International Workshop “Hadrons from Quarks and Gluons”
Hirschegg, Kleinwalsertal, Austria, Jan. 12-18, 2012

# The MUSE experiment at PSI

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* **Supported by NSF grant PHY-1207672, and DOE Early Career Award DE-SC0003884**

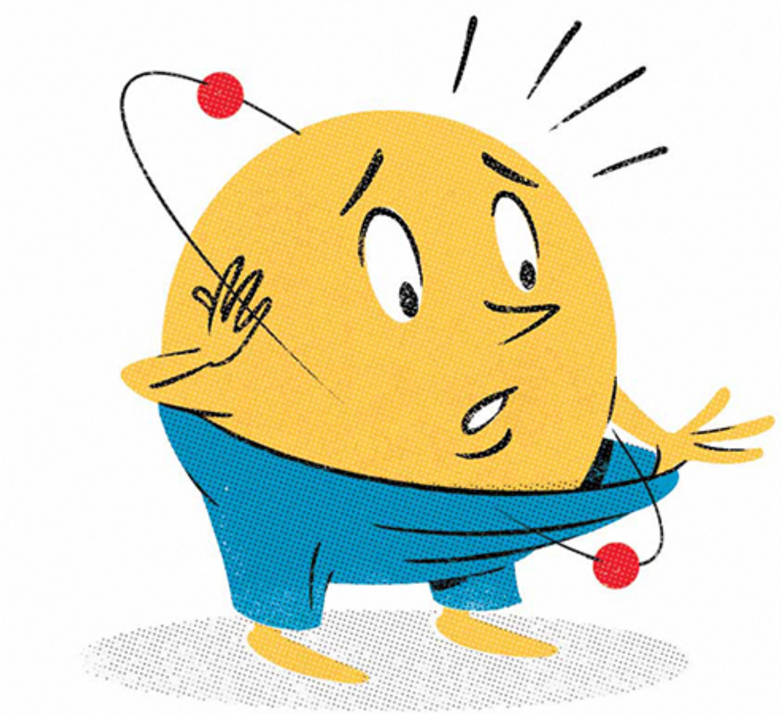
# MUon Scattering Experiment (MUSE) at PSI

PAUL SCHERRER INSTITUT

Appollo and the nine muses

# MUon Scattering Experiment (MUSE) at PSI

- Motivation
- Proposed experiment
  - Muon beamline
  - Detector
  - Expected sensitivity
- Status & Schedule



NY Times, July 12, 2010

# The proton radius puzzle in the media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The New York Times — **Space & Cosmos**

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ENVIRONMENT **SPACE & COSMOS**

## For a Proton, a Little Off the Top (or Side) Could Be Big Trouble

By DENNIS OVERBYE
Published: July 12, 2010

For most of us, 4 percent off around the waist — a couple of belt notches — would be a great triumph.

Enlarge This Image

Chris Gash

Not so for the proton, the subatomic particle that anchors atoms and is the building block of all ordinary matter, of stars, planets and people. Physicists announced last week that a new experiment had shown that the proton is about 4 percent smaller than they thought.

Instead of celebration, however, the result has caused consternation. Such a big discrepancy, say the physicists, led by Randolf Pohl of the Max Planck Institute for Quantum Optics in Garching, Germany, could mean that the most accurate theory in the history of physics, quantum electrodynamics, which describes how light and matter interact, is in trouble.

"What you have is a result that actually shocked us," said Paul Rabinowitz, a chemist from Princeton University, who was a member of Dr. Pohl's team.

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SCIENTIFIC METHOD / SCIENCE & EXPLORATION

## 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

PHYSICAL SCIENCES 102

The proton accelerator at the Paul Scherrer Institute, which was used to create the muons used in this experiment.
Paul Scherrer Institute

## Proton Mass Mystery Could Mean New Physics

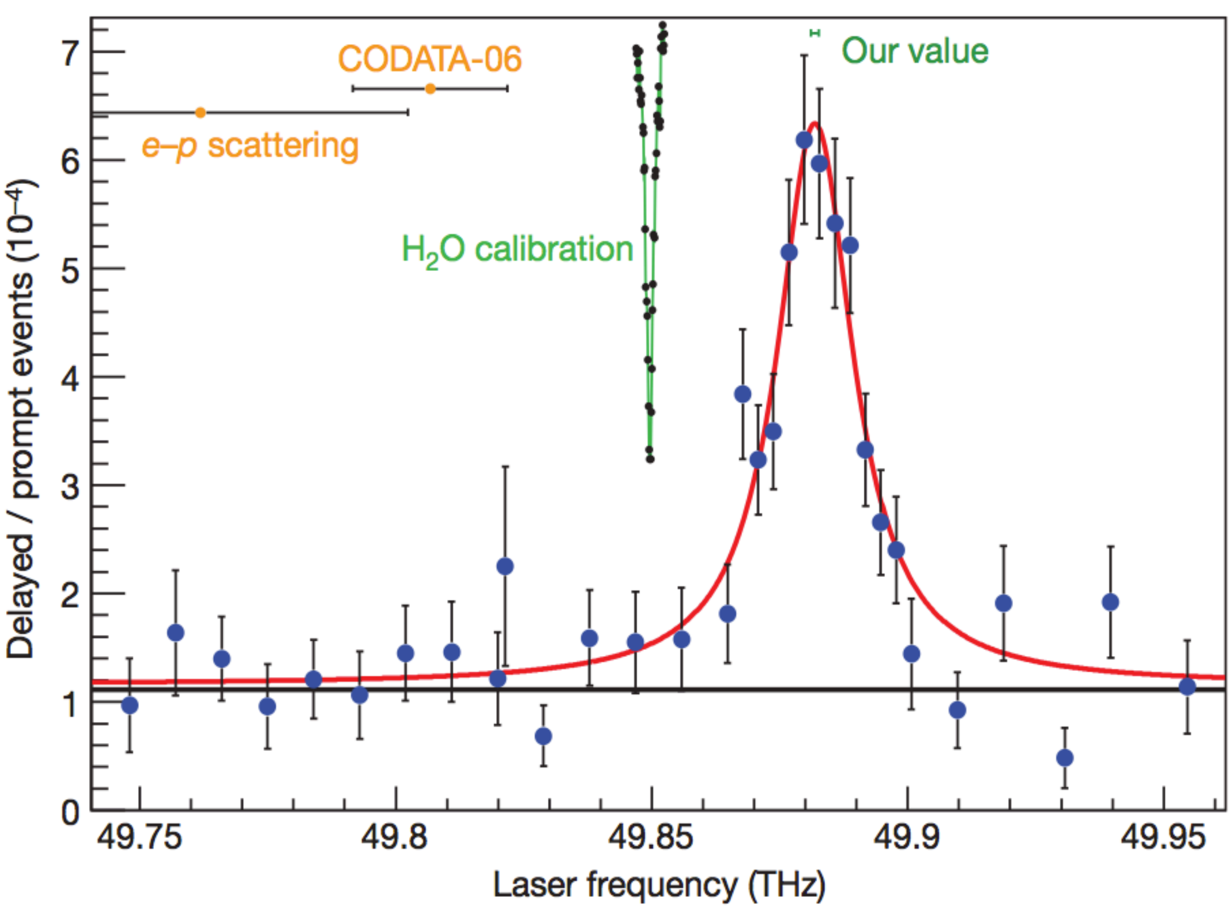
APR 15, 2013 08:35 PM ET // BY STEPHANIE PAPPAS, LIVESCIENCE

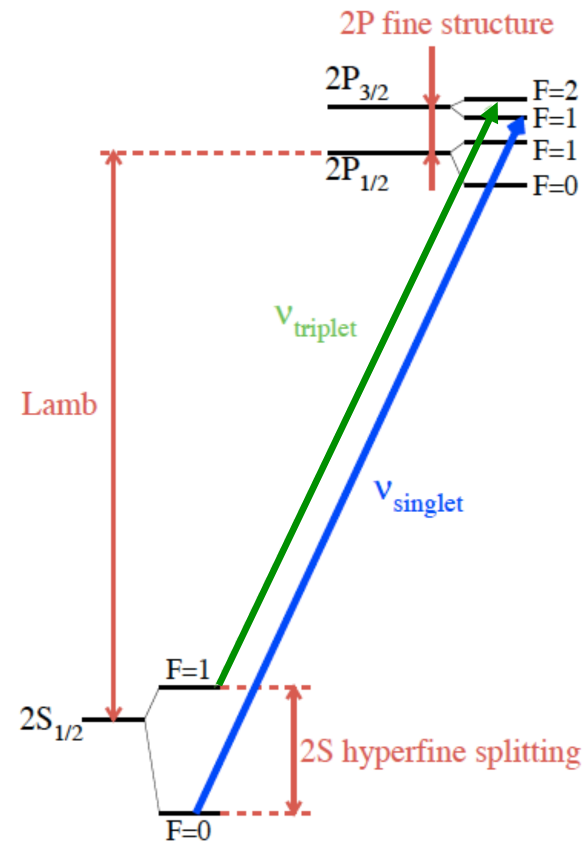
# PSI muonic hydrogen measurements

- R. Pohl et al., Nature 466, 09259 (2010): 2S➪2P Lamb shift
  $\Delta E(\text{meV}) = 209.9779(49) - 5.2262\ r_p^2 + 0.0347\ r_p^3$ ➪ $r_p = 0.84184 \pm 0.00067$ fm

  Possible issues: atomic theory & proton structure

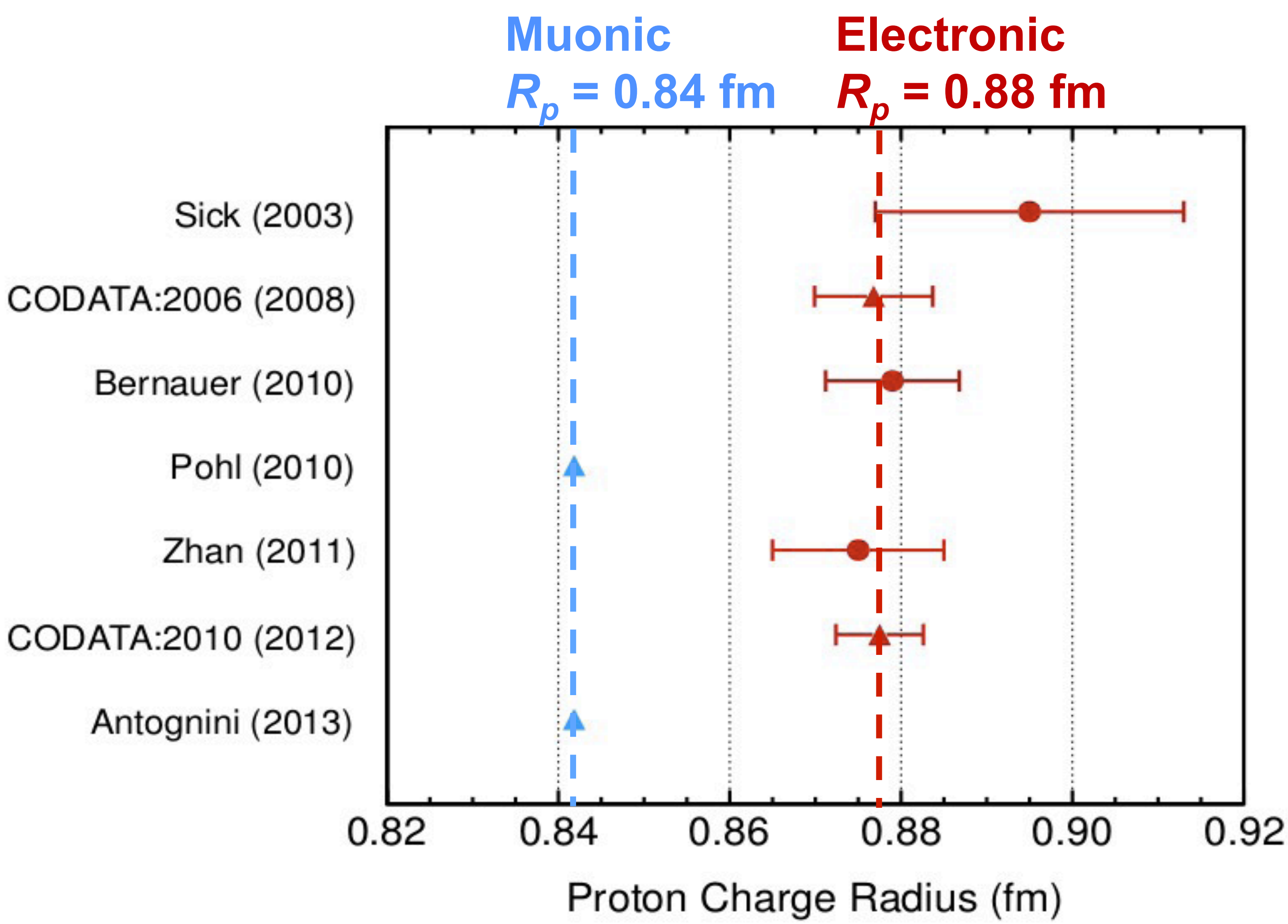
- UPDATE: A. Antognini et al., Science 339, 417 (2013): 2S➪2P Lamb + 2S-HFS
  $\Delta E_L(\text{meV}) = 206.0336(15) - 5.2275(10) r_p^2 + 0.0332(20)_{TPE}$ ➪ $r_p = 0.84087 \pm 0.00039$ fm



# The proton radius puzzle

- >7σ discrepancy between **muonic** and **electronic** measurements
- High-profile articles in Nature, NYTimes, etc.
- Puzzle unresolved, possibly New Physics





▲ Spectroscopy

● Scattering

$R_P$ = 0.84184(67) fm

$R_P$ = 0.875(10) fm

$R_P$ = 0.8775(51) fm

$R_P$ = 0.84087(39) fm

# JLAB ep scattering at low $Q^2$

**Hall A PR07-004, PR08-007 (PAC31/33)**

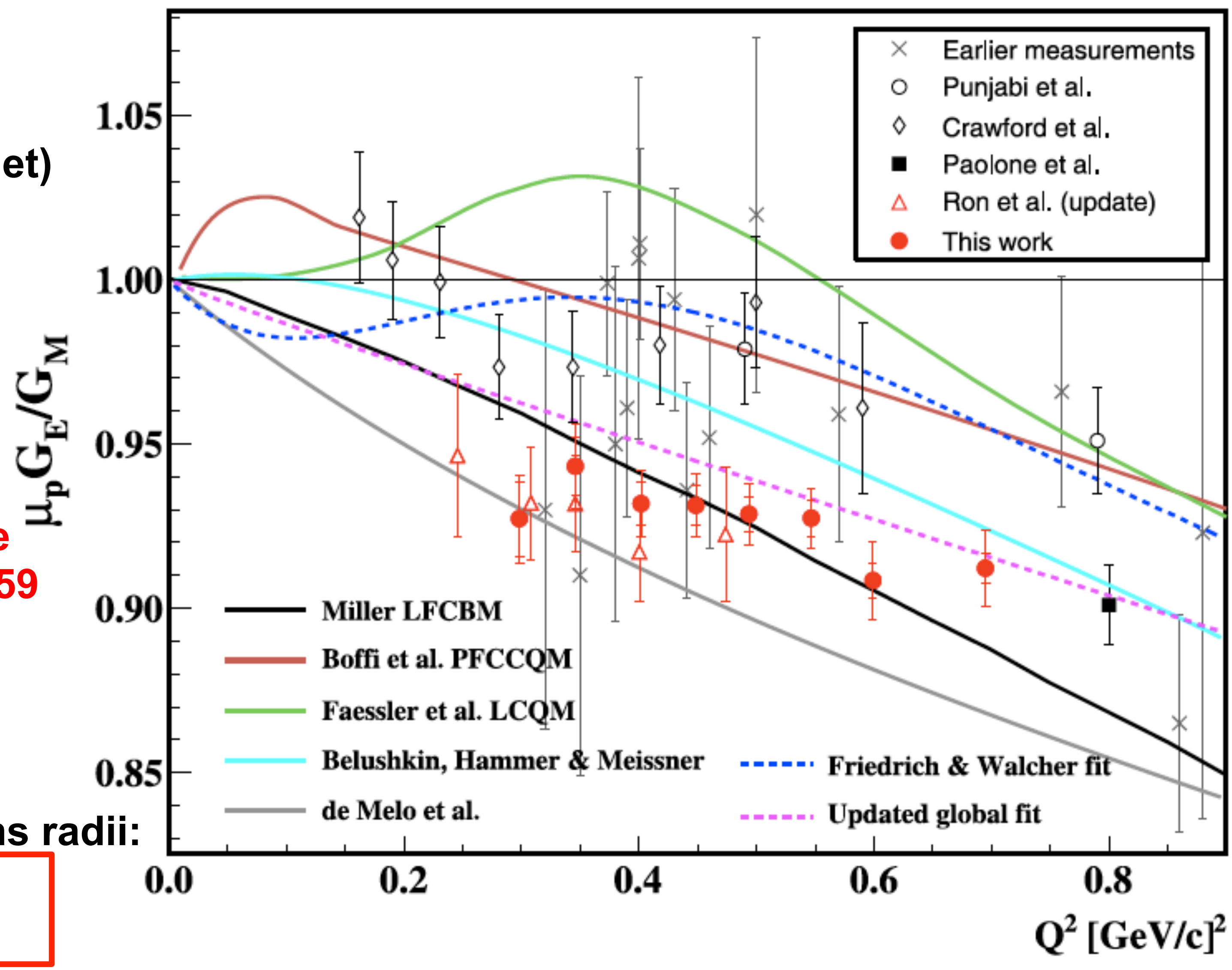
**•Recoil polarization, completed 2008**

