Technical Design Review
Studying the Proton "Radius" Puzzle with μp Elastic Scattering
Overview / Introduction

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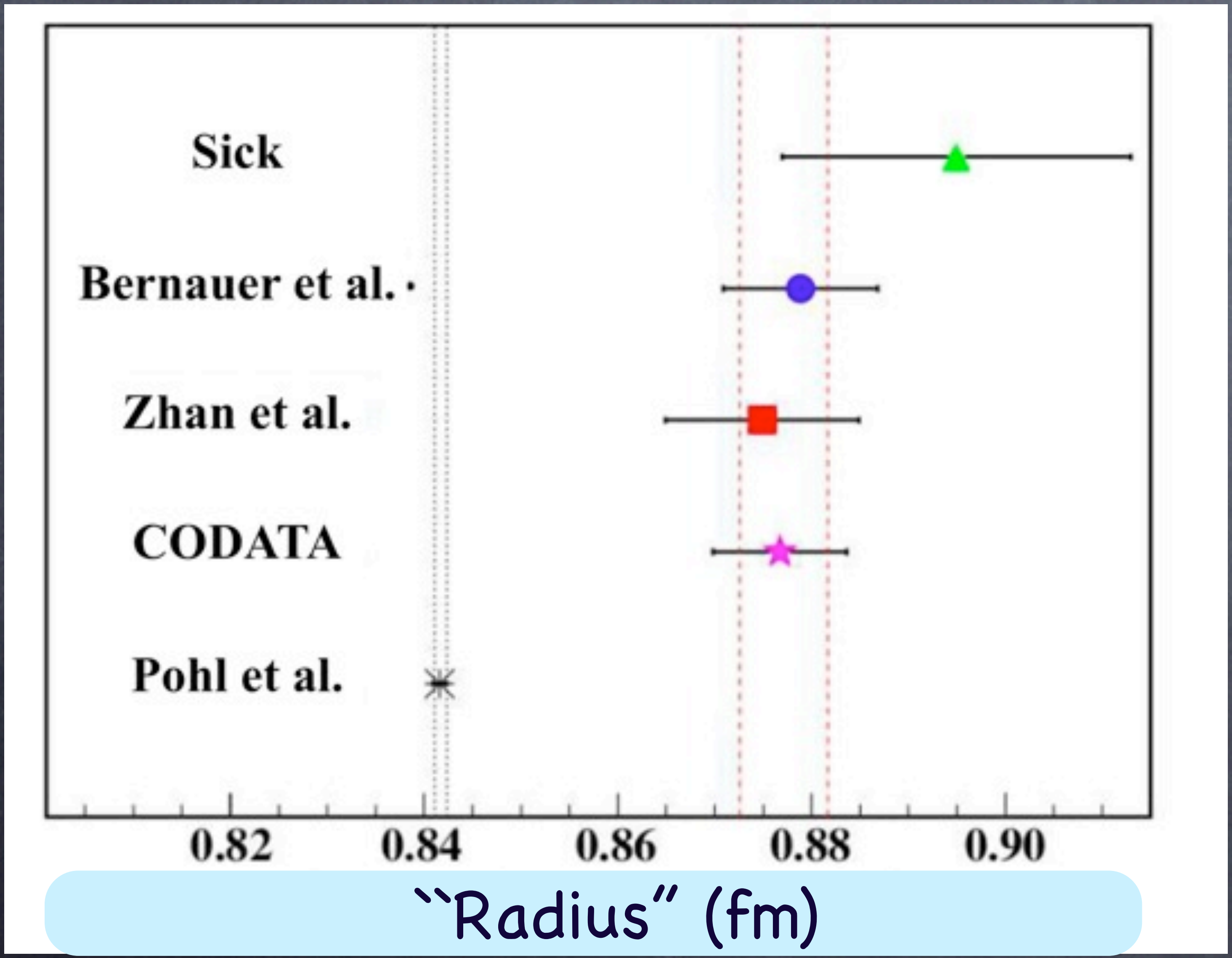
MUon proton Scattering Experiment (MUSE) Collaboration

The Proton "Radius" Puzzle

Muonic hydrogen disagrees with ep atomic physics and scattering determinations of the slope of FF at $Q^2 = 0$. The difference (#5 vs #6) is 7σ. This is a high-profile issue - Nature paper, APS plenary & many invited talks, PSAS2012 Symposium, Trento ECT* Workshop Nov 2012

What could explain the difference?



#	Extraction	$(\langle r_E \rangle^2)^{1/2}$ (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

Possible Resolutions to the Puzzle

- Novel beyond-Standard-Model Physics differentiates μ and e.
- Novel (but conventional) 2γ exchange differentiates μ and e.
- Proton EM structure not as generally believed.
- Corrections in ep scattering are wrong (bad data).
- Radius extractions in ep scattering are wrong (bad fits).
- Uncertainties in ep estimates are too optimistic.

After two years of study, the initial 5σ difference became 7σ with new ep scattering results, and the difference and lack of an explanation are more puzzling then before.

This proposal: μp Scattering at PSI

- Directly test the most interesting possibility, that μp and ep scattering are different:
- to higher precision, at low Q^2 region (same as Mainz and JLab) for sensitivity to radius
- with $\mu^\pm$ to study possible 2γ mechanisms, but with improved sensitivity from low energy and large angle
- measuring both $\mu^\pm p$ and $e^\pm p$ to have direct comparison and a robust, convincing result.
- Depending on the results, 2nd generation experiments (lower Q^2, $\mu^\pm n$, higher Q^2, polarized, light nuclei...) might be desirable or unneeded.

Our Approach in PSI R12-01.1

$(\langle r_E \rangle^2)^{1/2}$ (fm)	ep	μp
atom	0.877±0.007	0.842±0.001
scattering	0.875±0.006	?

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

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

$$d = \frac{\left[1-\frac{m^2}{E^2}\right]^{1/2}}{\left[1-\frac{m^2}{E'^2}\right]^{1/2}}$$

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

Normally given in the limit m/M→0, m/E→0, so d→1, η→ $\sin^2\theta/2$.
Thanks to Miller & Borie for pointing this out, and Carlson&Gross for pointing out Preedom and Tegen, PRC36.

