International Workshop “Experimental and theoretical aspects of the proton form factors”
St. Petersburg, July 9-11, 2012

Muon Scattering at PSI *

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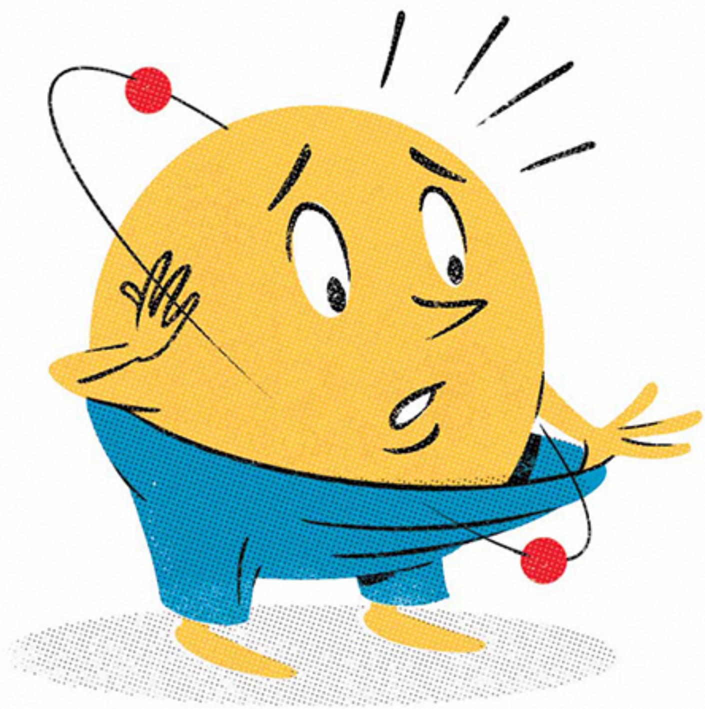
~30 **MU**on proton **S**cattering **E**xperiment (MUSE) collaborators from 20 institutions:

Argonne National Lab, Christopher Newport University, Technical University of Darmstadt, Duke University, George Washington University, Hampton University, Hebrew University of Jerusalem, Jefferson Lab, Massachusetts Institute of Technology, Norfolk State University, Paul Scherrer Institute, Rutgers University, University of South Carolina, Seoul National University, St. Mary's University, Tel Aviv University, Temple University, University of Virginia, College of William & Mary, Old Dominion University

* Supported partially by DOE Early Career Award DE-SC0003884 and NSF grants PHY-0855473 and PHY-0959521

Muon-proton scattering at PSI

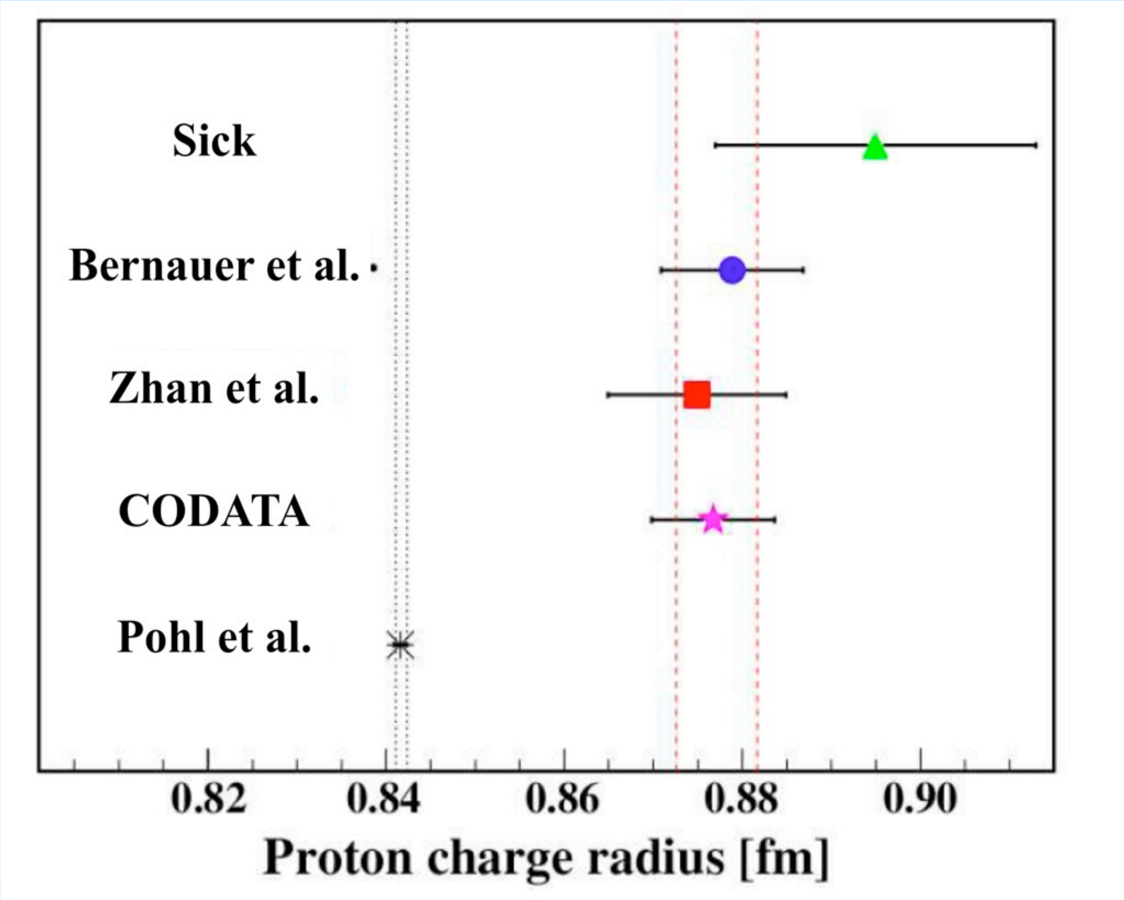
- **Motivation**
- **Proposed experiment**
  - **Muon beamline**
  - **Detector**
  - **Expected sensitivity**
- **Status & Schedule**



NY Times, July 12, 2010

The proton radius puzzle

- 7σ discrepancy between muonic hydrogen Lamb shift and combined electronic Lamb shift and electron scattering
- High-profile articles in Nature, NYTimes, etc.
- Special feature at many conferences



#	Extraction	$\langle r_E \rangle^2$ (fm)
1	Sick	0.895±0.018
2	Bernauer Mainz	0.879±0.008
3	Zhan JLab	0.870±0.010
4	CODATA	0.877±0.007
5	Combined 2-4	0.876±0.005
6	Muonic Hydrogen	0.842±0.001

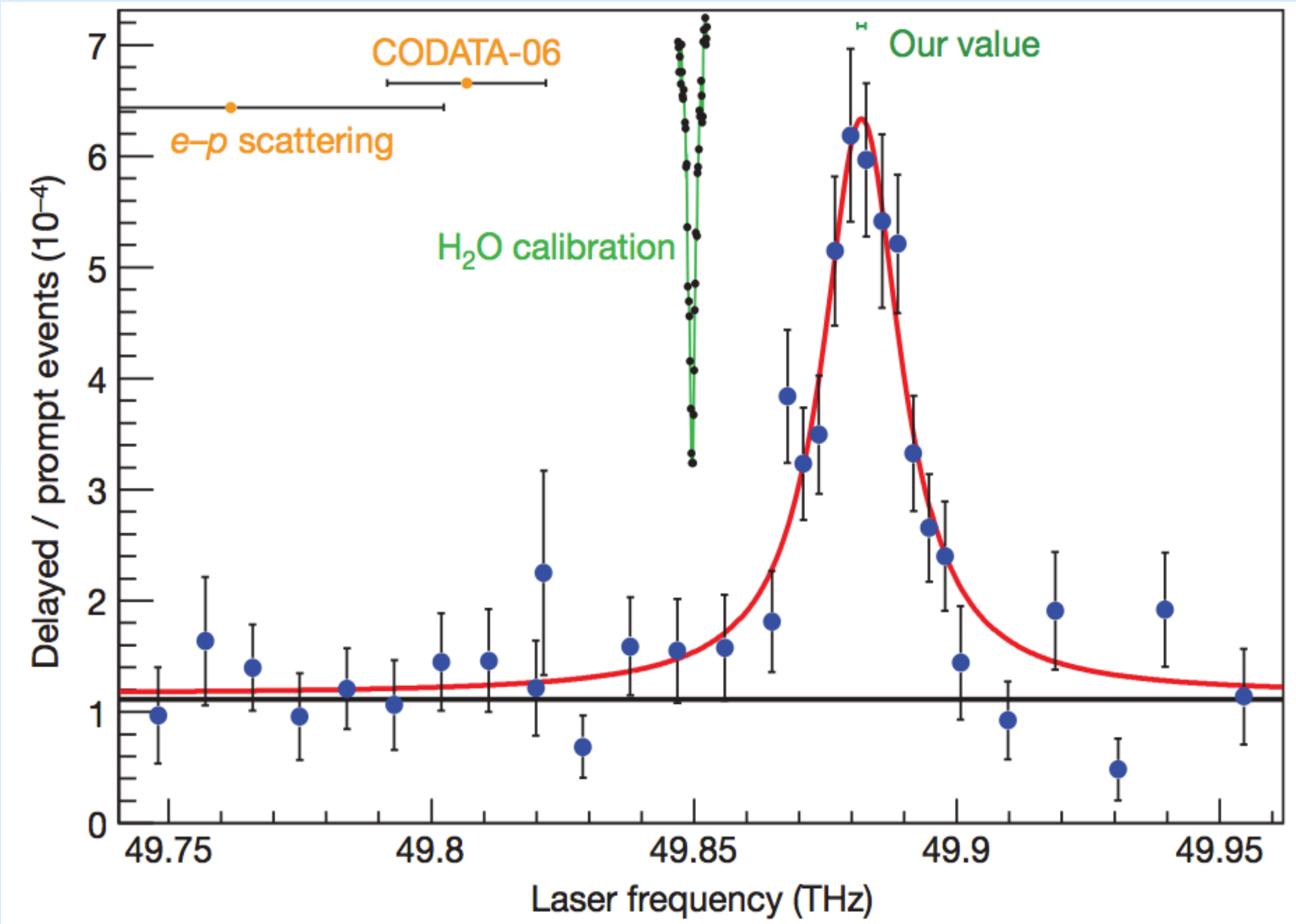
PSI muonic hydrogen measurements

R. Pohl et al., Nature 466, 09259 (2010): 2S⇨2P Lamb shift

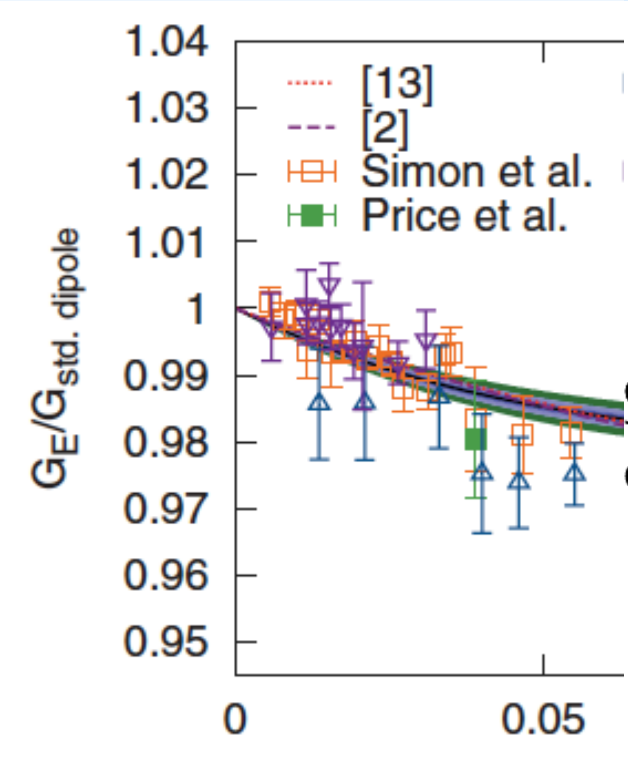
ΔE (meV) = 209.9779(49) - 5.2262 r_p^2 + 0.0347 r_p^3

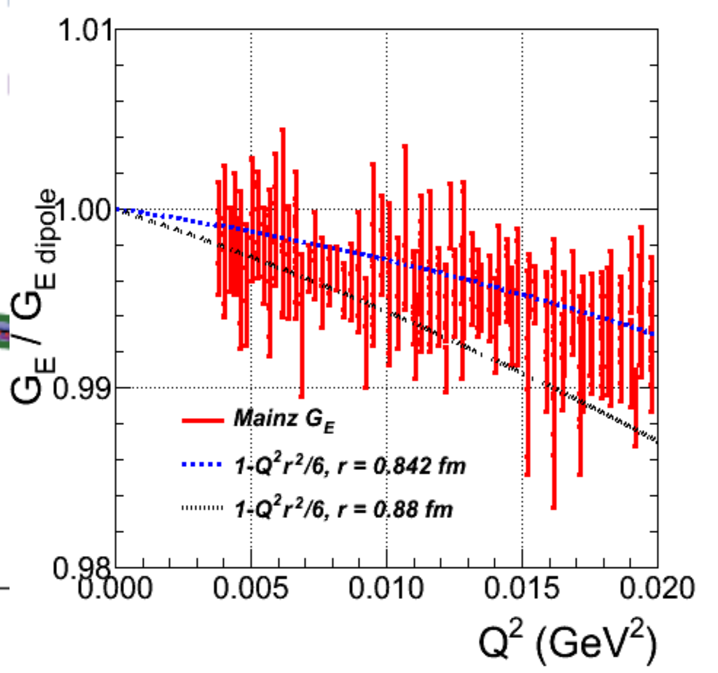
⇨ r_p = 0.842 ± 0.001.