**•Polarized target, completed 2012**

**◇ BLAST (polarized target)**
**C. Crawford et al., PRL98 (2007) 052301**

**X. Zhan, E08-007 + LEDEX update Phys. Lett. B 705 (2011) 59**

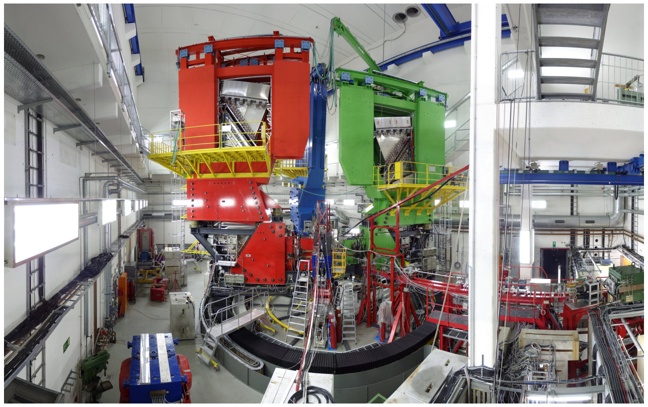
**2-sigma difference lower than BLAST**




**Charge and magnetic rms radii:**

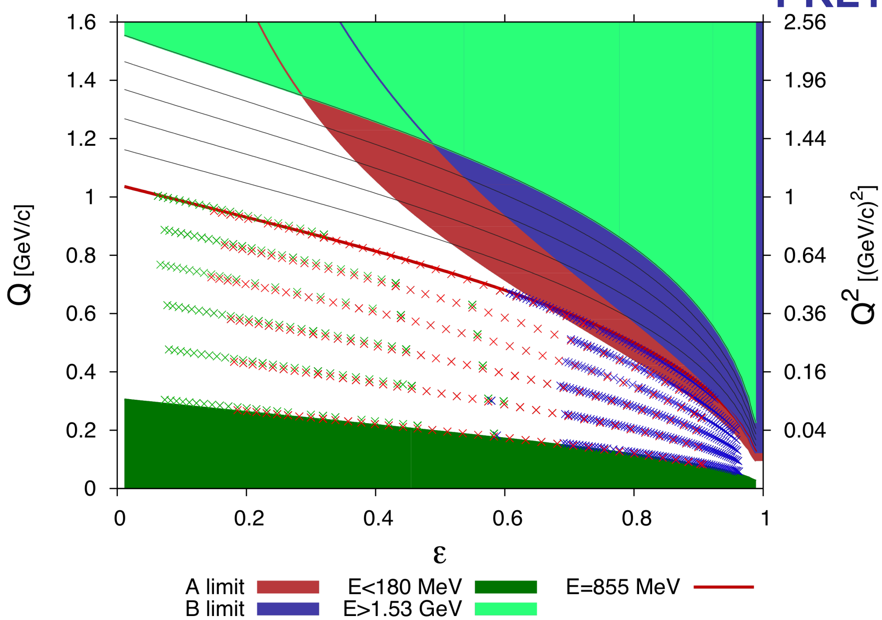
$R_E$ = 0.875 ± 0.010 fm
$R_M$ = 0.867 ± 0.020 fm

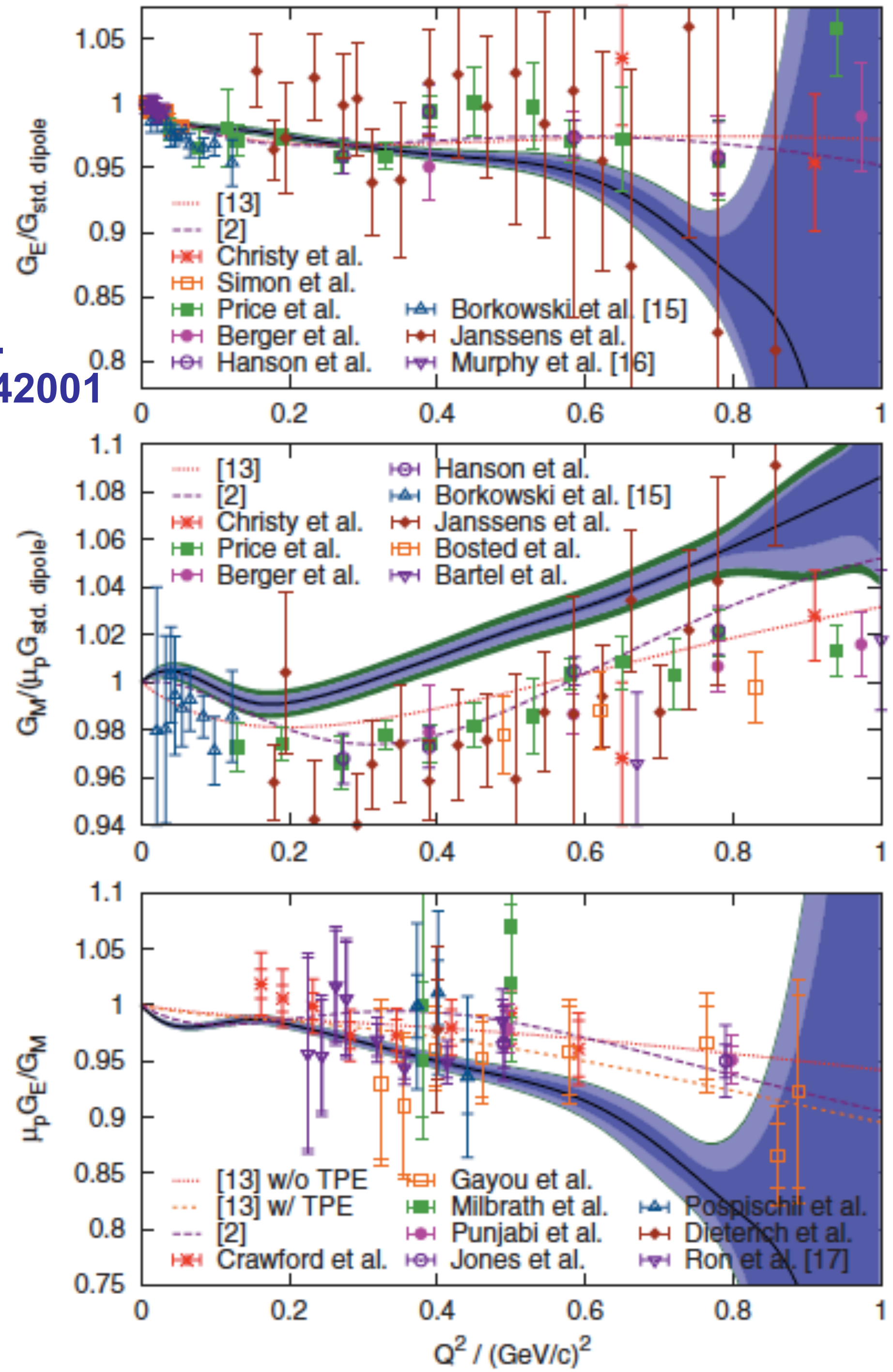
# Mainz ep scattering at low $Q^2$



**MAMI A1**

**J. Bernauer et al.**
**PRL105 (2010) 242001**




**Rosenbluth separation at low $Q^2$**

**Precise charge and magnetic rms radii:**

**$R_E = 0.879 \pm 0.008$ fm**

**$R_M = 0.777 \pm 0.017$ fm**

# Possible resolutions to the puzzle

- **The ep (scattering) results are wrong**
  Fit procedures not good enough
  $Q^2$ not low enough, structures in the form factors
- **The ep (spectroscopy) results are wrong**
  Accuracy of individual Lamb shift measurements?
  Rydberg constant could be off by 5 sigma
- **The μp (spectroscopy) result is wrong**
  Discussion about theory and proton structure for extracting the proton radius from muonic Lamb shift measurement
- **Proton structure issues in theory**
  Off-shell proton in two-photon exchange leading to enhanced effects differing between μ and e
  Hadronic effects different for μp and ep:
  e.g. proton polarizability (*effect* $\propto m_l^4$)
- **Physics beyond Standard Model differentiating μ and e**
  Lepton universality violation, light massive gauge boson
  Constraints on new physics from kaon decays

# New measurements are on their way

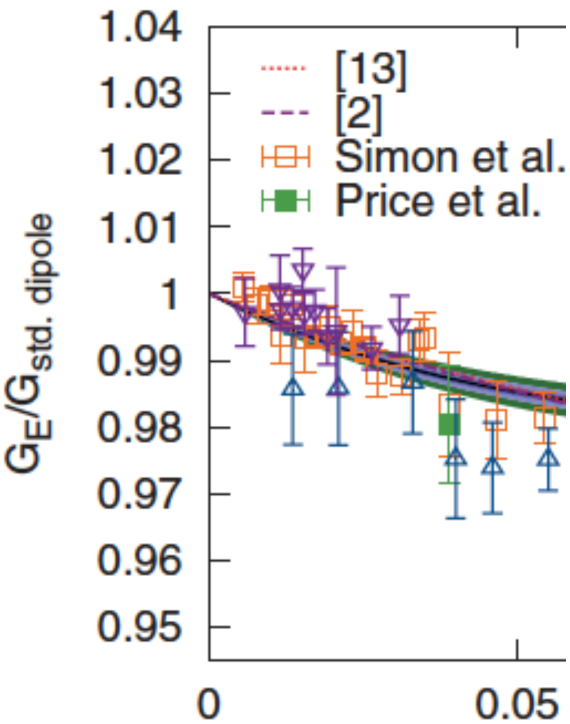
- **Additional measurements needed / in preparation**
  - Spectroscopy with μD, μHe, and regular H; Rydberg constant
  - ep-, ed-scattering
    (PRad at Jlab, ISR-ep and ed elastic at MAMI; MESA)
  - $\mu^{\pm}$p- and $e^{\pm}$p-scattering in direct comparison at PSI (MUSE)
  - Searches for lepton universality violating light bosons
    (e.g kaon decay such as TREK/E36 at J-PARC)

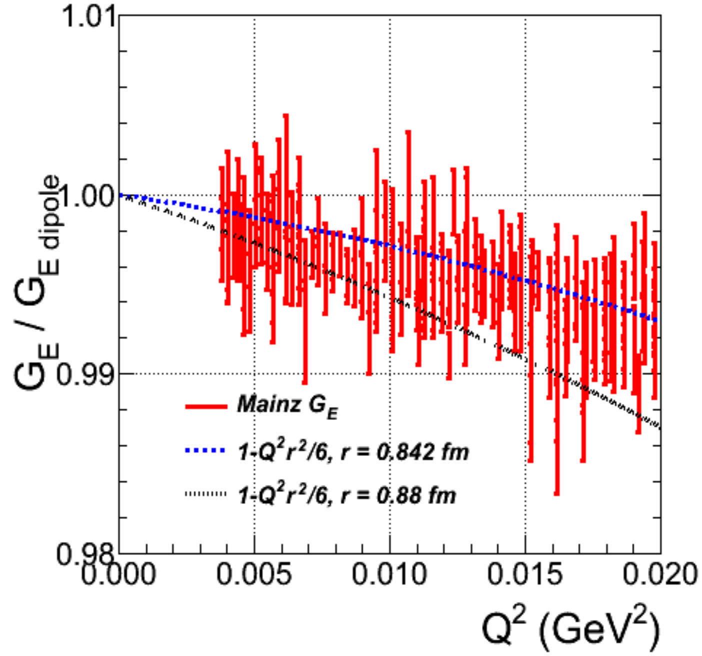
| $r_p$ (fm) | ep | μp |
|---|---|---|
| Spectroscopy | 0.8758 ± 0.077 | 0.84087 ± 0.00039 |
| Scattering | 0.8770 ± 0.060 | ??? |

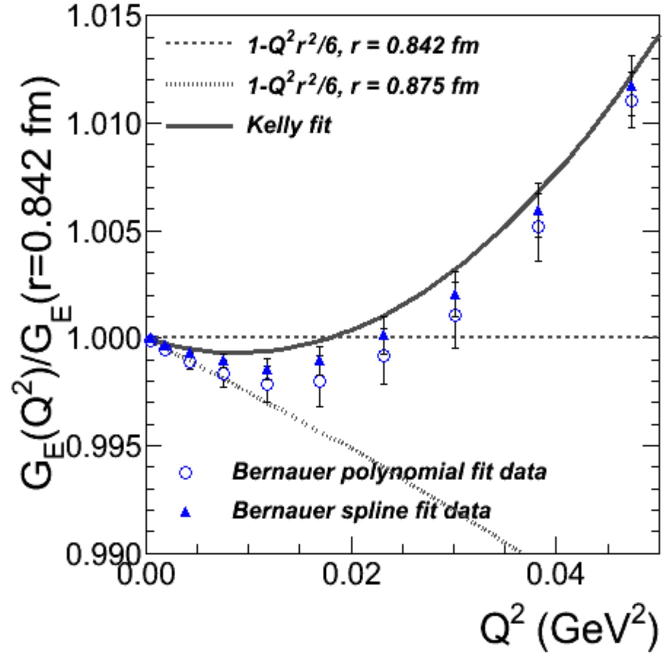
**Need more precision for extraction from scattering**
**More insights from comparison of ep and μp scattering**

# Proton radius from Mainz A1 data

$G_E(Q^2) = 1 - Q^2r^2/6 + \ldots$

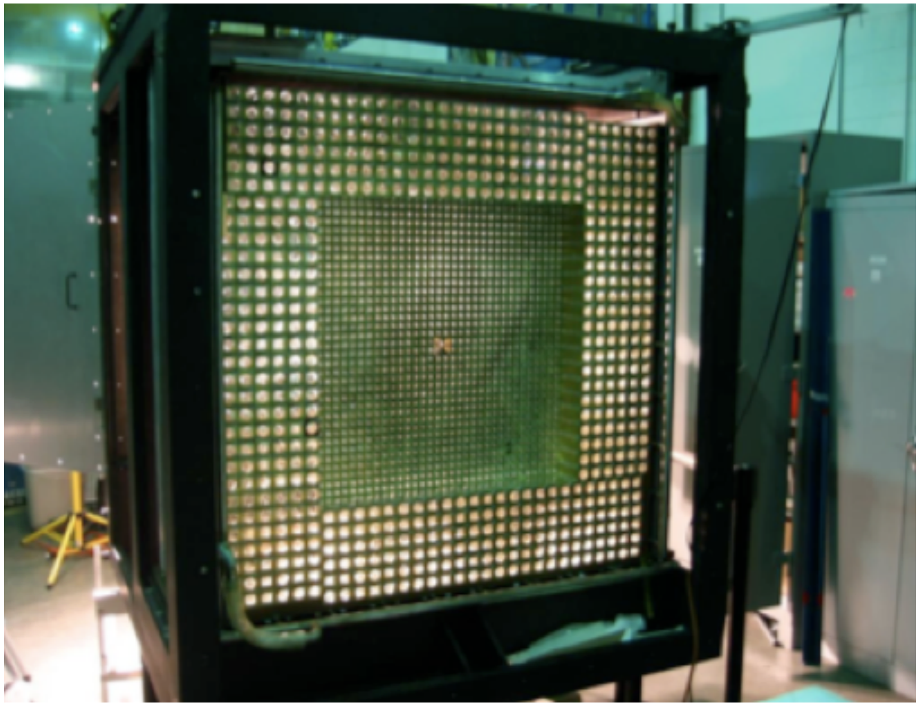


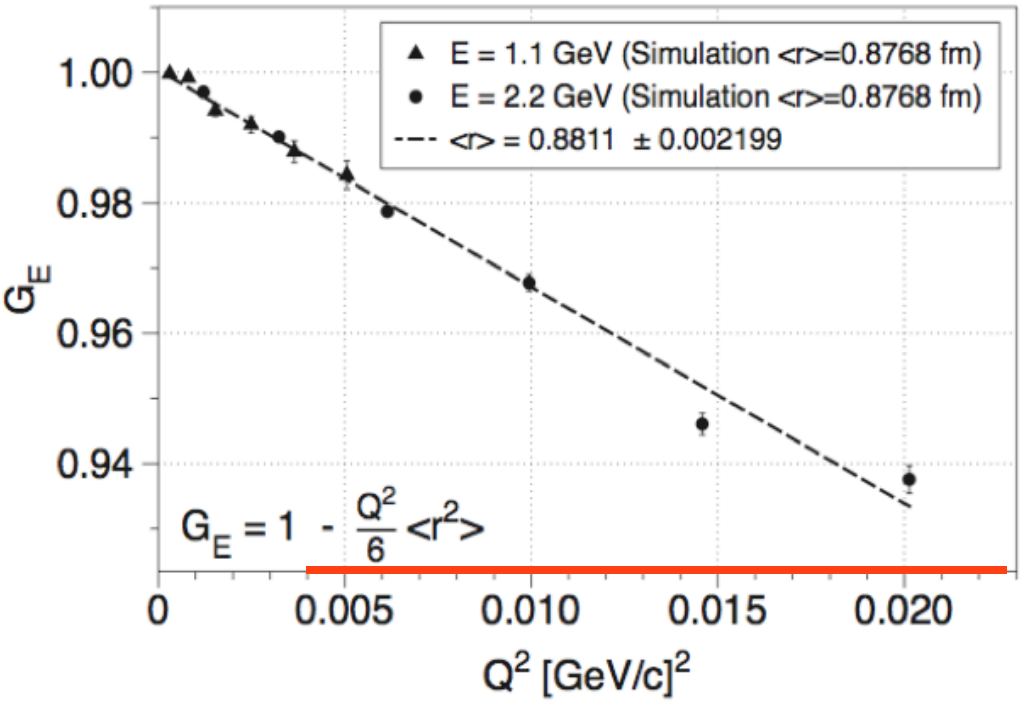




- Low $Q^2$ – J. Bernauer et al., PRL105 (2010) 242001
- Left: world + Mainz fit; Middle: Mainz raw data; Right rebinned $G_E$
- Large difference in slope between r = 0.84 and 0.88 fm
- Floating normalization, higher-order $Q^2$ terms present
- Need yet higher precision

