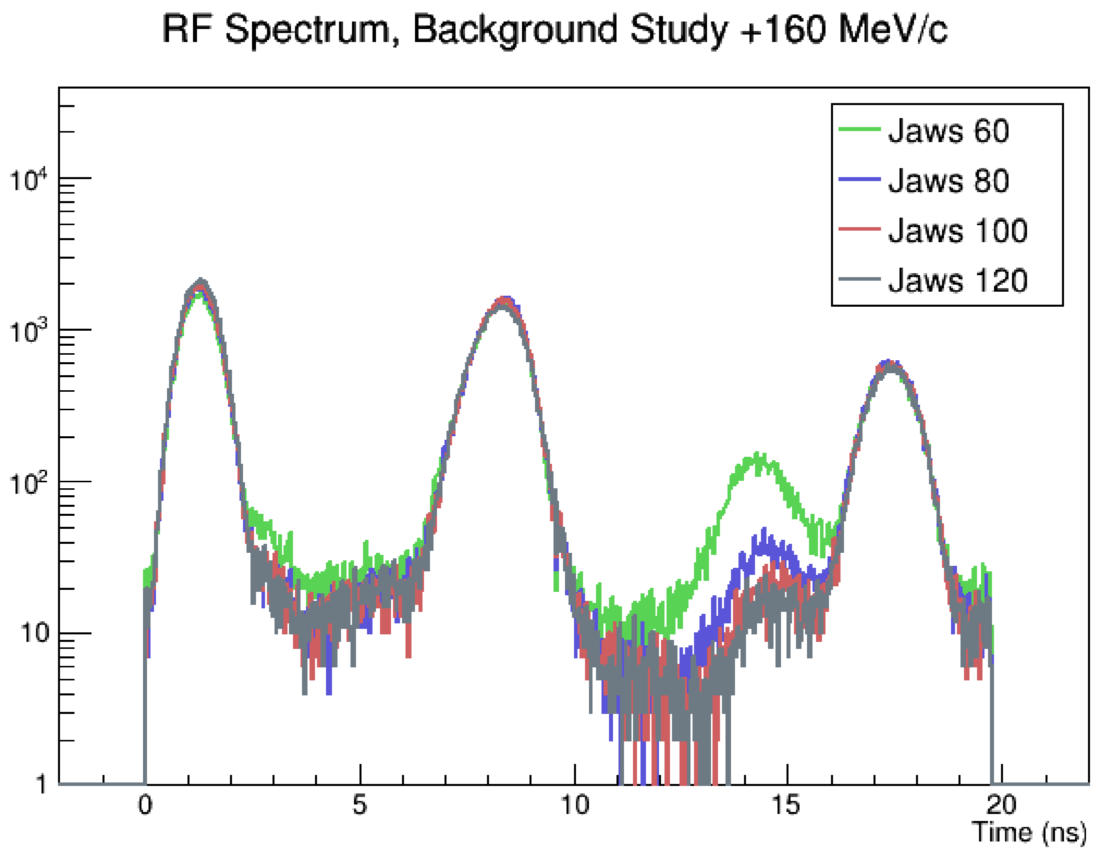


The good modern analyses tend to have fewer issues

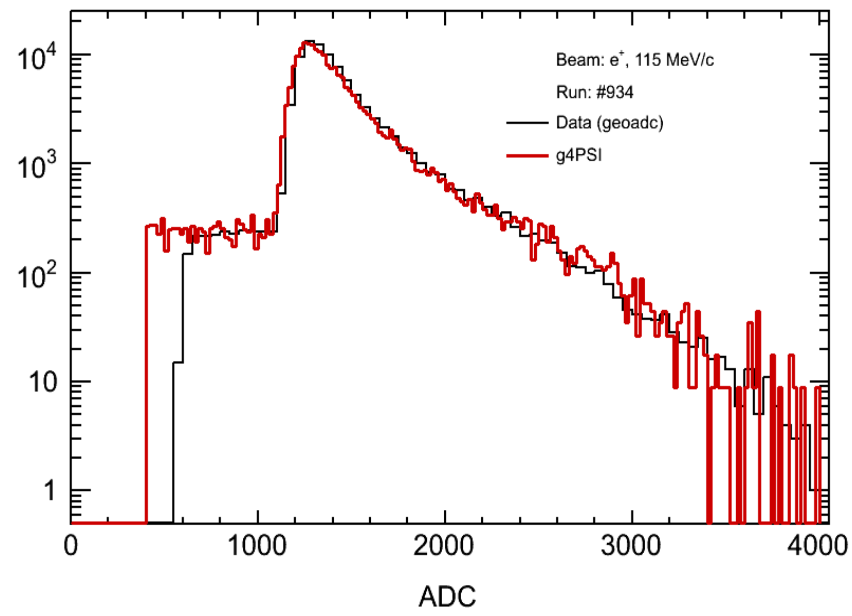
Beam test measurements

Studying backgrounds from “jaws”

