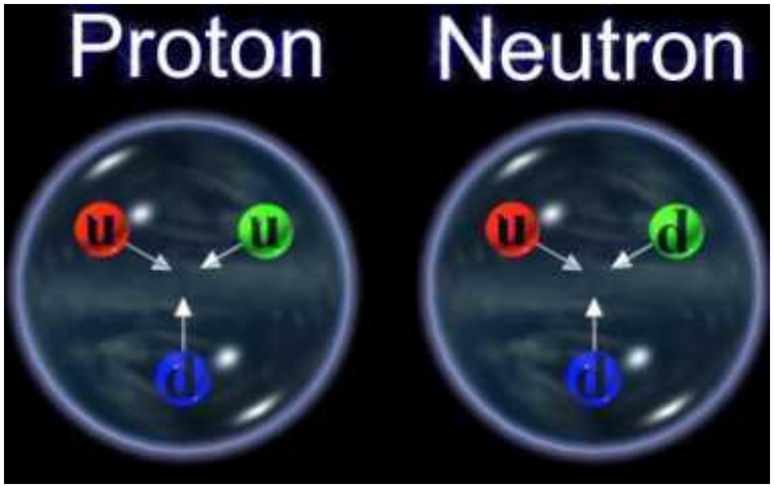
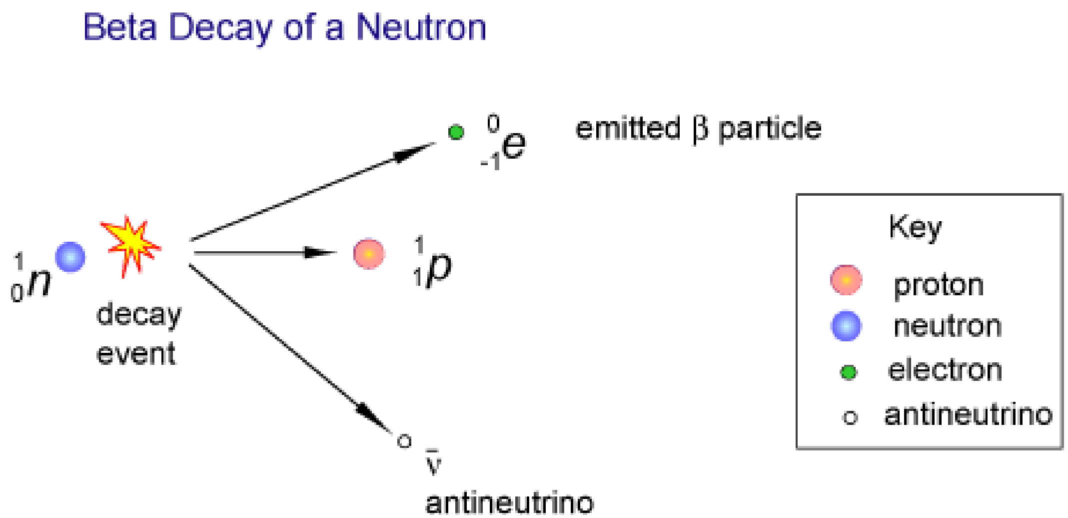
Nucleon Form Factors and the Nuclear Medium





Vincent Sulkosky

University of Virginia

HUGS 2014, Lecture 2

June 11th, 2014

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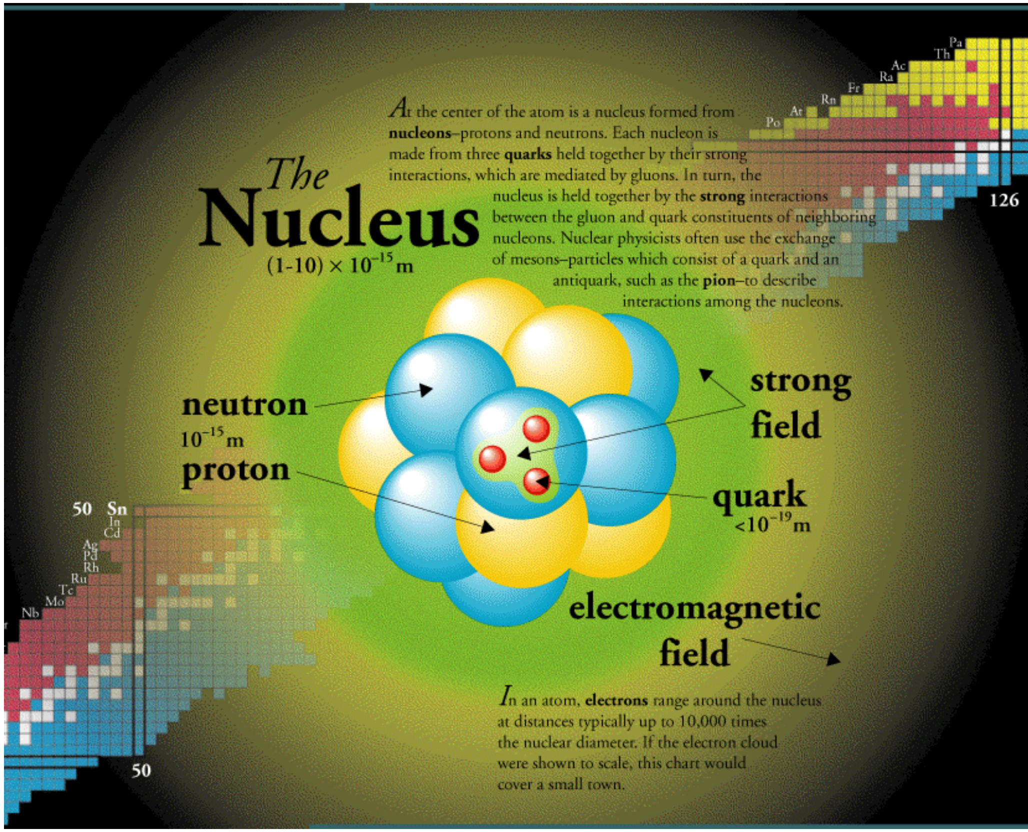
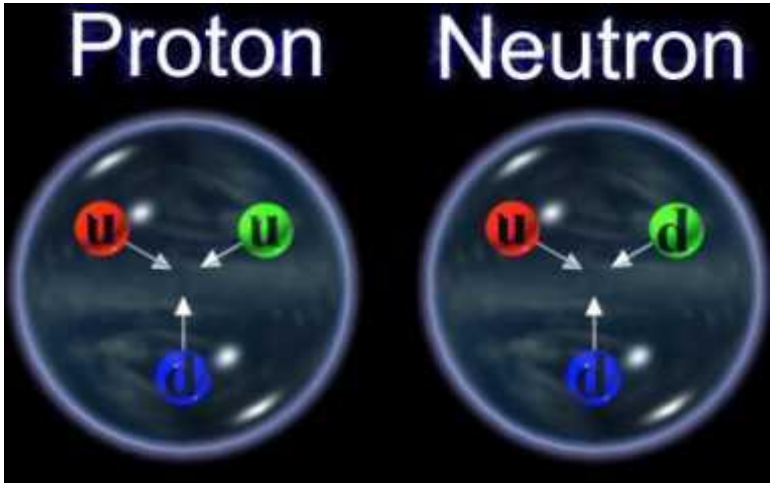
Questions to Ponder

1) What can we learn from form factors at low Q^2?
2) What is the proton radius puzzle?
3) What about neutron form factors?
4) What can we learn from combining proton and neutron information?



What do we know about their internal structure?



Mass: ~ 940 MeV, but u- and d-quark mass only a few MeV each!

1 MeV = 1.602 x 10^{-13} J

Charge: proton, +1; neutron, 0
Magnetic moment: large part is anomalous, > 150%!
Spin-1/2: but total quark spin contributes only ~ 30%!

Sum of the parts is not equal to the whole!

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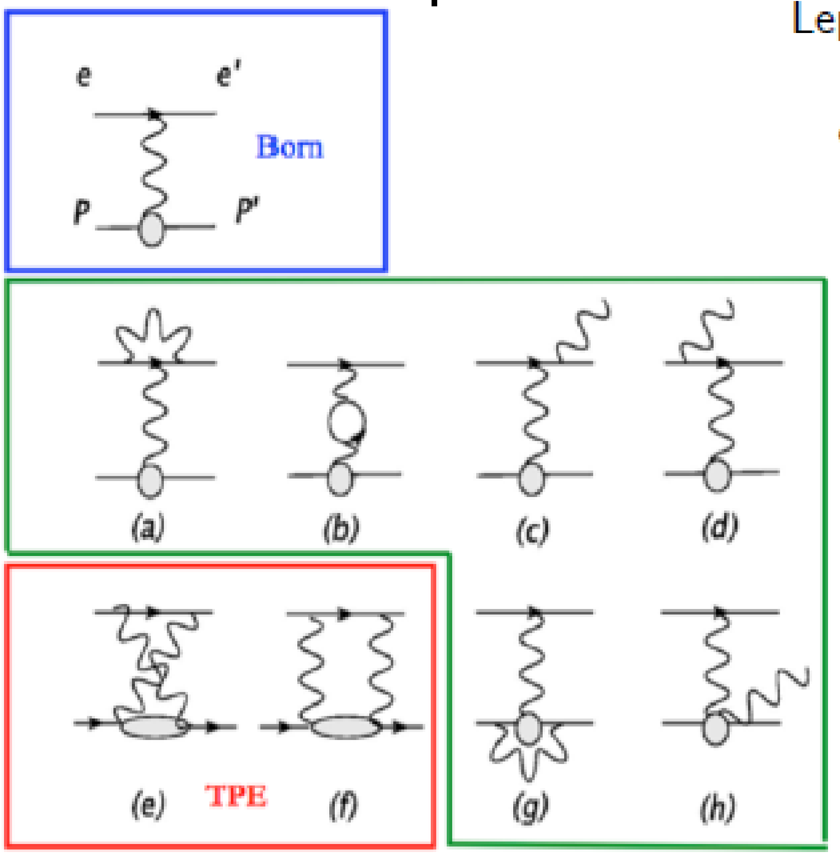
CLAS (Hall B) Two Photon Exchange Experiment

Measure the positron-proton to electron-proton cross section ratio to determine the TPE correction.

- $e^{+}p$ and $e^{-}p$ scattering measured simultaneously using a mixed electron-positron beam



Lepton-proton elastic scattering cross-section,

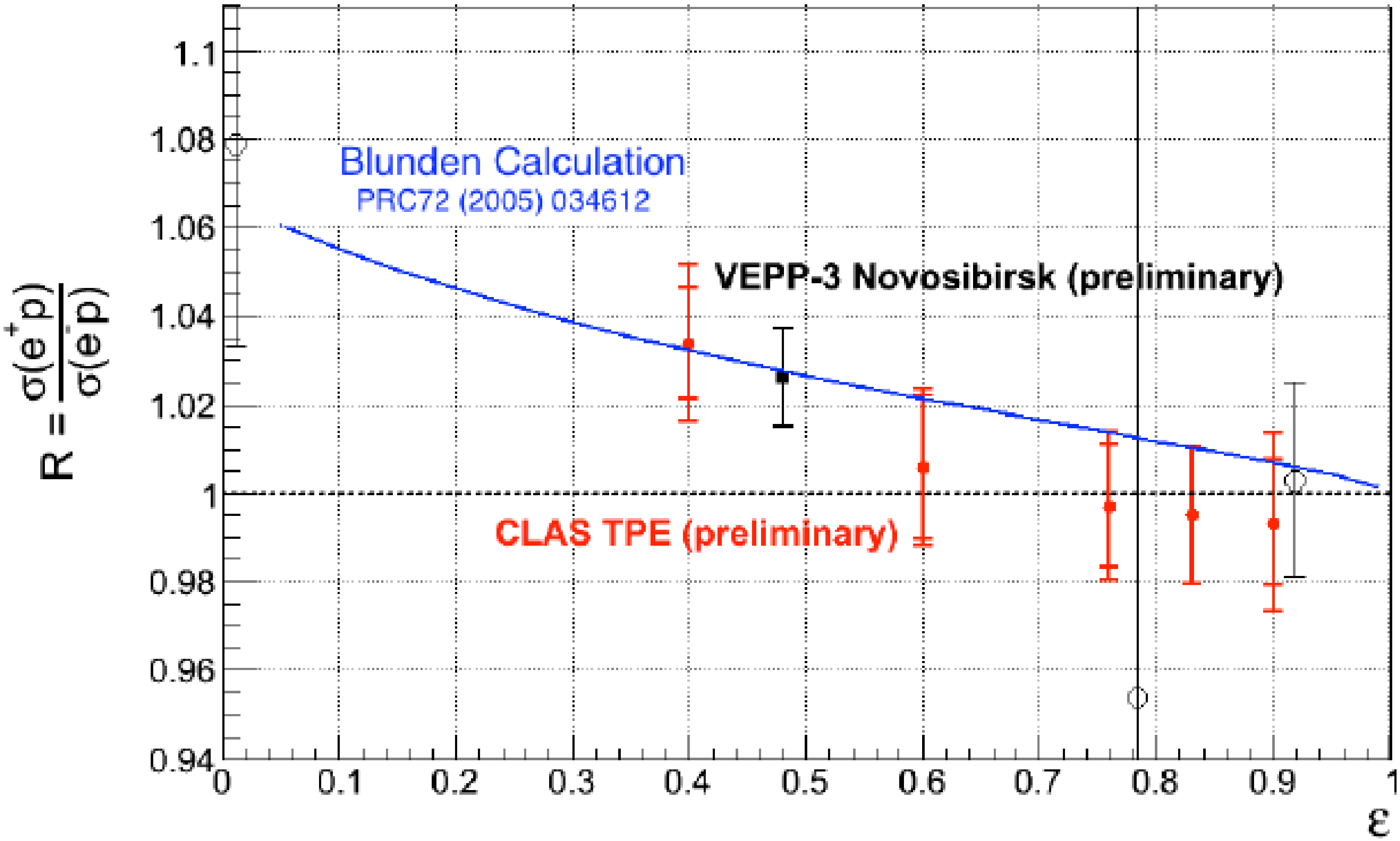
$$\sigma(e^{\pm}p) \propto |A_{ep\rightarrow ep}|^2 = |A_{\mathrm{Born}} + ... + A_{2\gamma}|^2$$

$$\sigma(e^{\pm}p) \propto |A_{\mathrm{Born}}|^2 \pm 2A_{\mathrm{Born}}\mathrm{Re}(A_{2\gamma})$$

$$R = \frac{\sigma(e^{+}p)}{\sigma(e^{-}p)} = 1 + \frac{4\mathrm{Re}(A_{2\gamma})}{A_{\mathrm{Born}}}$$

- R provides a model-independent measurement of the TPE contribution.

Results and World Data at Q^2 ~ 1.5 GeV^2



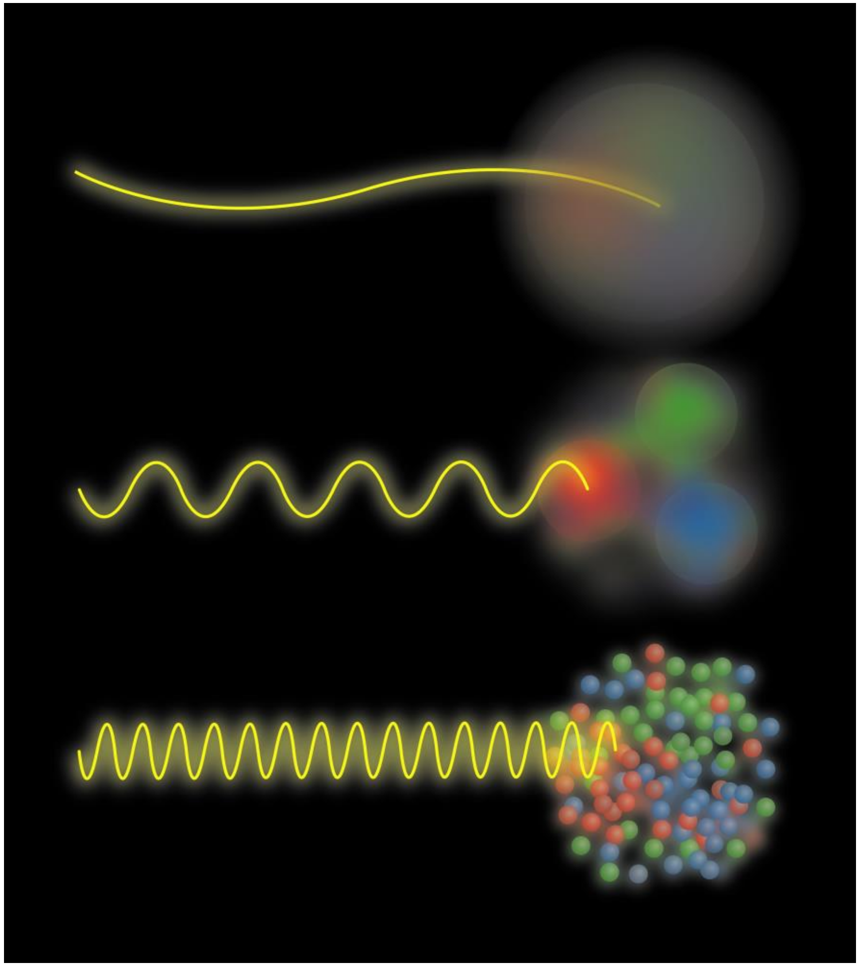
Plots from D. Adikaram

What can we learn from form factors?