# The PRad proton radius proposal (JLAB)






- Low intensity beam in Hall B @ Jlab into windowless gas target
- Scattered ep and Moller electrons into HYCAL at 0$^o$
- Lower $Q^2 > 2x10^{-4}$. Very forward angle, insensitive to 2γ, $G_M$
- Conditionally approved by PAC38 (Aug 2011): ``Testing of this result is among the most timely and important measurements in physics.''
- Approved by PAC39 (June 2012), graded "A"

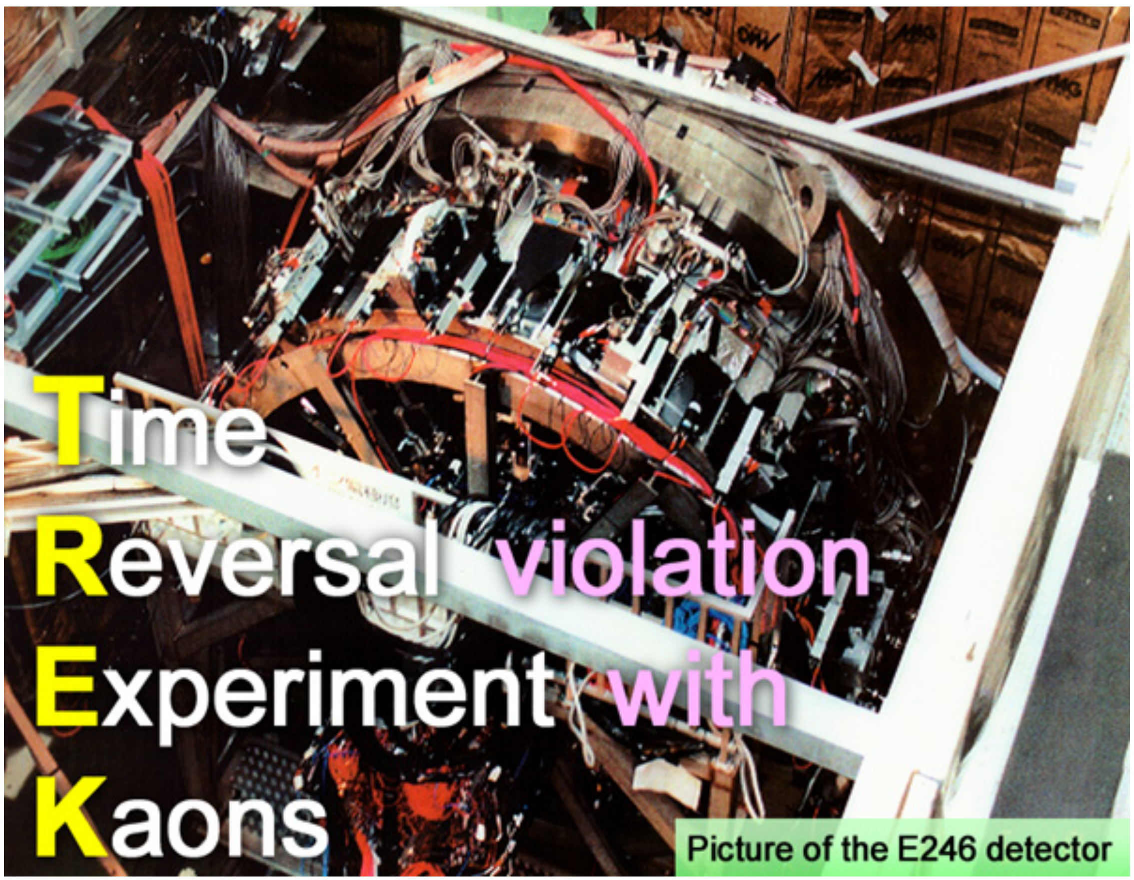
# TREK (E36) at J-PARC

**Measurement of $\Gamma(K^+ \rightarrow e^+\nu)/\Gamma(K^+ \rightarrow \mu^+\nu)$**

**and**

**Search for heavy sterile neutrinos**

**using the TREK detector system**

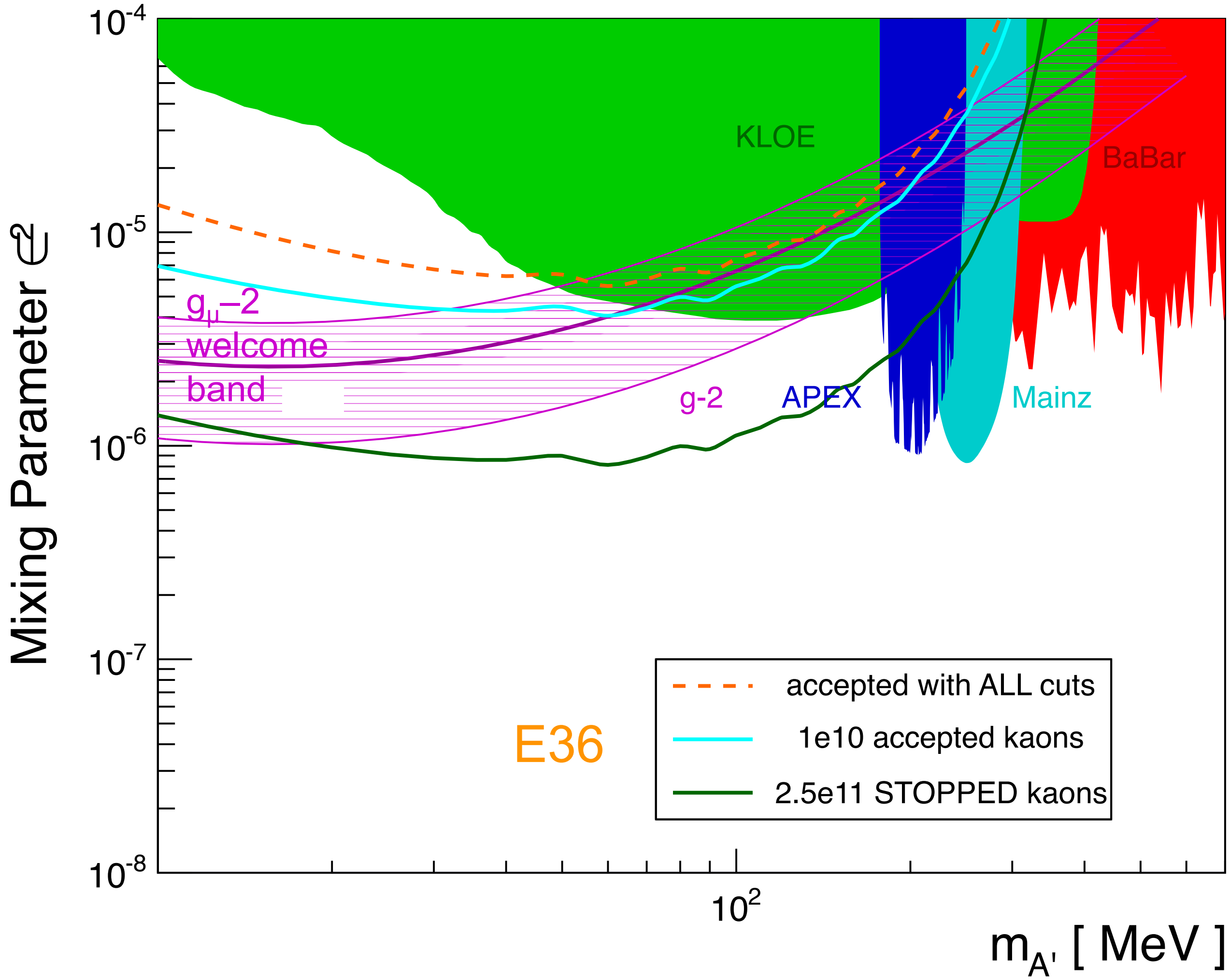


Picture of the E246 detector

Official website:
**http://trek.kek.jp**

**Scheduled to run beginning of 2015**

# Dark photon exclusion limit $K^+ \to \mu^+ \nu e^+ e^-$




P. Monaghan

**TREK/E36:**

Kaons delivered: $1.0 \times 10^{12}$

&& stopped: $2.5 \times 10^{11}$

&& $\mu^+$ accepted: $1.8 \times 10^{10}$

&& $e^+e^-$ accepted: $1.0 \times 10^{10}$

- Mixing parameter: dark photon framework, universal coupling
- Simulated signal channel $K^+ \to \mu^+ \nu A'$ for resolution
- Simulated background distribution with BR($K^+ \to \mu^+ \nu e^+ e^-$)=2.5e-5
- Obtain exclusion limit for signal > 2x background fluctuation
- Exclusion limit dependent on resolution and number of accepted $K^+$

# Search for a new particle in $K^+ \rightarrow \mu^+ \nu e^+ e^-$

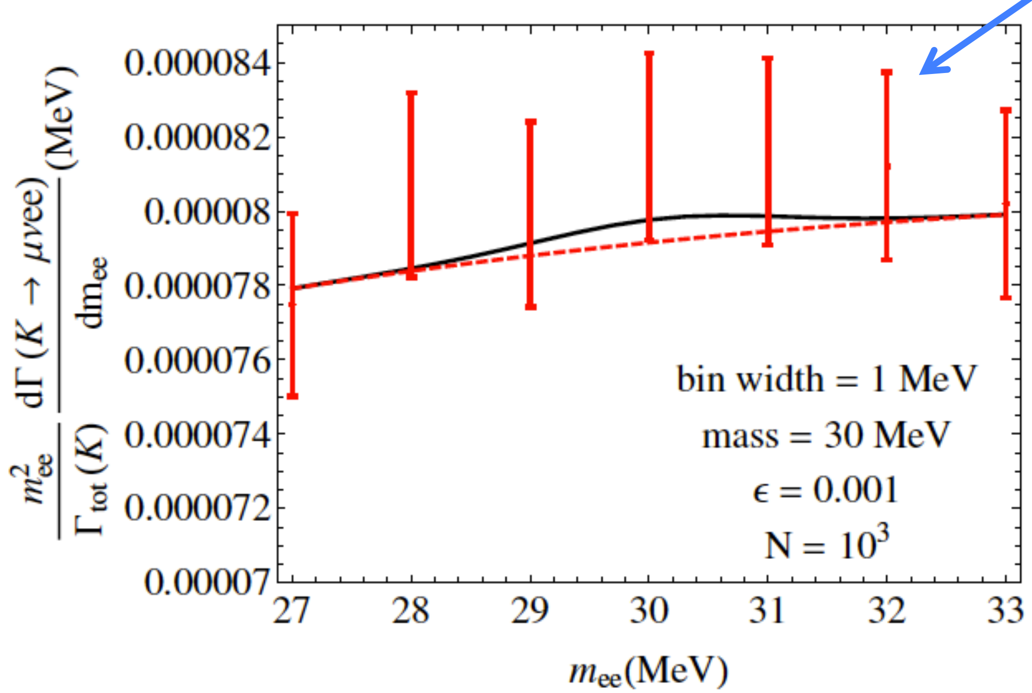
**QED background:** $K^+ \rightarrow \mu^+ \nu e^+ e^-$

- $\Gamma(K^+ \rightarrow \mu^+ \nu ee) \sim 2.5 \times 10^{-5}$
- *Expect $10^{10}$ stopped $K^+$ in E36*
- *250k QED evts or ~1000 / MeV*

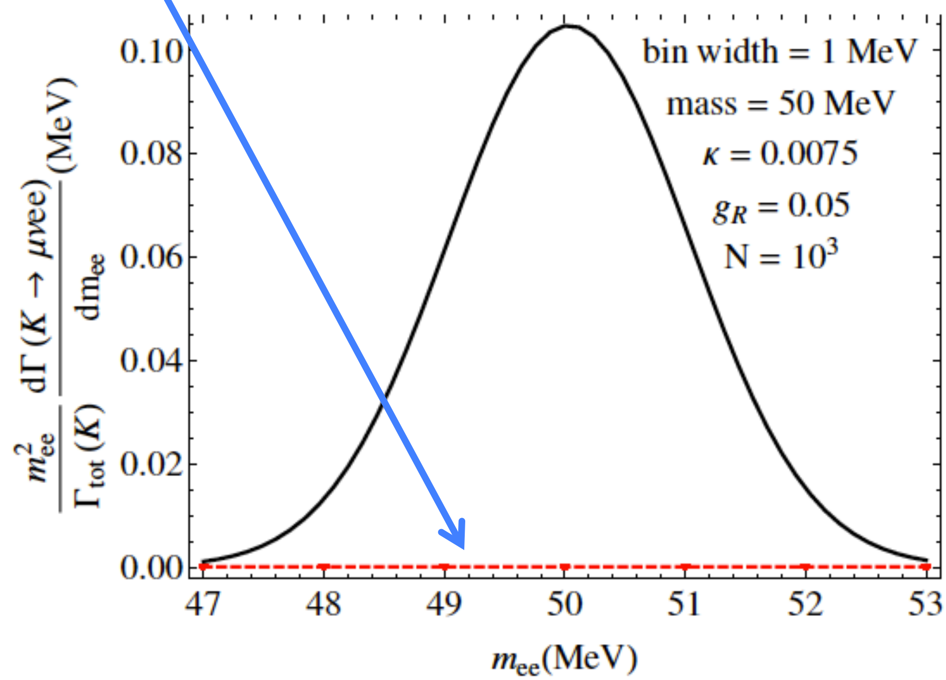
**Signal:** $K^+ \rightarrow \mu^+ \nu A'$, $A' \rightarrow e^+ e^-$

**C. Carlson, B. Rislow, hep-ph/1310.2786**

same background!




Dark photon model
(universal coupling)
$\Gamma(K^+ \rightarrow \mu^+ \nu A') \sim 10^{-9}$




Batell model
(univ.-violating, right-handed muons)
$\Gamma(K^+ \rightarrow \mu^+ \nu A') \sim 10^{-4} - 10^{-1}$

B. Batell, D. McKeen, and M. Pospelov, PRL107, 011803 (2011), 1103.0721

# Search for a new particle in $K^+ \to \mu^+ \nu e^+ e^-$

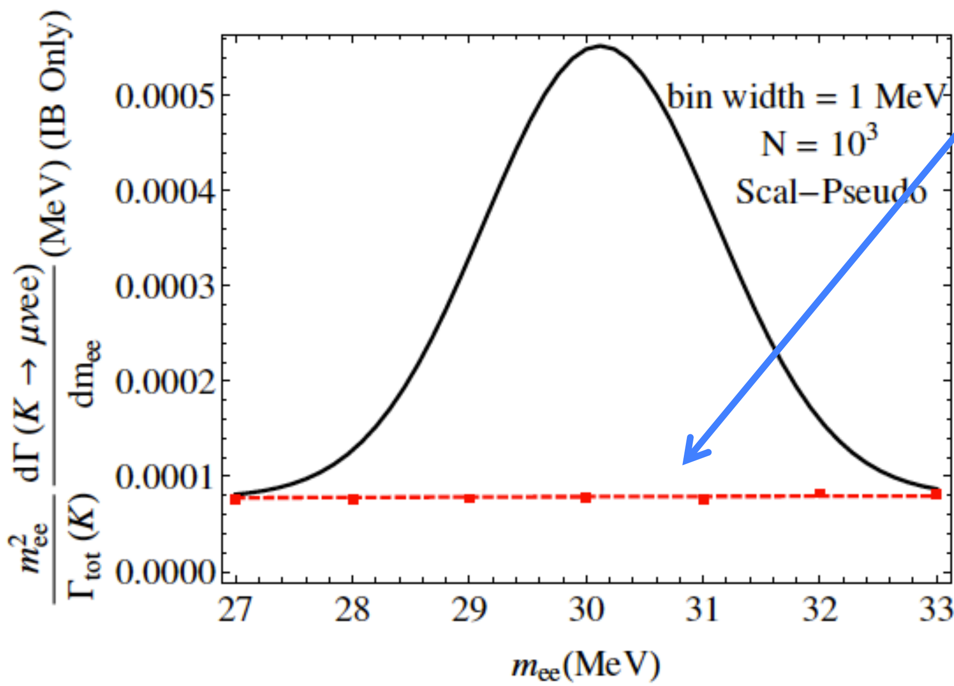
**QED background:** $K^+ \to \mu^+ \nu e^+ e^-$

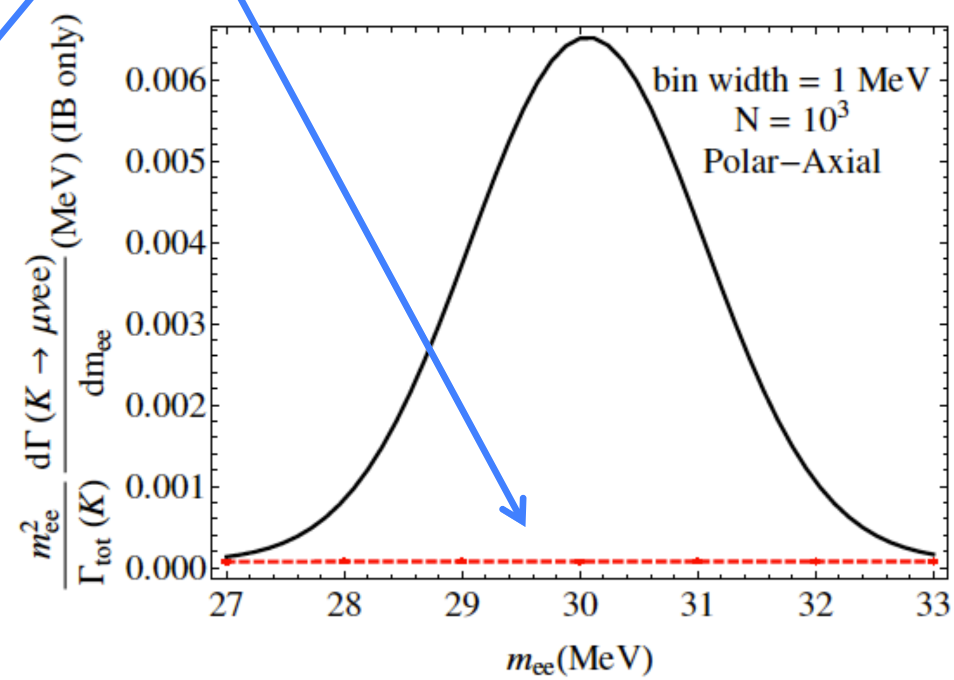
- $\Gamma(K^+ \to \mu^+ \nu ee) \sim 2.5 \times 10^{-5}$
- *Expect $10^{10}$ stopped $K^+$ in E36*
- *250k QED evts or ~1000 / MeV*

**C. Carlson, B. Rislow, hep-ph/1310.2786**

**Signal:** $K^+ \to \mu^+ \nu A', A' \to e^+ e^-$

same background!