- We will use a collimator to limit beam flux



Comparison of ADC spectrum to Geant4 simulation



Relative Systematics Table

Solid Angle	0.1%
Scintillator Efficiency	0.1%
Beam Momentum 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%

Total Relative Uncertainty in Cross Section*:

μ: 0.4%

e: 0.6%

- Negligible Systematics:
  - Beamline Detector Efficiency
  - Beam Flux
  - Target Thickness
  - Data set Normalization
- TBD Systematics (small)
  - Analysis Uncertainties
  - Detector Stability

* Uncertainties factor of two smaller for form factor

Radiative Corrections / TPE

Effect ~ 3% for 100^o 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

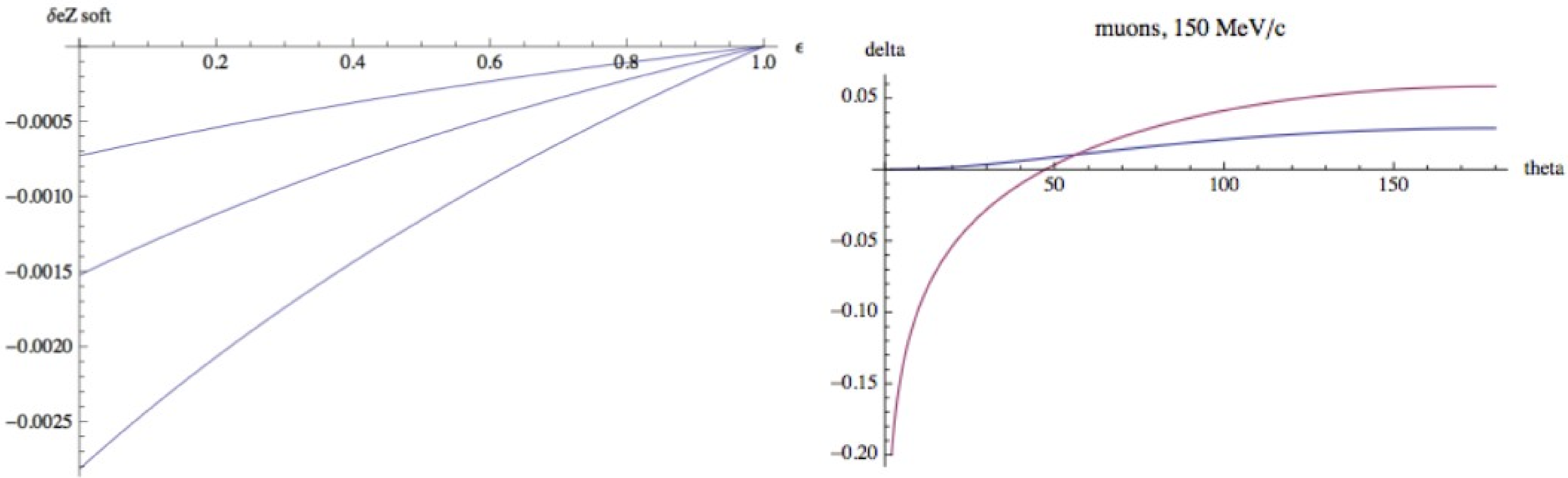


FIG. 37. Radiative correction calculations from Afanasev. Left: Soft two-photon corrections for the three MUSE beam energies as a function of ϵ. The correction grows with energy. Calculations shown are for electrons; the muon calculations are very similar. Right: Muon radiative corrections at 150 MeV/c for MUSE. The blue (red) curve is the full (approximate) calculation.

