The g2p experiment

Jefferson Lab

Pizza Seminar
4/18/2012

Karl Slifer
University of New Hampshire

This talk

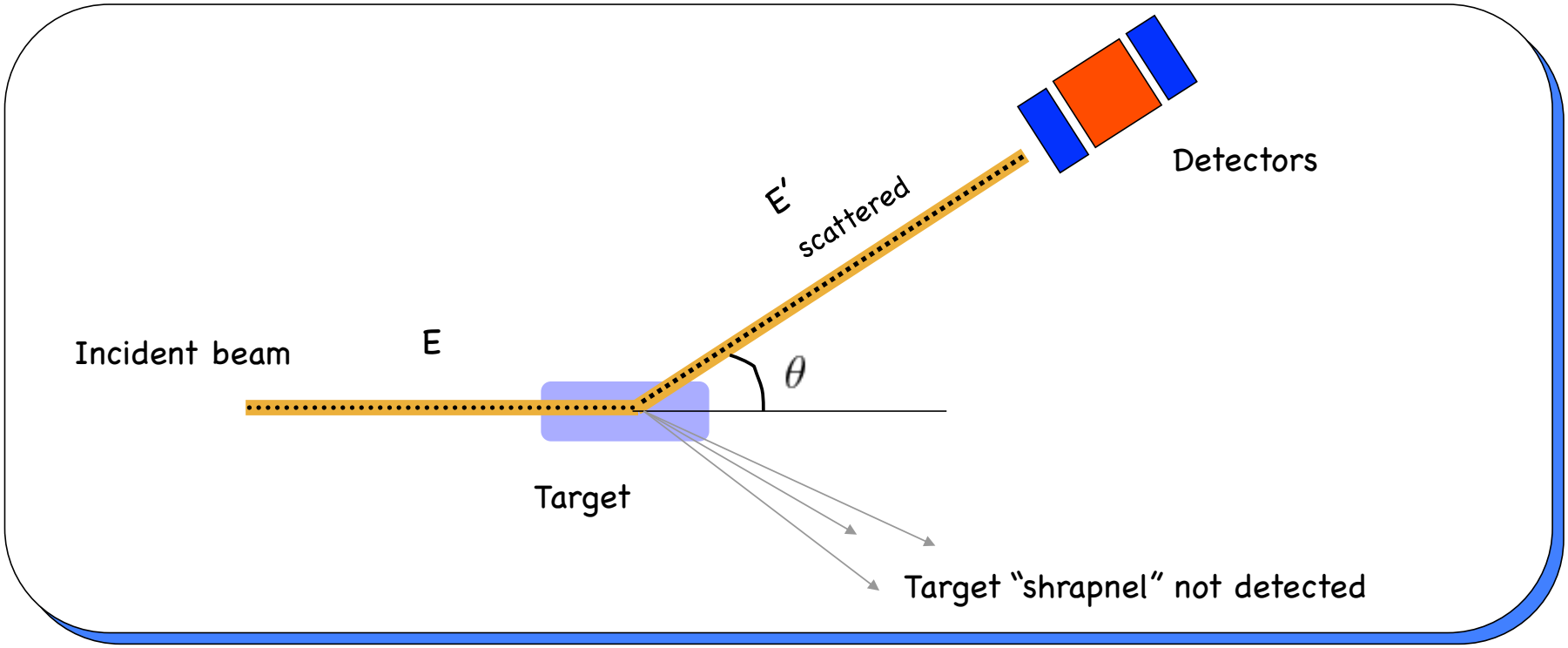
Brief review of Physics Motivation

Status/History of the Experiment

Online Results

E08-027
E08-007

"g2p & GEp"



Important Kinematic Variables

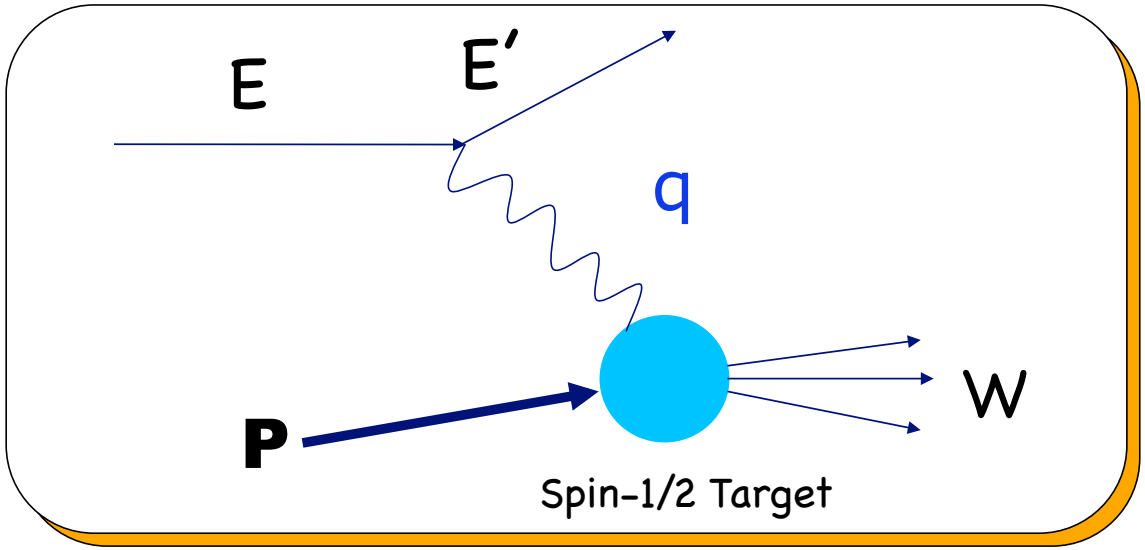
$$\nu = E - E'$$

Q^2 = Momentum transfer squared

W = Invariant Mass of target System

$$x = \frac{Q^2}{2M\nu}$$ Bjorken variable

Inelastic Scattering



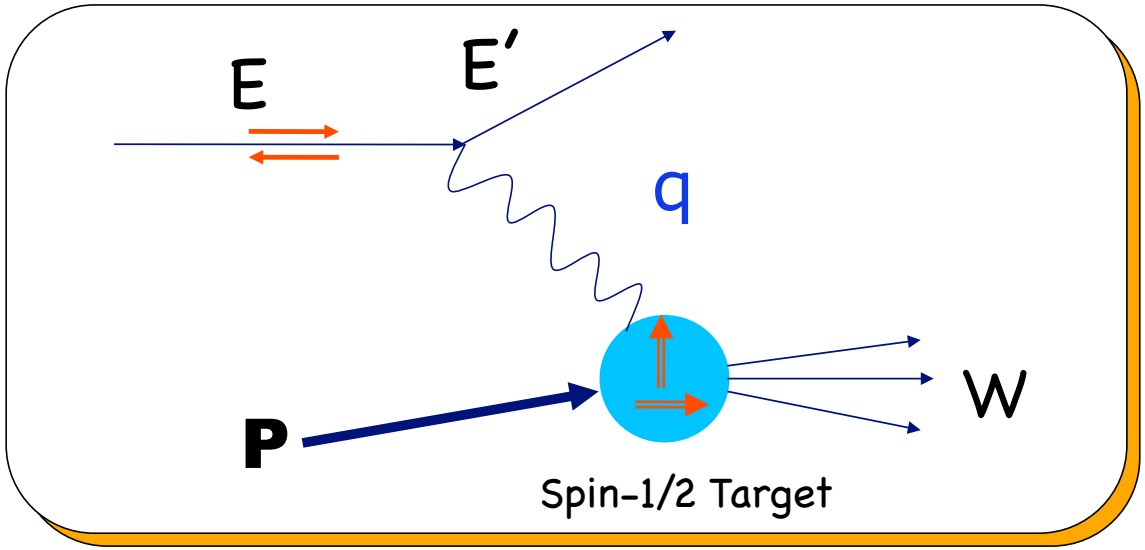
1st order Feynman diagram

Inclusive Cross Section

$$\frac{d^2\sigma}{d\Omega dE'} = \sigma_{Mott}\left[\frac{1}{\nu}F_2(x,Q^2) + \frac{2}{M}F_1(x,Q^2)\tan^2\frac{\theta}{2}\right]$$

Compositeness of target characterized by the Structure Functions

Inelastic Scattering



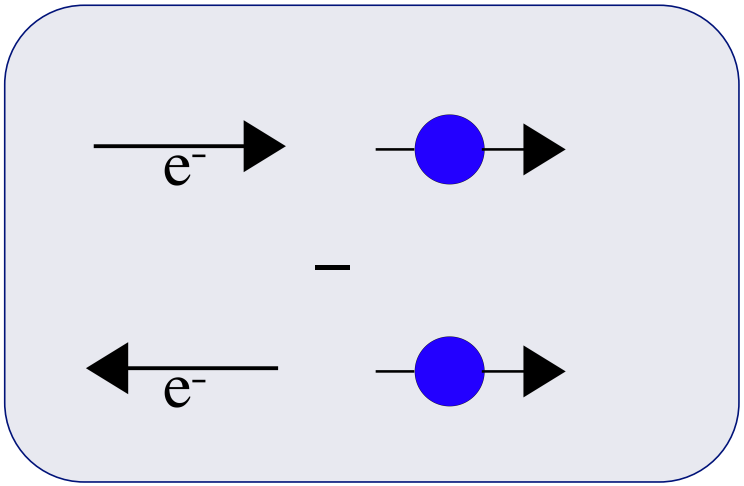
1st order Feynman diagram

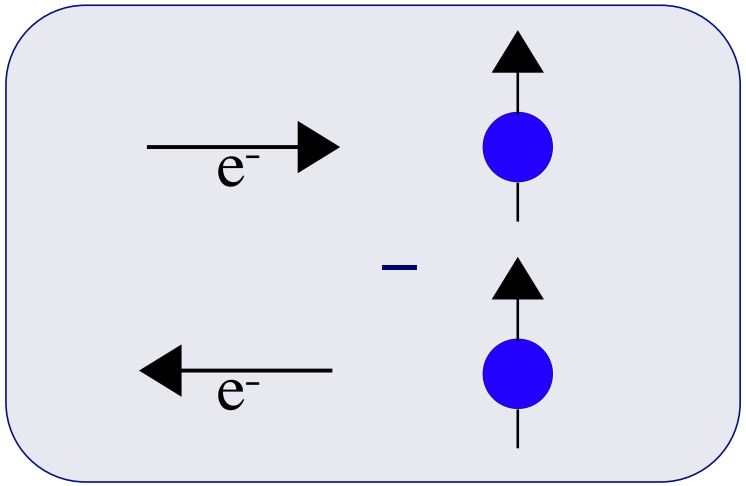
Inclusive Polarized Cross Section

$$\frac{d^2\sigma}{d\Omega dE'} = \sigma_{Mott}\left[\alpha F_1(x,Q^2) + \beta F_2(x,Q^2) + \gamma g_1(x,Q^2) + \delta g_2(x,Q^2)\right]$$

Two additional Structure Functions needed

Experimental Technique

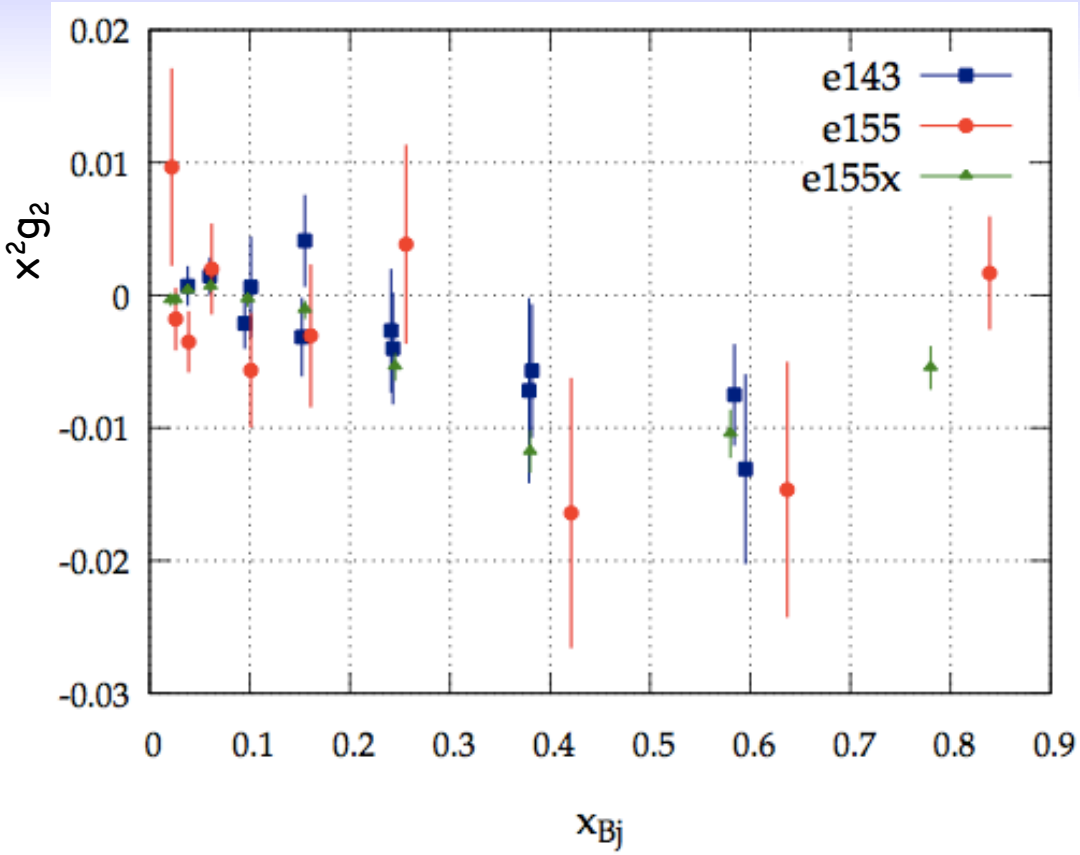




$$\frac{d^2\sigma^{\uparrow\Uparrow}}{d\Omega dE'} - \frac{d^2\sigma^{\downarrow\Uparrow}}{d\Omega dE'} = \frac{4\alpha^2}{\nu Q^2}\frac{E'}{E}\left[(E + E'\cos\theta)\, g_1 - 2Mx g_2\right]$$

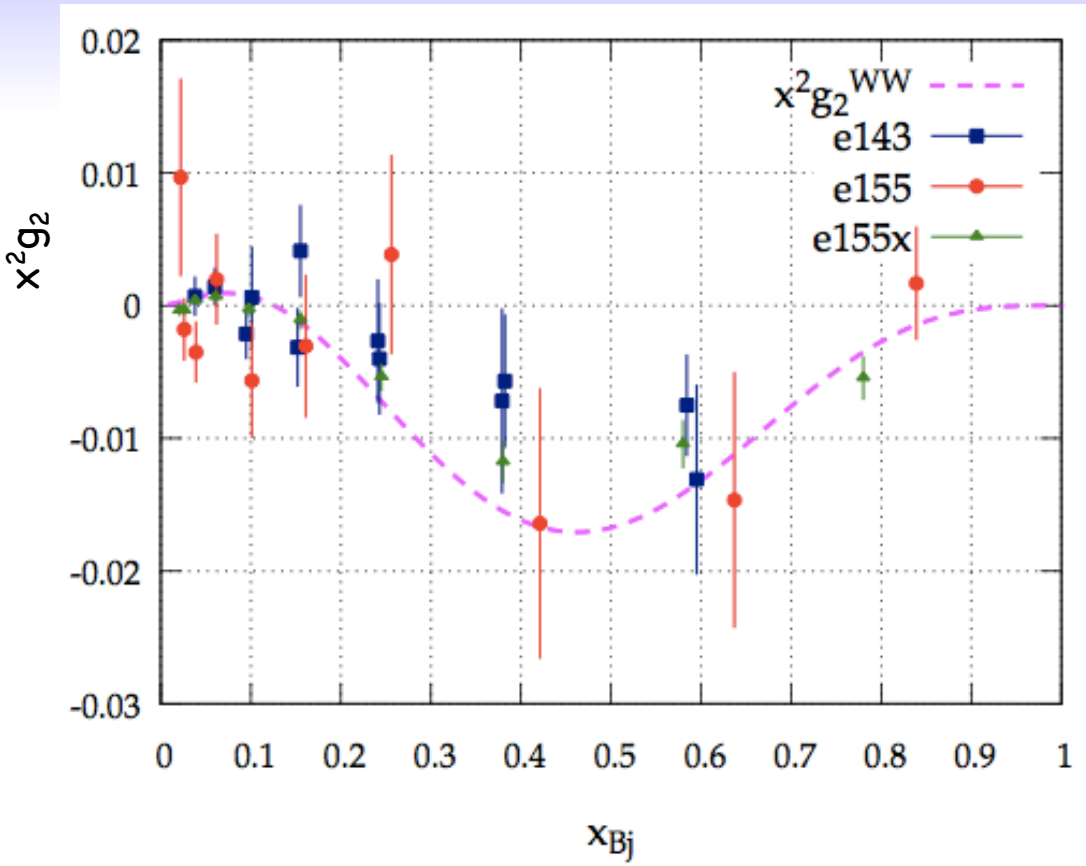
$$\frac{d^2\sigma^{\uparrow\Rightarrow}}{d\Omega dE'} - \frac{d^2\sigma^{\downarrow\Rightarrow}}{d\Omega dE'} = \frac{4\alpha^2}{\nu Q^2}\frac{E'}{E}\sin\theta\left[g_1 + \frac{2ME}{\nu} g_2\right]$$