Carlson&Rislow model
(universality-violating, fine tuned); $\Gamma(K^+ \to \mu^+ \nu A') \sim 10^{-6} - 10^{-5}$

**HUGE signals predicted, E36 very stringent test**

# Motivation for μp scattering

**Electronic hydrogen**

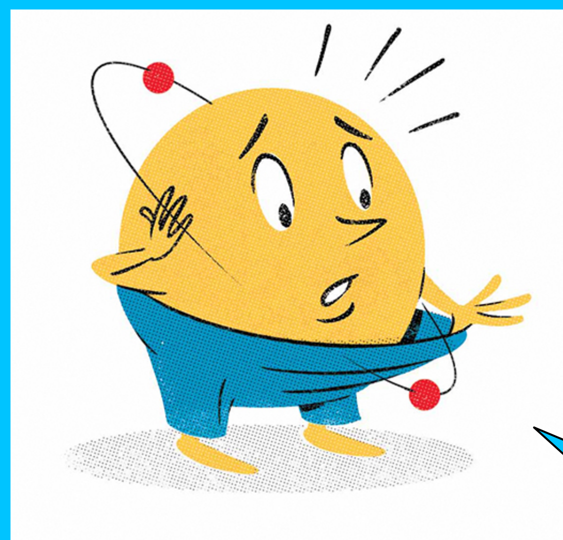
0.8758±0.0077

**Lamb shift**

**Muonic hydrogen**

0.84184±0.00067

0.84087±0.00039



**Electron scattering**

0.877±0.006

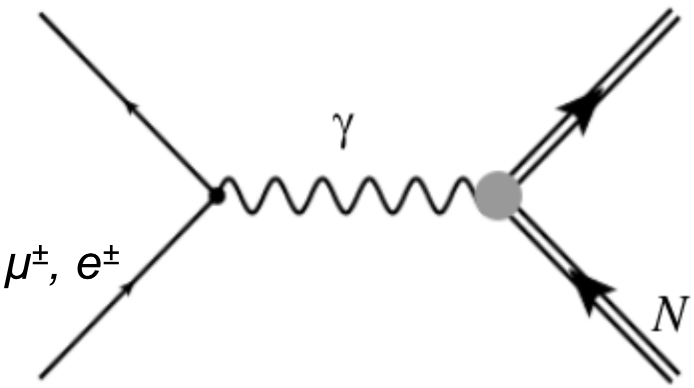
**Elastic scattering**

**Muon scattering**

???

# Lepton scattering and charge radius

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

**Sachs 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:**

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

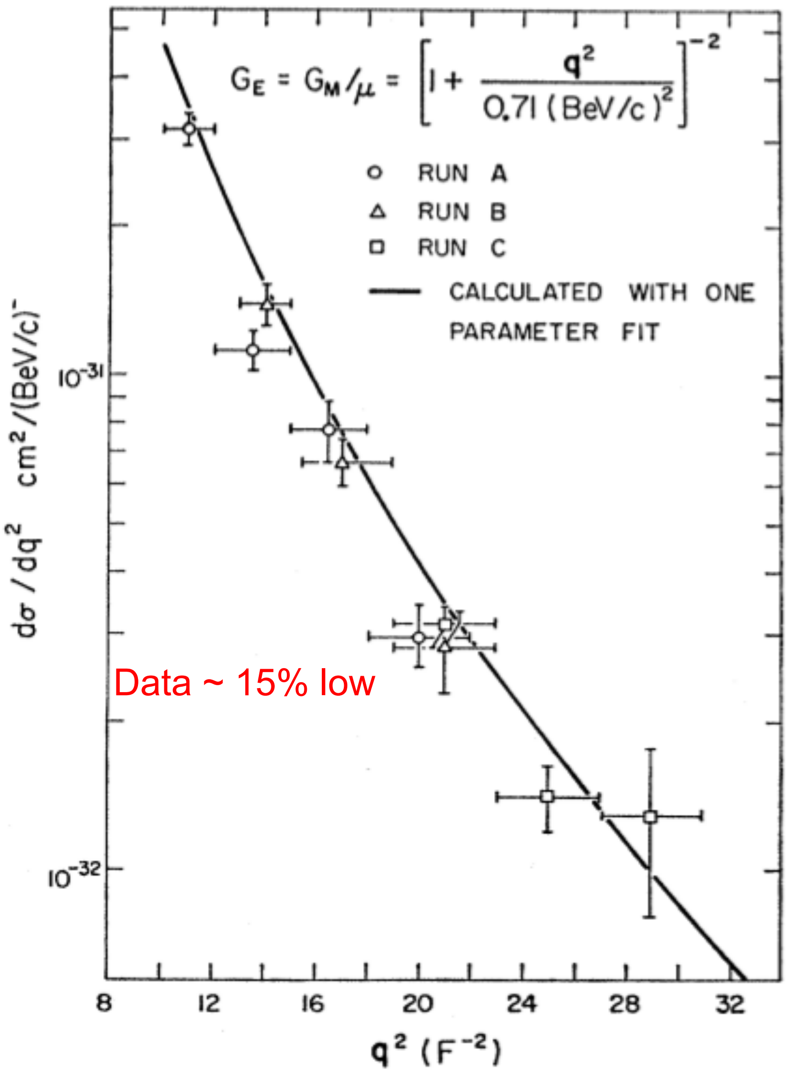
$$\langle r_M^2 \rangle = -6 \left. \frac{dG_M^p(Q^2)/\mu_p}{dQ^2} \right|_{Q^2 \to 0}$$

**Expect identical result for ep and μp scattering**

# e-μ universality in lepton scattering

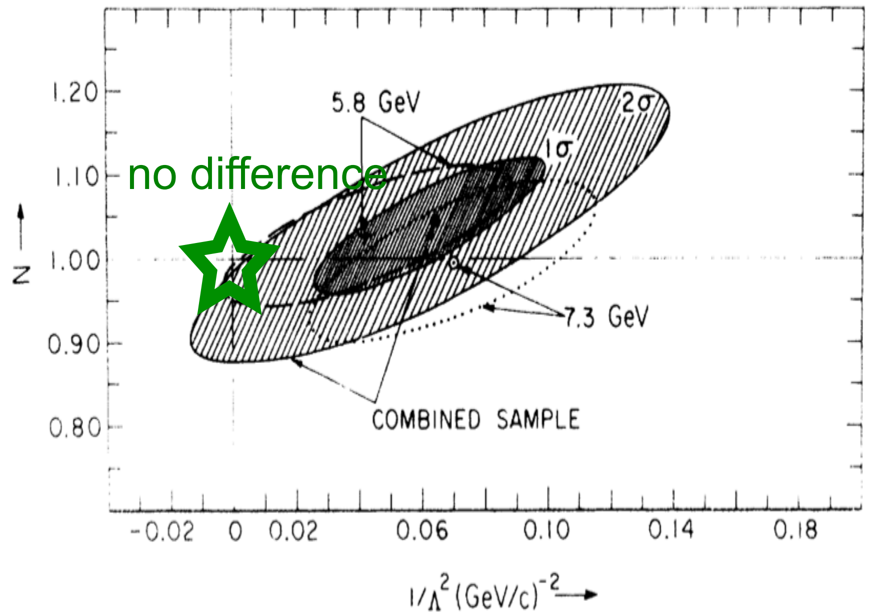
## 1960s-1970s: several experiments tested e-μ universality in scattering

Elastic μp scattering:
Ellsworth et al., Phys. Rev. 165 (1968)




Elastic μp: Kostoulas et al., PRL 32 (1974)

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




$1/\Lambda^2 = 0.006 \pm 0.016$ GeV$^{-2}$

- DIS μp scattering: Entenberg et al., PRL 32 (1974)
  $\sigma_{\mu p}/\sigma_{ep} \approx 1.0 \pm 0.04$ (±8.6% systematics)
- e-C, and μ-C are in agreement

**Constraints are not very good**

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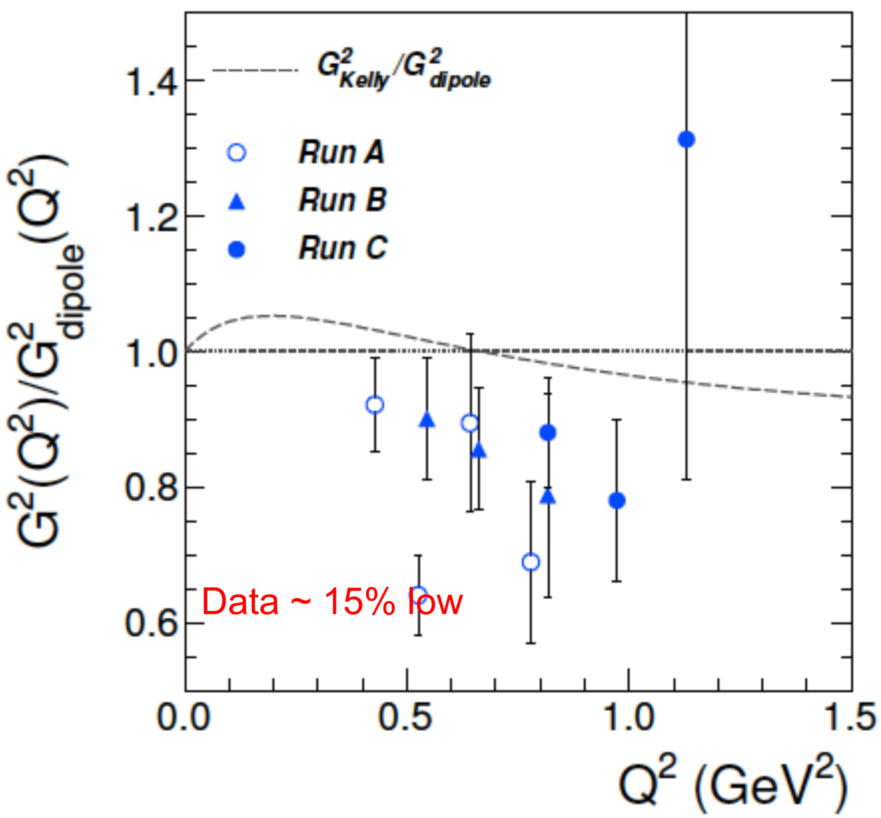


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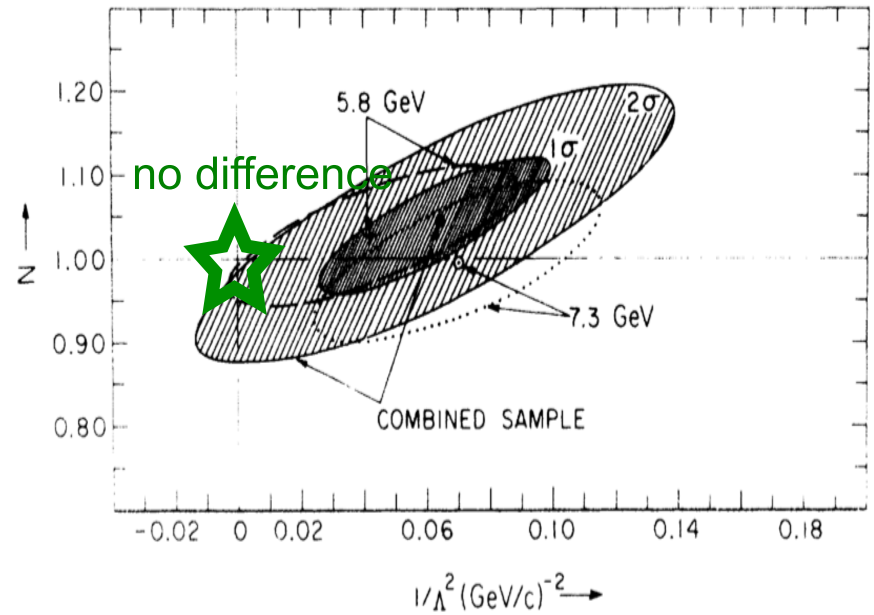


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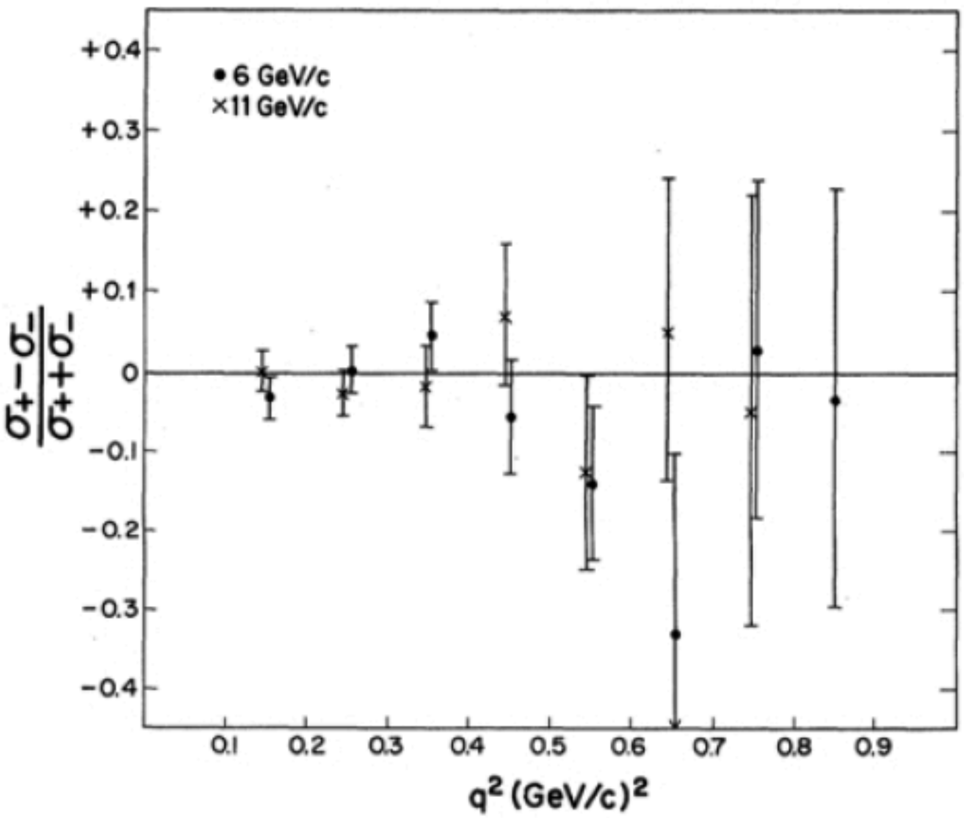
- e-C, and μ-C are in agreement

**Constraints are not very good**

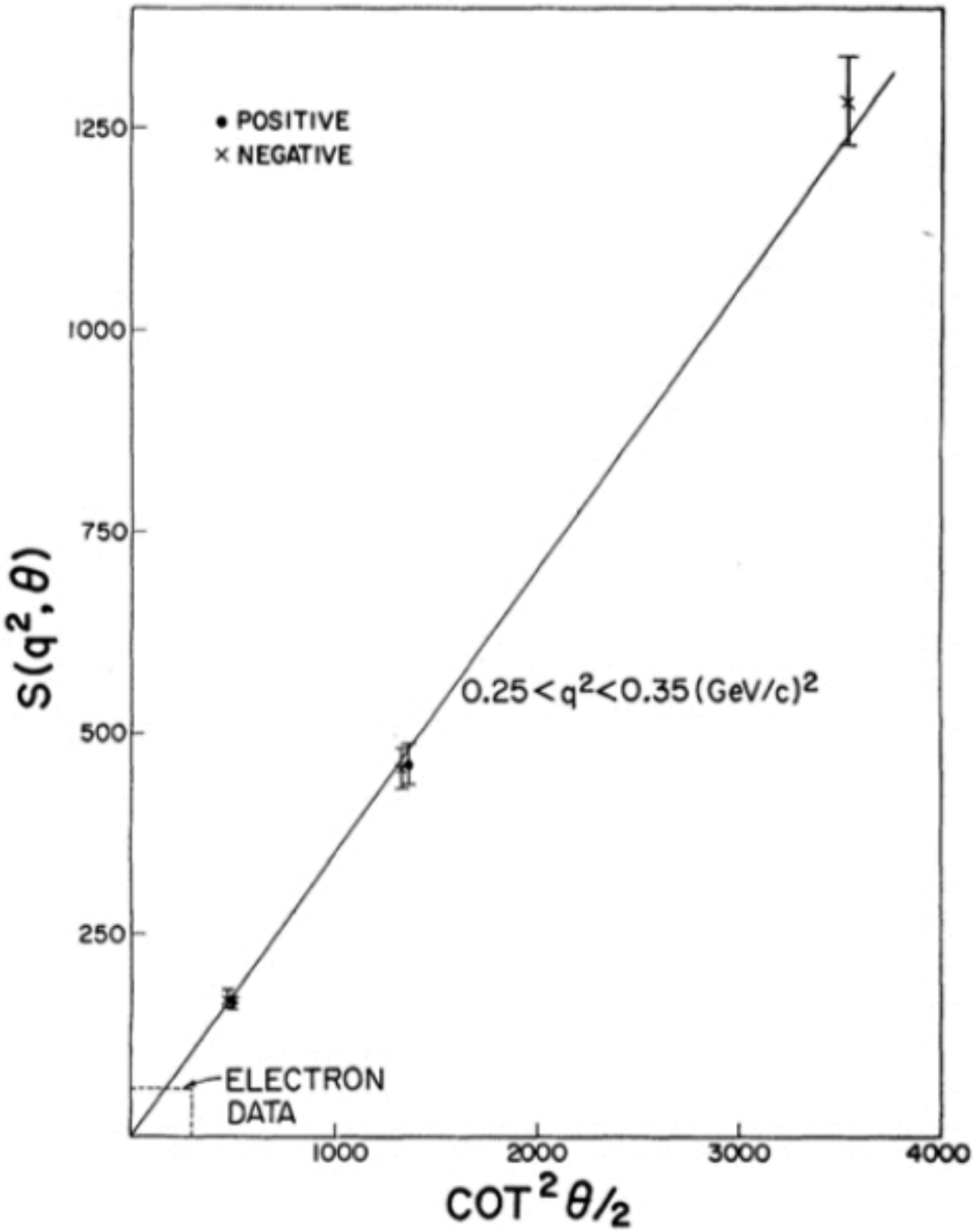
# Two-photon exchange tests in μp-elastic