Radiative Corrections / TPE

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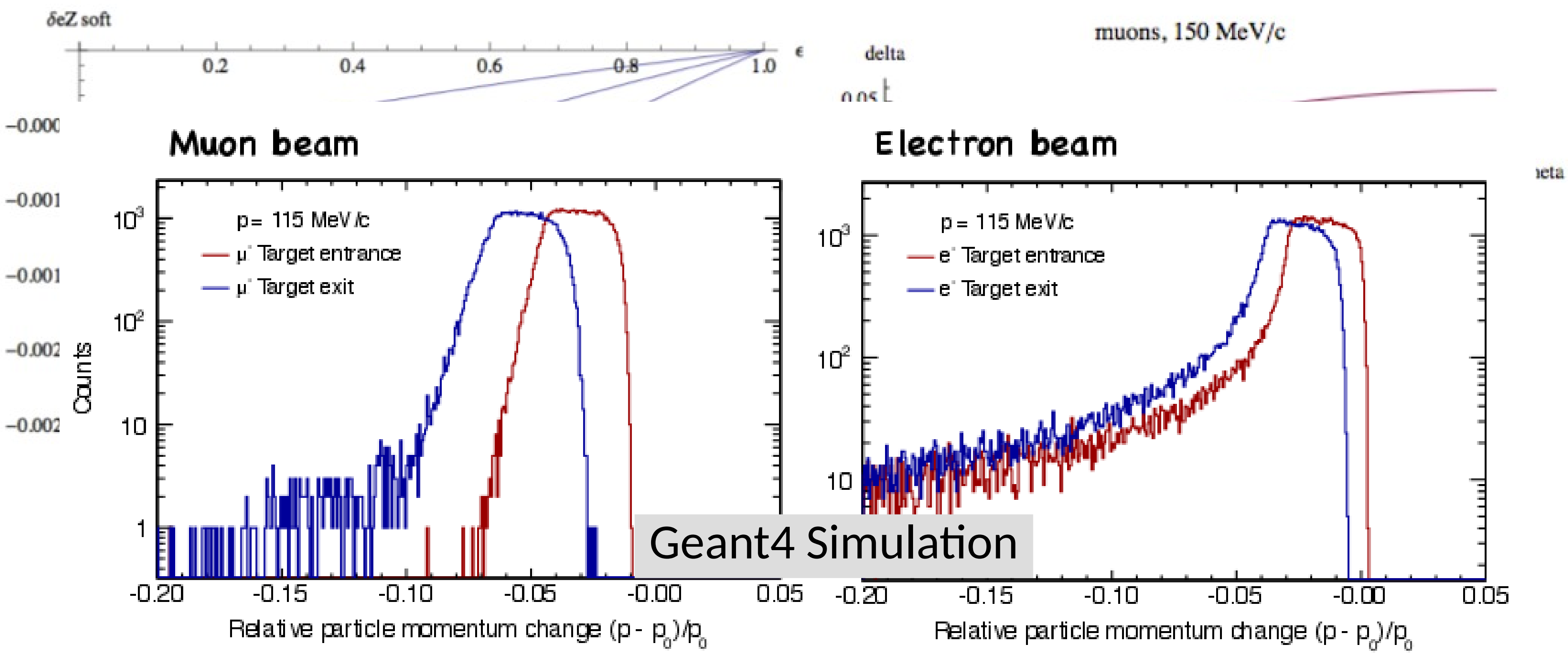


shown are for electrons; the muon calculations are very similar. Right: Muon radiative corrections at 150 MeV/c for MUSE. The blue (red) curve is the full (approximate) calculation.

Systematics for Ratios

- In the ratios (e+/e-, μ+/μ-, e/μ) some of the cross section systematics cancel further
- The uncertainty is reduced by a factor of 2 if we compare the form factor rather than the cross section:

  $d\sigma/d\Omega$ proportional to G^2
- Gain a normalization uncertainty of 0.2% (0.1%) for the cross section (form factor) ratios

TPE Ratios:

Syst. uncert: 0.3%

- Comparing same particle, different polarity, same scattering angle
- Solid angle, angle determination uncertainties vanish
- Non-2 photon part of radiative correction vanishes
- Multiple scattering and magnetic contributions vanish

Systematics for Ratios

- In the ratios (e+/e-, μ+/μ-, e/μ) some of the cross section systematics cancel further
- The uncertainty is reduced by a factor of 2 if we compare the form factor rather than the cross section:

  $d\sigma/d\Omega$ proportional to G^2

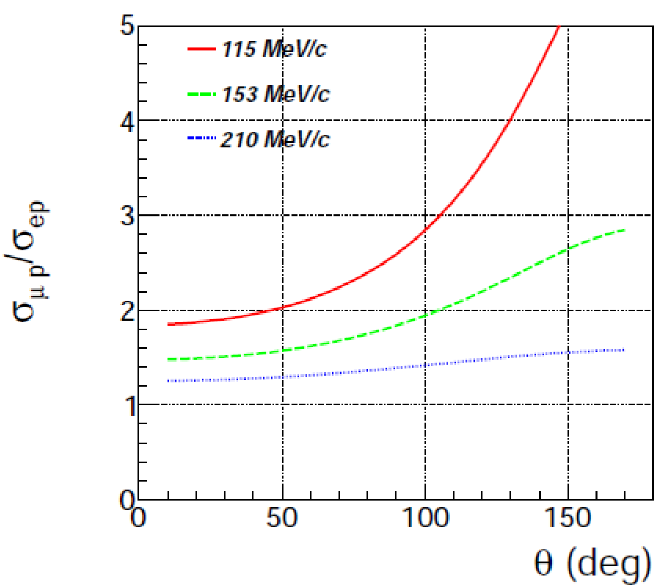
- Gain a normalization uncertainty of 0.2% (0.1%) for the cross section (form factor) ratios

Cross Section (FF) Ratios:

Syst. Uncert: 0.6% (0.3%)

- Comparing different particle, slightly different scattering angle
- Majority of systematics remain
- Partial cancellation of scintillator efficiency, angle determination, multiple scattering, and magnetic contribution due to few-percent difference in angle for e, μ

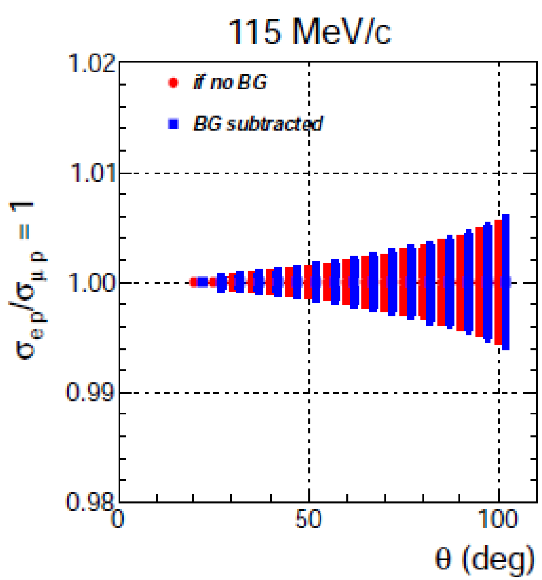
Estimated Results: μ/e

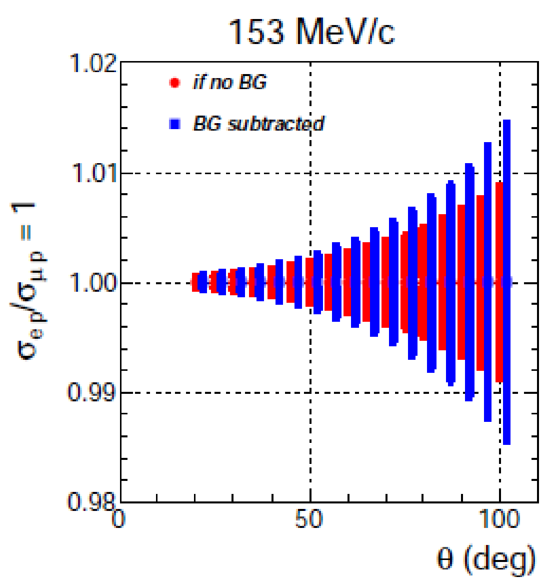


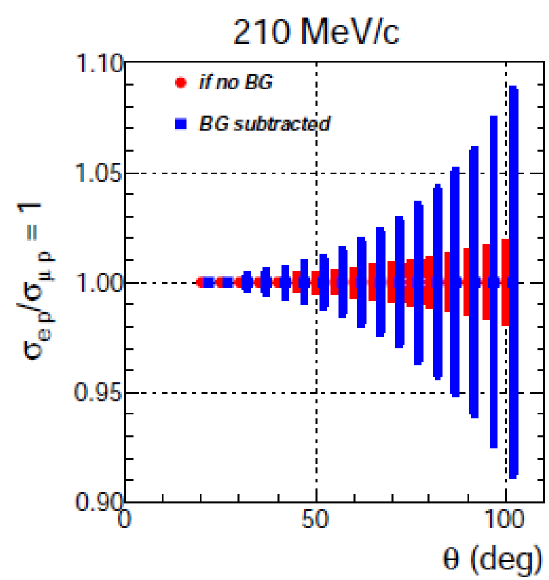
Left: Calculated difference in cross section
Below: Cross section ratio with statistical uncertainties

