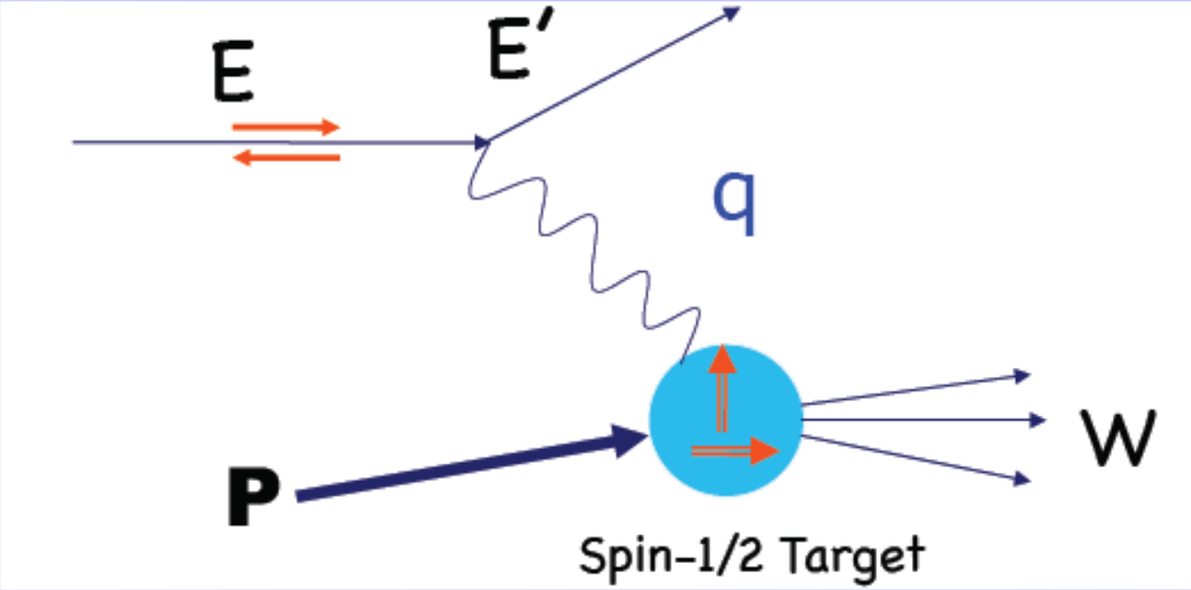
G2P(E08-027)

Status Update

Jixie Zhang
For g2p Collaboration

Hall A Collabortion Meeting, June 2012

Inclusive Scattering

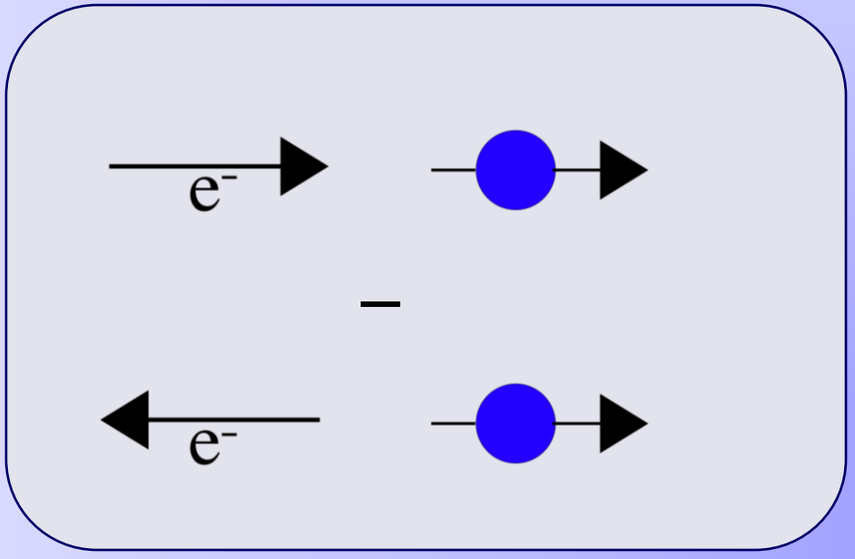


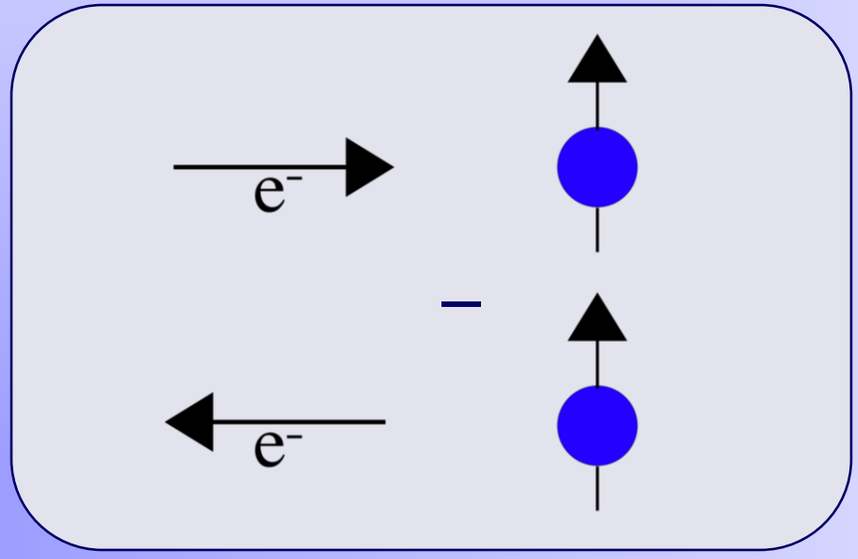
2 additional structure functions Needed for polarized cross section (compared with unpoloarized one).

Inclusive **Polarized** Cross Section:

$$\frac{d^2\sigma}{d\Omega dE'} = \sigma_{Mott}\left[\frac{1}{\nu}F_2(x,Q^2) + \frac{2}{M}F_1(x,Q^2)\tan^2\frac{\theta}{2} + \gamma\, g_1(x,Q^2) + \delta\, g_2(x,Q^2)\right]$$

How to get g_2?





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

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

Need to measure inclusive polarized cross section differences !!!
(through absolute cross section and asymetry)

E08-027 Experiment
Proton g2 Structure Function

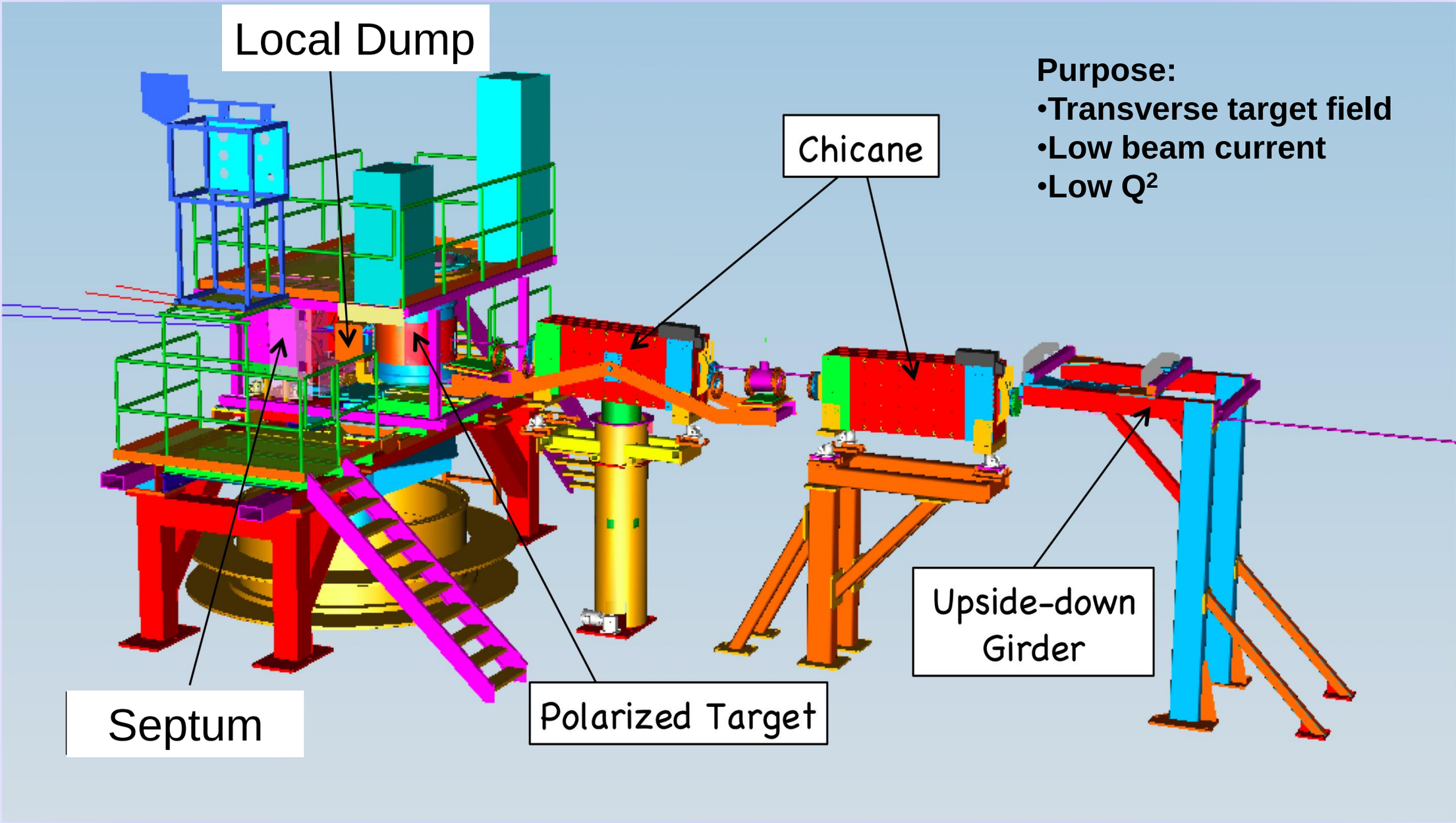
Primary Motivation

Measure the proton g_2 structure function at low or moderate Q^2(for the 1st time).

This will help to clarify several puzzles:

- **Test the Burkhardt-Cottingham sum rule at low Q^2 .**
- **Extract the generalized longitudinal-transverse spin polarizability δ_{LT} , allows to test Chiral Perturbation Theory (χPT)**
- **Hydrogen HyperFine Splitting :**
  Lack of knowledge of g_2 at low Q^2 is one of the leading uncertainties.
- **Proton Charge Radius :**
  One of the leading uncertainties in extraction of $\langle R_p \rangle$ from μ–H Lamb shift.

