Muon Scattering Experiments: COMPASS and MUSE

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Physics with muons beyond g-2 and mu2e

3 May 2016

I. COMPASS—DIS at CERN

Disclaimer: I am ***not*** a member of COMPASS

Thanks to Fabienne Kunne of CEA /IRFU Saclay, France & COMPASS

And to Eva-Maria Kabuss of Institut fuer Kernphysik Universitat Mainz & COMPASS

II. MUSE elastic scattering at PSI (the other Swiss lab)

Disclaimer: I am part of MUSE

Thanks to Ron Gilman of Rutgers & MUSE

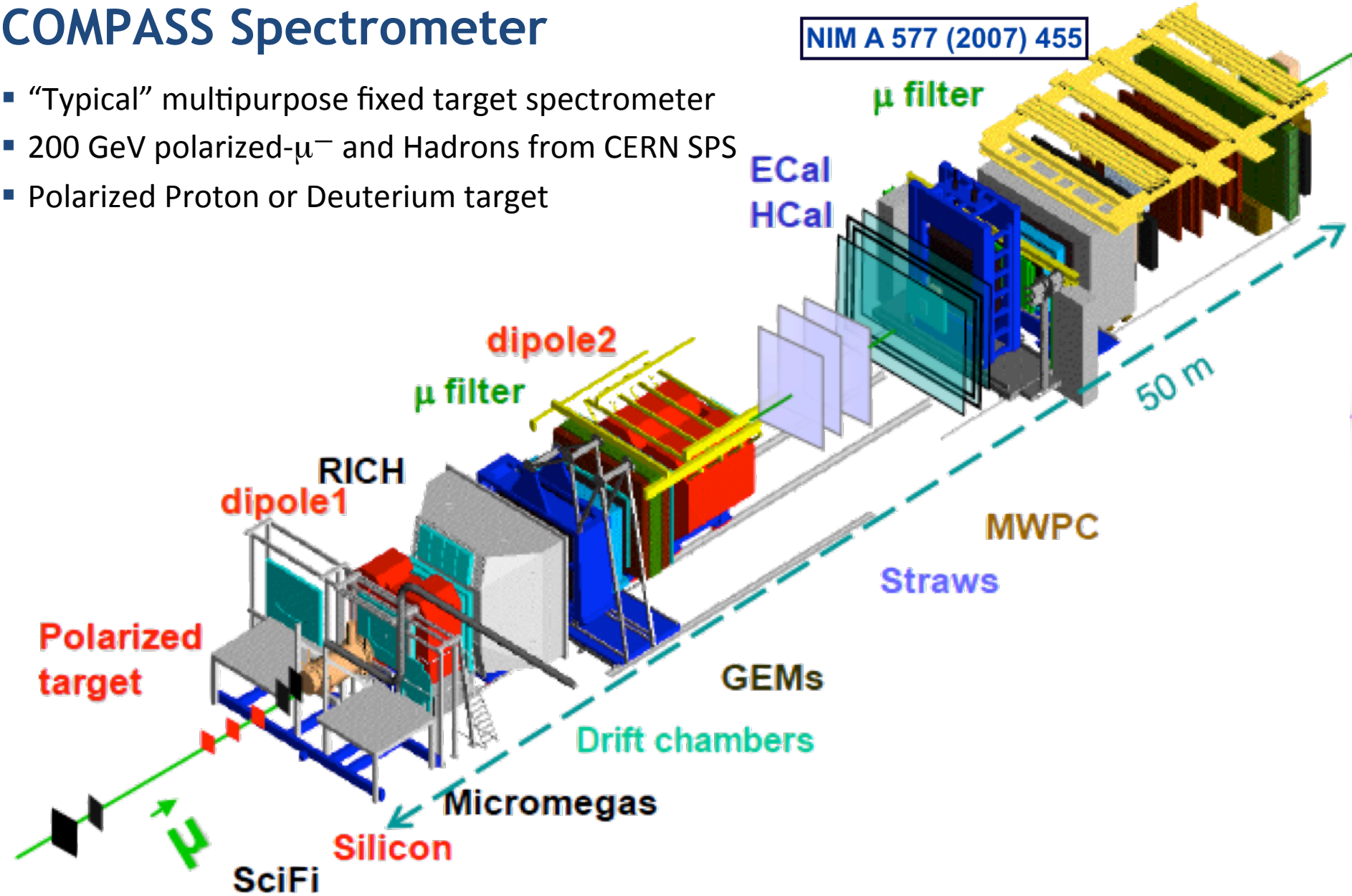
Why use Muons?

This work was partially supported under grant DE-AC02-06CH11357
from the US Department of Energy, Office of Nuclear Physics

COMPASS Spectrometer

NIM A 577 (2007) 455

- "Typical" multipurpose fixed target spectrometer
- 200 GeV polarized-μ^- and Hadrons from CERN SPS
- Polarized Proton or Deuterium target



COMPASS Spectrometer

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- "Typical" multipurpose fixed target spectrometer
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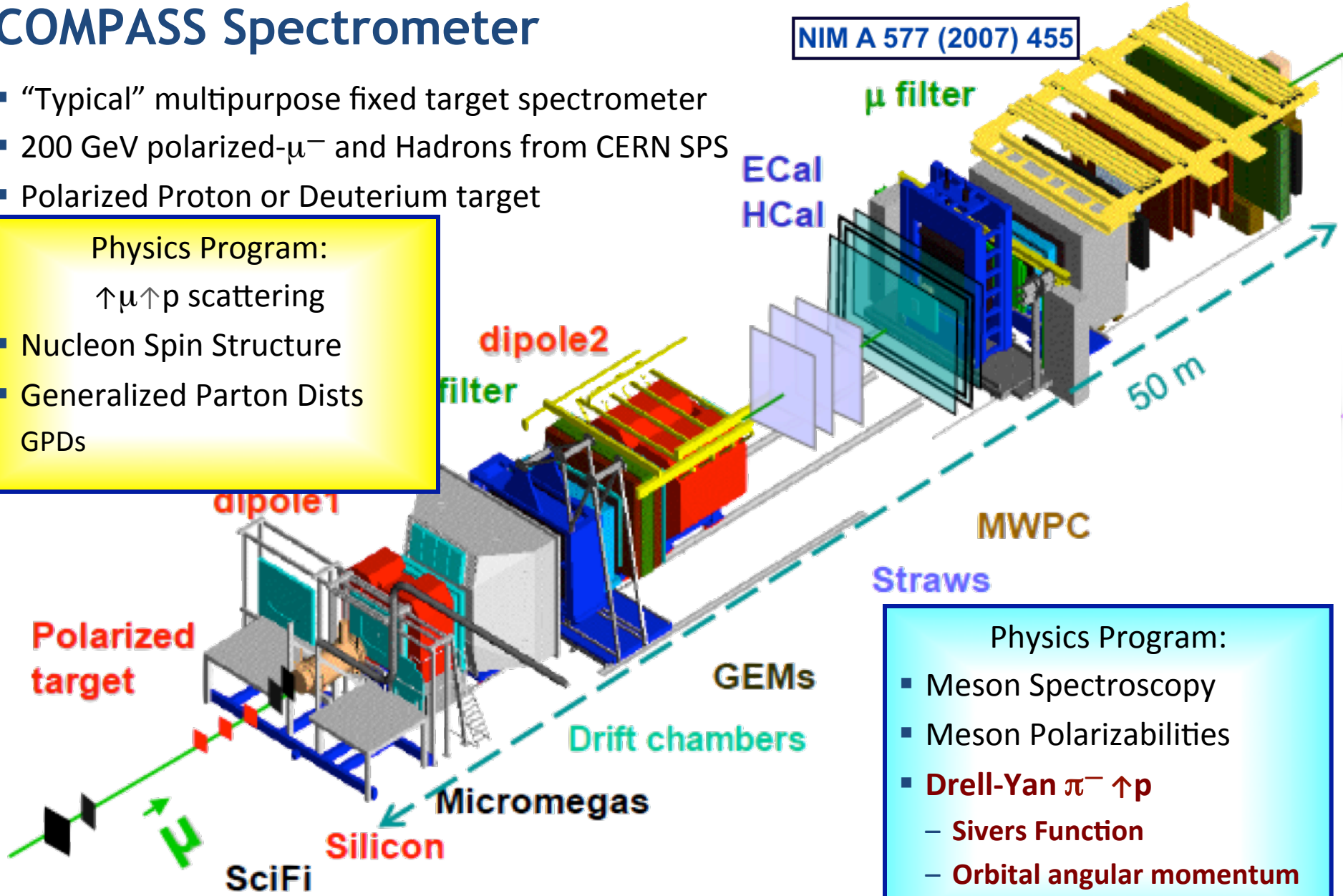
Physics Program:

$\uparrow\mu\uparrow p$ scattering

- Nucleon Spin Structure
- Generalized Parton Dists

GPDs



Physics Program:

- Meson Spectroscopy
- Meson Polarizabilities
- **Drell-Yan $\pi^- \uparrow p$**
  - **Sivers Function**
  - **Orbital angular momentum**
  - **QCD Gauge Formalism**

Transvers Parton Distributions

nucleon polarisation

quark polarisation	U	L	T
U	f_1  number density q		
L		g_1  helicity Δq	
T			h_1  transversity $\Delta_T q$

Where is the proton spin?

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_z$$

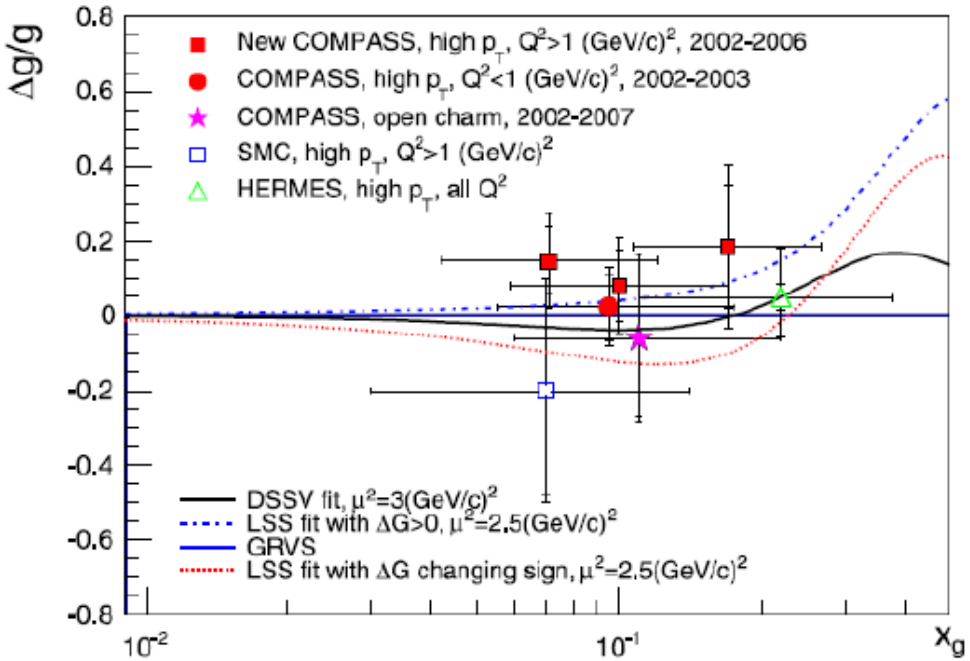
small

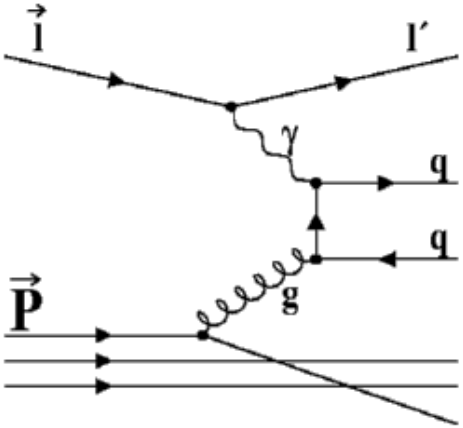
smallish, sign?

unknown, quark & gluon

in infinite-momentum frame

$\Delta g/g$ from PGF (LO)





- $Q^2 > 1$ GeV^2
- $Q^2 < 1$ GeV^2
- open charm (D mesons)