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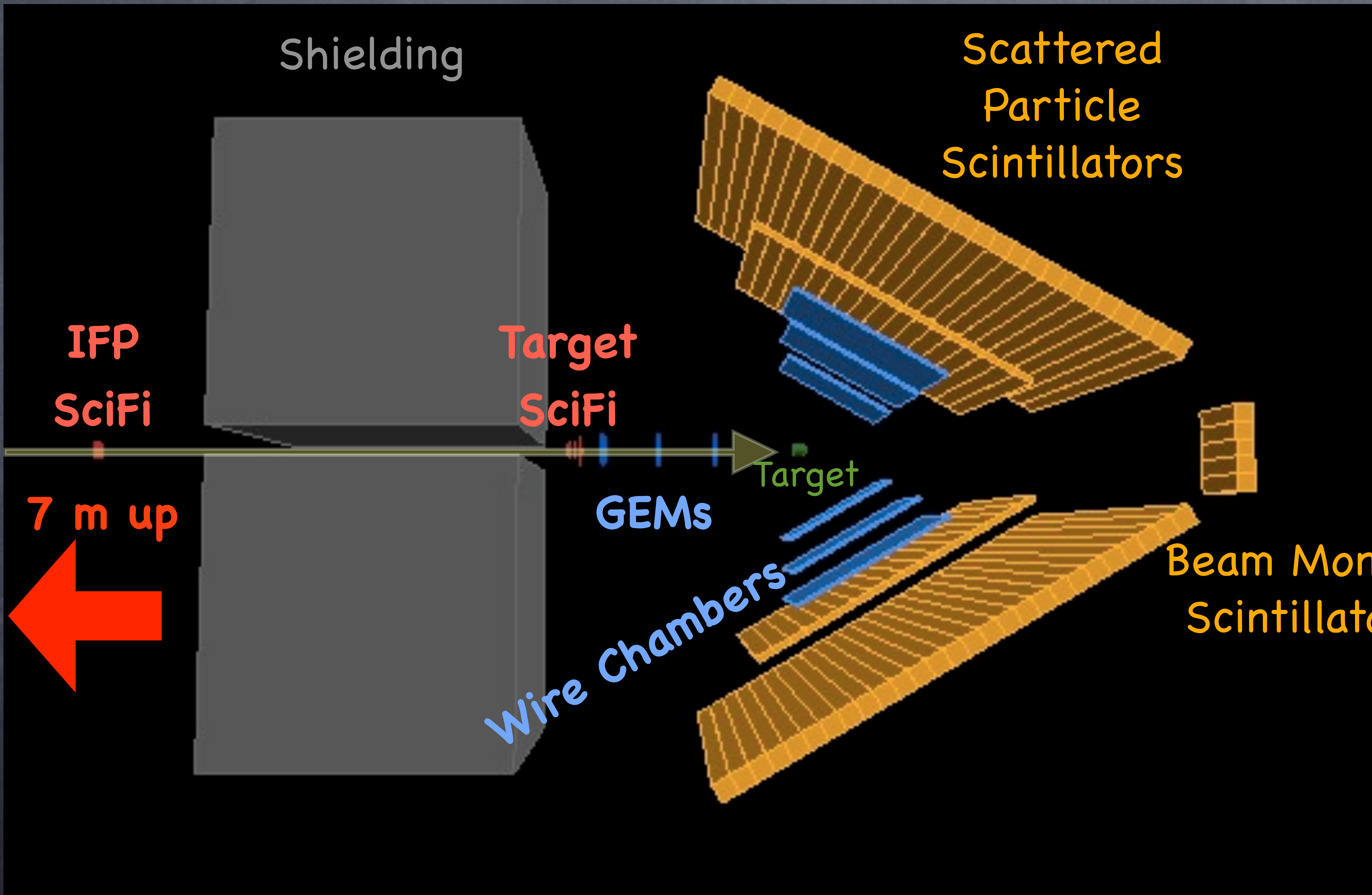
$$\eta = Q^2/4EE'$$