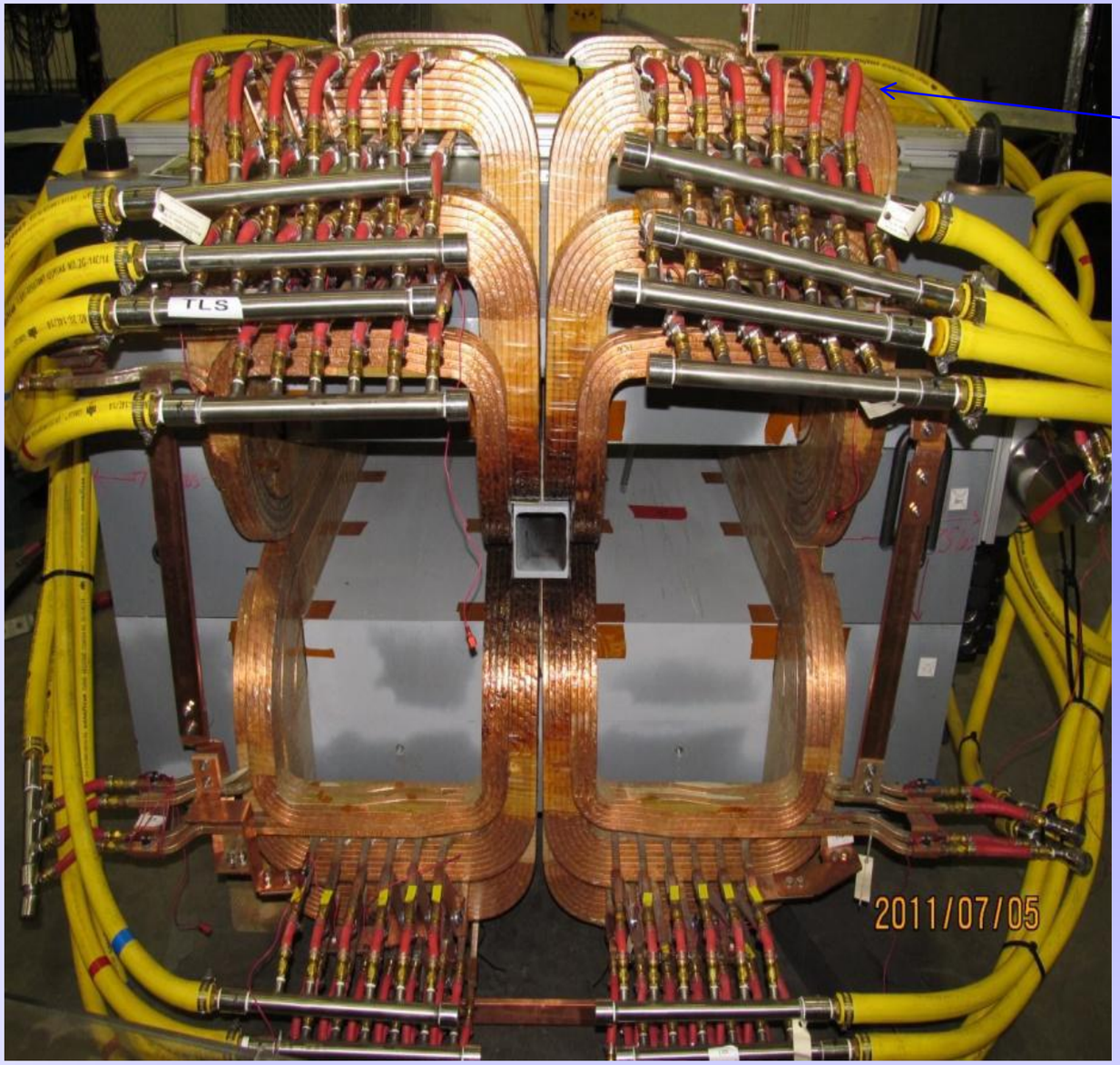
Major New Installation in Hall A



Purpose:

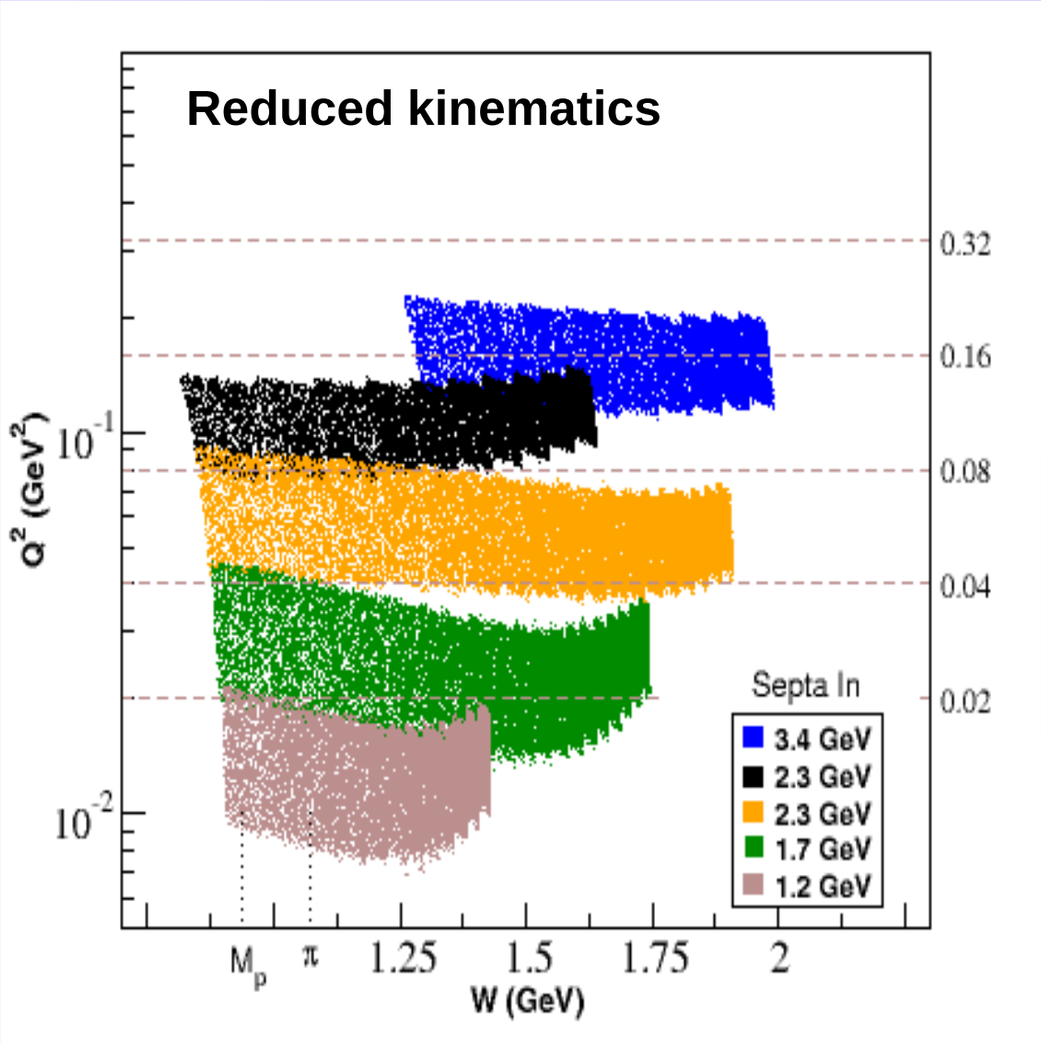
- **Transverse target field**
- **Low beam current**
- **Low Q^2**

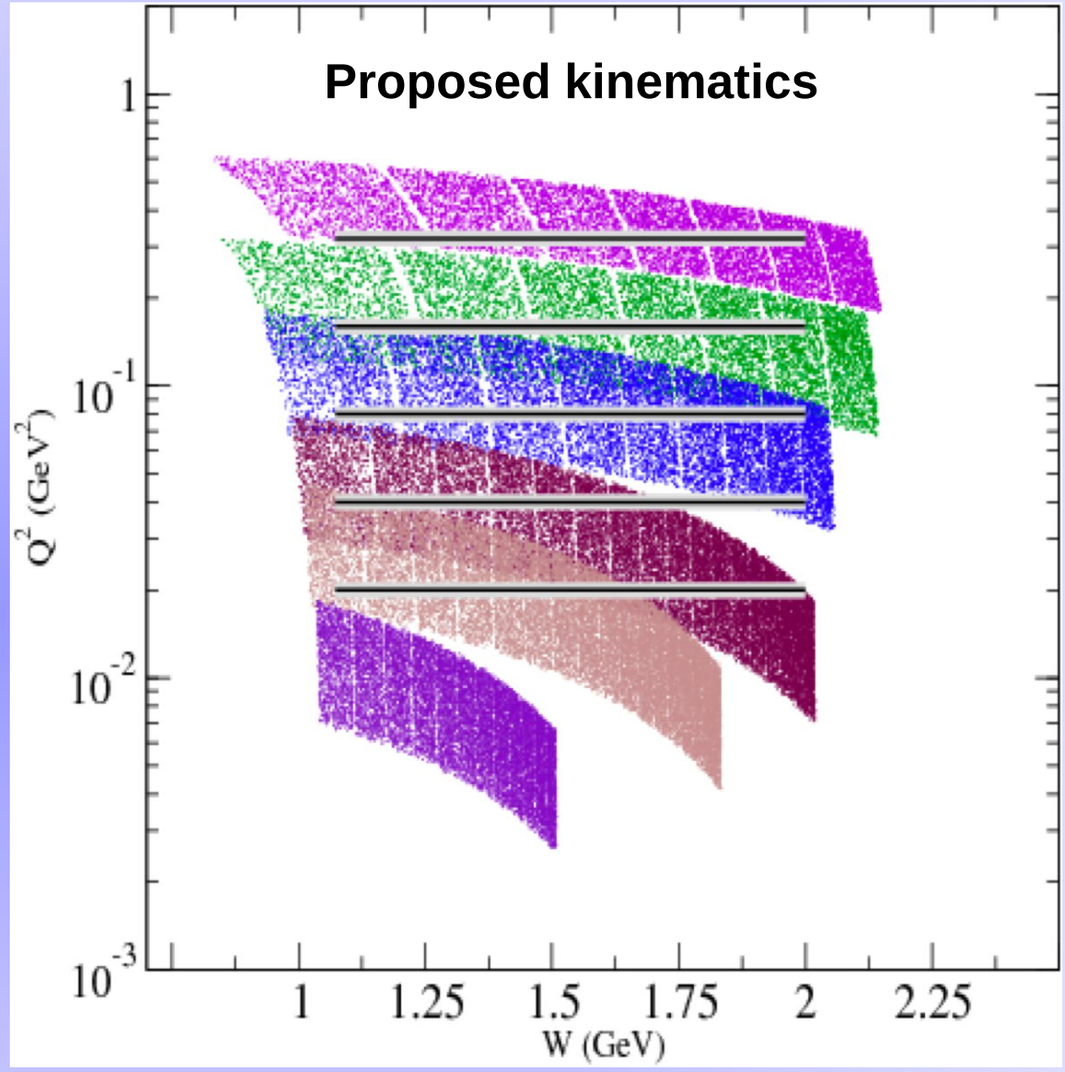
The Septum magnet



- Only 2 pairs of coils (00-48-16) turns was used in PREX
- Added 3rd pair of coils: 48-48-16 (can bend 2.82 GeV particles when run at 950A).
- 2 one-inch iron shims were added to each side, one on the top and the other at the bottom, to bend 2.89 GeV particles when run at 950 GeV.
- Left septum connected to HKS power supply (thanks to Hall-C)and right septum to BigBite power supply.
- Right septum short grounded after 3 weeks of runing and repaired as 40-32-16 turns of top coils, down coils were not changed
- 2 weeks later, right septum short grounded again and the top coils were repaired to be 40-00-16 coils.