- At small $Q^2 \rightarrow$ larger length scale, closely related to the proton size.
- In the non-relativistic limit:

$$\langle r_{E,M}^2 \rangle = \frac{-6}{G_{E,M}(0)} \left[\frac{d}{dQ^2} G_{E,M}(Q^2) \right]_{Q^2=0}$$

- The slope of the form factors versus Q^2 is related to the charge and magnetic radius of the proton.



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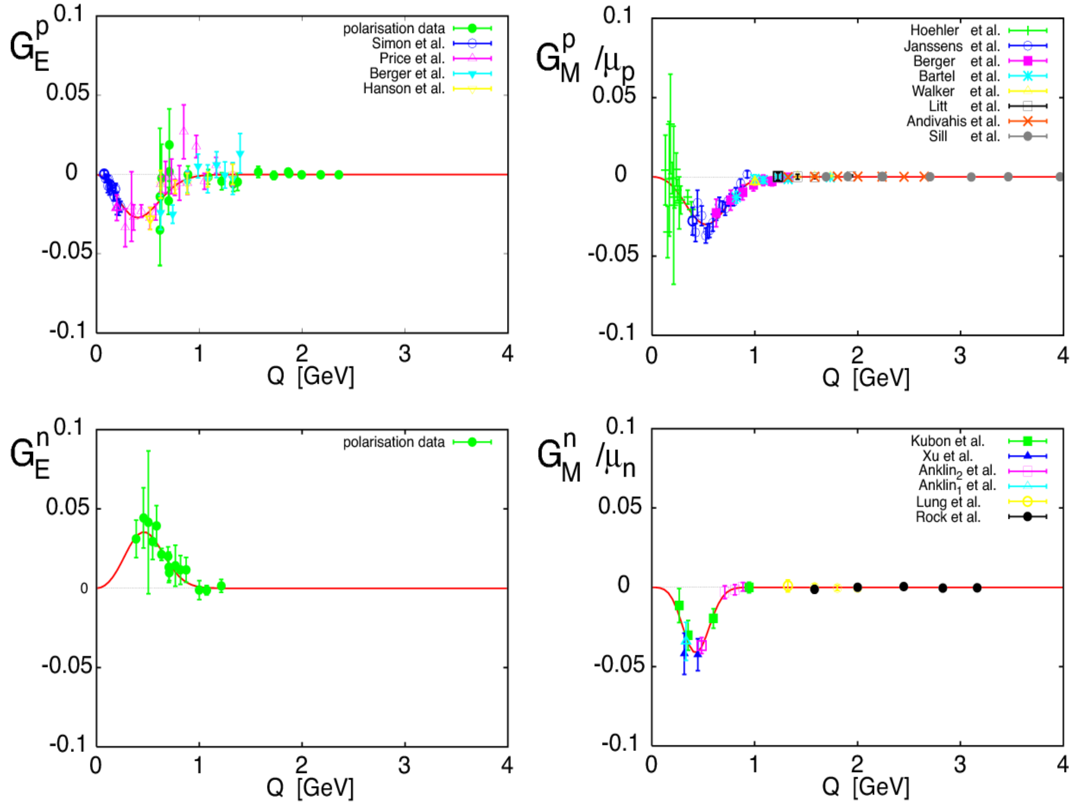
What about FFs at Low Q^2?

J. Friedrich and Th. Walcher, *Eur. Phys. J.* A **17**, 607 (2003)



- 2003 – Friedrich & Walcher fit:
  - Smooth dipole form + "bump & dip"
  - All four FFs exhibit similar structure at small momentum transfer (Q^2 ~ 0.25 GeV^2).
  - Was Interpreted as evidence for meson cloud effects.

Recent Experimental Efforts at low Q^2

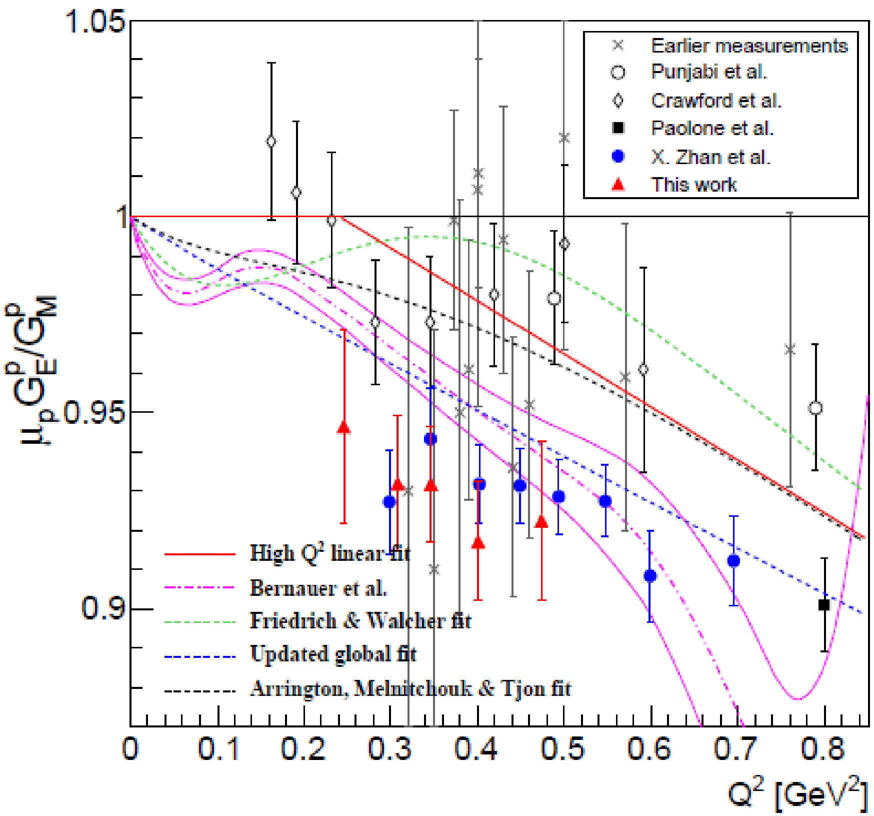
- **BLAST** - program for low Q^2 nucleon and deuteron structure with polarized beam - internal polarized target
- **Mainz A1** - unpolarized cross sections, 0.01 - 1 GeV^2
- **E05-103**

  Calibrations for low energy deuteron photodisintegration used to determine proton ratio of G_E/G_M
- **E08-007** run 2008

  Dedicated experiment to cover the 0.3 - 0.7 GeV^2 range with higher statistics
- **E08-007 part II** run 2012 (along with E08-027 “g2p”)

  Dedicated polarized beam - polarized NH_3 target measurements to cover the range about 0.015 - 0.16 GeV^2 with high precision

E08-007: Proton FFs at Low Q^2



- Bates **BLAST** result consistent with 1.
  Crawford et al., *Phys. Rev. Lett* 98 052301 (2007)
- Substantial deviation from unity is observed in **LEDEX** (Ron et al.) and **E08-007**, Part 1(Zhan et al.).
- Both data are inconsistent with F&W fit.
- Complementary to the high precision cross-section measurement at **Mainz** **(Q^2~ 0.1 – 2 GeV^2)**.
- Improved EMFFs:
  - strange form factors through PV

    A^{PV} + $G_{E,M}^{p,n\gamma}$ + G_A^{pZ} (calculated) --> $G_{E,M}^{s}$
  - proton Zemach radius and hydrogen hyperfine splitting

$$\Delta_Z = -2\alpha Z \frac{m_e m_p}{m_e + m_p} r_Z,\ r_Z = -\frac{4}{\pi}\int_0^\infty \frac{dQ}{Q^2}\left[\frac{\mu_N}{\mu_p} G_E(Q^2) G_M(Q^2) - 1\right]$$

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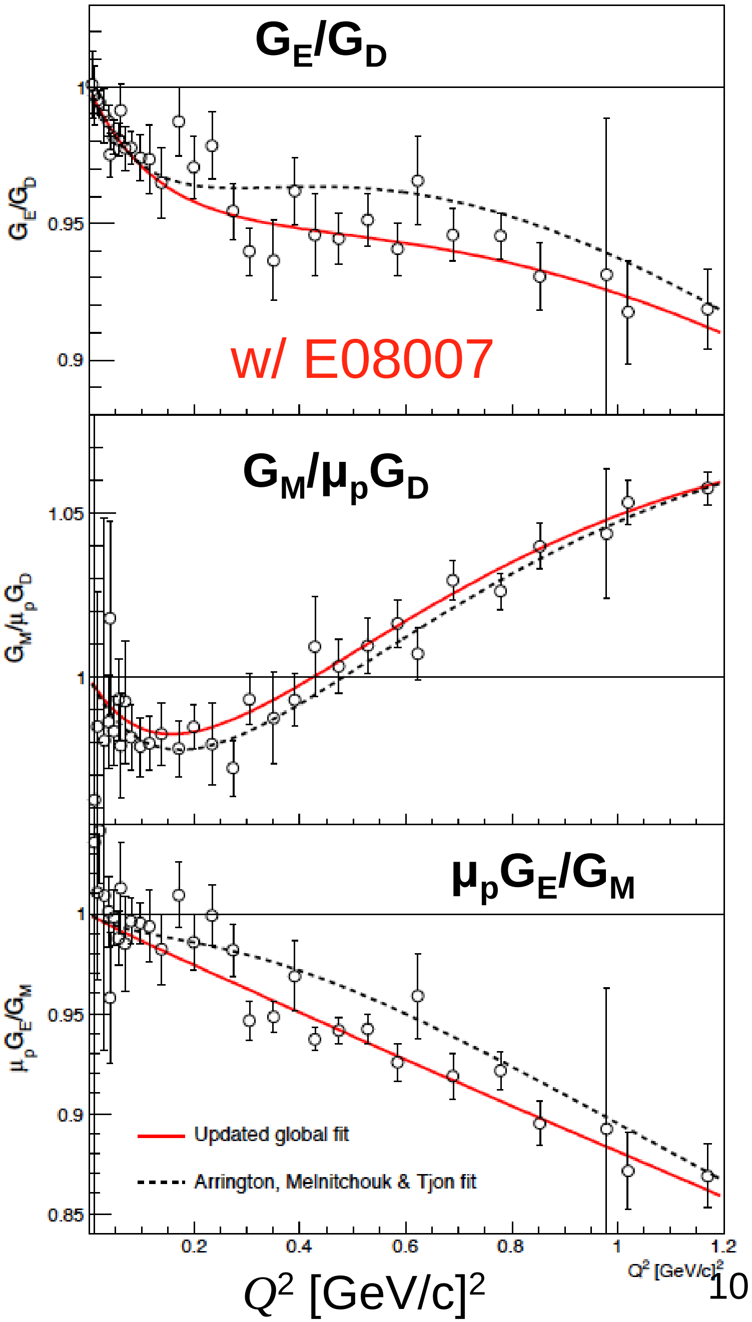
E08-007 Impact

Fit of world data except Mainz A1 data.

- G_E reduced up to ≈ 2% from 0.3 - 1 GeV^2
- G_M increased ≈ 0.5% from 0.1 - 0.8 GeV^2
- FF ratio smaller by up to ≈ 2.5% from 0.3 - 0.8 GeV^2
- Slopes changed at Q^2 = 0 changing ``radii''.



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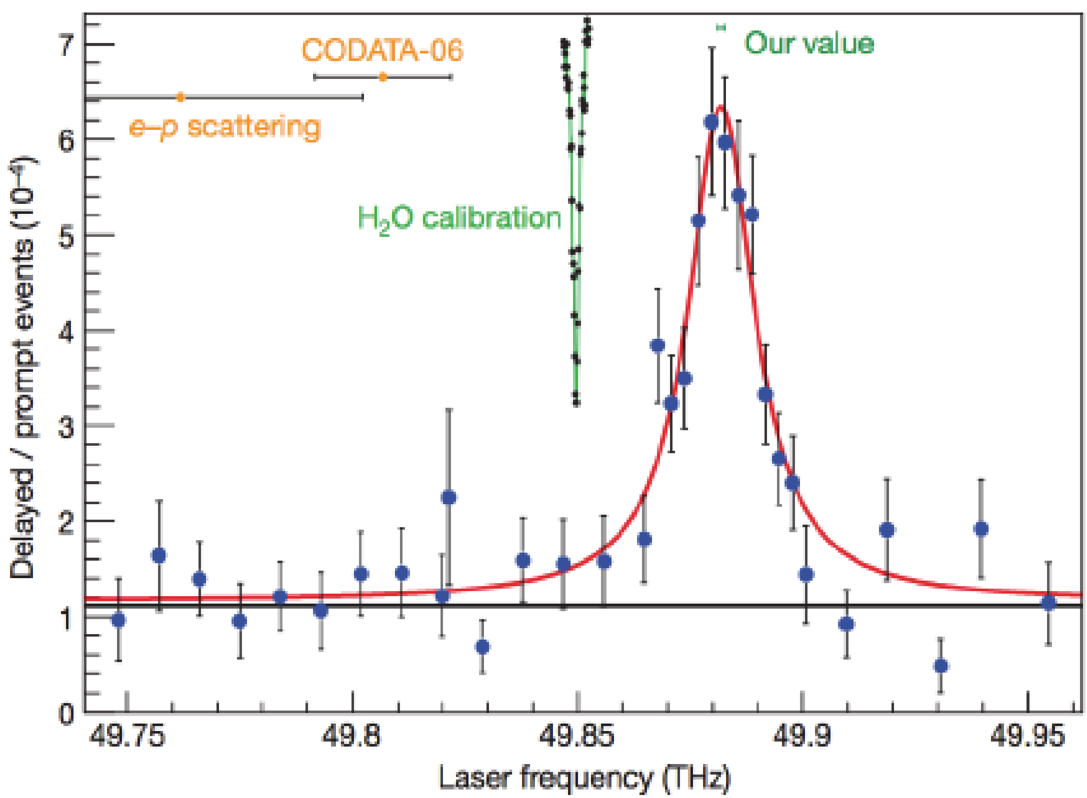
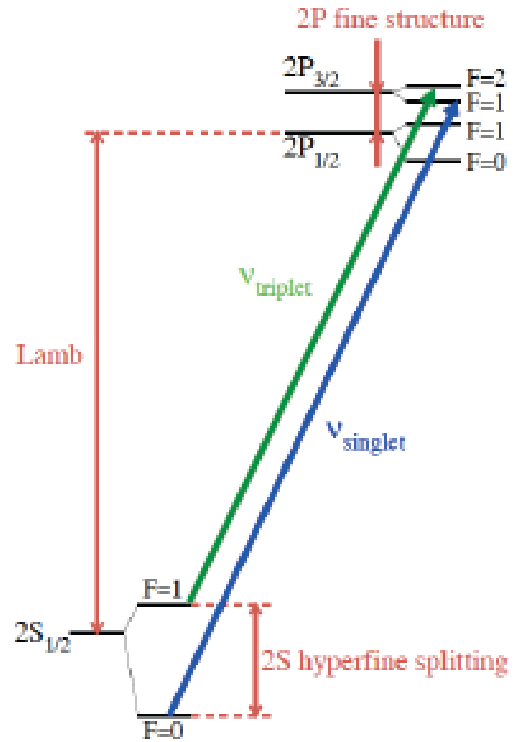
Muonic Hydorgen Measurements