Proton g_2 data from SLAC



$Q^2 \approx 5\ \mathrm{GeV}^2$

Proton g_2 data from SLAC



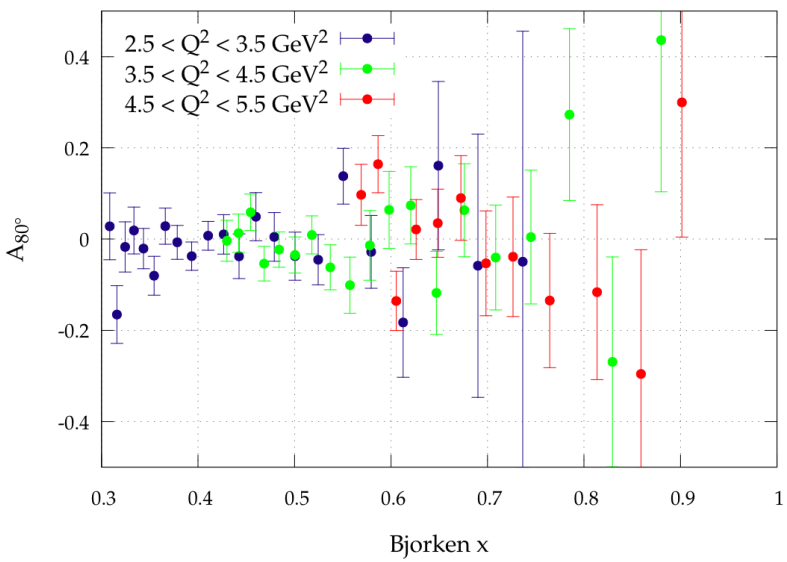
$Q^2 \approx 5\ GeV^2$

Leading Twist

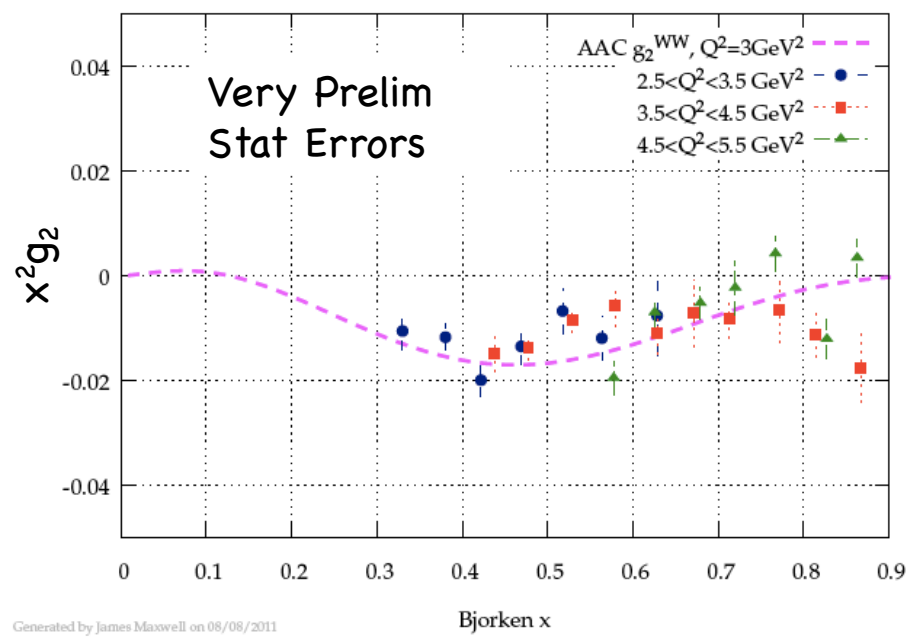
Precision does not allow unambiguous HT extraction

Proton g_2 data from JLAB SANE

$Q^2 \approx 3\text{-}6\ \mathrm{GeV}^2$

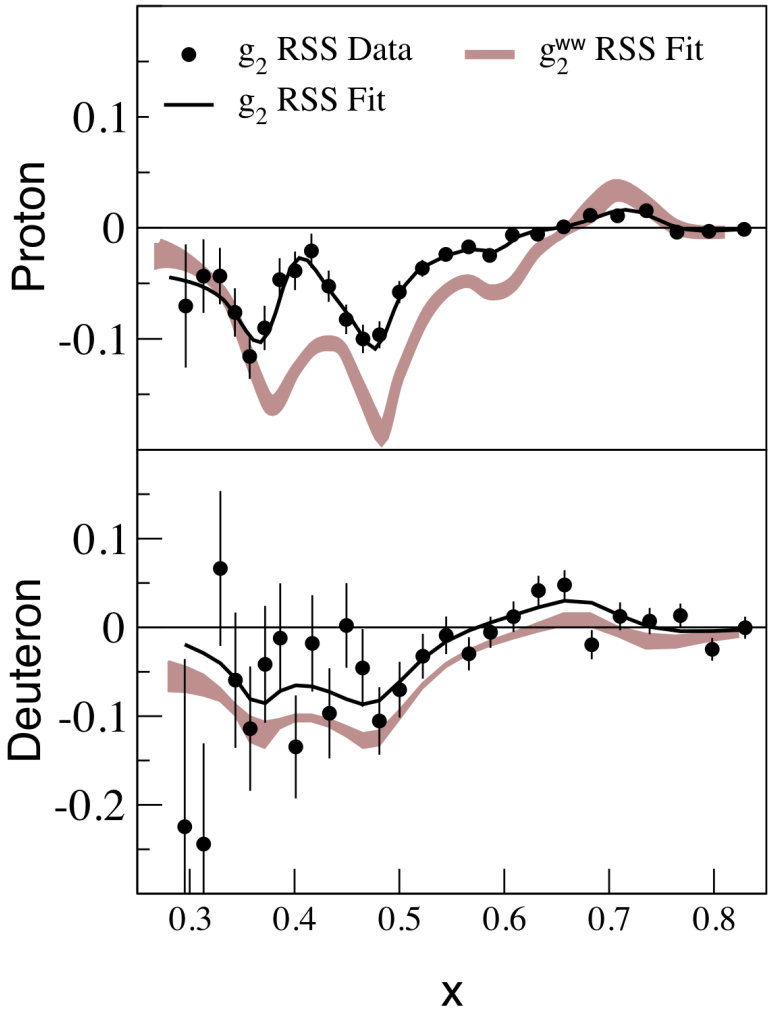


Leading Twist



RSS Experiment (Spokesmen: Rondon and Jones)

$Q^2 = 1.3\ GeV^2$



$$\overline{\Delta}\Gamma_2 = -0.0006 \pm 0.0021 \quad \text{(proton)}$$

consistent with zero
=> low x HT are small in proton.

$$\overline{\Delta}\Gamma_2 = -0.0092 \pm 0.0035 \quad \text{(neutron)}$$

non-zero by 2.6σ

=>Significant HT at low x needed to satisfy Neutron BC sum rule.

K.S., O. Rondon *et al.*
PRL 105, 101601 (2010)

BC Sum Rule

$$\int_0^1 g_2(x, Q^2)dx = 0$$

H.Burkhardt and W.N. Cottingham
Annals Phys. **56** (1970) 453.

Assumptions:

the virtual Compton scattering amplitude S_2 falls to zero faster than $1/x$

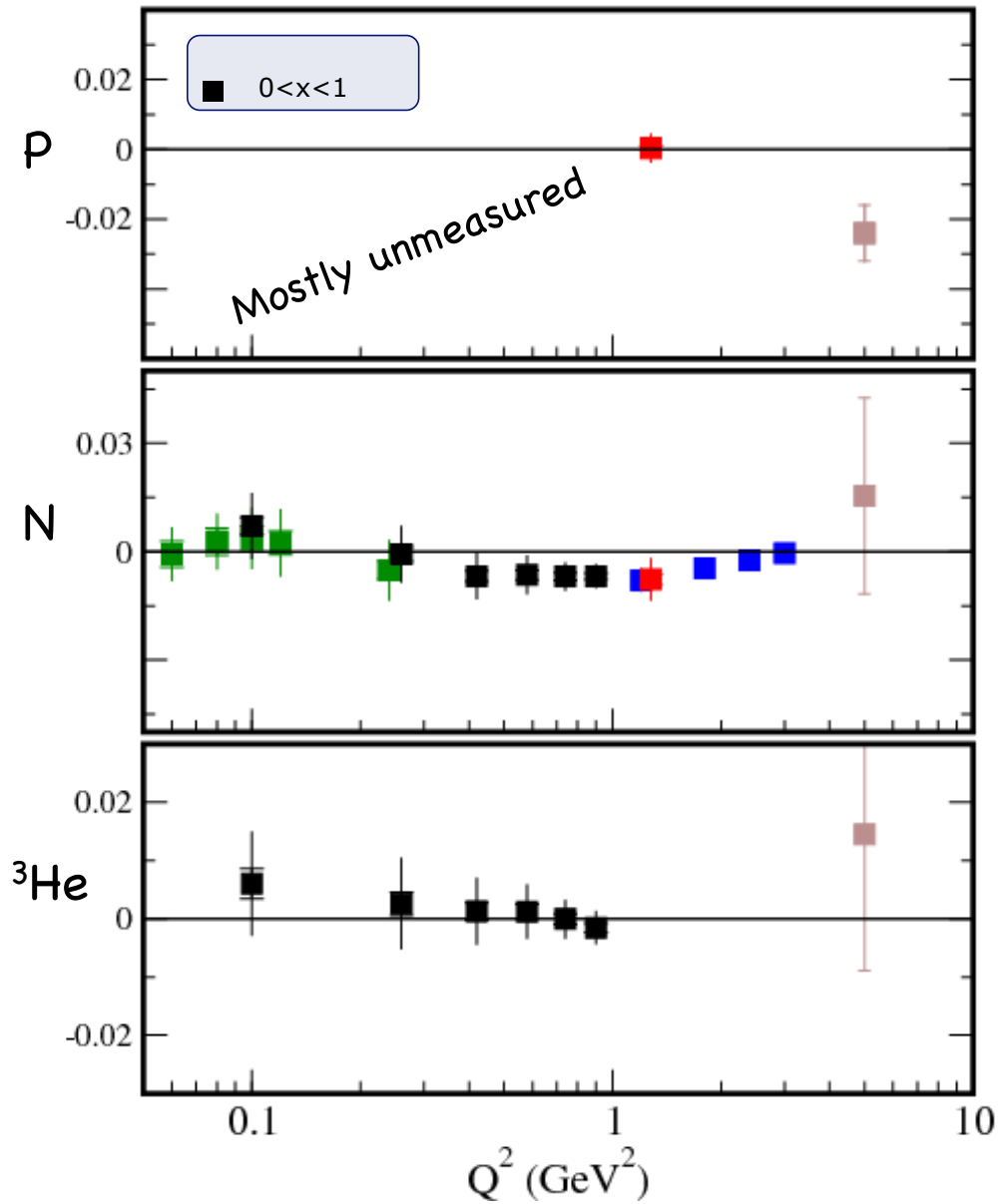
g_2 does not behave as $\delta(x)$ at $x=0$.

Discussion of possible causes of violations

R.L. Jaffe Comm. Nucl. Part. Phys. 19, 239 (1990)

"If it holds for one Q^2 it holds for all"

BC Sum Rule

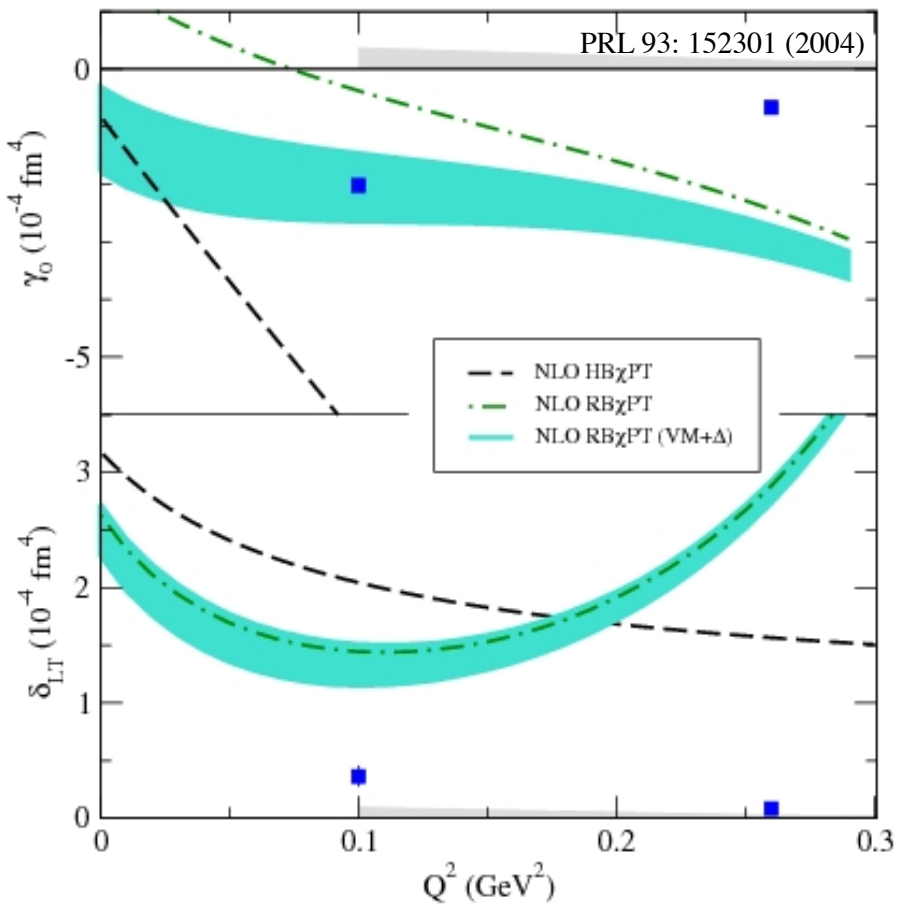


BC satisfied w/in errors for JLab Proton
2.8σ violation seen in SLAC data

Generalized Spin Polarizabilities

Forward Spin Polarizabilities

Neutron



$$\gamma_0 = \frac{16\alpha M^2}{Q^6}\int_0^{x_0} x^2\left[g_1 - \frac{4M^2}{Q^2}x^2 g_2\right]$$

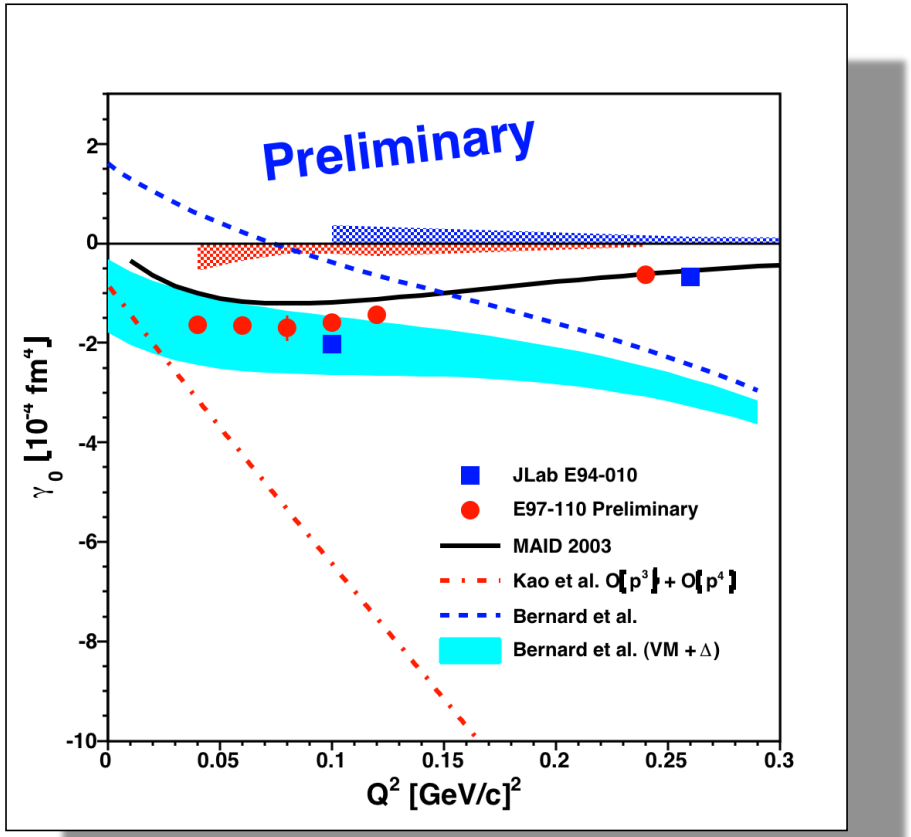
$$\delta_{LT} = \frac{16\alpha M^2}{Q^6}\int_0^{x_0} x^2\left[g_1 + g_2\right]$$

Dramatic Failure of ChiPT

Heavy Baryon χPT Calculation
Kao, Spitzenberg, Vanderhaeghen
PRD 67:016001(2003)

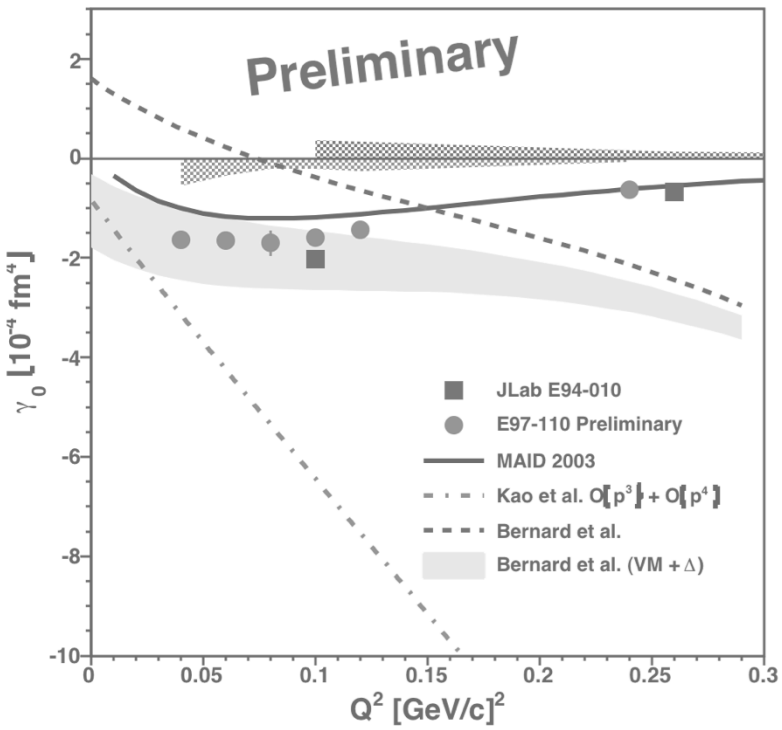
Relativistic Baryon χPT
Bernard, Hemmert, Meissner
PRD 67:076008(2003)