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

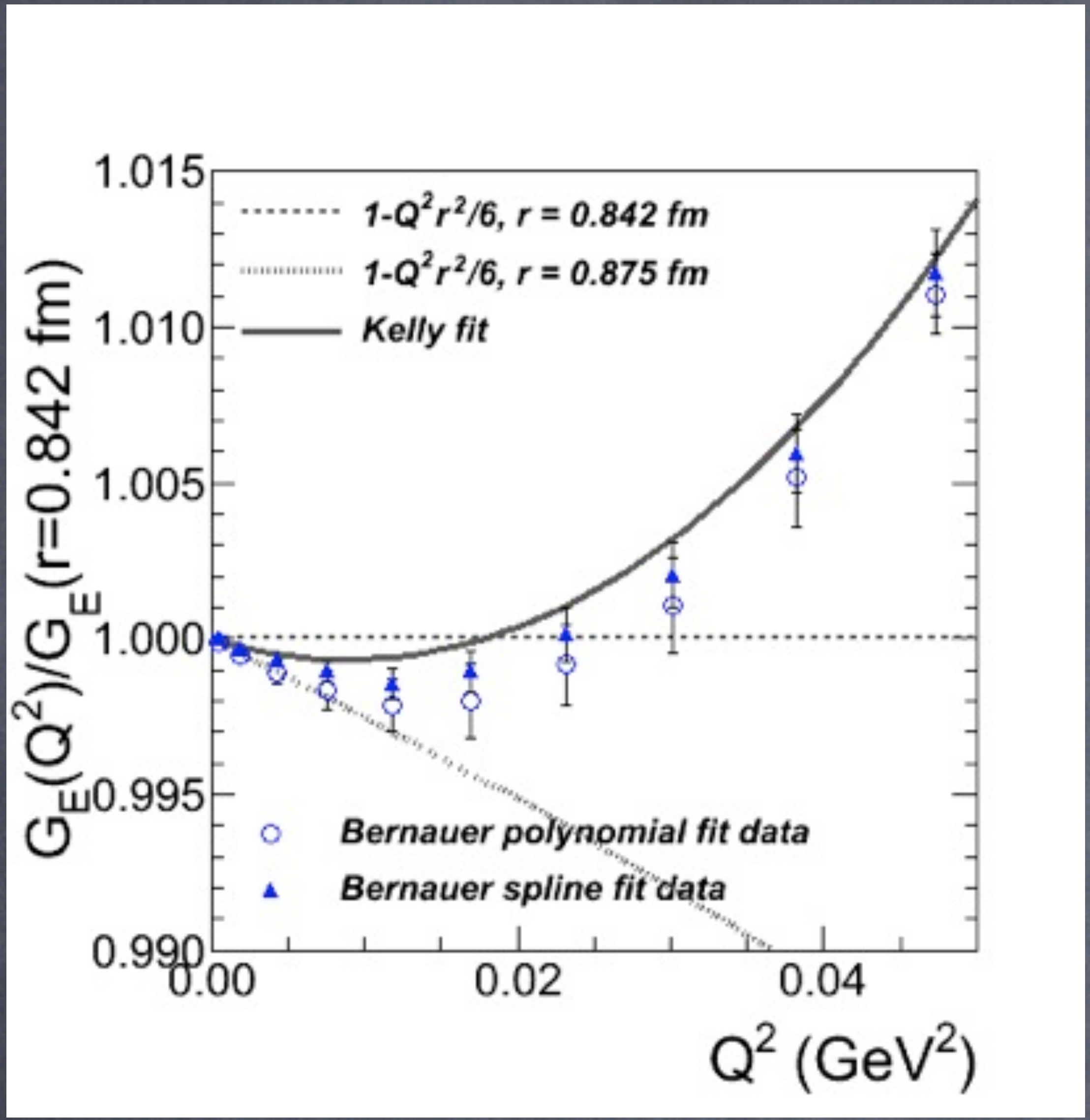
Overview - Geant4 Cartoon



Detectors

Component	Purpose
Shielding	Remove halo, lower decay particle rate in detectors
IFP SciFi	Particle ID (μ vs e vs π) and momentum
Target SciFi	Particle ID and triggering GEM track
GEMs	Trajectory into target
Wire Chambers	Scattered trajectory, define solid angle
Scintillators	Triggering (w/ SciFis), RF time, dE/dx