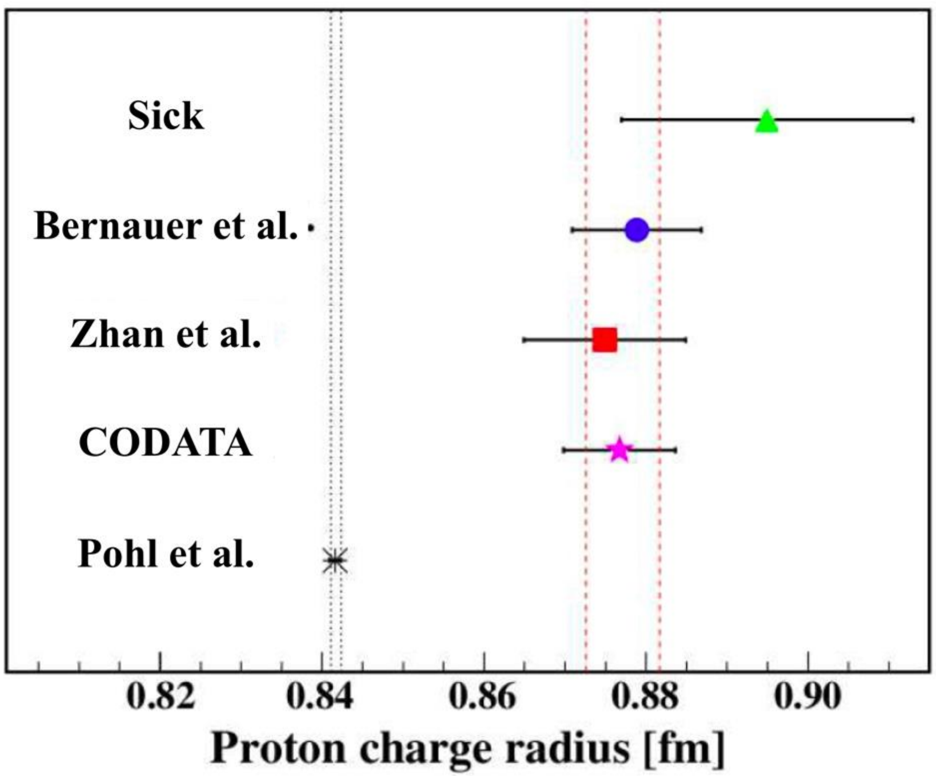
- 2S ➔2P Lamb Shift + 2S-HFS
- R. Pohl et al., Nature **466**, 213 (2010)
- **UPDATE**: A. Antognini et al., Science **339**, 417 (2013)





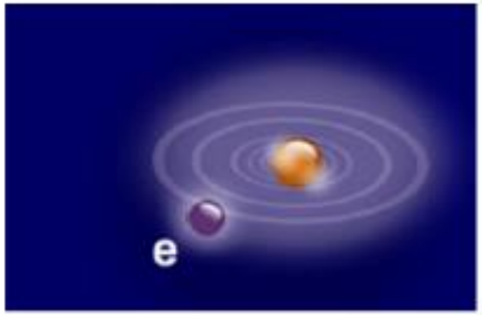
The Proton Charge Radius Puzzle

- 7σ discrepancy between **muonic** hydrogen Lamb shift and combined **electronic** Lamb shift and electron scattering
- High-profile articles in Nature, NYTimes, etc.
- Puzzle unresolved, possibly new physics

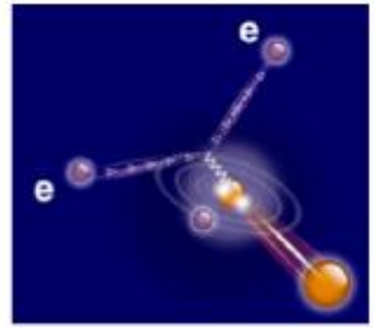


#	Extraction	$<r_E>^2$ (fm)
1	Sick	0.895±0.018
2	Bernauer Mainz	0.879±0.008
3	Zhan JLab	0.875±0.010
4	CODATA'06	0.877±0.007
5	Combined 2-4	0.877±0.005
6	Muonic Hydrogen	0.842±0.001

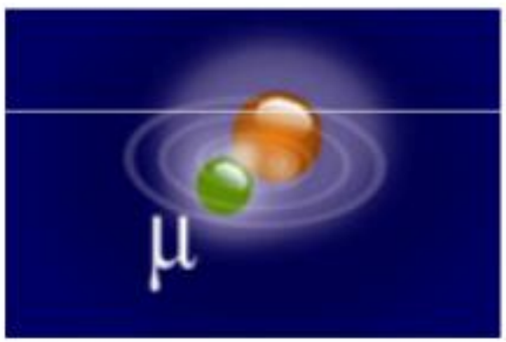
Electron vs Muon Radius Techniques



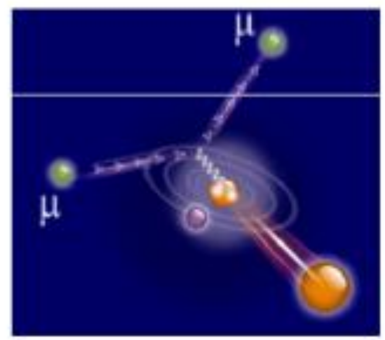
$< r_E^2 >_{ep}^{1/2} = 0.0.8768 \pm 0.0069$



$< r_E^2 >_{ep}^{1/2} = 0.875 \pm 0.009$



$< r_E^2 >_{ep}^{1/2} = 0.8418 \pm 0.0007$



$$\left\langle r_E^2 \right\rangle_{\mu p}^{1/2} = ?$$

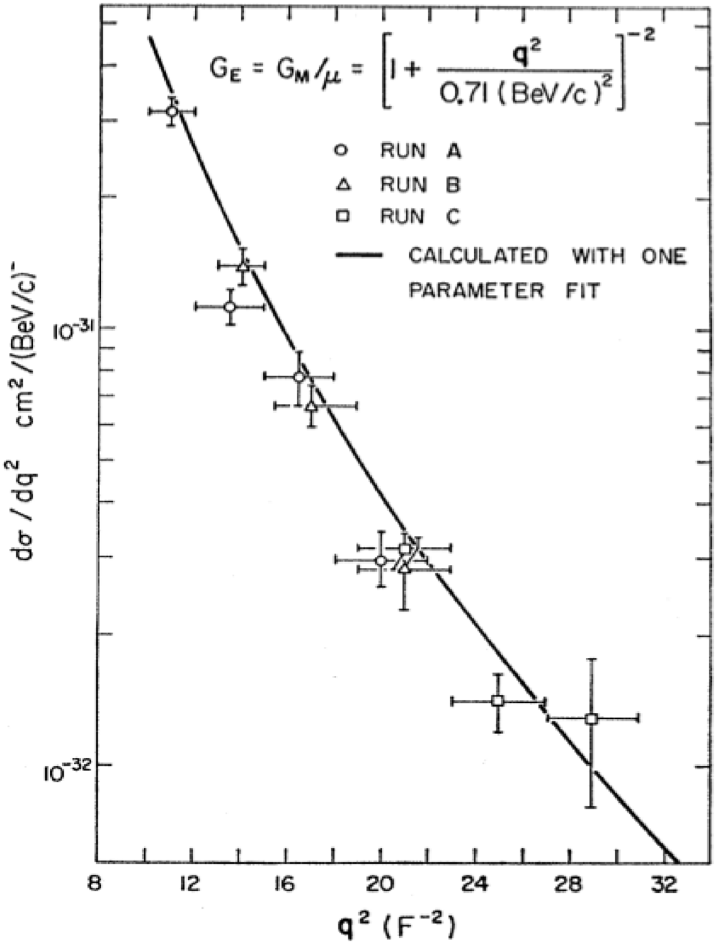
Resolutions to the Puzzle?

- Extraction from muonic-hydrogen is incorrect. No doubts about the experiment, but some discussion about the theory and proton structure for extracting the proton radius.
- Extraction from ep (scattering) is incorrect. The fit procedures are not good enough. Q^2 not low enough, and there could be structures in the form factors.
- Proton structure issues in theory. Theory critique of theory - off-shell proton in two-photon exchange leads to enhanced effects differing between μ and e, or leads to theoretically unjustified sticking-in-form-factor models.
- Novel missing physics. Physics differentiates between μ and e. Constraints on novel physics exist, and there seems to be no generally accepted solution at present.

e-μ Universality in Lepton Scattering

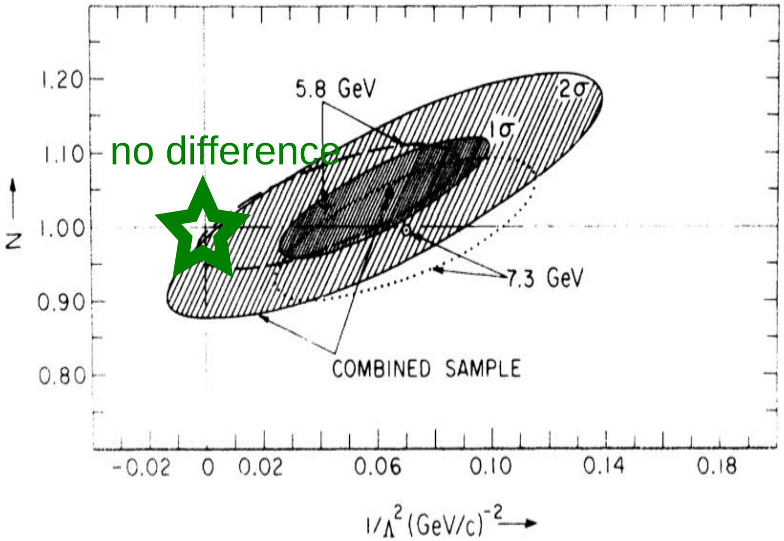
1960s-1970s: several experiments tested e-μ universality in scattering

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



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

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



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

- DIS μp scattering: Entenberg et al., PRL 32 (1974)

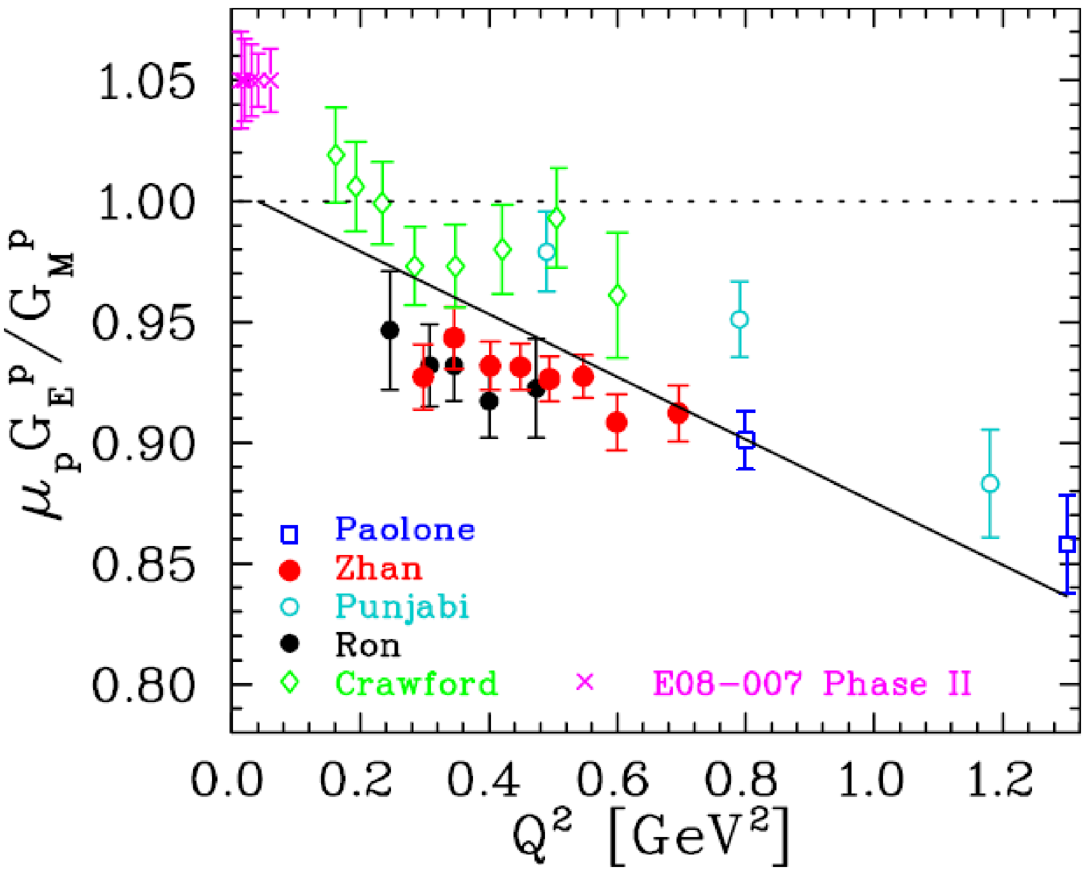
  $\sigma_{\mu p}/\sigma_{ep} \approx 1.0 \pm 0.04$ (±8.6% systematics)

- e-C, and μ-C are in agreement

Constraints are not as good as one would like

E08-007 Part II

- **High precision (≈1%)** survey of FF ratio at Q^2 = 0.01 – 0.05 GeV^2
- Beam-target asymmetry measurement by electron scattering from **polarized** $\mathbf{NH_3}$ target
- Electrons detected in two matched spectrometers
- Ratio of asymmetries cancels systematic errors.
- **Completed data taking in May 2012 and currently being analyzed**



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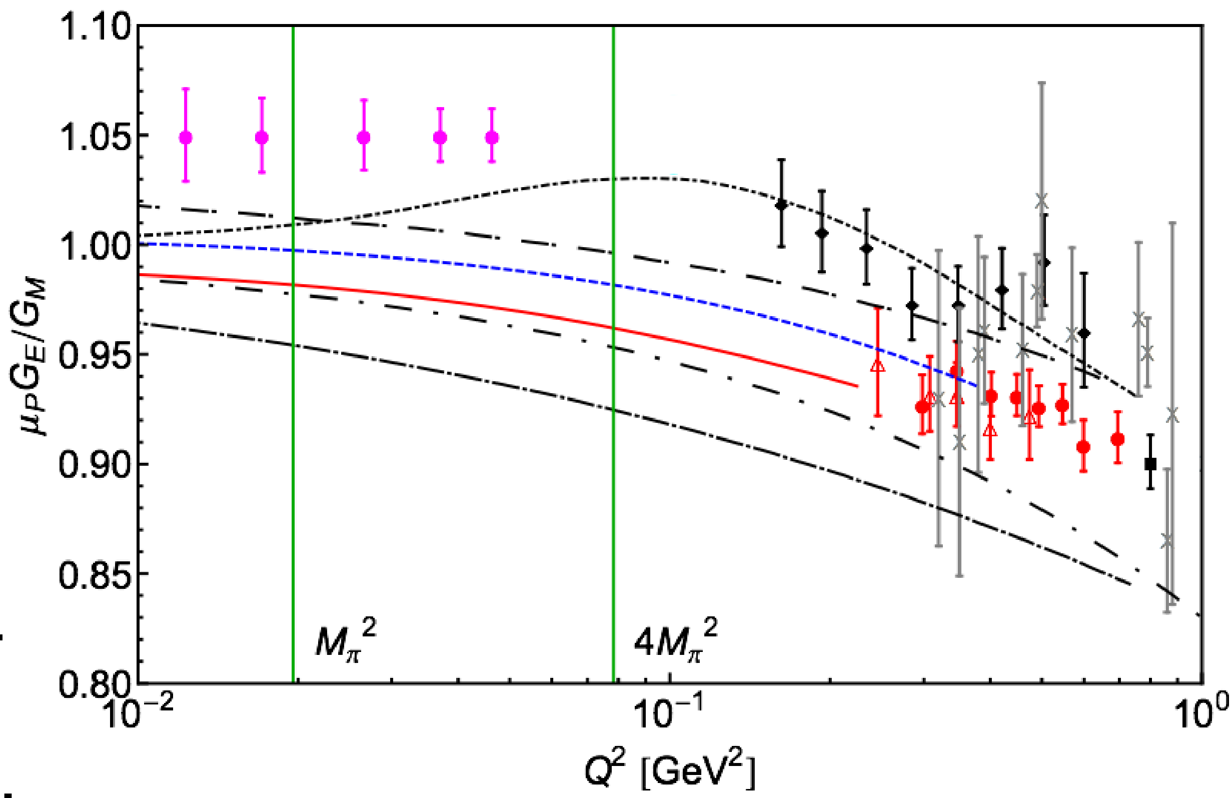