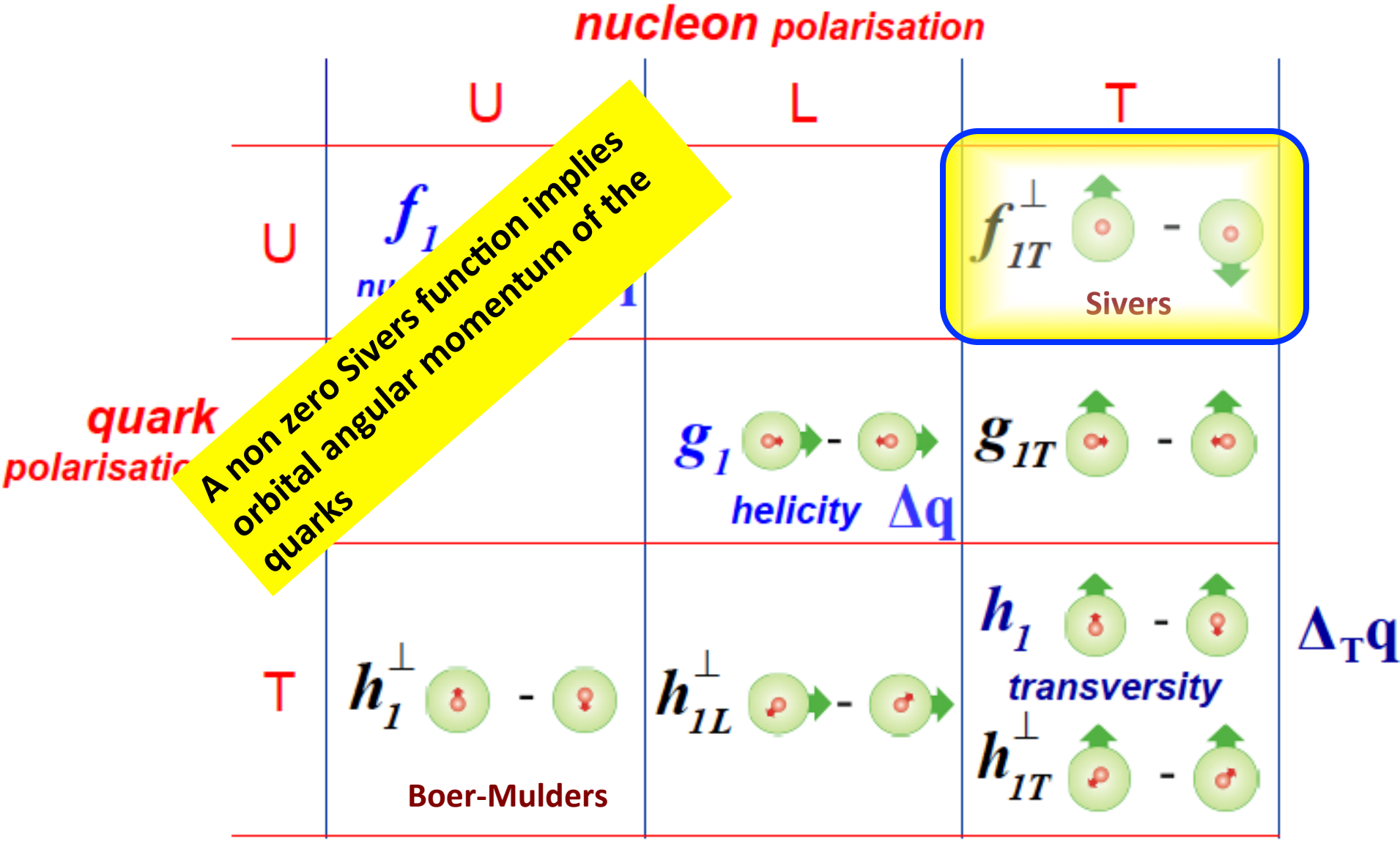
- gluon polarisation is much smaller than thought in the 1990s by many theorists (around $2\hbar$ [even up to $6\hbar$], axial anomaly); various methods
- confirmed by polarised *pp* at RHIC
- Δg still can make a substantial contribution to nucleon spin

Transvers Parton Distributions

nucleon polarisation

quark polarisation	U	L	T
U	f_1 number density q		$f_{1T}^{\perp}$ - Sivers
L		g_1 - helicity Δq	g_{1T} -
T	$h_1^{\perp}$ - Boer-Mulders	$h_{1L}^{\perp}$ -	h_1 - transversity $\Delta_T q$ $h_{1T}^{\perp}$ -

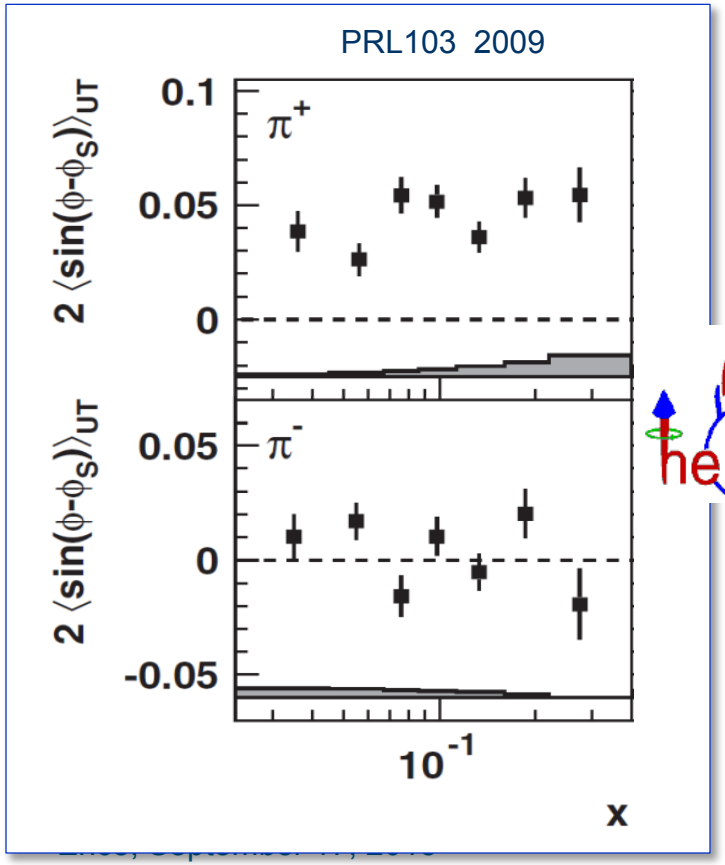
Transvers Parton Distributions

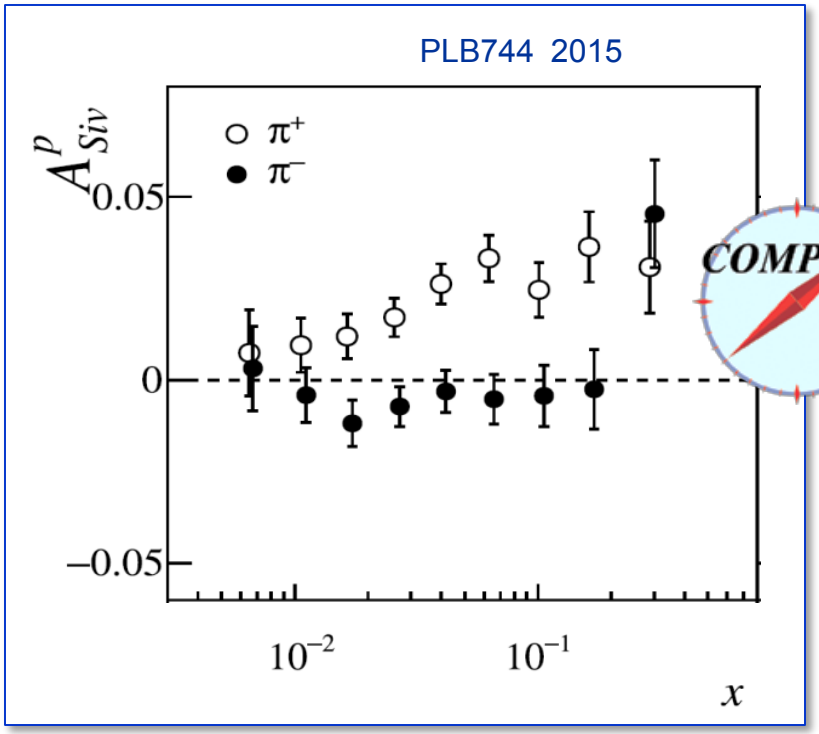


Sivers asymmetry $\sim f_{1T}^{\perp} \otimes D_1$

2004: first evidence for non-zero values on proton
compatible with zero on deuteron

final results on proton $z > 0.2$





Sivers function

from COMPASS and HERMES SIDIS data

it is clearly different from zero – *in spite it is T-odd*

final state interactions, gauge link

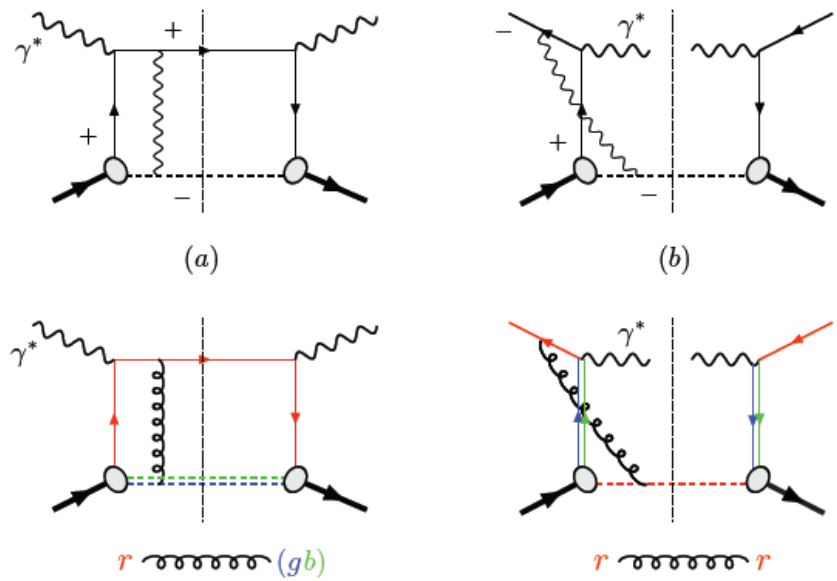
PER Note:

- Both COMPASS and SeaQuest will be measuring polarized Drell-Yan for valence and sea quarks (respectively) in the near future.
- Completely complementary experiments

process-dependence of Sivers functions

DIS: "attractive"

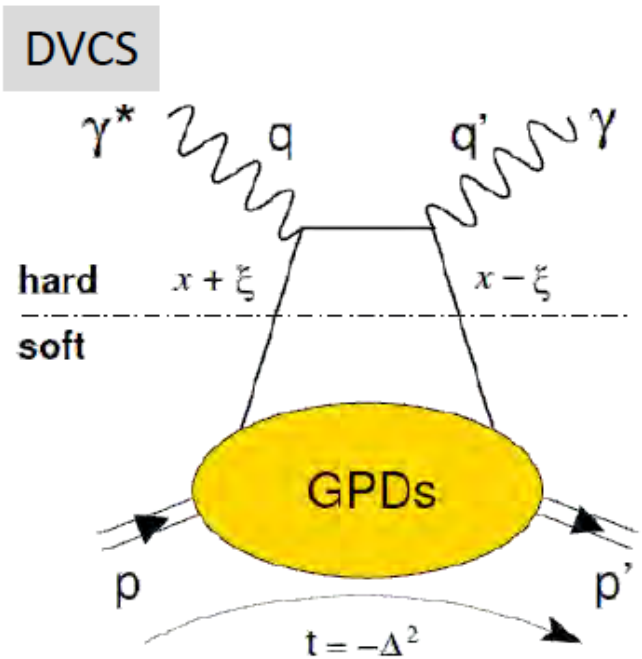
D-Y: "repulsive"



$$[f_{1T}^{q\perp}]_{\rm SIDIS} = -[f_{1T}^{q\perp}]_{\rm DY}$$

Generalized PDF's

- Correlating transverse spatial and longitudinal momentum degrees of freedom
- PDFs and elastic FF as limiting cases
- $H, \tilde{H} \to f_1, g_1$ for $\xi \to 0$;
- H (E) for nucleon helicity (non)conservation
- exclusive processes like DVCS, HEMP (vector & pseudoscalar)



$$H(x, \xi, t, Q^2); \quad Q^2 \text{ large, } t \text{ small}$$

$$H^f, E^f, \tilde{H}^f, \tilde{E}^f \text{ with } f = q, g$$

Total orbital momentum:

$$J^f(Q^2) = \frac{1}{2} \lim_{t \to 0} \int_{-1}^{1} dx\, x \quad \left[H^f(x, \xi, t, Q^2) + E^f(x, \xi, t, Q^2) \right]$$