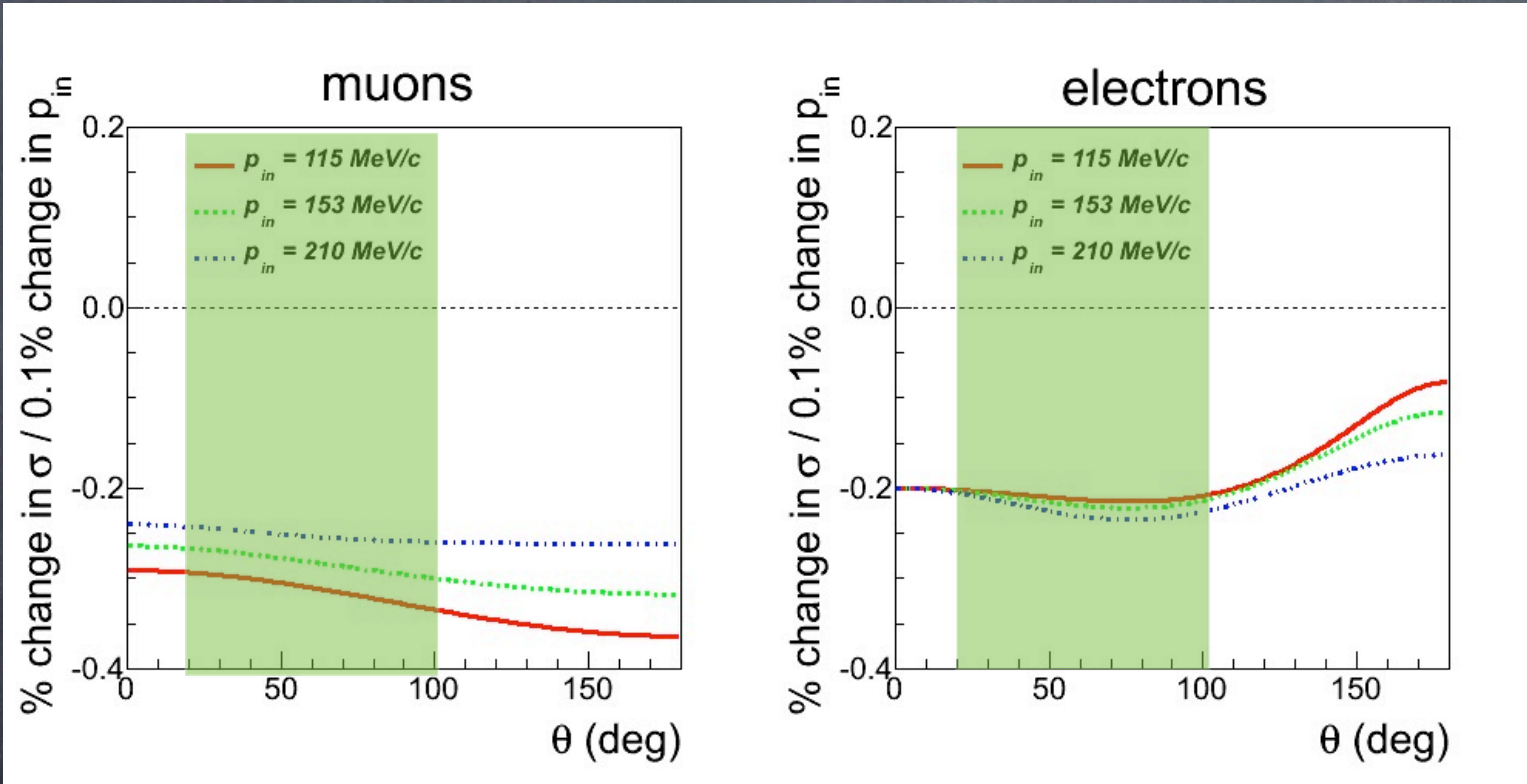
Precision of Data Needed



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

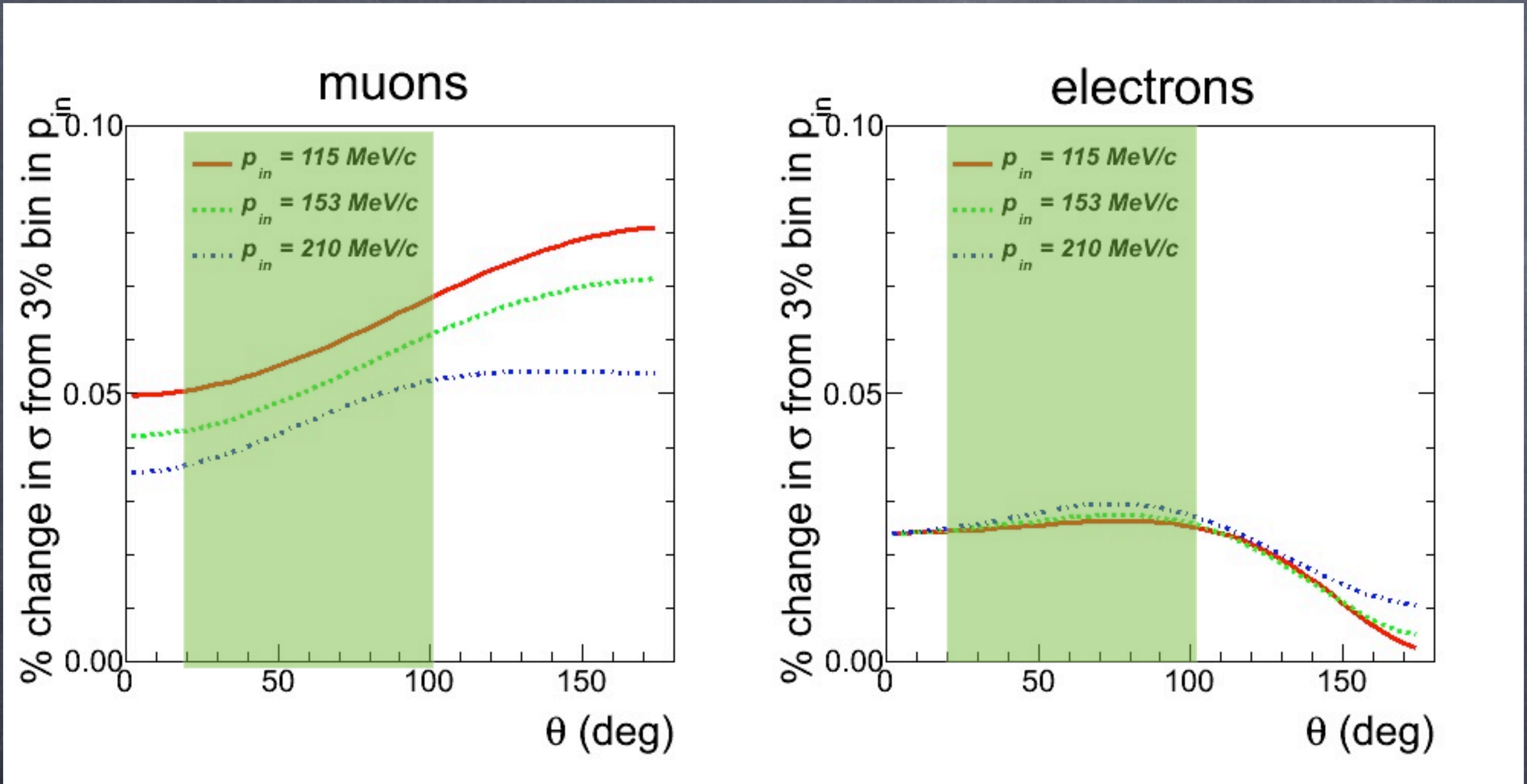
- At first glance, a 4% radius difference leads to a huge cross section differences, easy to measure...
- But higher order terms quickly add curvature, so sub-1% uncertainties are needed, similar to Mainz