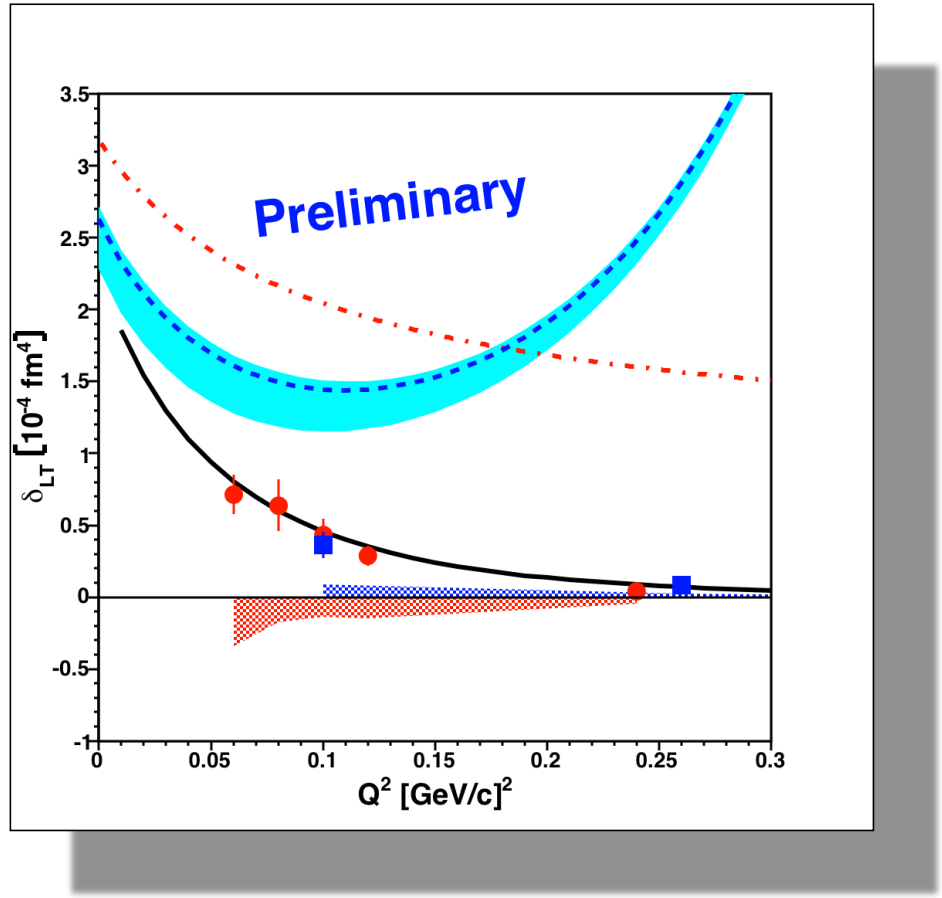
New Data on the Neutron Polarizabilities



Plots courtesy of V. Sulkosky

New Data on the Neutron Polarizabilities

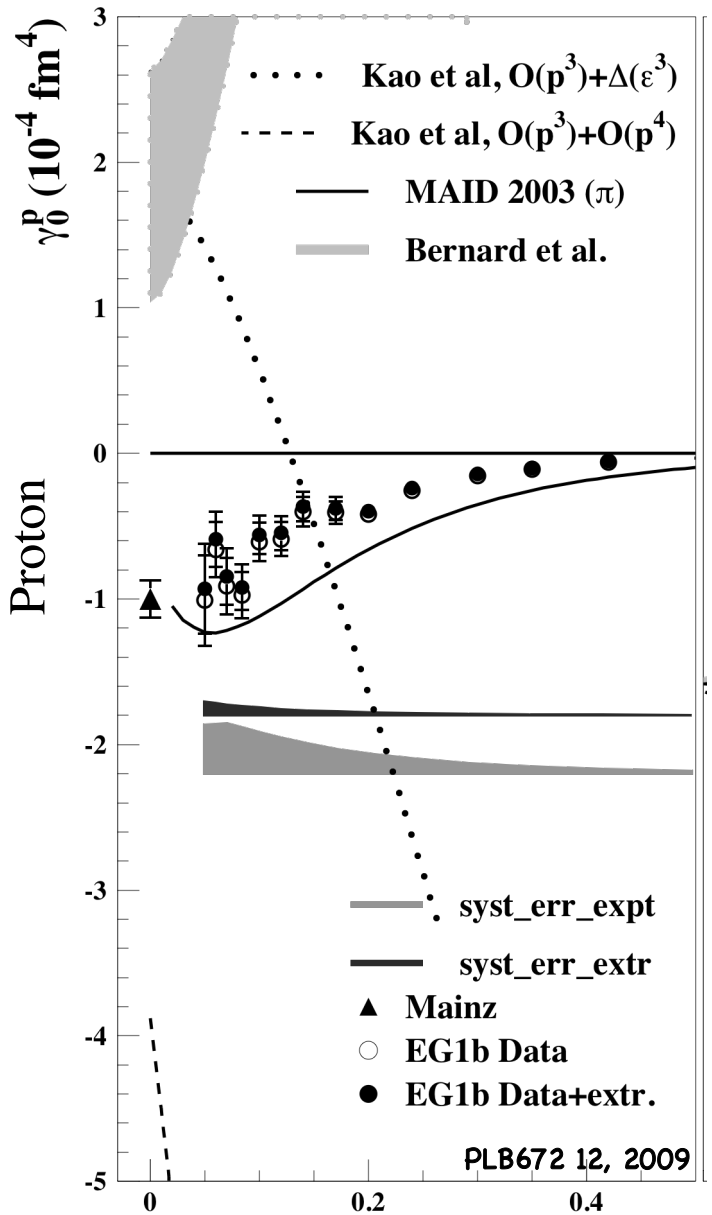




Large discrepency with δ_{LT} remains

Plots courtesy of V. Sulkosky

Proton γ_0



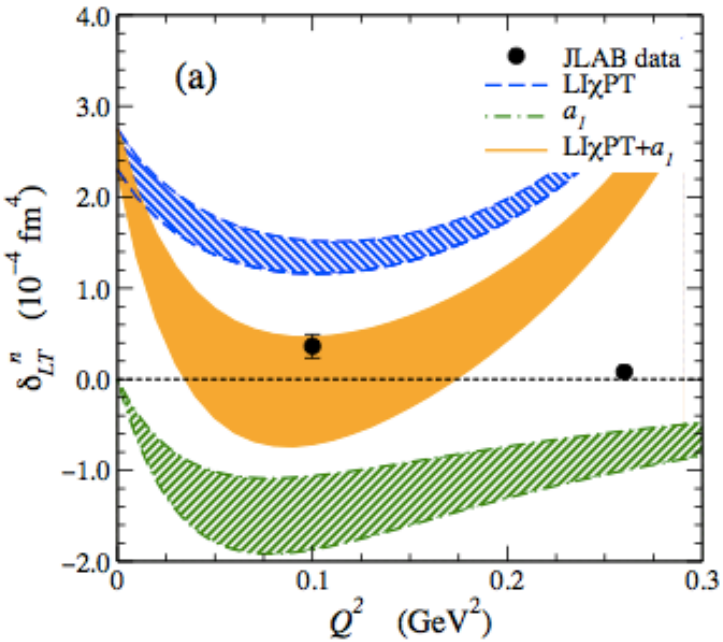
$$\gamma_0 = \frac{16\alpha M^2}{Q^6}\int_0^{x_0} x^2\left[g_1 - \frac{4M^2}{Q^2}x^2 g_2\right]$$

Calculations also fail for proton γ_0

LT Spin Polarizability

Kochelev & Oh. arxiv:1103.4892. (2011)
Improves agreement with neutron,

Neutron



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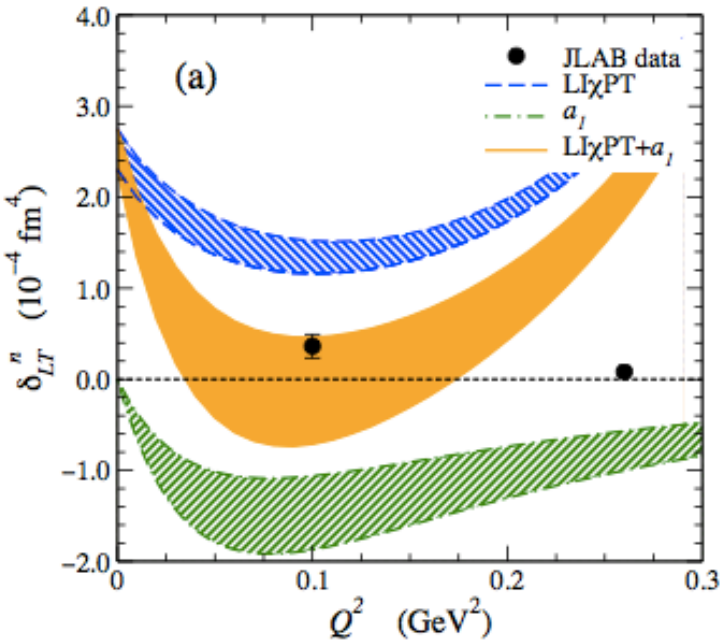
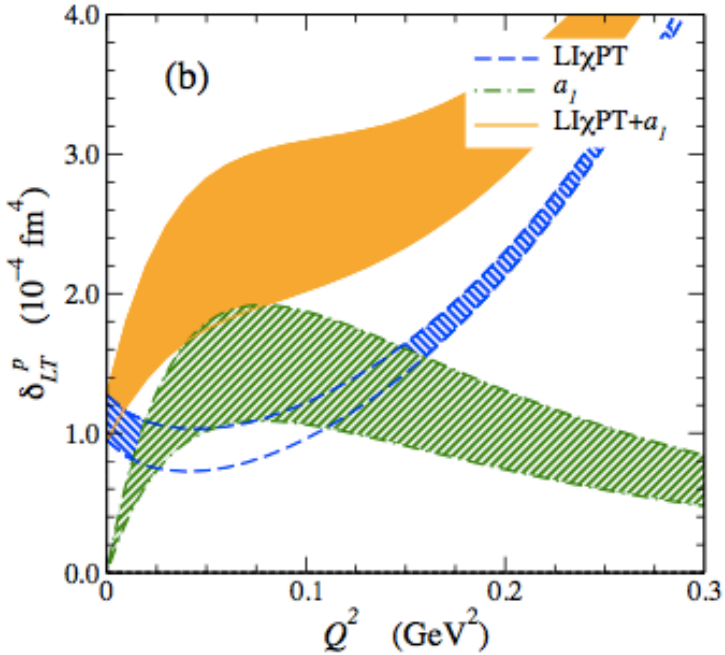
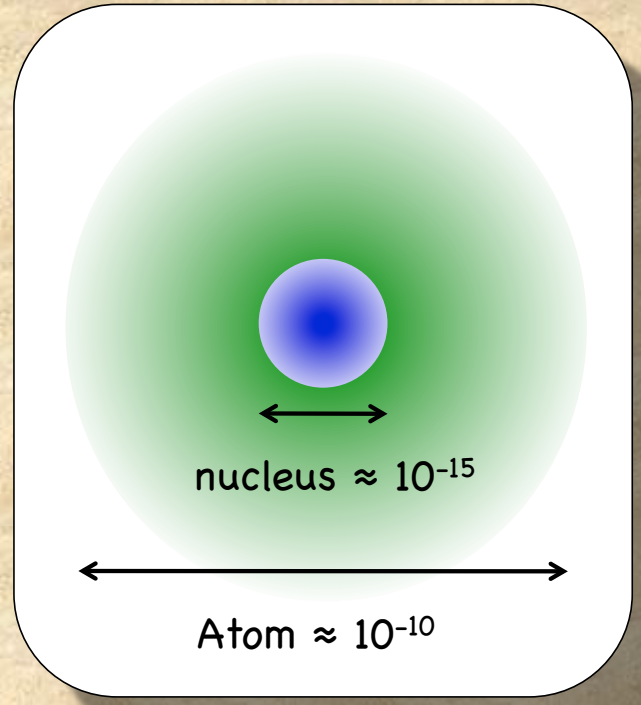


Proton



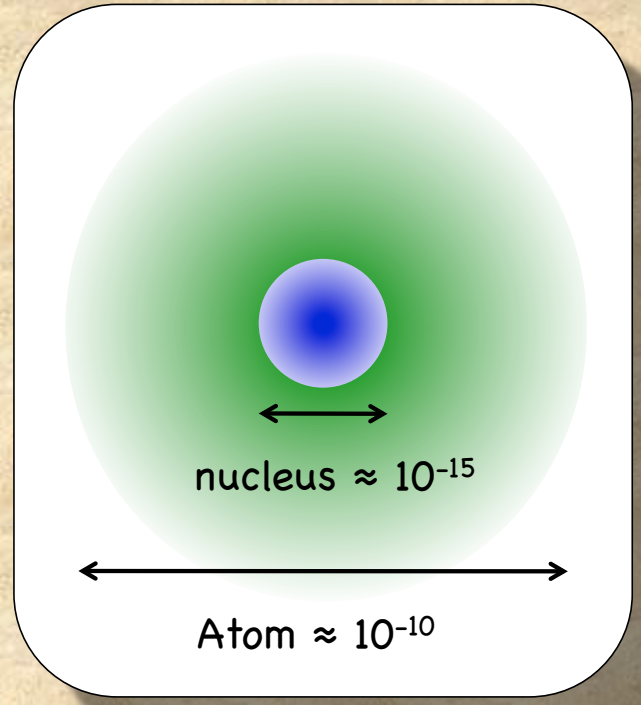
No data yet on proton LT polarizability

Applications to Bound State Q.E.D.



The finite size of the nucleus plays a small but significant role in atomic energy levels.

Applications to Bound State Q.E.D.

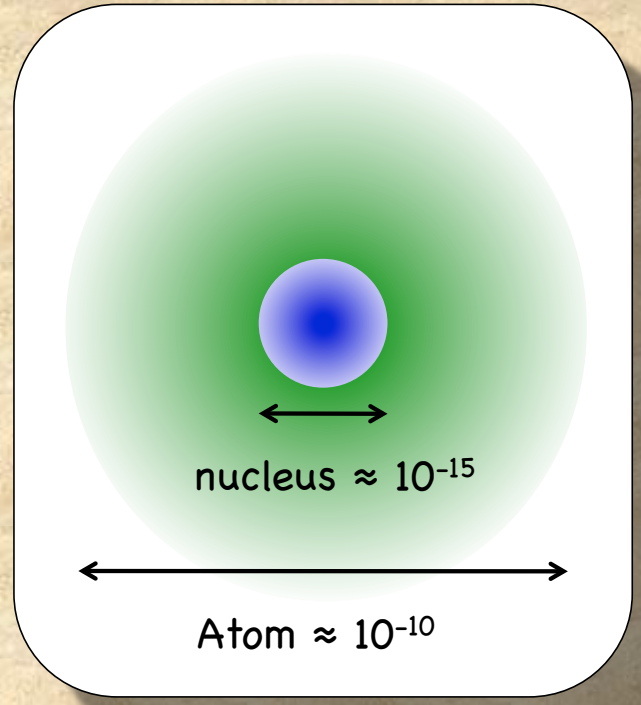


The finite size of the nucleus plays a small but significant role in atomic energy levels.

Hydrogen HF Splitting

$$\begin{aligned} \Delta E &= 1420.405\ 751\ 766\ 7(9)\ \ \mathrm{MHz} \\ &= (1+\delta)E_F \end{aligned}$$

Applications to Bound State Q.E.D.



Hydrogen HF Splitting

$$\begin{aligned} \Delta E &= 1420.405\ 751\ 766\ 7(9)\ \ \text{MHz} \\ &= (1+\delta)E_F \end{aligned}$$

$$\delta = (\delta_{QED} + \delta_R + \delta_{small}) + \Delta_S$$

The finite size of the nucleus plays a small but significant role in atomic energy levels.

Friar & Sick PLB **579** 285(2003)

Structure dependence of Hydrogen HF Splitting

$$\Delta_S = \Delta_Z + \Delta_{POL}$$

Elastic Scattering

Δ_Z=-41.0±0.5ppm

$$\Delta_Z = -2\alpha m_e r_Z (1 + \delta_Z^{\mathrm{rad}})$$

$$r_Z = -\frac{4}{\pi}\int_0^\infty \frac{dQ}{Q^2}\left[G_E(Q^2)\frac{G_M(Q^2)}{1+\kappa_p} - 1\right]$$

Structure dependence of Hydrogen HF Splitting

$$\Delta_S = \Delta_Z + \Delta_{POL}$$

inelastic

Nazaryan,Carlson,Griffieon
PRL **96** 163001 (2006)

Δ_Z=-41.0±0.5ppm

Δ_{pol}≈ 1.3±0.3 ppm

Elastic piece larger but with similar uncertainty

$$\Delta_{POL} = 0.2265 \quad (\Delta_1 + \Delta_2)\text{ppm}$$

integral of g1 & F1

pretty well determined from F_2,g_1 JLab data

Structure dependence of Hydrogen HF Splitting

$$\Delta_S = \Delta_Z + \Delta_{POL}$$

Inelastic

Nazaryan,Carlson,Griffieon
PRL **96** 163001 (2006)