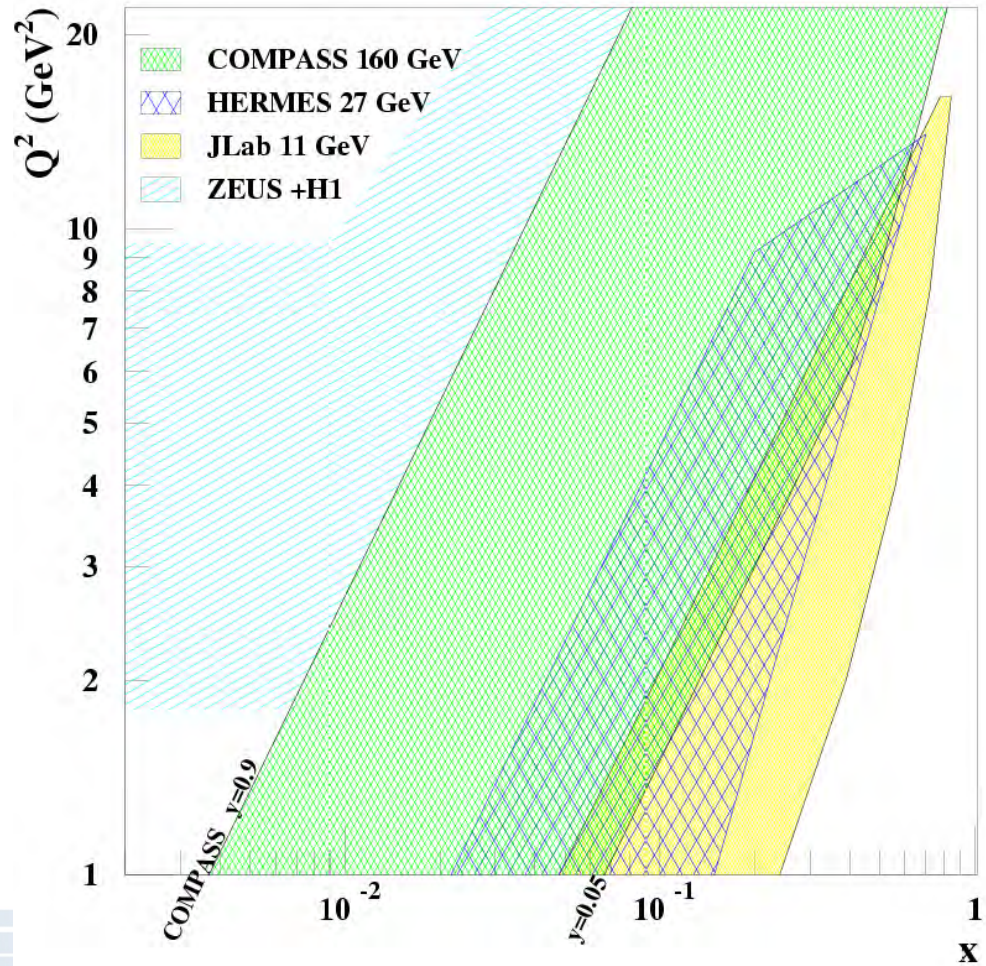
X.-D. Ji, PRL 78 (1997) 610

COMPASS Timeline—Future

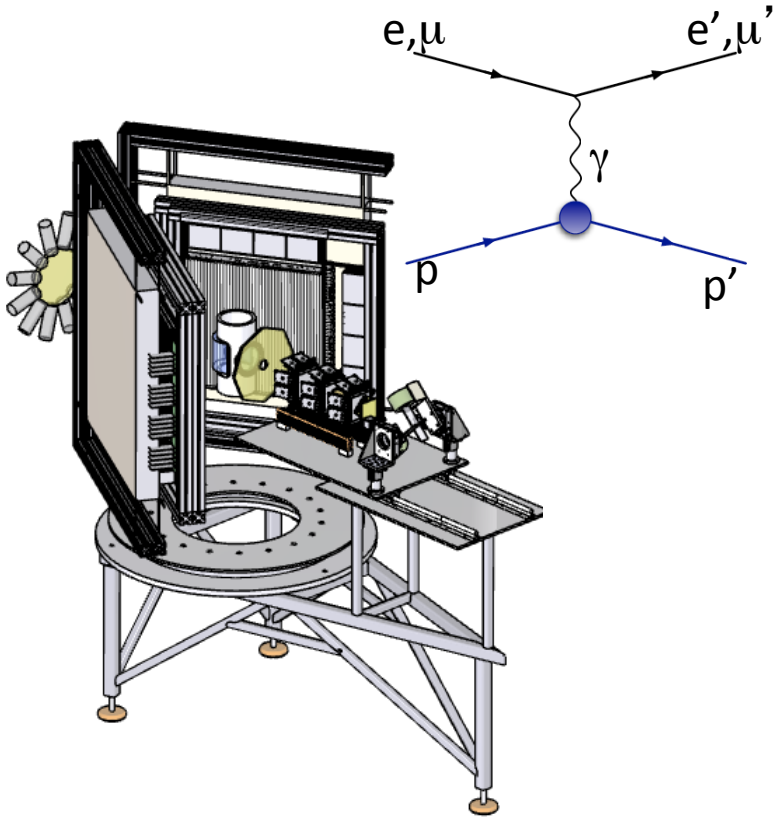
- 2015 & 2018 Polarized Drell-Yan: $\pi^- \uparrow p \rightarrow \mu^+\mu^- X$
  - Transverse Momentum Distributions
  - Sivers Function & Orbital angular momentum
  - QCD Gauge Formalism
- 2016 & 2017 Deep Virtual Compton Scattering: $\mu^- p \rightarrow \mu^- p \gamma$
  - Generalized Parton Distributions

Why Muons?

- Reach in High Q^2 and Low-x ⇒ High energy lepton beam
- Synchrotron radiation ⇒ Muon beam easier than electron beam
  - Down side is that this forces one to use a secondary pion beam that decays into muons



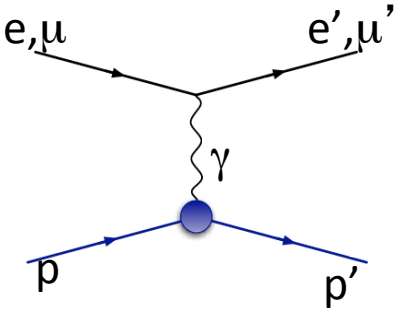
MuSE:
Muon Proton Scattering Expeirment



MuSE: Muon Proton Scattering Expeirment

The proton charge radius is **defined** as

$$\langle r_p^2 \rangle = -6\hbar^2 \left. \frac{dG_E}{dQ^2} \right|_{Q^2=0}$$



ep elastic cross section (one photon exchange):

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma}{d\Omega}_{\text{Mott}} \frac{\tau}{\epsilon(1+\tau)} \overbrace{\left(G_M^2 + \frac{\epsilon}{\tau} G_E^2 \right)}^{\text{Reduced cross section}}$$

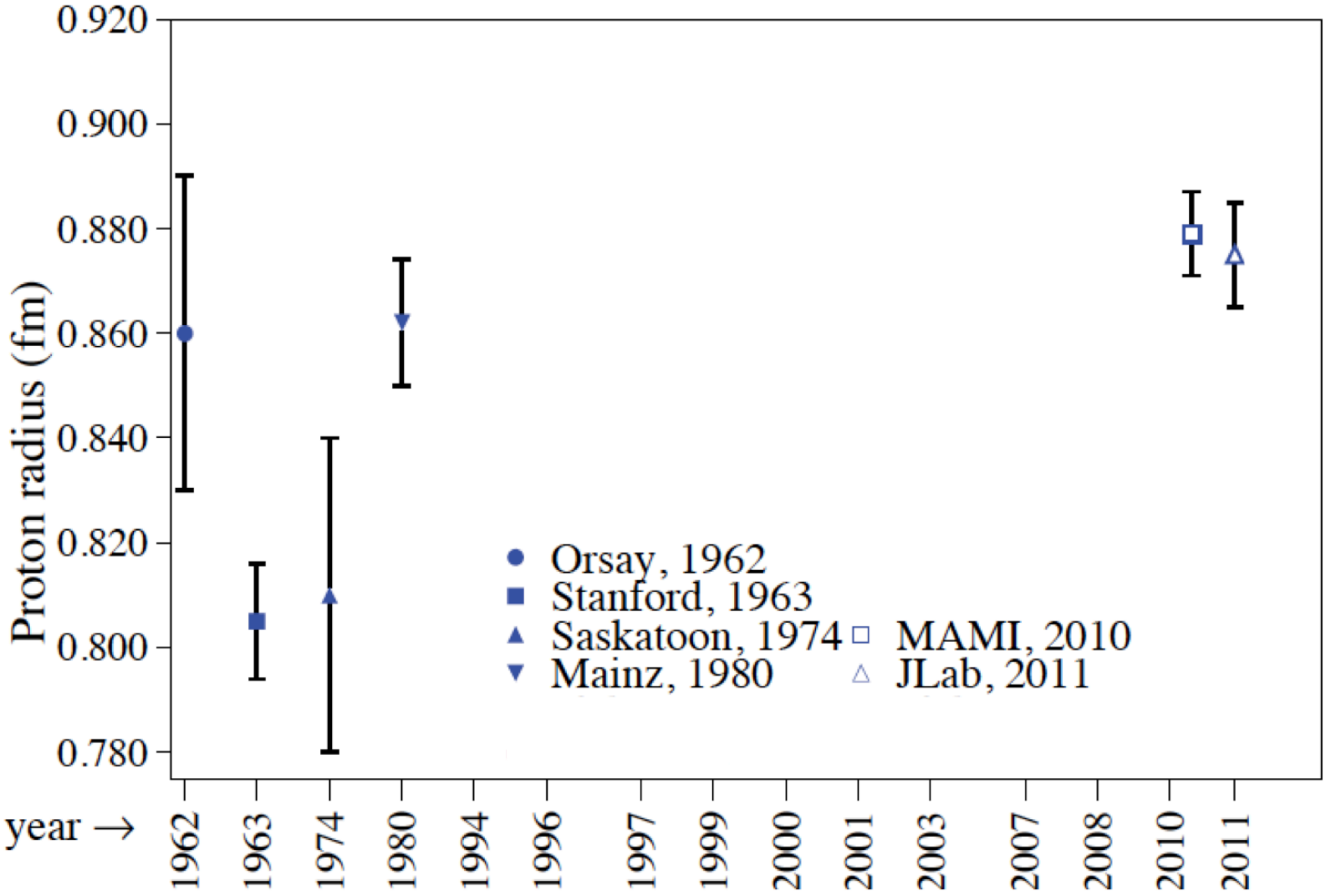
$$\tau = \frac{Q^2}{4M^2}$$

$$\frac{1}{\epsilon} = \left[1 + 2\,(1+\tau)\tan^2\frac{\theta}{2} \right]$$

Easy, what could go wrong?

- Rosenbluth separation—2γ exchange effects
- Is the data at sufficiently low Q^2?
- Does the fit functional form overly constrain the extrapolation?