Kinematic Coverage



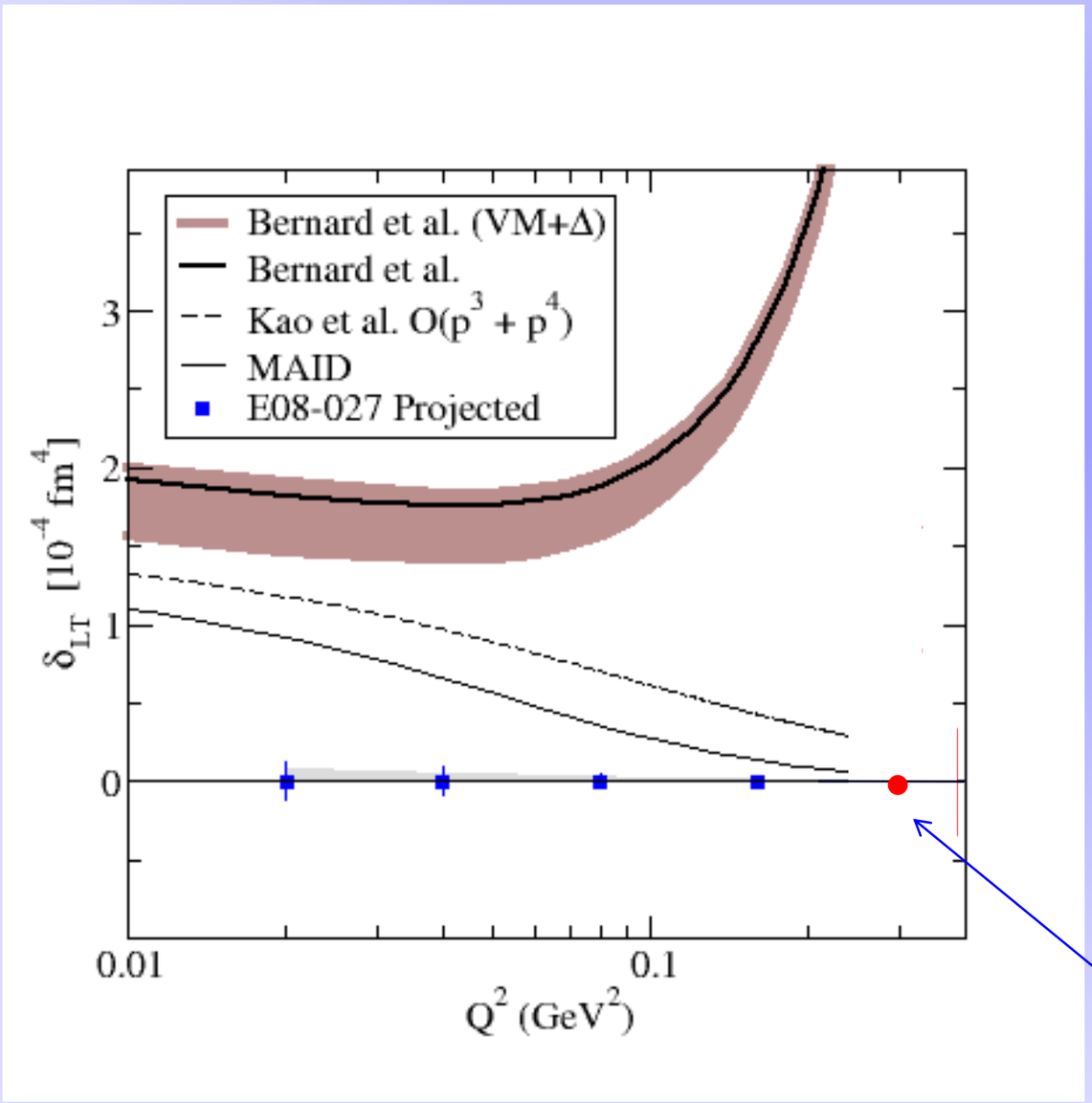


$M_p < W < 2$ GeV

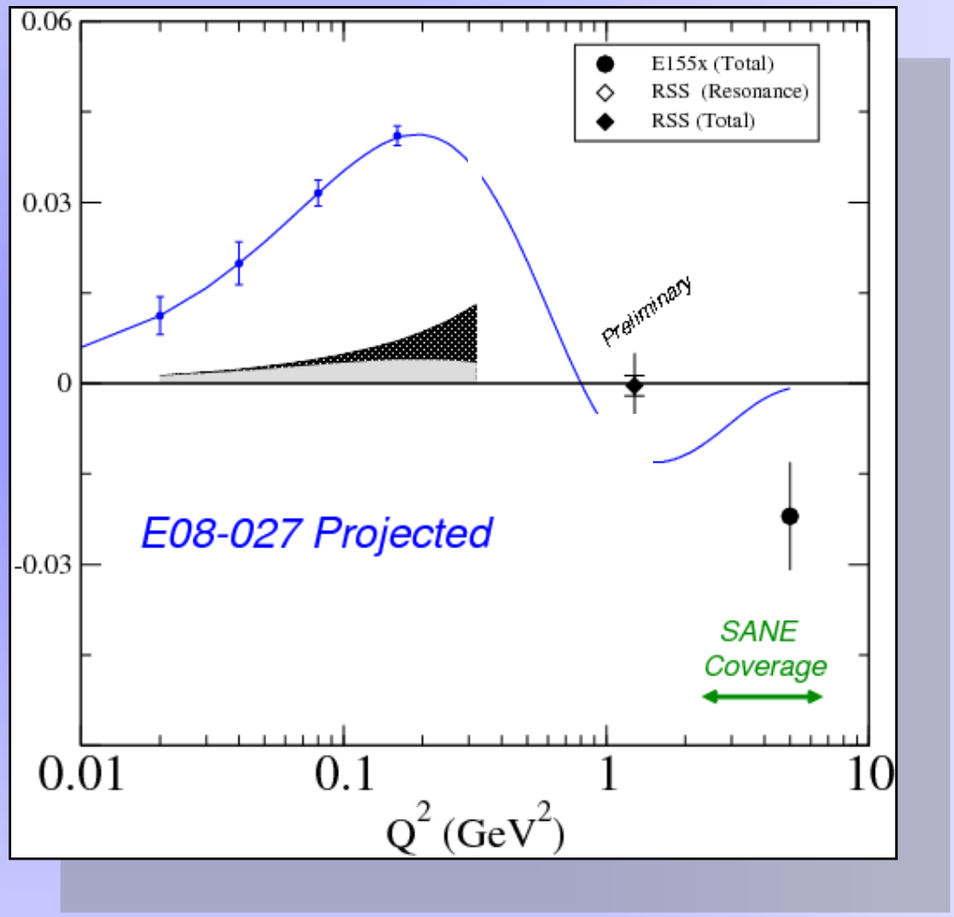
$0.02 < Q^2 < 0.2$ GeV^2

Projected Results

LT Spin Polarizability

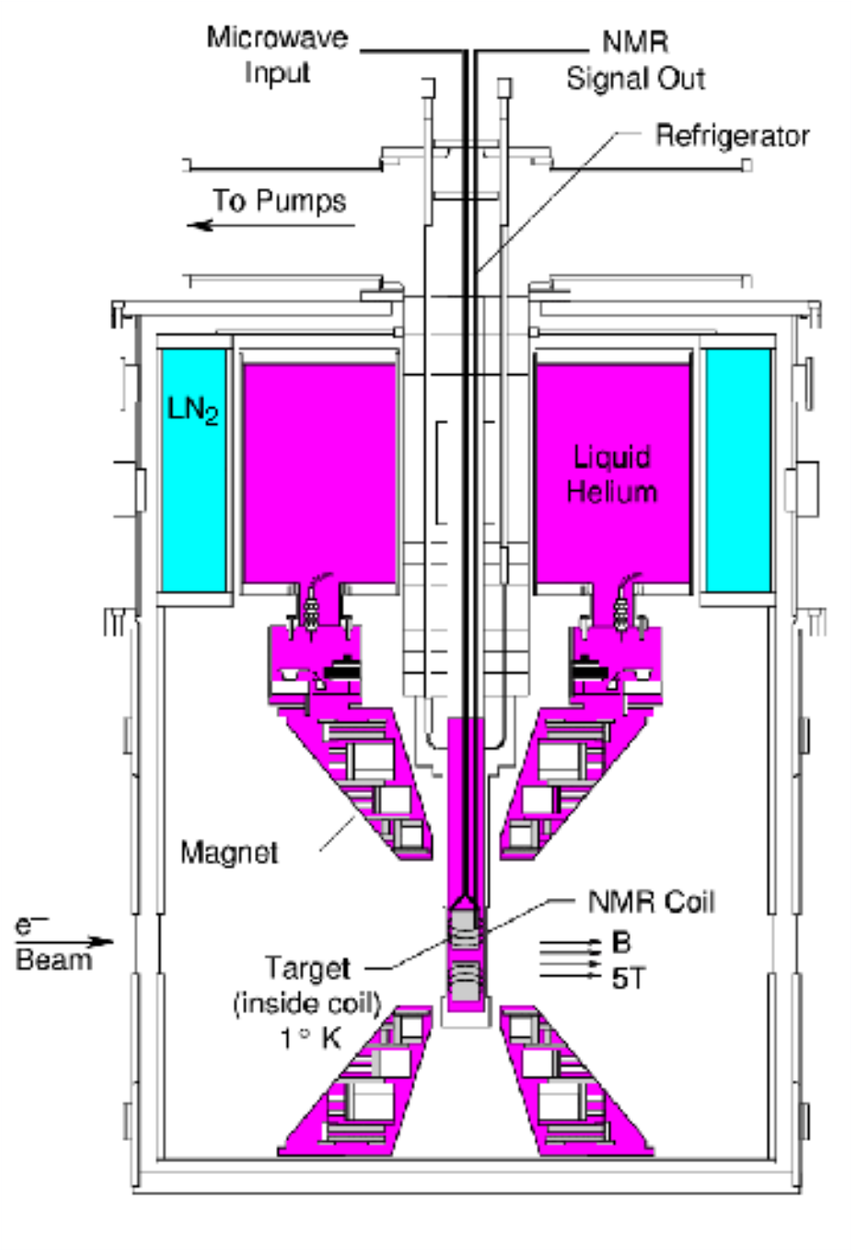


BC Sum Integral Γ_2



data not taken

Polarized Ammonia Target



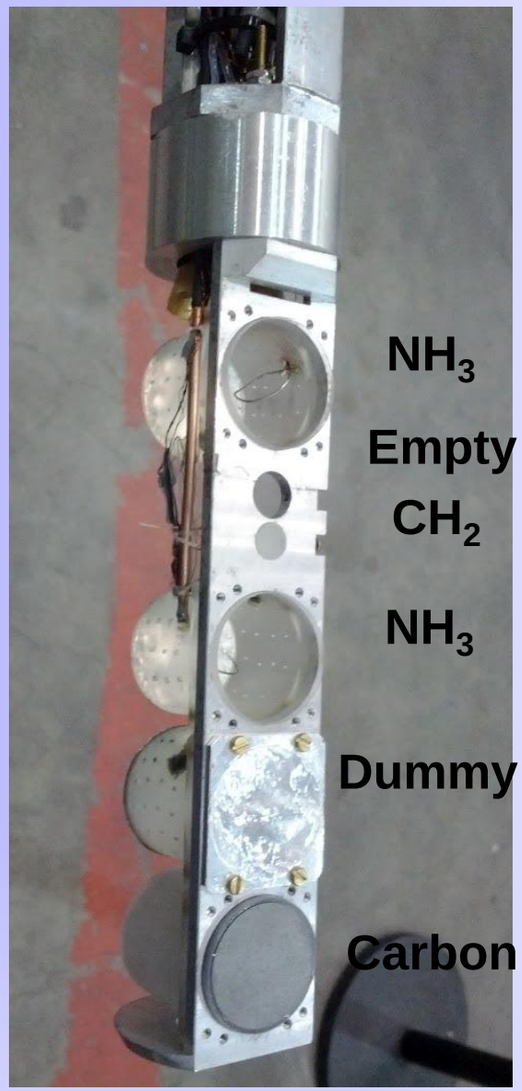
Dynamic Nuclear Polarization of NH_3

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