Possible issues: atomic theory & proton structure

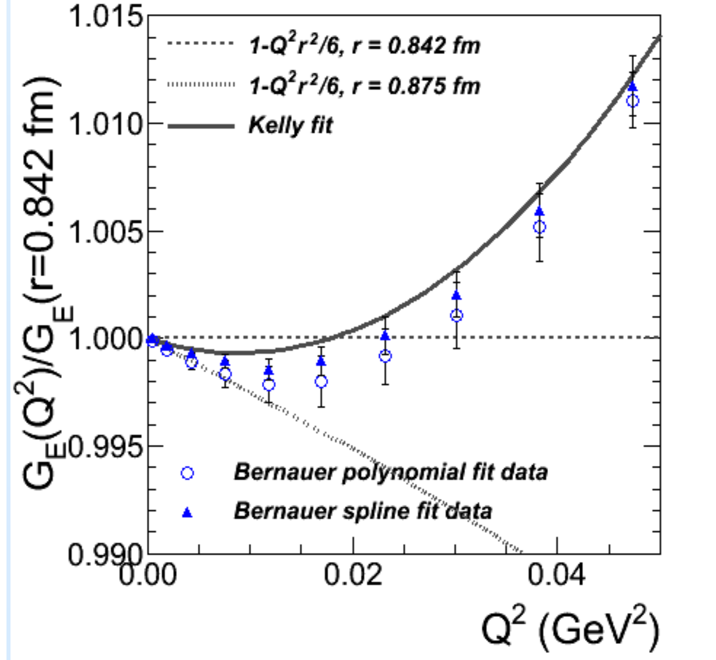


Proton radius from Mainz A1 data



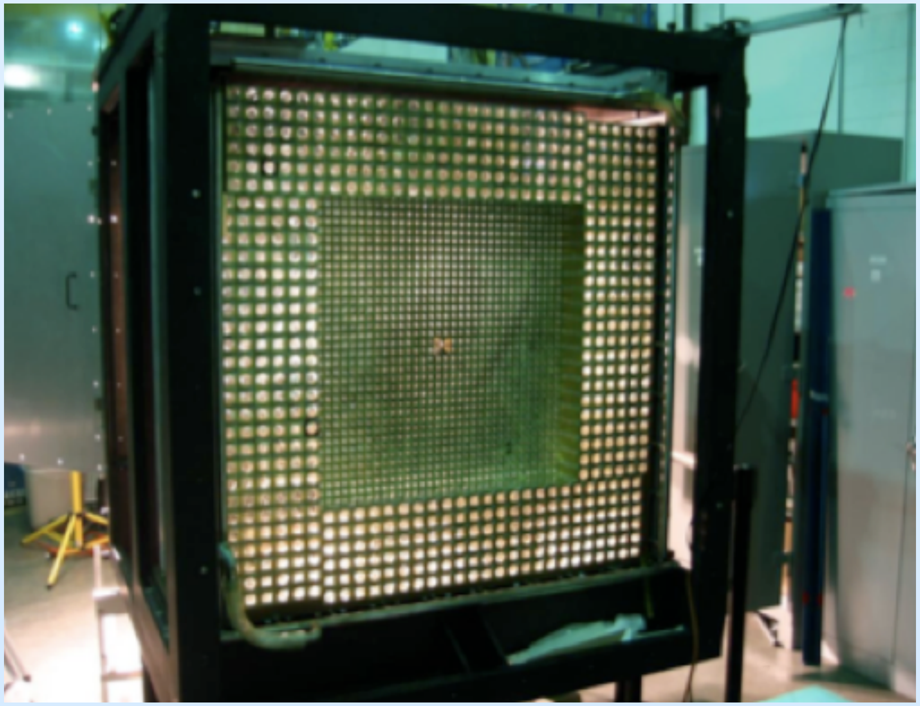


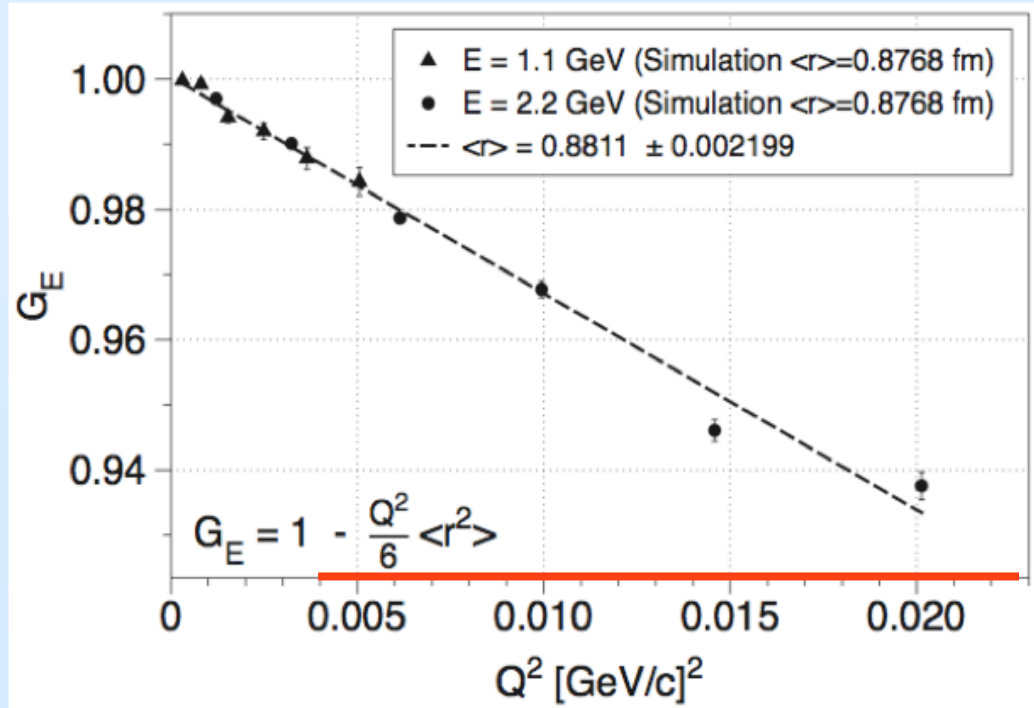
$G_E(Q^2) = 1 - Q^2r^2/6 + ...$



- 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 “PrimEx” proton radius proposal





- Low intensity beam in Hall B @ Jlab into windowless gas target.
- Scattered ep and Moller electrons into HYCAL at 0º.
- Lower Q^2 than Mainz. 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”

Possible resolutions to the puzzle

- **The μp result is wrong**
  Discussion about theory and proton structure for extracting the proton radius from Lamb shift measurement

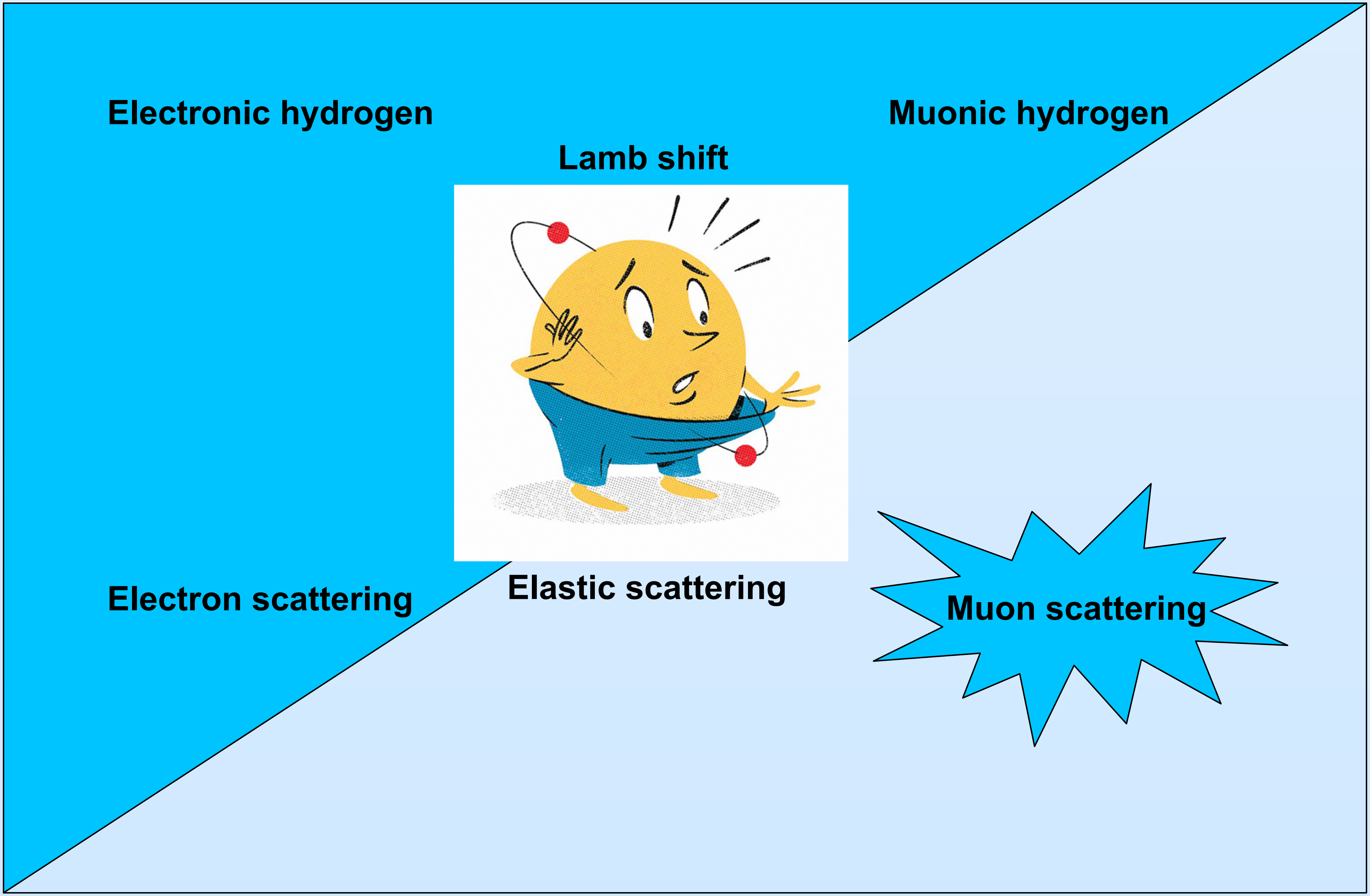
- **The ep (scattering) results are wrong**
  Fit procedures not good enough
  Q^2 not low enough, structures in the form factors

- **Proton structure issues in theory**
  Off-shell proton in two-photon exchange leading to enhanced effects differing between μ and e

- **Physics beyond Standard Model differentiating μ and e**
  Lepton universality violation
  Existing constraints on new physics

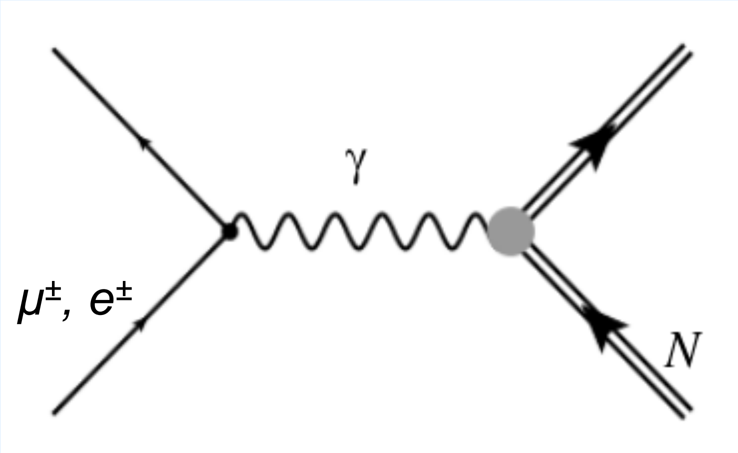
More insights from comparison of ep and μp scattering

Motivation for μp 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:

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

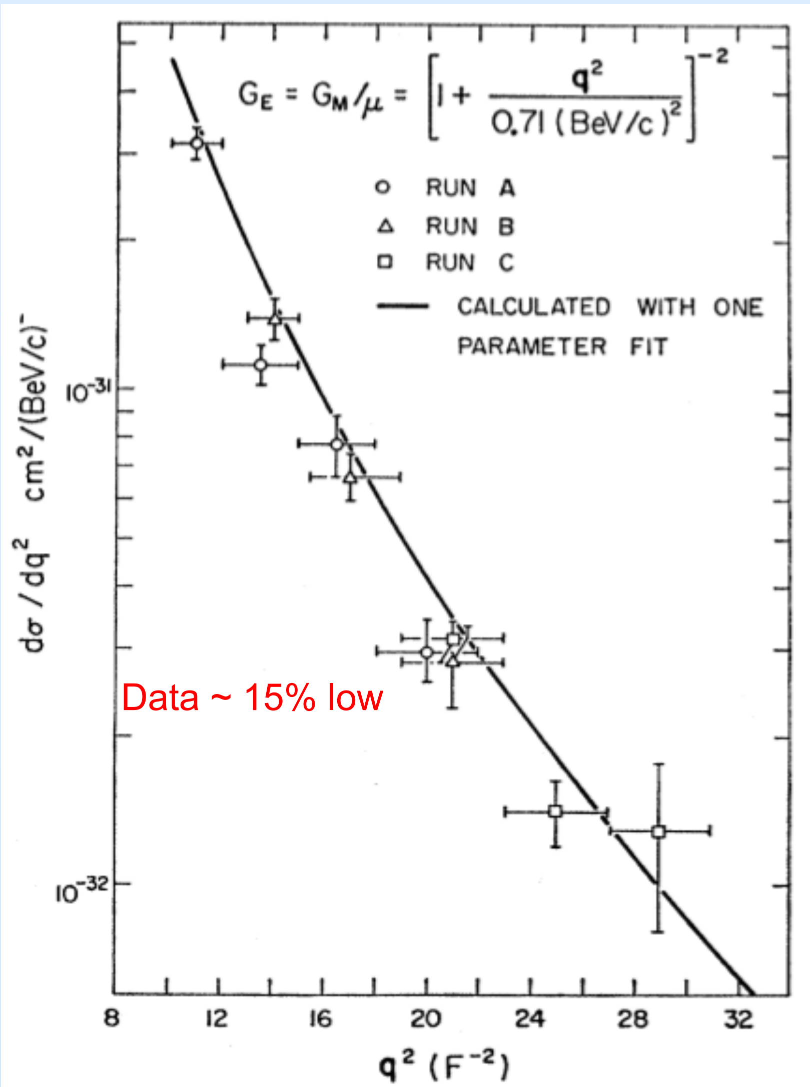
$$\langle r_M^2 \rangle = -6\frac{dG_M^p(Q^2)/\mu_p}{dQ^2}\bigg|_{Q^2\to 0}$$

Expect identical result for ep and μp scattering

e-μ universality in lepton scattering

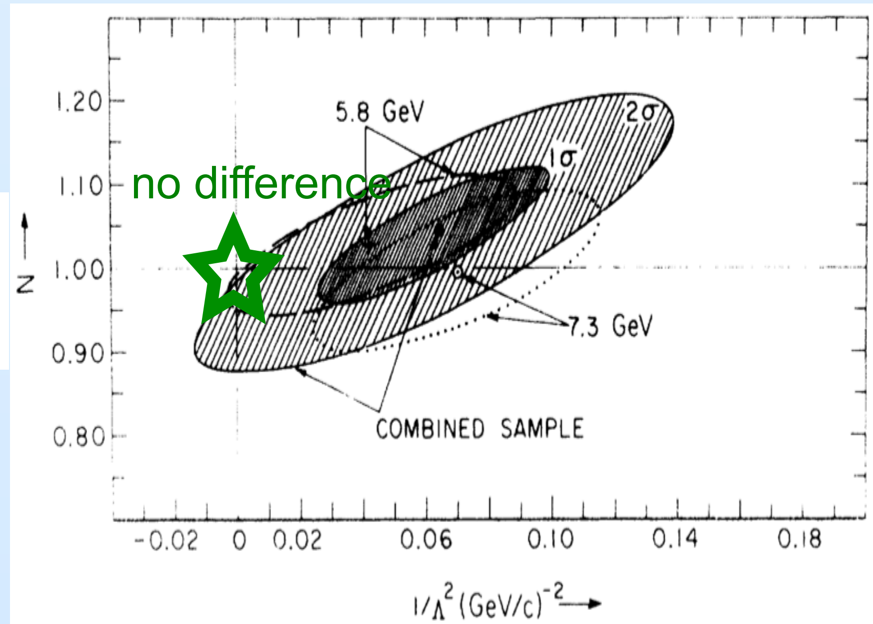
1960s-1970s: several experiments tested e-μ universality in scattering