Summary of analyses of existing data



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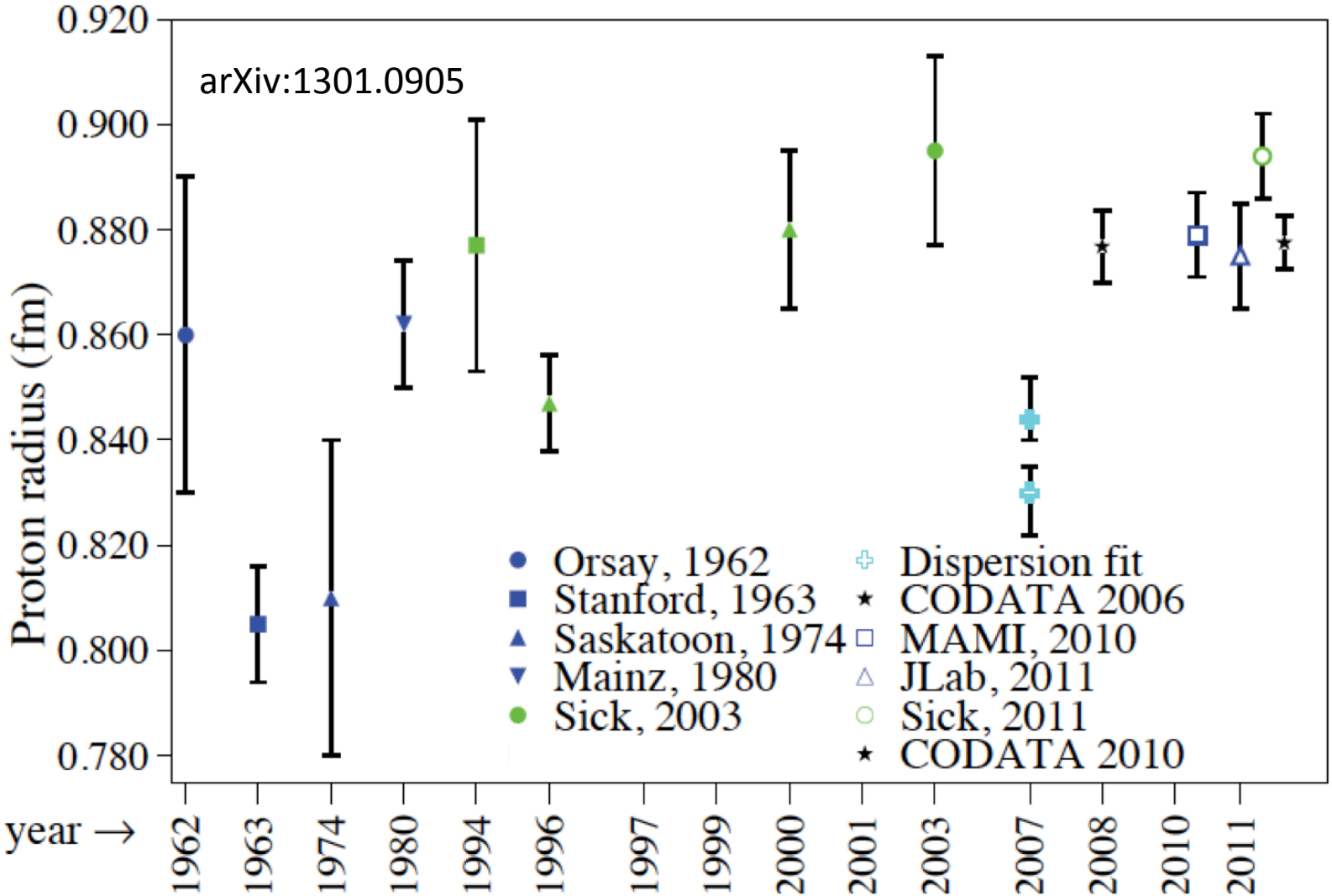
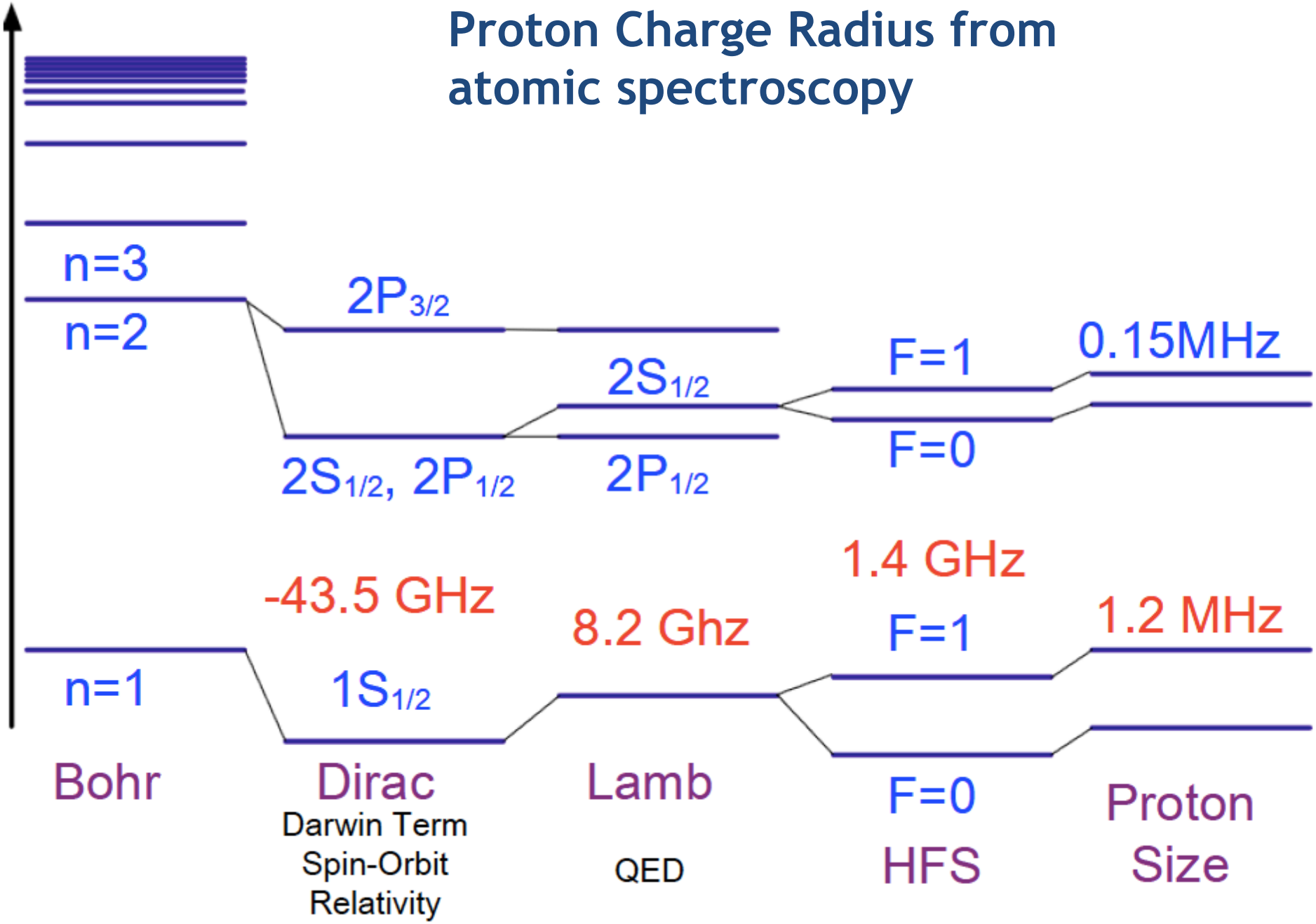


Proton Charge Radius from atomic spectroscopy



Proton Charge Radius from atomic spectroscopy

NRQM:

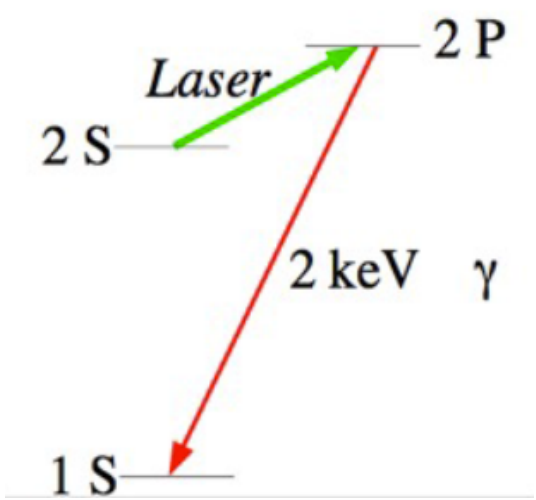
- finite size of proton perturbs energies of S states

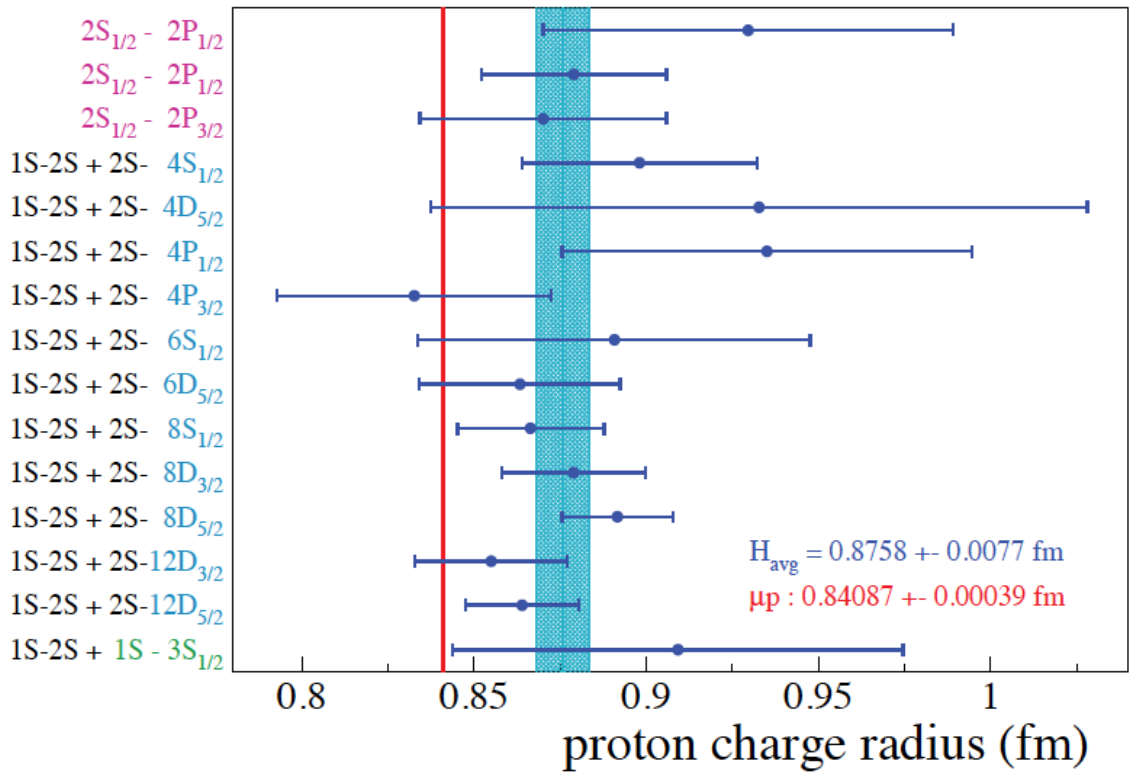
  r_p <<<< r_{atomic}, so effect proportional to $\psi^2_a(r=0)$.