<u>5.01 T/ 140 GHz or 2.5 T/70 GHz operation</u>
Helmholtz superconduct magnet

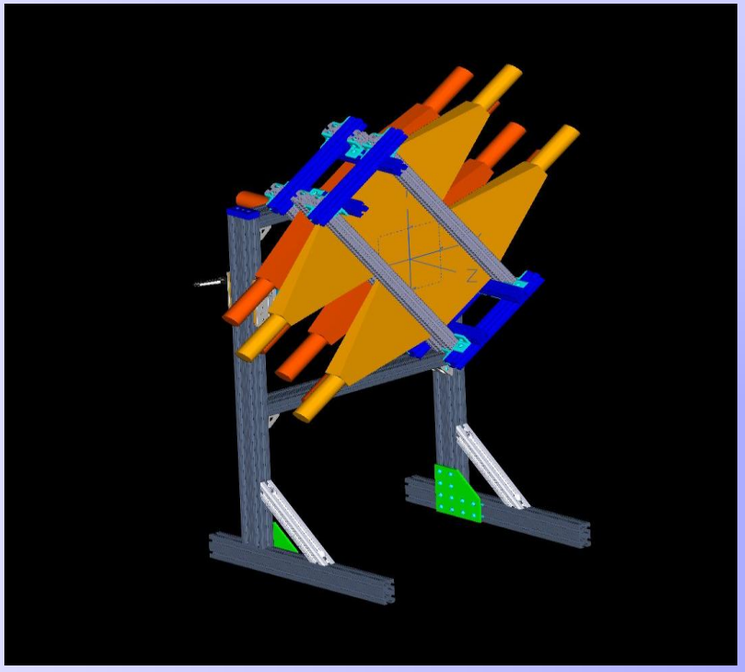
1K ^{4}He evaporation refrigerator
Cooling power: about 1 W

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

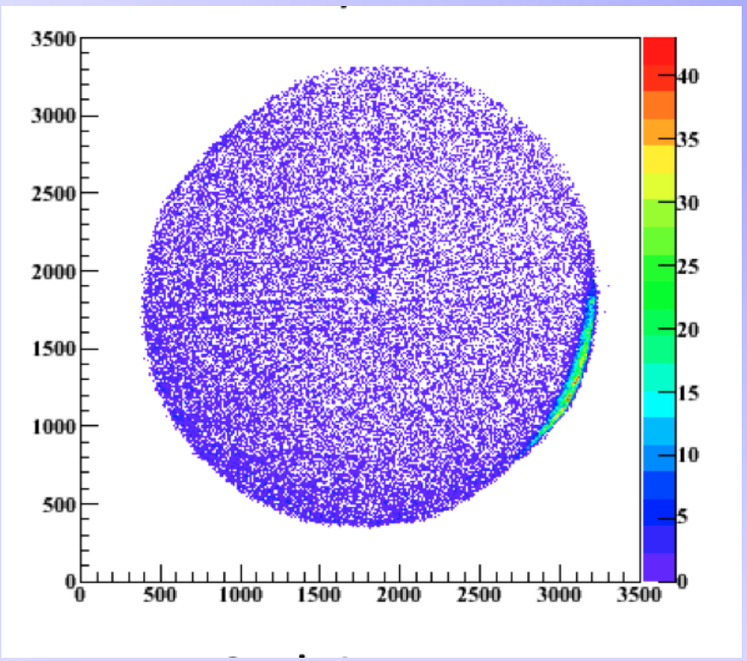


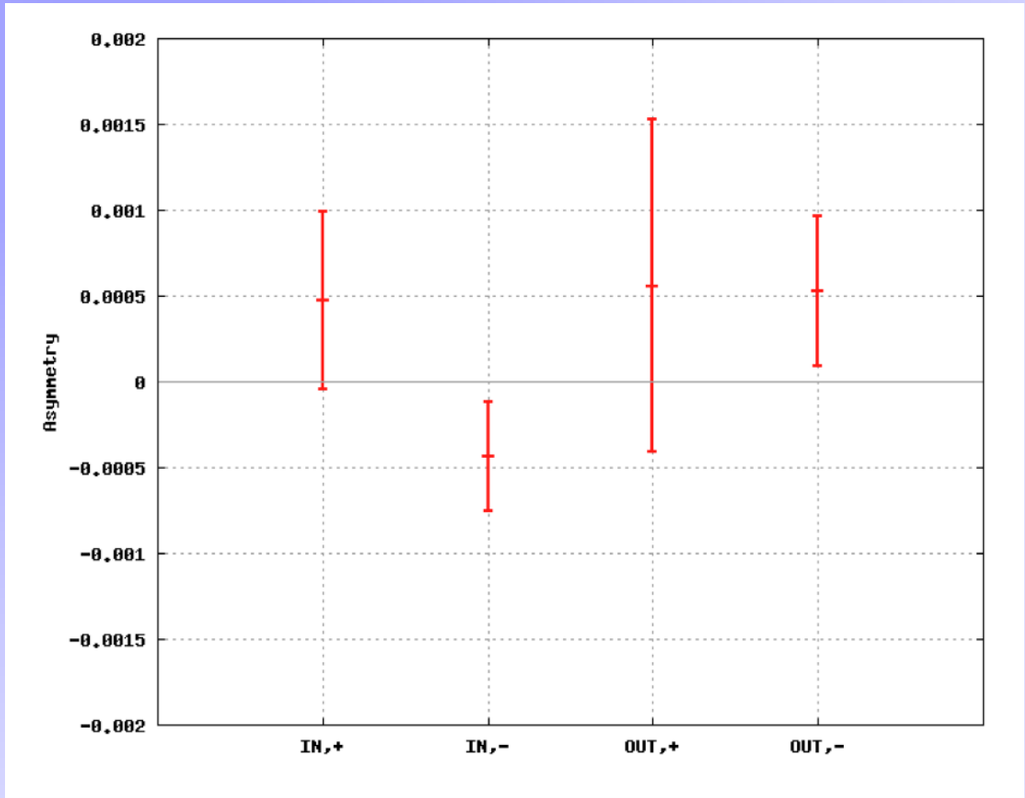
See Josh's talk for details

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 quality monitor.