$\Delta_{pol} \approx 1.3 \pm 0.3$ ppm

Elastic piece larger but with similar uncertainty

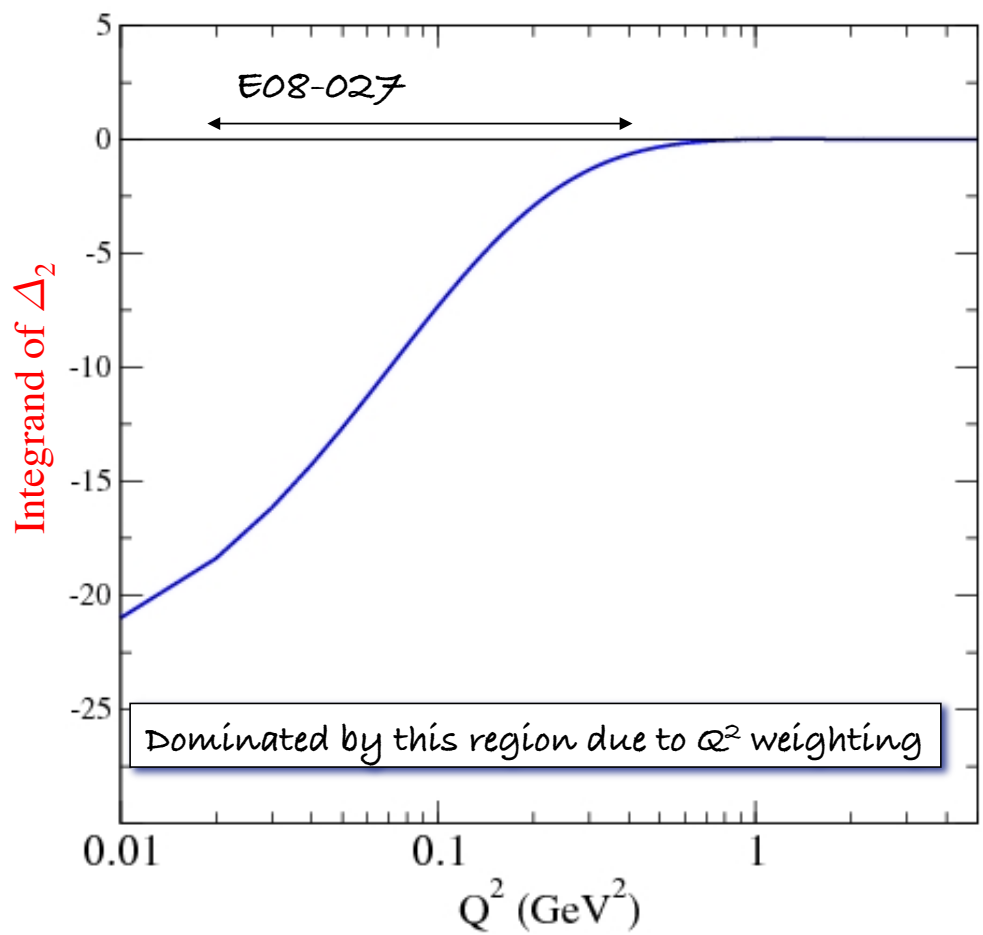
$$\Delta_{POL} = 0.2265 \quad (\Delta_1 + \Delta_2)\text{ppm}$$

$$\Delta_2 = -24 m_p^2 \int_0^\infty \frac{dQ^2}{Q^4} B_2(Q^2)$$

$$B_2(Q^2) = \int_0^{x_{th}} dx \beta_2(\tau) g_2(x, Q^2)$$

weighted heavily to low Q^2

Hydrogen Hyperfine Structure

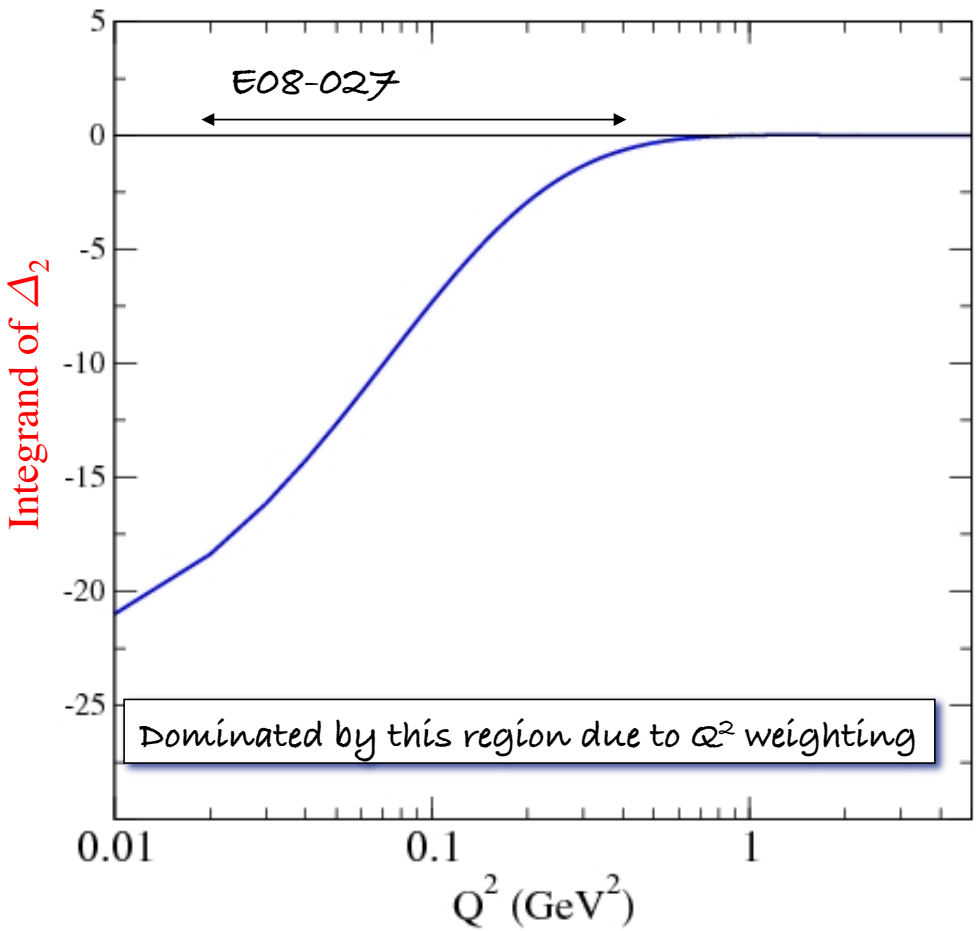


$$\Delta_2 = -24 m_p^2 \int_0^\infty \frac{dQ^2}{Q^4} B_2(Q^2)$$

$$= -0.57 \pm 0.57$$

assuming CLAS model with 100% error

Hydrogen Hyperfine Structure



$$\Delta_2 = -24 m_p^2 \int_0^\infty \frac{dQ^2}{Q^4} B_2(Q^2)$$

$$= -0.57 \pm 0.57$$

assuming CLAS model with 100% error

But, g_2^p unknown in this region:

$$\Delta_2 = -1.98 \quad \text{MAID Model}$$

$$\Delta_2 = -1.86 \quad \text{Simula Model}$$

So 100% error probably too optimistic

E08-027 will provide first real constraint on Δ_2

PSI measurement of the RMS proton radius

Spectroscopic measurement of the energy splitting of the

$2S_{1/2}$-$2P_{1/2}$ levels in muonic hydrogen (Lamb shift).

$$\Delta\tilde{E} = 209.9779(49) - 5.2262\ r_p^2 + 0.0347\ r_p^3\ \text{meV}$$

Proton Charge Radius from μP lamb shift disagrees with eP scattering result by about 6%

$\langle R_p \rangle = 0.84184 \pm 0.00067$ fm — Lamb shift in muonic hydrogen
R. Pohl *et.al Nature, July 2010*

$\langle R_p \rangle = 0.8768 \pm 0.0069$ fm — CODATA world average

I. Sick (Basel) :	*"What gives? I don't know". "Serious discrepency"*	[*ELBA XI, Nature.com*]
C. Carlson (W&M) :	*"Something is missing, this is very clear."*	[*Nature.com*]
P. Mohr (NIST) :	*"would be quite revolutionary."*	[*L.A. Times.*]
B. Odom (N.Western) :	*"...very surprised to find strong disagreement."*	[*N.P.R.*]
J. Flowers (N.P.L.)	*"...could mean a complete rethink of QED".*	[*National Geographic*]
	"...opens door for a theorist to come up with next theoretical leap, and claim their Nobel prize".	[*NY Times*]

Vol 466|8 July 2010|doi:10.1038/nature09250 nature

LETTERS

The size of the proton

Randolf Pohl[1], Aldo Antognini[2], François Nez[2], Fernando D. Amaro[3], François Biraben[2], João M. R. Cardoso[3], Daniel S. Covita[3,4], Andreas Dax[5], Satish Dhawan[5], Luis M. P. Fernandes[3], Adolf Giesen[6]†, Thomas Graf[6], Theodor W. Hänsch[1], Paul Indelicato[2], Lucile Julien[2], Cheng-Yang Kao[7], Paul Knowles[8], Eric-Olivier Le Bigot[2], Yi-Wei Liu[7], José A. M. Lopes[3], Livia Ludhova[8], Cristina M. B. Monteiro[3], Françoise Mulhauser[8]†, Tobias Nebel[1], Paul Rabinowitz[9], Joaquim M. F. dos Santos[3], Lukas A. Schaller[8], Karsten Schuhmann[10], Catherine Schwob[2], David Taqqu[11], João F. C. A. Veloso[4] & Franz Kottmann[12]

The proton is the primary building block of the visible Universe, but many of its properties—such as its charge radius and its anomalous magnetic moment—are not well understood. The root-mean-square charge radius, r_p, has been determined with an accuracy of 2 per cent (at best) by electron–proton scattering experiments[1,2]. The present most accurate value of r_p (with an uncertainty of 1 per cent) is given by the CODATA compilation of physical constants[3]. This value is based mainly on precision spectroscopy of atomic hydrogen[4–7] and calculations of bound-state quantum electrodynamics (QED; refs 8, 9). The accuracy of r_p as deduced from electron–proton scattering limits the testing of bound-state QED in atomic hydrogen as well as the determination of the Rydberg constant (currently the most accurately measured fundamental physical constant[3]). An attractive means to improve the accuracy in the measurement of r_p is provided by muonic hydrogen (a proton orbited by a negative muon); its much smaller Bohr radius compared to ordinary atomic hydrogen causes enhancement of effects related to the finite size of the proton. In particular, the Lamb shift[10] (the energy difference between the $2S_{1/2}$ and $2P_{1/2}$ states) is affected by as much as 2 per cent. Here we use pulsed laser spectroscopy to measure a muonic Lamb shift of 49,881.88(76) GHz. On the basis of present calculations[11–15] of fine and hyperfine splittings and QED terms, we find $r_p = 0.84184(67)$ fm, which differs by 5.0 standard deviations from the CODATA value[3] of 0.8768(69) fm. Our result implies that either the Rydberg constant has to be shifted by −110 kHz/c (4.9 standard deviations), or the calculations of the QED effects in atomic hydrogen or muonic hydrogen atoms are insufficient.

Bound-state QED was initiated in 1947 when a subtle difference between the binding energies of the $2S_{1/2}$ and $2P_{1/2}$ states of H atoms was established, denoted as the Lamb shift[10]. It is dominated by purely radiative effects[8], such as 'self energy' and 'vacuum polarization'. More recently, precision optical spectroscopy of H atoms[4–7] and the corresponding calculations[8,9] have improved tremendously and reached a point where the proton size (expressed by its root-mean-square charge radius, $r_p = \sqrt{\langle r_p^2 \rangle}$) is the limiting factor when comparing experiment with theory[16].

The CODATA value[3] of $r_p = 0.8768(69)$ fm is extracted mainly from H atom spectroscopy and thus relies on bound-state QED (here and elsewhere numbers in parenthesis indicate the 1 s.d. uncertainty of the trailing digits of the given number). An H-independent but less precise value of $r_p = 0.897(18)$ fm was obtained in a recent reanalysis of electron-scattering experiments[1,2].

A much better determination of the proton radius is possible by measuring the Lamb shift in muonic hydrogen (μp, an atom formed by a proton, p, and a negative muon, μ^-). The muon is about 200 times heavier than the electron. The atomic Bohr radius is correspondingly about 200 times smaller in μp than in H. Effects of the finite size of the proton on the muonic S states are thus enhanced. S states are shifted because the muon's wavefunction at the location of the proton is non-zero. In contrast, P states are not significantly shifted. The total predicted $2S^{F=1}_{1/2} - 2P^{F=2}_{3/2}$ energy difference, $\Delta\tilde{E}$, in muonic hydrogen is the sum of radiative, recoil, and proton structure contributions, and the fine and hyperfine splittings for our particular transition, and it is given[8,11–13] by

$$\Delta\tilde{E} = 209.9779(49) - 5.2262\, r_p^2 + 0.0347\, r_p^3 \text{ meV} \qquad (1)$$

where $r_p = \sqrt{\langle r_p^2 \rangle}$ is given in fm. A detailed derivation of equation (1) is given in Supplementary Information.

The first term in equation (1) is dominated by vacuum polarization, which causes the 2S states to be more tightly bound than the 2P states (Fig. 1). The μp fine and hyperfine splittings (due to spin–orbit and spin–spin interactions) are an order of magnitude smaller than the Lamb shift (Fig. 1c). The uncertainty of 0.0049 meV in $\Delta\tilde{E}$ is dominated by the proton polarizability term[15] of 0.015(4) meV. The second and third terms in equation (1) are the finite size contributions. They amount to 1.8% of $\Delta\tilde{E}$, two orders of magnitude more than for H.

For more than forty years, a measurement of the μp Lamb shift has been considered one of the fundamental experiments in atomic spectroscopy, but only recent progress in muon beams and laser technology made such an experiment feasible. We report the first successful measurement of the μp Lamb shift. The energy difference between the $2S^{F=1}_{1/2}$ and $2P^{F=2}_{3/2}$ states of μp atoms has been determined by means of pulsed laser spectroscopy at wavelengths around 6.01 μm. This transition was chosen because it gives the largest signal of all six allowed optical 2S–2P transitions. All transitions are spectrally well separated.

The experiment was performed at the πE5 beam-line of the proton accelerator at the Paul Scherrer Institute (PSI) in Switzerland. We

[1]Max-Planck-Institut für Quantenoptik, 85748 Garching, Germany. [2]Laboratoire Kastler Brossel, École Normale Supérieure, CNRS, and Université P. et M. Curie-Paris 6, 75252 Paris, Cedex 05, France. [3]Departamento de Física, Universidade de Coimbra, 3004-516 Coimbra, Portugal. [4]I3N, Departamento de Física, Universidade de Aveiro, 3810-193 Aveiro, Portugal. [5]Physics Department, Yale University, New Haven, Connecticut 06520-8121, USA. [6]Institut für Strahlwerkzeuge, Universität Stuttgart, 70569 Stuttgart, Germany. [7]Physics Department, National Tsing Hua University, Hsinchu 300, Taiwan. [8]Département de Physique, Université de Fribourg, 1700 Fribourg, Switzerland. [9]Department of Chemistry, Princeton University, Princeton, New Jersey 08544-1009, USA. [10]Dausinger & Giesen GmbH, Rotebühlstr. 87, 70178 Stuttgart, Germany. [11]Paul Scherrer Institute, 5232 Villigen-PSI, Switzerland. [12]Institut für Teilchenphysik, ETH Zürich, 8093 Zürich, Switzerland. †Present addresses: Deutsches Zentrum für Luft- und Raumfahrt e.V. in der Helmholtz-Gemeinschaft, 70569 Stuttgart, Germany (A.G.); International Atomic Energy Agency, A-1400 Vienna, Austria (F.M.).

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The size of the proton

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The proton is the primary building block of the visible Universe, but many of its properties—such as its charge radius and its anomalous magnetic moment—are not well understood. The root-mean-square charge radius, r_p, has been determined with an accuracy of 2 per cent (at best) by electron–proton scattering experiments[1,2]. The present most accurate value of r_p (with an uncertainty of 1 per cent) is given by the CODATA compilation of physical constants[3]. This value is based mainly on precision spectroscopy of atomic hydrogen[4–7] and calculations of bound-state quantum electrody-

deviations from the CODATA value[3] of 0.8768(69) fm. Our result implies that either the Rydberg constant has to be shifted by −110 kHz/c (4.9 standard deviations), or the calculations of the QED effects in atomic hydrogen or muonic hydrogen atoms are insufficient.

Bound-state QED was initiated in 1947 when a subtle difference between the binding energies of the $2S_{1/2}$ and $2P_{1/2}$ states of H atoms was established, denoted as the Lamb shift[10]. It is dominated by purely radiative effects[8], such as 'self energy' and 'vacuum polarization'. More recently, precision optical spectroscopy of H atoms[4–7] and the corresponding calculations[8,9] have improved tremendously and reached a point where the proton size (expressed by its root-mean-square charge radius, $r_p = \sqrt{\langle r_p^2 \rangle}$) is the limiting factor when comparing experiment with theory[2,6].

The CODATA value[3] of $r_p = 0.8768(69)$ fm is extracted mainly from H atom spectroscopy and thus relies on bound-state QED (here and elsewhere numbers in parenthesis indicate the 1 s.d. uncertainty of the trailing digits of the given number). An H-independent but less precise value of $r_p = 0.897(18)$ fm was obtained in a recent reanalysis of electron-scattering experiments[1,2].

A much better determination of the proton radius is possible by measuring the Lamb shift in muonic hydrogen (μp, an atom formed by a proton, p, and a negative muon, μ^-). The muon is about 200 times heavier than the electron. The atomic Bohr radius is correspondingly about 200 times smaller in μp than in H. Effects of the finite size of the proton on the muonic S states are thus enhanced. S

states (Fig. 1). The μp fine and hyperfine splittings (due to spin–orbit and spin–spin interactions) are an order of magnitude smaller than the Lamb shift (Fig. 1c). The uncertainty of 0.0049 meV in $\Delta\tilde{E}$ is dominated by the proton polarizability term[15] of 0.015(4) meV. The second and third terms in equation (1) are the finite size contributions. They amount to 1.8% of $\Delta\tilde{E}$, two orders of magnitude more than for H.

For more than forty years, a measurement of the μp Lamb shift has been considered one of the fundamental experiments in atomic spectroscopy, but only recent progress in muon beams and laser technology made such an experiment feasible. We report the first successful measurement of the μp Lamb shift. The energy difference between the $2S^{F=1}_{1/2}$ and $2P^{F=2}_{3/2}$ states of μp atoms has been determined by means of pulsed laser spectroscopy at wavelengths around 6.01 μm. This transition was chosen because it gives the largest signal of all six allowed optical 2S–2P transitions. All transitions are spectrally well separated.

The experiment was performed at the πE5 beam-line of the proton accelerator at the Paul Scherrer Institute (PSI) in Switzerland. We

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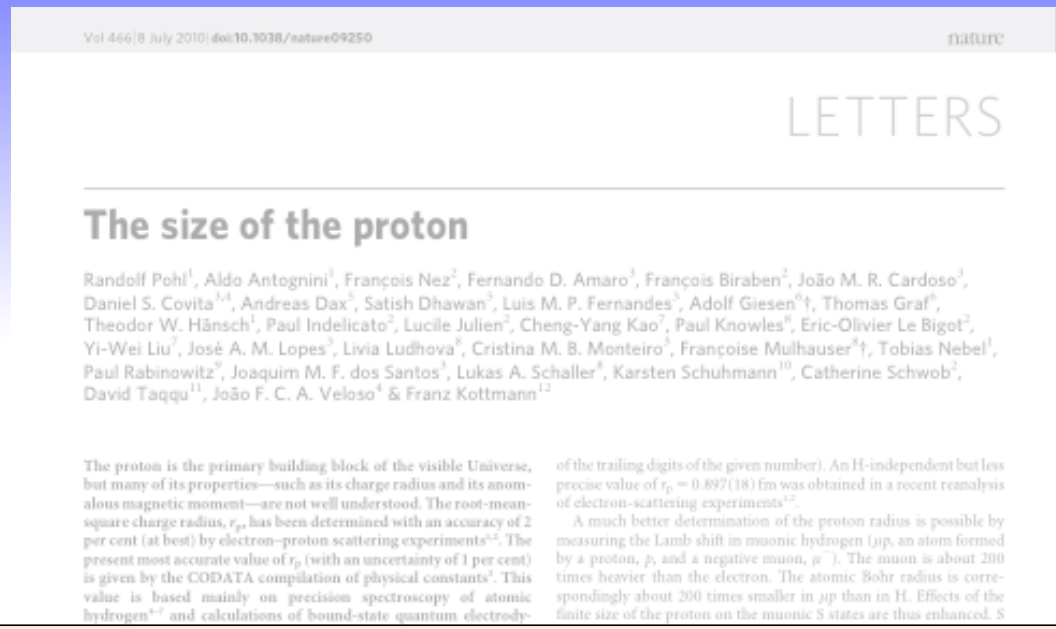
The main uncertainties originate from the proton polarizability, and from different values of the Zemach radius.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LETTERS

The size of the proton

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states (Fig. 1). The μp line and hyperfine splittings (due to spin–orbit and spin–spin interactions) are an order of magnitude smaller than the Lamb shift (Fig. 1c). The uncertainty of 0.0049 meV in ΔE is

<u>Polarizability</u> : Integrals of g_1 and g_2 weighted by $1/Q^4$

<u>Zemach radius</u> : Integral of $G_E G_M$ weighted by $1/Q^2$

Dominated by Kinematic region of E08-027 and E08-007

E08-027 : Proton g2 Structure Function

A. Camsonne J.P. Chen D. Crabb K. Slifer

Primary Motivation

Proton g_2 structure function has never been measured at low or moderate Q^2.