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



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

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



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

- 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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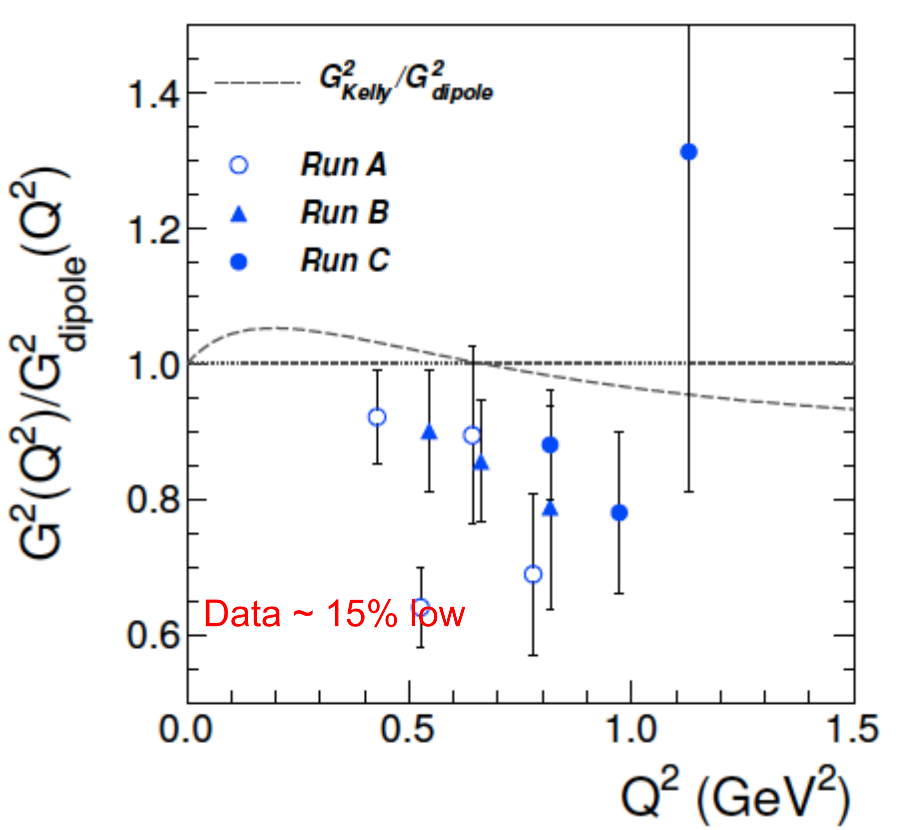

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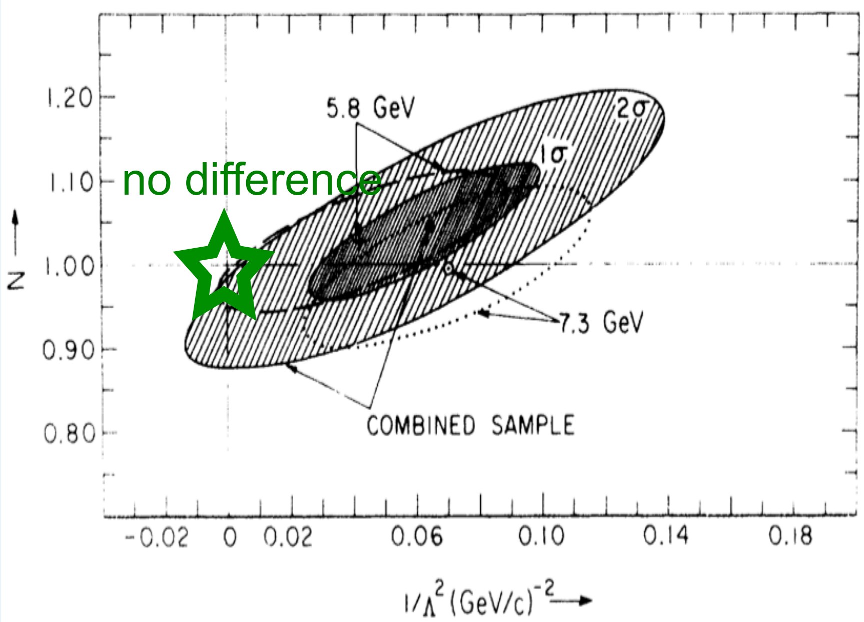

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Constraints are not very good

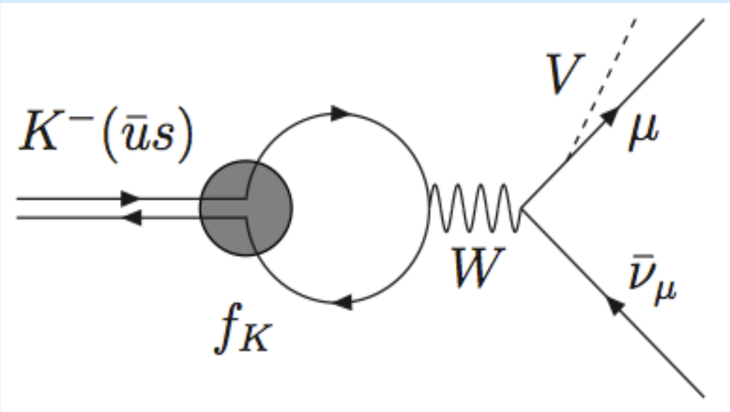
Lepton universality beyond SM

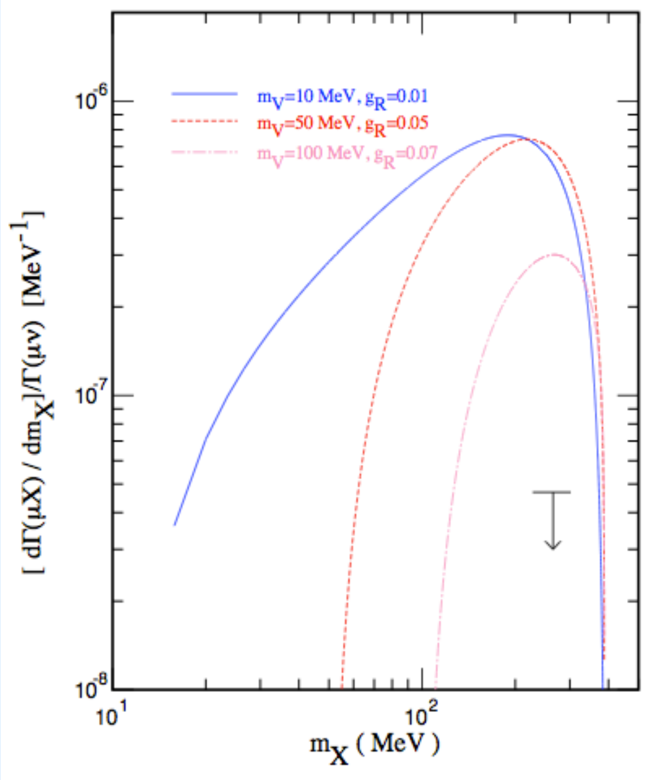
Batell, McKeen, Pospelov (arXiv:1103.0721):

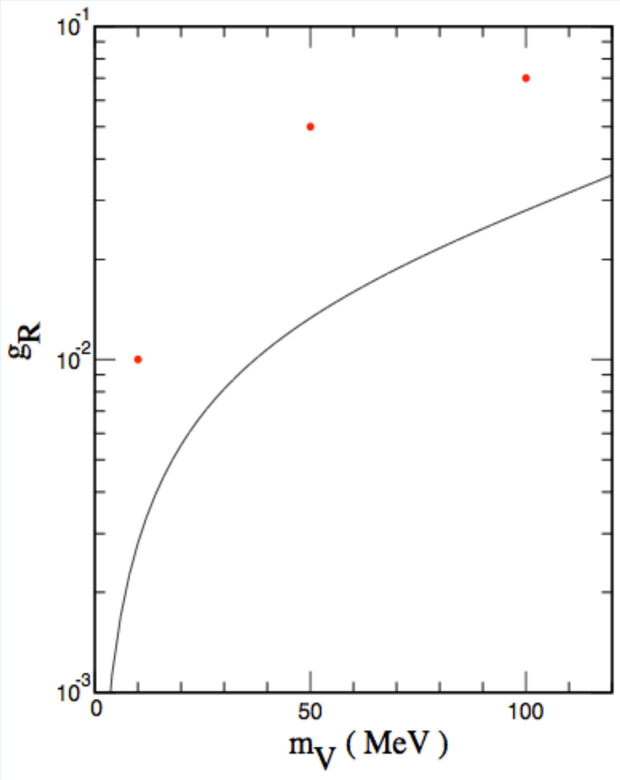
- new e/μ differentiating force consistent with g_μ-2
- <100 MeV gauge boson V or dark photon
- resulting in large PV μp scattering

Barger, Chiang, Keung, Marfatia (arXiv:1109.6652):

- constrained by K → μν decay

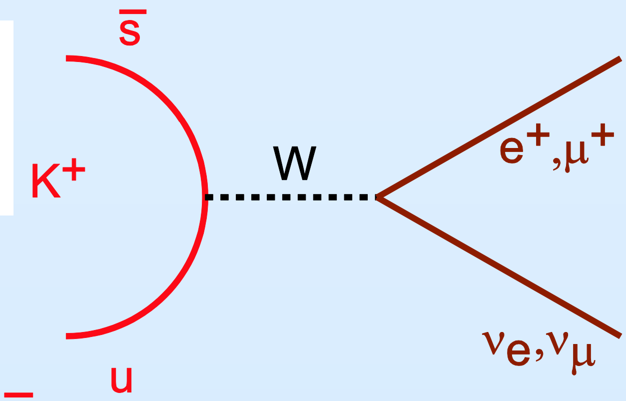






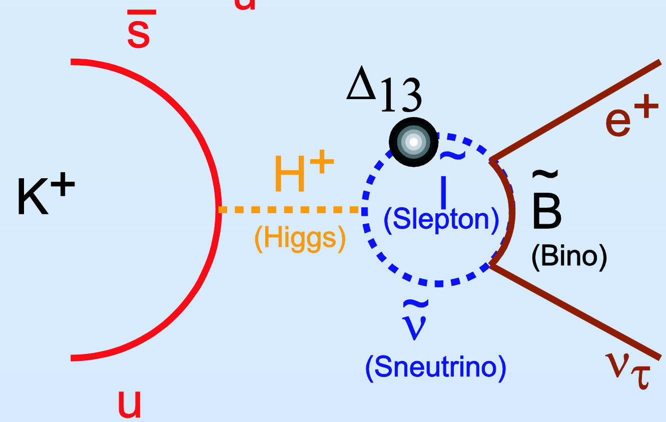
Lepton universality in K_{l2} decays

$$R_K^{SM} = \frac{\Gamma(K^+ \to e^+\nu)}{\Gamma(K^+ \to \mu^+\nu)} = \frac{m_e^2}{m_\mu^2}\left(\frac{m_K^2 - m_e^2}{m_K^2 - m_\mu^2}\right)^2 (1+\delta_r)$$



- **Highly precise SM value**

  $R_K^{SM} = (2.477 \pm 0.001) \times 10^{-5}$



- **LFV beyond SM** PRD74,11701 (2005)

  e.g. MSSM with charged-Higgs SUSY-LFV

$$R_K^{LFV} = R_K^{SM}\left(1 + \frac{m_K^4}{M_{H^+}^4} \cdot \frac{m_\tau^2}{m_e^2} \Delta_{13}^2 \tan^6\beta\right)$$

⇒ $R_K^{LFV} \sim R_K^{SM}(1 \pm 0.013)$

- **Current experimental precision (KLOE, NA62)**

  $R_K = (2.488 \pm 0.012) \times 10^{-5}$, $\delta R_K / R_K = 0.48\%$

TREK (P36) proposed at J-PARC for 0.25% precision

Proposal for $\mu^{\pm}p/e^{\pm}p$ scattering 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:

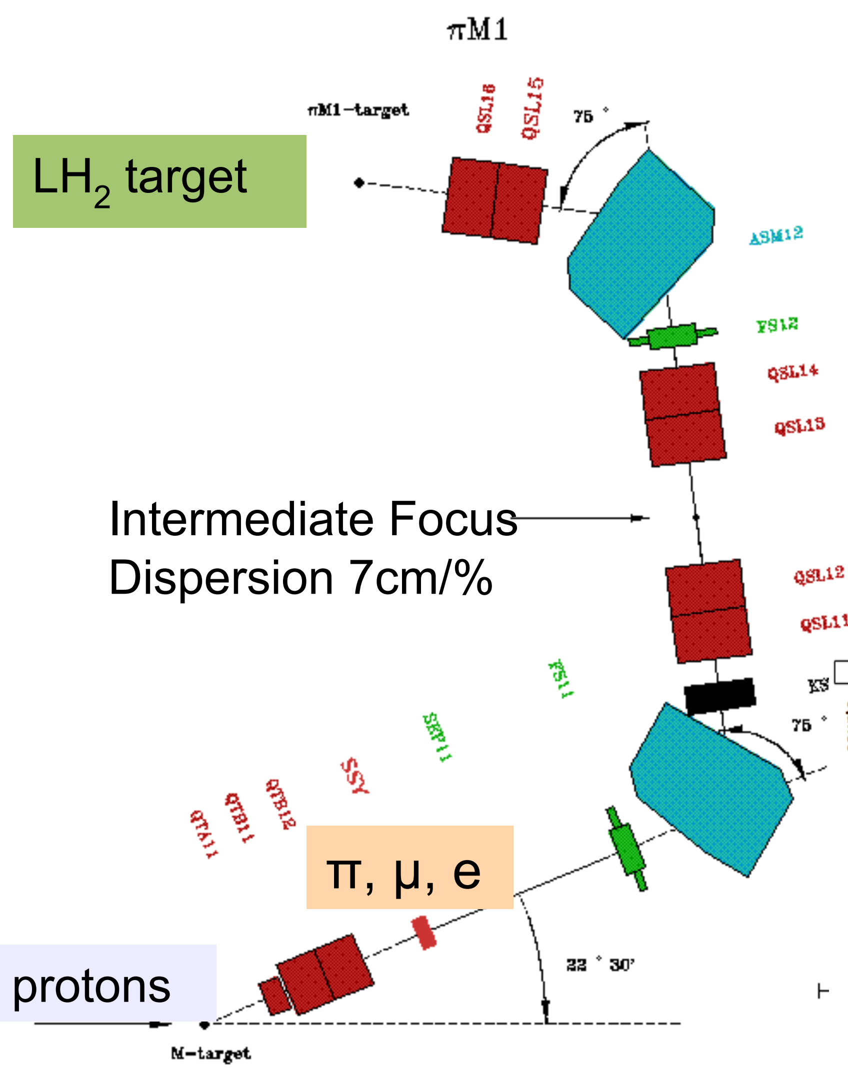
- to higher precision than previously
- in the low Q^2 region (same as Mainz and latest JLab experiment just completed) for sensitivity to radius
- measure both $\mu^{\pm}p$ and $e^{\pm}p$ for direct comparison and a robust, convincing result
- depending on the results, 2nd generation experiments (lower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