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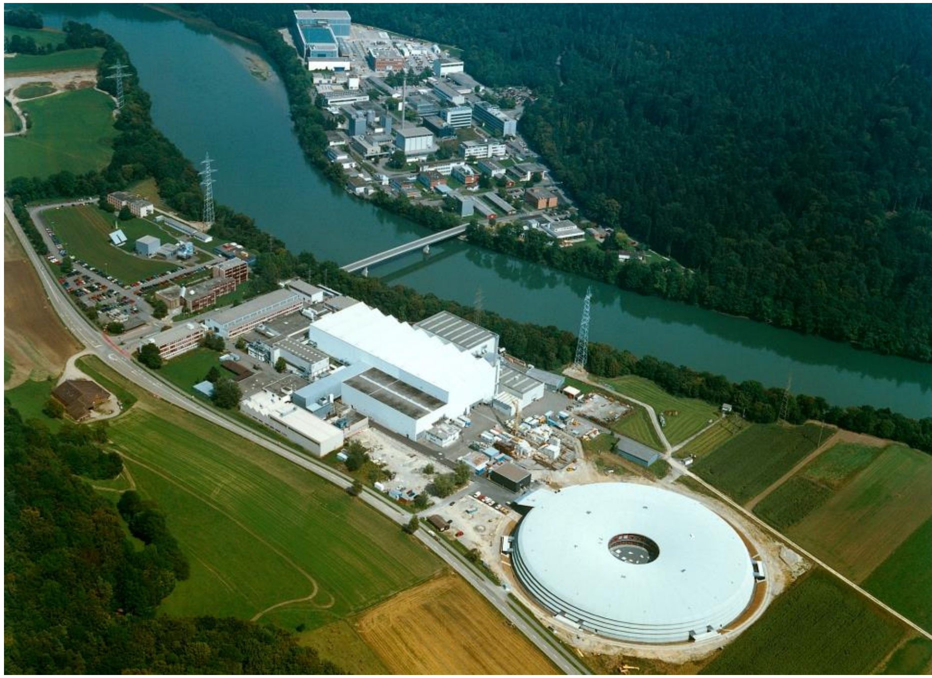
Approved Experiment: μ-p Scattering at PSI

- Directly test the most interesting possibility, that **muon** and **electron** scattering are different at Paul Scherrer Institut (PSI) in Switzerland:
  - to higher precision, in the low Q^2 region for sensitivity to the radius
  - Measuring both $\mu-p$ and $e-p$ to have direct comparisons and a robust, convincing result.



- Depending on the results, a 2nd generation experiment might be desirable.

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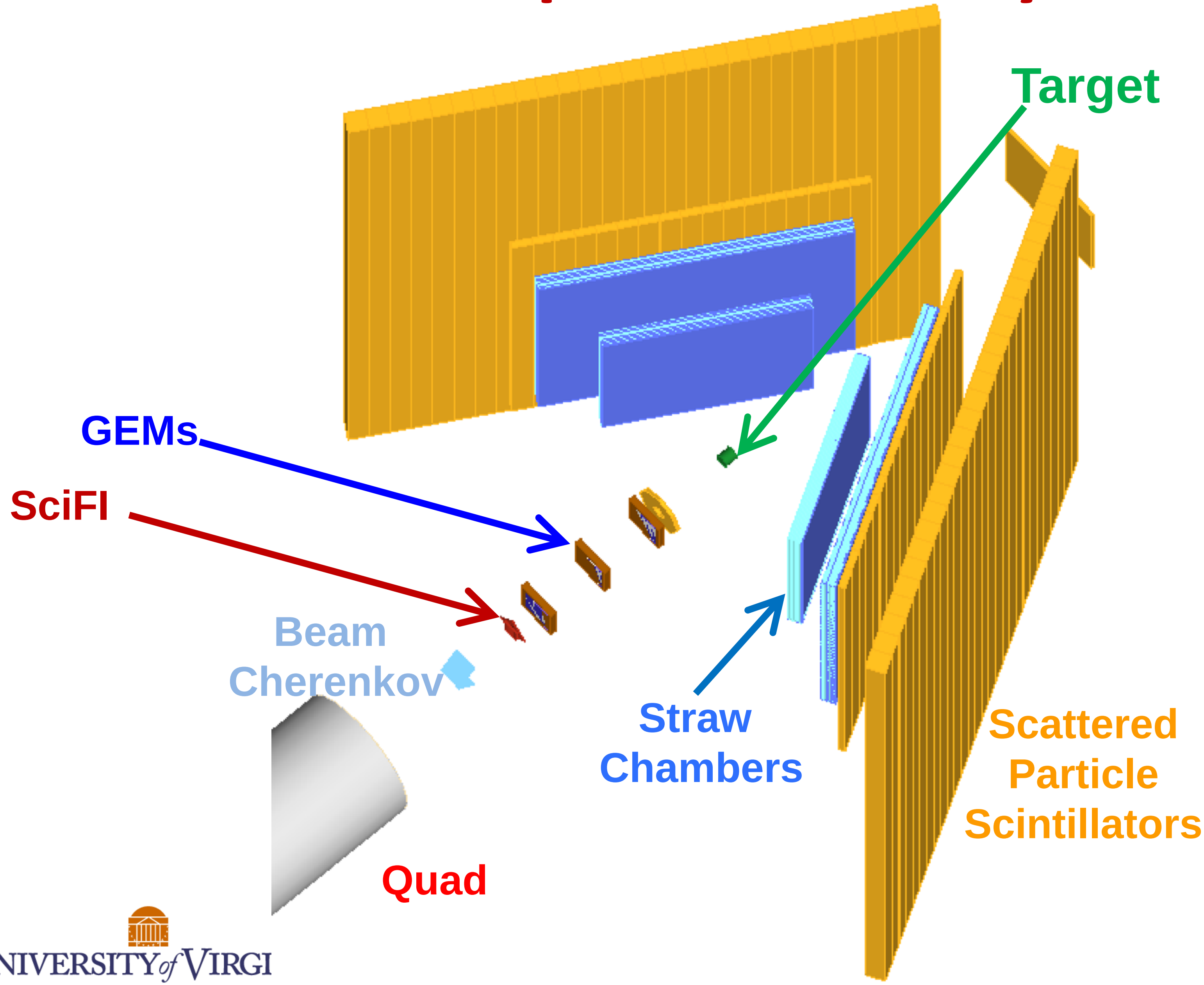
MUSE Experimental Layout



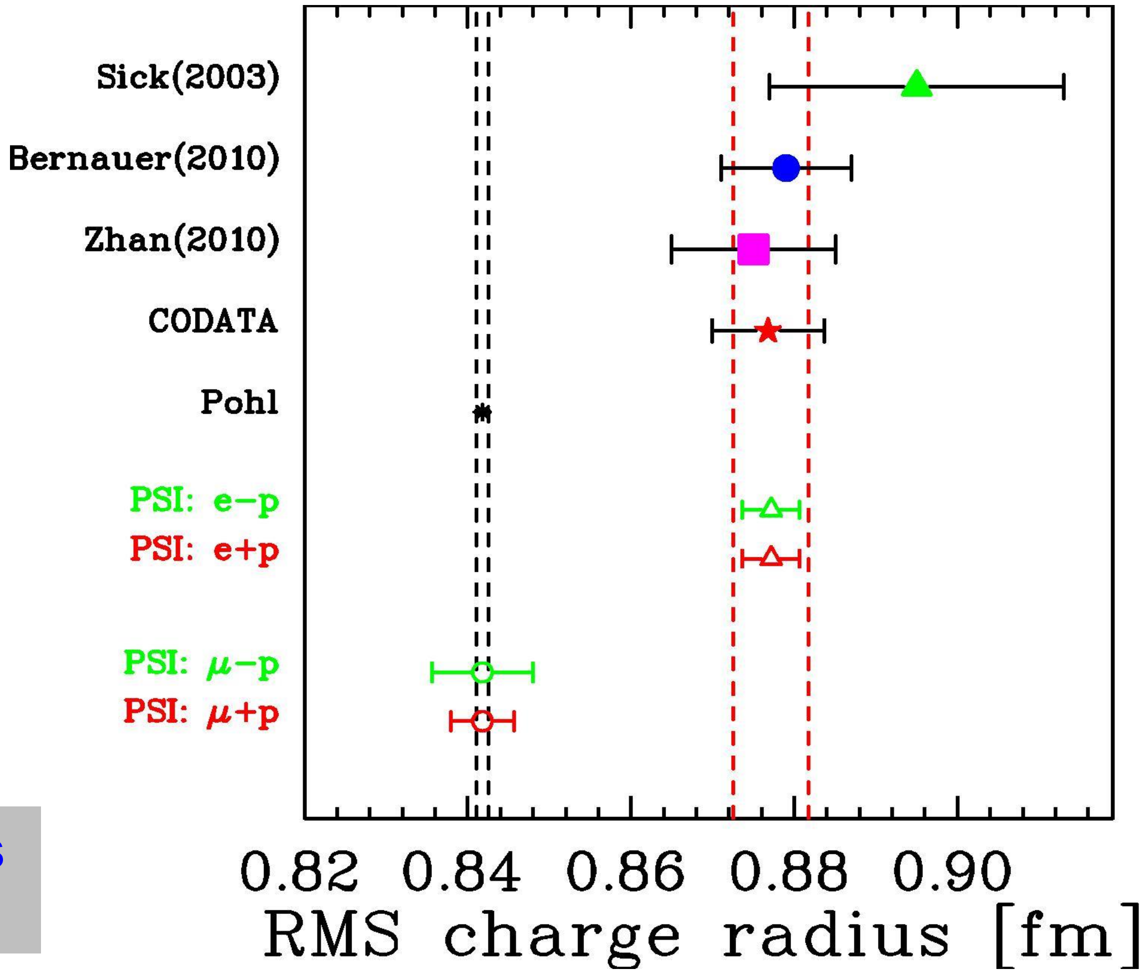
Projected Sensitivity

Charge radius extraction limited by systematics, fit uncertainties

Comparable to existing electron-proton 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 a factor of 2



Should measure $r_{ep} - r_{\mu p}$ = 0.0 vs. 0.034 to ≈ ±0.0045

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MUSE Time Line

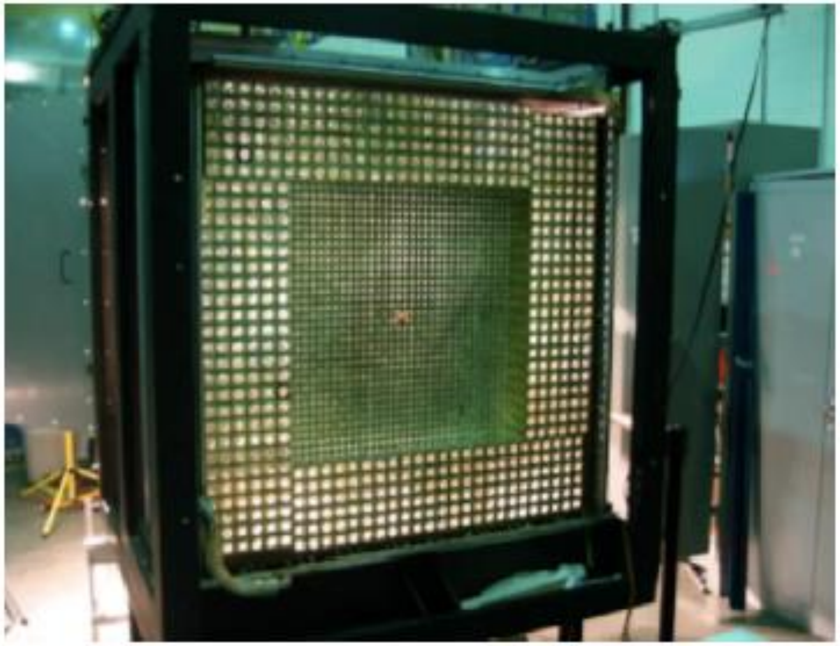
Feb 2012	Physics Approval, proposal Deferral
July 2012	PAC/PSI technical review
Fall 2012	Test run in πM1 beam-line
January 2013	Experiment approved
Summer 2013	Second test run in πM1 beam-line
Fall 2013	Third test run in πM1 beam-line

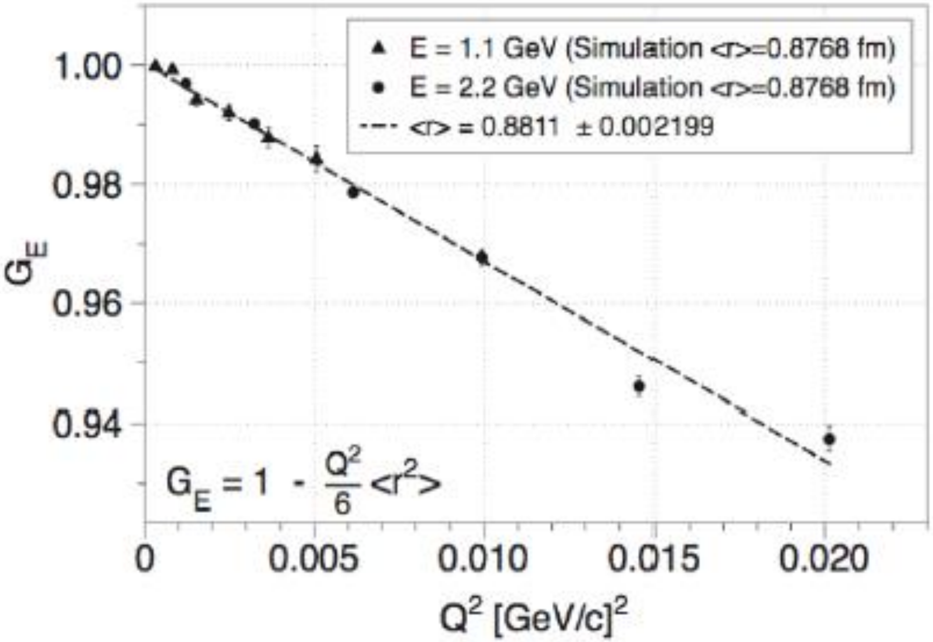
2012 Test run verified the basic properties of the muon beam at PSI.

