Studying the Proton ``Radius'' Puzzle with μp Elastic Scattering

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see: http://www.physics.rutgers.edu/~rgilman/elasticmup/muse-collaboration.html

- Introduction
- The Puzzle
- Status report on the MUon proton Scattering Experiment (MUSE)
- Outlook

What is a radius, how do we measure it?

Classical physics radius: $r^2 = \int \rho(r)\, r^2\, d^3r$

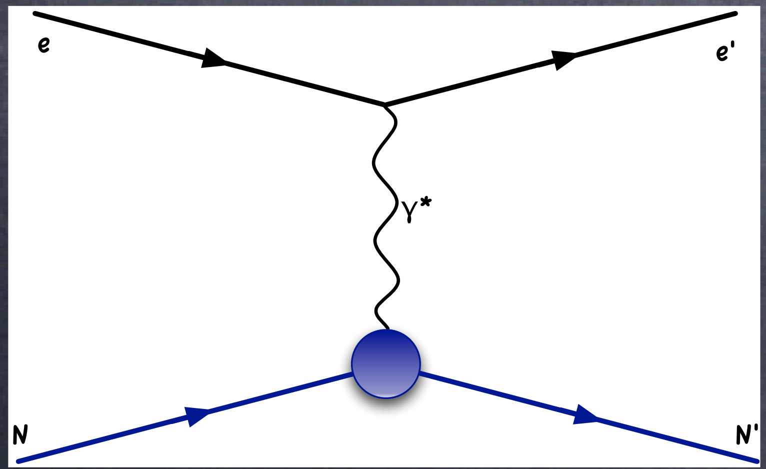
Non-relativistic quantum mechanics radius: $r^2 = \int \langle \psi^*(r)|r^2|\psi(r)\rangle\, d^3r$

Relativistic quantum mechanics ``radius'': $r^2 = -6\, dG(Q^2)/dQ^2|_{Q2=0}$.

Electron scattering

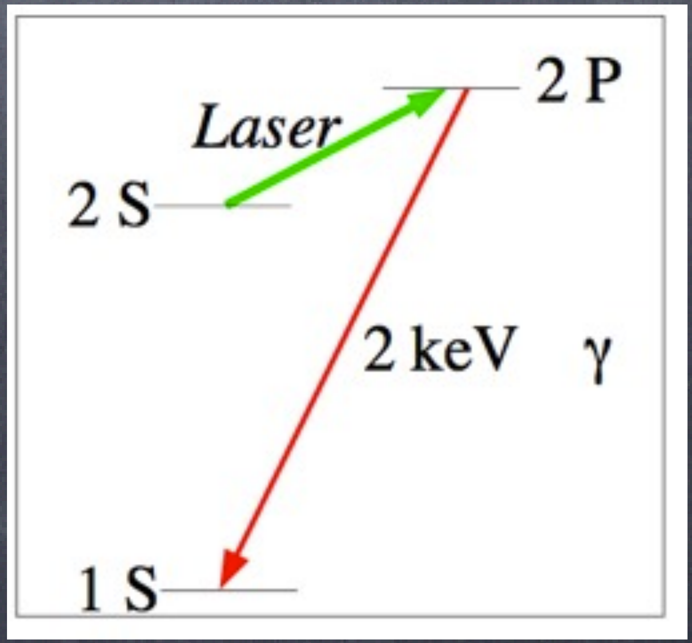
$G_E \approx 1 - Q^2\langle r^2\rangle/6 + Q^4\langle r^4\rangle/120 - \ldots$

$``r^2" = -6\, dG_E/dQ^2 \approx \langle r^2\rangle - Q^2\langle r^4\rangle/10 + \ldots$



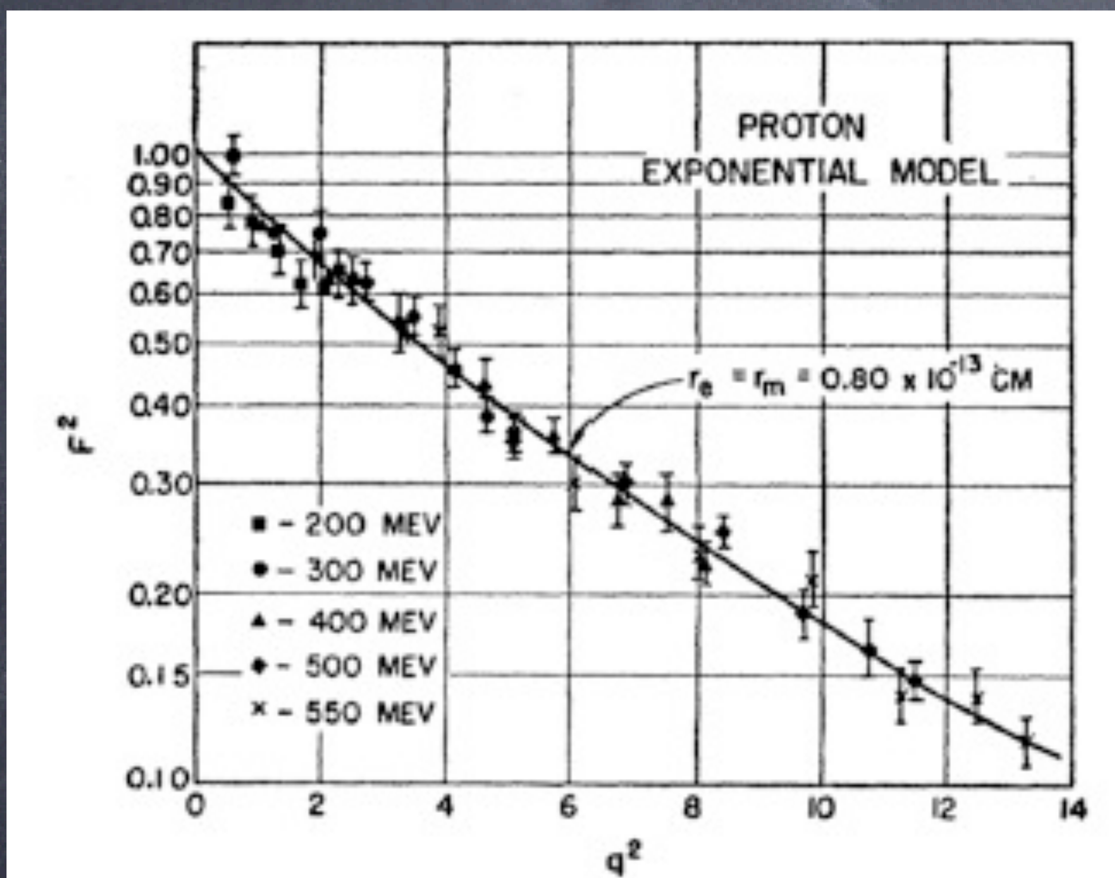
Atomic energy levels

NRQM: finite size of proton perturbs energies of s states - $r_p \lll r_{atomic}$, so effect proportional to $\psi^2_a(r=0)$.