We will determine this fundamental quantity at the lowest possible Q^2

This will help to clarify several outstanding puzzles

Experimental Technique

Inclusive Polarized Cross Section differences

Major Installation in Hall A

Polarized proton target

upstream chicane
downstream local dump

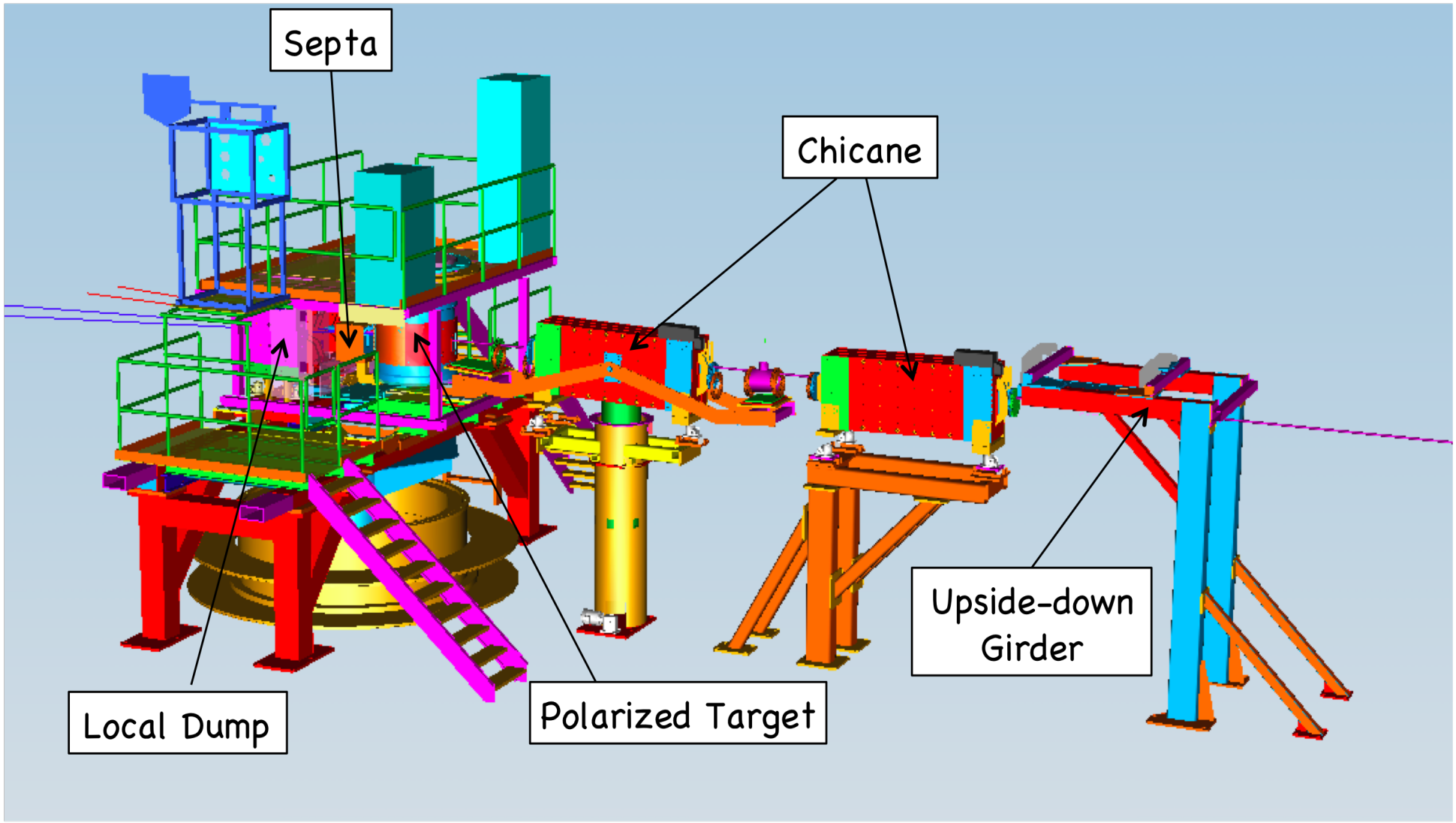
Low current polarized beam

Upgrades to existing Beam Diagnostics to work at 85 nA

Lowest possible Q^2 in the resonance region

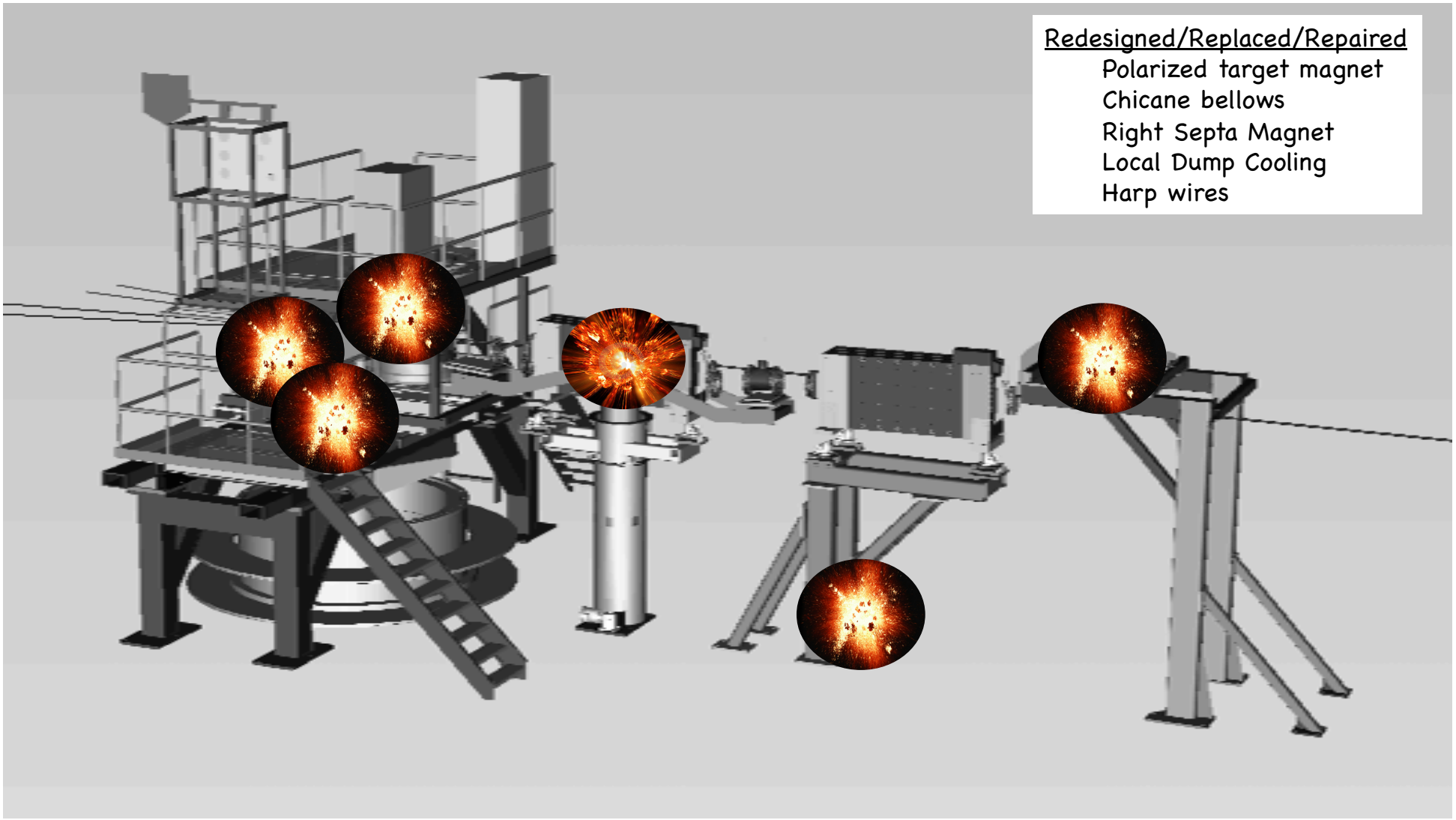
Septa Magnets to detect forward scattering

Major New Installation in Hall A



A few minor mechanical setbacks

delayed the start of the experiment by 149 days



A few minor mechanical setbacks

delayed the start of the experiment by 149 days

Redesigned/Replaced/Repaired

- Polarized target magnet
- Chicane bellows
- Right Septa Magnet
- Local Dump Cooling
- Harp wires

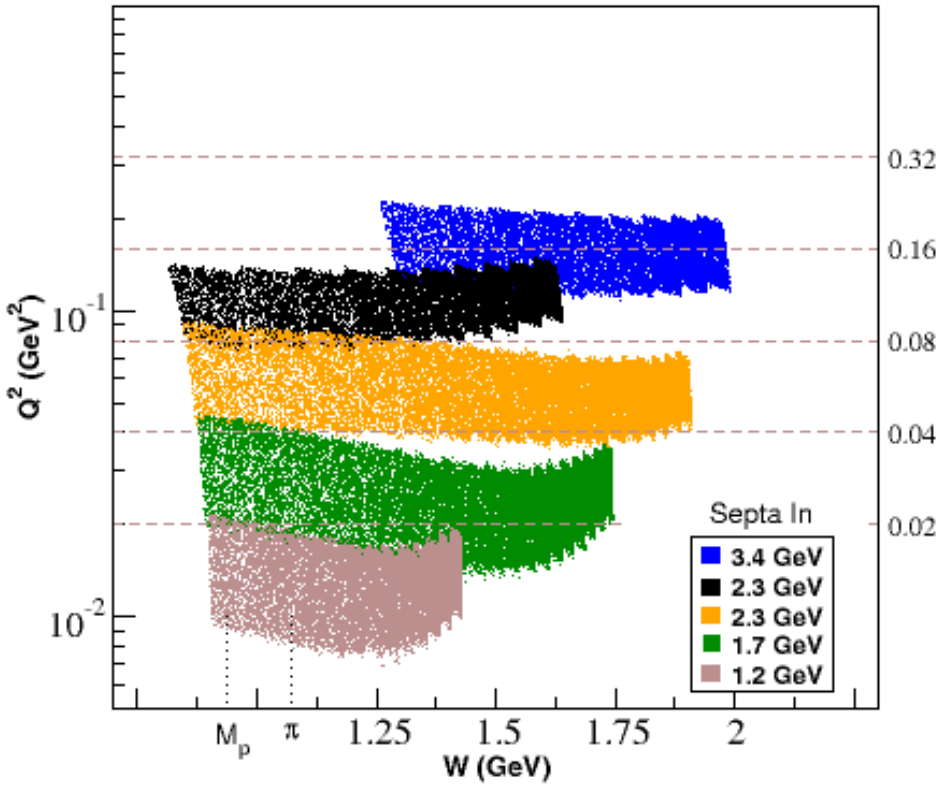
Lab Support in dealing with these issues has been

Greatly Appreciated!

Grad Student and Post-Doc response also amazing

g2p: "A New Test of Life"

Kinematic Coverage



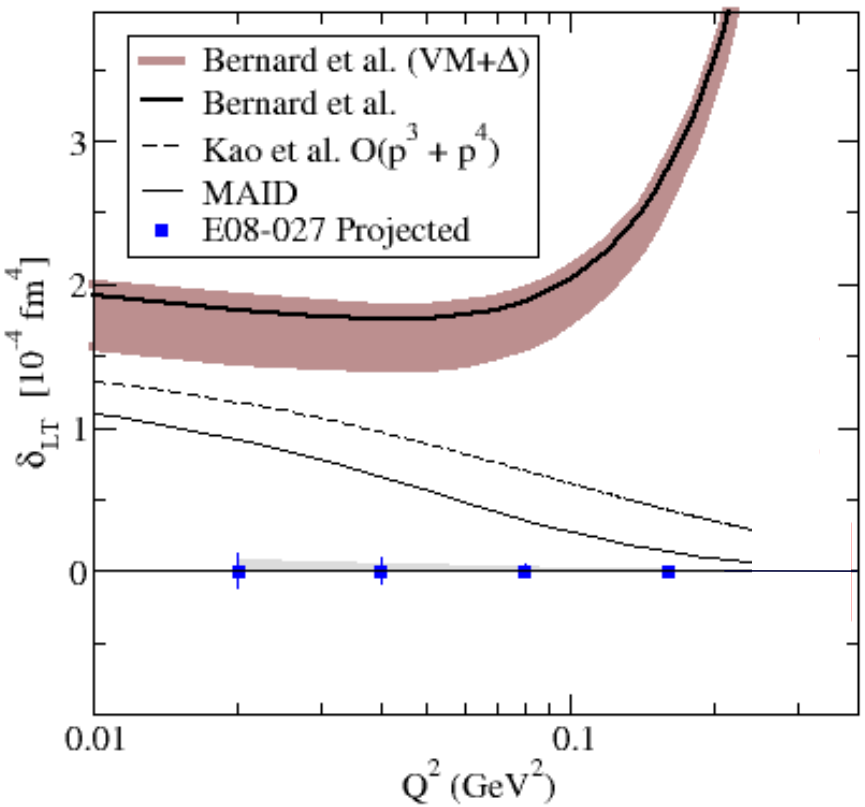
Reduced kinematics

$M_p < W < 2$ GeV

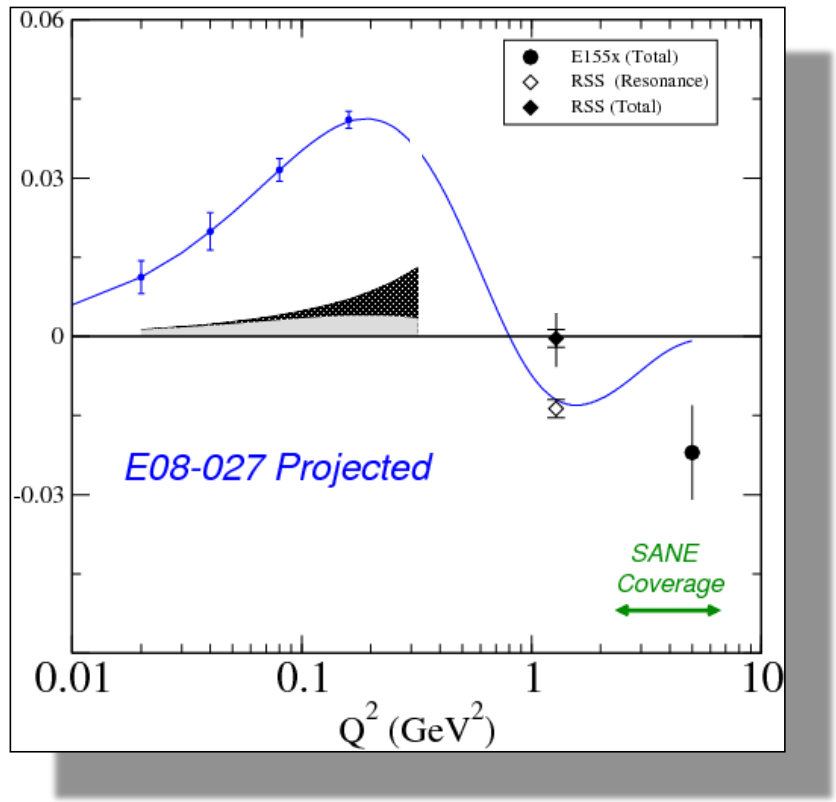
$0.02 < Q^2 < 0.2$ GeV^2

Projections

LT Spin Polarizability

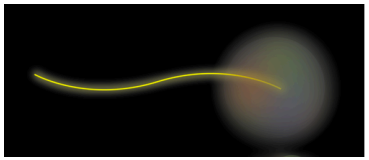


BC Sum Integral Γ_2



Elastic Scattering,

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{Mott} \left[\frac{Q^2}{4M^2} G_M^2(Q^2) + \epsilon G_E^2(Q^2)\right]$$



Form factors are normalized such that:

$$G_E^P(Q^2 = 0) = 1$$ Charge

$$G_M^P(Q^2 = 0) = \mu_P$$ Magnetic moment

FF's represent the momentum-space charge and magnetization distributions

=>fourier transforms of the coordinate space distributions. (non-rel limit).

$$G_E(Q^2) = \int \rho(r) e^{i\vec{q}\vec{r}} d\vec{r}$$

<u>Expansion at low Q^2 gives</u>

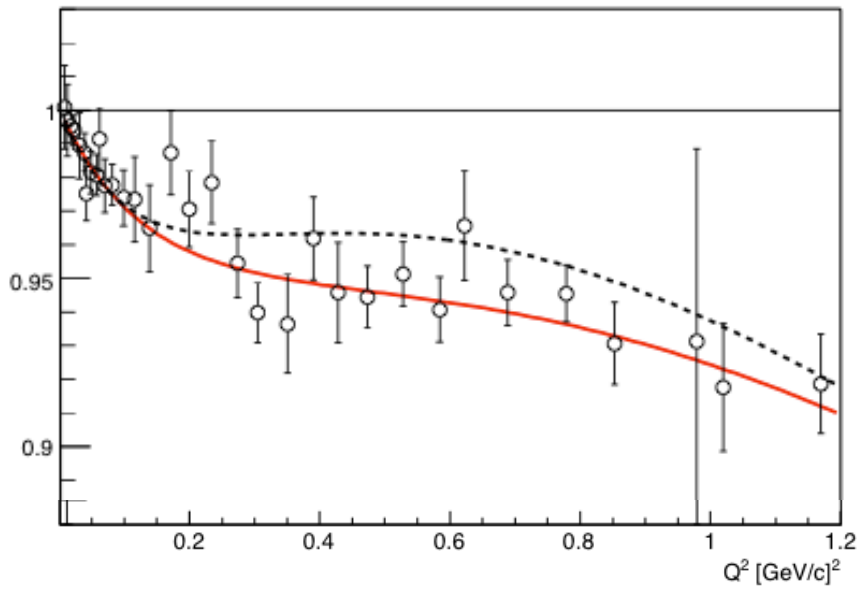
$$G_E(Q^2) = 1 - \frac{Q^2}{6}\langle R^2 \rangle + ...$$

RMS charge radius

the slope of G_E at Q^2=0 determines the "size" of the proton.