MUSE Time Line

2013-2014	Seek funding via grant proposals
June 2014	Beam tests in πM1 beam-line
mid 2014	Start development activities (TBD)
December 2014	Beam tests in πM1 beam-line
February 2015	PSI review
Mid 2015	Mini-dress rehearsal
Late 2016	Dress rehearsal
2017-2018	2 year experiment run

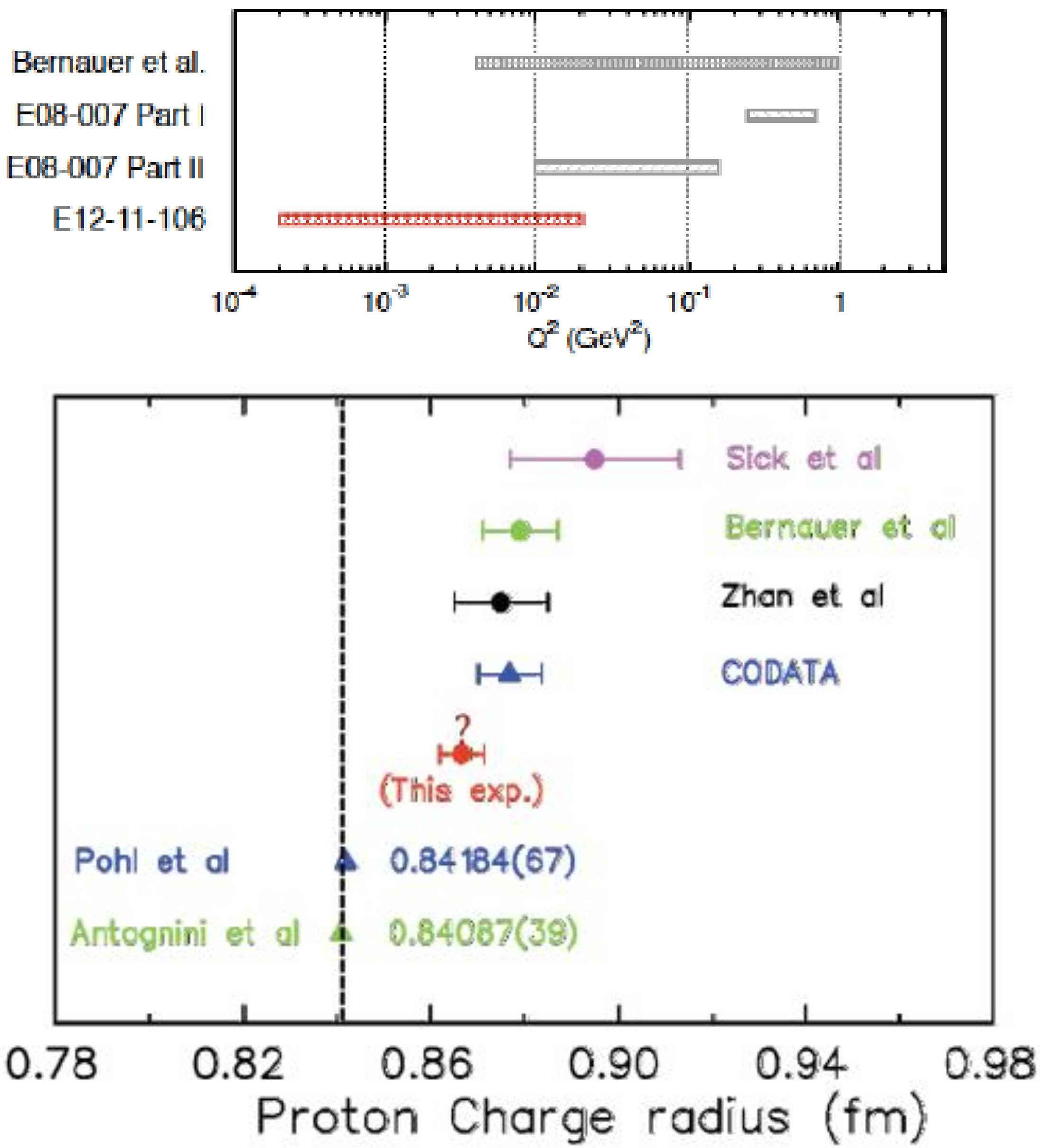
PRad Proton Radius Experiment (JLab)





- Low intensity beam in Hall B @ JLab into windowless gas target
- Scattered ep and Moller electrons into HYCAL at 0°
- Lower Q^2 than Mainz. Very forward angle, insensitive to 2γ, G_M
- **Approved June 2012, A-rated experiment**

Expected Q^2 Range & Precision of PRad



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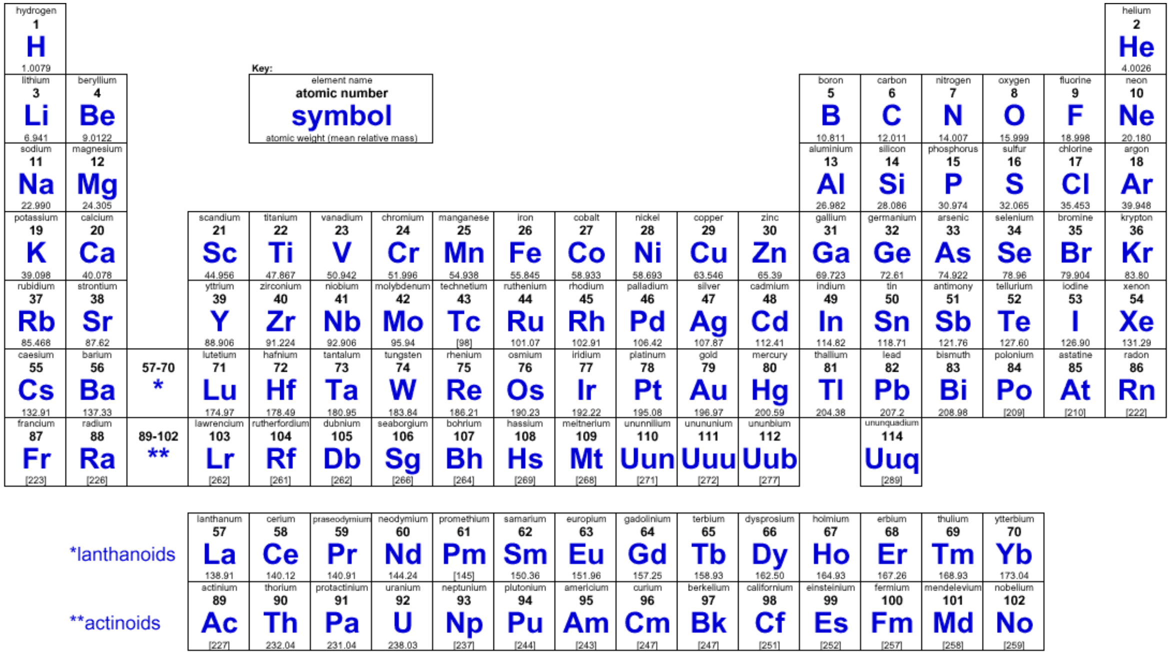
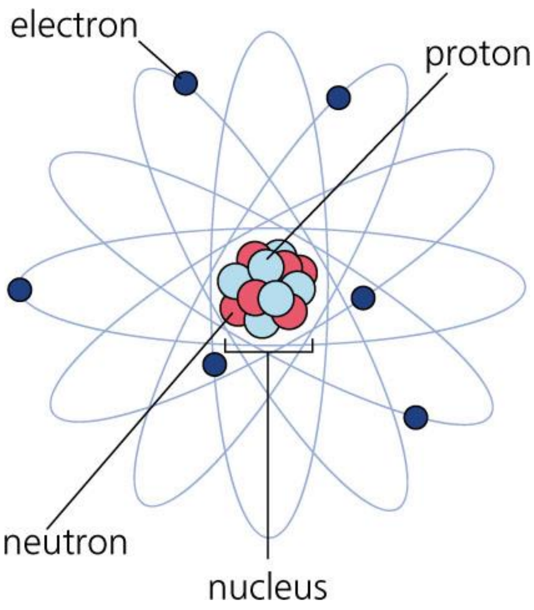
Periodic Table of Elements

Notice there are no nuclei that only contain neutrons





Protons, neutrons, and electrons <u>seem</u> like our fundamental particles.

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Why is the structure of the neutron interesting?

1) At first glance the proton and neutron are very similar:
   a) Approximately the same **mass** (1.3 MeV difference)
   b) Both **spin-1/2**
2) But clearly they are different:
   a) Charge: +1 versus 0 (**Electrostatics**)
   b) Magnetic moment: +2.79 versus -1.91 (**Magnetism**)
   c) Stability: proton seems to be stable, neutron decays (**Weak force**)

To fully check our understanding of the **strong force**, it would be negligent to ignore the neutron and solely focus on the proton, especially since we rely on effective theories and models to approximate QCD

However, there are no nuclei that only contain neutrons and free neutrons decay in 15 minutes.

Light Nuclei as Effective Neutron Targets

- **Proton** is well known and its properties are reasonably measured.

- **Neutron** not understood to a desirable accuracy, especially charge, magnetization and spin distributions

Problem: no neutron target, direct measurements not possible.

Solution: indirect measurements using appropriate targets:

1) **Deuteron**

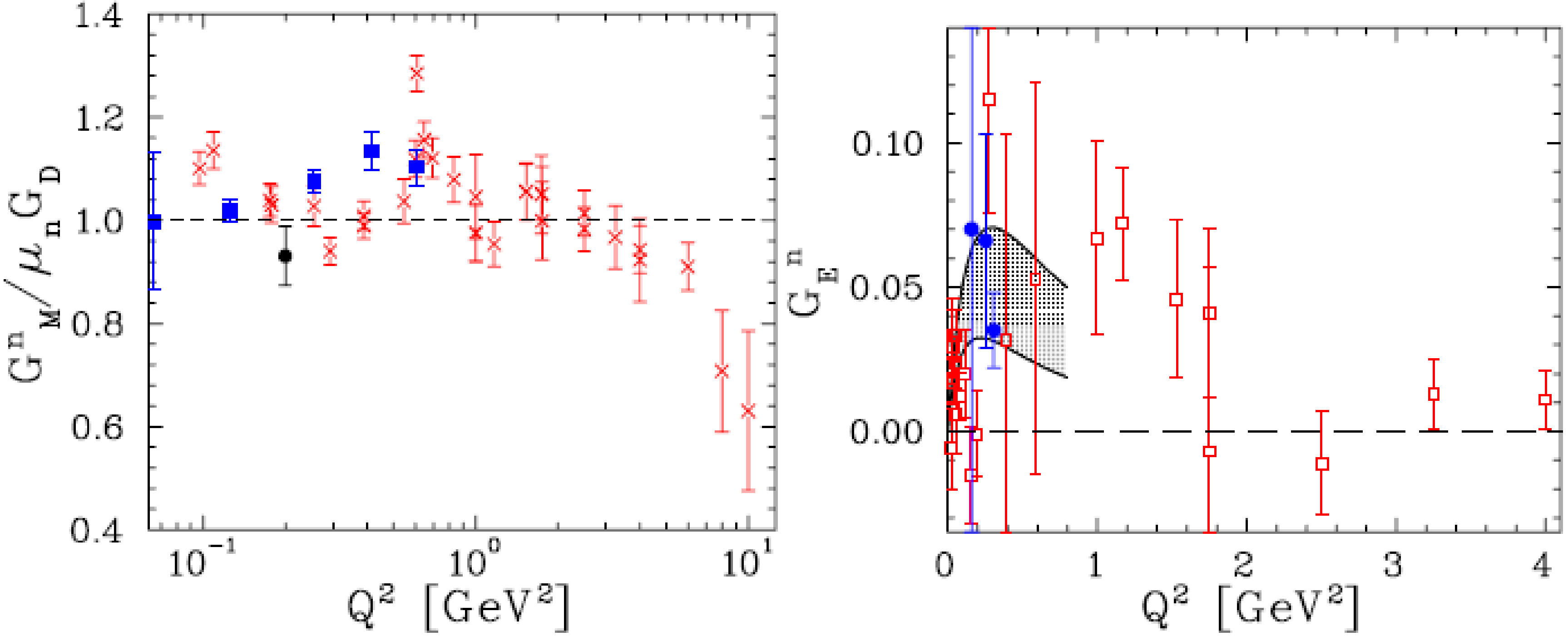
Proton + Neutron

2) ^{3}**He**

Two Protons + Neutron

Detailed knowledge on the **structure of light nuclei is crucial** for extracting precise information on **neutron structure**.

Neutron Form Factors Before JLab



J. Arrington et al., JoP **299**, 012002 (2011)

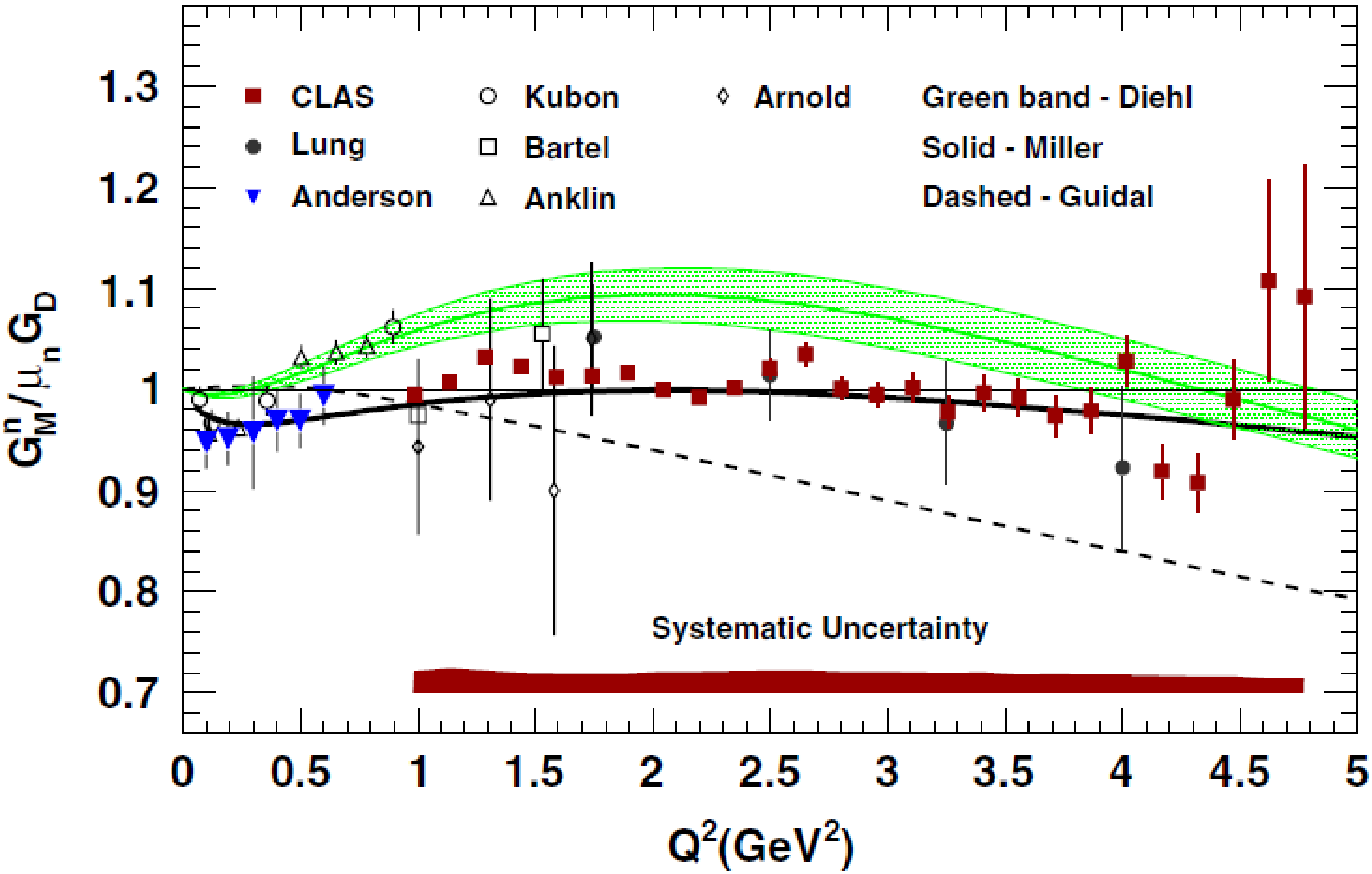
Measuring G_M^n by the Ratio Method

QE scattering: simultaneous d(e,e'p) and d(e,e'n)

$$\frac{d(e,e'n)}{d(e,e'p)} \sim \frac{n(e,e')}{p(e,e')} \sim \frac{\kappa\left(G_E^2 + \frac{\tau}{\varepsilon} G_M^2\right)}{\sigma_p(e,e')}$$

- Bound-nucleon effects should be very small in ratio
- Expect $G_E << G_M$ so correction is very small
- Many experimental systematic effects cancel in ratio
- Neutron/proton acceptance and detection efficiency