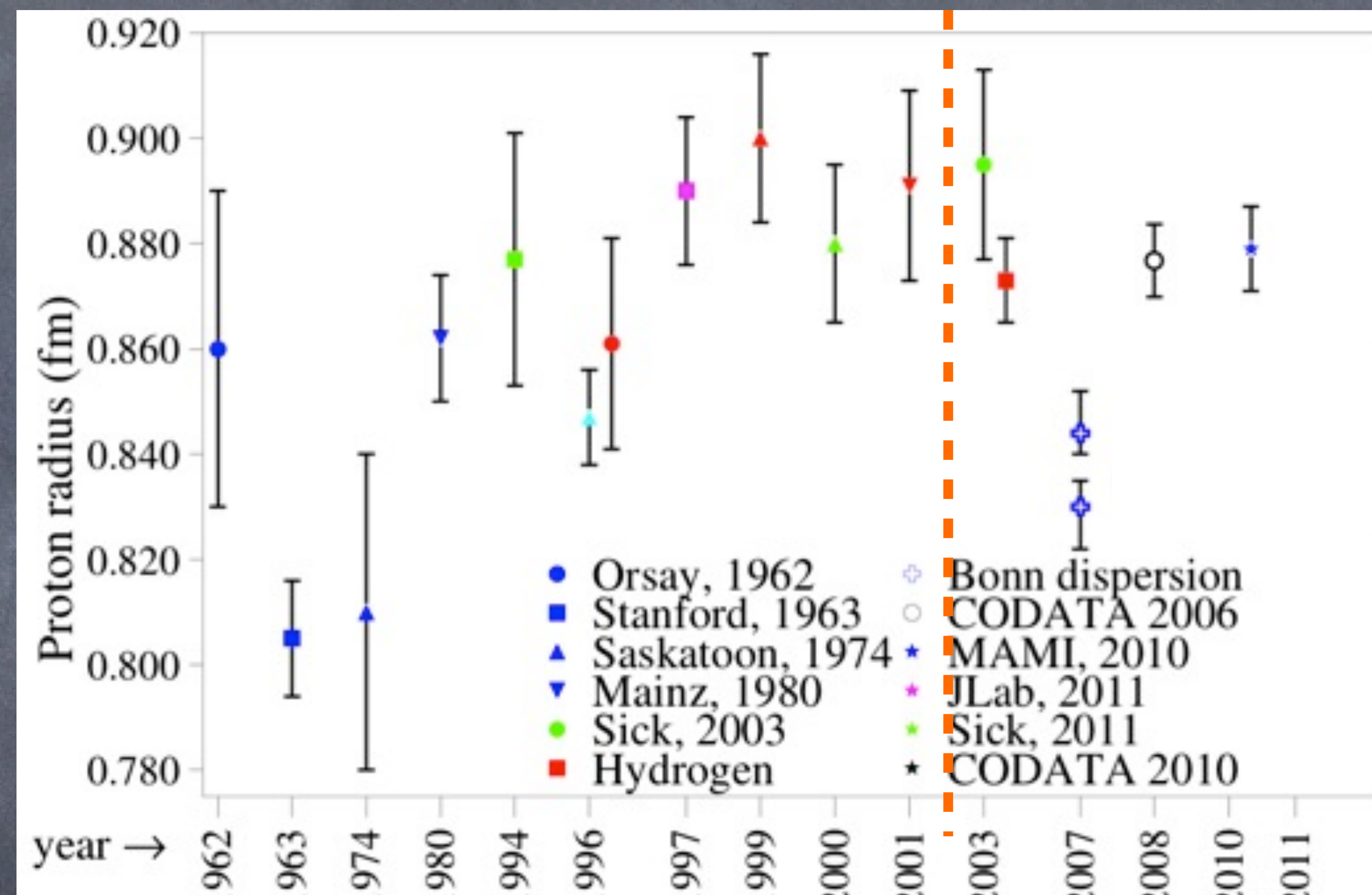


The Radius vs Time

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



From Pohl, Gilman, Miller, Pachucki review, arXiv:1301.0905, AnnRevNPS, modified



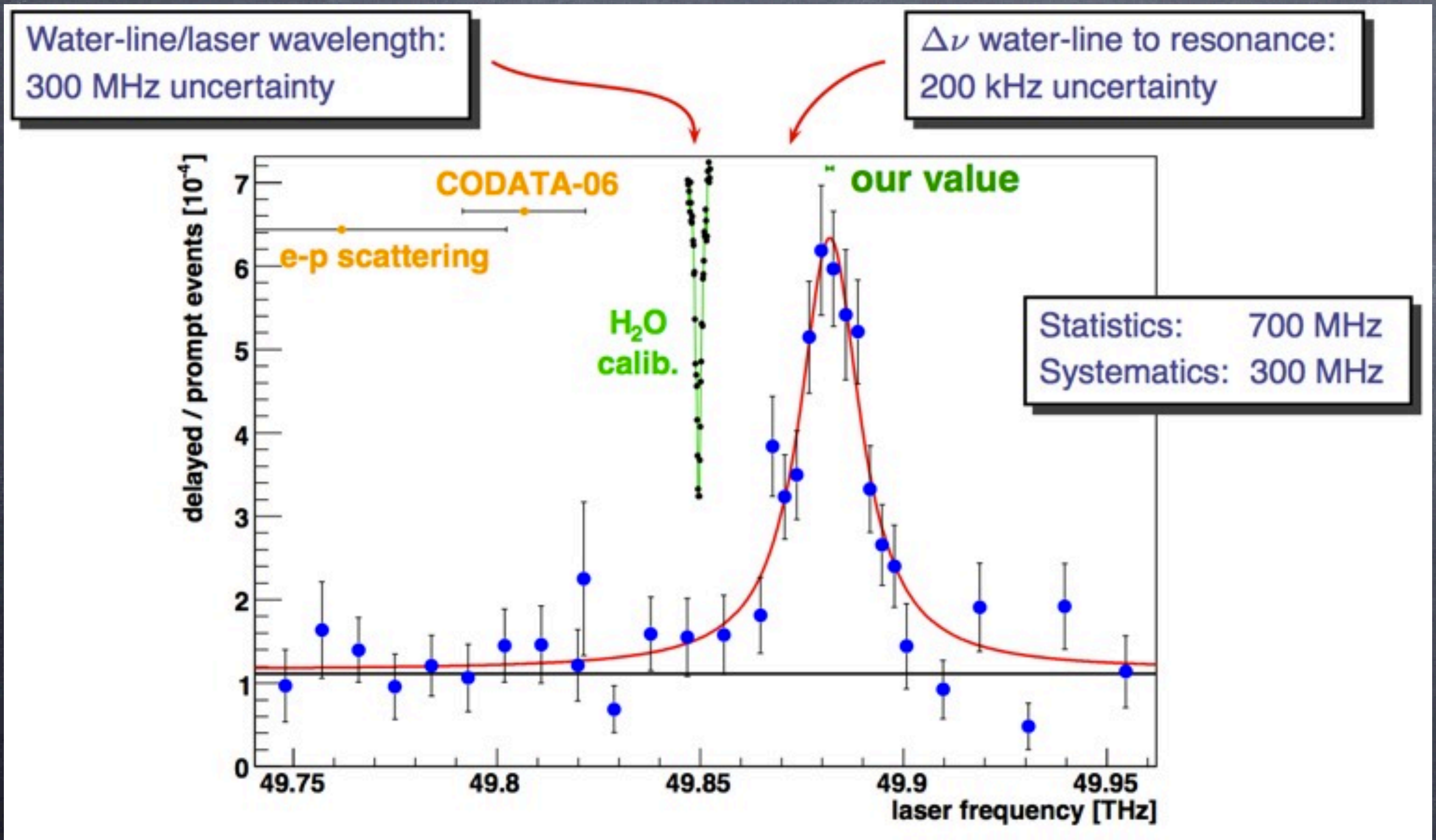
The Proton Radius Puzzle I

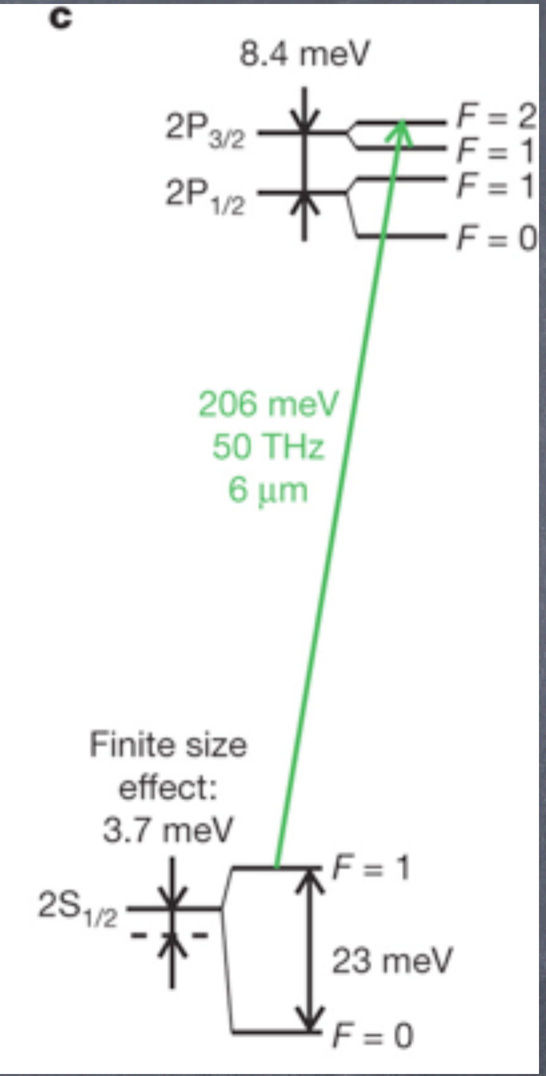
Randolf Pohl et al., Nature 466, 213 (2010):

0.84184 ± 0.00067 fm

5σ off 2006 CODATA

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



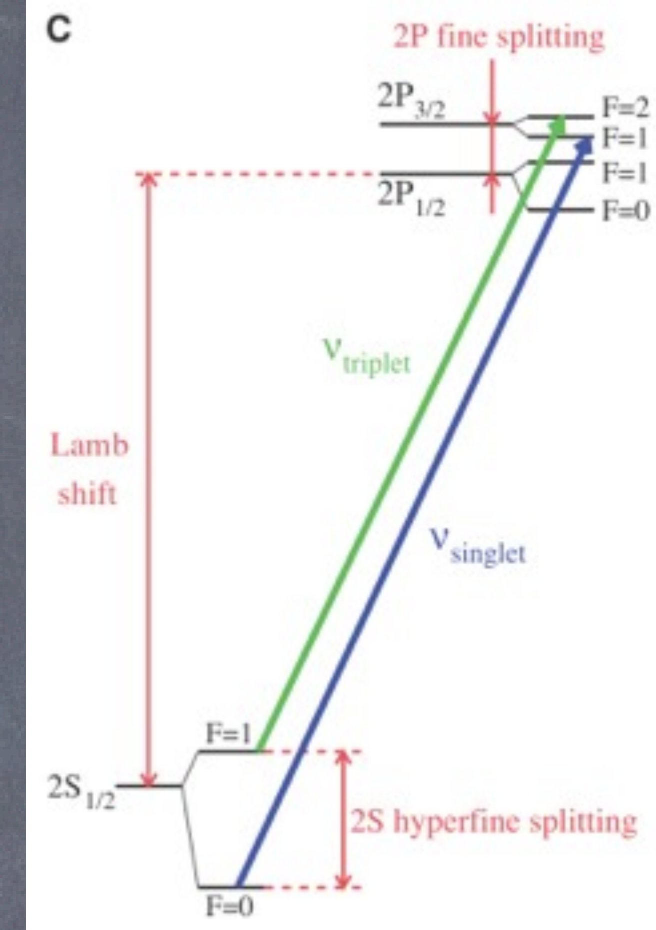


The Proton Radius Puzzle II

Aldo Antognini et al., Science 339, 417 (2013):

0.84087 ± 0.00039 fm

7σ off 2010 CODATA



$$\Delta E = 206.0336(15) - 5.22275(10)r^2 + E_{TPE} \text{ (meV)}$$

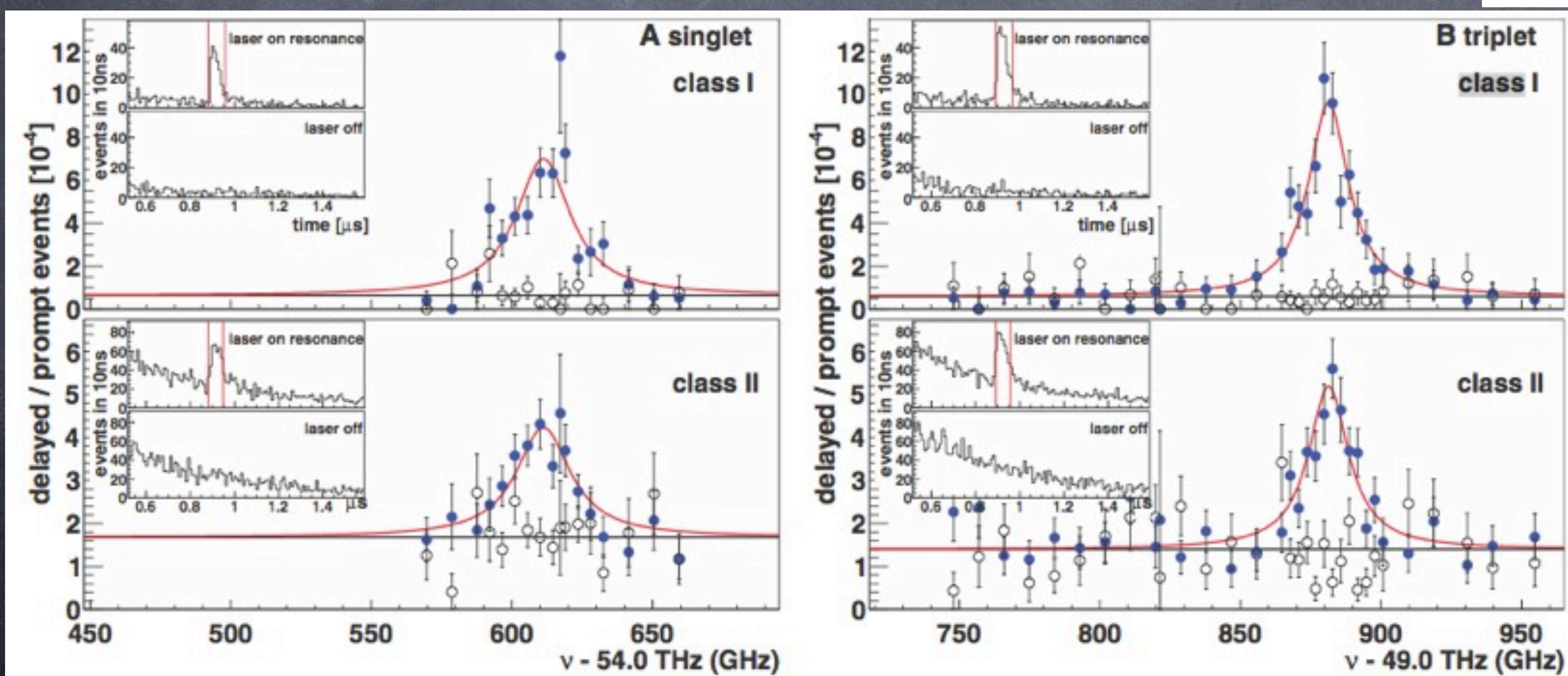
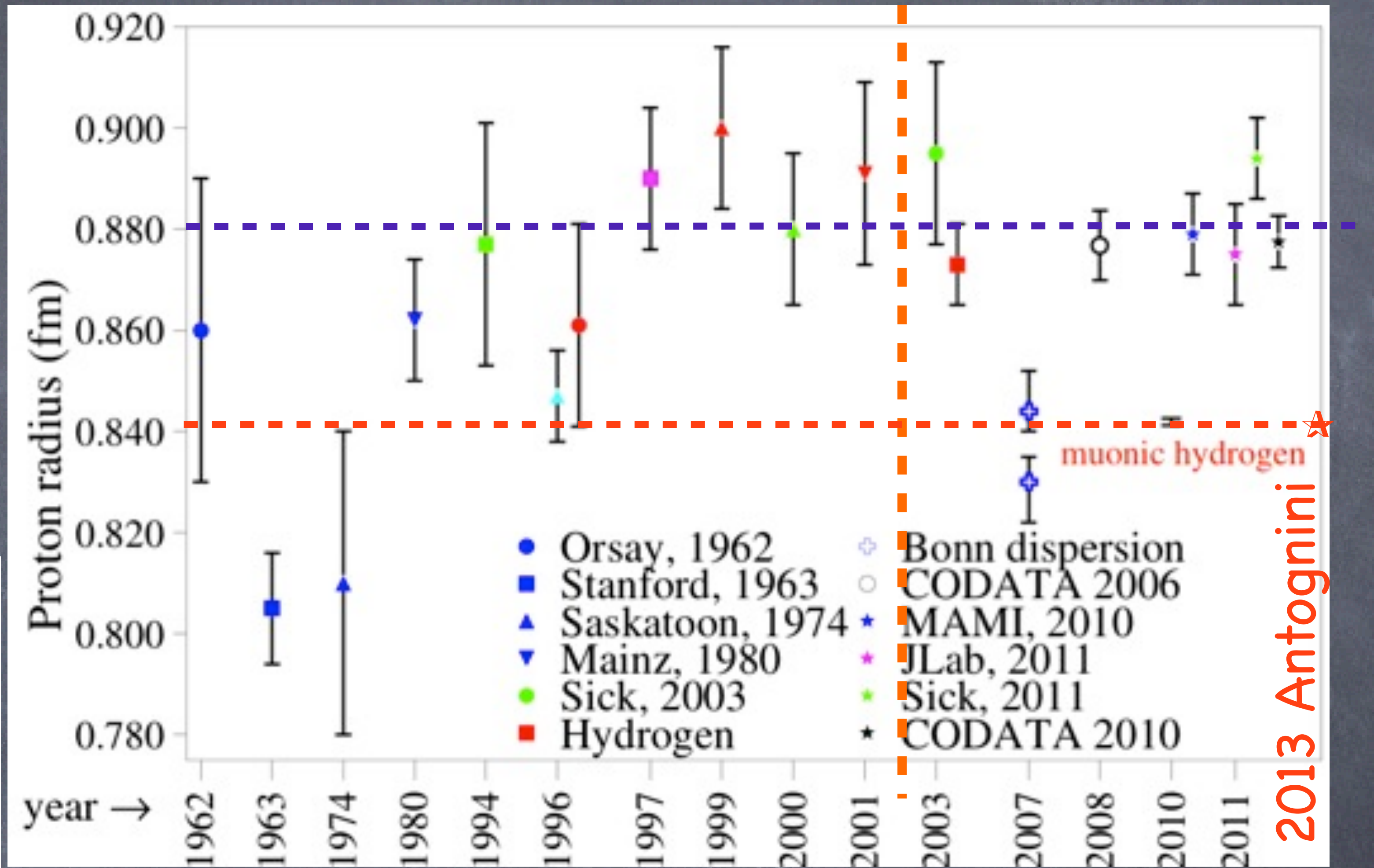
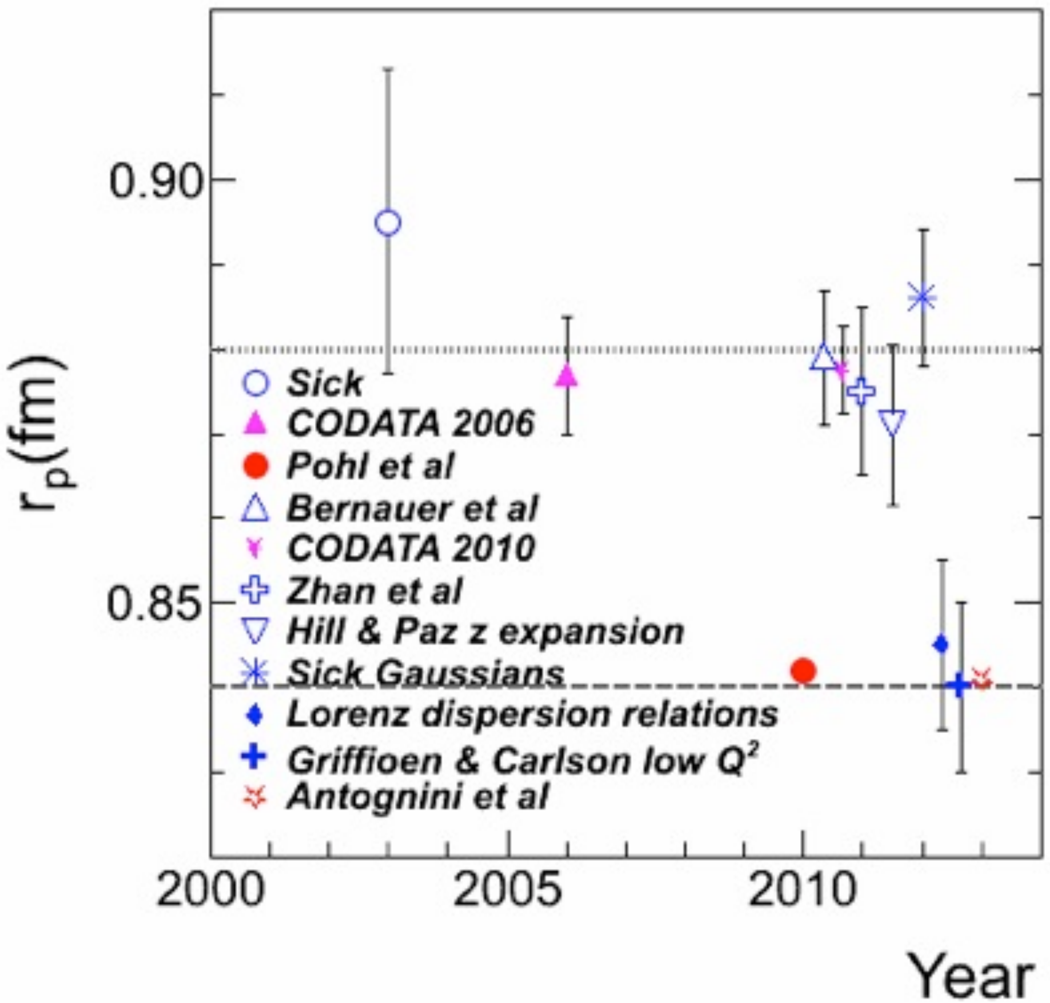