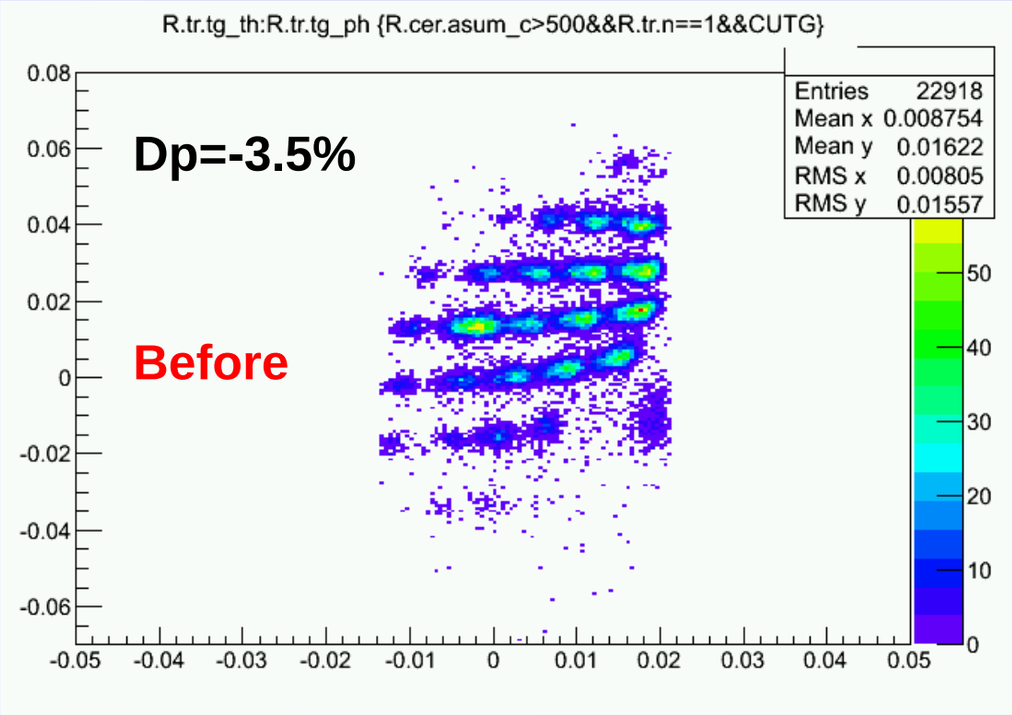
courtesy Kalyan Allada and Chao Gu

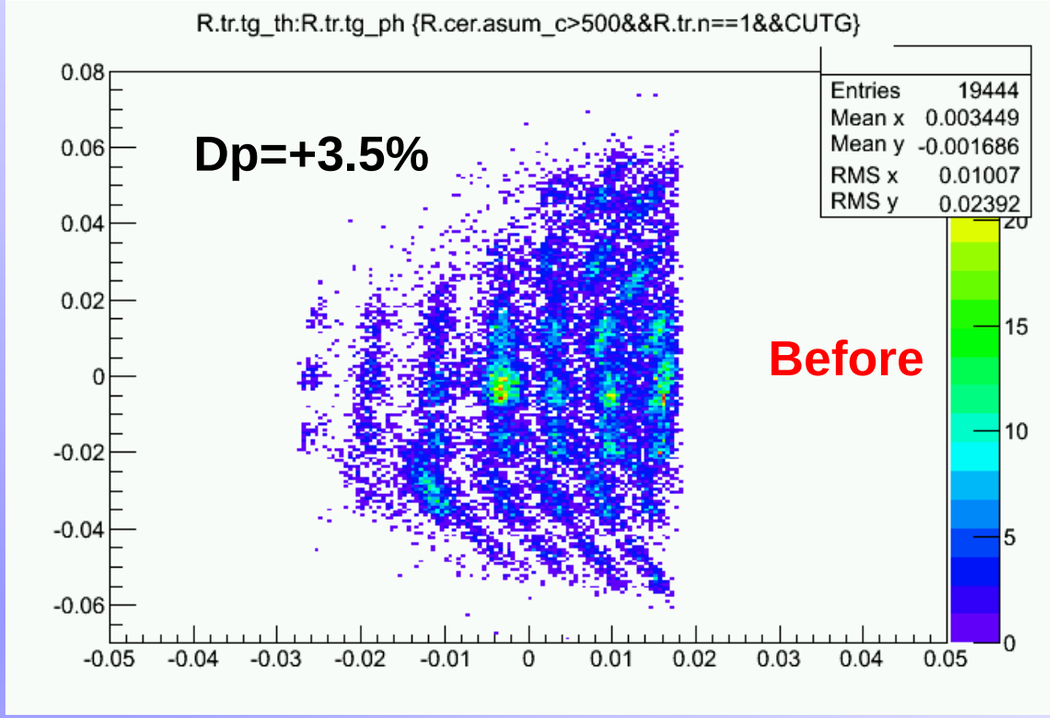
Optics for g2p

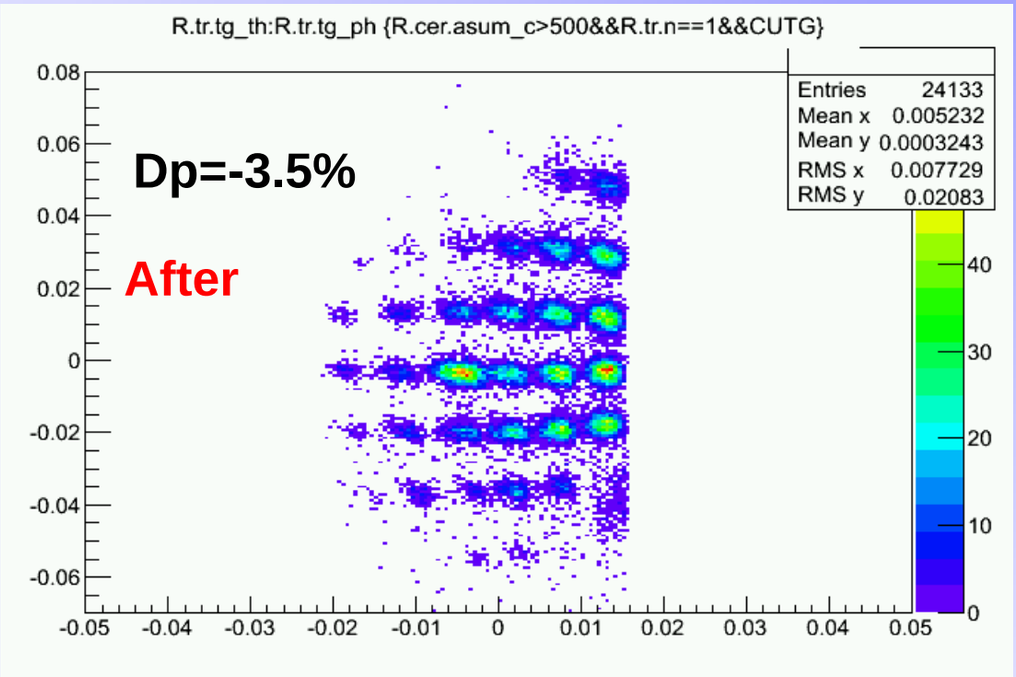
- Goals:
  - About 1% uncertainty of scattering angle (require good accuracy of ϕ_{tg} (horizontal) θ_{tg} (vertical)
  - A few 10^{-4} precision of momentum
- NEW g2p "I vs P_0"setting of HRS Quads from SNAKE tuning and
- NEW g2p optics matrix for online analysis based on SNAKE tuning.
- Straight through calibration is closed to finish (good for no target field data only).
- Strategy for data with the target field:

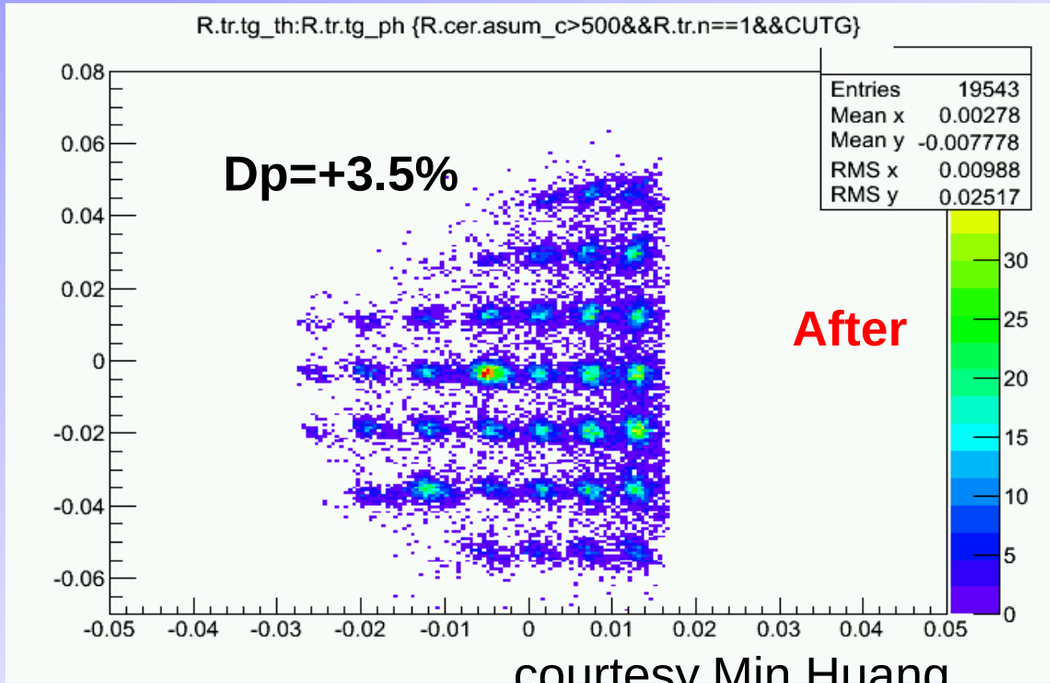
Focus plane to target plane straight through reconstruction → linear project to sieve plane → sieve to target reconstruction (get matrix from simulation, will be calibrate with real data)

θ_{tg} vs ϕ_{tg} after calibration (no target field)