Results on G_M^n from Hall A and CLAS



J. Lachniet et al., PRL **102**, 192001 (2009)
B. Anderson et al., PRC **75**, 034003 (2007)

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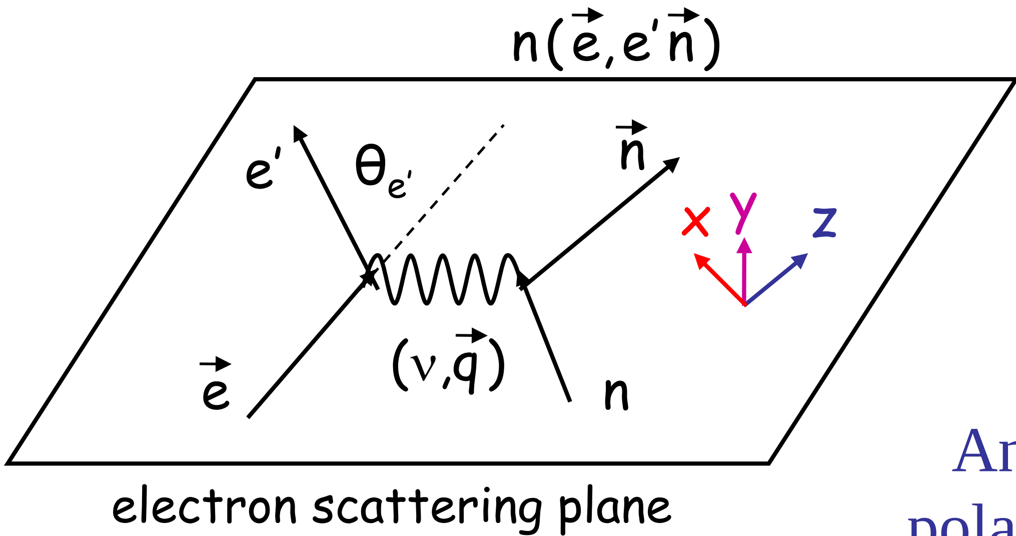
Measuring G_E^n/G_M^n Using Recoil Polarimetry



Recoil polarization

$$P_x = -P_e K_t G_{En} G_{Mn}$$

$$P_z = P_e K_\ell G_{Mn}^2$$

Analyzed by second scattering in polarimeter with analyzing power A_y

Ratio Technique:
Measure P_x and P_z

$$\rightarrow \frac{P_x}{P_z} = -\frac{K_t}{K_\ell}\frac{G_{En}}{G_{Mn}} \rightarrow$$

small systematics
$A_y(\theta)$ and P_e cancel

- Electrons detected in spectrometer
- Neutron spin precessed in dipole magnet
- Neutron detected, polarization analyzed in neutron polarimeter
- Detect two linear combinations of P_x and P_z (two spin precession angles)

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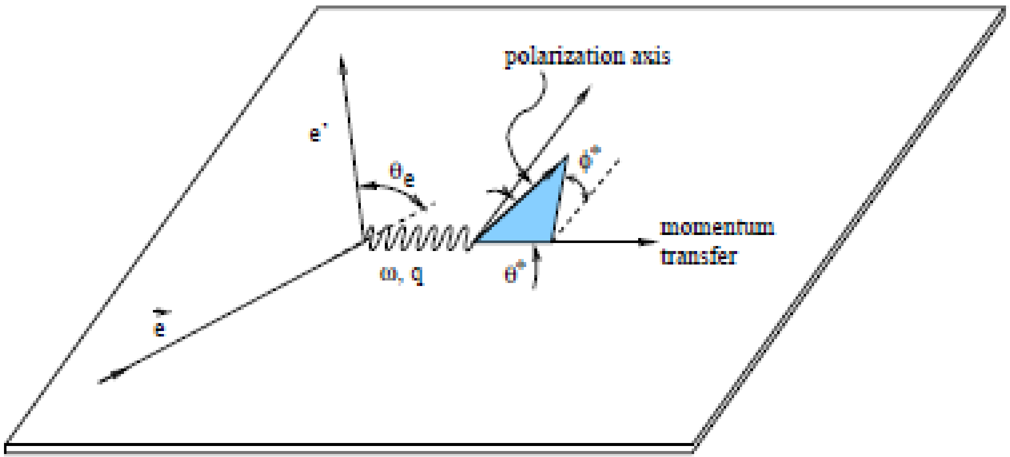
Polarized Target Measurements

Longitudinal polarized beam/target transverse to $\vec{q}$ in scattering plane



Helicity-dependent asymmetry roughly proportional to G_E/G_M

$$\frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} \approx A_\perp = -\frac{2\sqrt{\tau(\tau+1)}\tan(\theta/2) G_E/G_M}{(G_E/G_M)^2 + (\tau + 2\tau(1+\tau)\tan^2(\theta/2))}$$

Caveats of Measuring Asymmetries

Asymmetry:

$$A_{meas} = \frac{N^{+} - N^{-}}{N^{+} + N^{-}}$$

Asymmetry Uncertainty: $1/\sqrt{(N_{total})}$, where $N_{total} = N^{+} + N^{-}$

- The physics asymmetry is diluted by the unpolarized target material, which also increases the uncertainty on the asymmetry

$$A_{phys} = \frac{A_{meas}}{f \cdot P_B \cdot P_T}$$

- f is a dilution factor, P_B is the beam polarization, P_T is the target polarization

Typically these factors are much less than 1 and dependent on the target material

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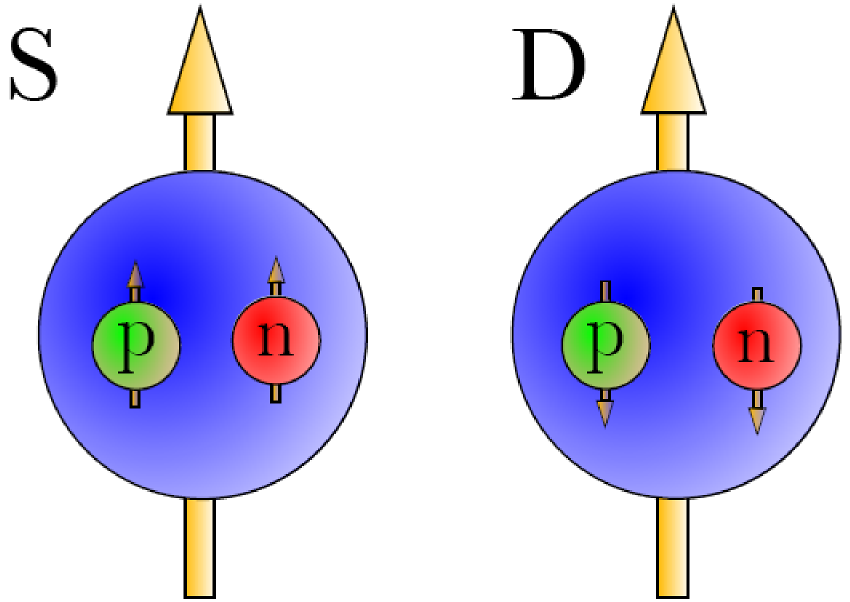
Deuterium Spin Structure

Spin-1 Particle, 2 spin-$^1/_2$ Nucleons (Proton and Neutron)

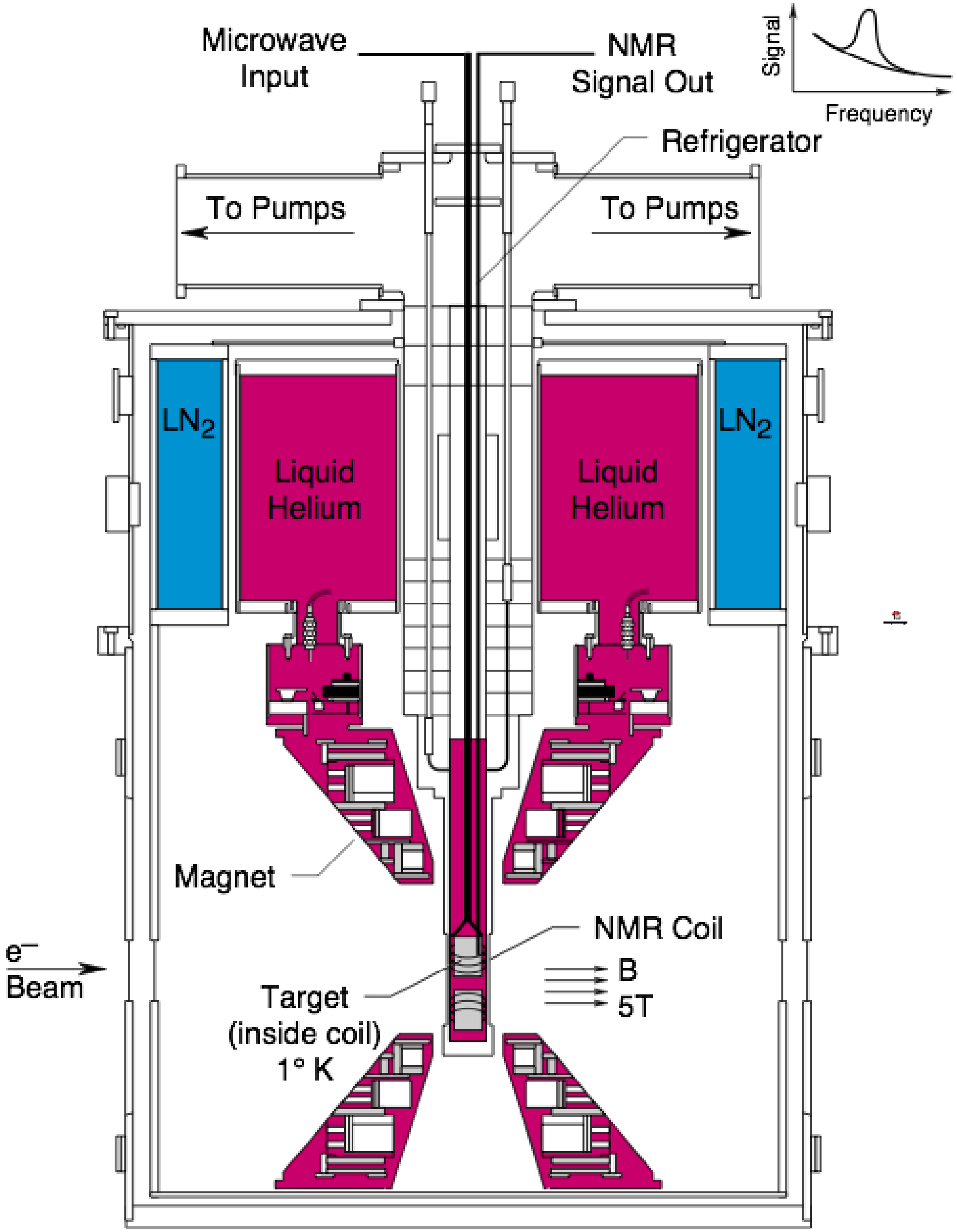


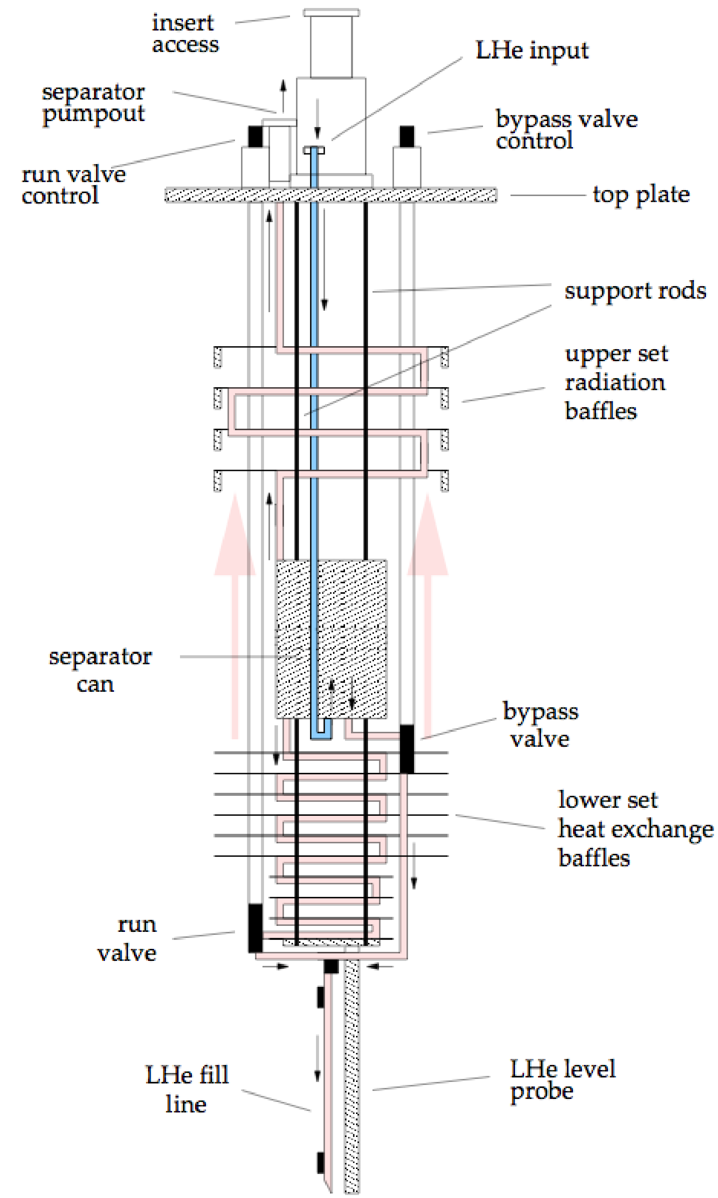
Angular Momentum L=0 ~90% L=2 ~10%

Requirements for DNP

- Target material doped with paramagnetic centers
- Cryogenic system to reach temperatures of < 1K
- Magnetic field > ~ 2 Tesla
- Microwave system – 140 GHz at 5 T
- NMR to measure polarization

UVA/SLAC/JLAB Target

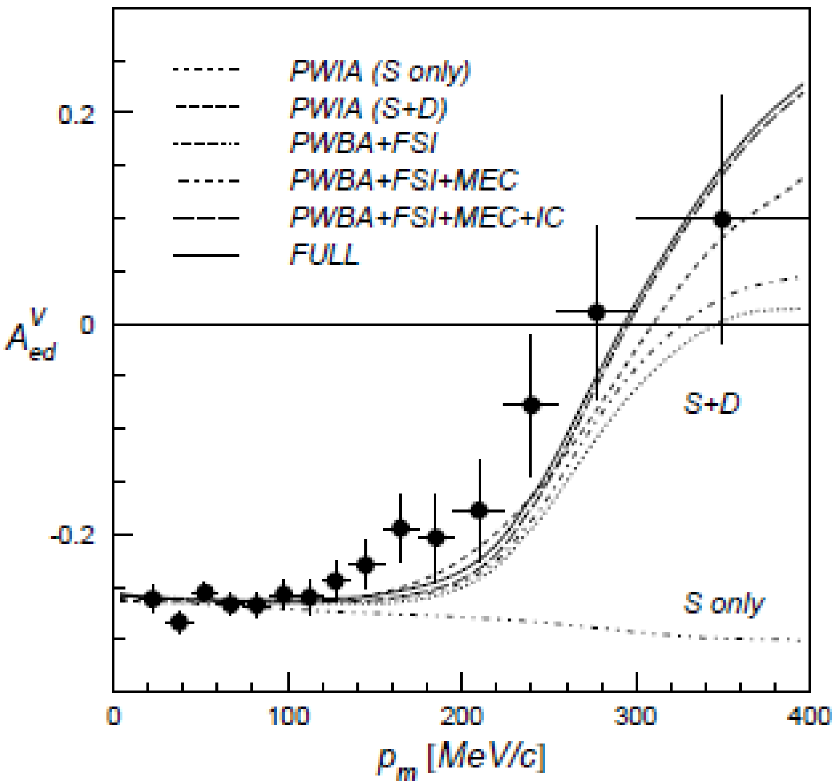




Asymmetry Measurements at NIKHEF

$$\vec{D}(\vec{e}, e'p)n$$

- A sign flip of asymmetry is a clear sign that **D-state component manifests itself in the nucleus at high p_{miss}**
- Sign flip happened at around Fermi momentum of deuterium nucleus
- **Asymmetries** are the ratio of cross-section differences over the unpolarized cross-section for different orientations of electron and target spins



Passchier *et al.*, Phys. Rev. Lett. **88** (2002) 102302.