Fig. 3. Muonic hydrogen resonances (solid circles) for singlet ν_s (**A**) and triplet ν_t (**B**) transitions. Open circles show data recorded without laser pulses. Two resonance curves are given for each transition to account for two different classes, I and II, of muon decay electrons (*12*). Error bars indicate the standard error. (Insets) The time spectra of K_α x-rays. The vertical lines indicate the laser time window.

The Proton Radius vs Time

From Pohl, Gilman, Miller, Pachucki review, arXiv: 1301.0905, AnnRevNPS, modified





Focusing in on recent results...

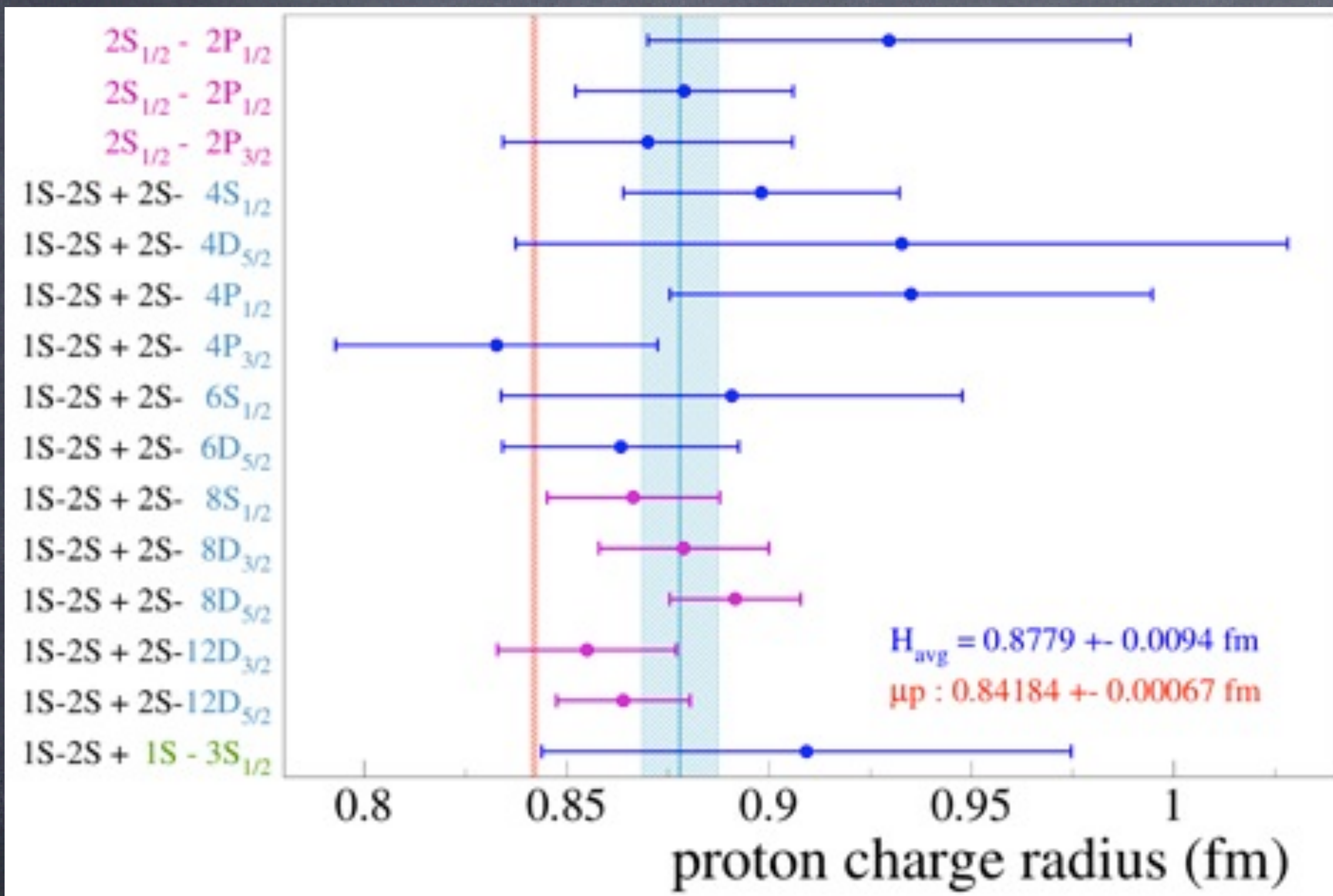
There are reasons to think that the scattering analyses giving larger radii are better.

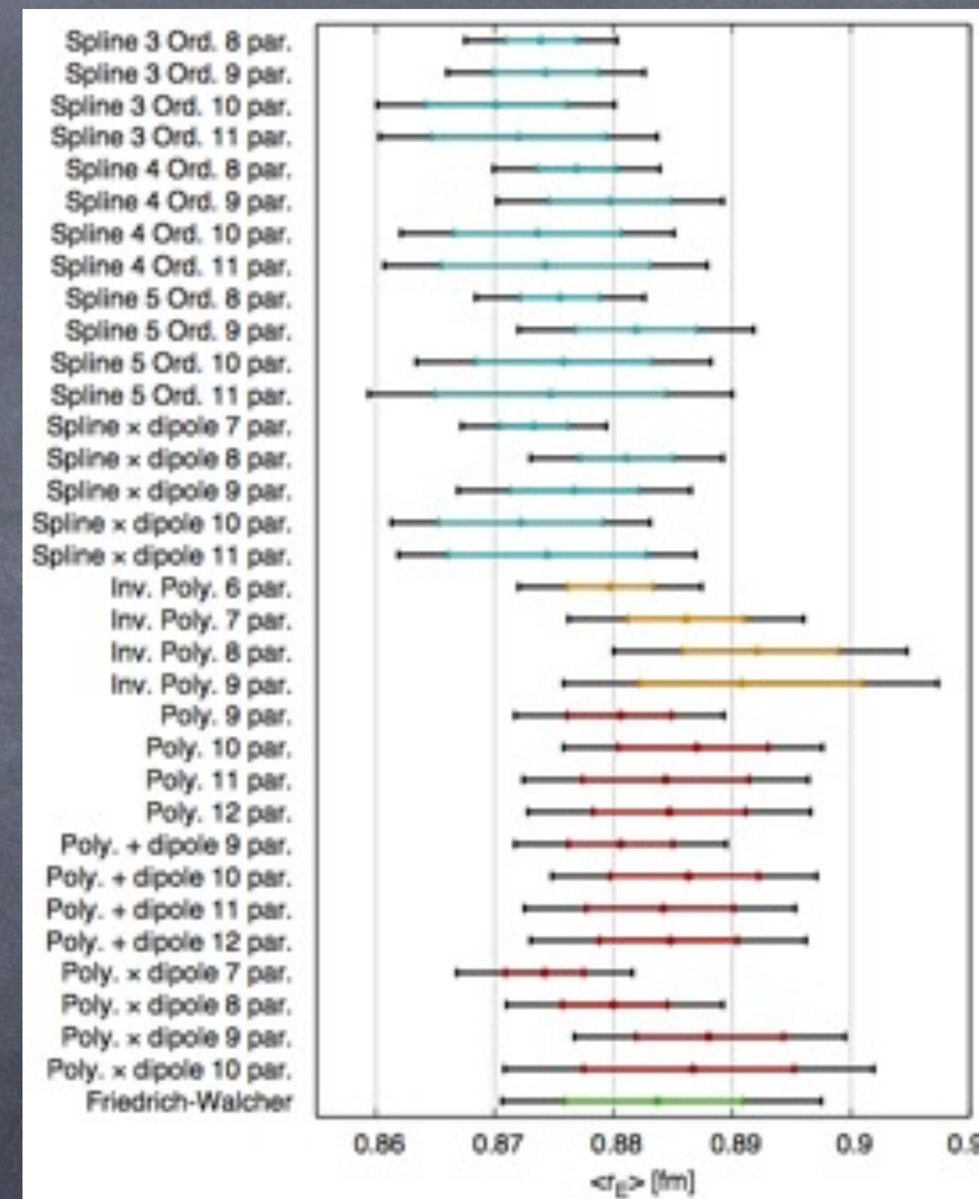
It is a feature of the dispersion analyses for ≈20 years that they give smaller radii.

What is the Proton Radius?

Atomic hydrogen summary

Electron scattering model dependence





From Pohl, Gilman, Miller, Pachucki review, arXiv: 1301.0905, AnnRevNPS

From J. Bernauer's thesis

Do the muon and electron give different proton radii?

- Muonic hydrogen looks to be the best experimental measurement - 200^3 times more sensitive than atomic hydrogen
- Odd, but possible, that atomic hydrogen and ep scattering give the same wrong result
  - But individual atomic hydrogen measurements do not disagree with muonic hydrogen too much, and
  - Some competing ep scattering analyses favor small slope
- I think the answer right now is yes, though the issue needs to be investigated more with new experiments - because if the answer is yes, there is interesting new physics!