Systematics: Effect of Beam Momentum Offset



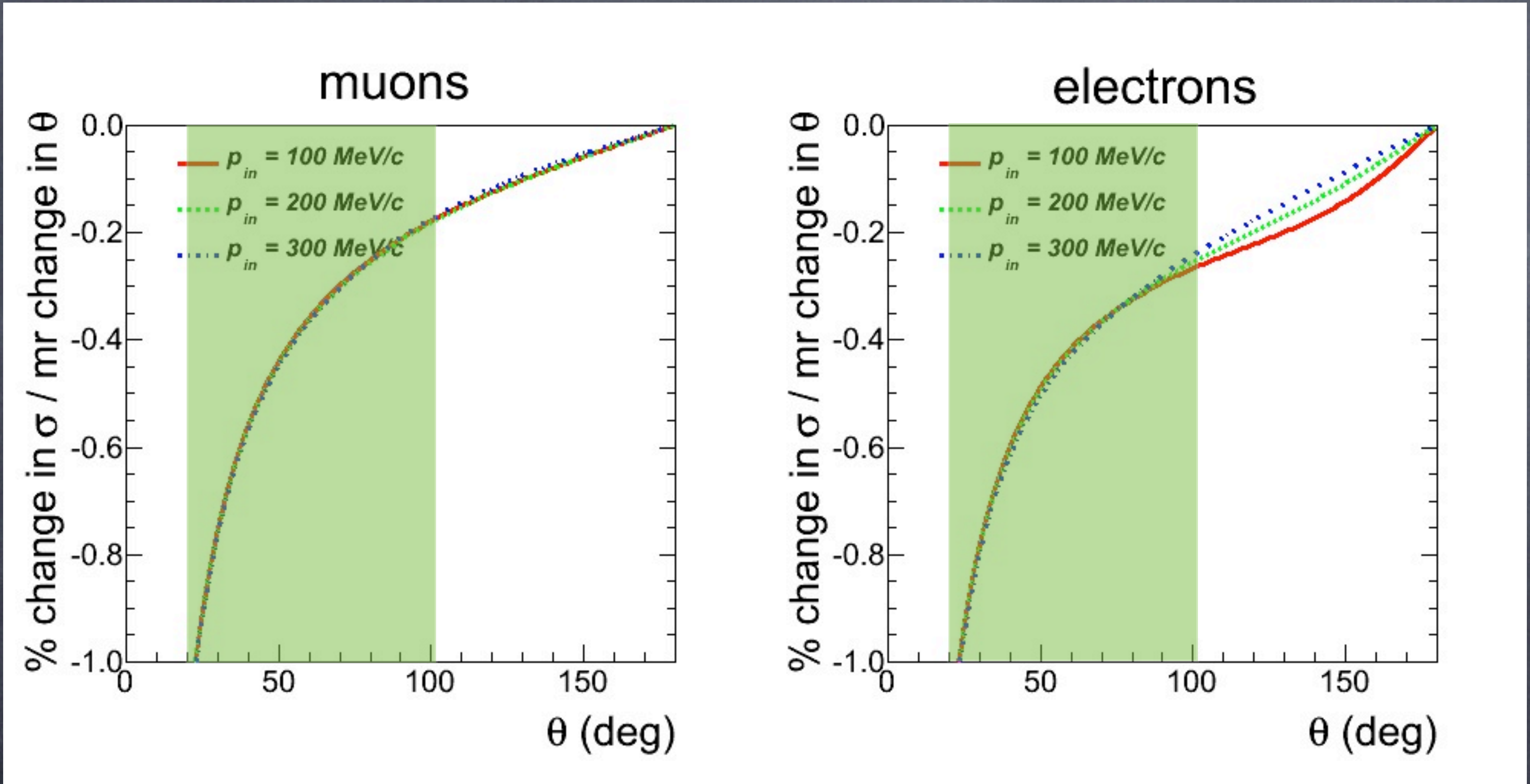
Beam momentum offsets are nearly angle independent, and to << 0.1% act like normalization offsets. The offset comes from the channel and energy loss in materials before scattering.

Systematics: Effect of Momentum Averaging



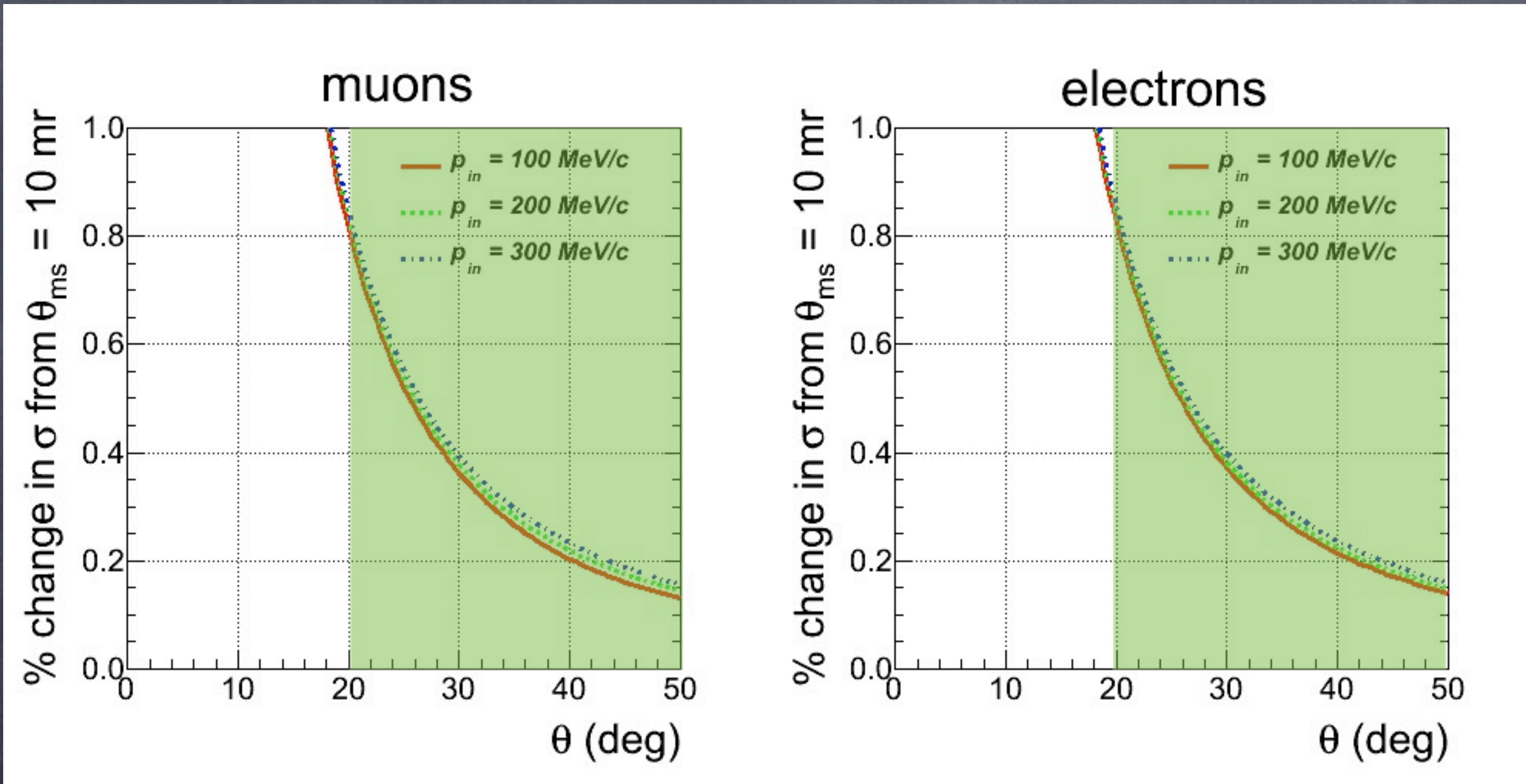
Shown is $d\sigma/d\Omega_{average}$ vs. $d\sigma/d\Omega_{central\text{-}momentum}$, assuming a uniform distribution in momentum. The effects are very small and nearly angle independent. Not getting the right mean momentum for the averaging will act largely like a normalization error.