- Uncertainty reduced by factor of 2 in the form factor, leading to <1% statistical uncertainties for most of the dataset

(renormalized to unity, stat. errors only)

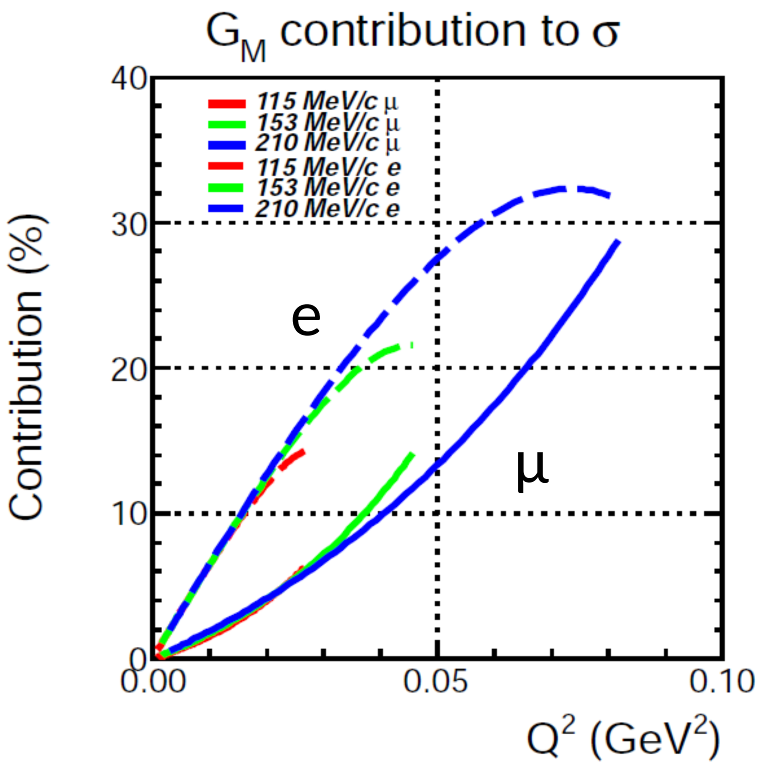




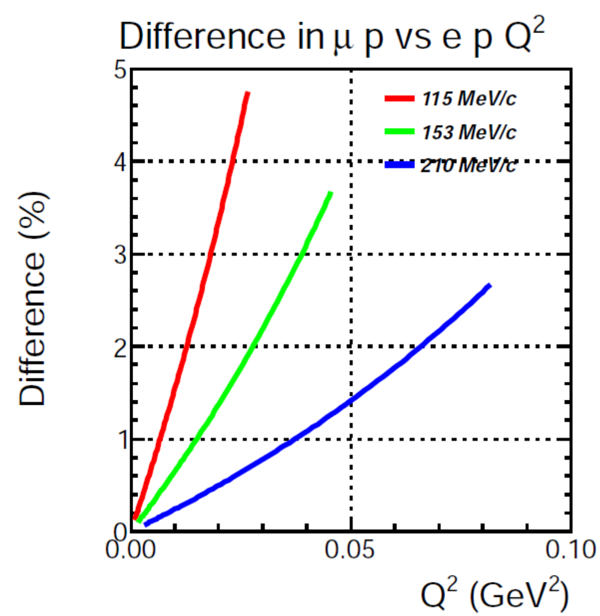


Slightly diff. y scale

Magnetic Contribution



- Magnetic contribution ~30% at largest Q^2 setting
- Bernauer data: uncertainty in magnetic form factor ~0.3%
- There is a 1% difference in magnetic radius between Bernauer and Arrington (1/2 may be from different two photon corrections)



- Uncertainty 0.1-0.14% level
- Drops out in +/- comparisons
- Goes away to some degree in e/mu comparison since kinematics are similar (Q^2 different by a few percent)