Proton G_E Data at low Q^2

G_E/G_D



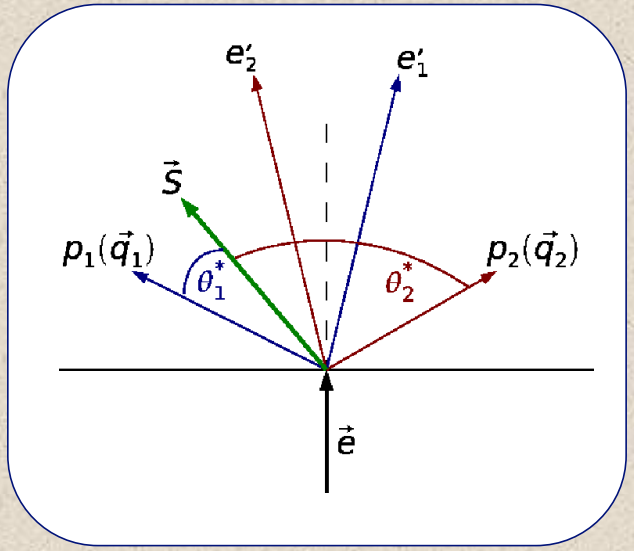
$\langle R_p \rangle = 0.897 \pm 0.018$ fm

Best value of $\langle R_p \rangle$ from elastic proton scattering

I. Sick PLB 2003

Normalized to the dipole form

$$G_D = \frac{1}{\sqrt{1 + Q^2/0.71}}$$



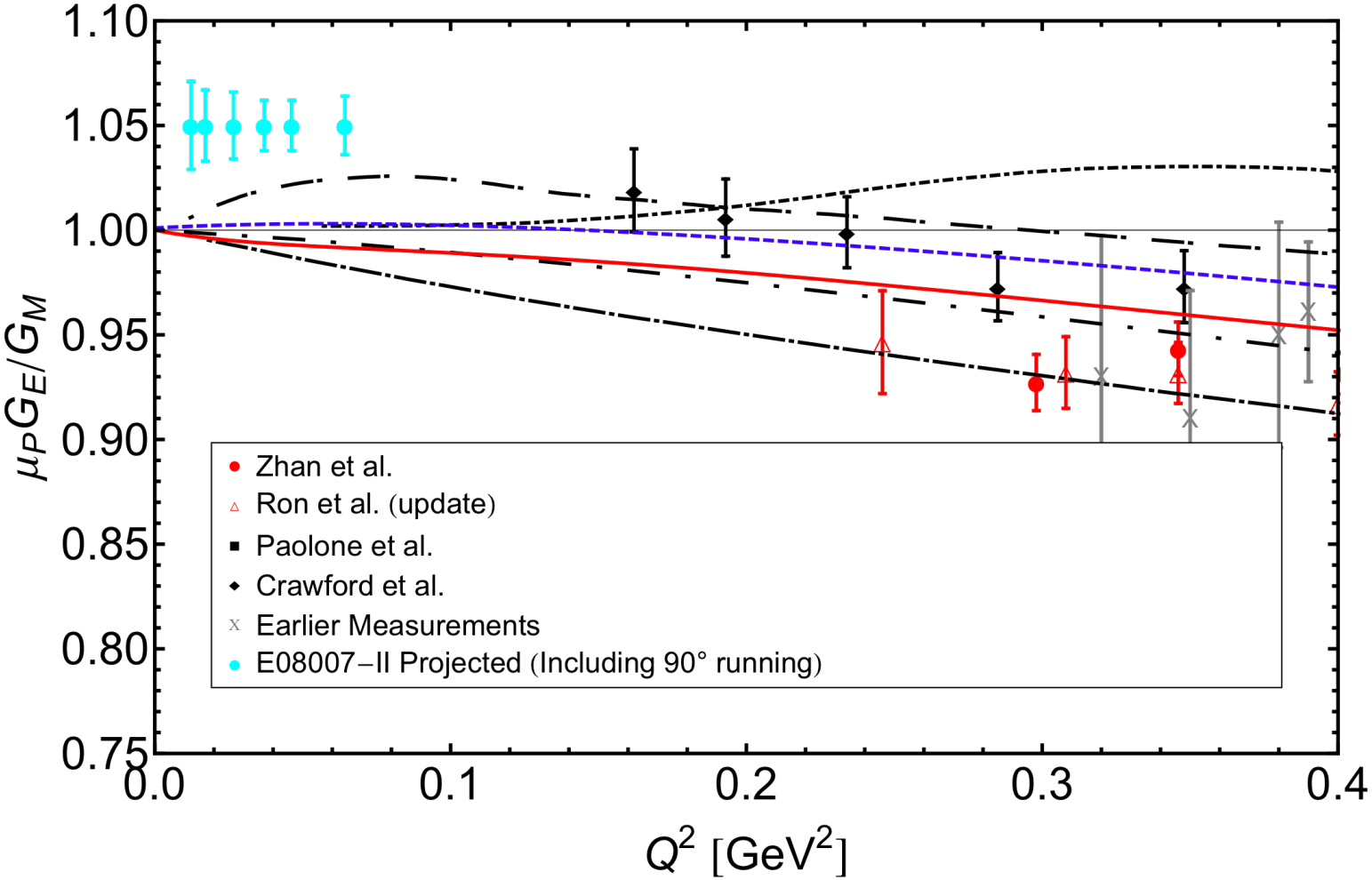
E08-007 : G_E/G_M

G. Ron*, D. Higintbothan, R. Gilman
J. Arrington, A. Sarty, D. Day

Super-ratio of left/right Asymmetries:

$$\mu_p \frac{G_E}{G_M} = -\mu_p \frac{a(\tau,\theta)\cos\theta_1^* - \frac{f_2}{f_1}\frac{A_1}{A_2} a(\tau,\theta)\cos\theta_2^*}{\cos\phi_1^*\sin\theta_1^* - \frac{f_2}{f_1}\frac{A_1}{A_2}\cos\phi_2^*\sin\theta_2^*}$$

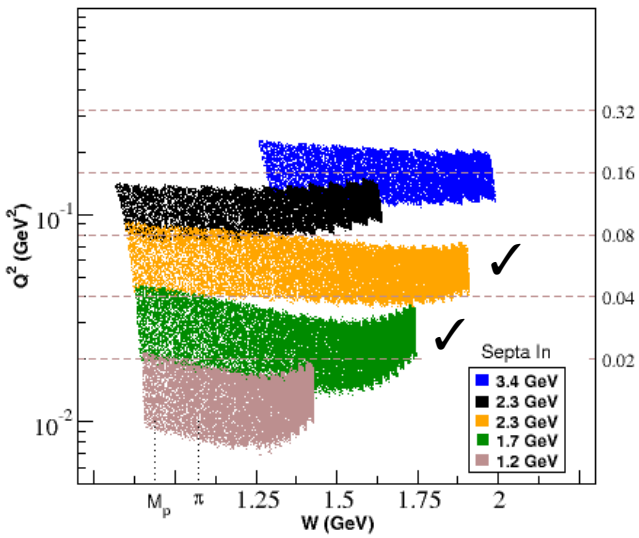
Projected Results



Online Results

2.2 GeV, 90 degrees at 2.5T : about 3.8E9 inelastic triggers recorded

1.7 GeV, 90 degrees at 2.5 T : about 3.2E9 inelastic triggers recorded

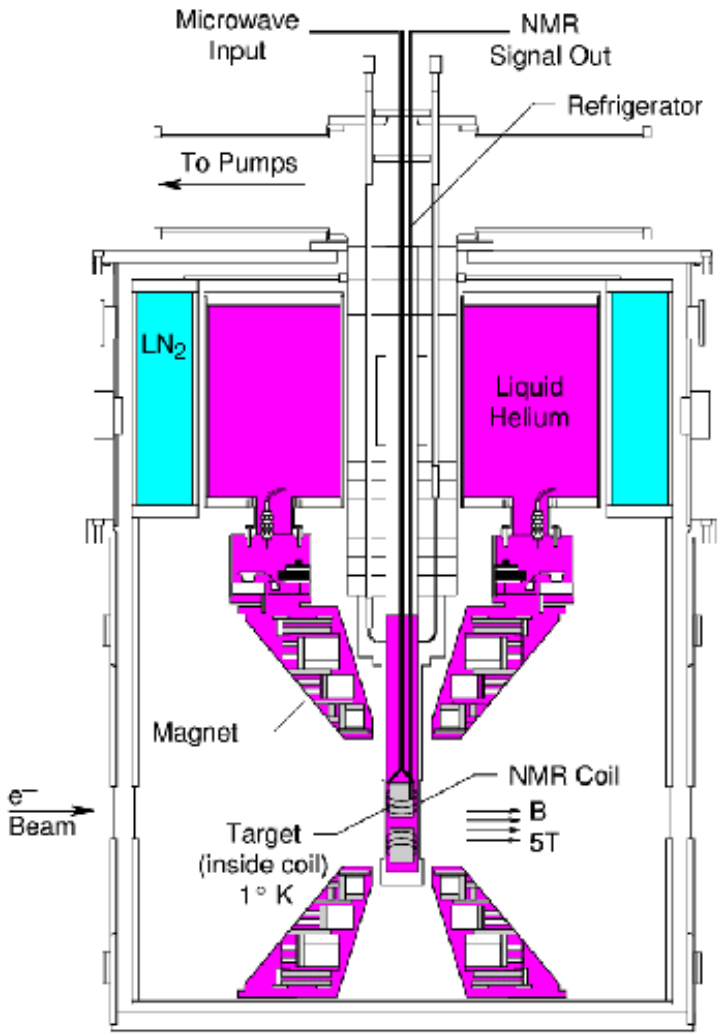


$\langle P_T \rangle^+ = 31.6\%$

$\langle P_T \rangle^- = 28.3\%$

DAQ Rate 6-7kHz with less than 30% Deadtime

Polarized Ammonia Target



Dynamic Nuclear Polarization of NH_3

Has performed **remarkably well** after target group transplanted the Hall B coil package

<u>5 T/ 140 GHz or 2.5 T/70 GHz operation</u>
Helmholtz superconduct magnet

1K ^{4}He evaporation refrigerator
Cooling power: about 1 W

<u>Microwave Power</u>
>1W at 140 GHz

<u>Insulated cryostat</u>
85 L Liquid He resevoir
57 L Liquid N shield (300K BB shield)

Polarized Ammonia Target

NH_3

Empty

CH_2

NH_3

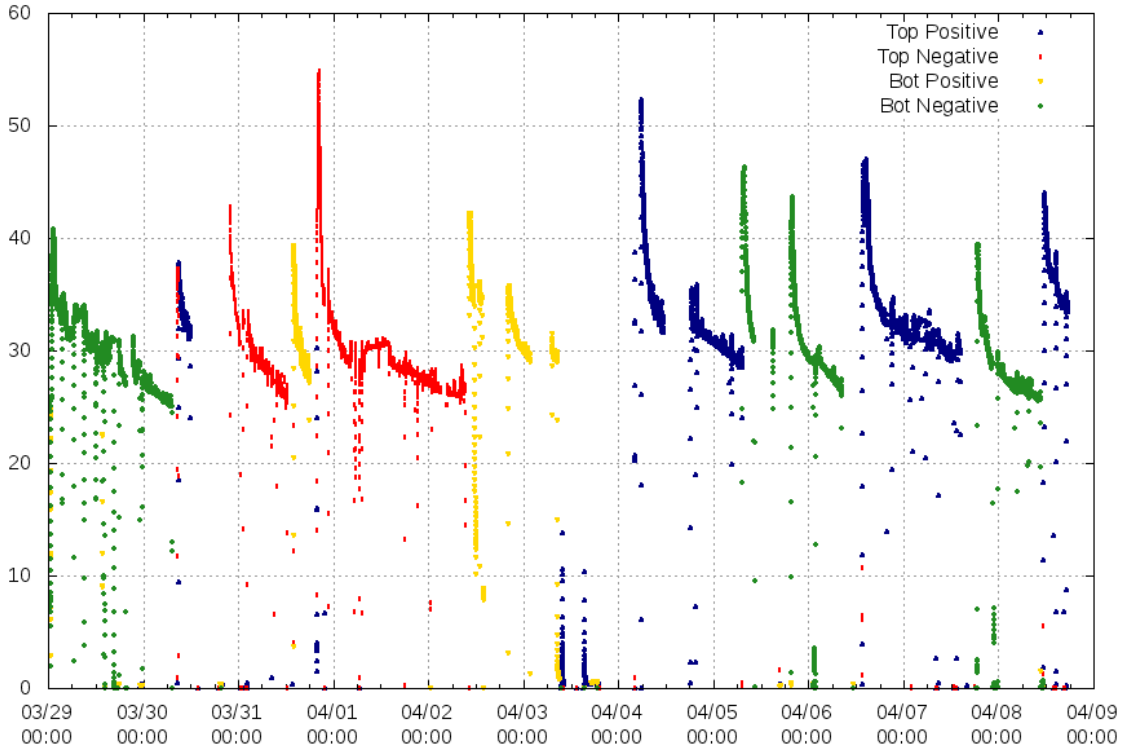
Dummy

Carbon

Dynamic Nuclear Polarization of NH_3

Has performed **remarkably well** after target group transplanted the Hall B coil package

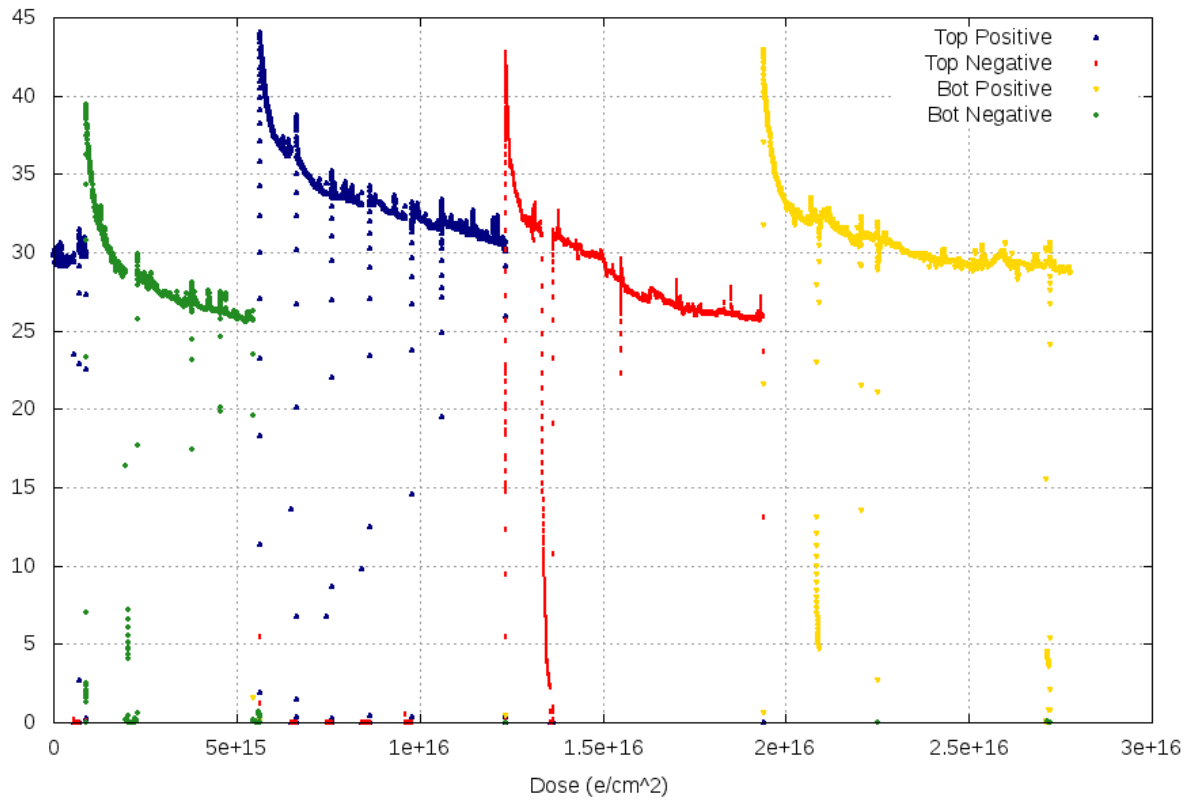
Online Polarimetry



Average Polarization >30%
at 2.5 Tesla/70 GHz

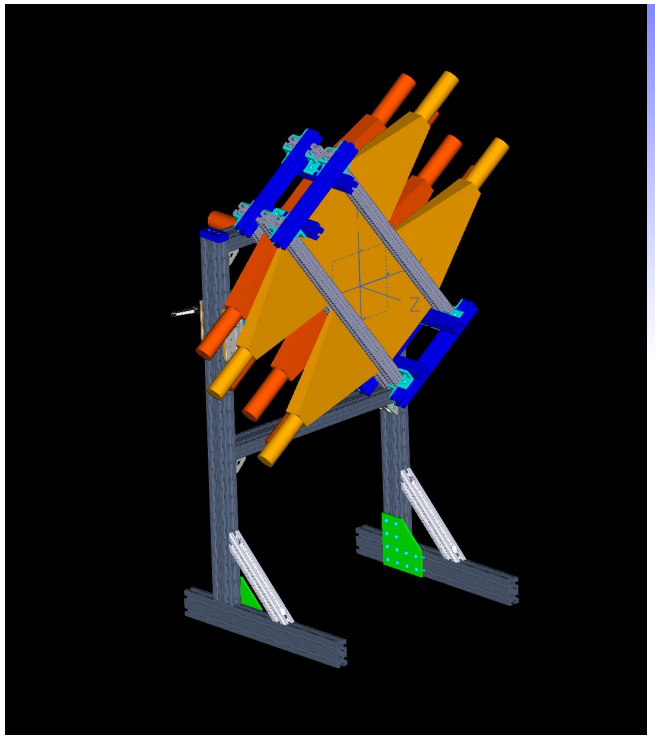
courtesy James Maxwell

Online Polarimetry



Decay with accumulated dose has been very slow

courtesy James Maxwell



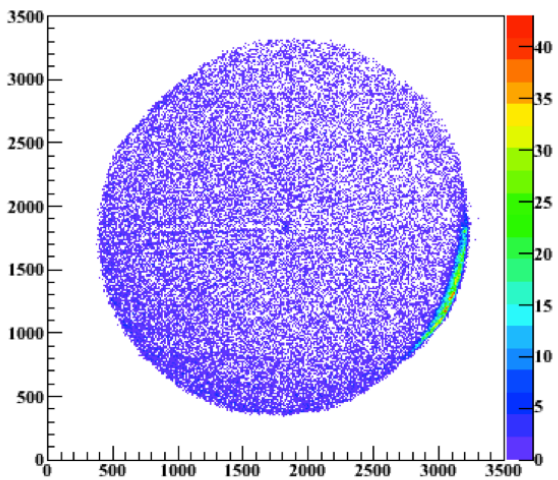
Third Arm

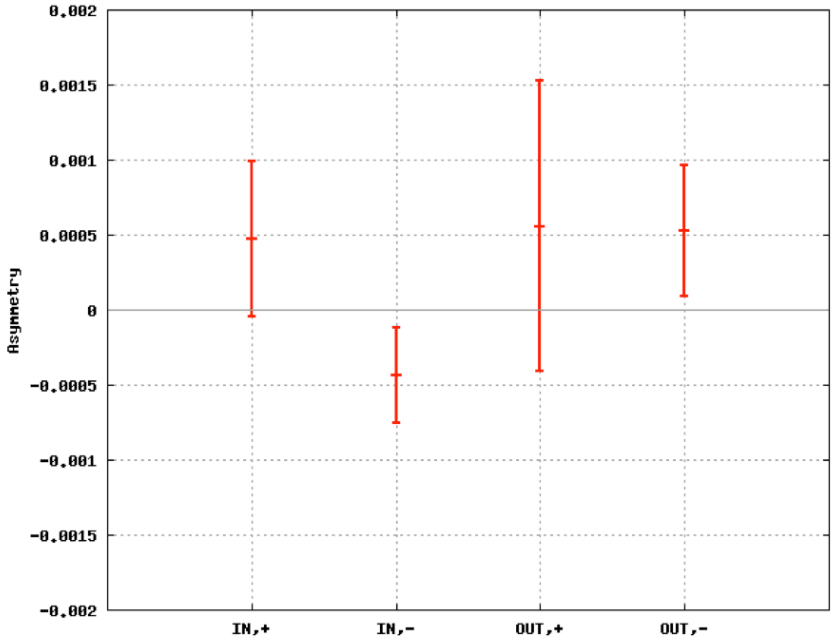
Measure the asymmetry of the elastic recoil proton