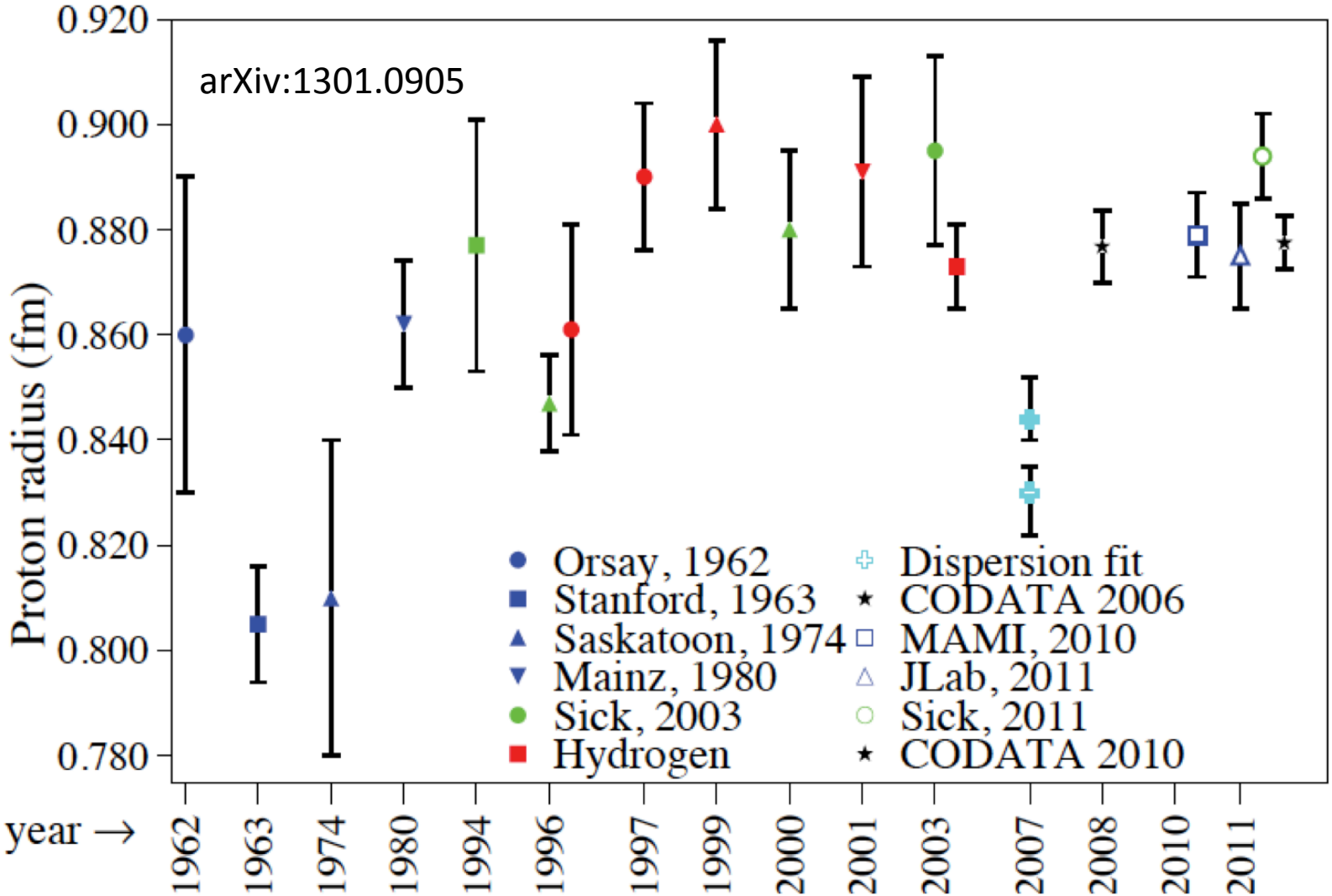
$$E(nS) \simeq -\frac{R_\infty}{n^2} + \frac{L_{1S}}{n^3}$$

$$L_{1S}[\mathrm{MHz}] \simeq 8172 + 1.56\,(r_p[\mathrm{fm}])^2$$

- Precise transition measurements in atomic hydrogen have been made for many transitions
- Also sensitive to the Rydberg constant, R_∞






arXiv:1301.0905
Proton radius (fm)
0.920
0.900
0.880
0.860
0.840
0.820
0.800
0.780
year →
1962
1963
1974
1980
1994
1996
1997
1999
2000
2001
2003
2007
2008
2010
2011
Orsay, 1962
Stanford, 1963
Saskatoon, 1974
Mainz, 1980
Sick, 2003
Hydrogen
Dispersion fit
CODATA 2006
MAMI, 2010
JLab, 2011
Sick, 2011
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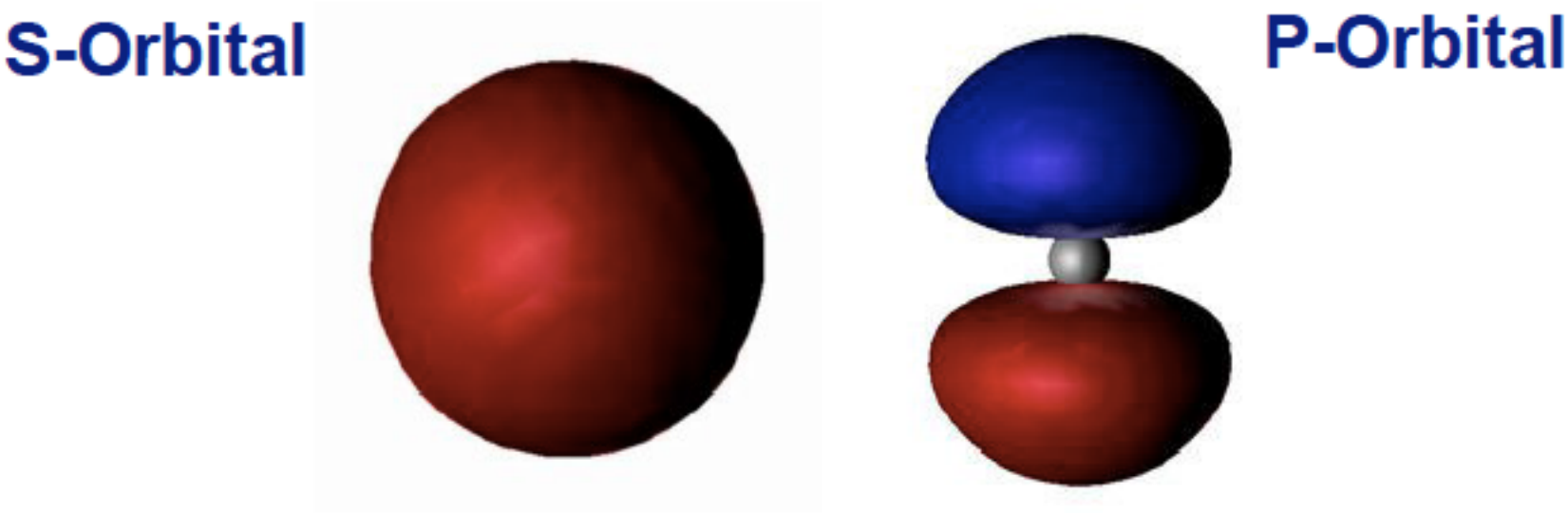
Why Measure μH?

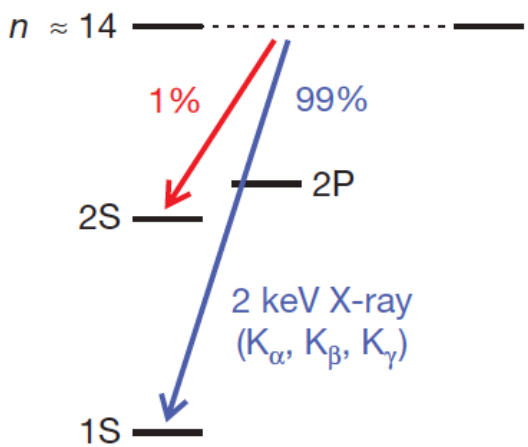


- While lepton is inside proton, attractive potential is modified
- Average potential reduced the longer lepton spends inside proton
- Strongly affects S orbitals, much less so P, so S⇄P transitions change
- Probability for lepton to be inside proton = volume of P / volume of atom:
- $m_\mu \approx 205 m_e$ so

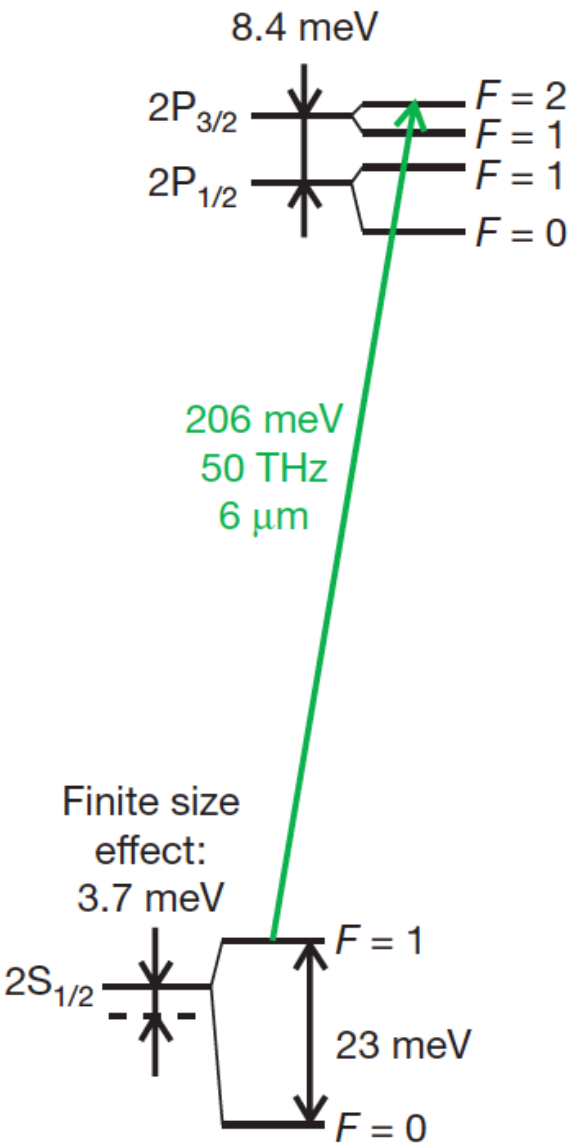
μH is $\approx 205 \times 10^3 \approx 8$ million times more sensitive to r_P