Systematics: Effect of Angle Offset



Angle offset effect is nearly energy independent. Plan to determine central angle to ±0.5 mr. Correlations between overall normalization and angle offsets will make it difficult to ``fit out'' much better.

Systematics: Effect of Multiple Scattering

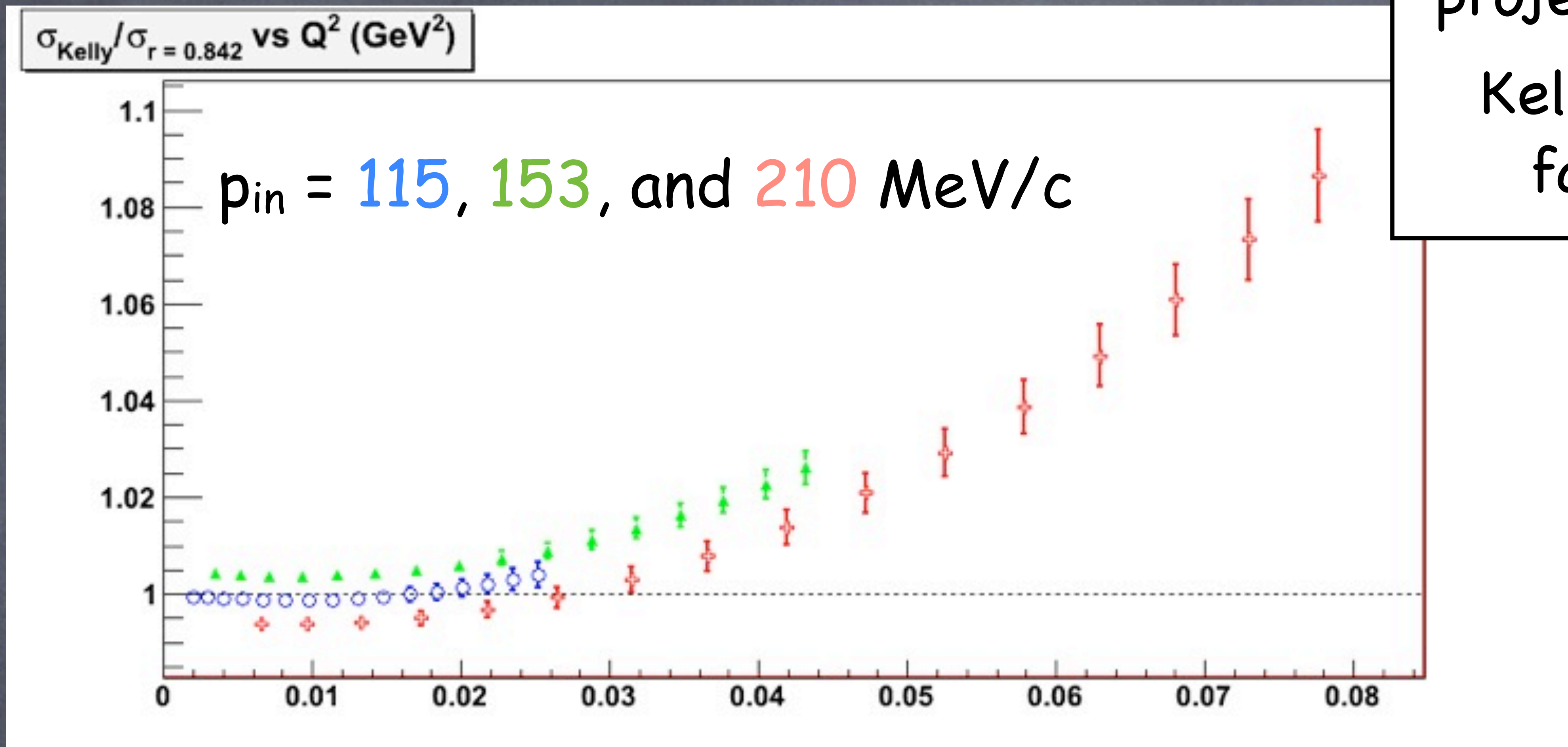


Multiple scattering effects are nearly energy independent. The multiple scattering can be reasonably well determined and corrections can be applied. Estimated M.S. is ≈7-14 mr.

Systematics: Summary

- Momentum offsets and averaging act like overall normalization uncertainties, and are likely of size ≈ 0.1% - 0.2%.
- Multiple scattering is 0.3% - 0.5% at 30°, has a nearly energy independent shape; corrections look feasible.
- Angles offsets warp the angular distribution shape in similar ways at all energies. The typical uncertainty is about 0.4%.
- All effects are quite similar for e's and μ's. There will be some differences since the beam distributions are not the same and since multiple scattering is larger for μ's, while dE/dx is larger for e's. But to a large degree these systematics cancel in a comparison of e's to μ's.