L. Camilleri et al., PRL23, 149 (1969)

- No evidence for two-photon exchange effects

**Constraints are not very good**

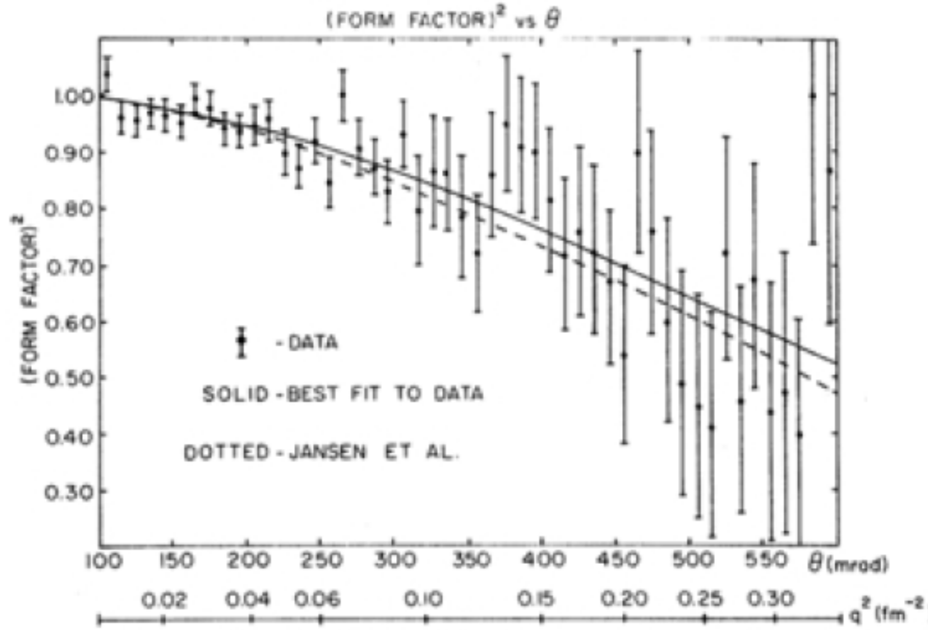



- Rosenbluth plots linear

# Carbon radius and e-μ universality

- **$^{12}$C radius determinations from eC scattering, μC scattering, and μC atoms agree**

➔ Cardman et al. eC: 2.472 ± 0.015 fm
➔ 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




- If carbon is right ➔ e's and μ's are the same
- If hydrogen is right ➔ e's and μ's are different
- If both are right - opposite effects for proton and neutron canceling in carbon?

- Investigate μd, μHe

- Muonic H + eH/D isotope shift ➭ $r_d$ = 2.12771(22) fm (A. Antognini et al.)
- ed elastic scattering: ➭ $r_d$ = 2.130(10) fm
- Muonic D consistent (preliminary, unpublished, large polarizability correction)

# MUon Scattering Experiment (MUSE) at PSI

**Use the world's most powerful low-energy separated e/π/μ beam for a direct test if μp and ep scattering are different:**

- to higher precision than previously
- in the low $Q^2$ region (same as Mainz and latest JLab experiment just completed) for sensitivity to radius
- measure both $\mu^{\pm}p$ and $e^{\pm}p$ for direct comparison and a robust, convincing result
- depending on the results, 2nd generation experiments (lower $Q^2$, $\mu^{\pm}$n,D,He, higher $Q^2$, ...) might be desirable

# MUon Scattering Experiment (MUSE) at PSI

**Use the world's most powerful low-energy separated e/π/μ beam for a direct test if μp and ep scattering are different:**

- **Simultaneous, separated beam of (e+/π+/μ+) or (e-/π-/μ-) on liquid $H_2$ target**

→ **Separation by time of flight**

→ **Measure absolute cross sections for ep and μp**

→ **If radii differ by 4%, then form factor slope by 8%, x-section slope by 16%**

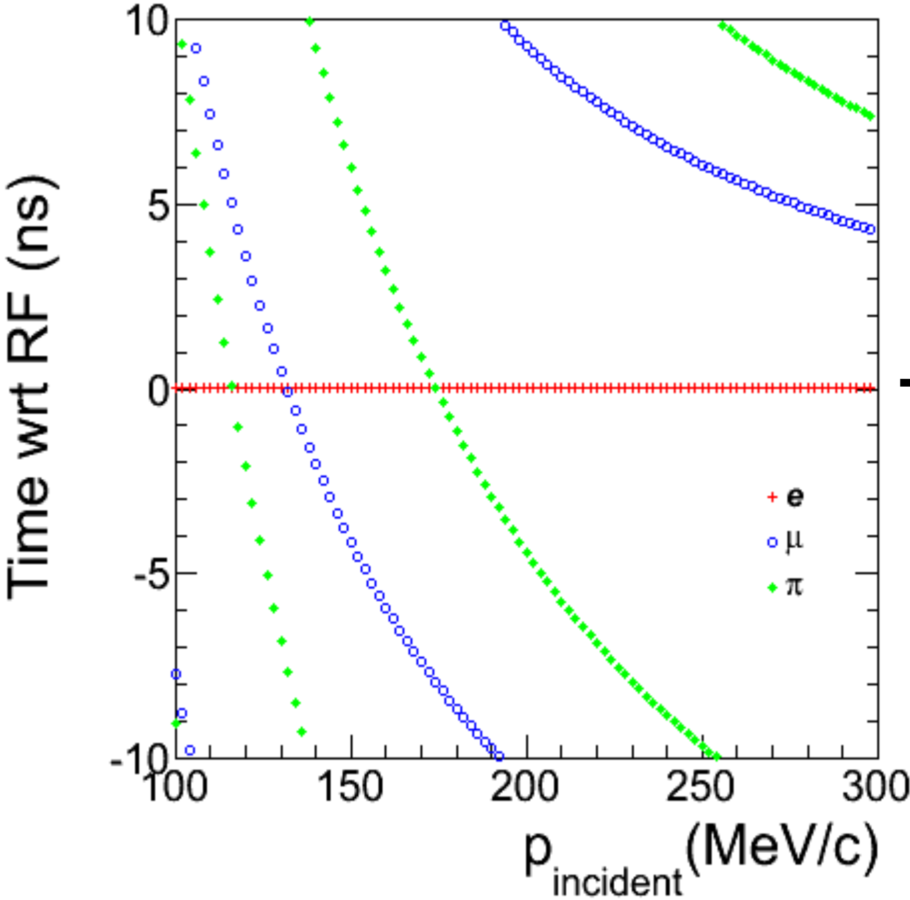
→ **Measure e+/μ+, e-/μ- ratios to cancel certain systematics**

- **Directly disentangle effects from two-photon exchange (TPE) in e+/e-, μ+/μ-**
- **Multiple beam momenta 115-210 MeV/c to separate $G_E$ and $G_M$ (Rosenbluth)**

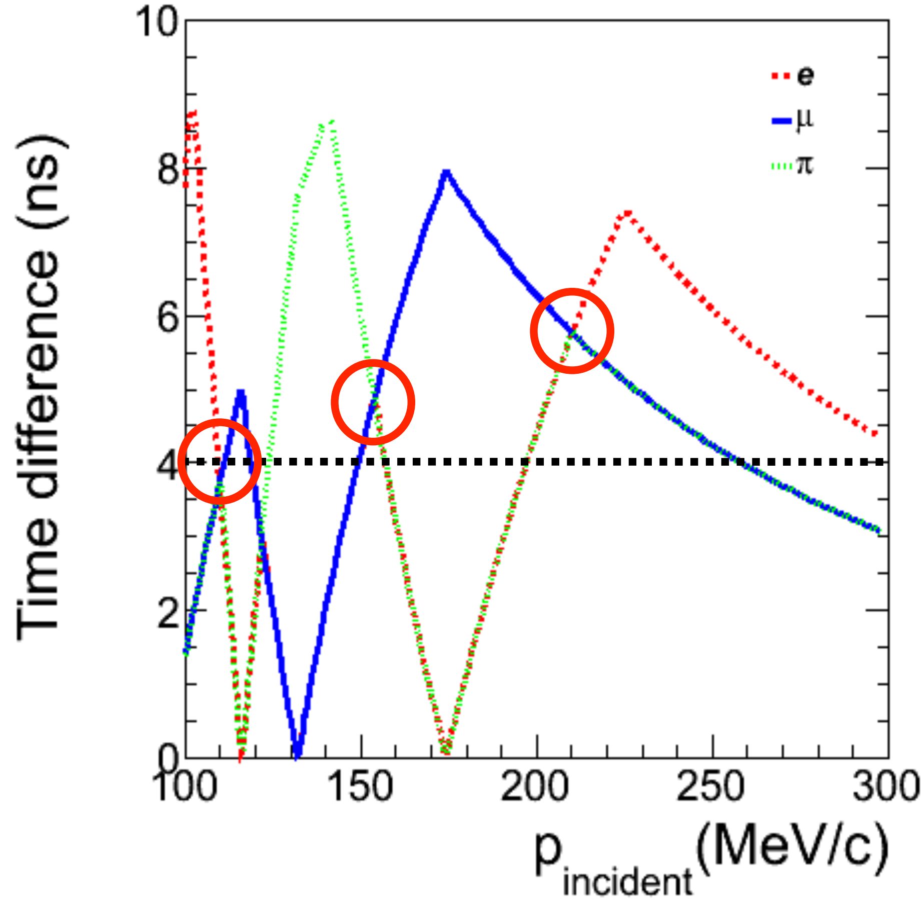
# Separation of e, π, μ by RF time

Requirement: particle separation in time for PID
50 MHz RF → 20 ns between bunches

Timing of particles in target region wrt electron ($\beta = 1$)



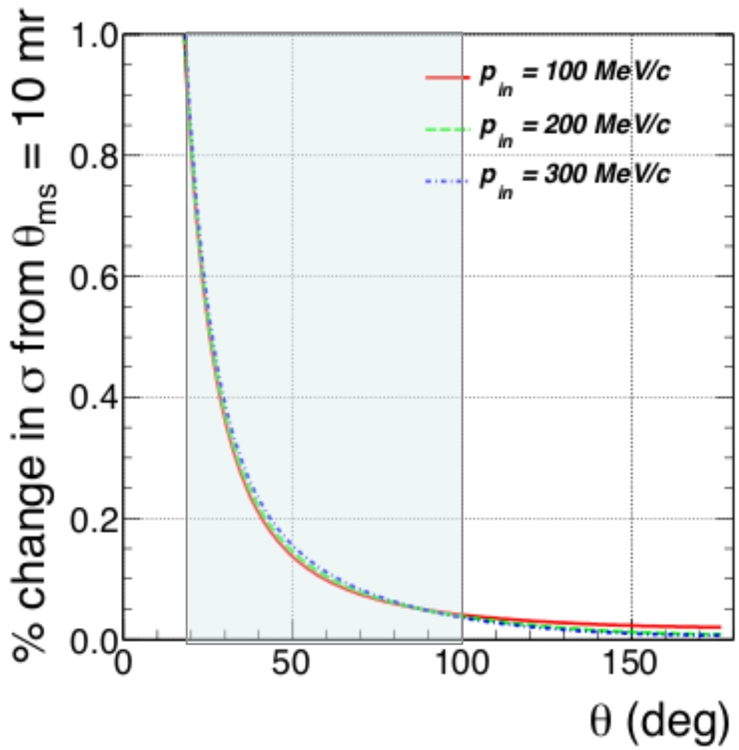

Minimum time separation of particles in target region




**p = 115, 153, and 210 MeV/c**

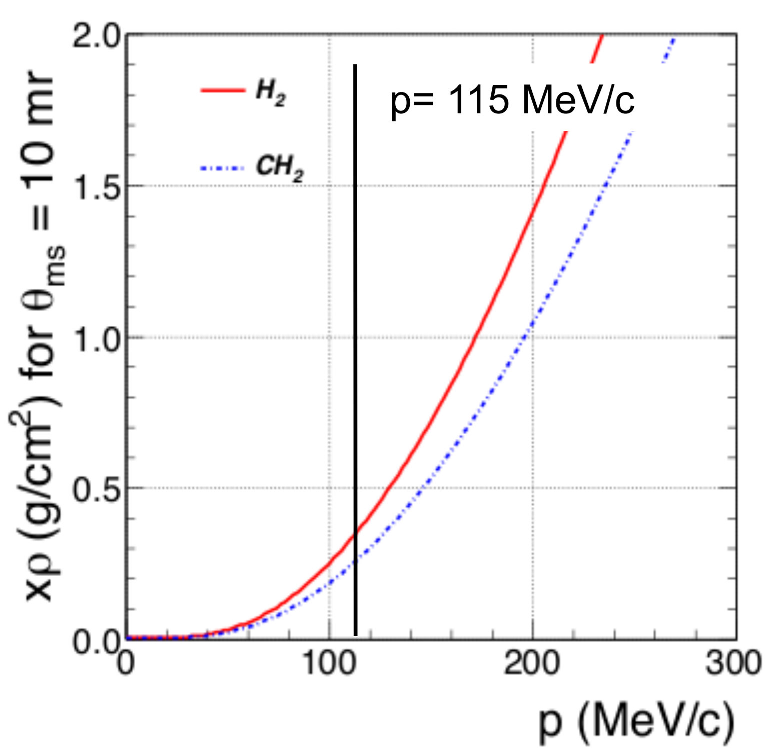
# Beamline and target considerations

**Target**: → 4 cm LH2, thickness constrained by effects of multiple scattering




% change in cross section for $\theta_{ms}$ = 10 mr

→ Limits acceptance to > 20°




Target thickness giving $\theta_{ms}$ = 10 mr

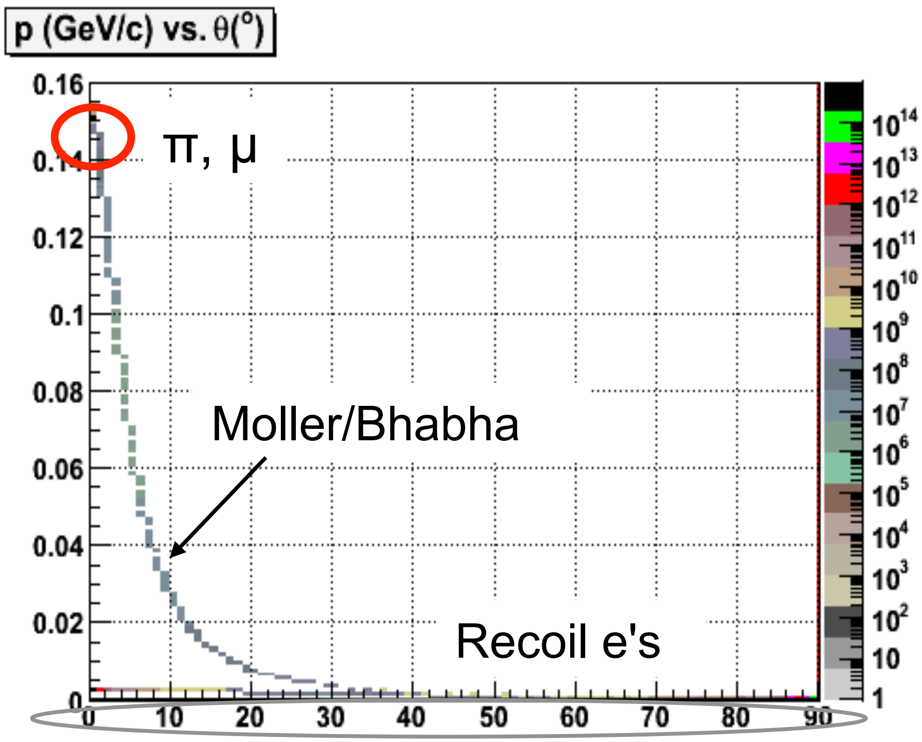
→ Limits target thickness to 0.3 g/cm$^2$

Beamline Cerenkov: provide redundant PID, and provide cross check for RF timing calibration