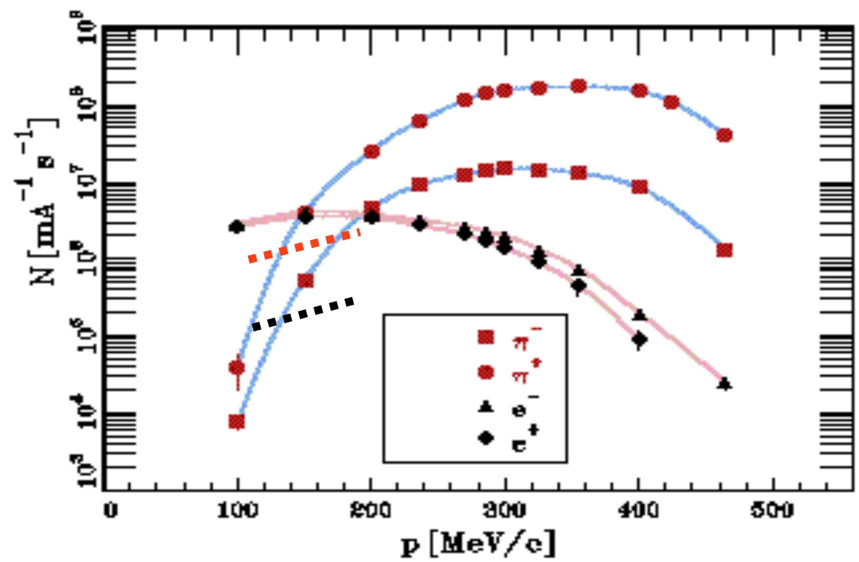
Proposal for μ±p/e±p scattering at PSI

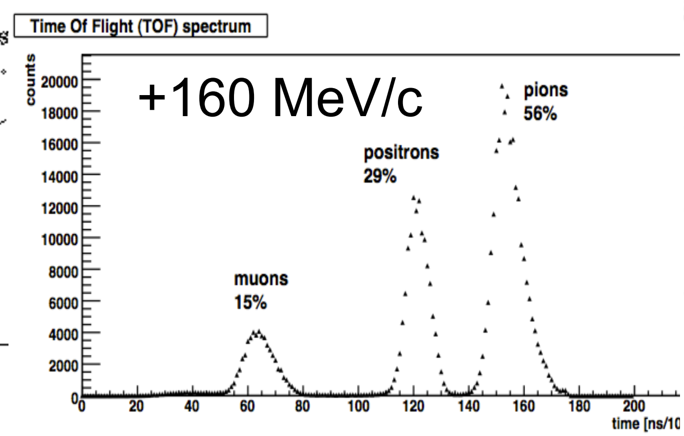
Use the world's most powerful low-energy separated e/π/μ beam for a direct test if μp and ep scattering are different:

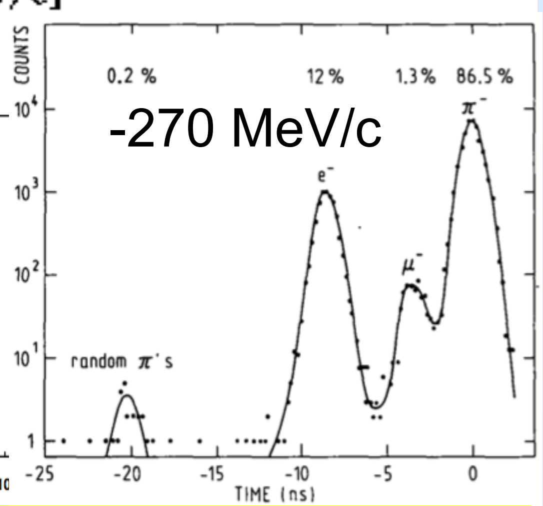
- Measure absolute cross section for μp scattering and cross section ratios to other species
- Simultaneously measure ep scattering
  → μ/e ratio to cancel certain systematics
  → If radii differ by 4%, form factor slope differs by 8%, and cross section slope differs by 16%
- Measure e+, e- and μ+, μ- on target
  → Directly extract information on two-photon exchange (TPE) effect and compare for e, μ
- Use multiple beam energies
  → separate G_E and G_M with the Rosenbluth method

PSI πM1 channel: 100-500 MeV/c μ/e/π









Beam spot (nominal):
XY = 1.5x1 cm^2; X'Y' = 35x75 mr^2

Momentum acceptance: 3%, resolution: 0.1%

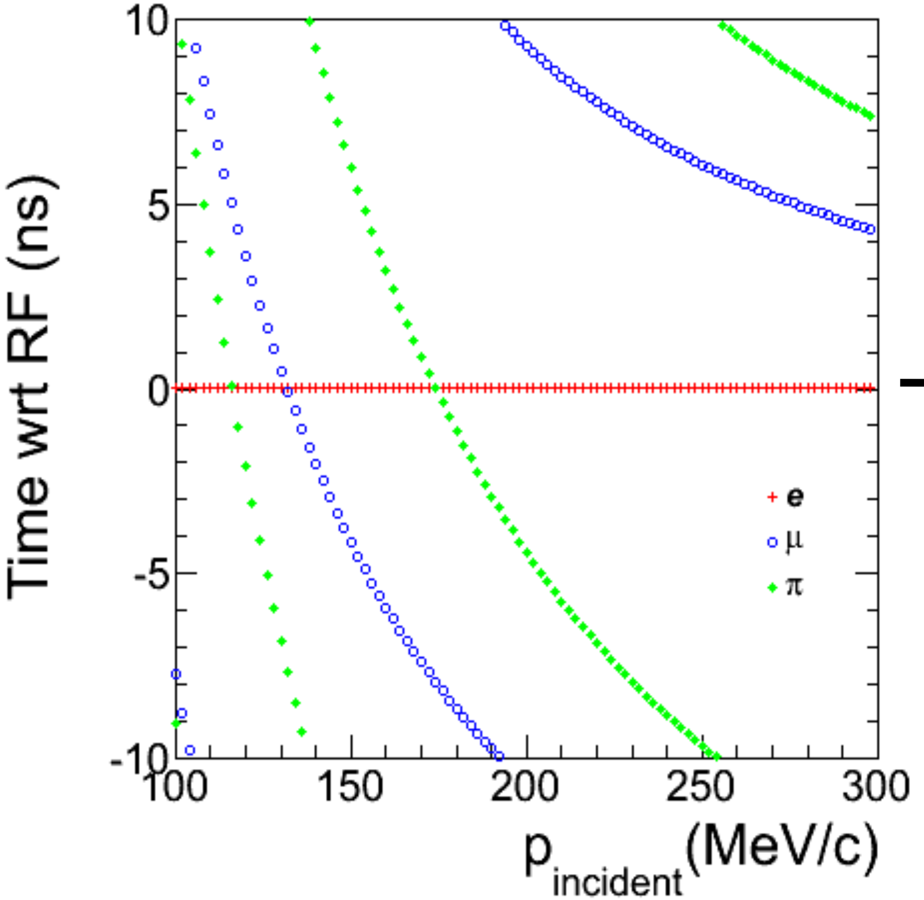
Spots from 0.7x0.9 cm^2 up to 16x10 cm^2, and Δp/p from 0.1-3.0%, used previously

Separation of e, π, μ by RF time

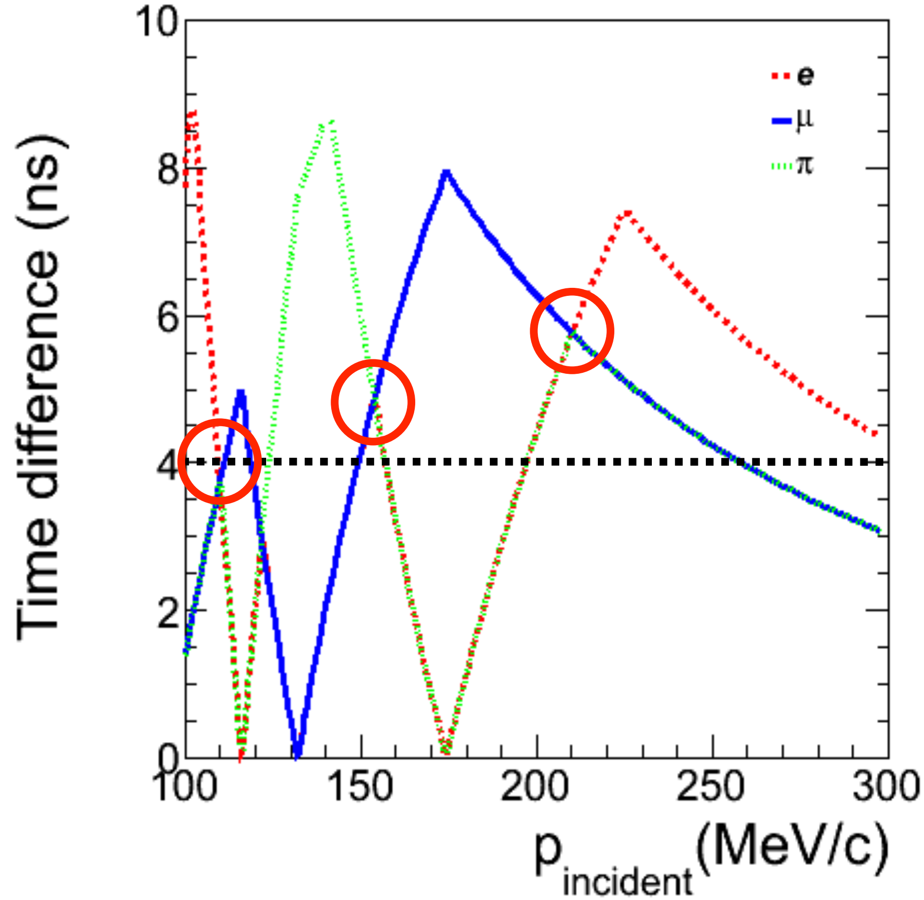
Requirement: particle separation in time for PID

50 MHz RF → 20 ns between bunches

Timing of particles in target region wrt electron (β = 1)

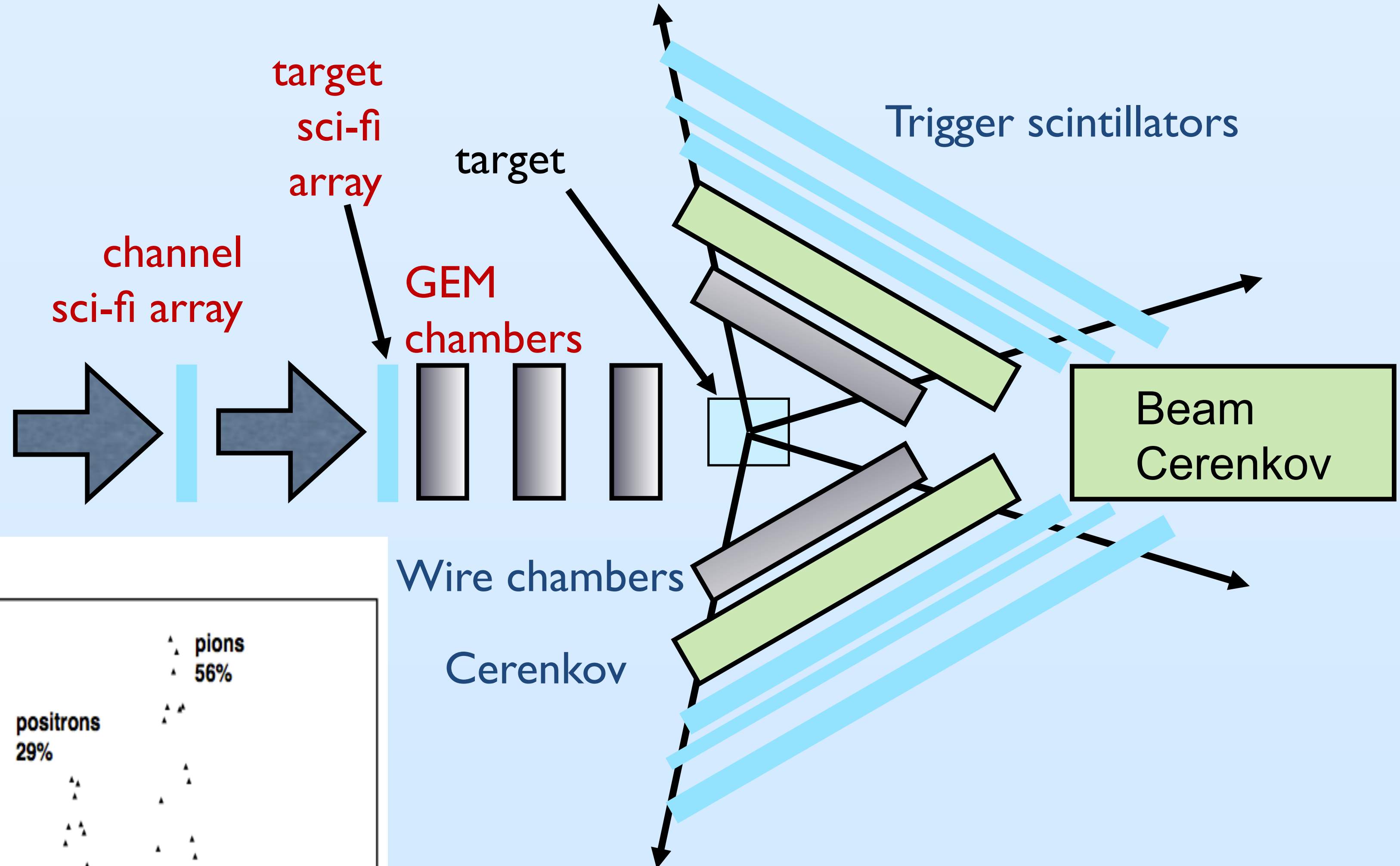


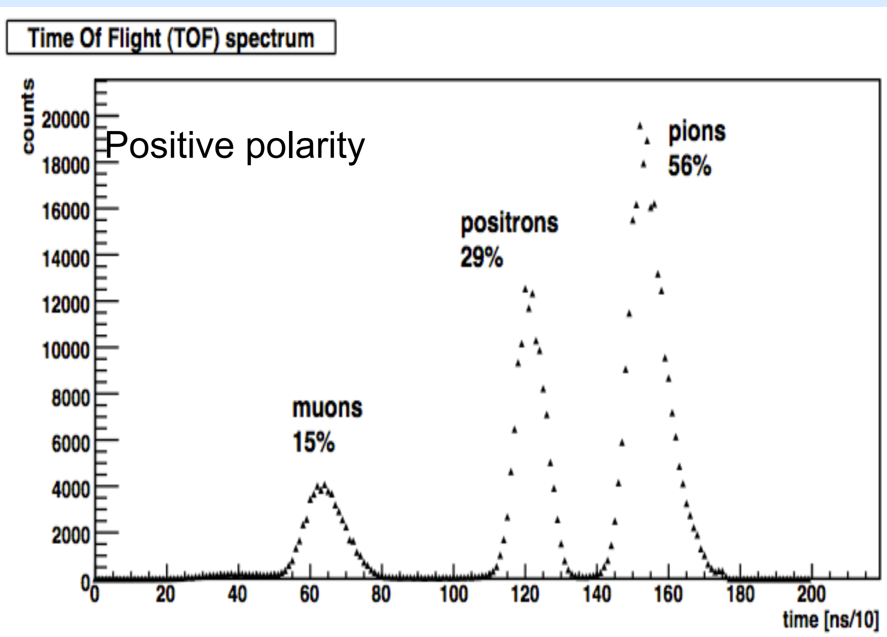
Minimum time separation of particles in target region