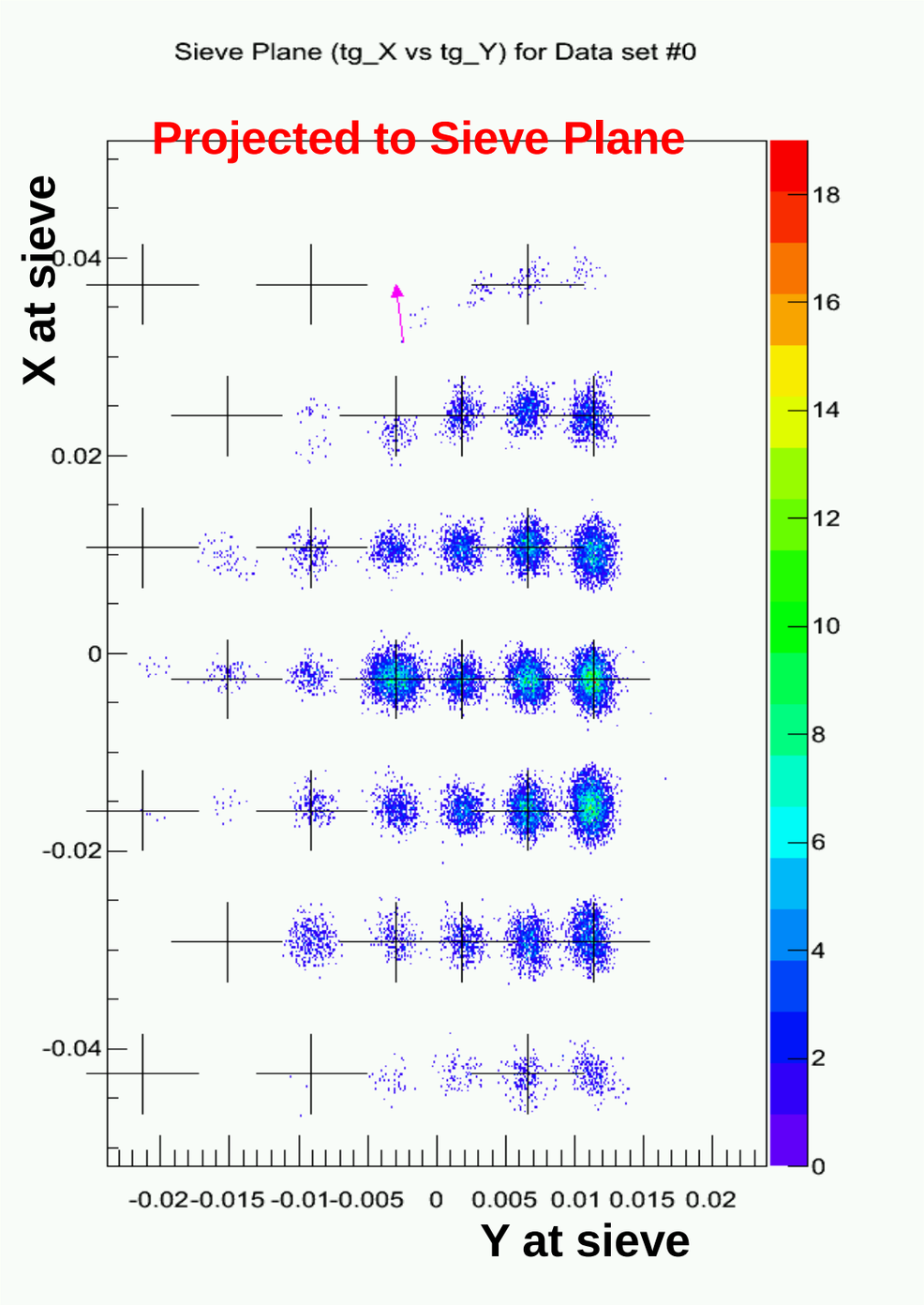


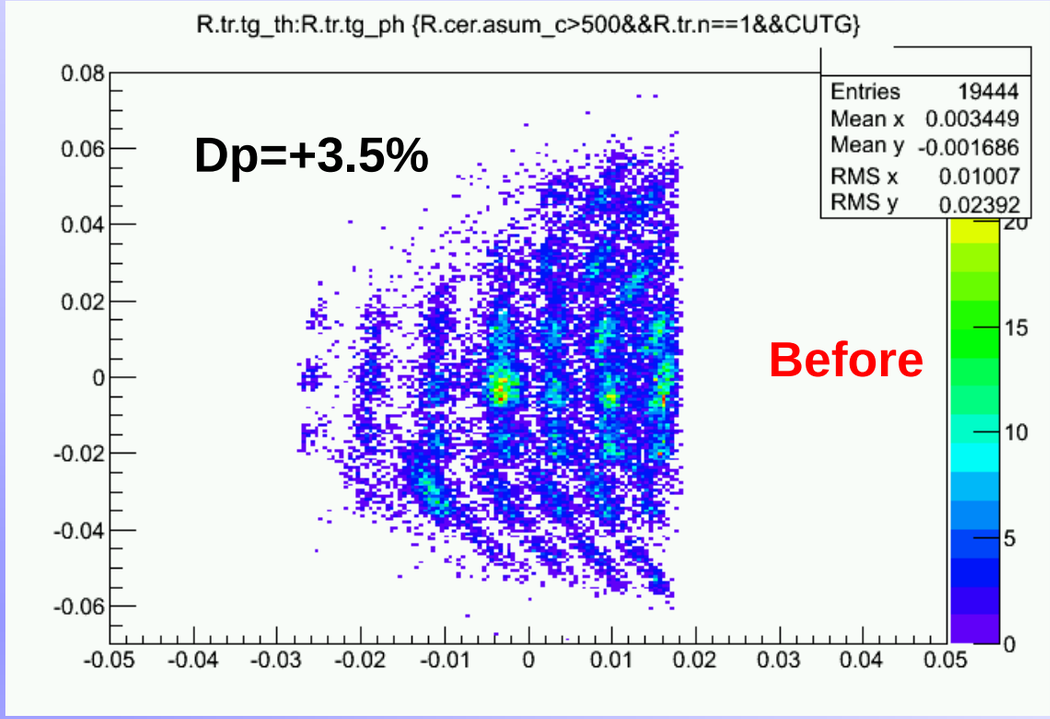


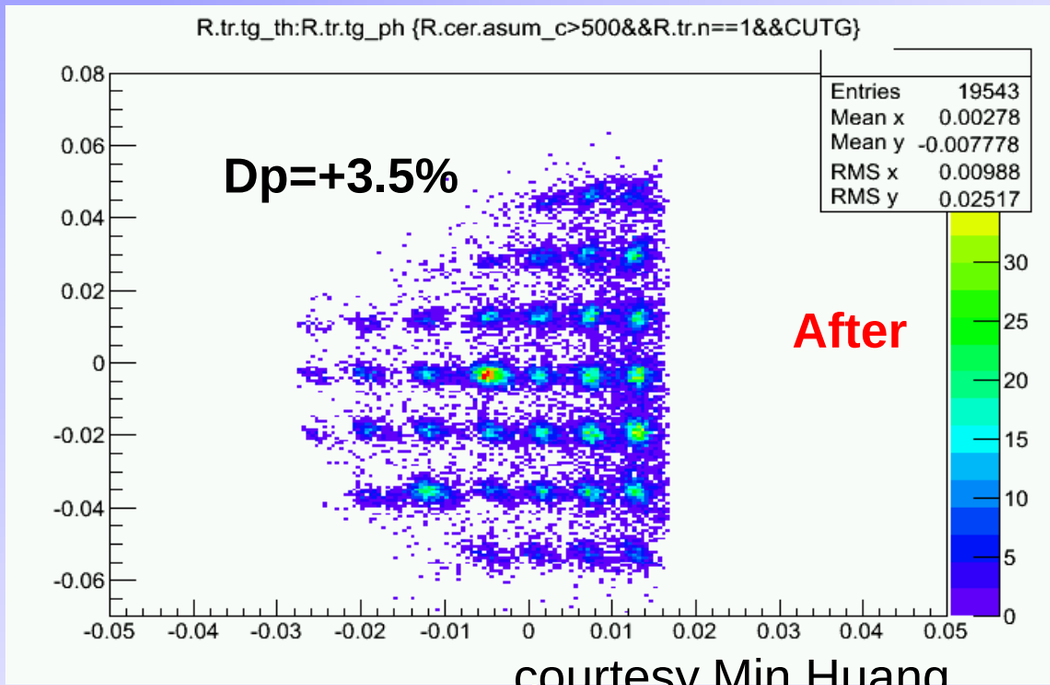


courtesy Min Huang

θ_{tg} vs ϕ_{tg} after calibration (no target field)





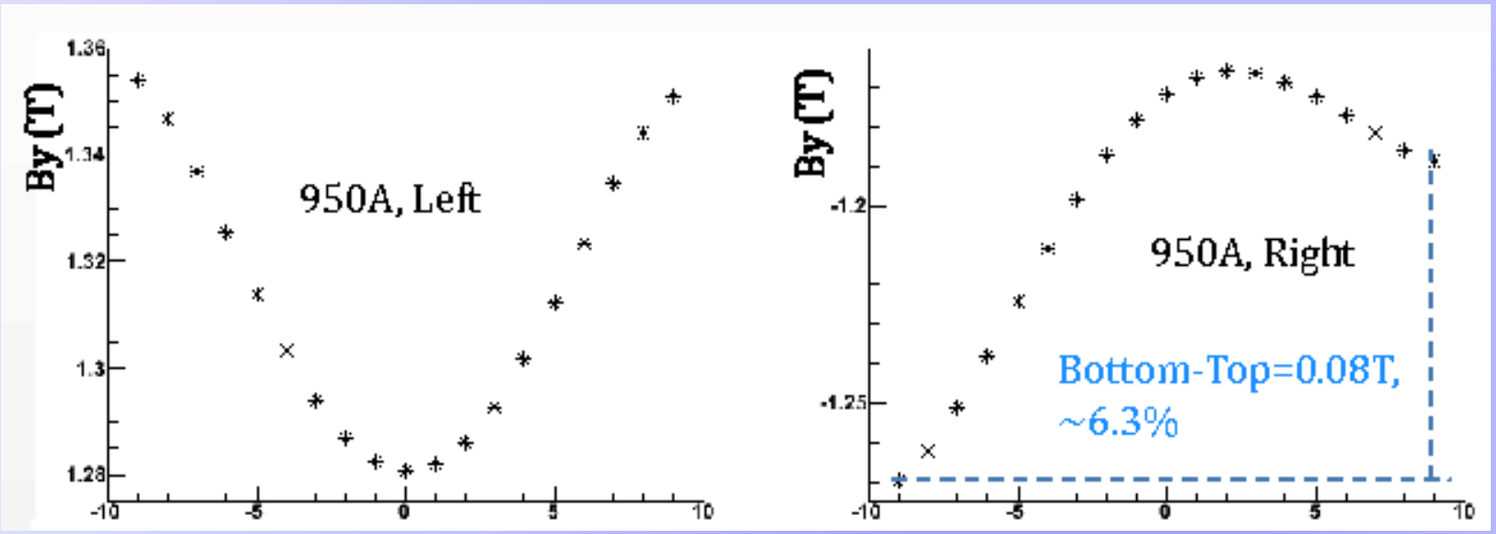


courtesy Min Huang

Special Situation for Right Septum

Initial perfect design: 48-48-16 coils (top) & 16-48-48 (bottom)

After first broken: 40-32-16 coils (top) & 16-48-48 (bottom)

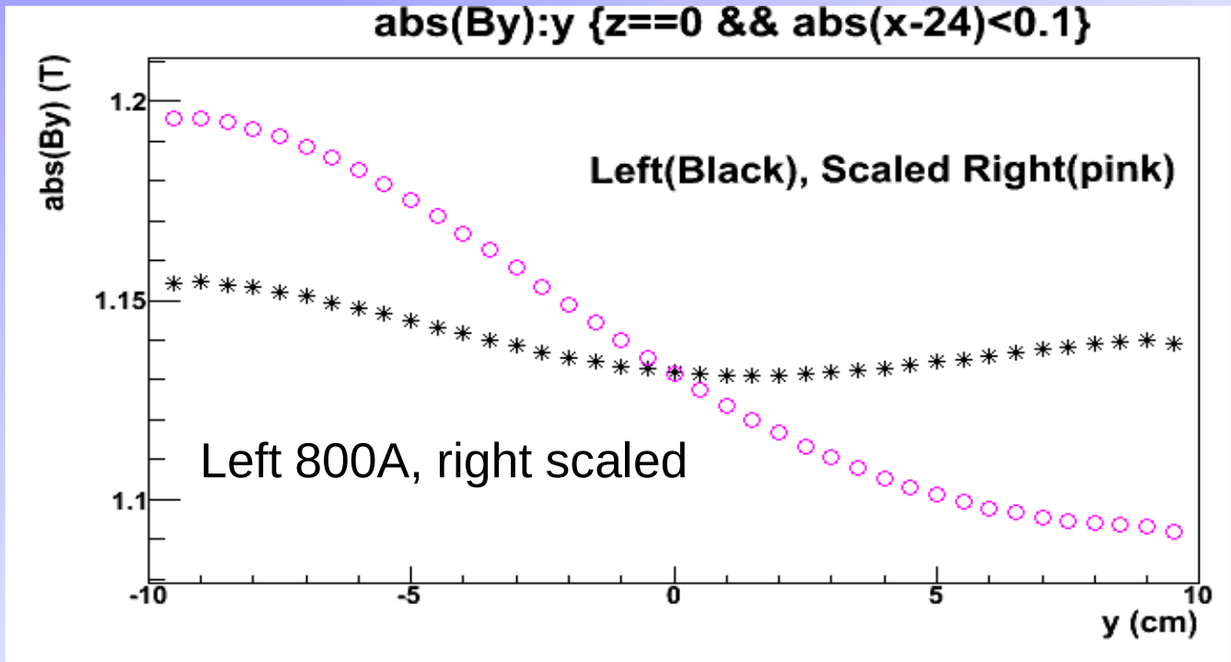


←40-32-16 coils Left almost no change;