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, ...
  - 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!**

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MUSE tests these

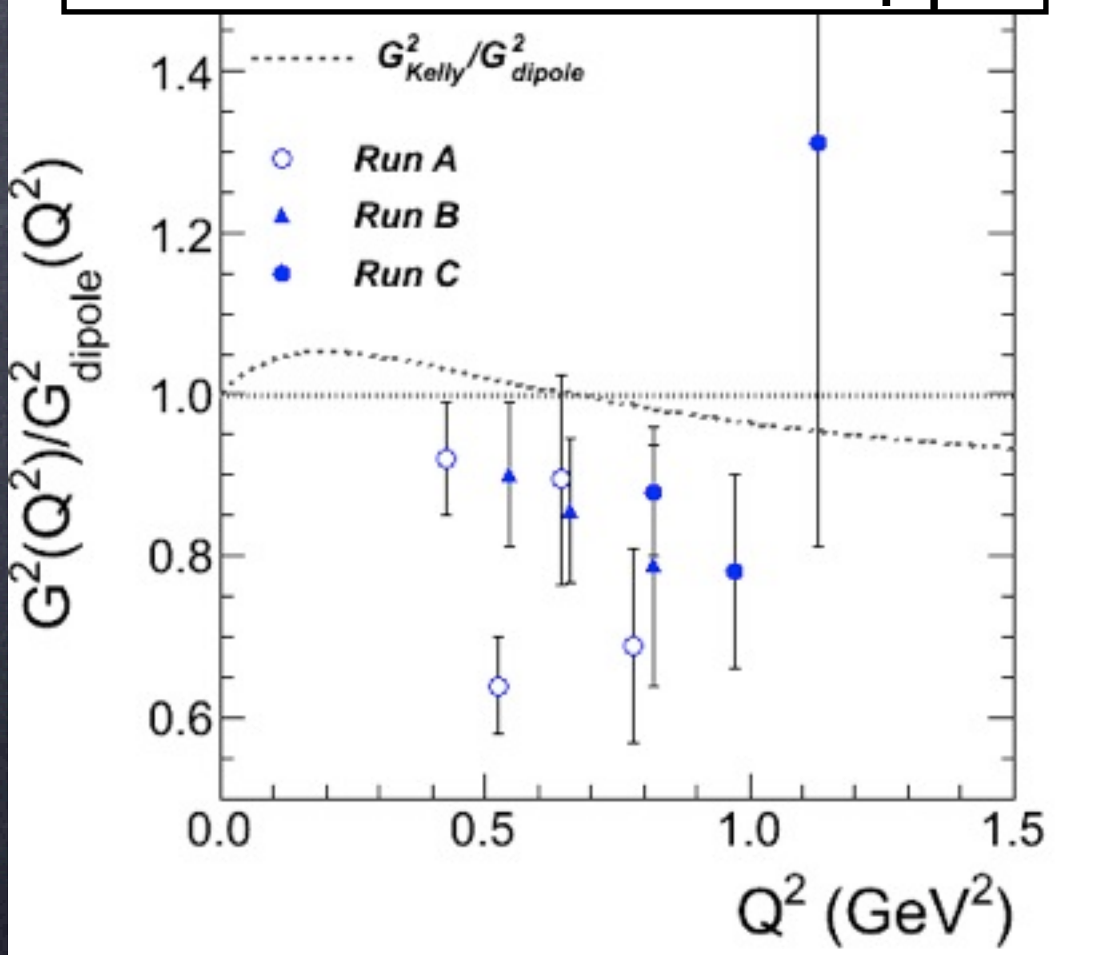
Preceding and following talks

Possible 2nd generation experiment

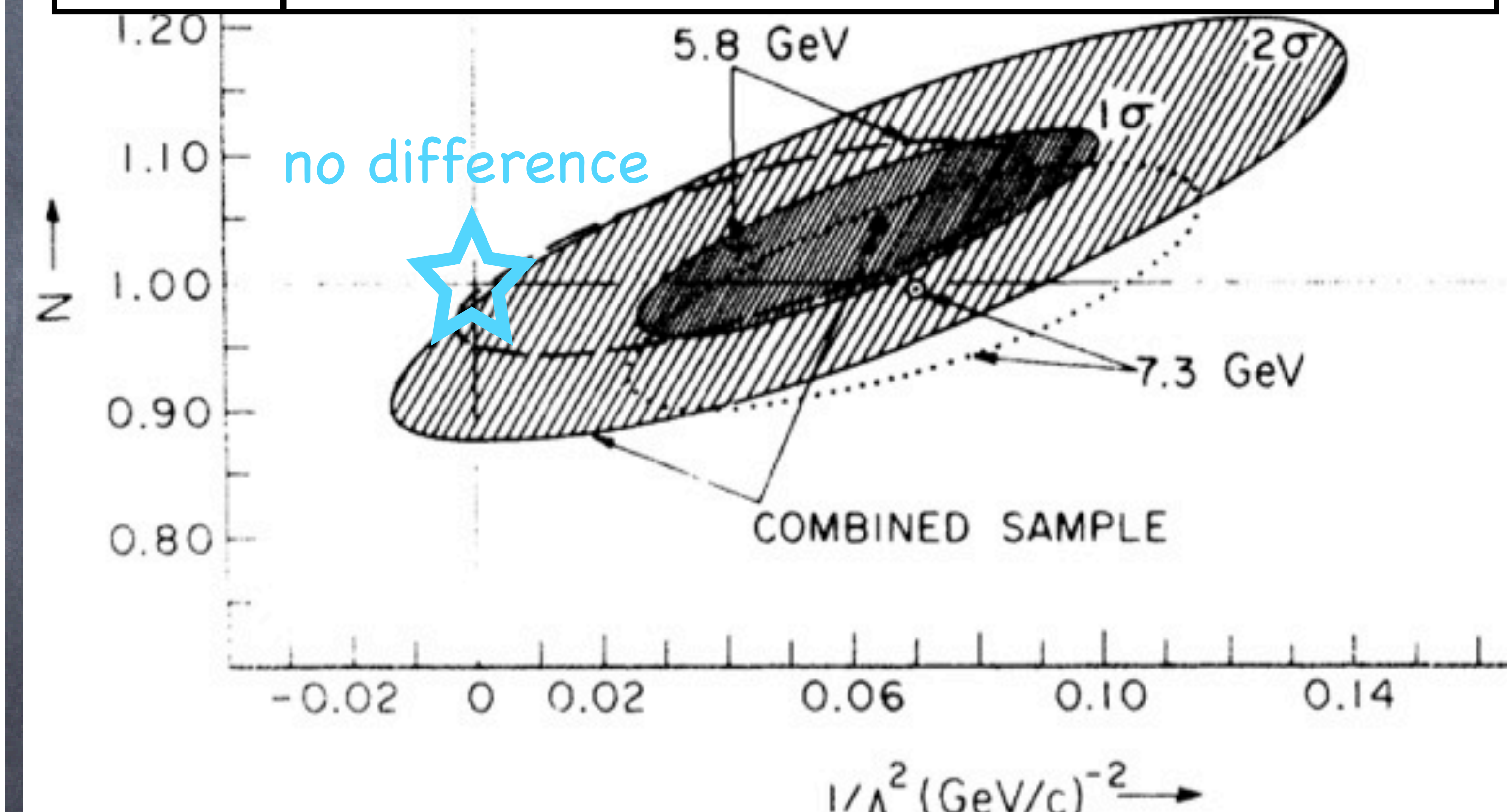
Previous e-μ Scattering Comparisons

In the 1970s / 1980s, several scattering experiments tested whether ep and μp interactions are equal, to within the 10% precision of the experiments. In light of the proton ``radius" puzzle, the 10% experiments are not as good as one would like.

Ellsworth et al.: form factors from elastic μp



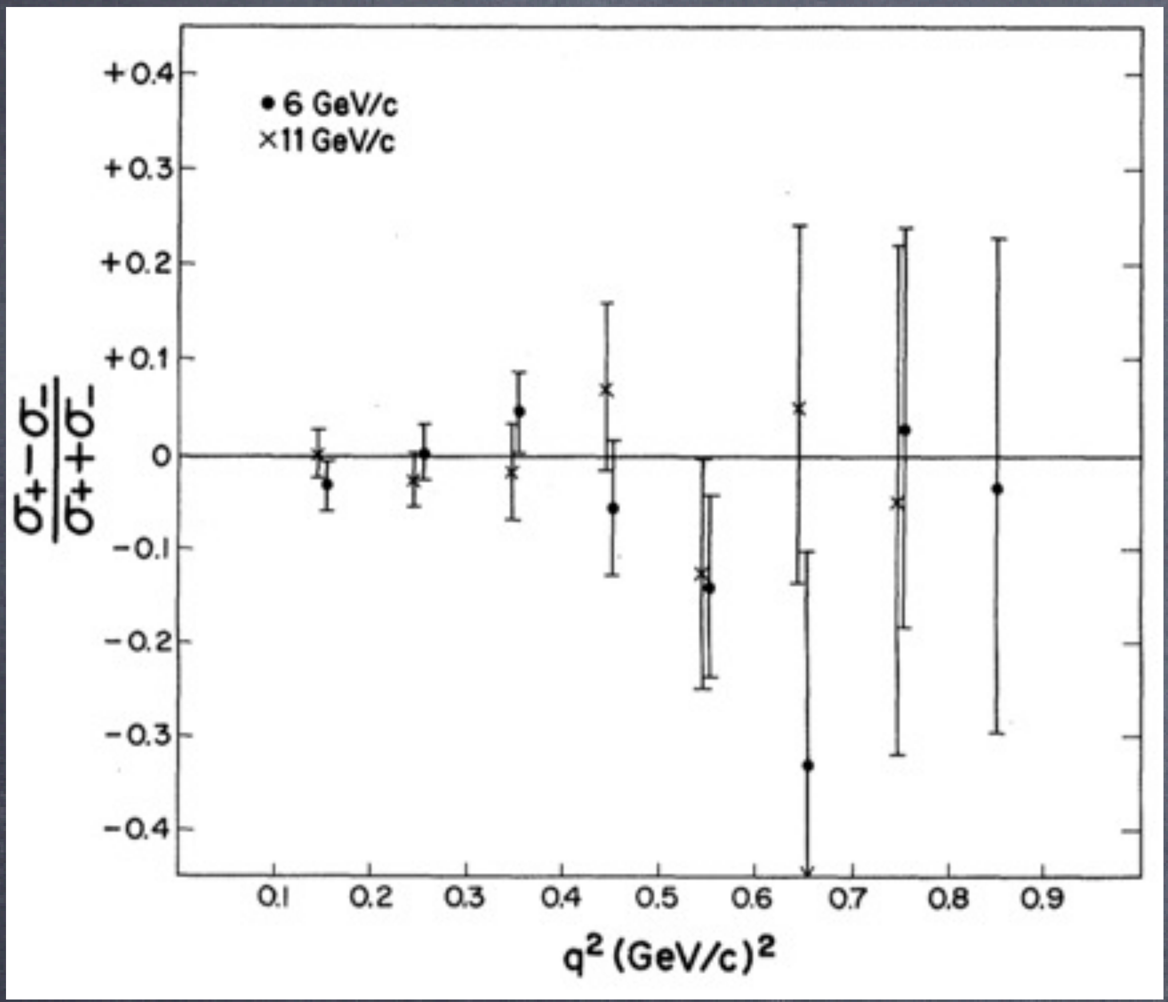
Kostoulas et al. parameterization of μp vs. ep elastic differences