Pohl et al Nature 466 8 July 2010 doi:10.1038/nature09250

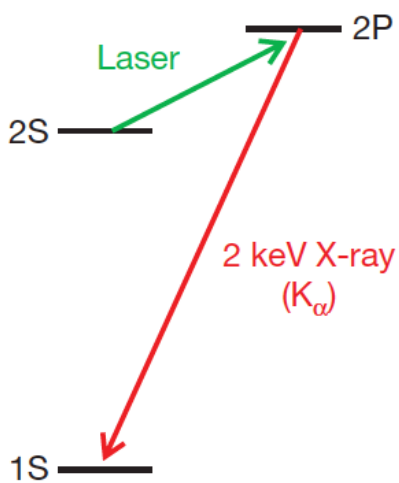
- Step 1: Produce muonic hydrogen



- Step 2: scan for 1S 2P transition



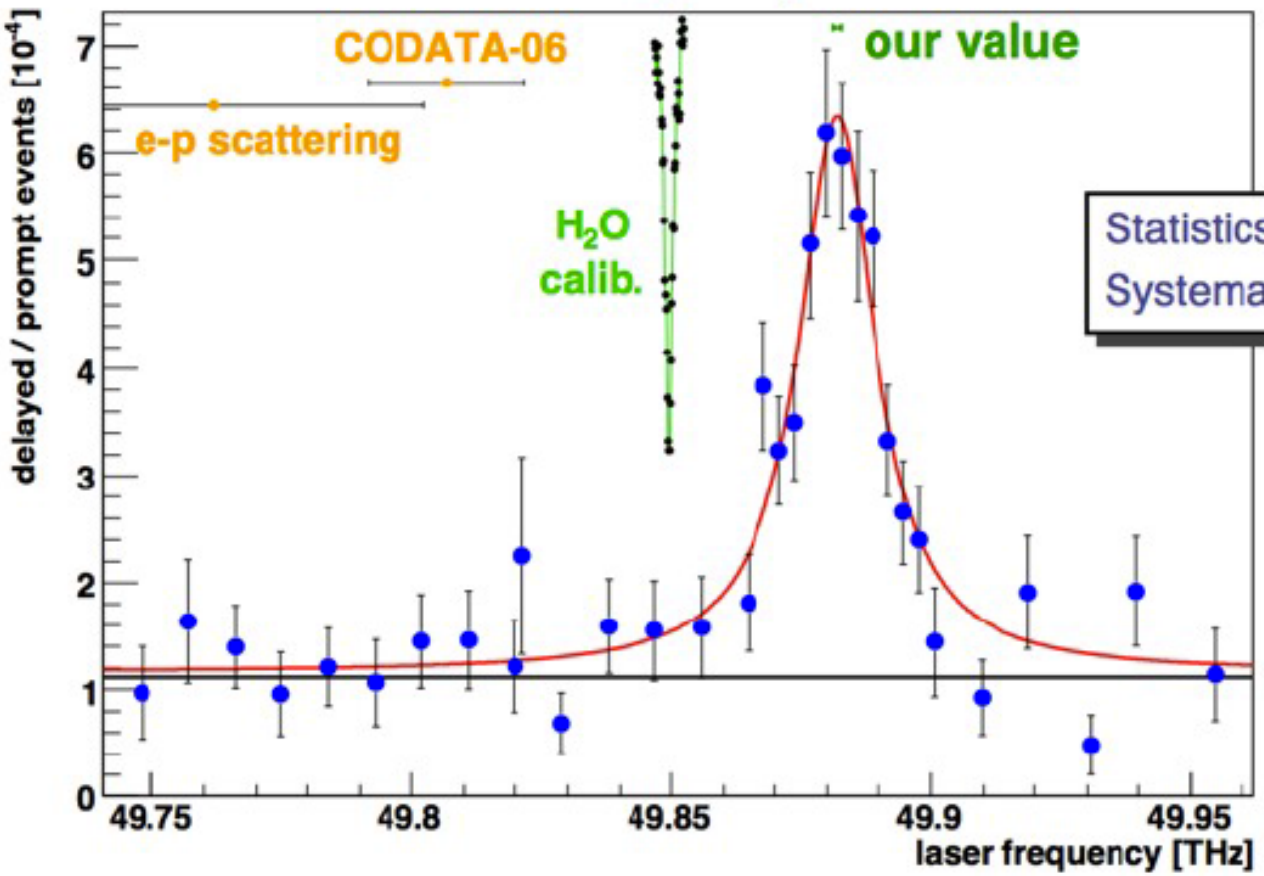
- Step 3: Detect 2keV decay x-ray



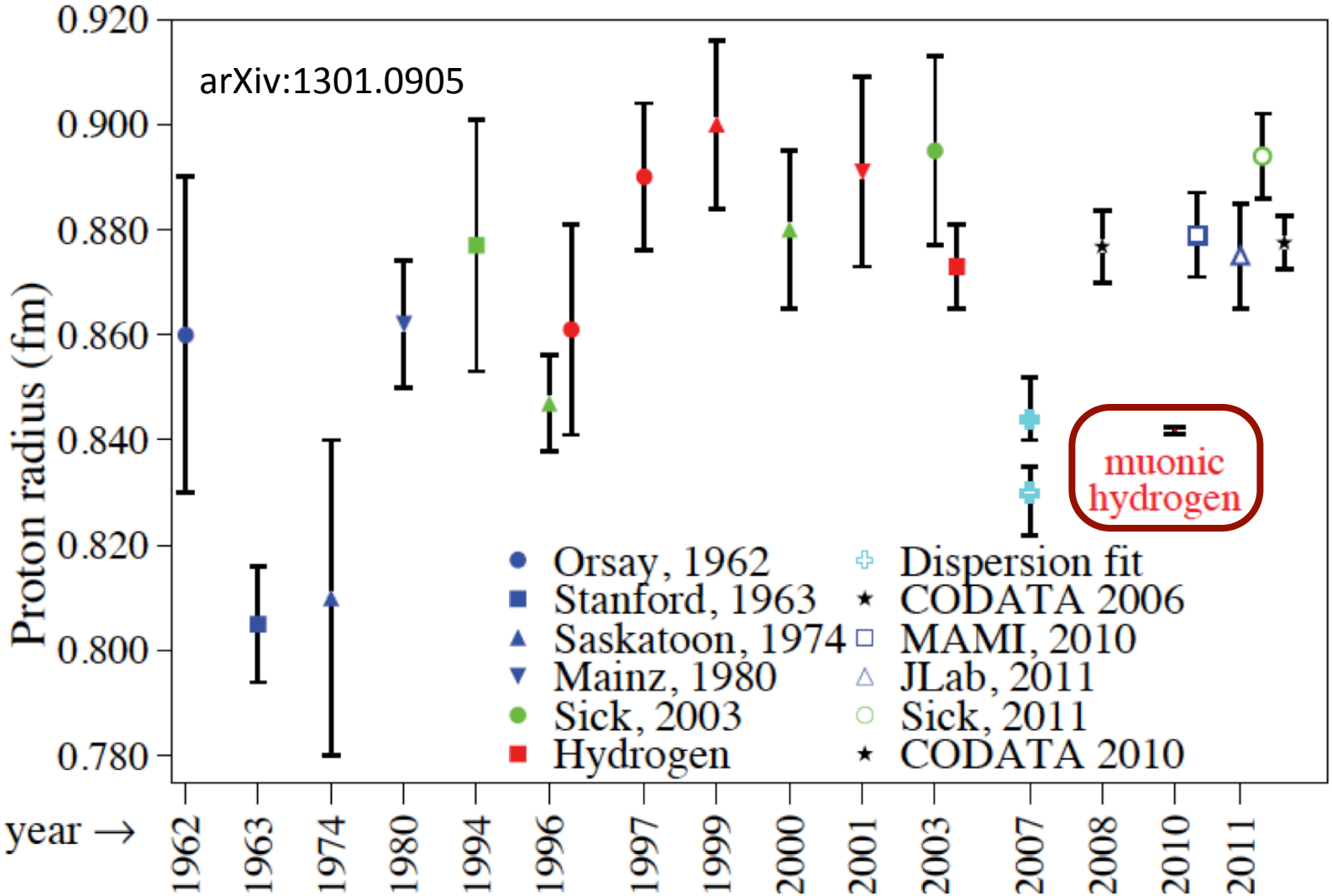
Muonic Hydrogen

Water-line/laser wavelength:
300 MHz uncertainty

$\Delta\nu$ water-line to resonance:
200 kHz uncertainty



Statistics: 700 MHz
Systematics: 300 MHz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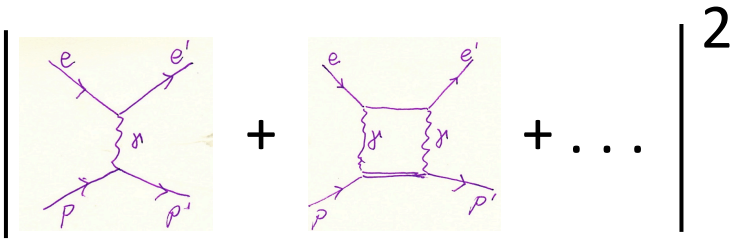
muonic hydrogen

Proton Radius Explanations and Summary

1. One (or more) or the experiments is wrong
   - Underestimating errors?
   - Strived to obtain previous results?
   - Solution: Repeat experiments
     - ✓ Muonic Hydrogen has already been done
     - ✓ Electronic Hydrogen is underway at various places
     - ✓ Electron scattering done (MAMI, JLab)
   - Two photon effects?
   - Extraction of slope at $Q^2 \rightarrow 0$ is difficult
     - many studies with different assumptions obtain same results.

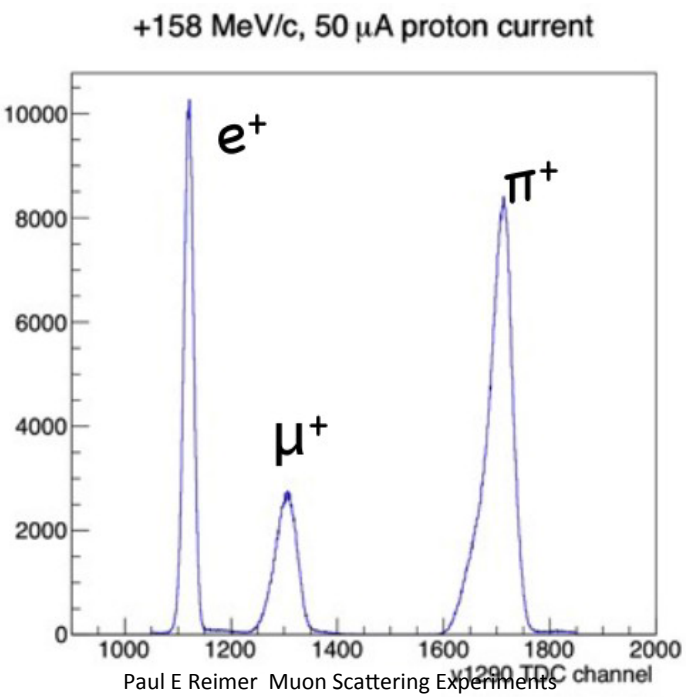
$\sigma_{ep} =$



2. Measurements of different effective radii?—ruled out.
   - $e^{12}C$ scattering and $\mu^{12}C$ atomic measurements agree
   - This would produce a disagreement between scattering and spectroscopy, not muon and electron.
3. Lamb shift incorrectly calculated—ruled out.
4. Novel Hadronic Physics?
5. Violation of lepton universality?

	Electron	Muon
Scattering	0.875±0.006	??
Spectroscopy	0.877±0.007	0.841±0.0004

MUSE



- Determine $\langle r_p^2 \rangle = -6\hbar^2 \left.\frac{dG_E}{dQ^2}\right|_{Q^2=0}$ with muons to test universality
- Measure μ^+, μ^-, e^+, e^- at the same time
  - Removes common systematic uncertainties in e μ measurements
  - +/- comparison will measure 2γ contribution
- Precision determination of scattering angle
- Precision determination of incoming particle momentum (time of flight)

Radius effect on Cross Section

Ratio of elastic scattering cross sections for calculated for two possible proton charge radii