p = 115, 153, and 210 MeV/c

Schematic layout



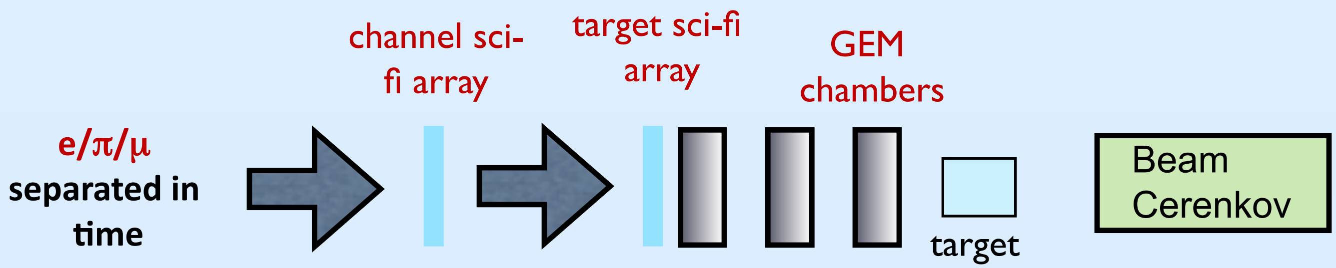


Momentum acceptance: 3%, resolution: 0.1%

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

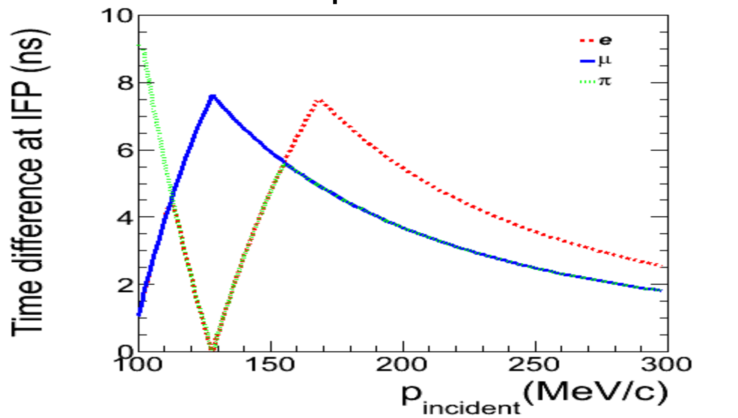
Beamline instrumentation

Beamline Elements:



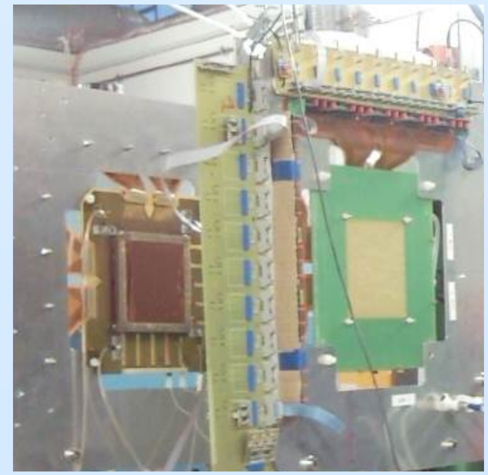
Beam and target sci-fi arrays:
→ Flux, PID, TOF, momentum

Particles well separated at IFP:



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

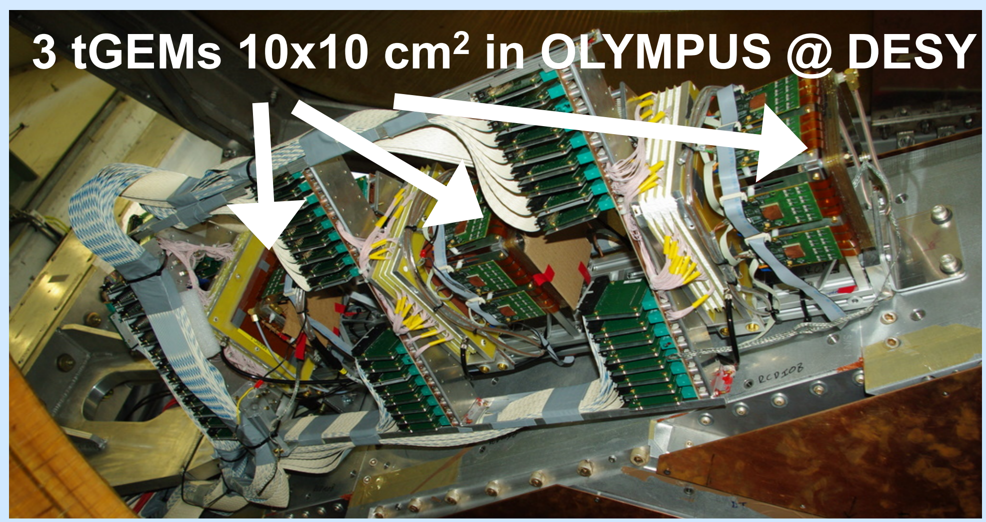
UVa GEM



COMPASS GEMs
routinely operated to ≈2.5 MHz/cm^2

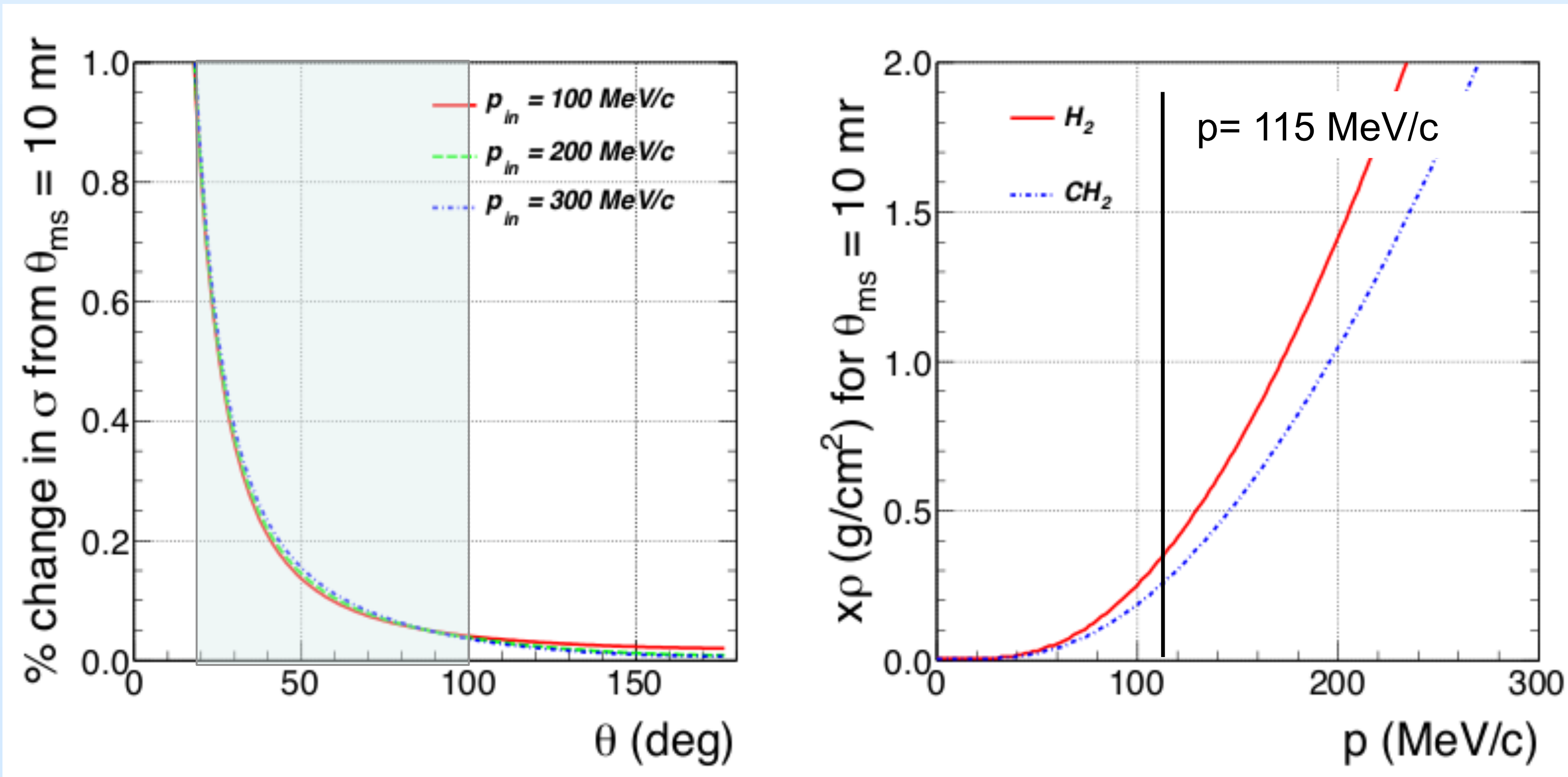
Tested up to several 10s of MHz/cm^2

PSI: 10 MHz/1.5 cm^2 = 6.7 MHz/cm^2 (average) rate



Beamline instrumentation

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



% change in cross section for θ_{ms} = 10 mr

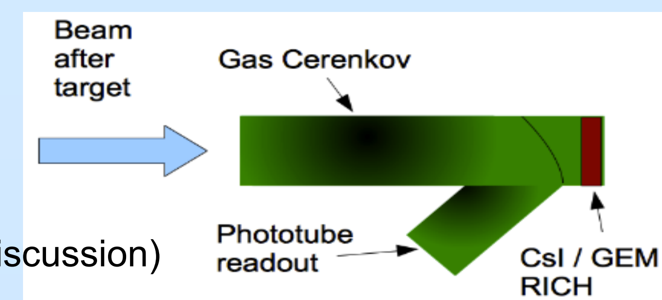
Target thickness giving θ_{ms} = 10 mr

→ Limits acceptance to > 20°

→ Limits target thickness to 0.3 g/cm^2

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

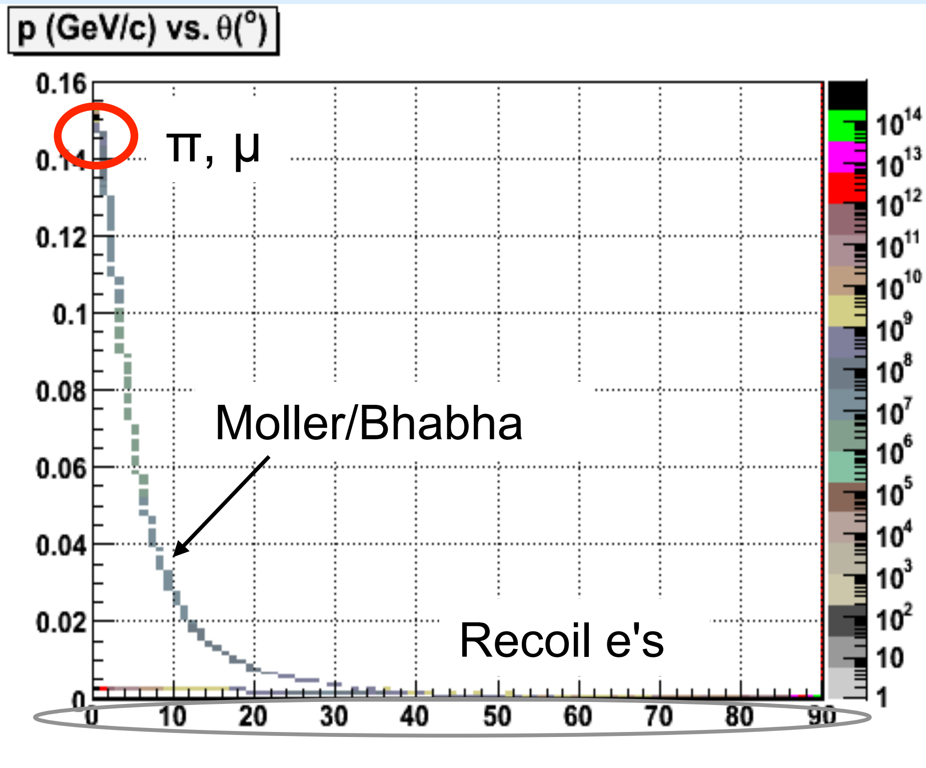
(design under discussion)



Background considerations

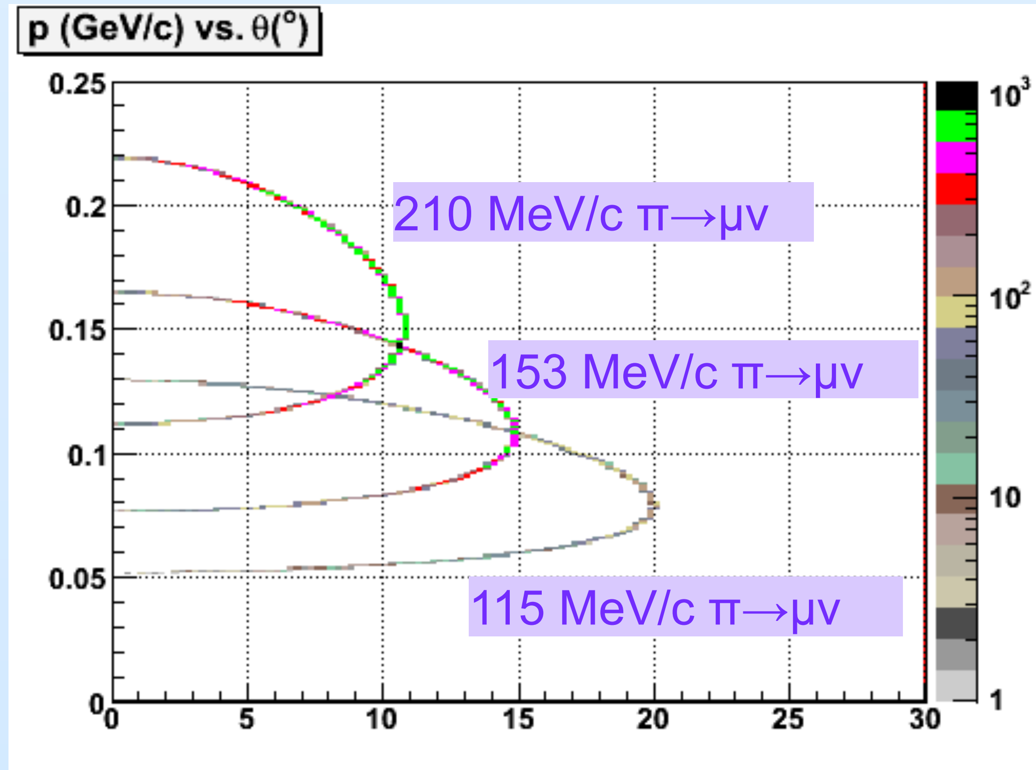
Requirement: low backgrounds or background rejection

Scattering from electrons:



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

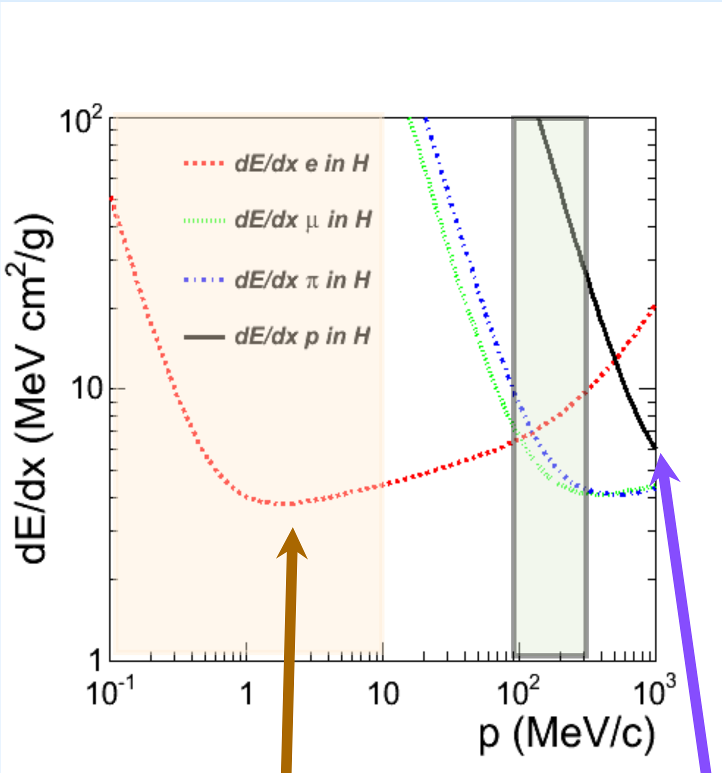
Muons from π decays

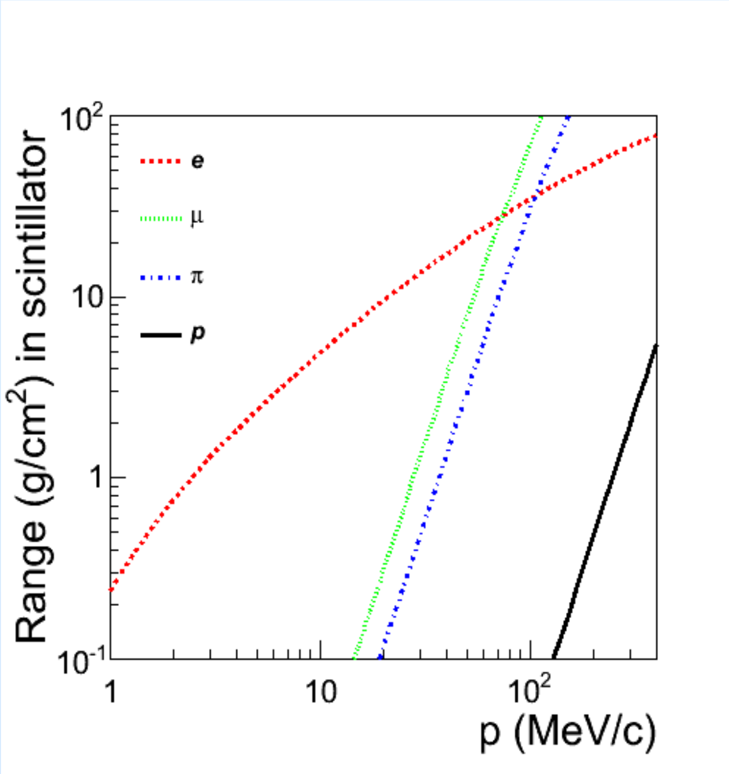


→ Will have π RF time
(3 orders of magnitude suppression)
→ Track will not point back to the target

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

Scattered particle considerations



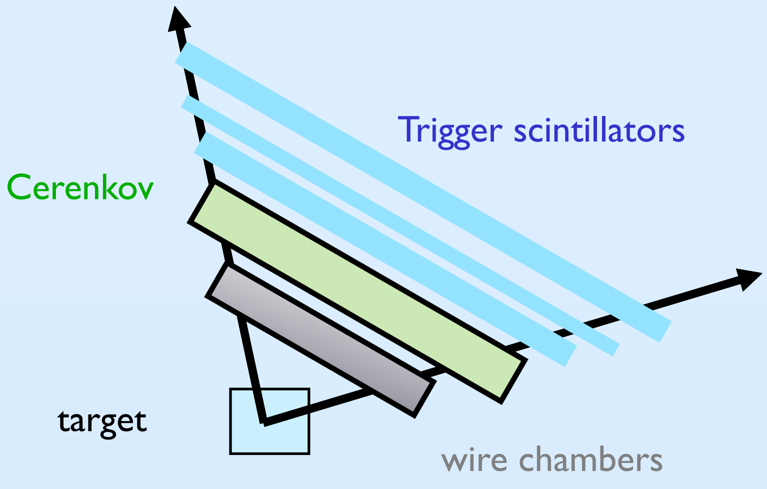


Large angle, very low energy Moller / Bhabha e's lose large fraction of energy in target

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

Detector: trigger scintillators

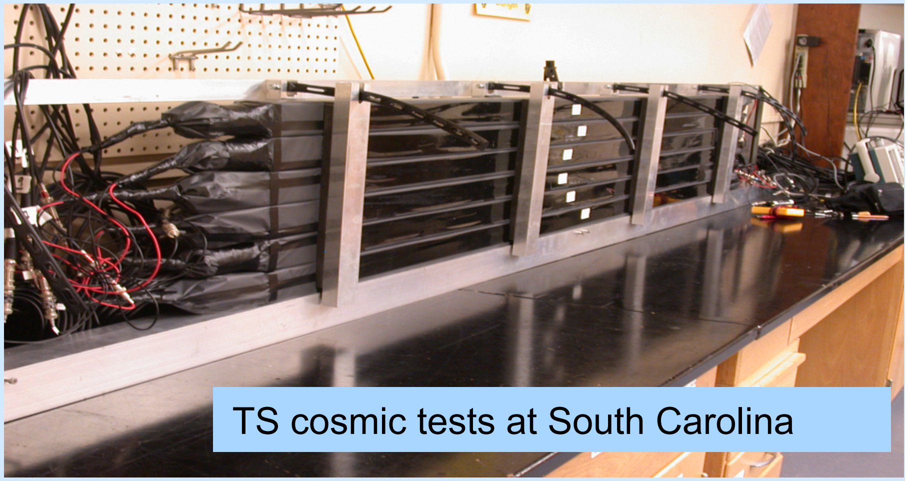


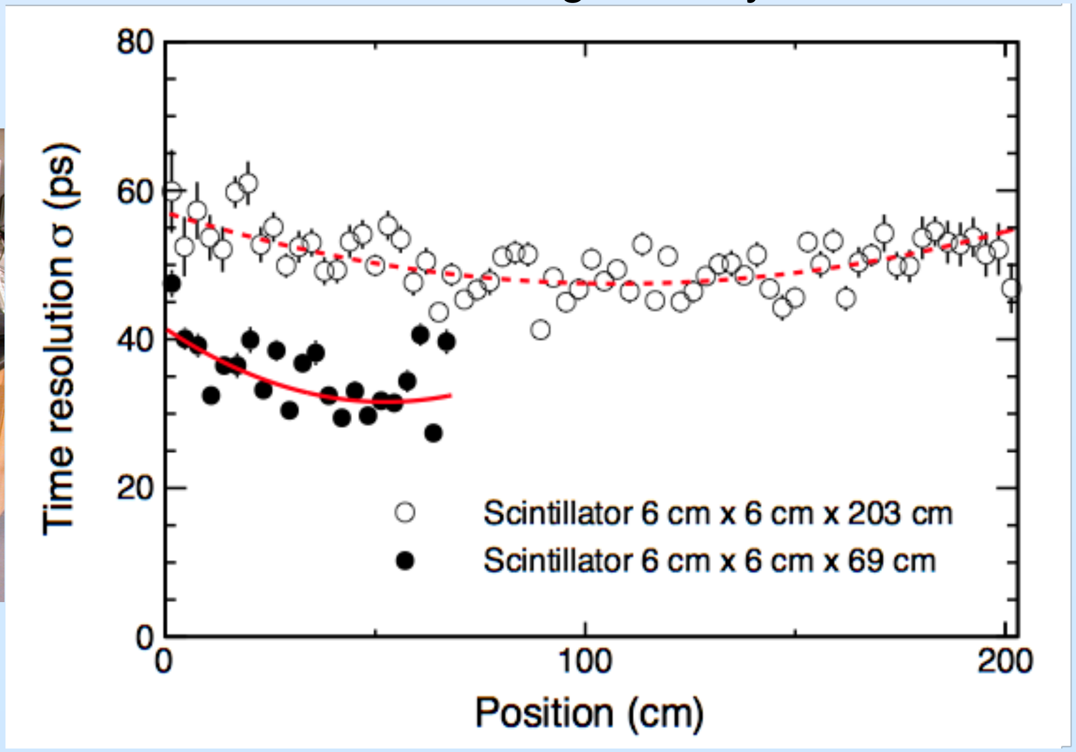
Trigger Scintillators: outermost element of detector stack, 70-100 cm from target

→ Based on 6 cm x 6 cm x 2 m long scintillators built for CLAS12
→ Thick enough to stop low energy e+,e-
→ Demonstrated ~50 ps resolution at analysis level (We will have ~1.4 m long bars → better timing)

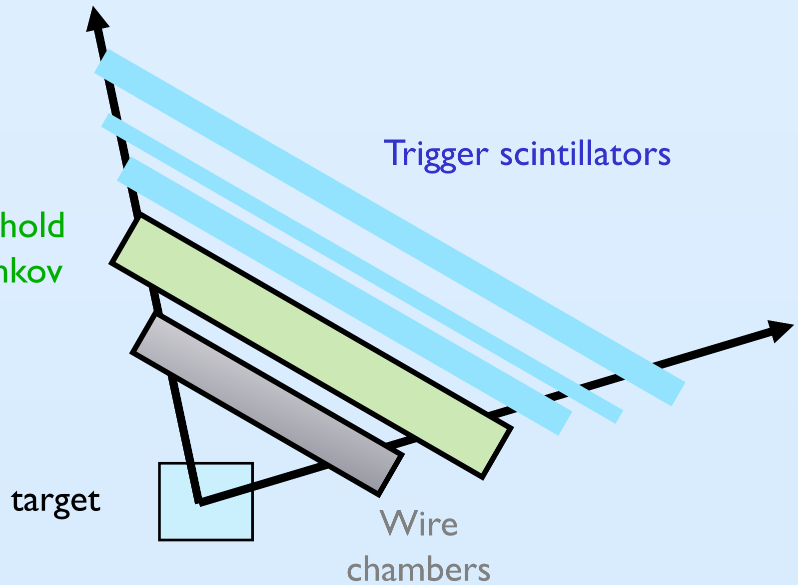
Cover angular range of 20-100^o

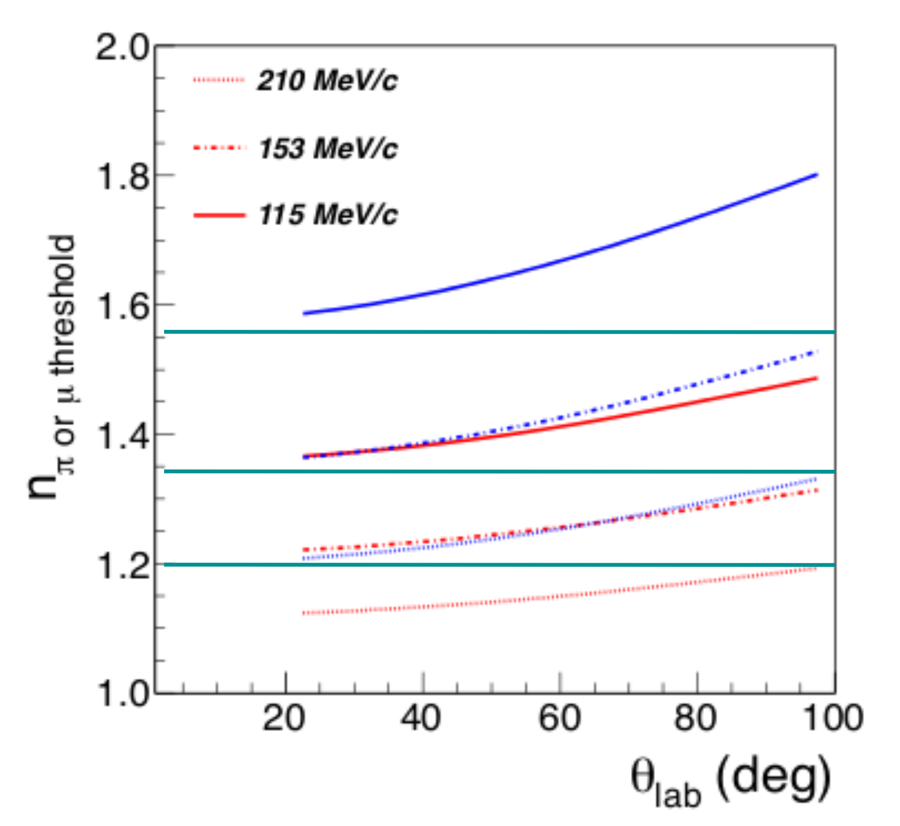
Use for PID based on RF timing at analysis level to 70σ





Detector: wire chambers, Cerenkov





Wire chambers: ~400 kHz rate

→ Position resolution ~100 μm

→ Angular resolution < 1 mr (neglecting m.s.)