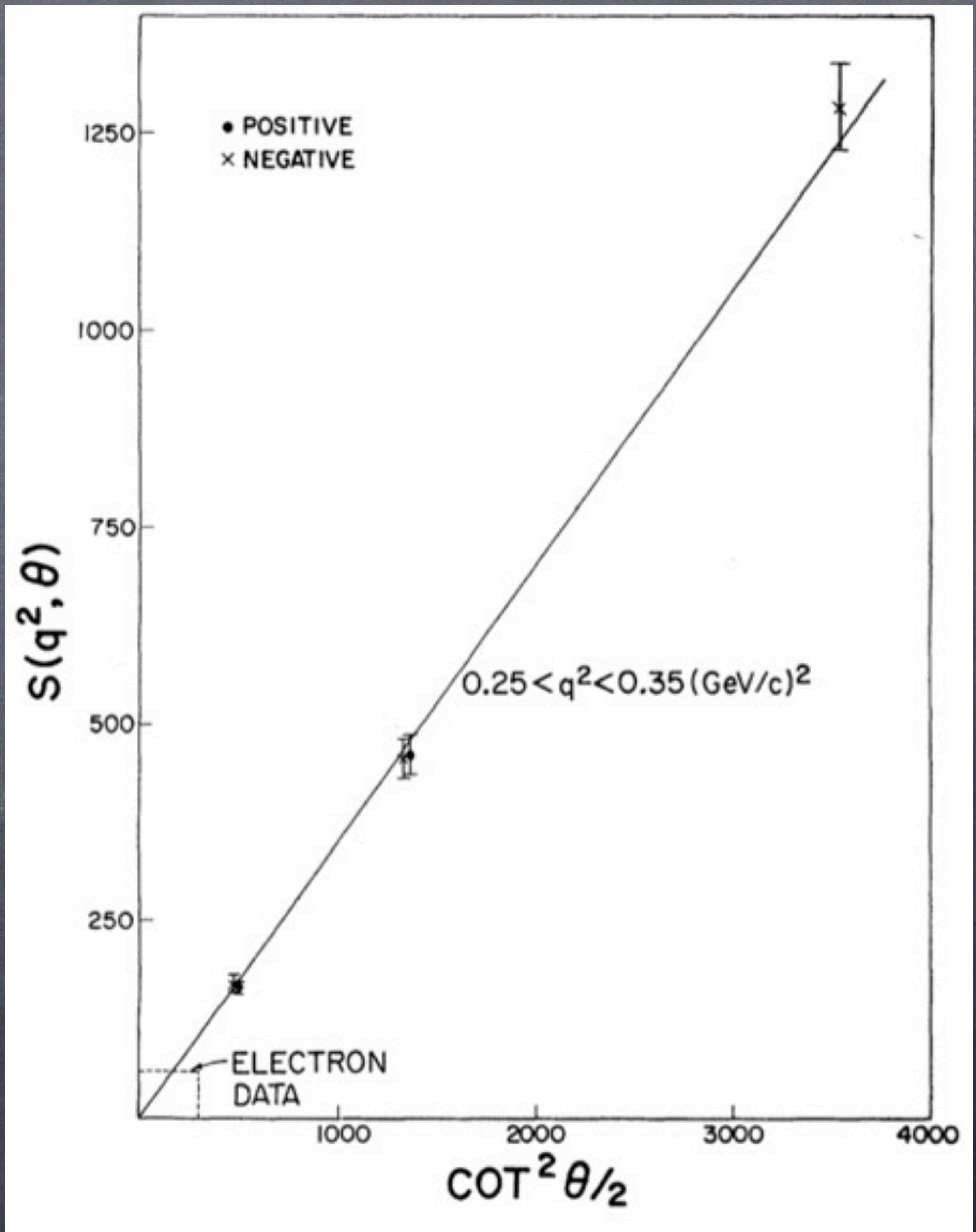
Entenberg et al DIS: $\sigma_{\mu p}/\sigma_{ep} \approx 1.0 \pm 0.04$ (±8.6% systematics)

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.



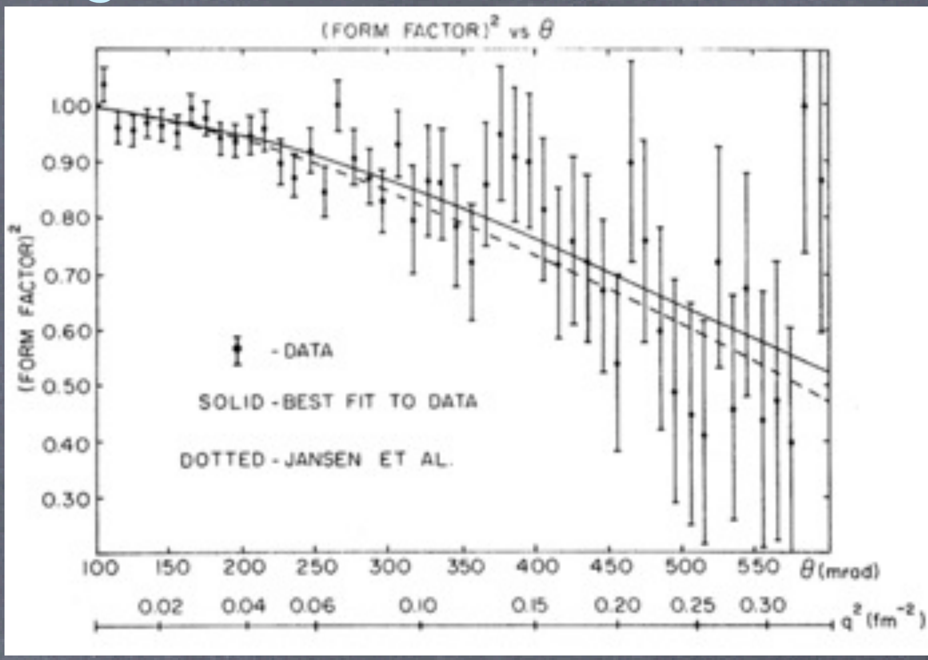
No difference between μ^+p and μ^-p elastic scattering



Rosenbluth plot is linear.

C Radius and e-μ Universality

The ^{12}C radius was determined with eC scattering and μC atoms. The results 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 - PSI R12-01.1 Technique

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

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

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

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

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

following Preedom & Tegen, PRC36, 2466 (1987)

Experiment Overview

PSI πM1 channel

≈115, 153, 210 MeV/c mixed beams of $e^{\pm}$, $\mu^{\pm}$ and $\pi^{\pm}$

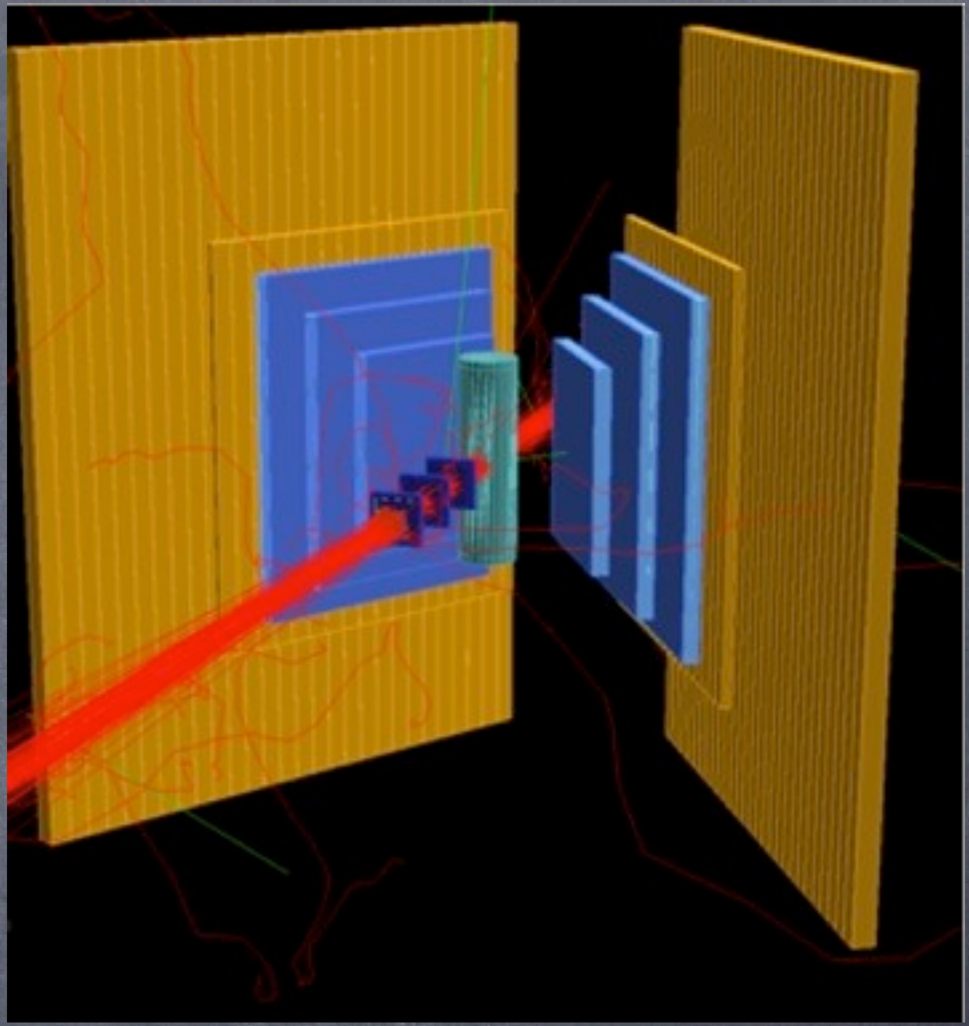
$\theta \approx 20^o - 100^o$

$Q^2 \approx 0.002 - 0.07$ 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 wire chambers and scintillators



Not run like a normal cross section experiment - 7-10 orders of magnitude lower luminosity.

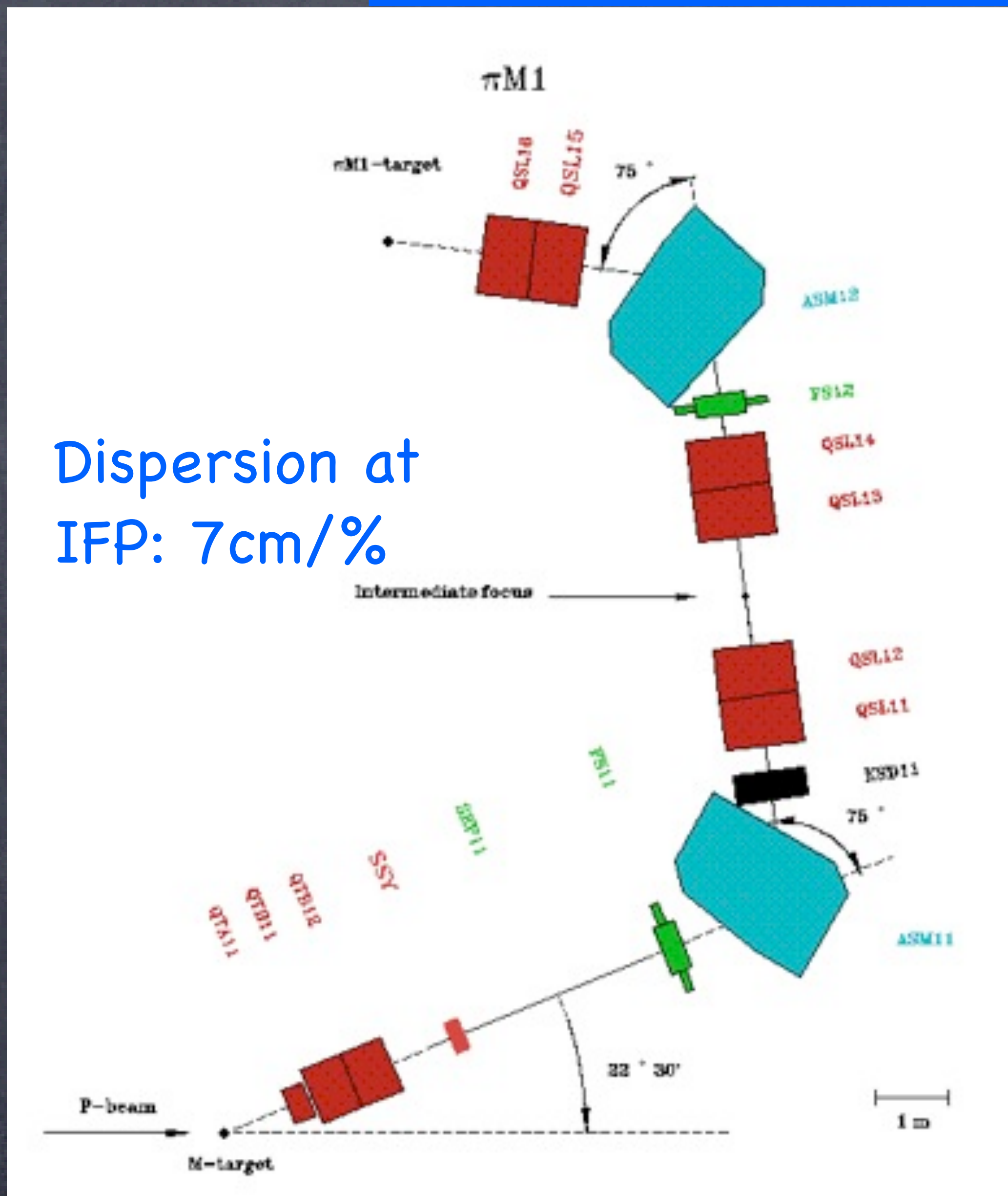
But there are some benefits: count every beam particle, no beam heating of target, low rates in detectors, ...