Relative measurement of the product $P_B P_T$

Non-magnetic: sampling set by the trigger threshold

Very useful as an independent Beam position monitor.

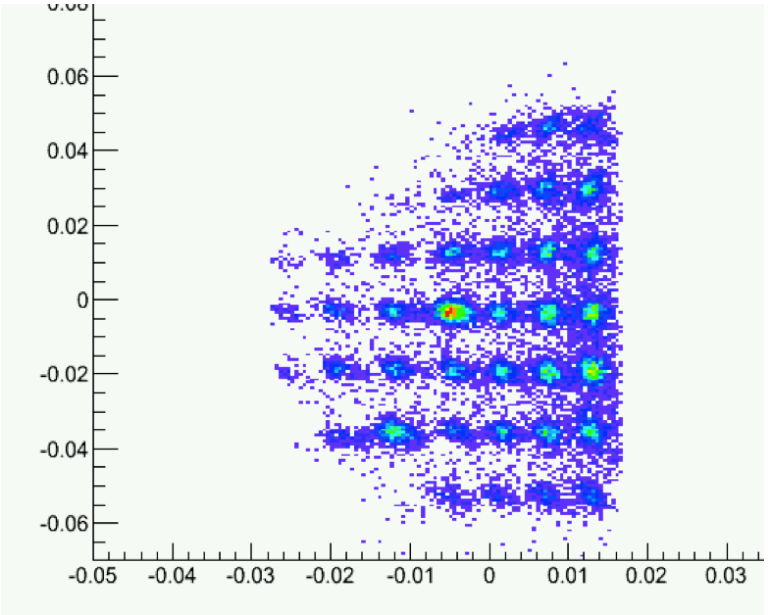


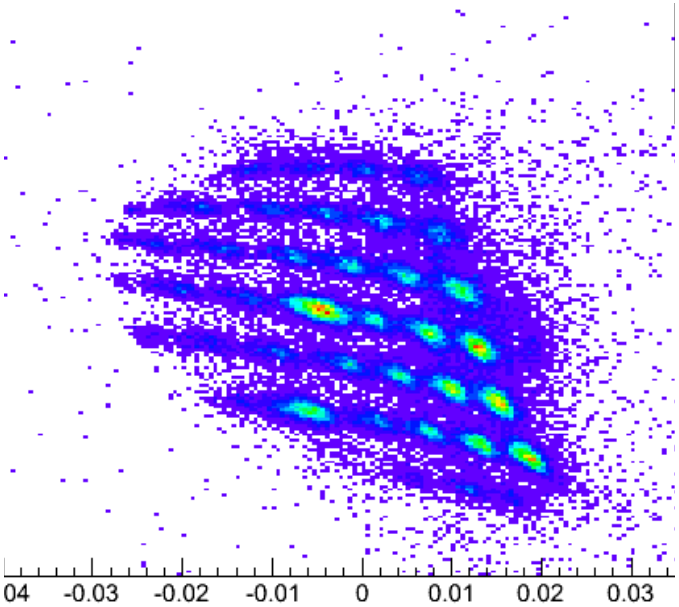


courtesy Kalyan Allada and Chao Gu

Optics

Right Septa Before/After surgery

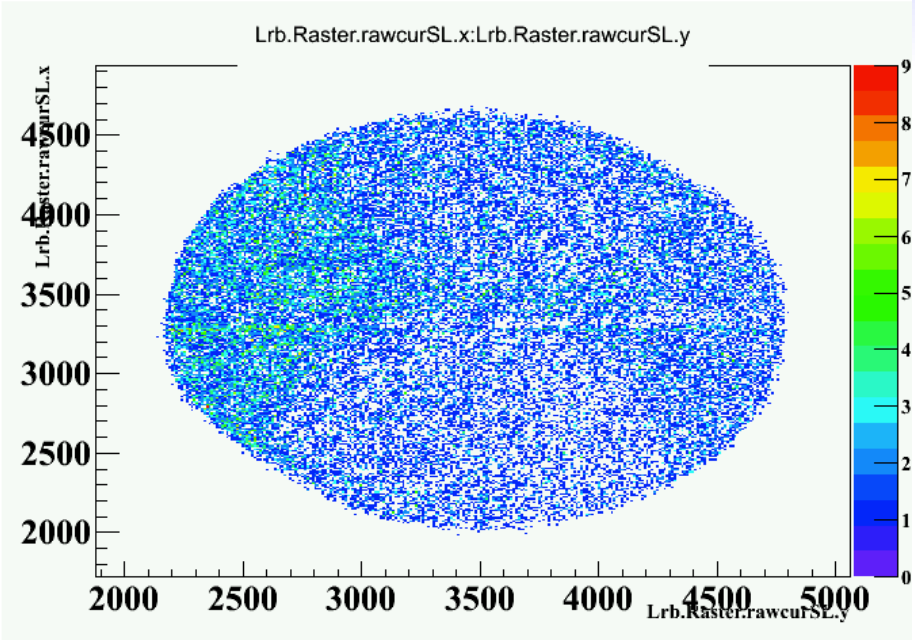




Right Septum field is no longer symmetric or uniform
Horizontal bending of the e′ depends on vertical position/angle distorts the sieve pattern

courtesy Jixie Zhang and Min Huang

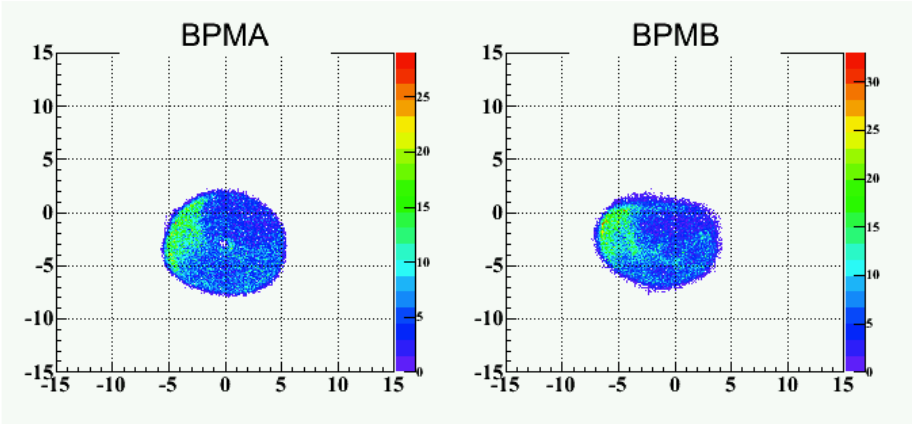
Beamline Diagnostics

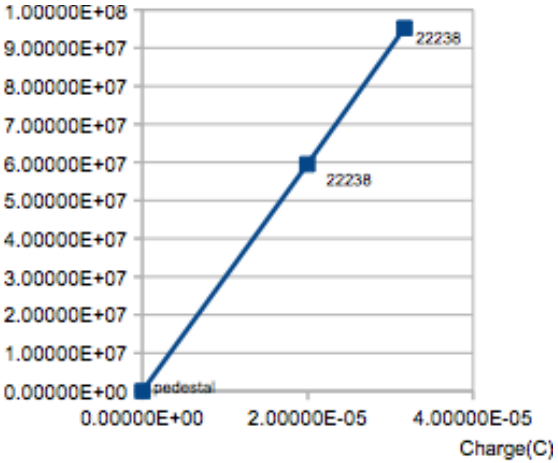


Massive effort to commission new
- BPMs
- BCMs
- Harps
- Tungsten Calo

to operate Hall a beam at < 100 nA

FIGURE 2

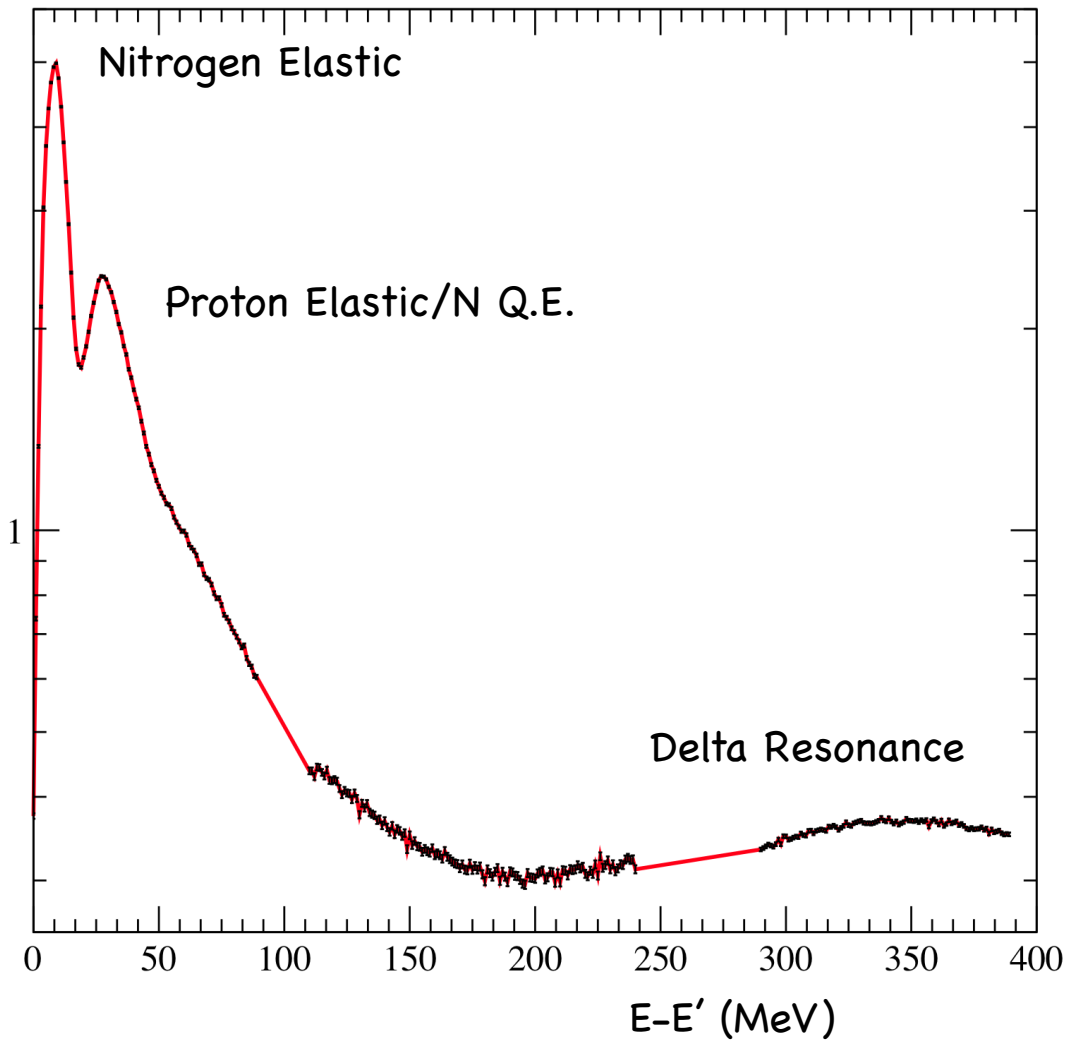




courtesy Pengia Zhu

Normalized Yields

E=2.2 GeV Left Arm



courtesy Ryan Zielinski

Normalized Yields

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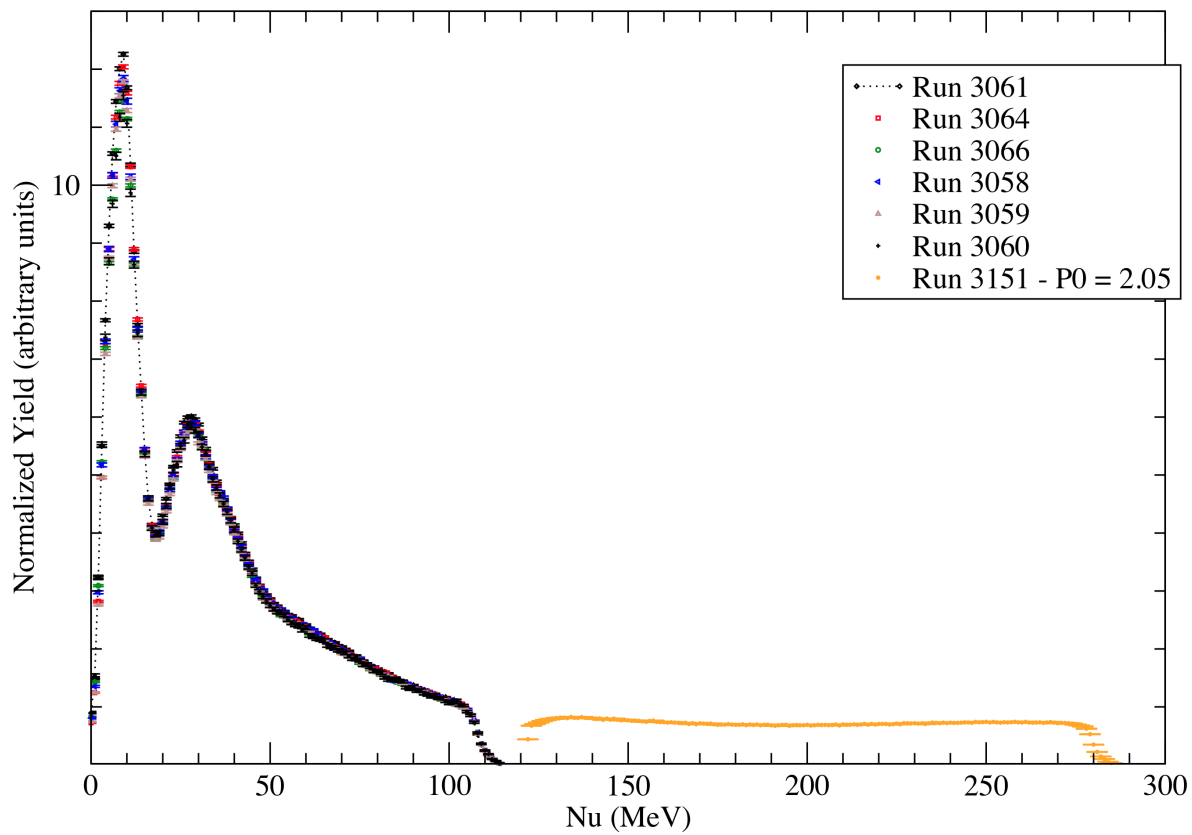
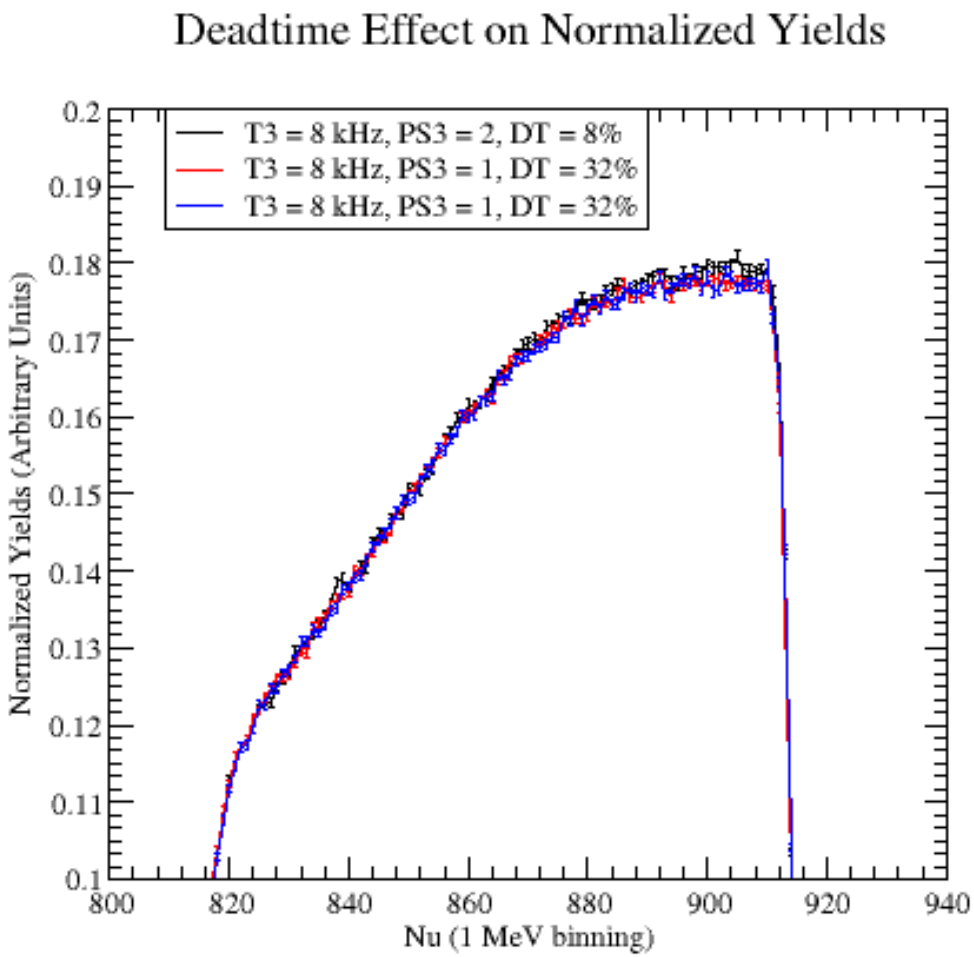