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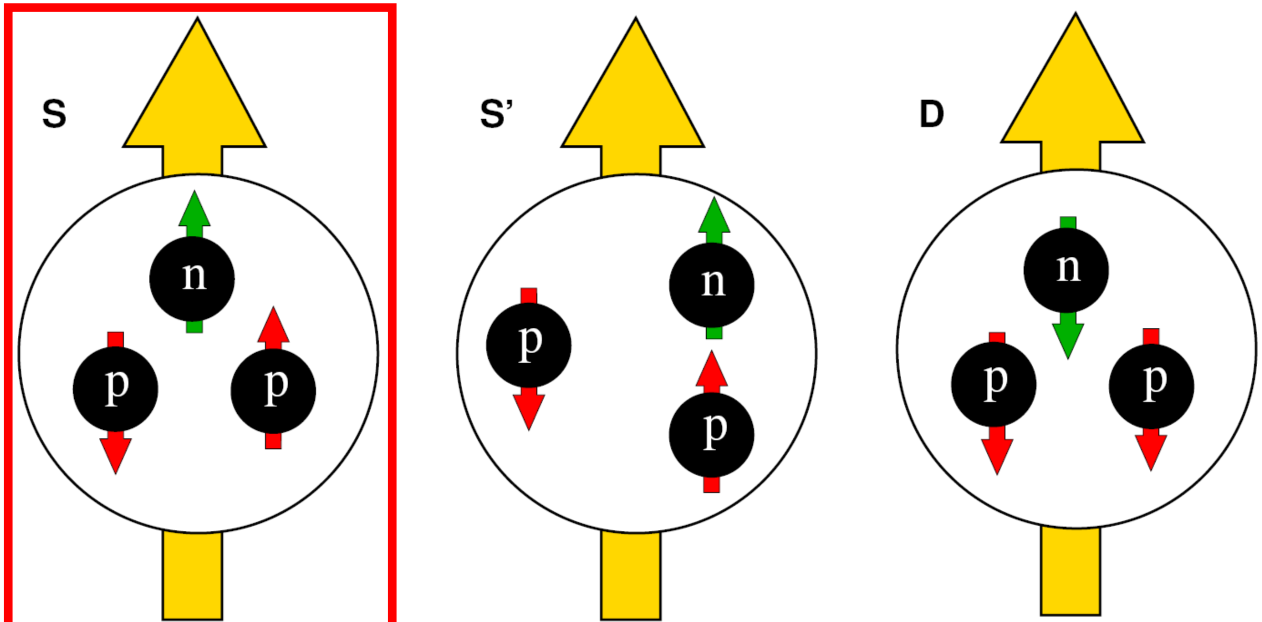
^{3}He spin structure

- Spin-1/2 Particle, 3 spin-1/2 Nucleons (Proton and Neutron)
- Protons are in spin-singlet state. ^{3}He spin is dominated by **n** spin. Therefore **^{3}He can be used as an effective n target**
- **S'** mixed symmetry, higher energy level compared to **S**-state

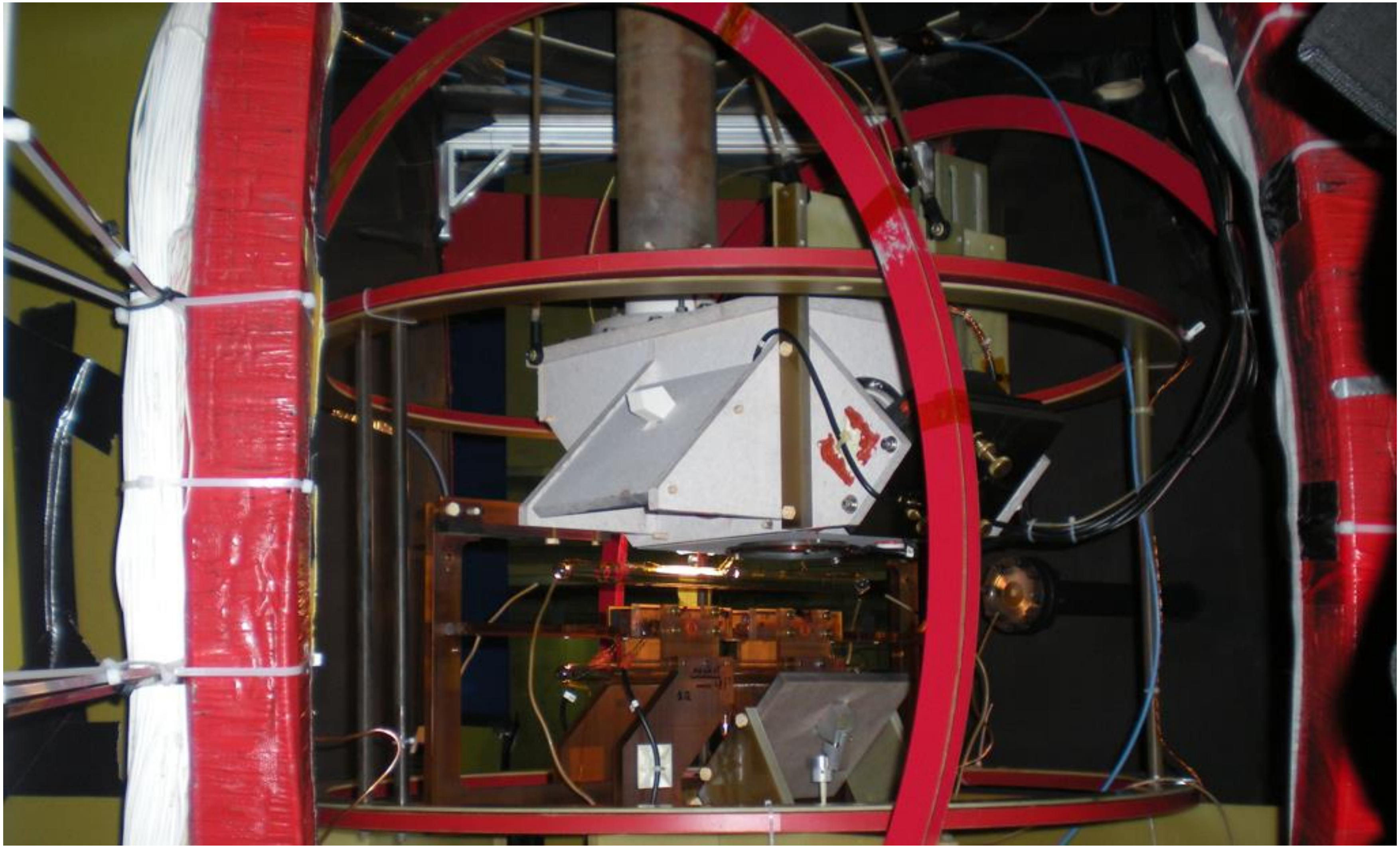
Effective Polarized Neutron Target

$$\frac{\mu_{^3He}}{\mu_n} = \frac{-2.131}{-1.913} \approx 1$$

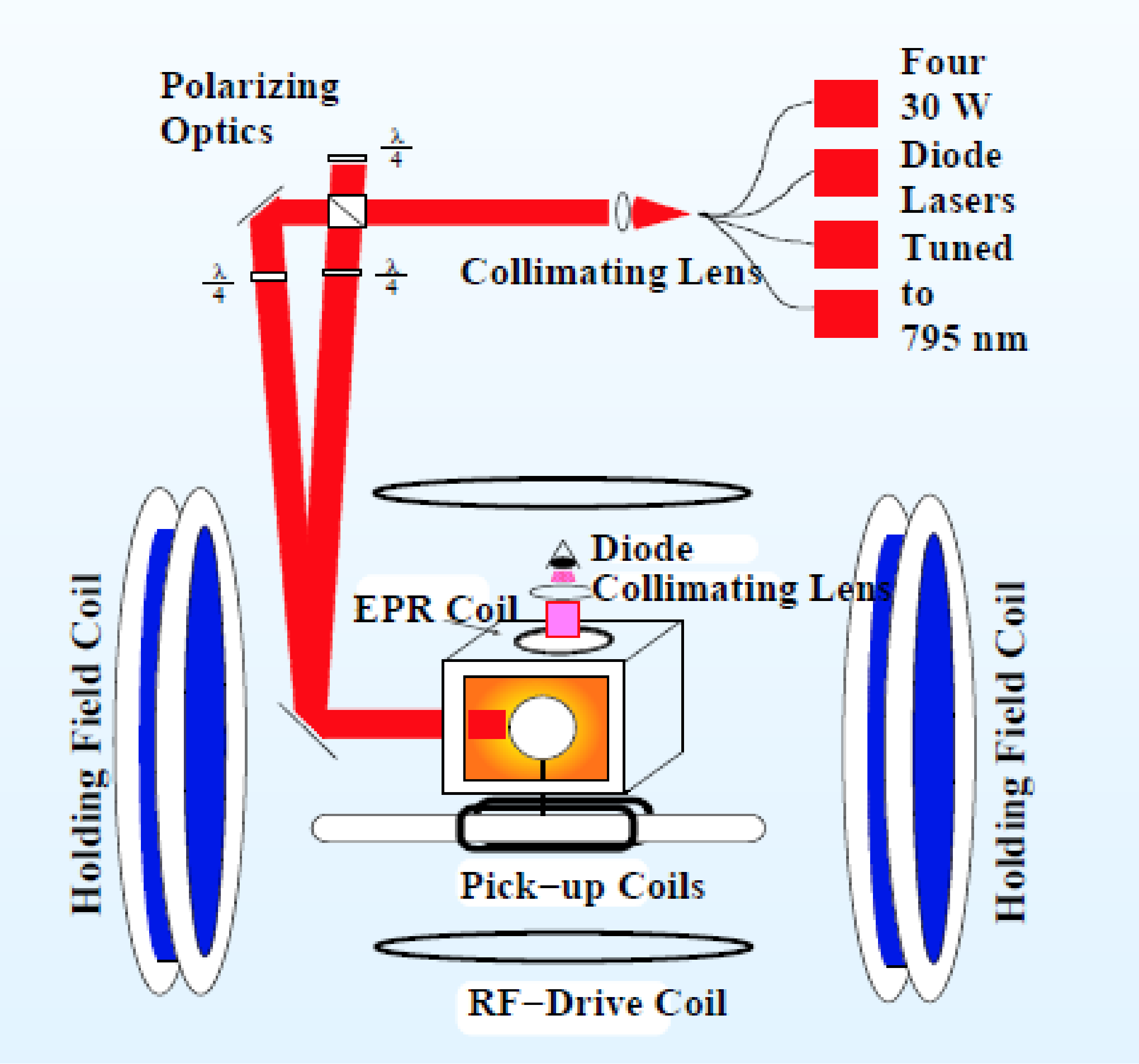


Angular Momentum:	L=0	L=0	L=2
	~90%	~1-2%	~8%

Polarized ^{3}He Target

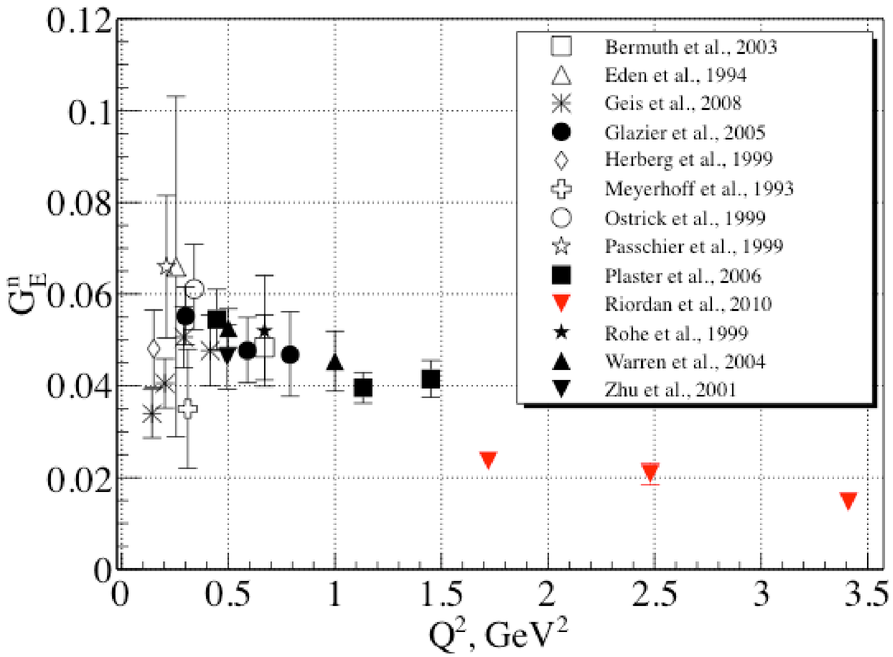


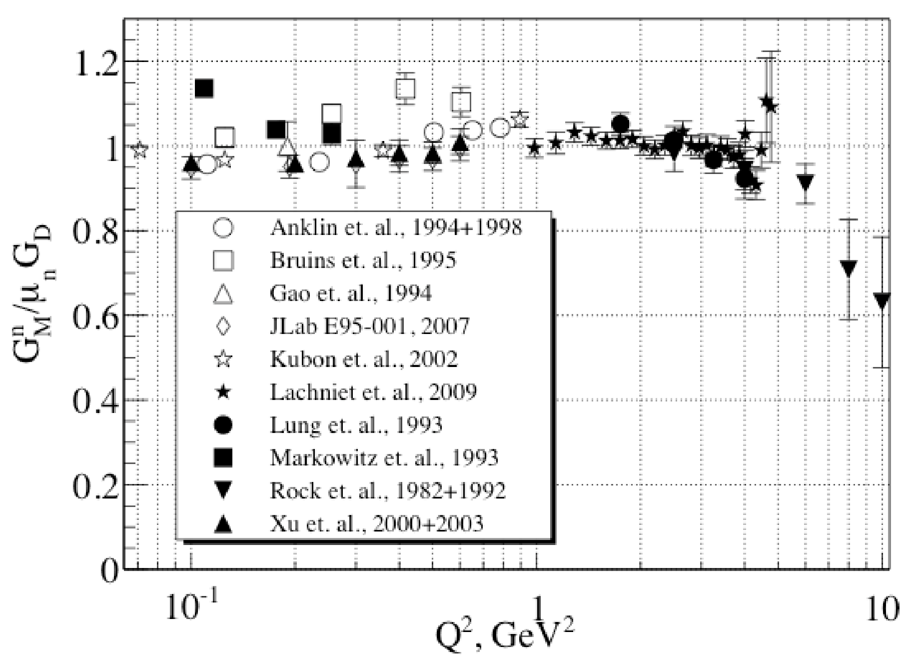
Polarized ^{3}He Target



Neutron FFs Including JLab Data

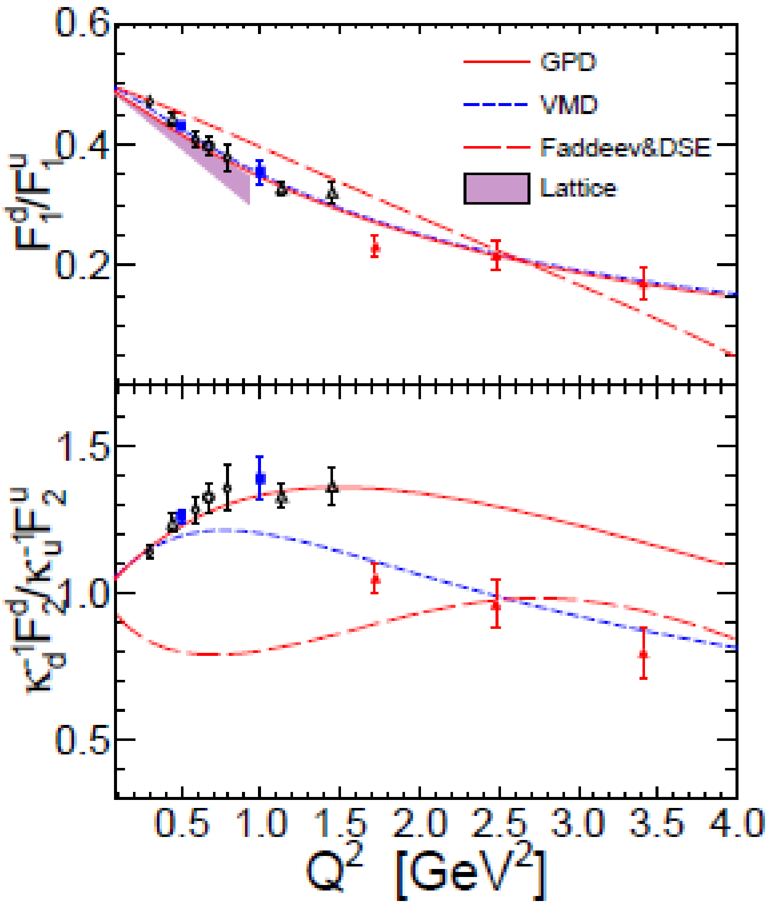
G_{En} and $G_{Mn}/\mu \sim G_D$





Requires the use of light nuclei such as the deuteron and ^{3}He

Quark Flavor Decomposition



- General Parton Distribution (GPD) models are constrained by nucleon form factors:

$$F_{1,2}^p = \frac{2}{3}F_{1,2}^u - \frac{1}{3}F_{1,2}^d$$

$$F_{1,2}^n = -\frac{1}{3}F_{1,2}^u + \frac{2}{3}F_{1,2}^d$$

- High Q^2 for G_E^n data allows for quark decomposition
- Lattice QCD is better suited for isovector FF