MUSE: μp Scattering at PSI

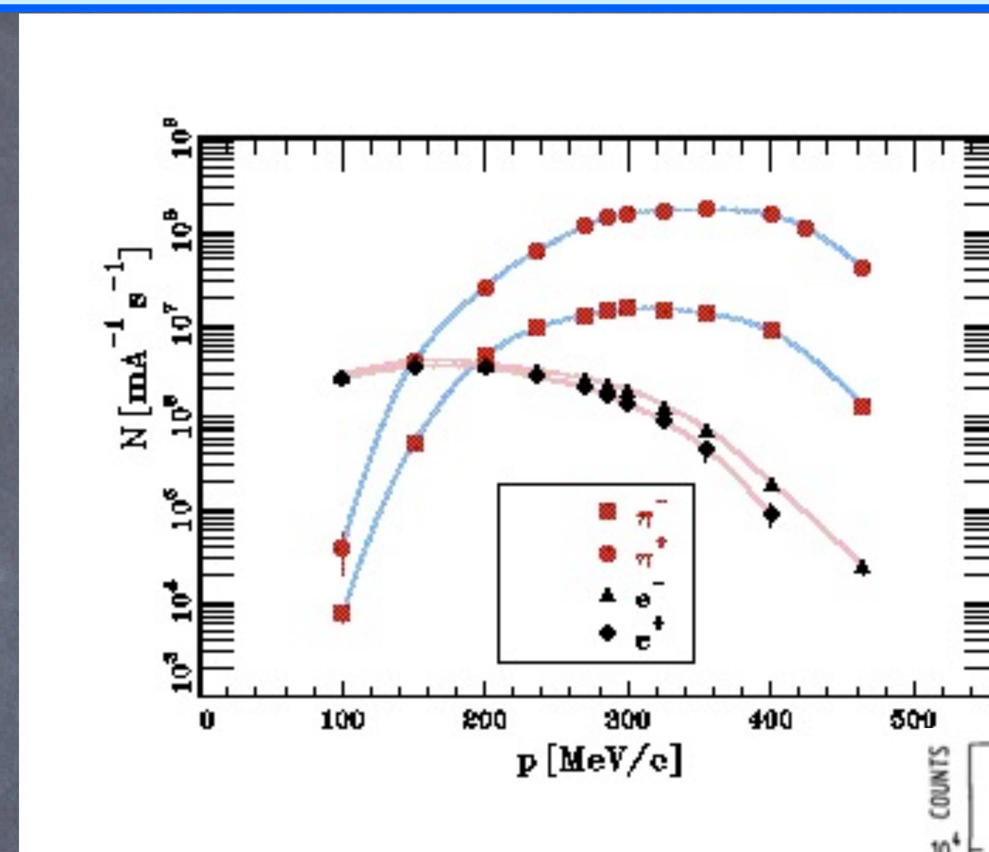
- μp and ep comparison:
  - BSM physics could lead to different FF and radii although the effect in scattering experiments could go away once $Q^2 > m^2_{new}$
- Measure both $\mu^{\pm}p$ and $e^{\pm}p$ for 2γ exchange
  - Proton polarizibility effect enhances 2γ exchange
- MUSE is in the low Q^2 region, 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.

PSI πM1 Channel Characteristics

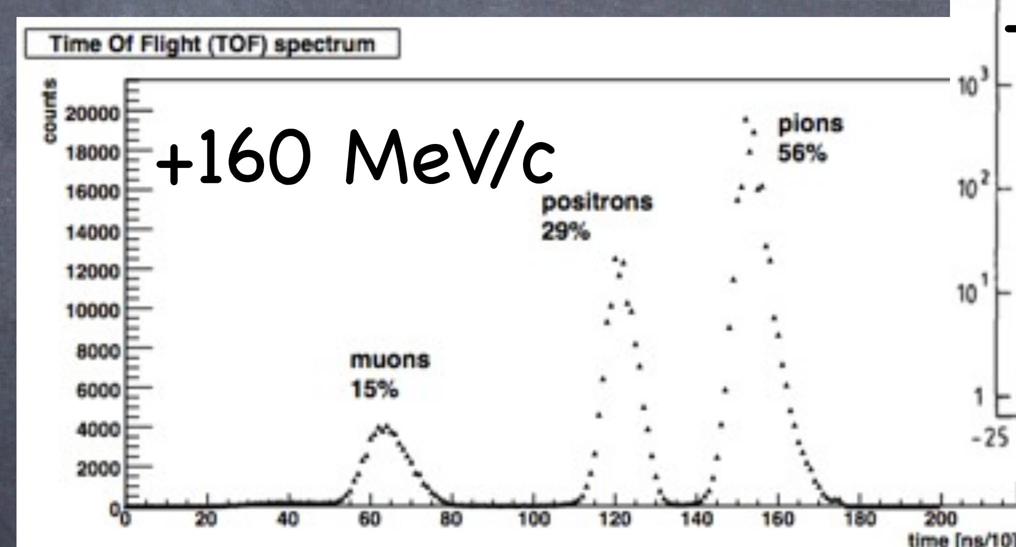
≈100 - 500 MeV/c mixed beam of μ's + e's + π's

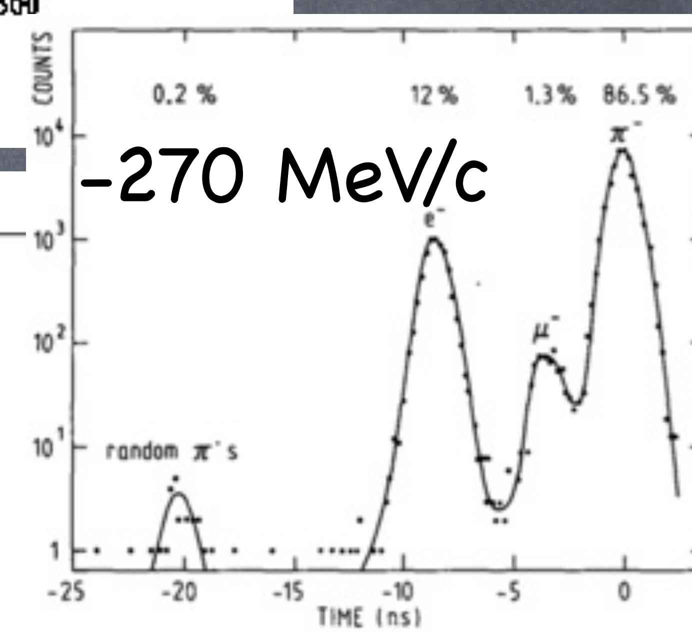


Dispersion at IFP: 7cm/%



Used in past as pion line, so muon properties were not well studied





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

Momentum acceptance: 3% resolution: 0.1%

Spot sizes from 0.7x0.9 cm^2 up to 16x10 cm^2, and Δp/p from 0.1–3.0%, used previously.

Fall 2012 Test Run

MUSE Test Run Report

The MUon proton Scattering Experiment collaboration (MUSE):

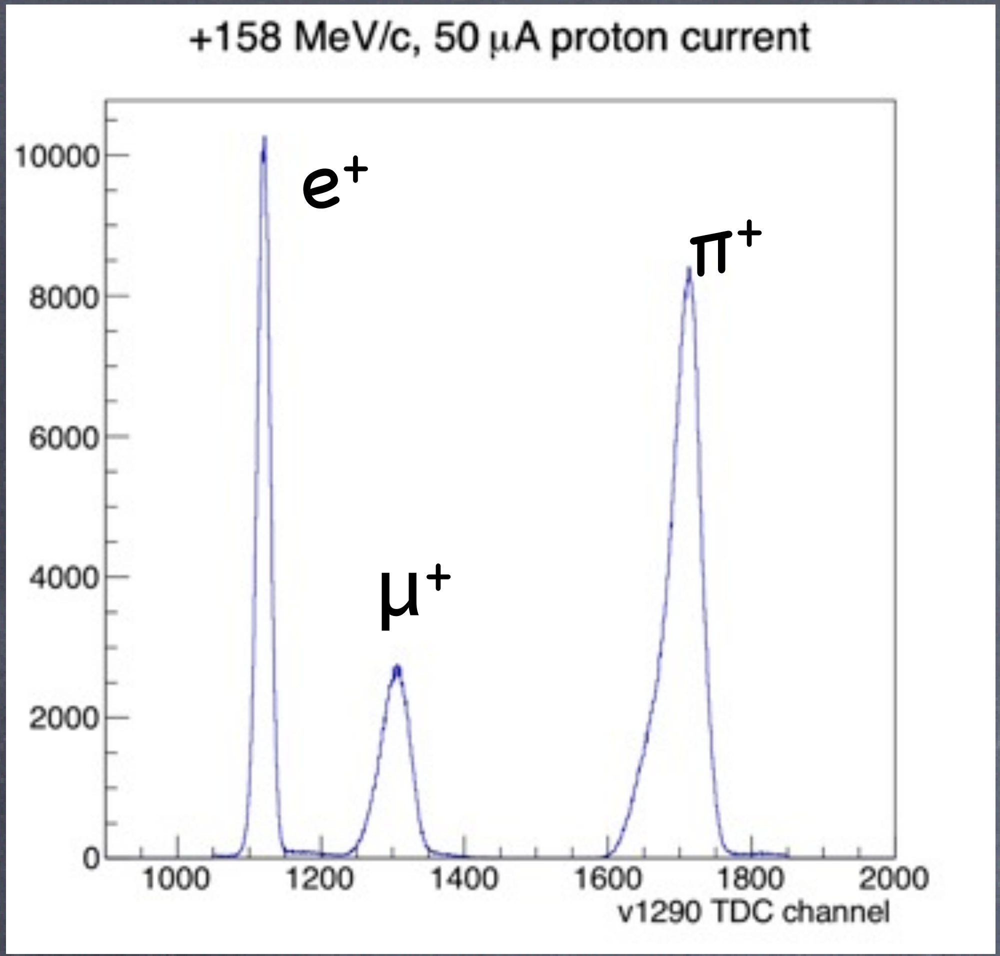
W.J. Briscoe,[1] K. Deiters,[2] E. Downie,[1] R. Gilman,[3] K.E. Myers,[3] E. Piasetzsky,[4] D. Reggiani,[2] P. Reimer,[5] G. Ron,[6] V. Sulkosky,[7] and M. Taragin[8]

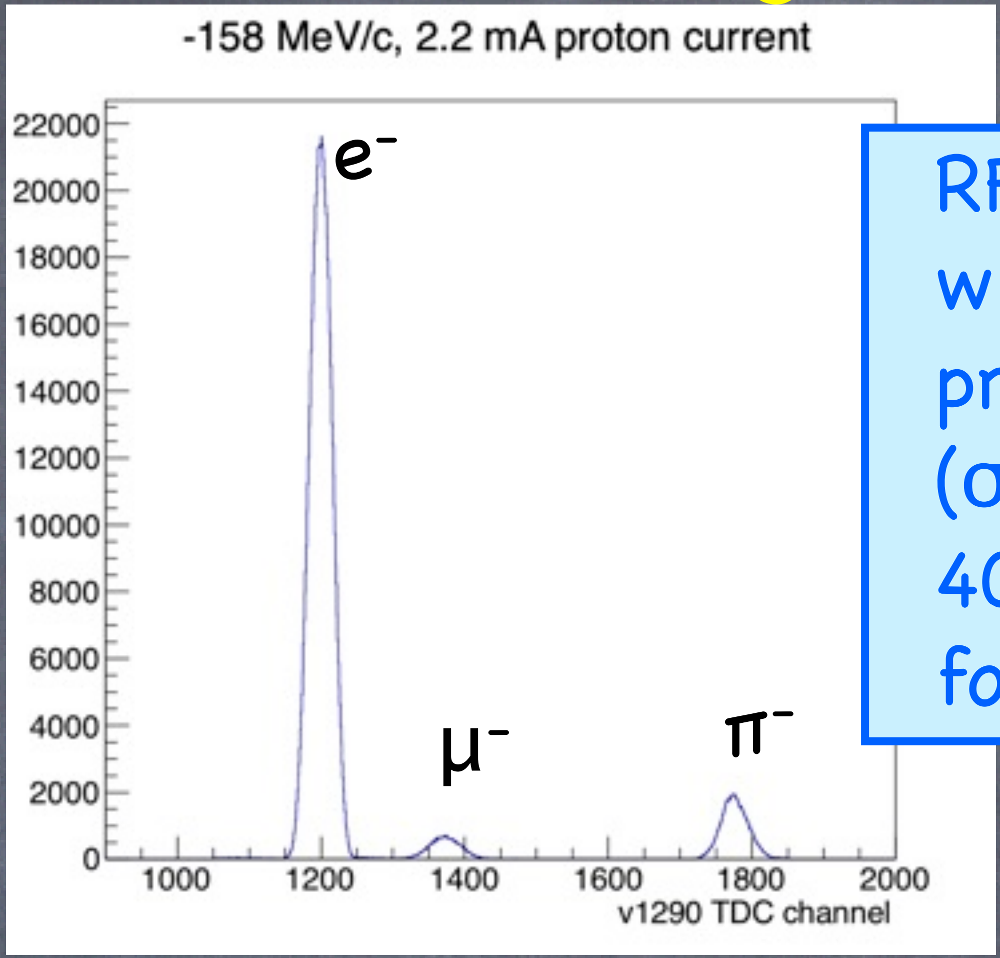
Recycled (3 mm) SciFi + prototype SC scintillators (5 cm x 5 cm)