Excellent reproducibility in normalization factors

courtesy Ryan Zielinski

Normalized Yields

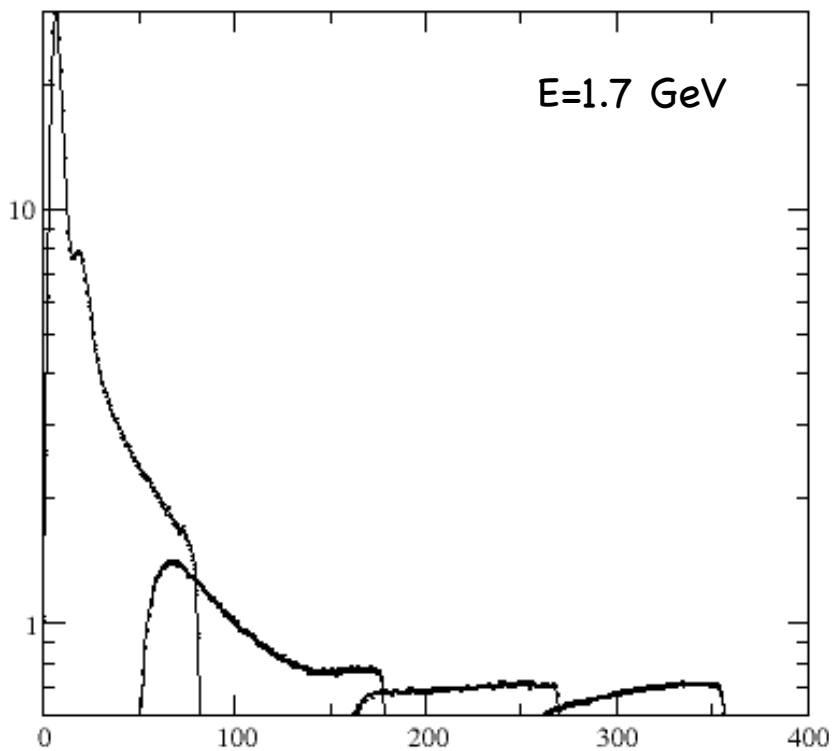


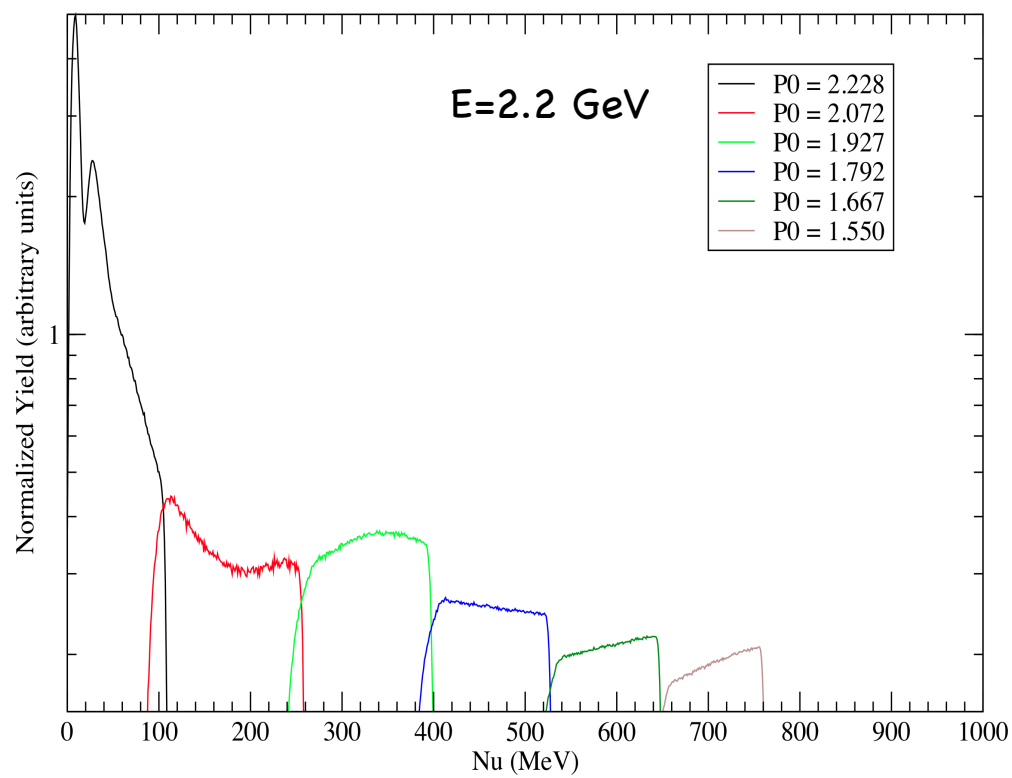
Excellent reproducibility in normalization factors

courtesy Ryan Zielinski

Normalized Yields

Acceptance effects becomes much more pronounced at low momentum

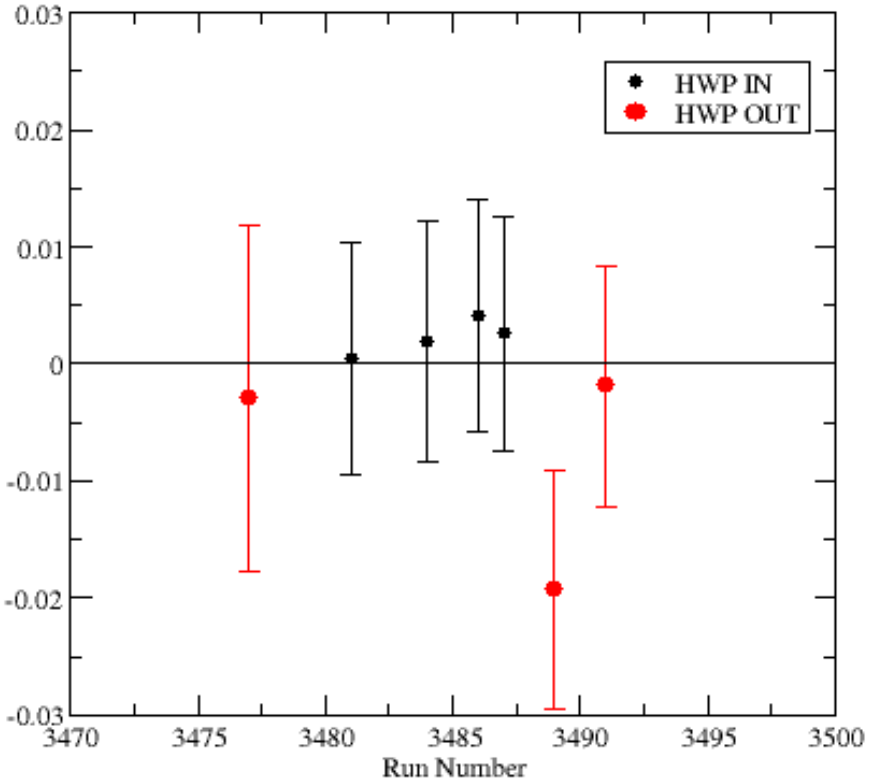




courtesy Ryan Zielinski

Raw Asymmetries

E=2.2 GeV Inelastic

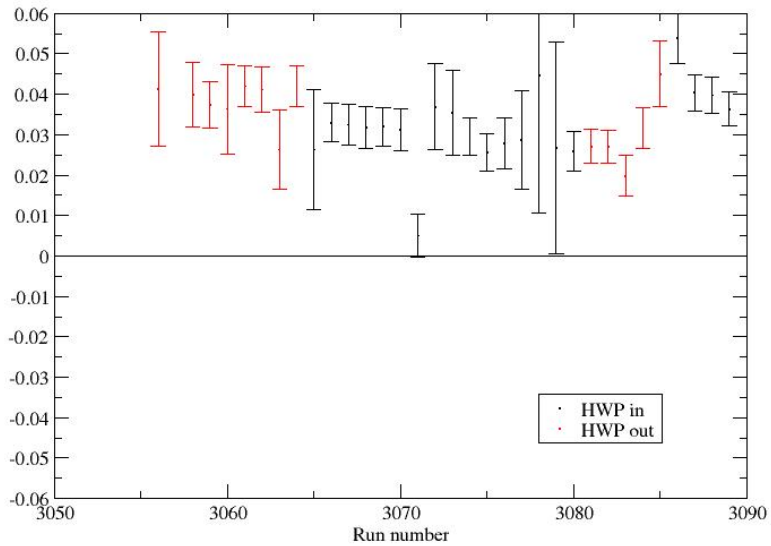


Can see HWP flips on run by run basis

courtesy Toby Badman

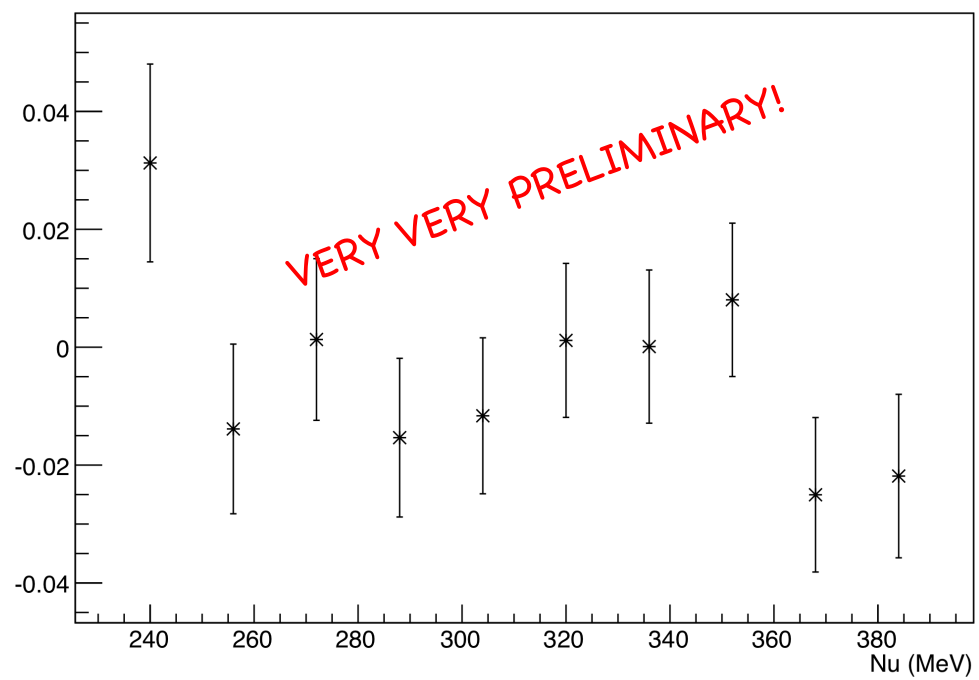
Raw Asymmetries

E=2.2 GeV Elastic



E=2.2 GeV Inelastic

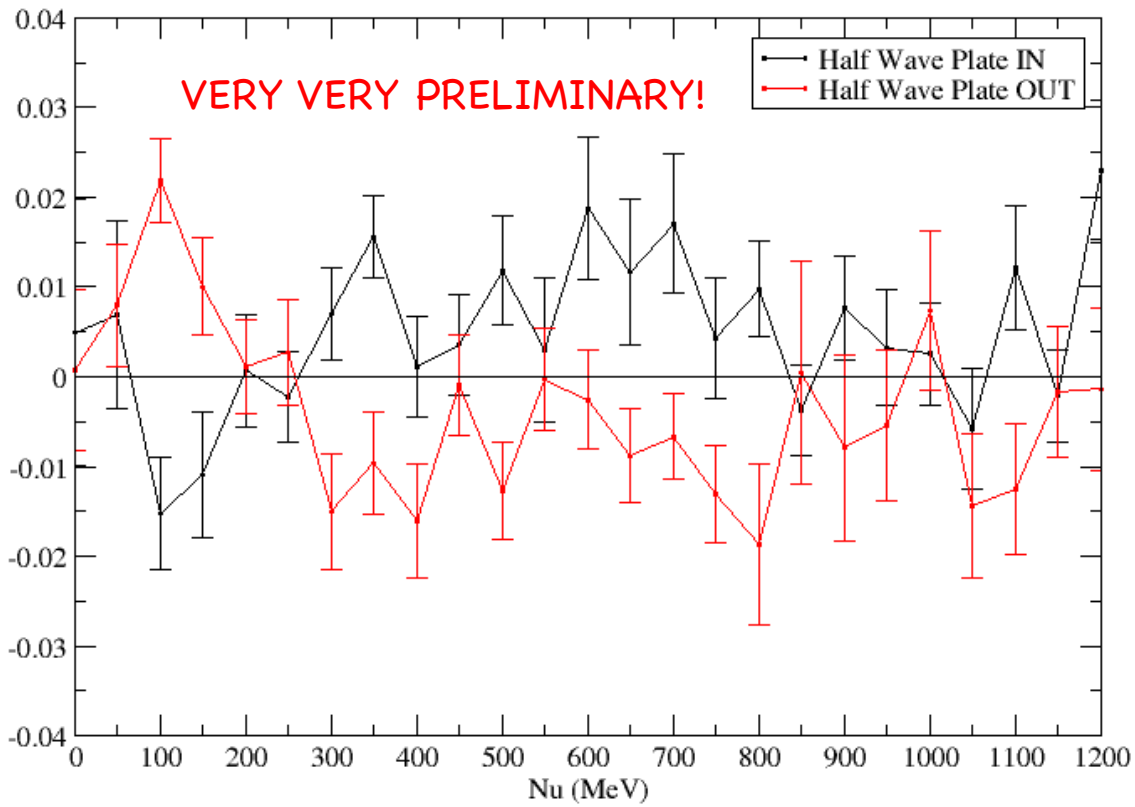
Weighted Asymmetry for P-1927 MeV/c



courtesy Toby Badman

Raw Asymmetries

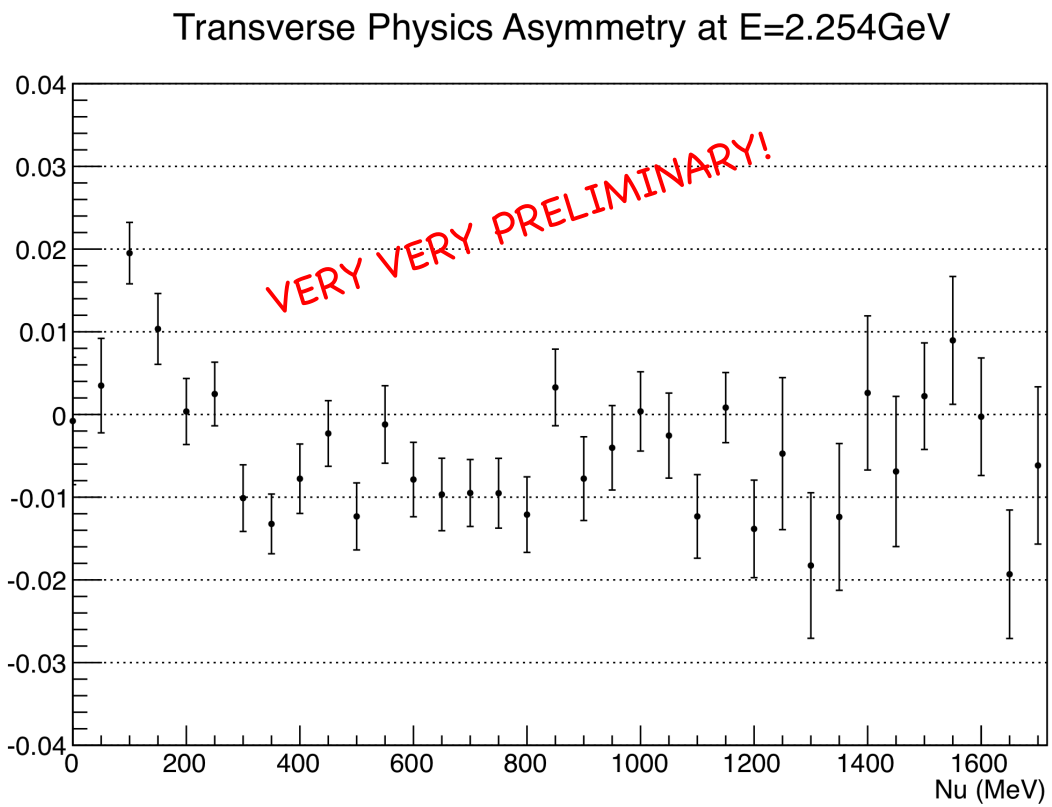
E=2.2 GeV Inelastic



No charge normalization

courtesy Toby Badman

Raw Asymmetries



W<1.6GeV

About 1E9 events

No charge normalization

courtesy Toby Badman

Summary

Long string of mechanical problems, But running fairly smoothly now

Right septa compromised significantly, but still operating.
Will be challenge to understand the optics

Beamline diagnostics working reasonably at 50nA

Third Arm working well

g2p
Recorded 3.8E9 inelastic events at 2.2 GeV
Recorded 1.7E9 inelastic events at 1.7 GeV

GEp completed two Q2 points as well

We should still provide the definitive measurement of g_2 and G_E/G_M at low Q^2