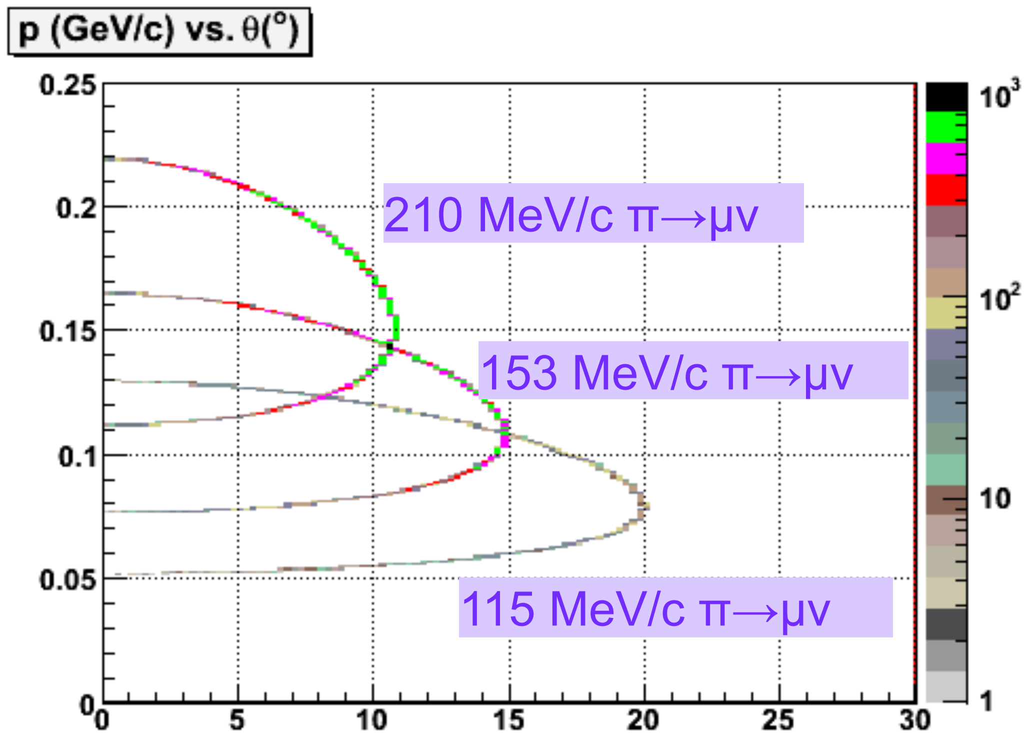
# Background considerations

Requirement: low backgrounds or background rejection

**Scattering from electrons:**




**Muons from π decays**

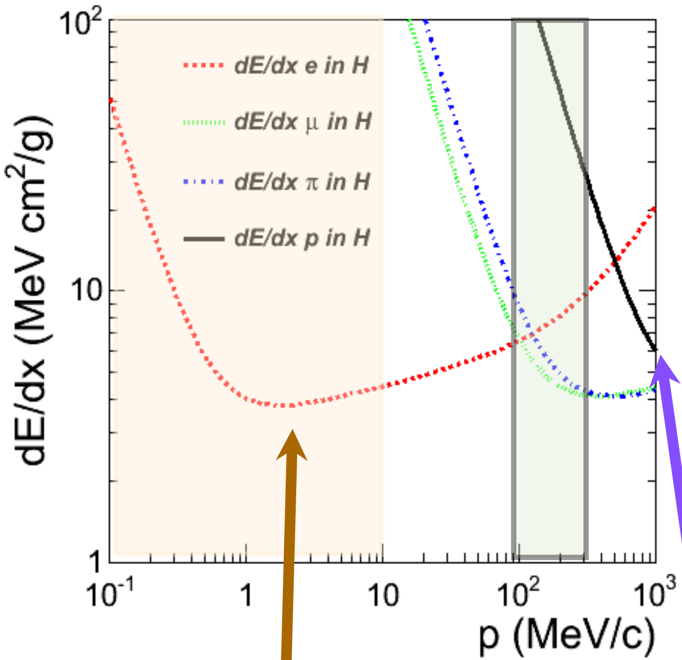


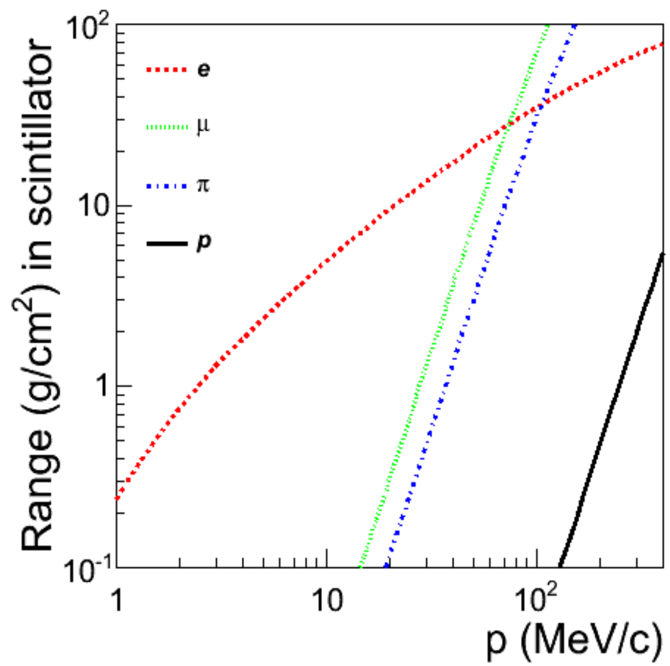

→ π, μ at forward angles
→ e-,e+ <10 MeV above 15°
→ Recoil e's low momentum

→ Will have π RF time
(3 orders of magnitude suppression)
→ Track will not point back to the target

Suppression of **μ → eνν background** with offline time-of-flight (8-20 σ)

# Scattered particle considerations



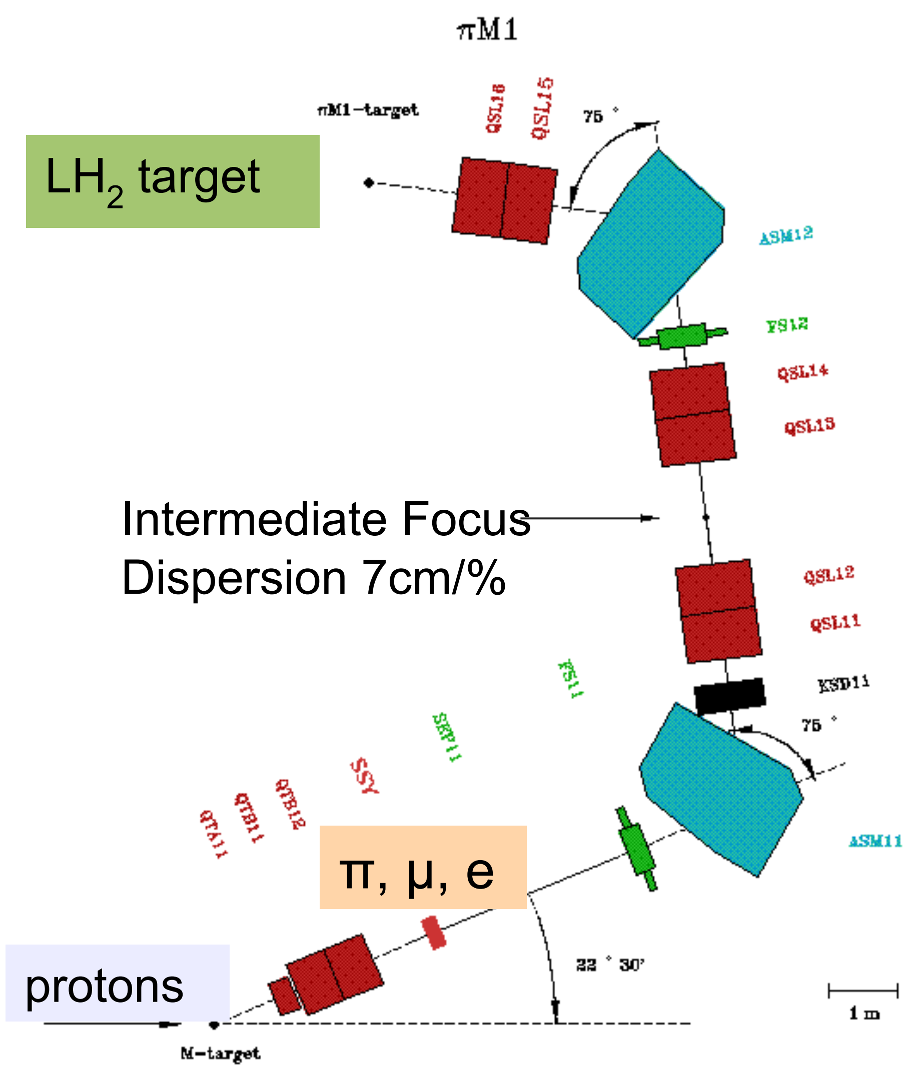



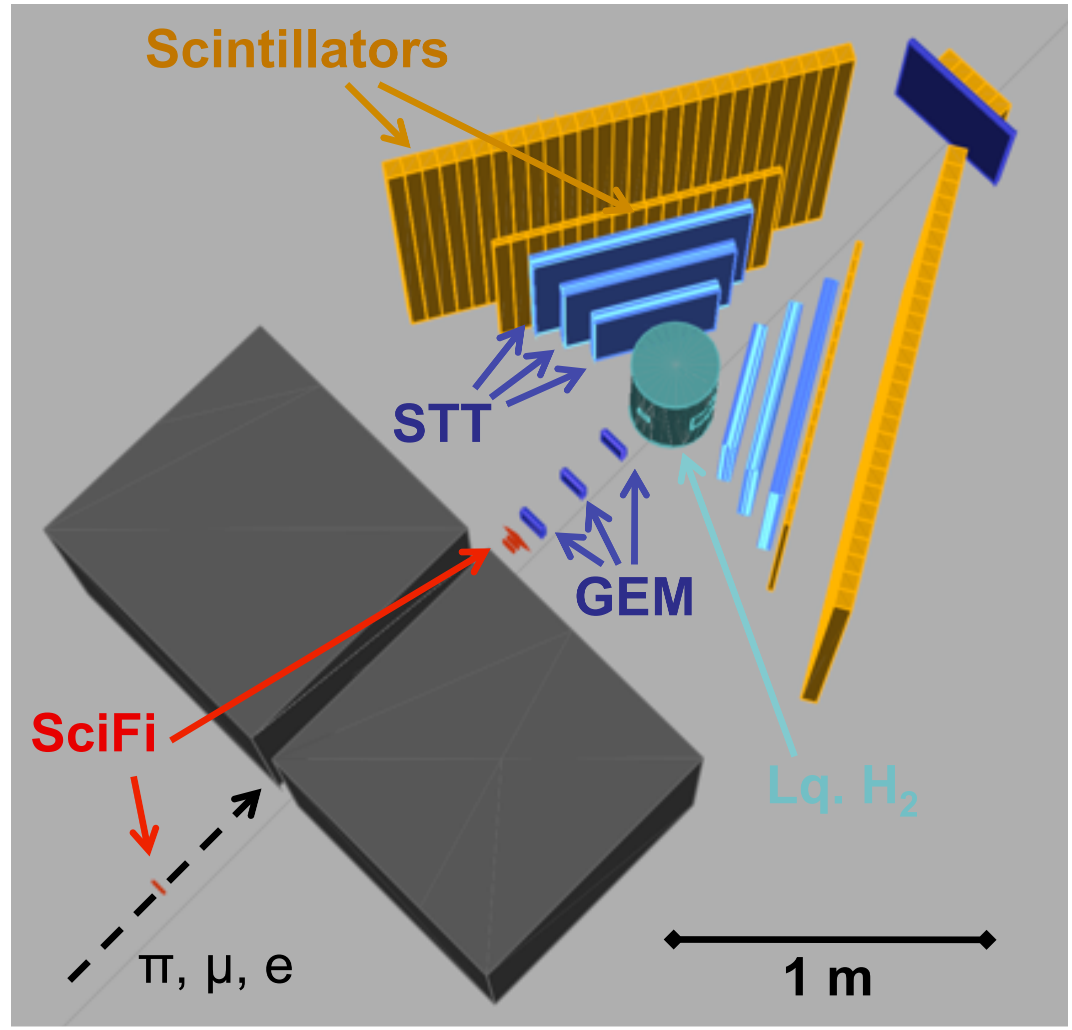

Large angle, very low energy Moller / Bhabha e's lose large fraction of energy in target

Recoil protons E loss so large that all except forward angle recoil protons stopped in target

All the low-energy electron and proton backgrounds are ranged out in the first scintillator layer

# MUSE beamline and experiment layout

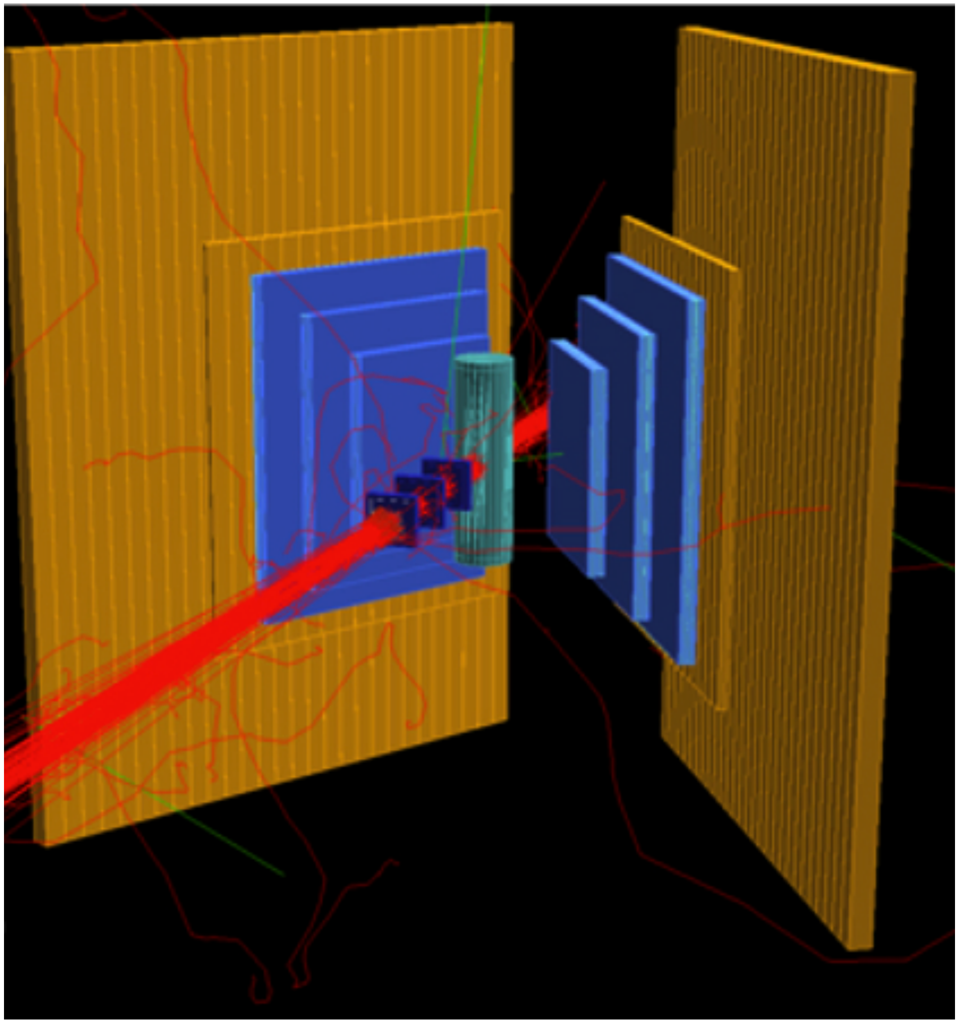


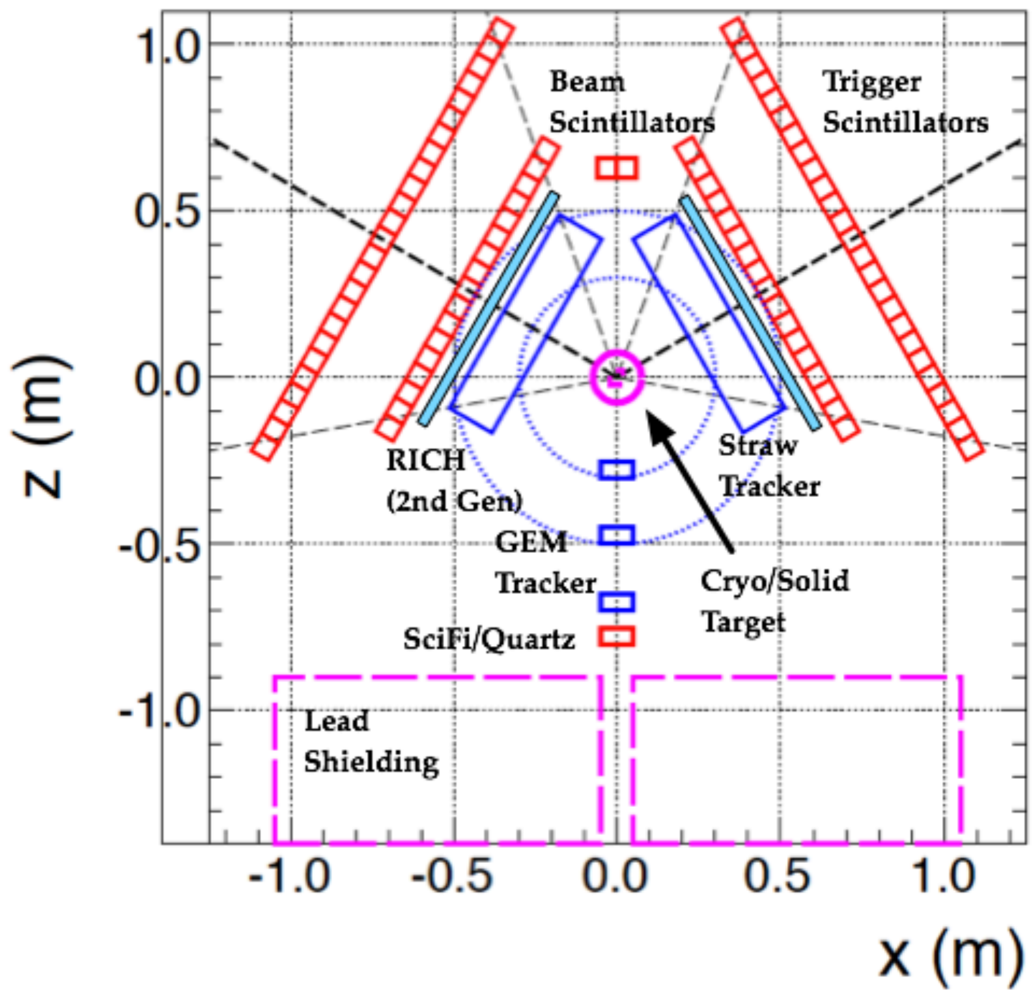




πM1: 100-500 MeV/c
Momentum measurement
RF+TOF separated π, μ, e

Beam particle tracking
Liquid hydrogen target
Scattered lepton detection

# Reference design

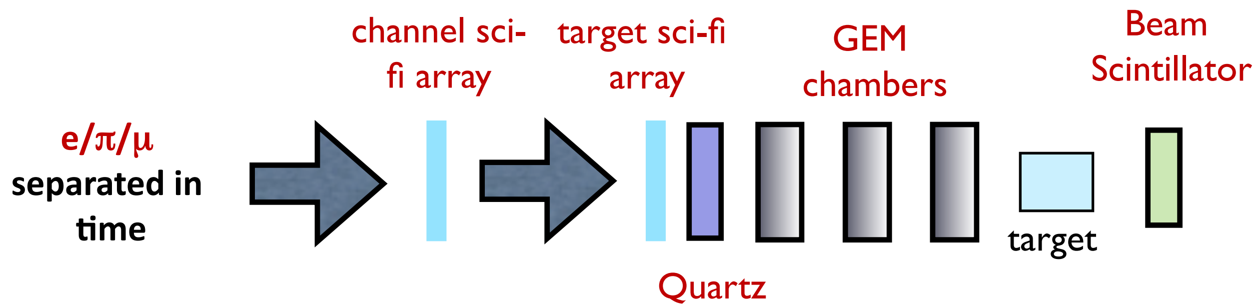





- Limited beam flux (5 MHz) → Large angle, non-magnetic detectors
- Secondary beam → Tracking of beam particles to target
- Mixed beam → Identification of beam particle in trigger