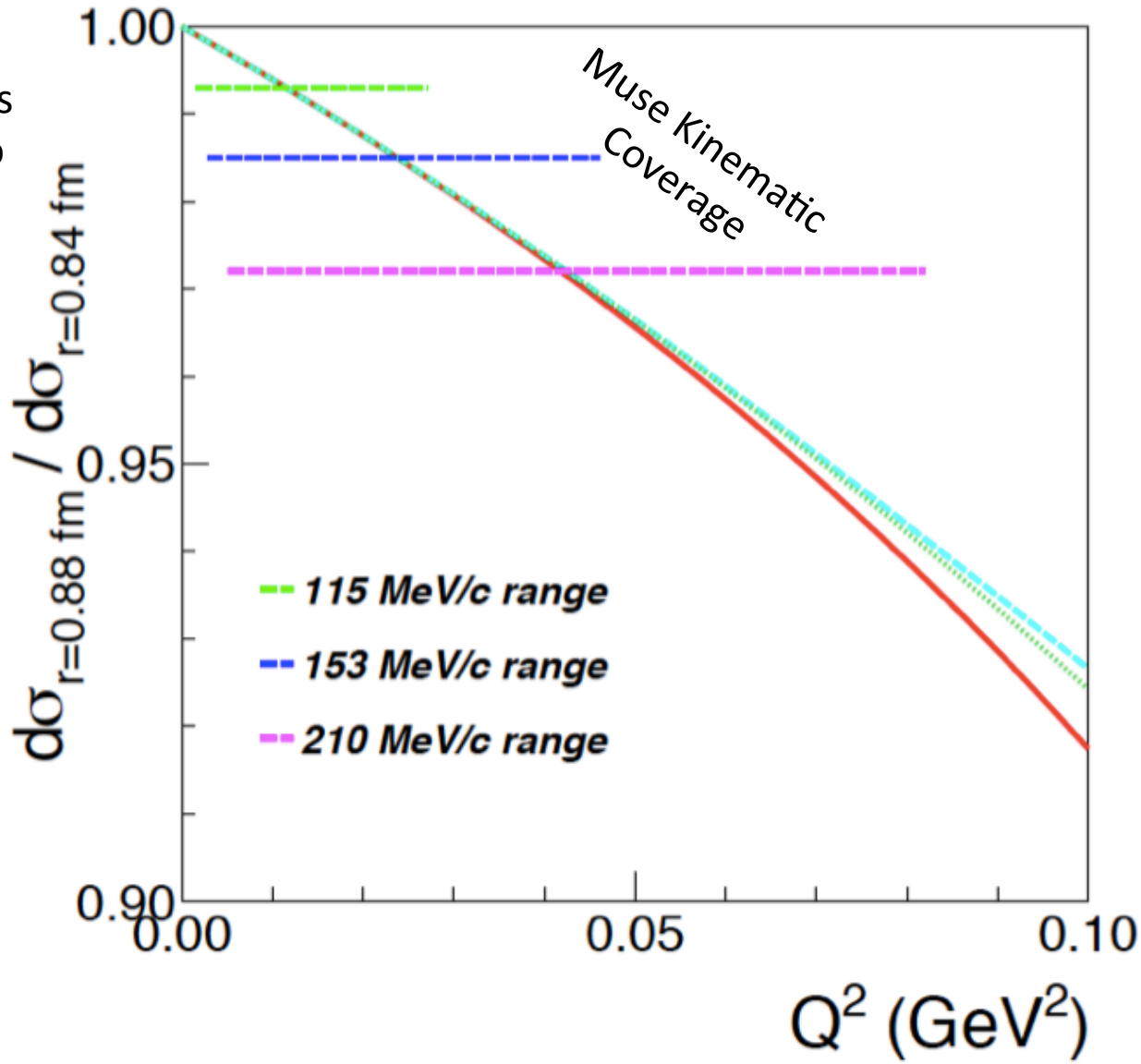
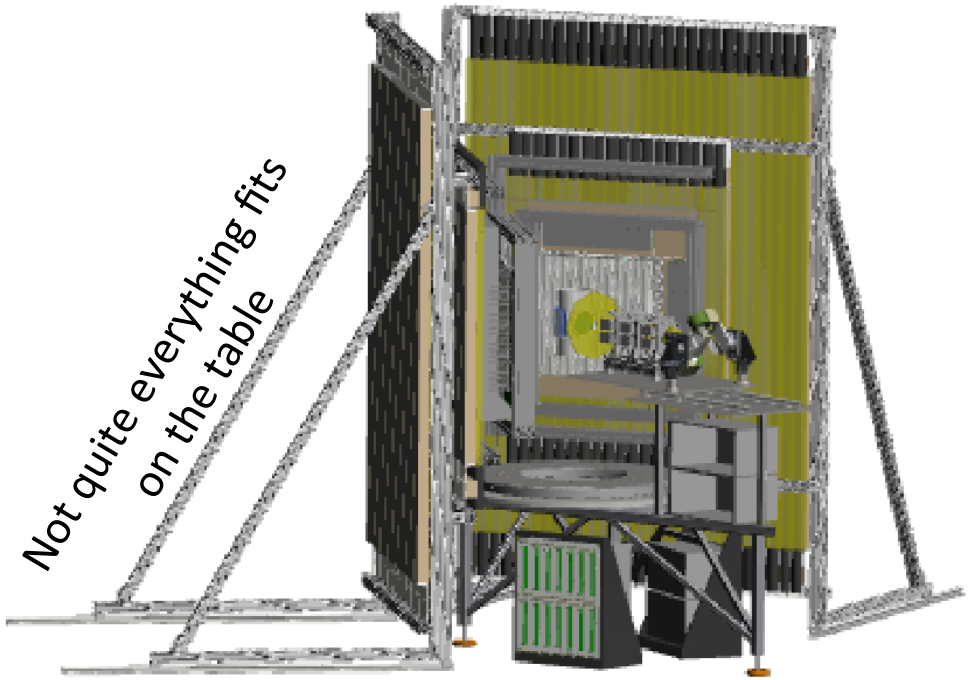
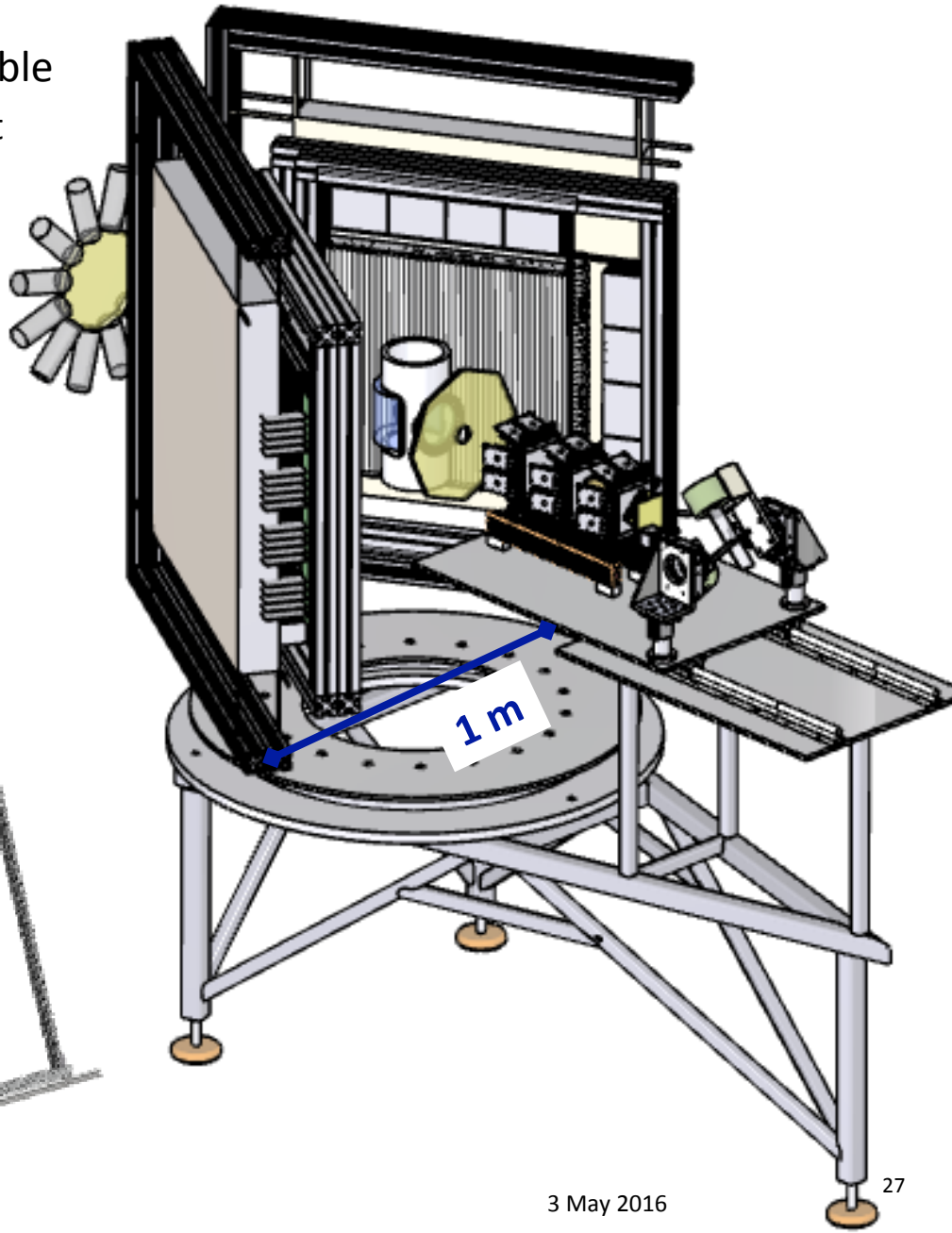


Table Top Experiment—literally

- I know—I'm responsible for building the table
  - And make sure that everyone else's pieces fit





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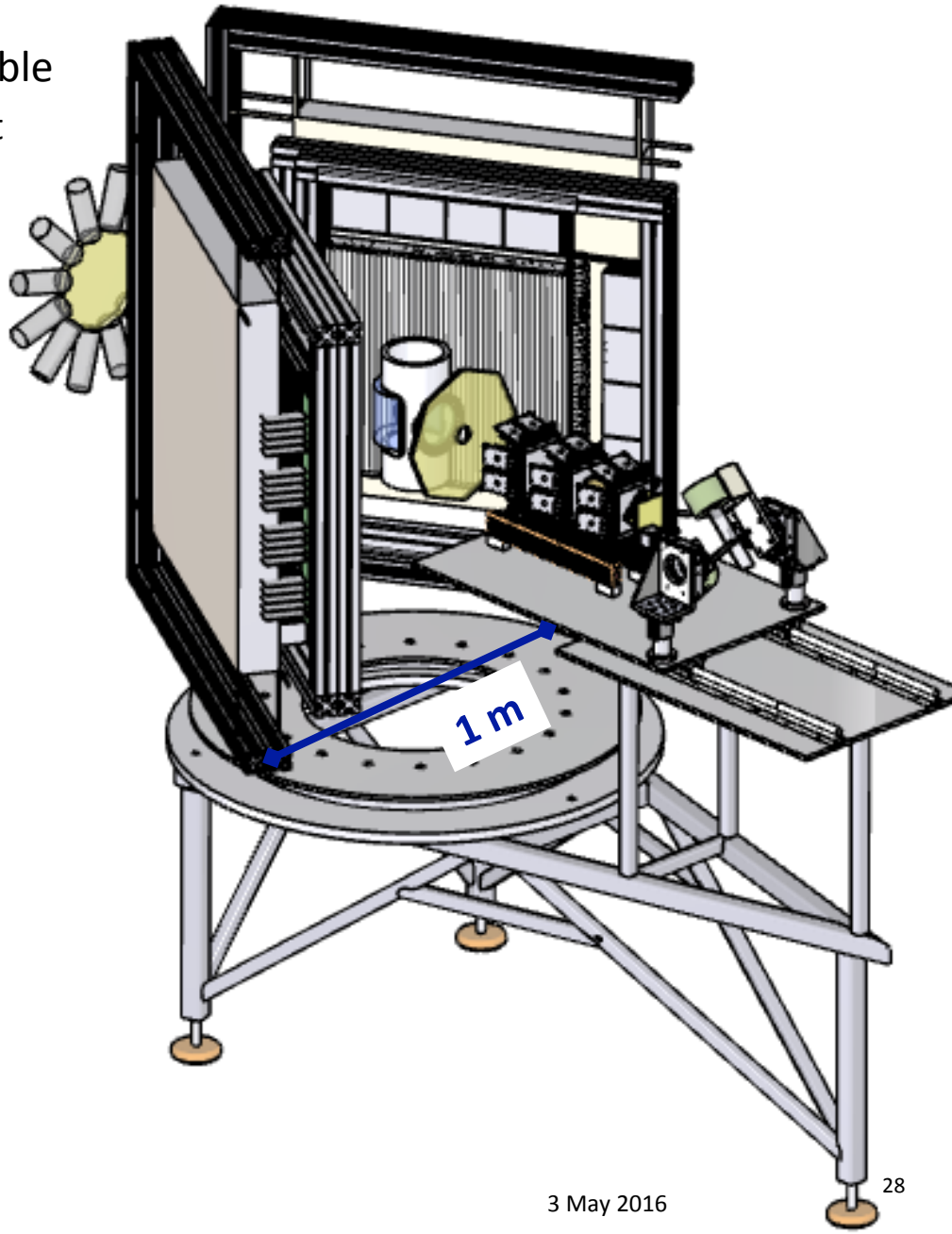
- PSI πM1 channel
  - 5 MHz total beam flux
  - 115, 153 and 201 MeV $e^{\pm}$, $\mu^{\pm}$ and $\pi^{\pm}$
- θ 20° – 100°
- Q^2 0.002 – 0.07 GeV^2
- Beam monitored with Cherenkov, ToF and tracked with GEMs