NIM trigger, VME read out, working physicists

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

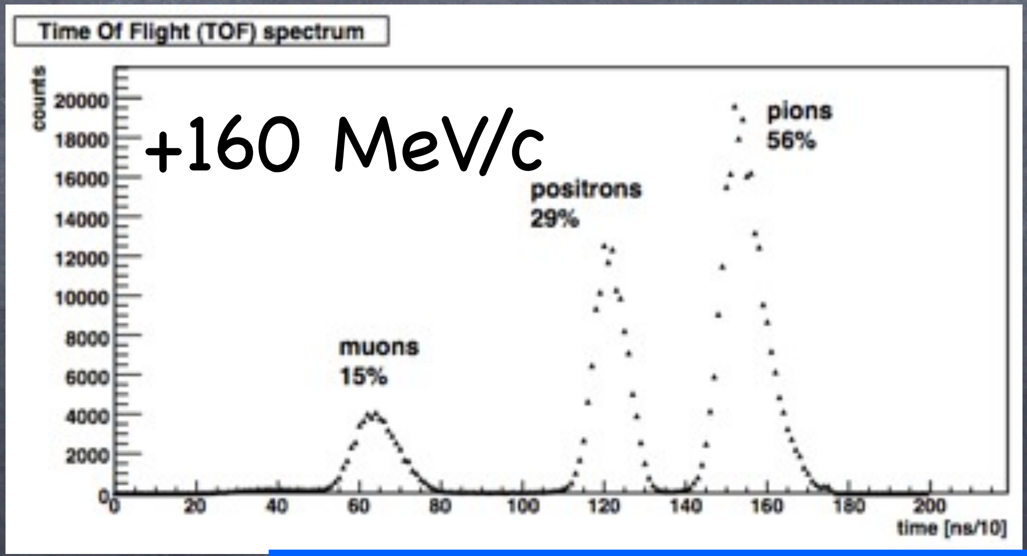
πM1 Channel - RF time in target region





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

πM1 Channel - particle fluxes

limiting flux to 5 MHz total, by cutting the 3% momentum bite

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

Flux of e's 1.4 - 35 times larger than flux of μ's

Beam Line Summary

- Good flux of μ's at target, much better flux of e's
- Beam spot smaller than nominal (σ)
- 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 500 ps (σ), except electrons appear to be ≈350 ps ⇨ necessitates high timing precision beam Cerenkov for rejection of μ decays

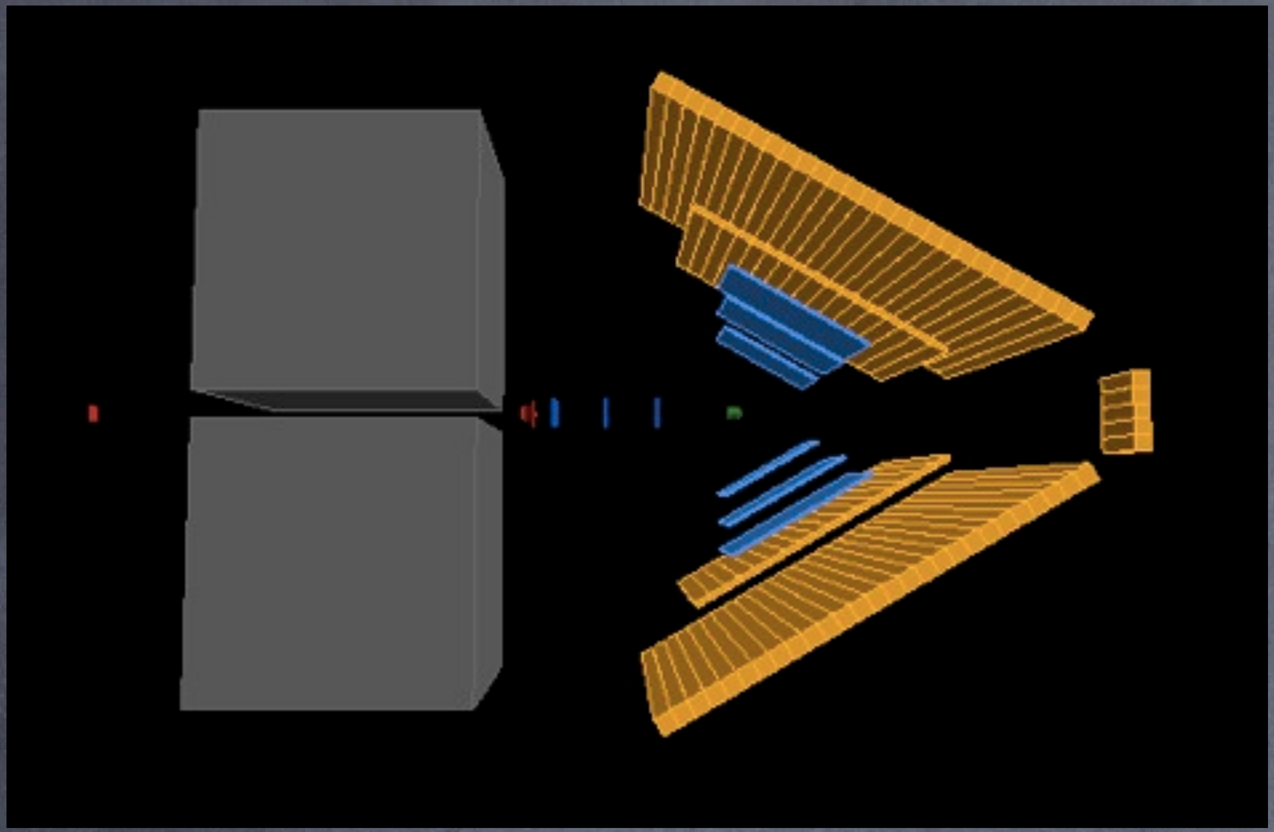
Next Few Years for MUSE

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 rehearsal
2016-2017	2 6-month experiment production runs

Second Test Run

- Use GEMs to more thoroughly characterize beam
- "Quartz" Cerenkov test
- Mini-scattering experiment

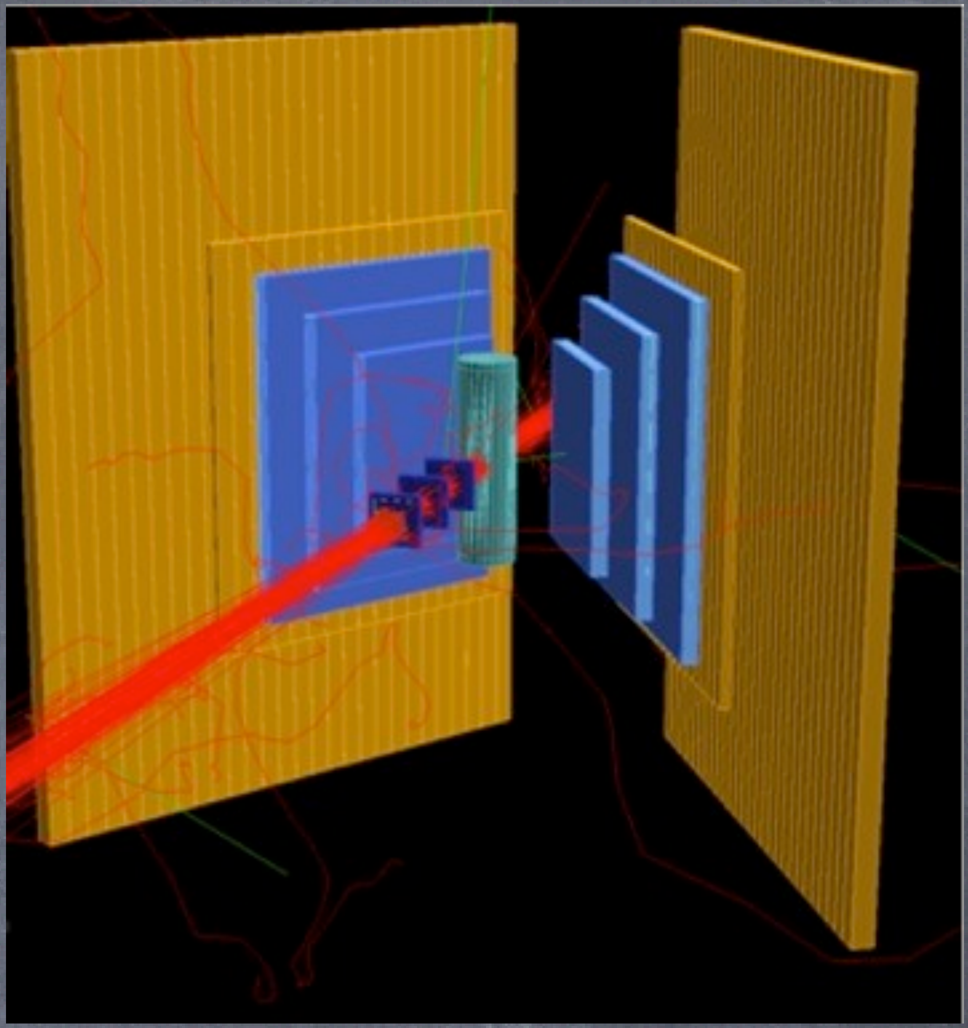
Reference Design



Beam passes though IFP SciFi array, shielding wall, target SciFi array, beam quartz Cerenkov, GEM chambers, target, and beam monitor scintillators.

Wire chambers and scintillator walls detect scattered particles.

Generally standard technology.



Geant4 estimates of background singles and trigger rates. Target / collimator backgrounds are very sensitive to beam distributions.

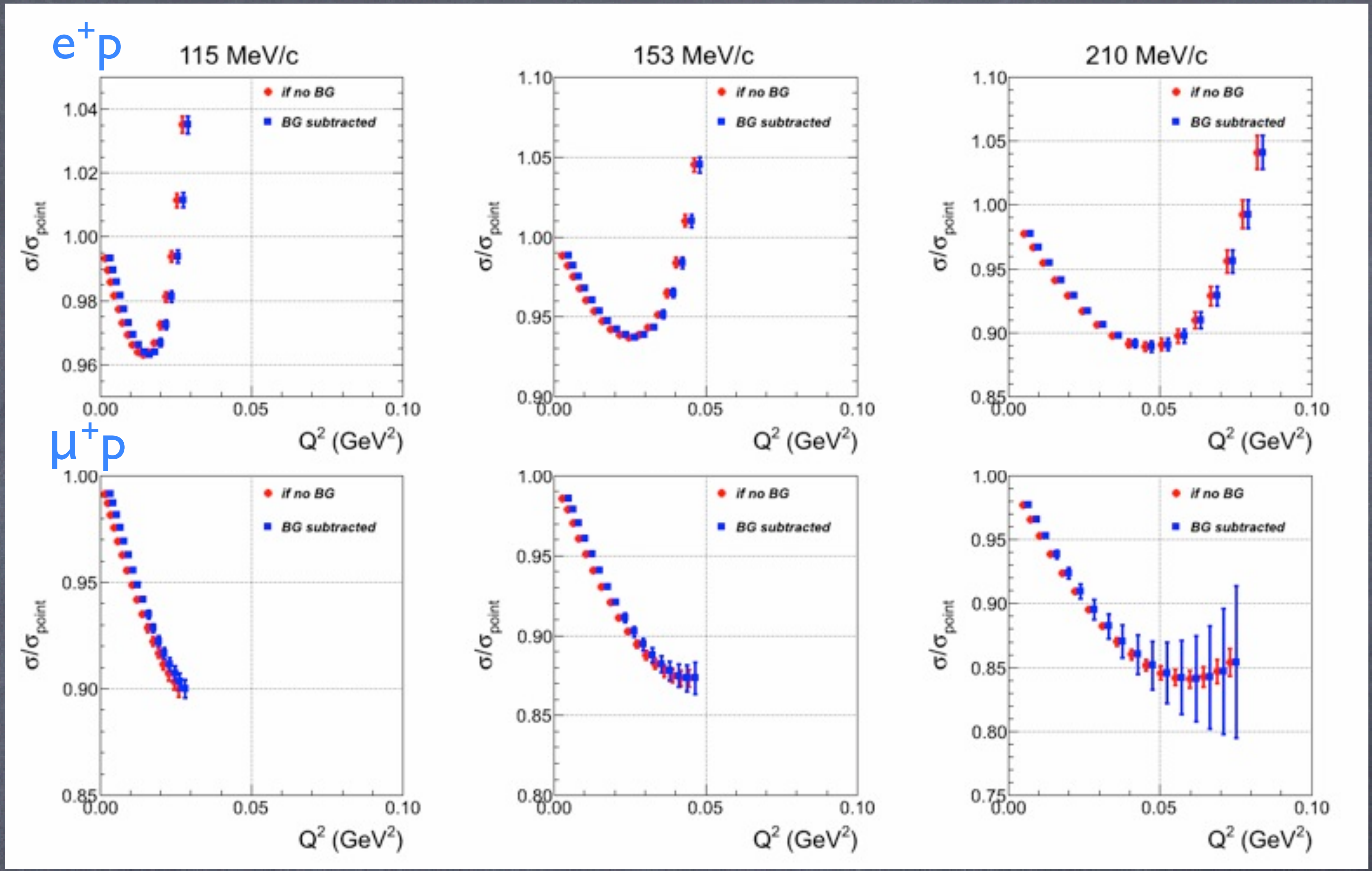
Need custom FPGA trigger to trigger on scattering events while rejecting all π-induced events.