Lattice: Bratt et al., arXiv: 1001.3620, m_π = 140 MeV

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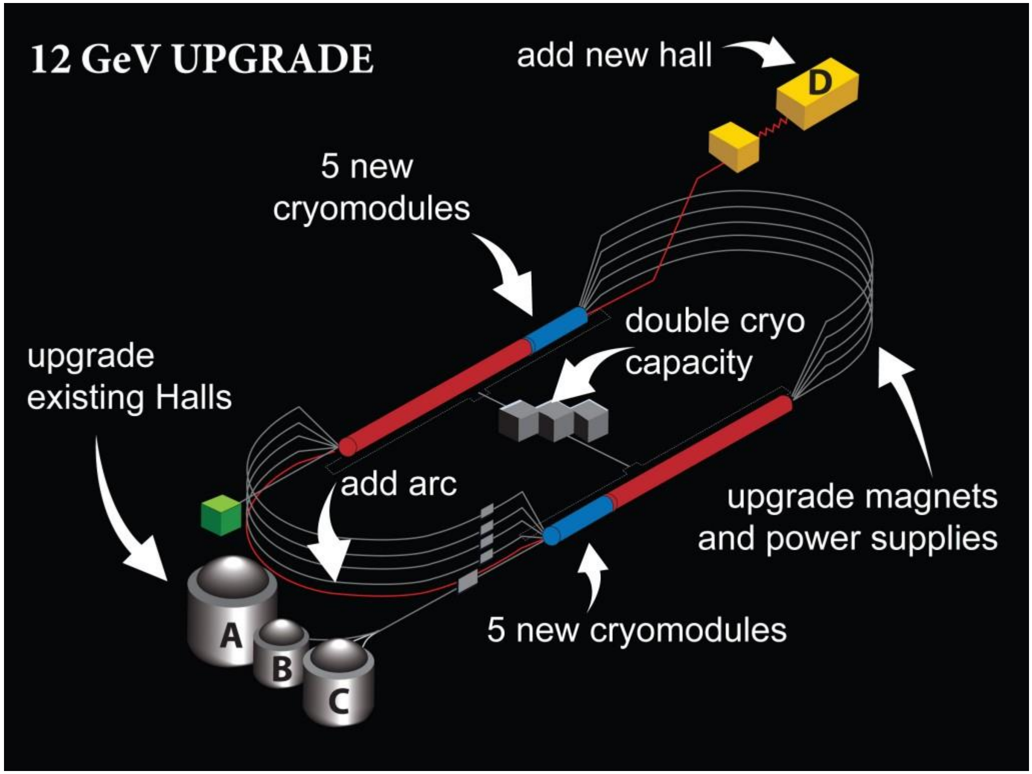
JLab 12 GeV Upgrade

- JLab's 12 GeV upgrade is currently in the construction phase
- Hall D will be added
- The three current experimental halls are being upgraded
- Several new experiments are already approved to run after the 12-GeV upgrade with **6 approved form factor experiments**



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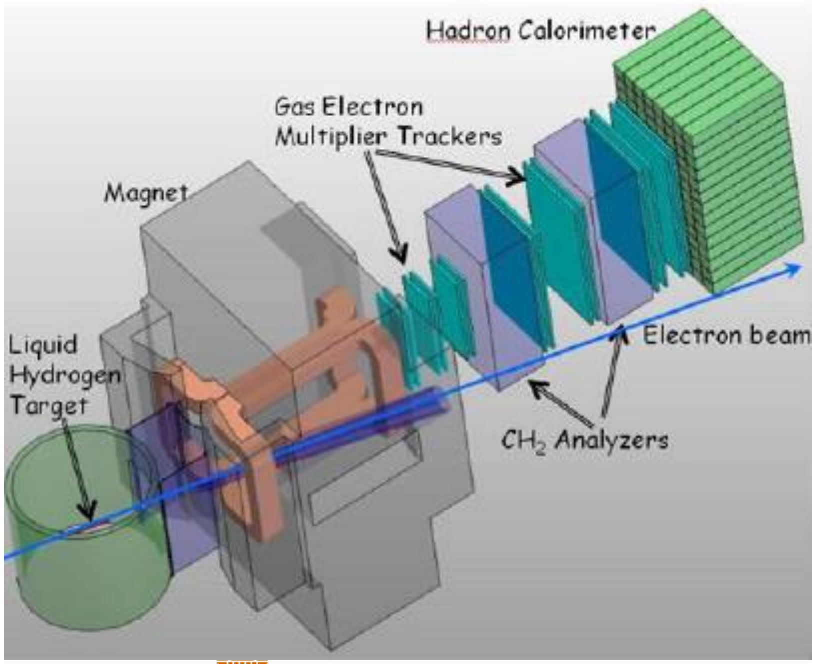
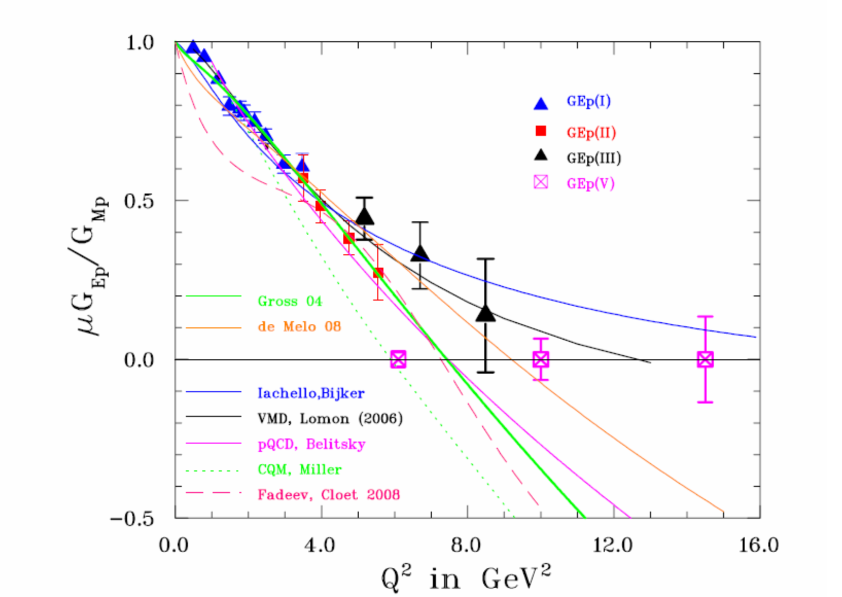
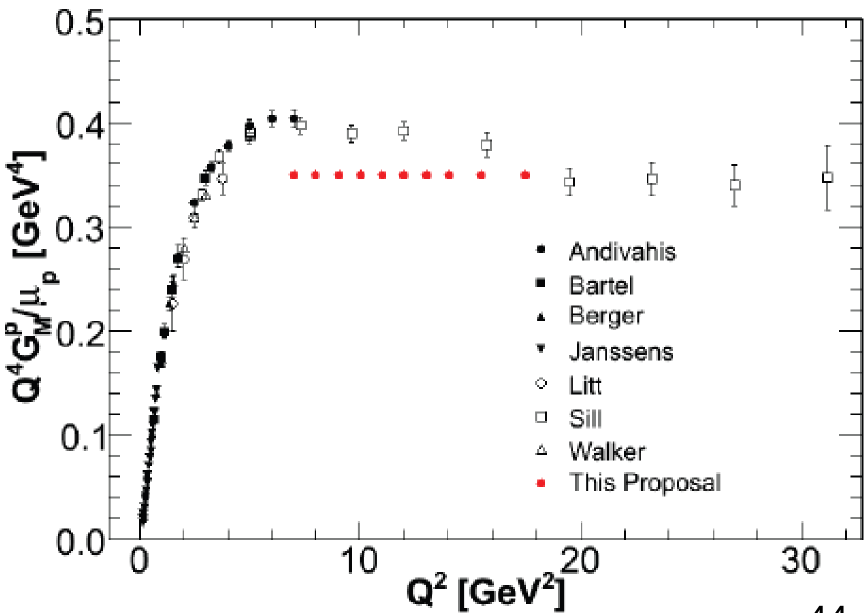
Approved FF Experiments: 12 GeV

Proton

- E12-07-108: elastic cross section experiment H(e,e')p
- E12-07-109: FF ratio experiment using Super BigBite Spectrometer (SBS)







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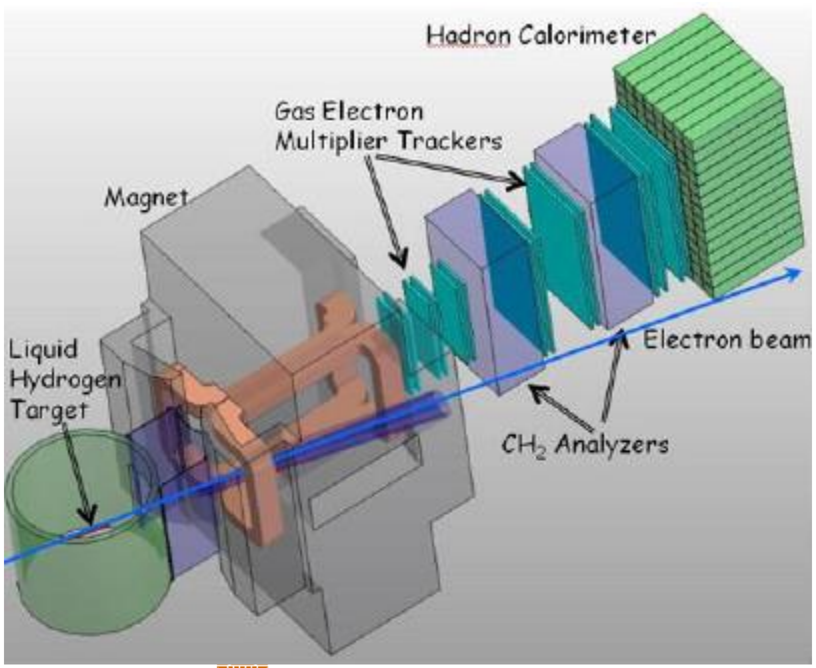
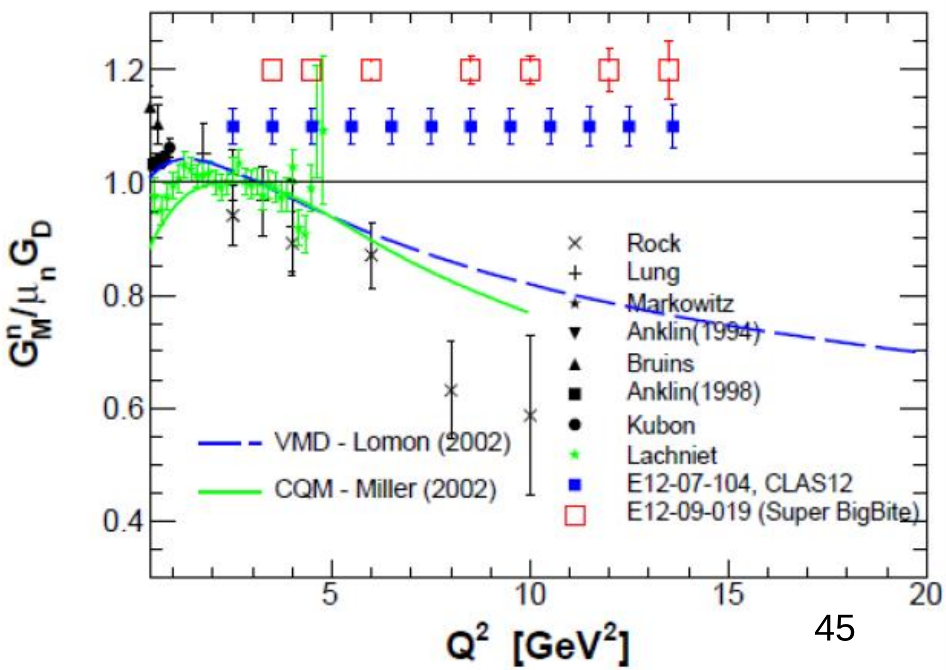


Neutron

- E12-07-108: cross section ratio: ^{2}H(e,e'n)/^{2}H(e,e'p) to measure G_{Mn} with CLAS12
- E12-09-019: also cross section ratio to measure G_{Mn} using SBS



Approved FF Experiments: 12 GeV

Proton

- E12-07-108: elastic cross section experiment H(e,e')p
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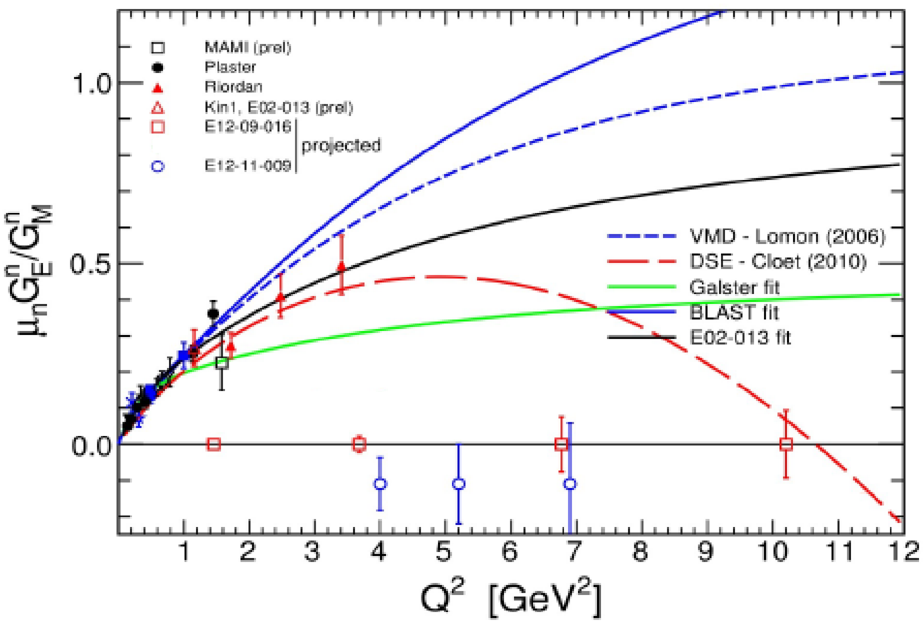

Neutron

- E12-07-108: cross section ratio: ^{2}H(e,e'n)/^{2}H(e,e'p) to measure G_{Mn} with CLAS12
- E12-09-019: also cross section ratio to measure G_{Mn} using SBS
- E12-09-016 (GEn II): polarized ^{3}He(e,e'n) using SBS, ratio G_{En}/G_{Mn}
- E12-11-009: D(e,e'n) using recoil polarimetry in Hall C to measure ratio G_{En}/G_{Mn}

Motivations to Study FFs

- Form factors are a fundamental property of the nucleon
- Provide excellent testing ground for QCD and QCD-inspired models
- Gives constraints on models of nucleon structure
- Are not yet calculable from first principles
- Electromagnetic form factors of the proton were thought to be well understood prior to Jefferson Lab data:
  - At high Q^2, discovery of significant difference between techniques
  - Proton radius puzzle at low Q^2; experiments at JLab and PSI (MUSE) continue the investigation