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M Meziane
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A Afanasev, W. Briscoe, **E. J. Downie**
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M Kohl
Hampton University
G Ron
Hebrew University of Jerusalem
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Jefferson Lab
S Gilad, V Sulkosky
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Paul Scherrer Institute
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St. Mary's University
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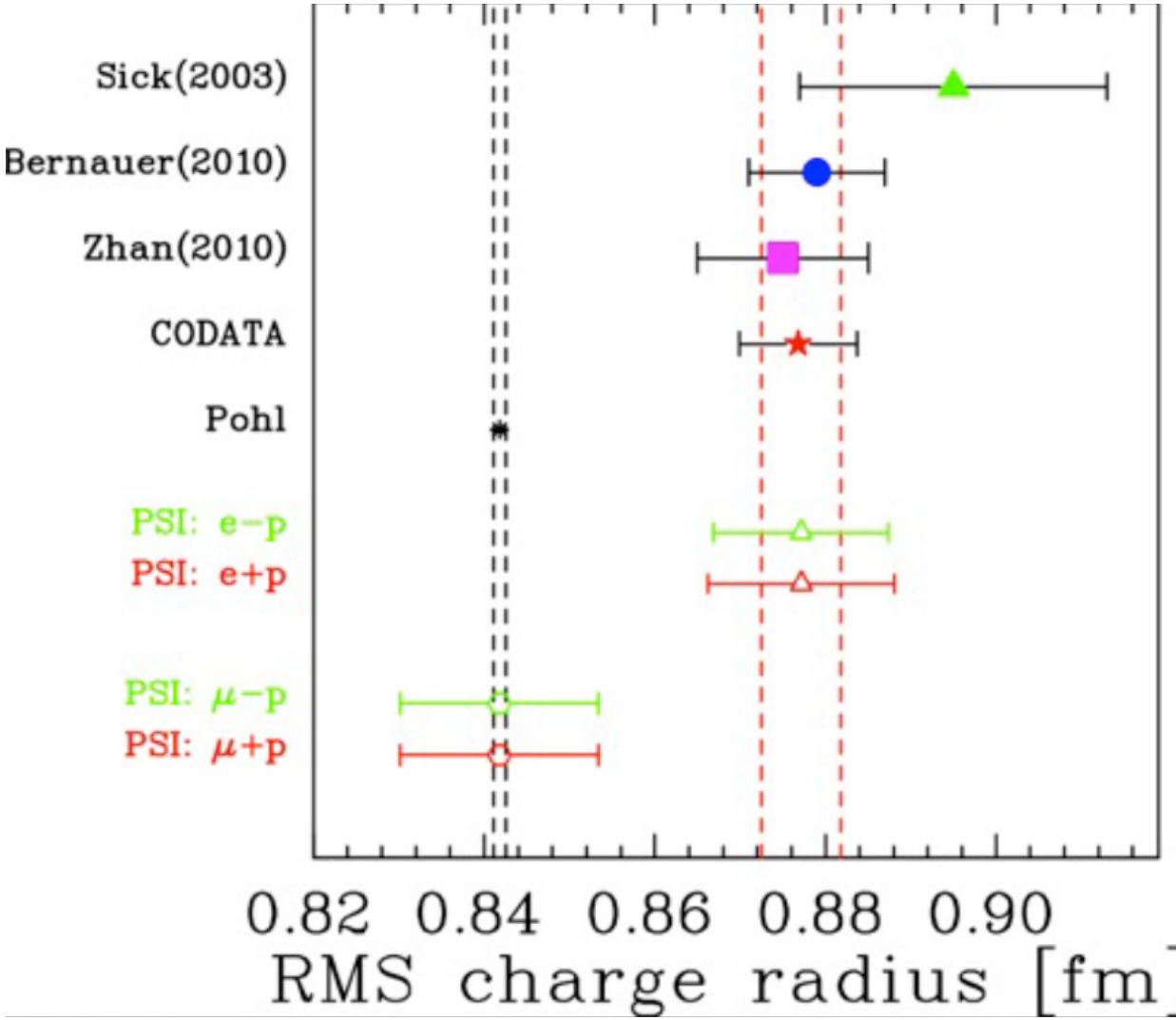
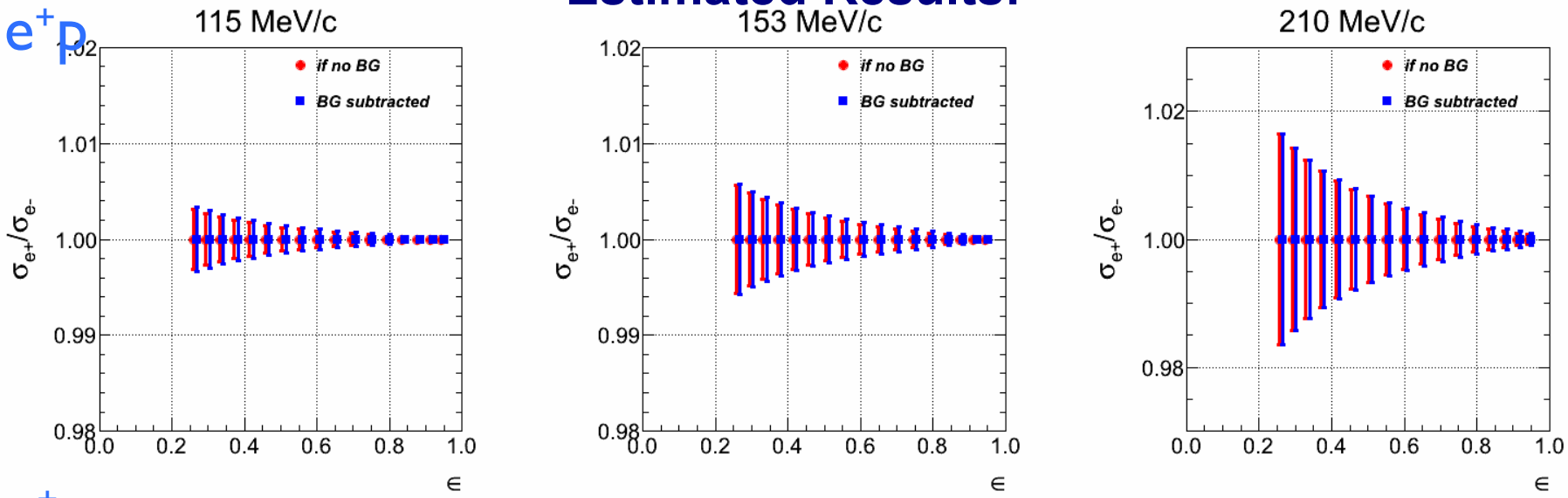
Temple University
N Liyanage
University of Virginia
C Perdrisat
College of William & Mary

MUSE: How well will we do?

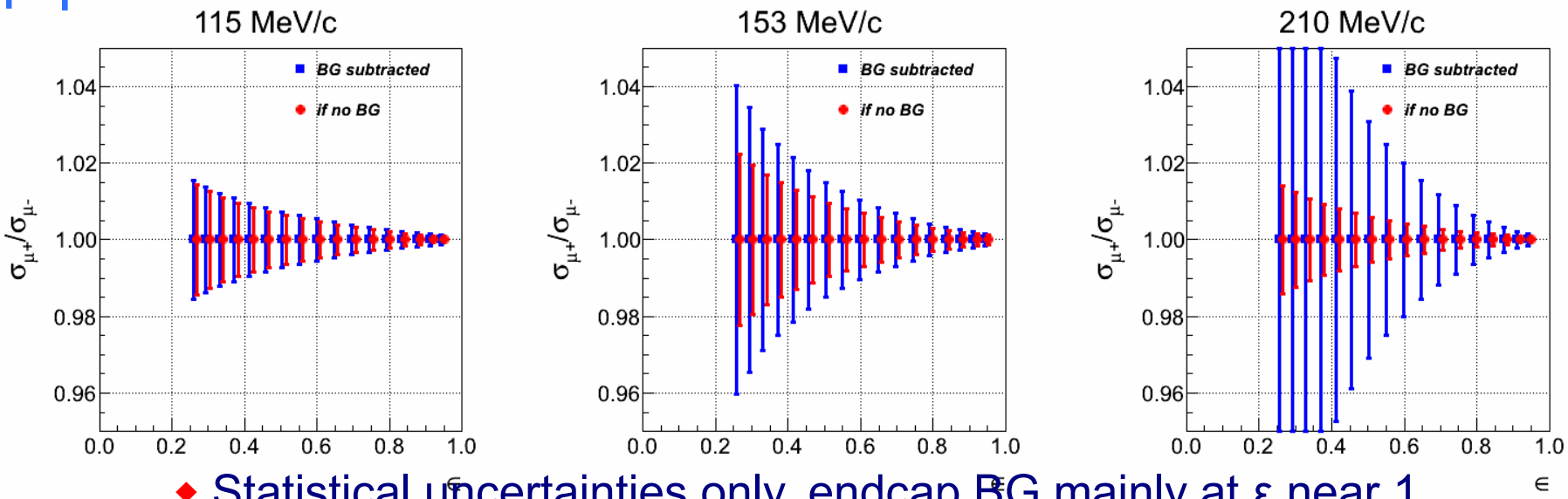


Estimated Results!

e^+p

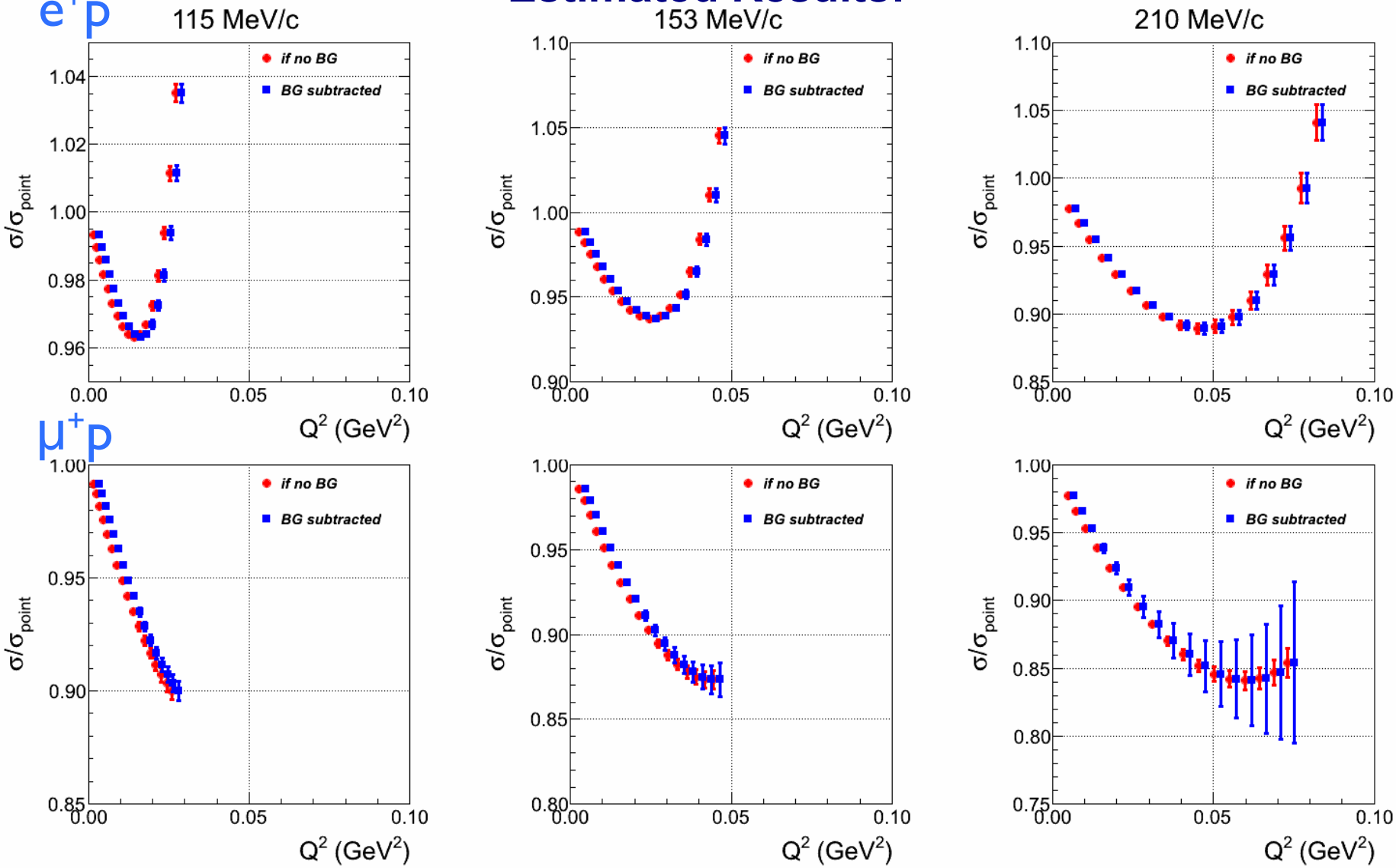


μ^+p



- Statistical uncertainties only, endcap BG mainly at ε near 1
  - μ limited by μ decay rejection (conservatively estimated)
- $e^{+/-}$ mainly limited by radiative corrections, here 1γ cancels, prob. det. response

Estimated Results!



- Statistical uncertainties only, similar results for ep & μp
- 6 month run, equal time for each setting, $\theta_{scatter}$ = 20 – 100°
- Uncertainities include endcap and μ decay subtractions