Threshold Cerenkov: (discussed)

→ provide alternate method of PID at the trigger level

→ additional suppression of pion triggers

→ medium different for each momentum

Beam (MeV/c)	$n_{threshold}$	Material
210	1.19-1.20	Pinhole dried Aerogel
154	1.32-1.36	Water/teflon
115	1.50-1.58	Quartz/lucite

Rate considerations

- 10 MHz beam rate / 50 MHz RF
  82% chance clean
  16% chance 2 particles
  2% chance >2 particles
  in RF bucket
- Reduce acceptance to limit rates for +210, +153 MeV/c
- 250 ns chamber time scale ➪ 2.5 background tracks per event
- Eventually handle 2nd particle in same RF bucket as μ trigger

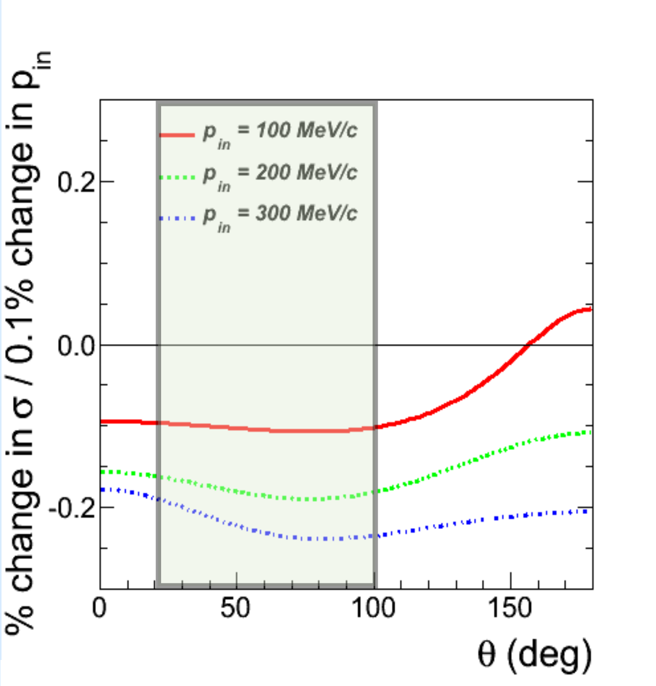
p (MeV/c)	+/-	π (MHz)	μ (MHz)	e (MHz)	Σ (MHz)
115	+	0.6	2	6	9
153	+	8	2	8	18
210	+	60	5	6	70
115	-	0.06	0.2	6	6
153	-	0.7	0.2	8	9
210	-	6	0.5	6	12

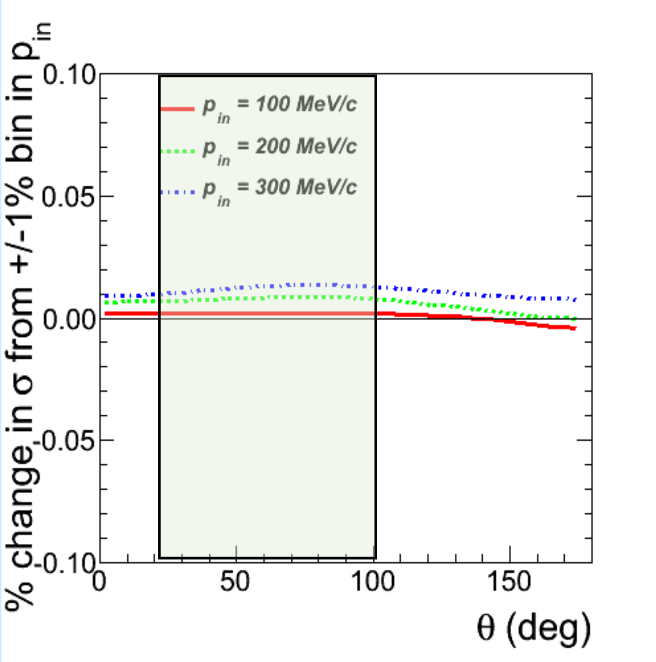
Rate considerations

Momentum (MeV/c)	Positive beam charge +115	+153	+210	Negative beam charge -115	-153	-210
μp elastic scattering	**6.4**	**5.5**	**1.6**	**1.3**	**1.8**	**1.3**
μAl elastic scattering	7.7	6.6	2.0	1.5	2.6	1.6
μ decays in flight $\to$ e's in detector	460	440	160	90	140	125
μ knockout of δ's	≈ 0	≈ 0	≈ 0	≈ 0	≈ 0	≈ 0
ep elastic scattering	**67**	**27**	**2.4**	**67**	**50**	**11**
eAl elastic scattering	81	33	2.9	81	60	14
ee Bhabha / Moller scattering	$7200 \to \approx 0$	$5300 \to \approx 0$	$900 \to \approx 0$	≈ 0	≈ 0	≈ 0
$\pi^{\pm} p$ elastic scattering	$62 \to 8$	$5500 \to \approx 0$	$48k \to \approx 0$	$10 \to 1.3$	$630 \to \approx 0$	$5700 \to \approx 0$
π decays in flight $\to$ μ's in detector	$3600 \to 480$	$660k \to 0.9$	$173k \to 1$	$700 \to 92$	$210k \to 0.3$	$120k \to 1$
π knockout of δ's	≈ 0	≈ 0	≈ 0	≈ 0	≈ 0	≈ 0

- **Trigger rates in Hz for total beam flux of 10 MHz – always < 1kHz**
- **Singles rates can exceed 1 MHz**
- **Up to ~15% accidental triggers from pion induced processes at high momentum**

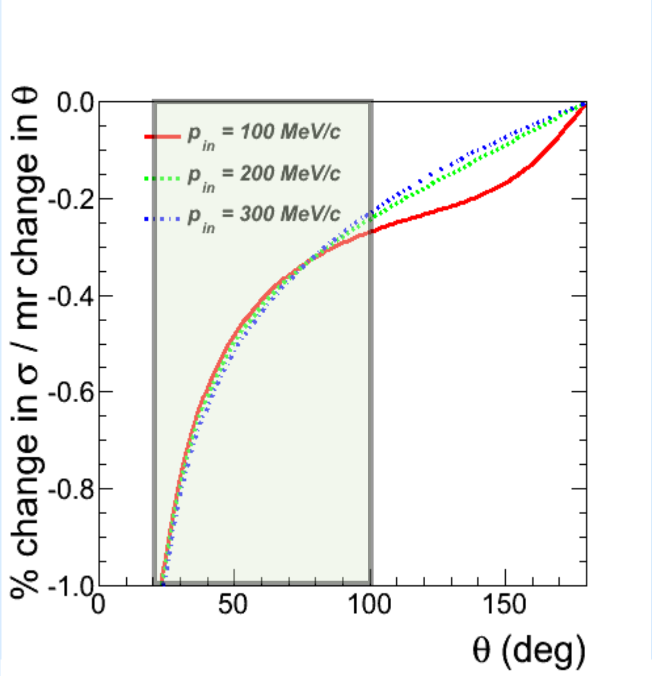
Systematics to be controlled

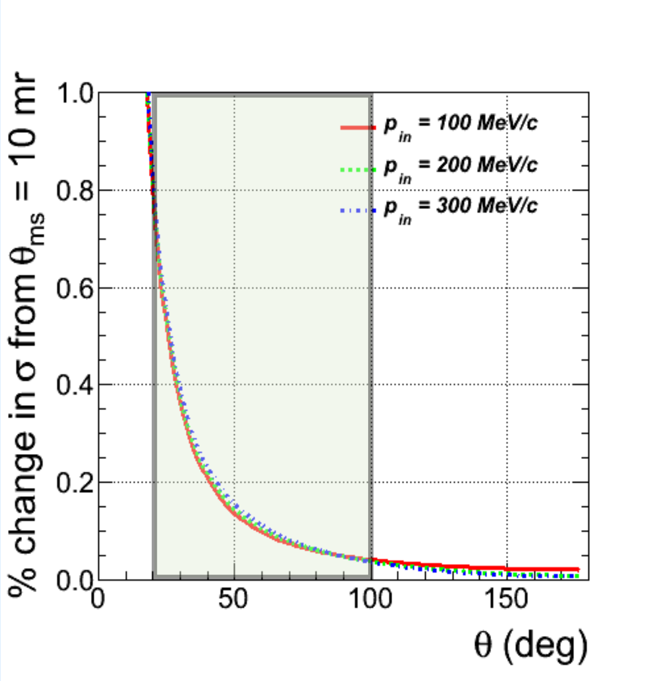




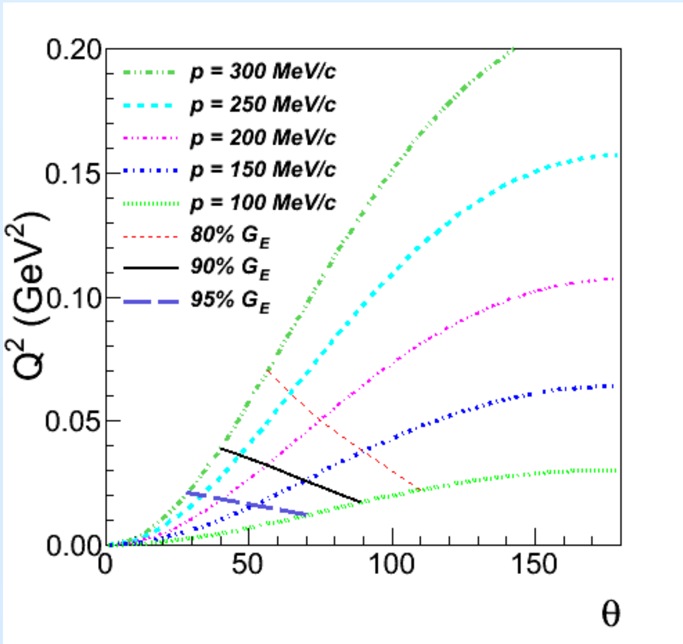
Left:
need to know central momentum to tenths of a percent, but can average over a few percent bin.
Can "fit this out".

Right:
need to know central angle to mr level, but can average over several mr.
Can ``fit out'' offset and correct cross sections for resolution.

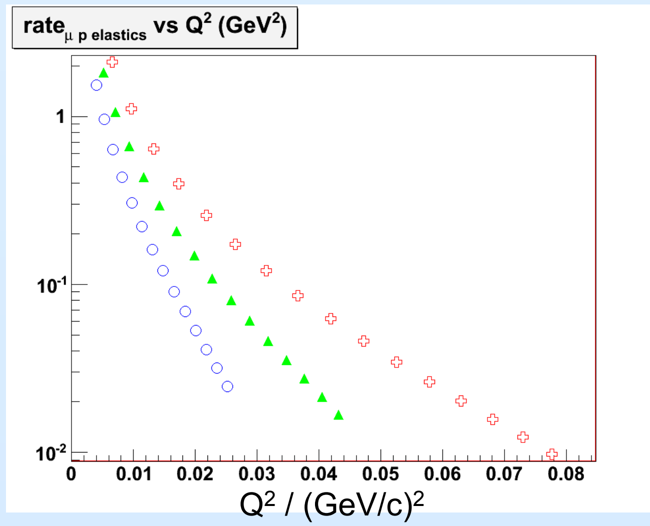


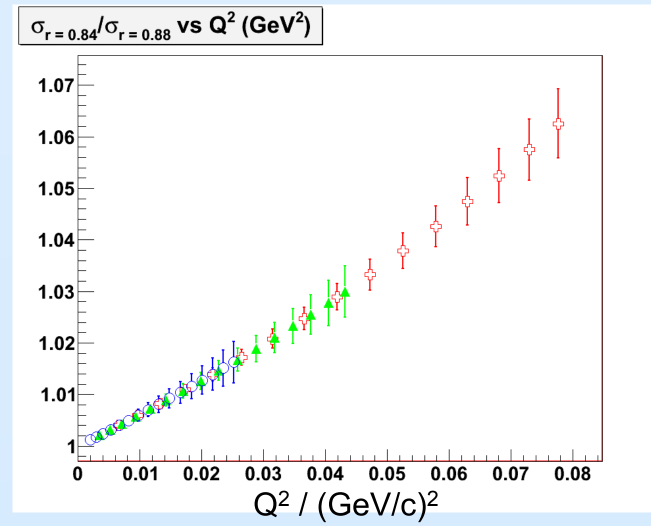


Projected sensitivity



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

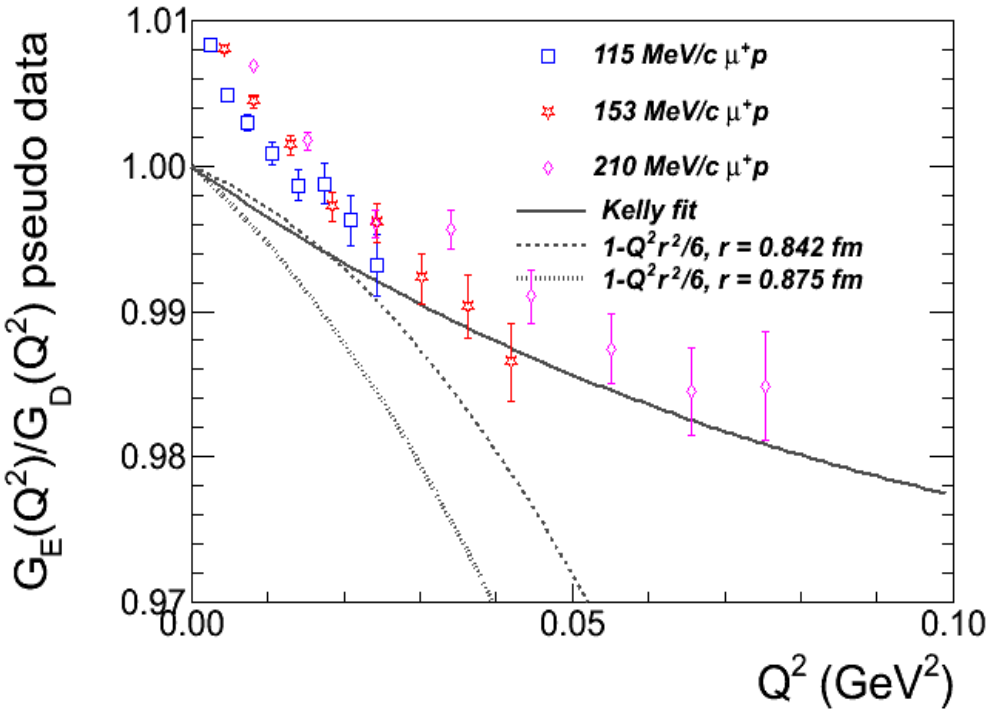




- **πM1 channel, with p_{in} = 115, 153, and 210 MeV/c: PID reasons**
- **Choose θ = 20 - 100°: rates, backgrounds, systematics**
- **Statistics for 30 days/setting at 10 MHz on 0.3 g/cm² liq. H_2**
- **Statistics plus estimated systematics lead to δR ≈ 0.01 fm for μ^+, $e^\pm$, and 0.015 fm for μ^-**
- **ΔR = 4% ➪ slopes ΔG' = 8% ➪ Δσ' = 16%**
- **If radius difference is real, are the slope differences that large?**

Projected sensitivity

Pseudo-random data with errors:



→ 30 days of running at each energy
→ sub 1% statistical uncertainty (μ^+p)
→ slightly worse for μ^-p, but sufficient for comparison of TPE

Estimate of systematic uncertainties for μ^+p:

Systematic Uncertainty	Absolute (%)	Point-to-point (%)
$x\rho_{target}$	1.0	-
Beam flux (π / μ / e misidentification)	small	-
Radiative correction	0.3	0.1
Solid angle	0.2	0.2
Efficiencies - triggering, analysis, etc.	0.5	0.1
Beam energy	0.2	0.1
Averaging over beam energies	small	small
Knowledge of angle	0.45	0.3
Averaging over angles / multiple scattering	0.2	0.2
Cell wall subtraction	small	small
Cosmic ray subtraction	small	small
π / μ decay corrections	small	small
TOTAL	1.3	0.5