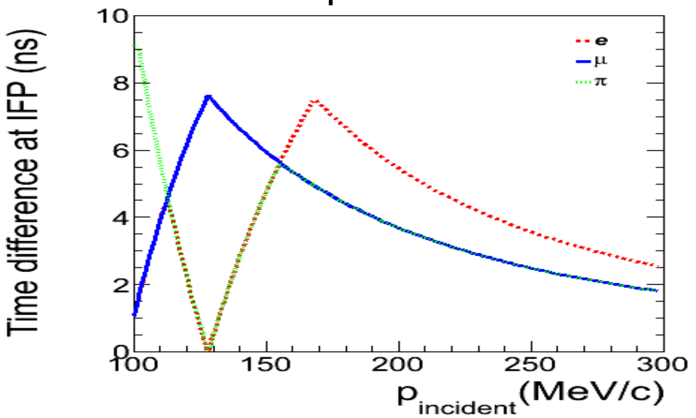
# Beamline instrumentation

**Beamline Elements:**

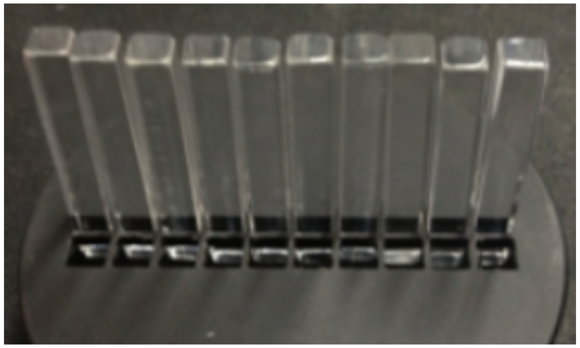


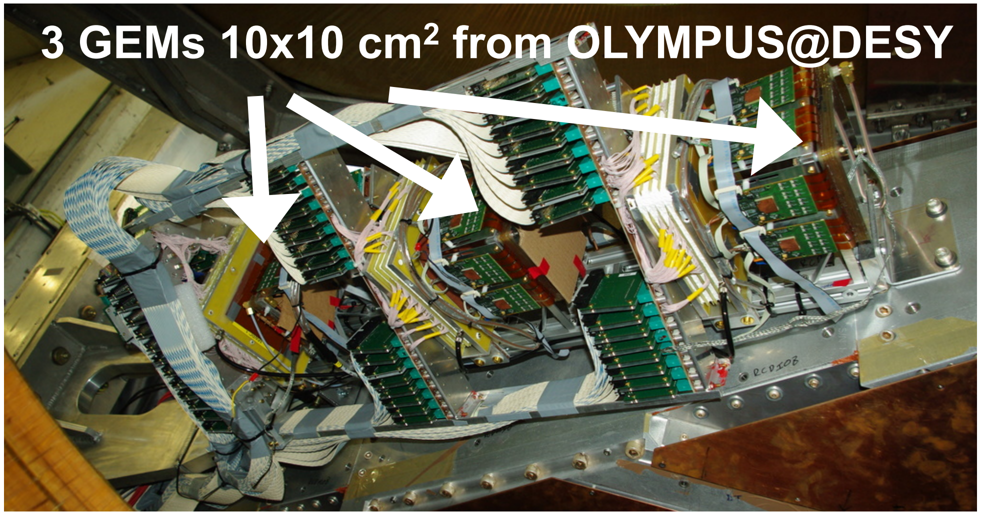

Beam and target sci-fi arrays and scintillator:
→ Flux, PID, Trigger, TOF, momentum

Particles well separated at IFP:




Beam Cerenkov
(quartz or sapphire)
→ Timing: beam TOF, scattered particle TOF

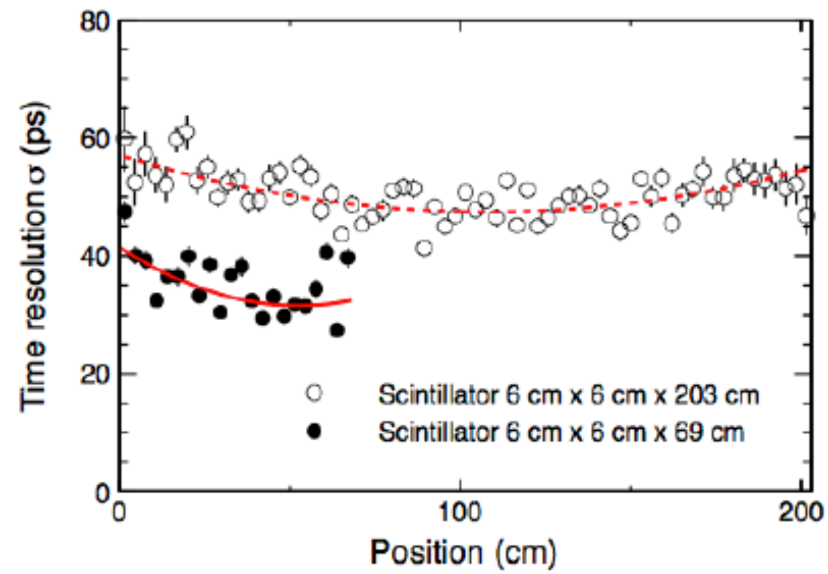


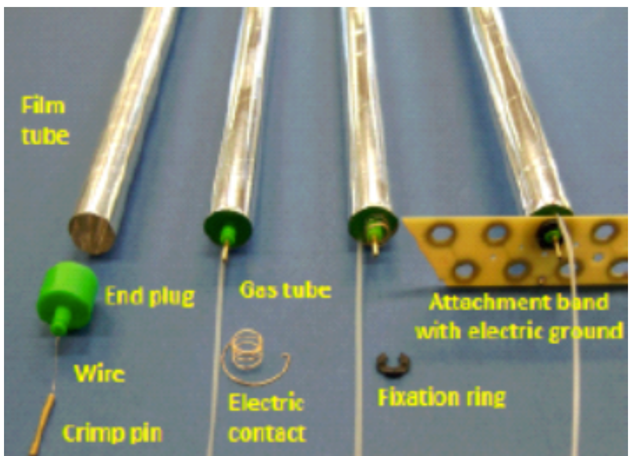


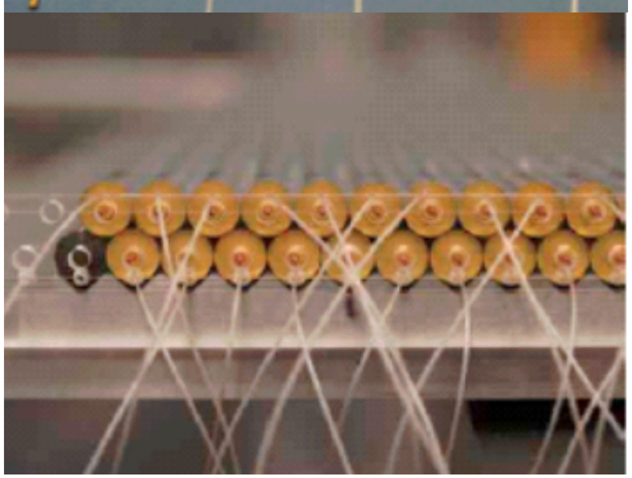

GEM telescope
→ Determine incident angle to 0.5 mr
→ Third GEM to reject ghost tracks
→ Existing chambers from OLYMPUS
(Hampton University)

# Main detector instrumentation

- 2 planes of scintillators (CLAS12 design)
- 94 bars (2 sides + beam)
- High precision (40-50ps) timing
- PID and trigger, background rejection

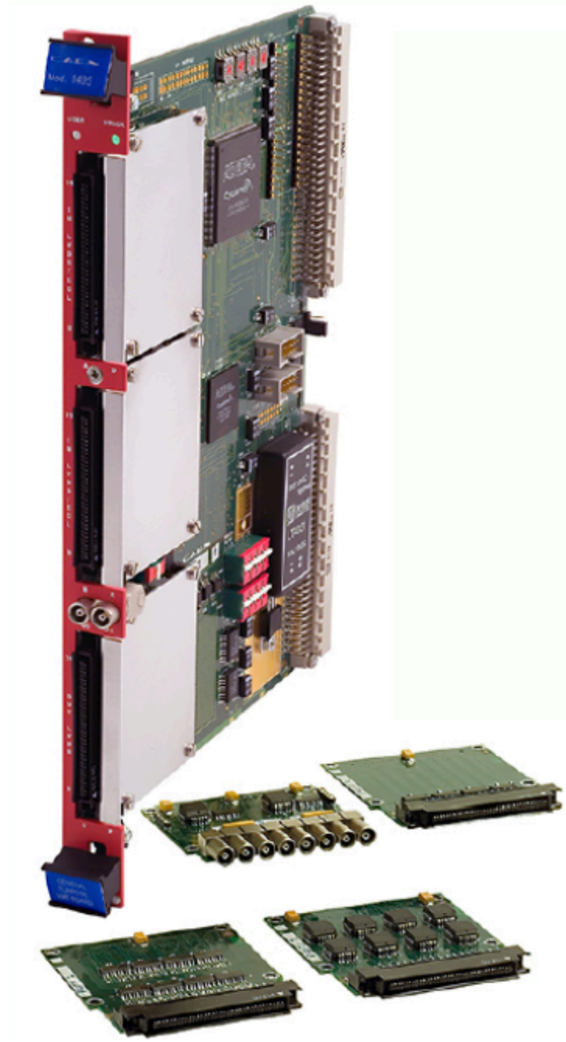



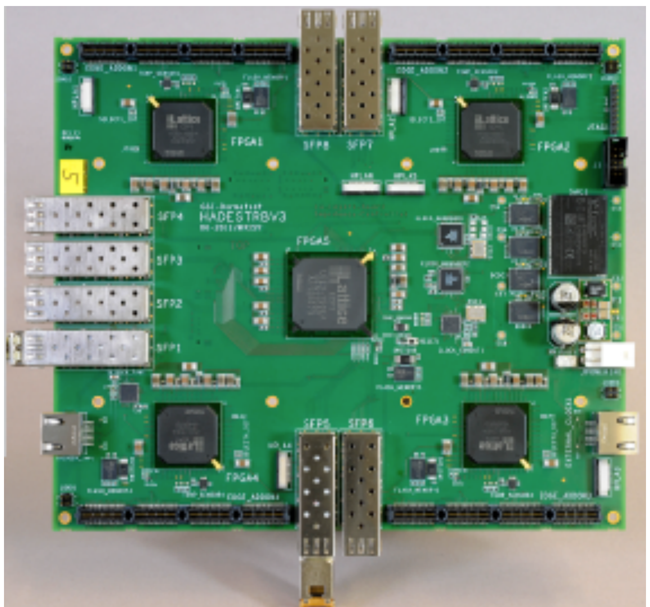



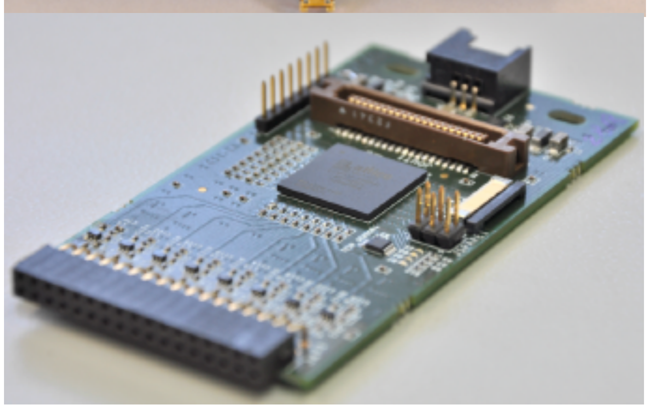
- Straw Tube Tracker (STT), ~3000 straws
- Determine scattered particle trajectory
- Existing PANDA design - 140μm resolution
- Thin walled (25μm), overpressured (2 bar)
- Directly coupled to fast readout boards

# Trigger and DAQ

- FPGA design for beam PID (custom or v1495)
- SciFi + Beam RF + Cerenkov -> Beam PID
- Count particles and reject pions
- Need 99.9% pion rejection efficiency





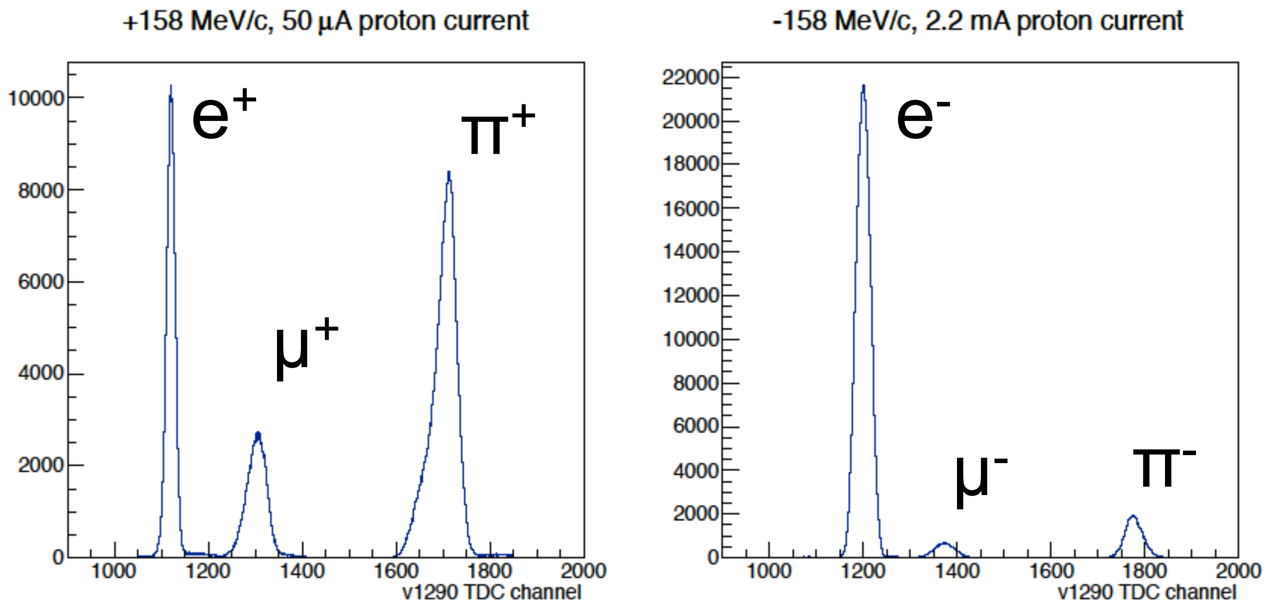


- Custom signal splitters
- FPGAs as front end discriminator/amplifier, custom designed TDCs (PADIWA/TRB3)
- High channel density (256ch/board).
- Standard CAEN ADCs