Estimated Statistics



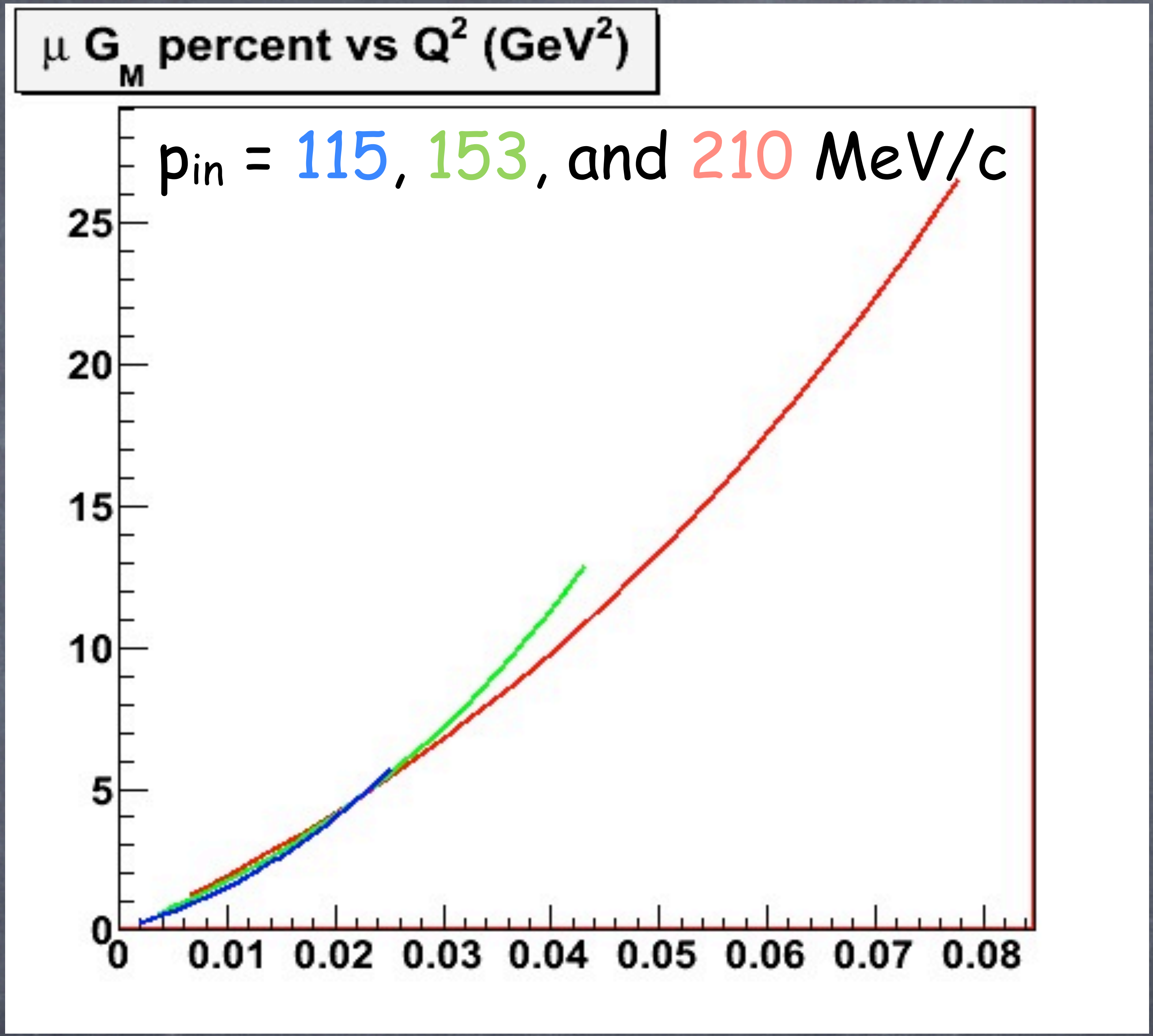
projected μ^+p Kelly form factors

- πM1 channel.
- Different momenta offset for clarity.
- Choose $\theta_{scatter}$ = 20 - 100°: rates, backgrounds, systematics.

Systematic Uncertainties

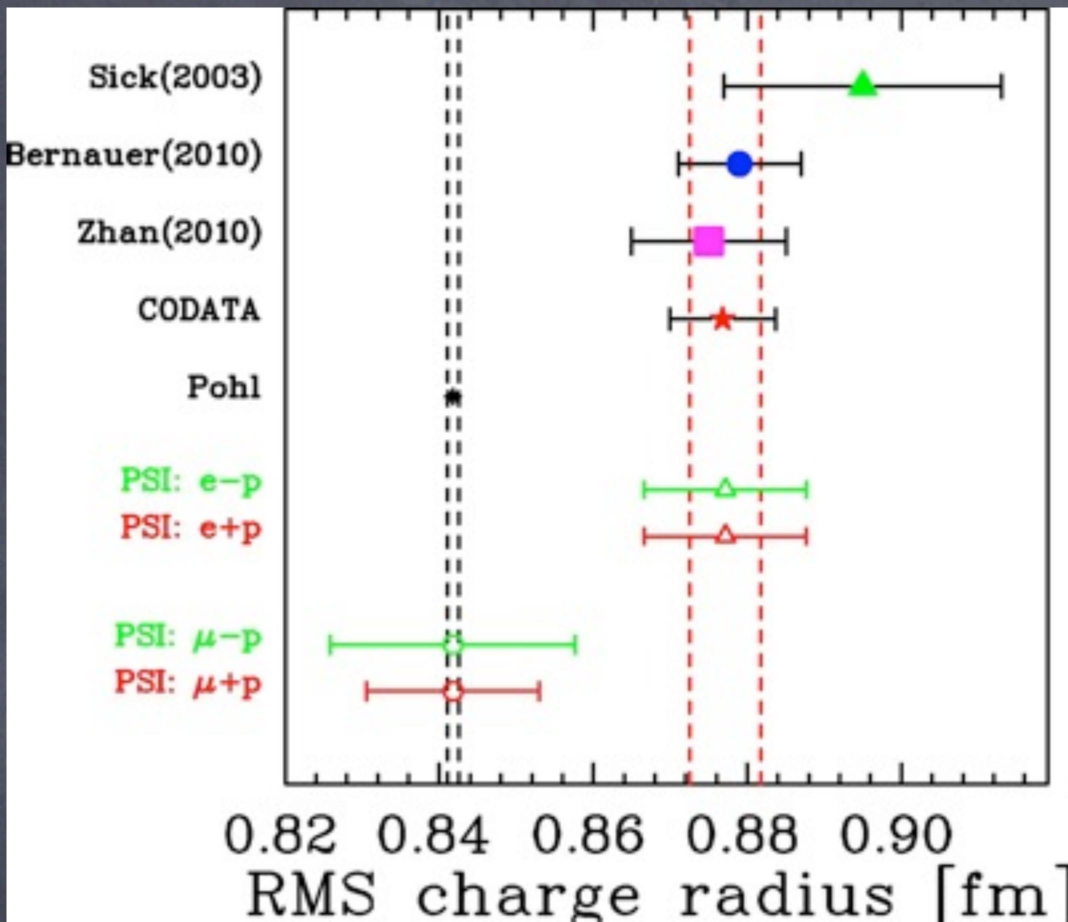
Systematic	Relative (%)	Absolute (%)
beam flux	0.1	0.1
GEM efficiency	0.1	0.1
target thickness	0.1	1.0
scintillator efficiency	0.1	0.1
wire chamber efficiency	0.1	0.2
angle determination	0.3	0.5 (max)
multiple scattering	0.3	0.5
solid angle	0.1	0.1
radiative corrections	0.5	0.5
TOTAL	0.7	1.4