$\Delta r \approx 0.01$ fm for μ^+, $e^\pm$,
but about 0.015 fm for μ^-

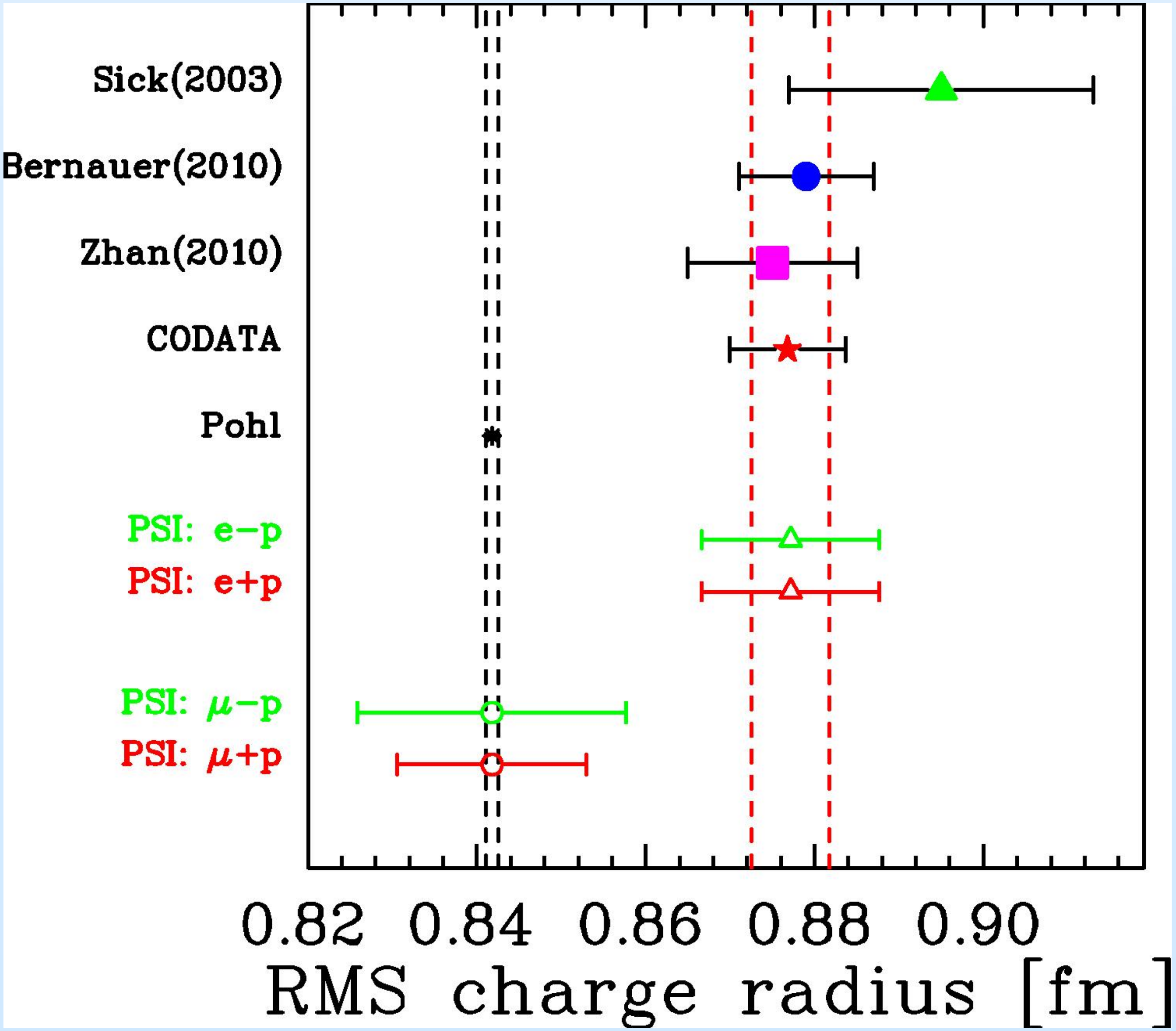
Systematics: ~1.3% absolute precision, 0.5% pt-to-pt

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



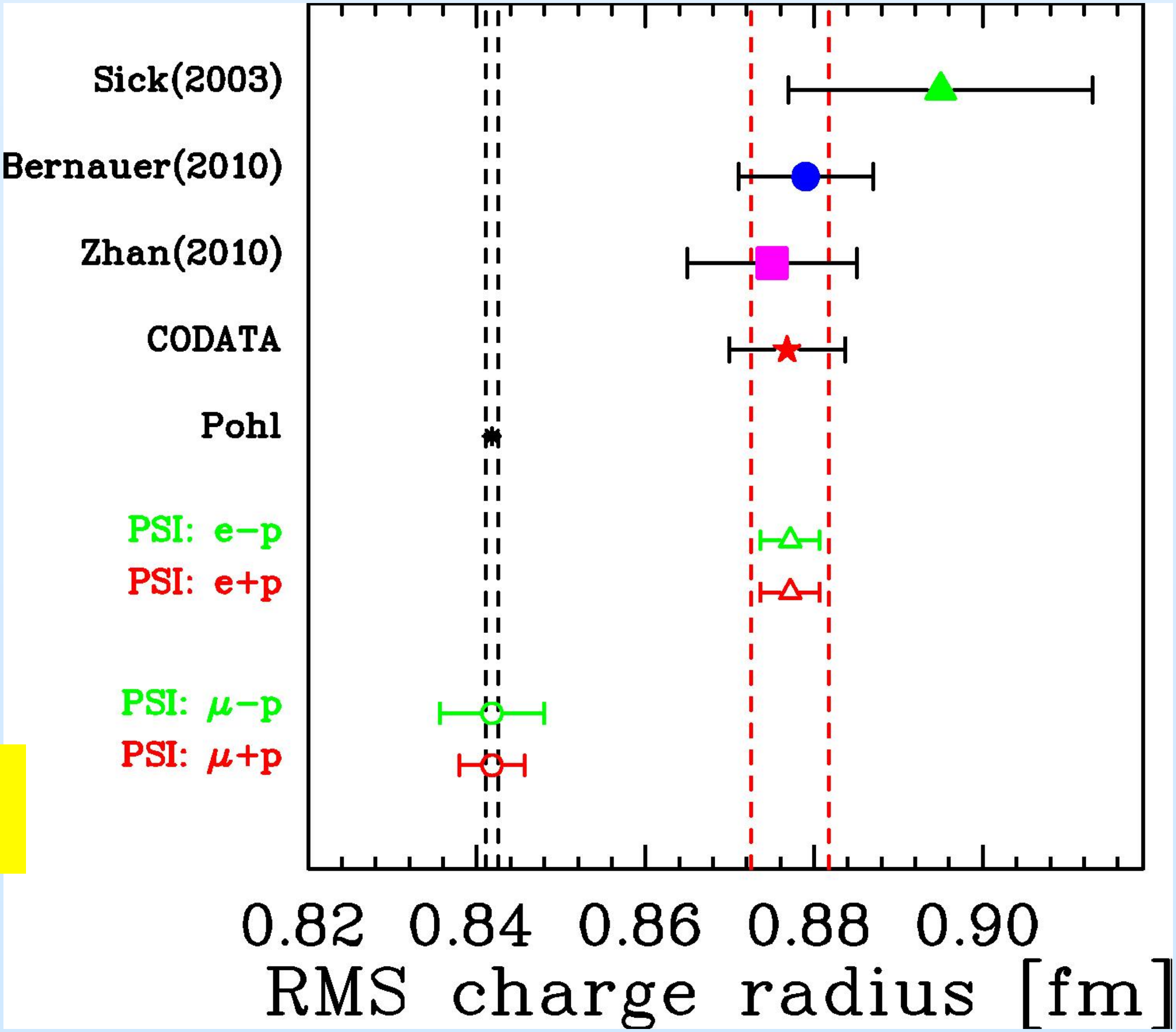
Projected sensitivity

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



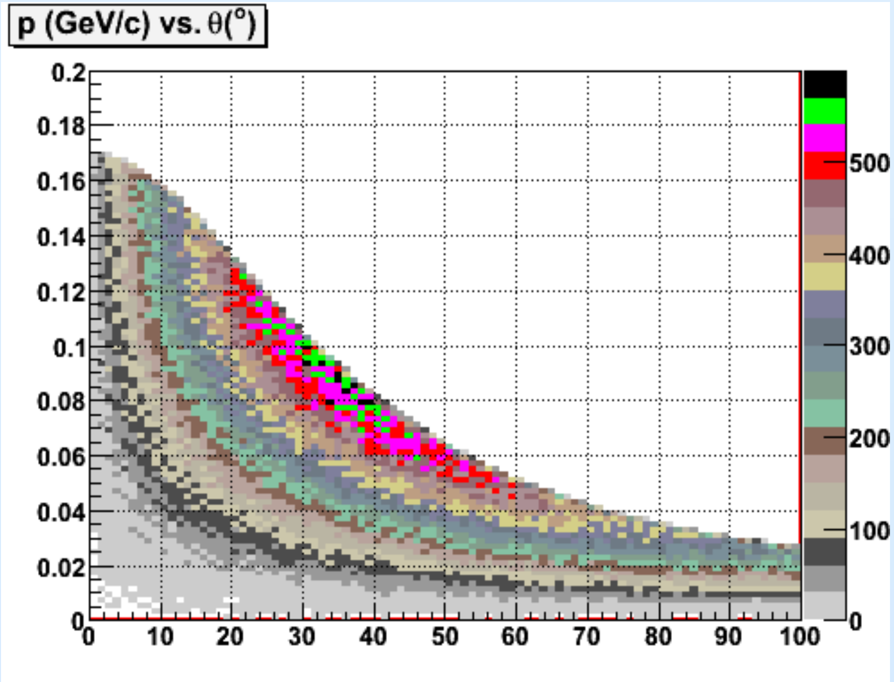
Summary

- **Proton Radius Puzzle** – a 7σ discrepancy between ep and muonic Lamb shift measurements
- **Still unresolved ~2 years later**
- **PSI Experiment**
  - Measure μp and ep scattering and compare directly
  - Measure e+/e- and μ+/μ- to study/constrain TPE effects
- **Technical Challenges** – particle ID, timing resolution, background rejection, momentum and flux determination
- **MUSE timeline**
  - Initial proposal February 2012
  - Technical Review July 2012
  - Engineering test run – Fall 2012
  - Production run 2014-2015 (6 months)

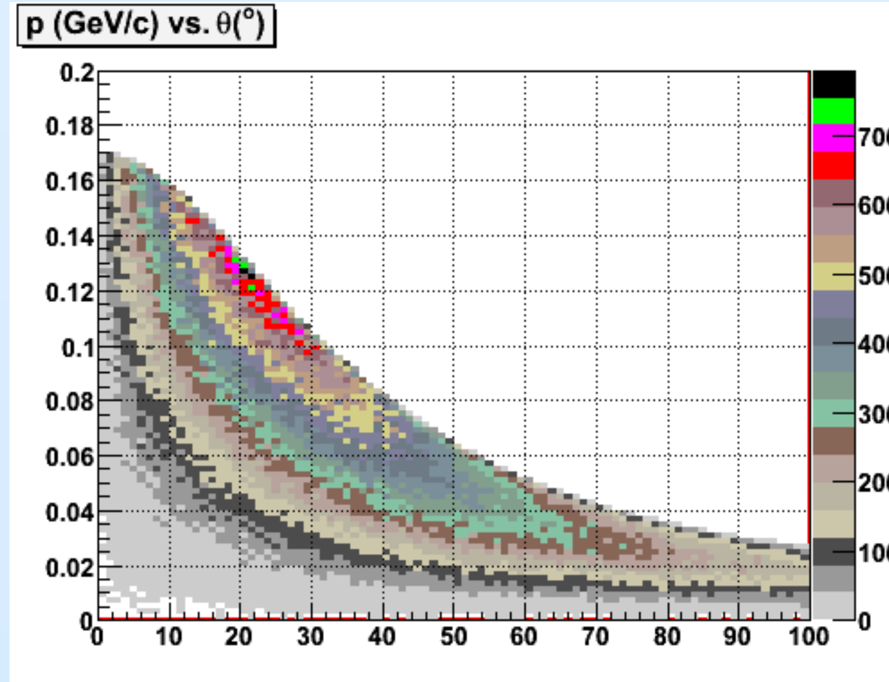
The nine muses

Backup slides

μ decay background



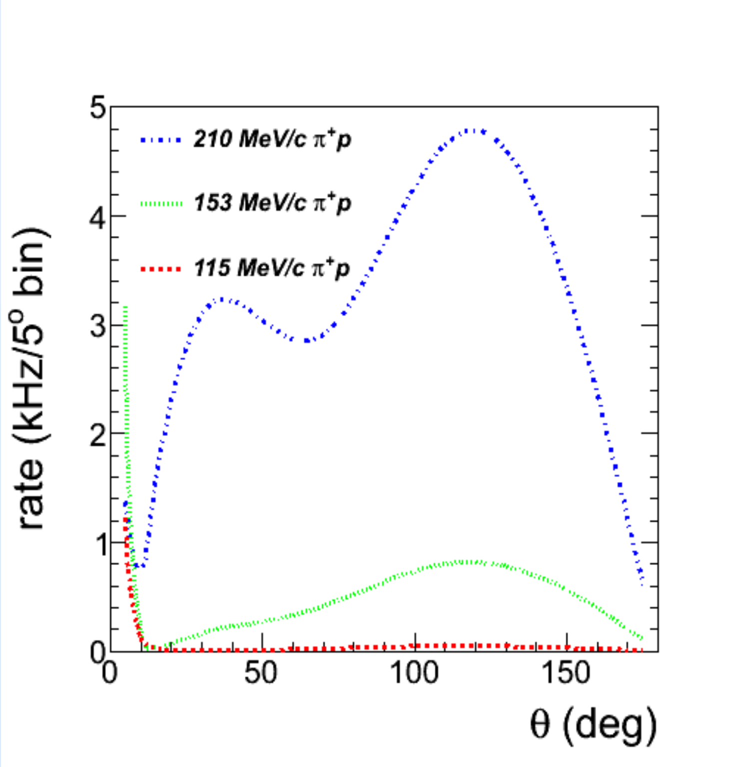
Distribution of electrons from 153 MeV/c μ decay.

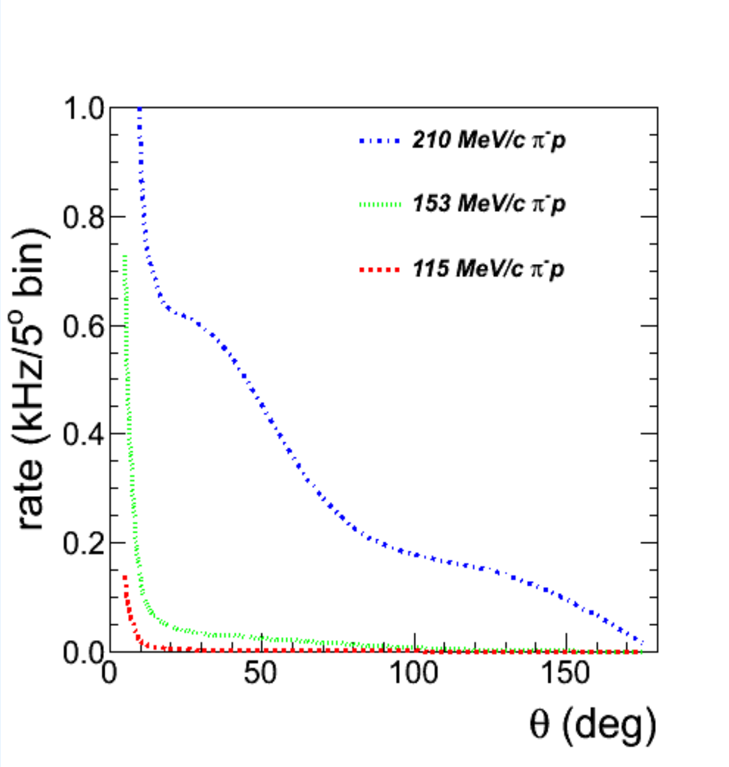


Distribution modified if μ polarized - here for S || p.

$\mu^+ \rightarrow e^+\nu_\mu\nu$ gives several kHz track rate and ≈400 Hz e^+ background trigger rate. Rejected at analysis level by requiring tracks from the target, and μ RF time from the detector - the decay electrons will be ≈ 0.8 ns faster than μ scattering events. Rate can be directly measured with empty target.

Hadronic scattering of π





πp scattering rates calculated with cross sections from SAID and expected luminosities, assuming 2π azimuthal acceptance. Up to a few tens of kHz chamber rates, plus a DAQ rate issue for some kinematics, if not suppressed at the trigger level.