# Responsibilities for new equipment

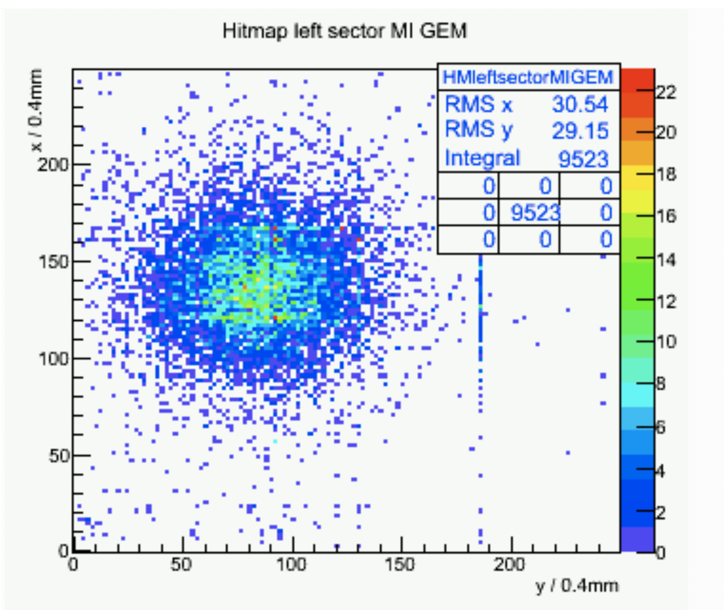
| Detector | Who | Technology |
|---|---|---|
| Beam SciFi | Tel Aviv | conventional |
| GEMs | Hampton | detector exists |
| Sapphire Cerenkov | Rutgers | prototyped (Albrow et al) |
| FPGAs | Rutgers | conventional |
| Target | George Washington | conventional - very low power |
| Straw Tube Tracker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

# First beam tests

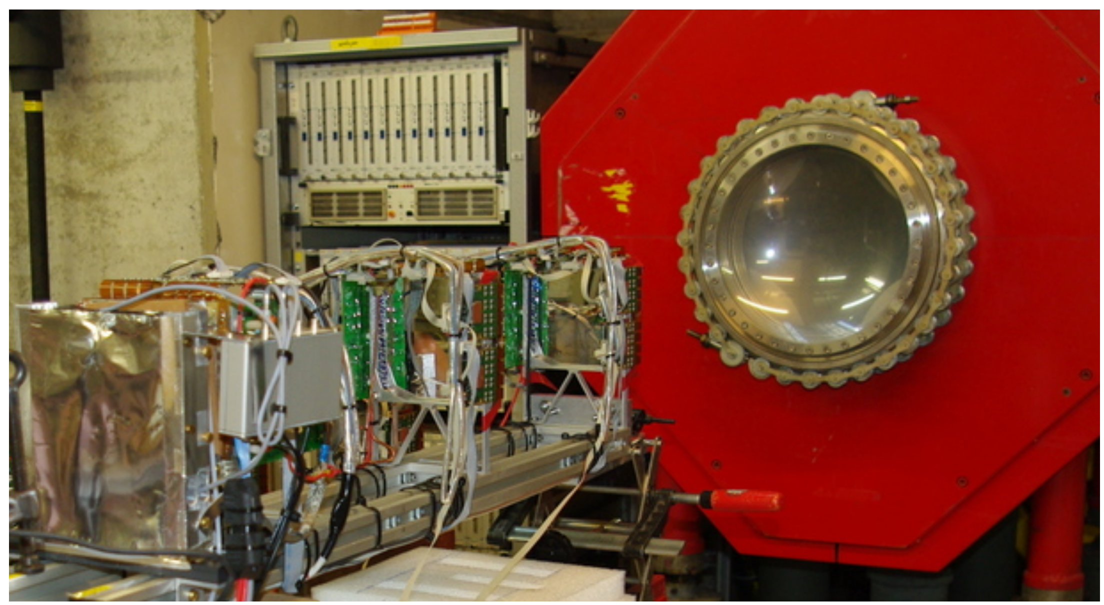



Time of flight relative to RF time (Fall 2012)

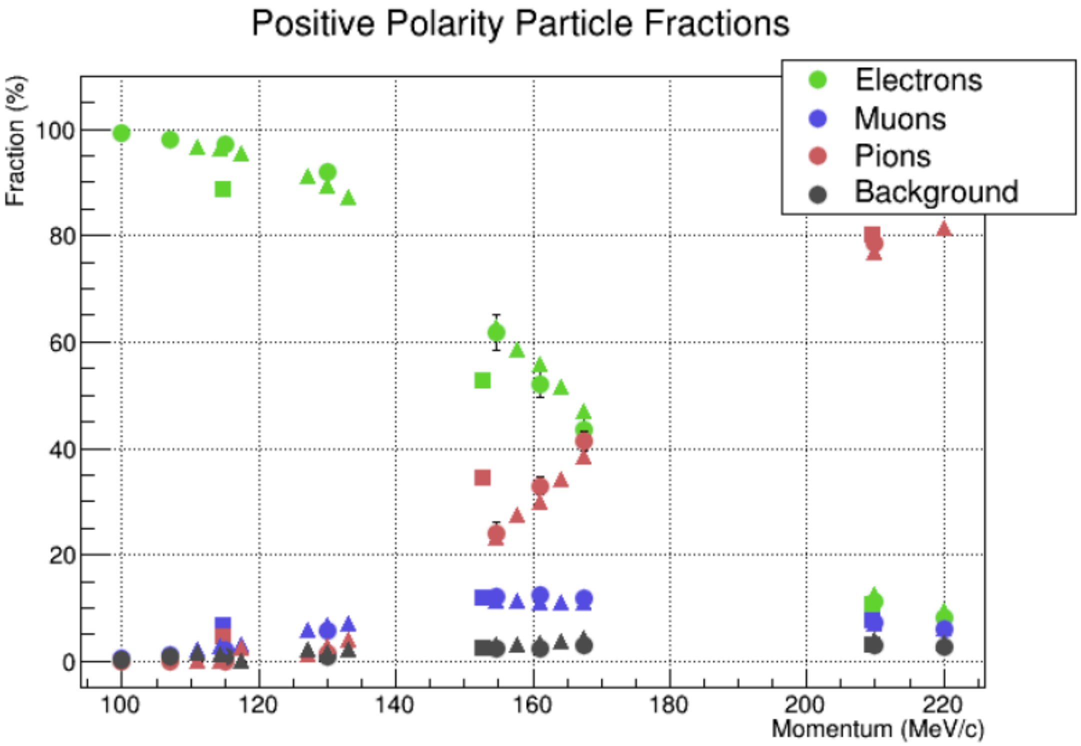
Beam spot with GEM – May 23, 2013



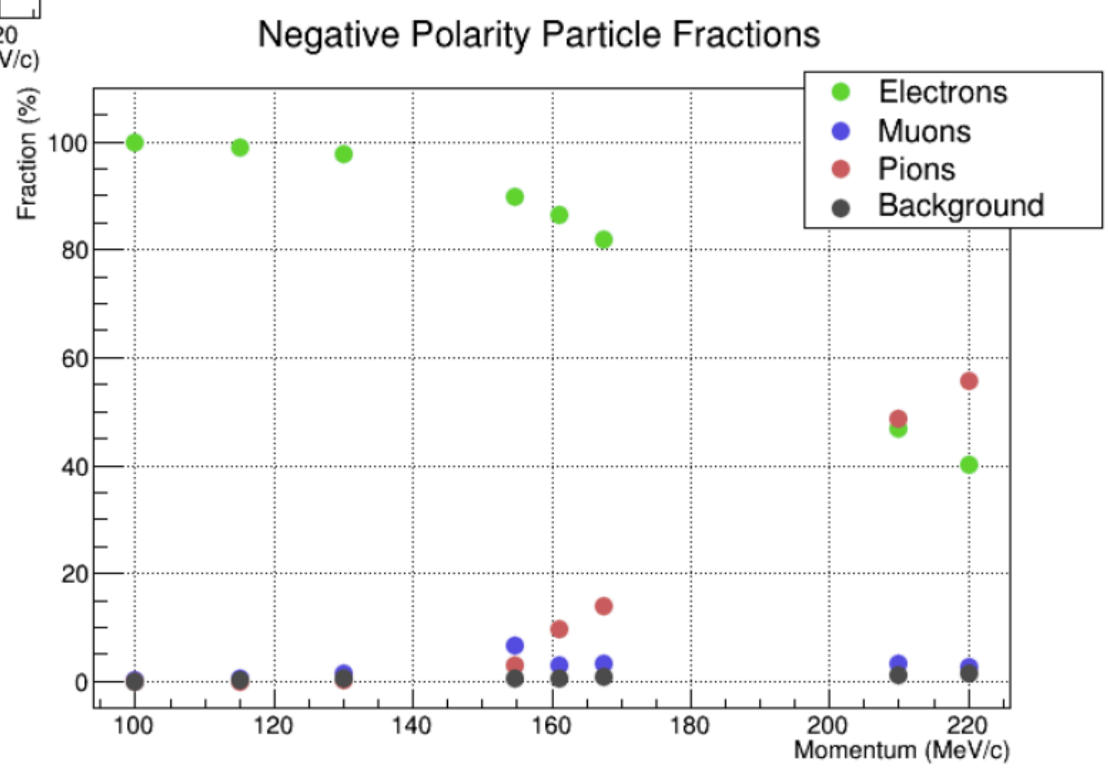

More tests in Dec. 2013



# Composition of the πM1 secondary beam




Beam test result from December 2013

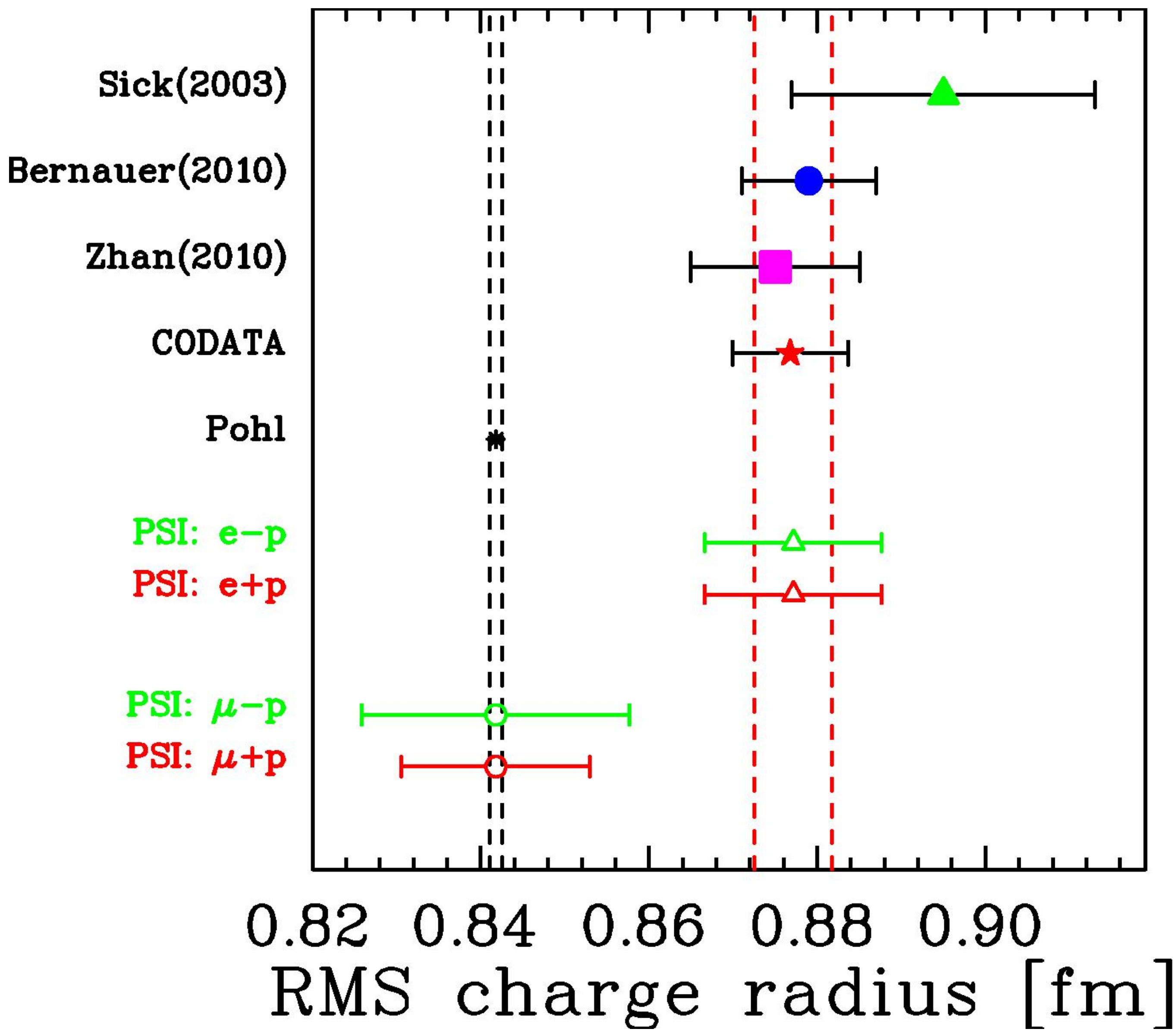


# Projected sensitivity

Charge radius extraction limited by systematics, fit uncertainties

Comparable to existing e-p extractions, but not better

Many uncertainties are common to all extractions in the experiments: Cancel in e+/e-, μ+/μ-, and μ/e comparisons



# Projected sensitivity

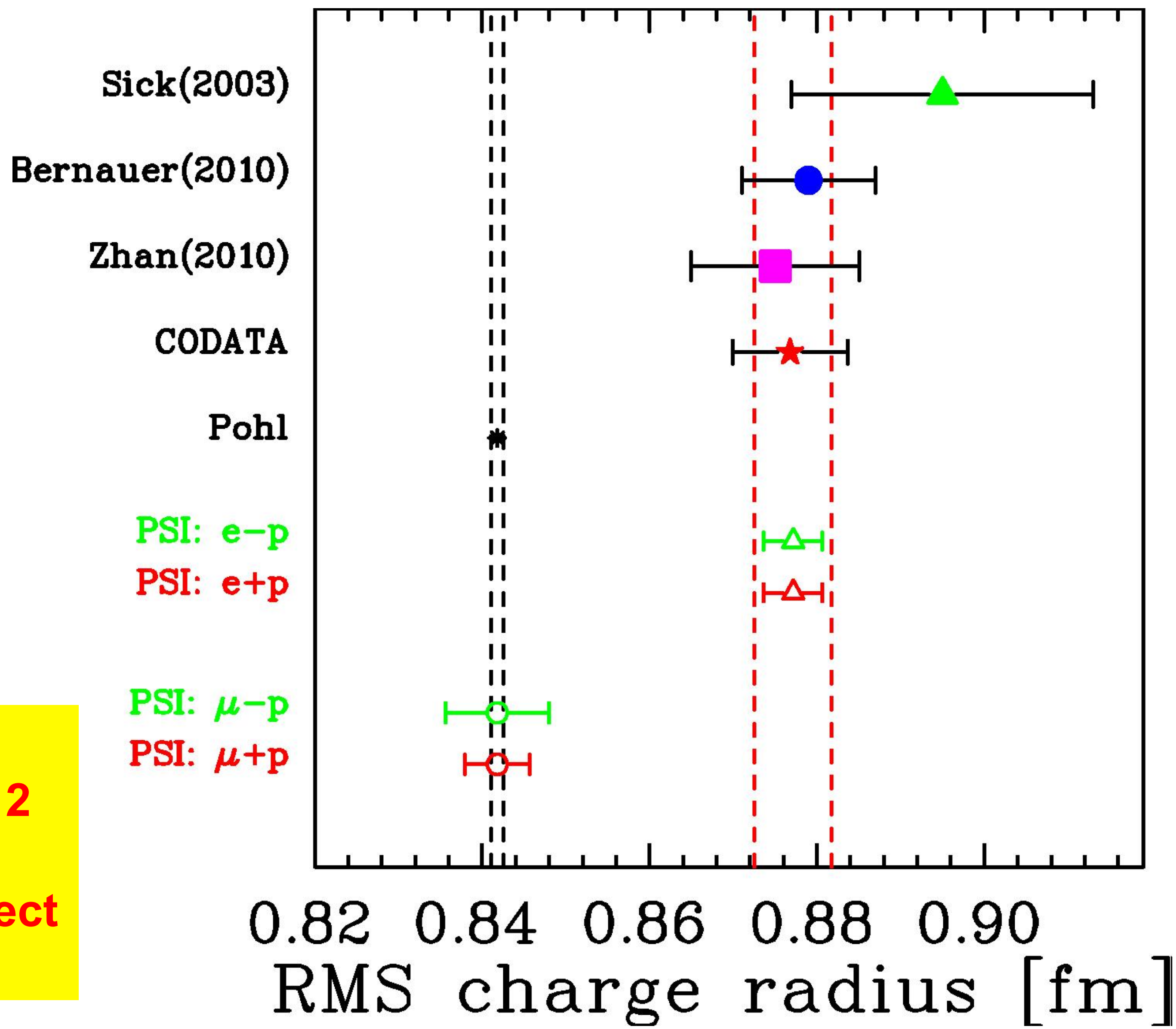
Charge radius extraction limited by systematics, fit uncertainties

Comparable to existing e-p extractions, but not better

Many uncertainties are common to all extractions in the experiments: Cancel in e+/e-, μ+/μ-, and μ/e comparisons

**Relative comparison reduces errors by factor of 2**

**MUSE suited to verify 7σ effect with similar significance**



# MUon Scattering Experiment – MUSE

- **Proton Radius Puzzle – still unresolved ~4 years later**
- **MUSE Experiment at PSI**
  - Measure μp and ep scattering and compare μ+/e+ and μ-/e- directly
  - Measure e+/e- and μ+/μ- to study/constrain TPE effects
- **Technical Challenges**
  - PID, timing, background rejection, momentum and flux determination
- **Timeline**
  - Initial proposal February 2012
  - Technical review July 2012
  - First beam tests in fall 2012
  - **PAC-approved in January 2013**
  - Further beam tests in summer and December 2013
  - ➡ Funding & construction 2014–2015
  - Production running 2016–2017 (2x 6 months)

**More collaborators welcome**

# MUon Scattering Experiment – MUSE

## 47 MUSE collaborators from 24 institutions in 6 countries:

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# Backup