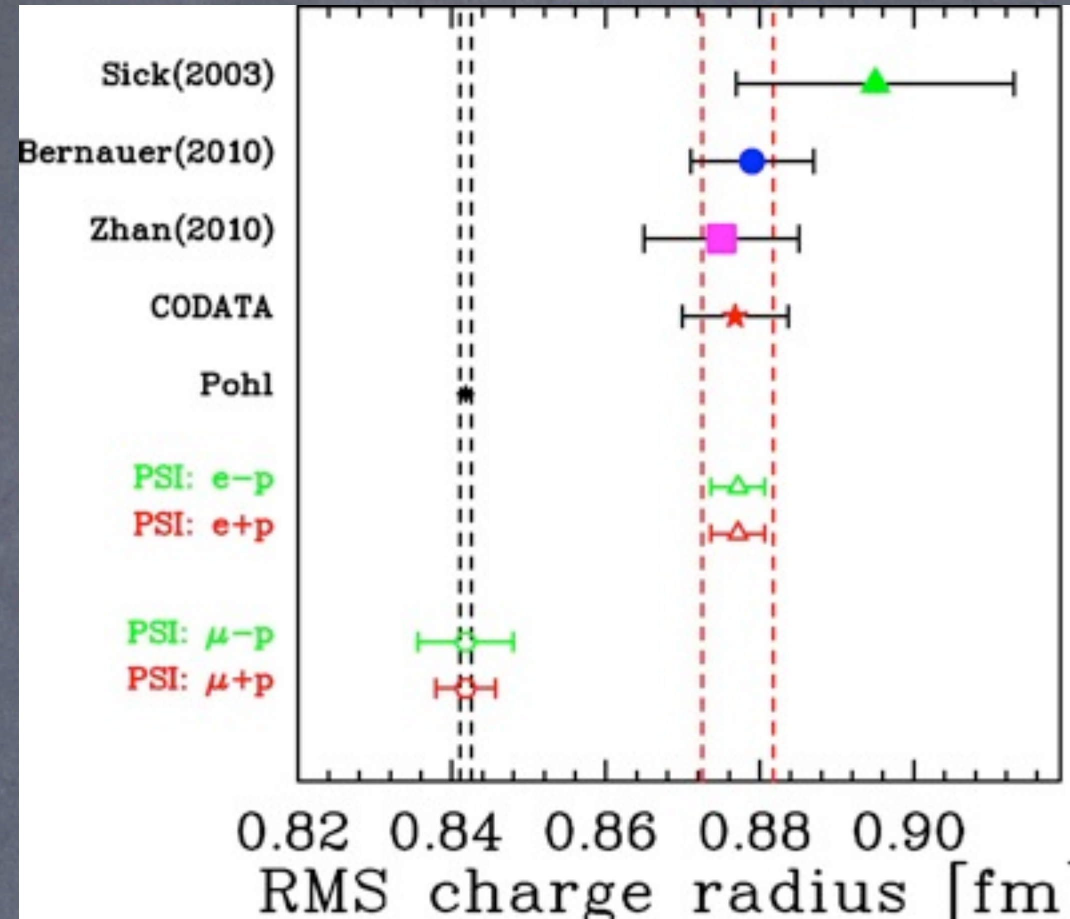
Magnetic Form Factor Correction



- G_E^p/G_M^p probably known to 1-2% in this region, directly measured to ≈2% at JLab, data under analysis.
- ➪ correction uncertainty ranges from negligible to ≈0.25%-0.5% at highest Q^2

Expected Results





- Left: **absolute** uncertainties considered in generating radius uncertainty.
- Right: only **relative** uncertainties consider in generating radius uncertainty.
- Should measure $r_{ep} - r_{\mu p} = 0.0$ vs. 0.034 to ≈ ±0.0045

Summary of Equipment

Beam SciFi	Tel Aviv	300 k*
Beam GEMs	Hampton, UVa	existing#
Target	Rutgers / St. Mary's	300 k#
Wire Chambers	MIT	450 k*
Scintillators	So Carolina	240 k*
Beam PID, Trigger	Rutgers	130 k*

* includes labor #no added labor needed

For electronics, see G Ron's talk.

Time Line

Feb 2012	Physics Approval, Proposal Deferral
July 2012	PAC/PSI Technical Review
Fall 2012	Funding proposals to agencies*
Fall 2012	test measurement in πM1 beamline
spring 2013	finalize designs
summer 2013	money arrives - start construction
fall 2014	start assembling equipment at PSI
late 2014 / early 2015	experiment ready to run
2015	6 month experiment run

* Hebrew U: ERC starting grant for DAQ and 2nd generation experiment
* St. Mary's: Canadian funding
* GW, Rutgers and So. Carolina: NSF MRI
* MIT: DOE

Agenda

Topic	Speaker	Institution
Beam line	RG for DR	PSI
Backgrounds & Shielding	Katherine Myers	Rutgers U
Beam SciFi	Eli Piasetzky	Tel Aviv U
GEMs	Michael Kohl	Hampton U
Target	Ron Gilman	Rutgers U
Wire Chambers	Vince Sulkosky	MIT
Scintillators	Steffen Strauch	U South Carolina
Trigger	Ron Gilman	Rutgers U
Electronics, DAQ	Guy Ron	Hebrew U
Radiative Corrections	Andrei Afanasev	GW
Analysis, Fits, and Radius	John Arrington	Argonne