Right septum is not symmetric in Y any more, top is ~ 6.3% lower than bottom

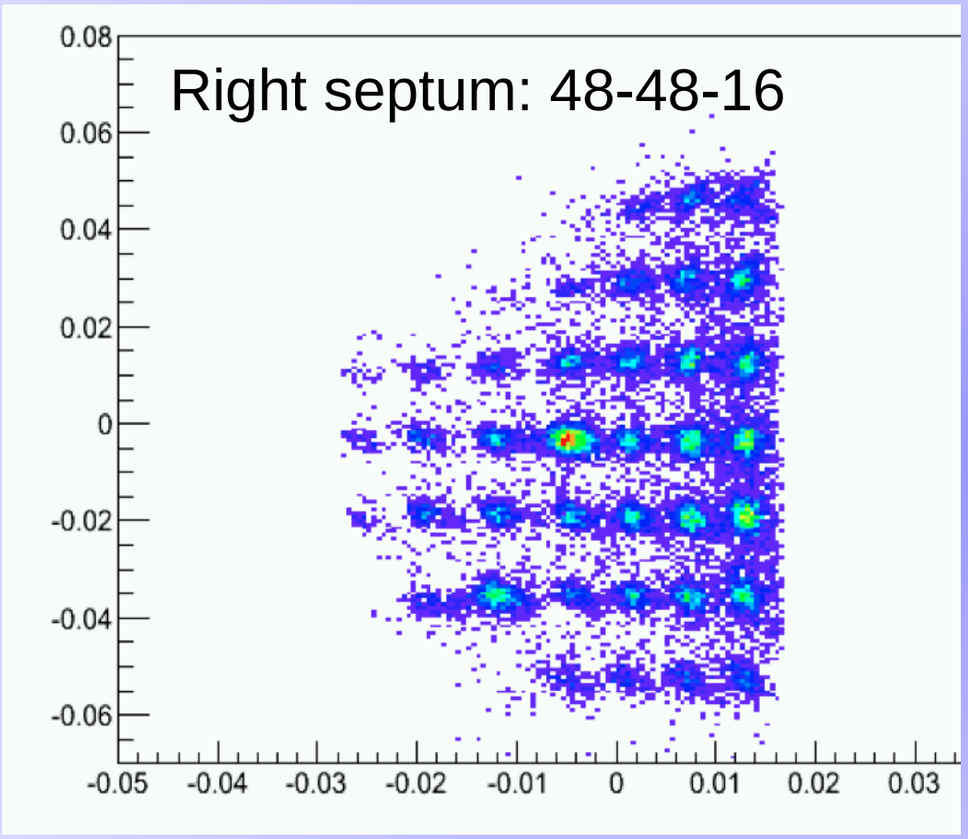
After 2nd repair: 40-00-16 coils (top) →

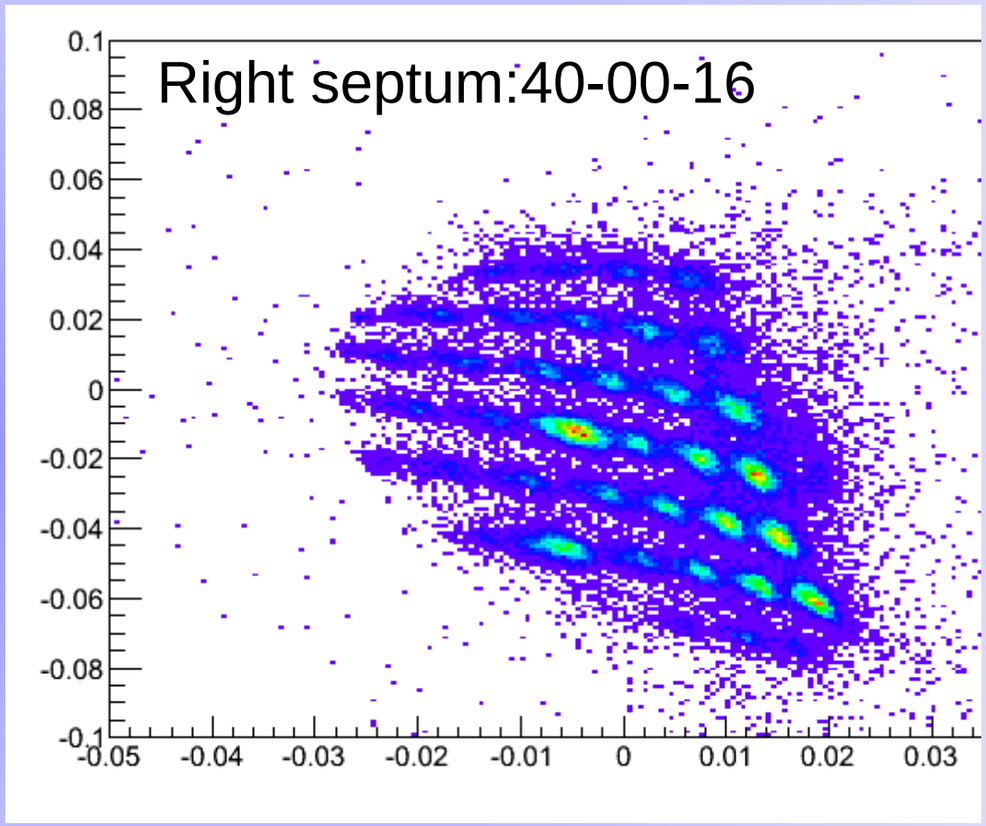
Field at the top of left septum top is about 1% smaller than that at the bottom, while ~10% at the right septum at 800A, (~12% at 950A)