New Equipment Summary

Detector	**Who**	**Technology**
Beam SciFi	Tel Aviv, St. Mary's	conventional
GEMs	Hampton	detector exists
Quartz Cerenkov	Hebrew	prototyped
FPGAs	Rutgers	conventional
target	Hebrew	conventional
wire chambers	MIT	copy existing system
scintillators	SC	copy existing system
DAQ	GWU	conventional, except TRB3 prototyped

Estimated Results!

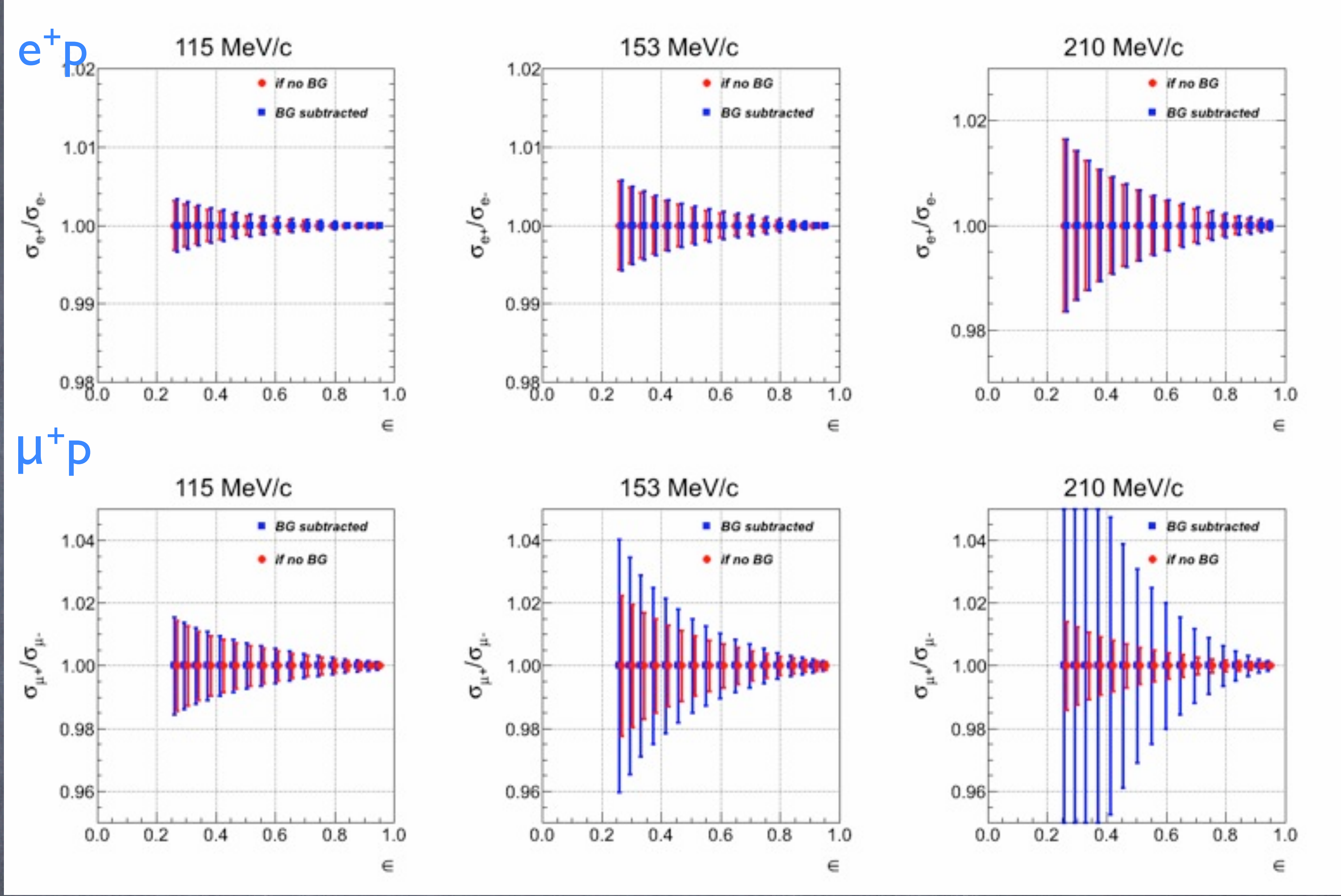
- statistical uncertainties only
- similar results for e^-p and μ^-p



- πM1 channel, with p_{in} = 115, 153, and 210 MeV/c: PID reasons.
- 6 month run, equal time for each setting
- Choose $\theta_{scatter}$ = 20 - 100°: rates, backgrounds, systematics.
- Statistical uncertainties include end cap subtractions and μ decay subtractions (for μ's) - the issue for 210 MeV/c at larger Q^2

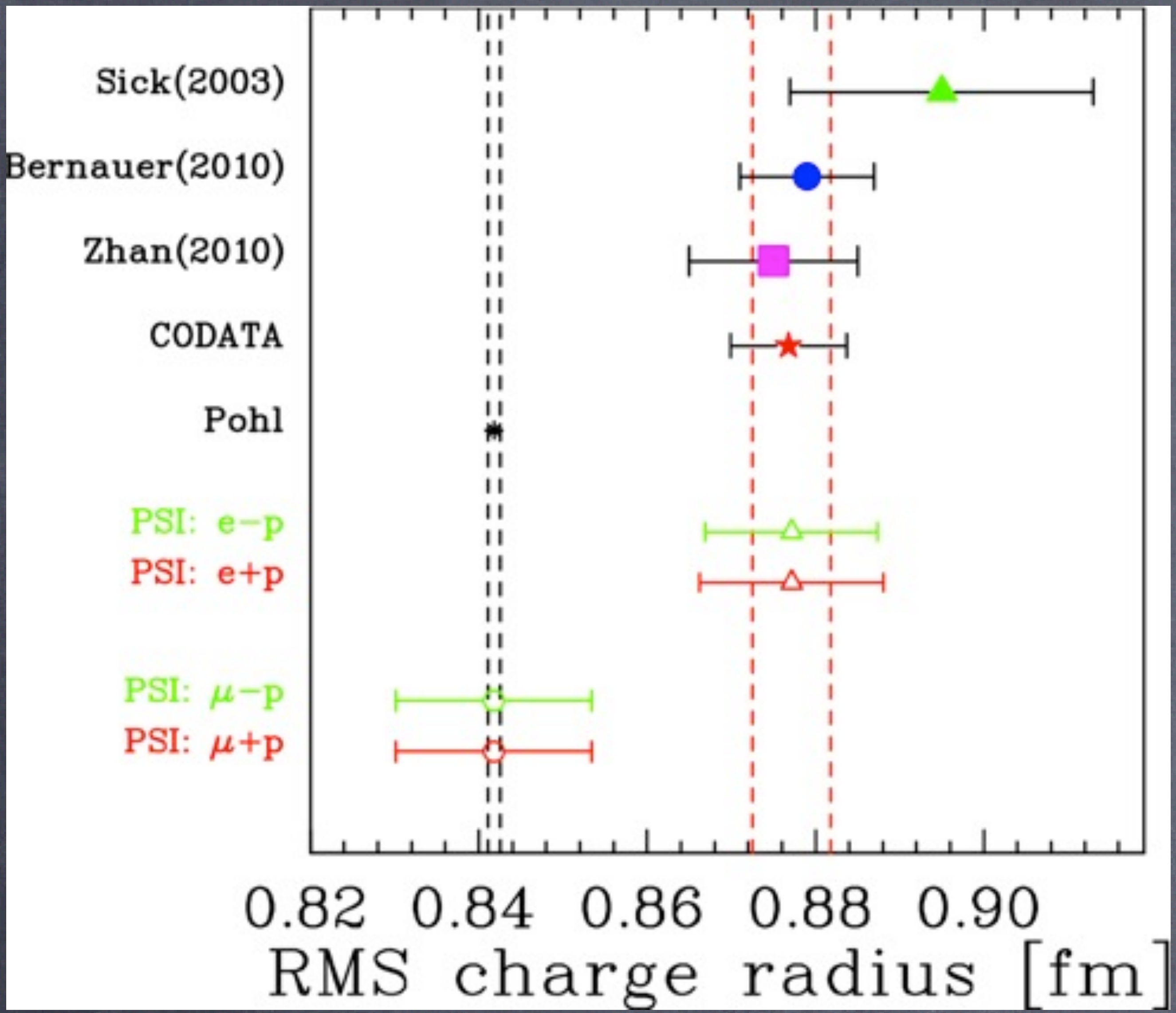
Estimated Results!

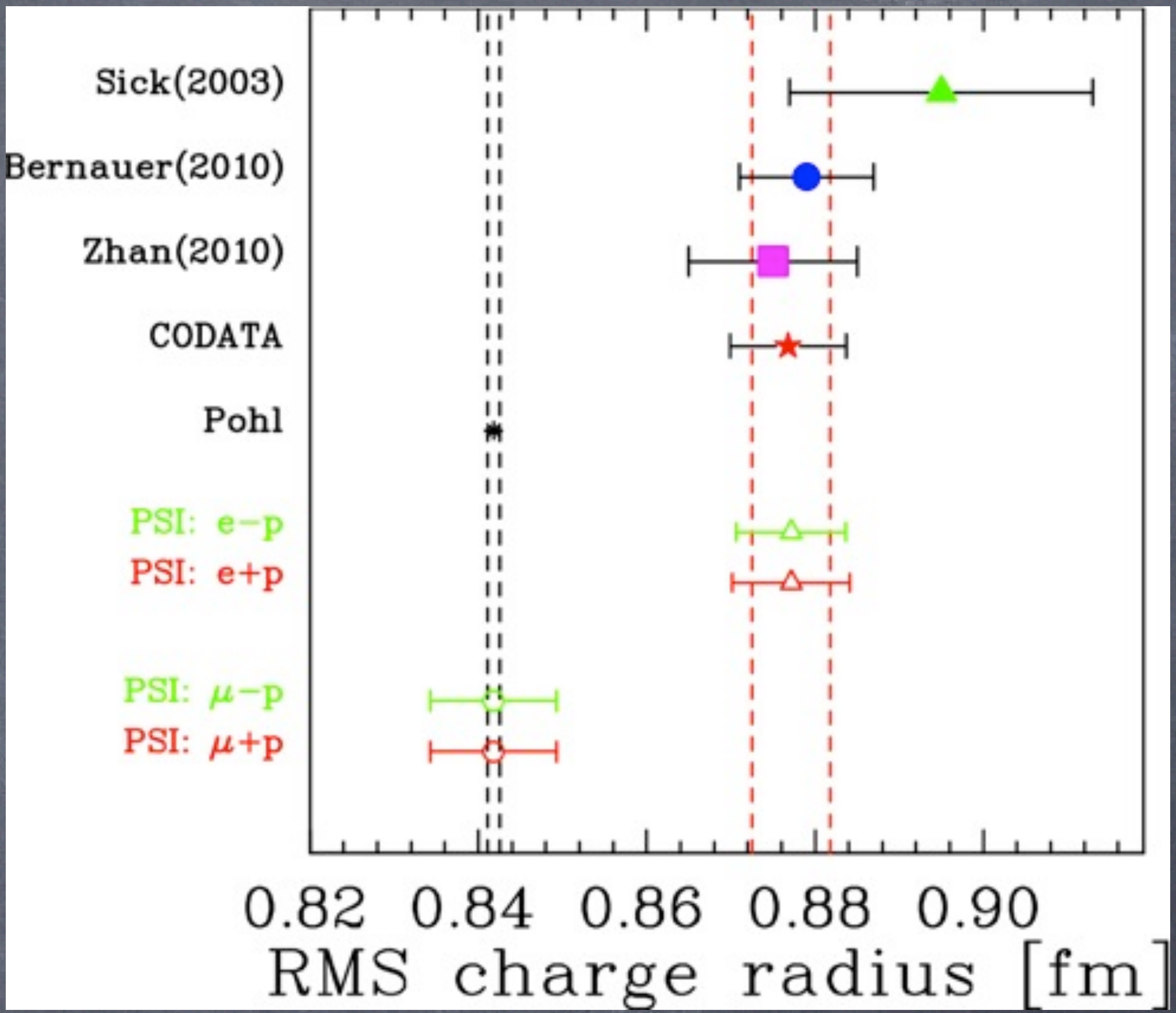
- statistical uncertainties only
- endcap BG mainly at ε near 1



- μ's are limited by μ decay rejection - here with very conservative estimate - rather than by systematics
- e^+/e^- generally limited by radiative corrections, but here 1γ radiative corrections cancel and a concern is detection response systematics from e^+ annihilation (One check: 2γ → 0 as ε → 1)

Physics





Radius extraction from J 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!

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]