Right HRS Optics

θ_{tg} vs ϕ_{tg}

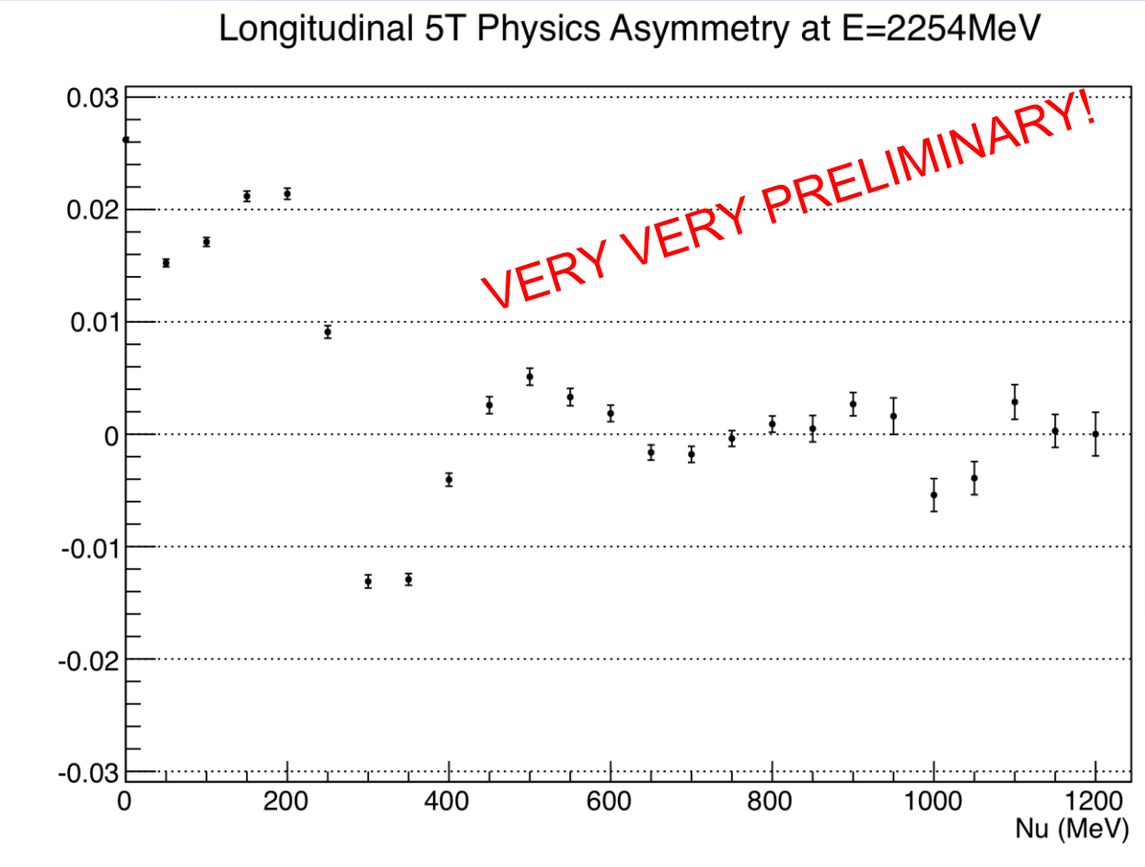


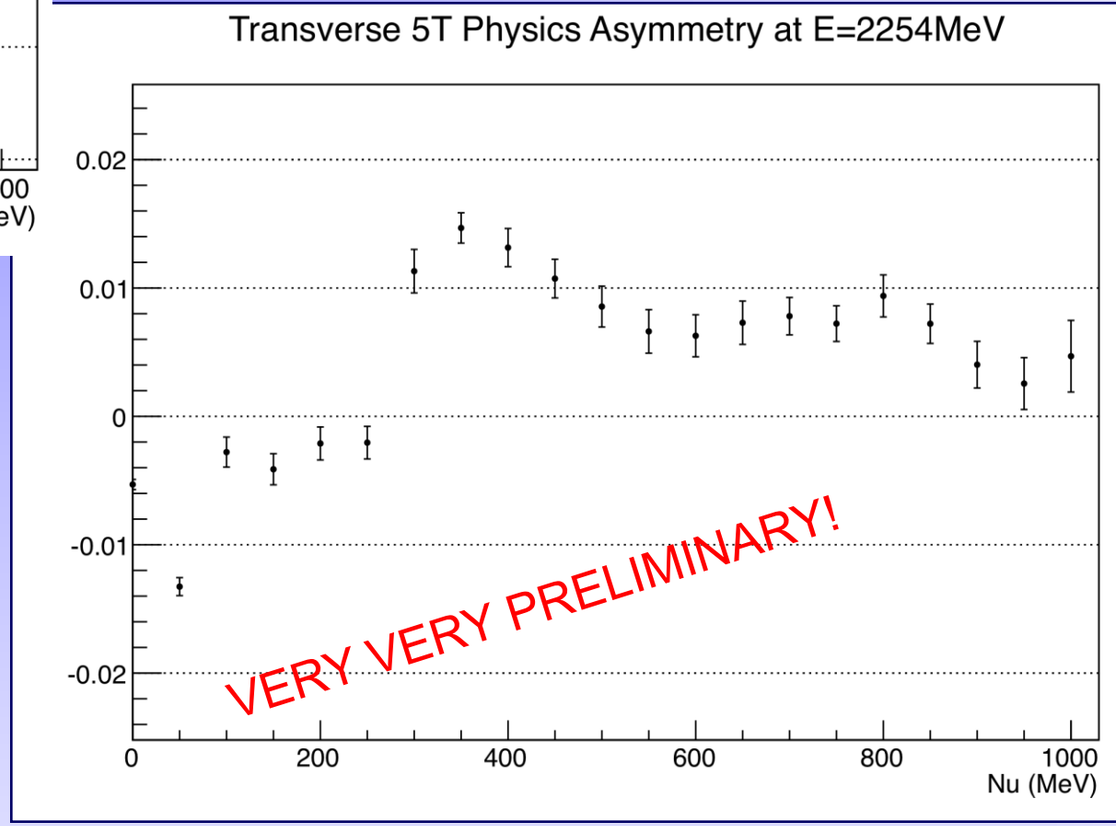


Right Septum field is no longer symmetric in vertical (y)

courtesy Min Huang

Asysmetry





courtesy Toby Badman

Summary

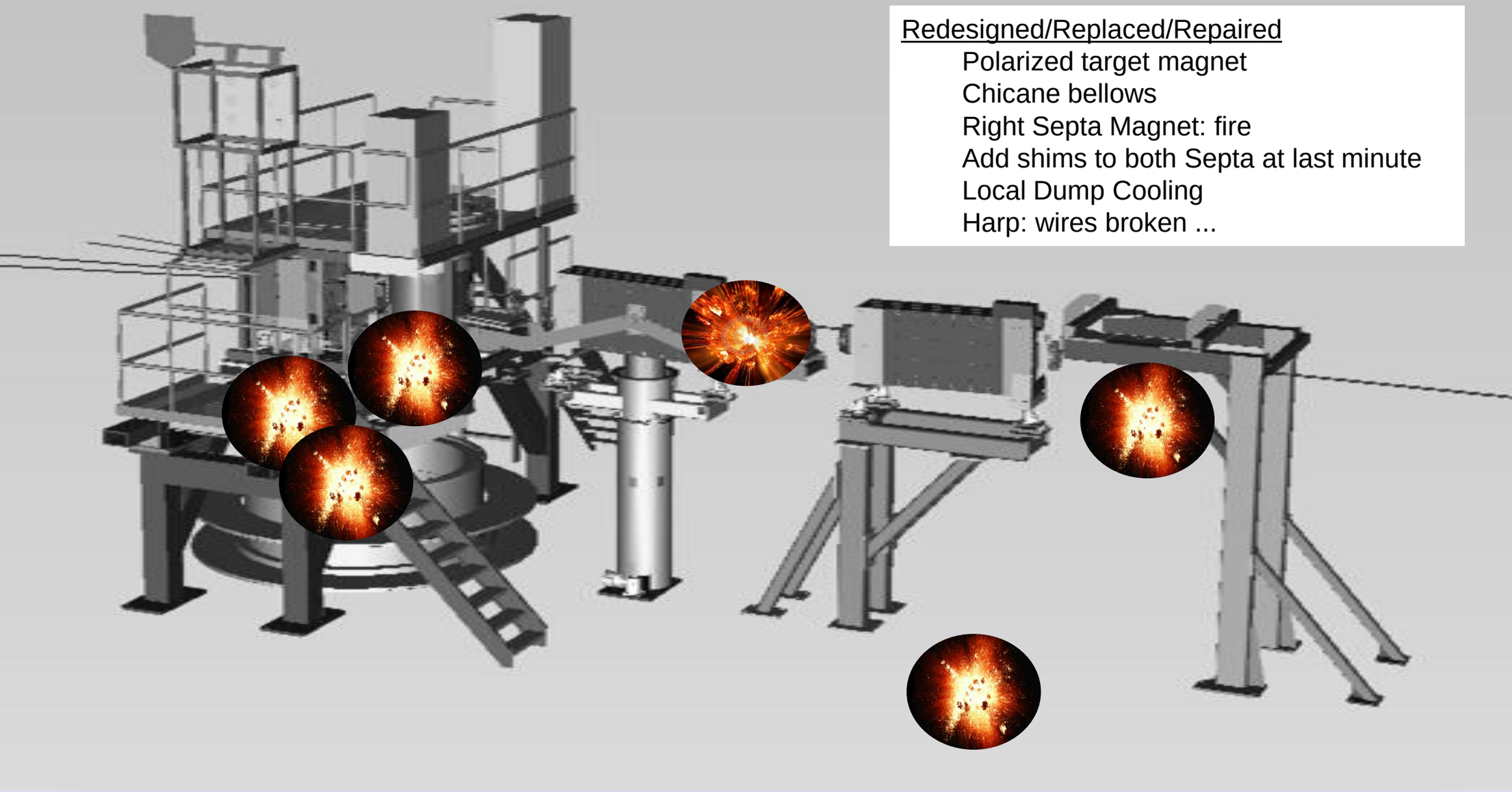
- We managed to accomplished most of our physics goals.
- This is the first time for the polarized amonia target system used in Hall-A. It worked very well. Average target polarization is about 30% at 2.5T and 75% at 5.0T target field.(See Josh's talk for details).
- DAQ system was impoved to take data at 6~7 kHz with <30% deadtime (see Ryan's talk for detail).
- Beamline diagnostics worked well in range 50-100 nA. (See Pengjia's talk for details).
- A transverse target field was added into the optics matrix for the first time, which make it really challenge.
- Will provide the definitive measurement of g_2 at low Q^2.

Back up

Reasons for delay

A few minor mechanical setbacks

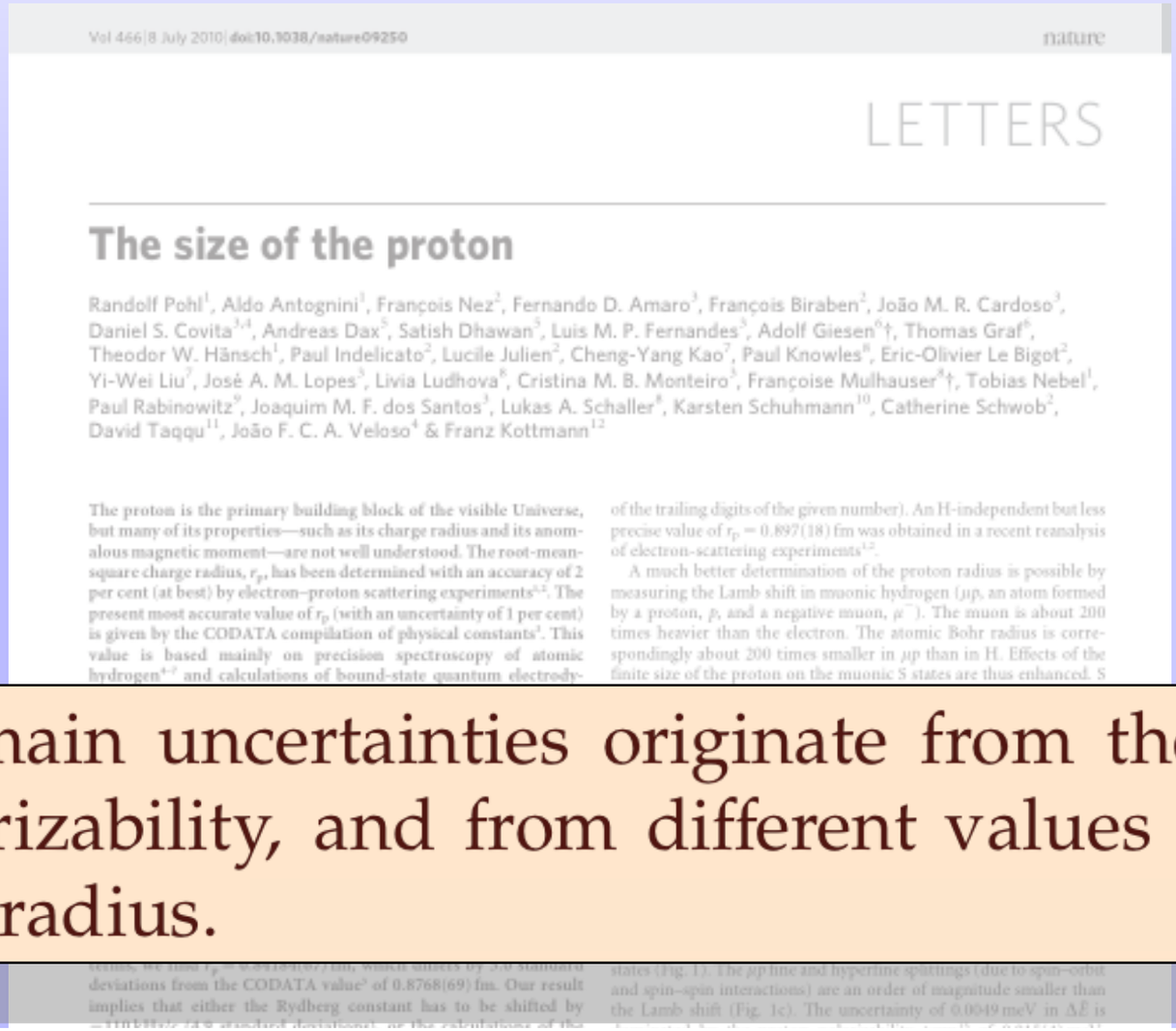
delayed the start of the experiment by 149 days



Redesigned/Replaced/Repaired

- Polarized target magnet
- Chicane bellows
- Right Septa Magnet: fire
- Add shims to both Septa at last minute
- Local Dump Cooling
- Harp: wires broken ...

Thanks to all amazing supports!!!


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

LETTERS

The size of the proton

Randolf Pohl[1], Aldo Antognini[1], 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 electrody-

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

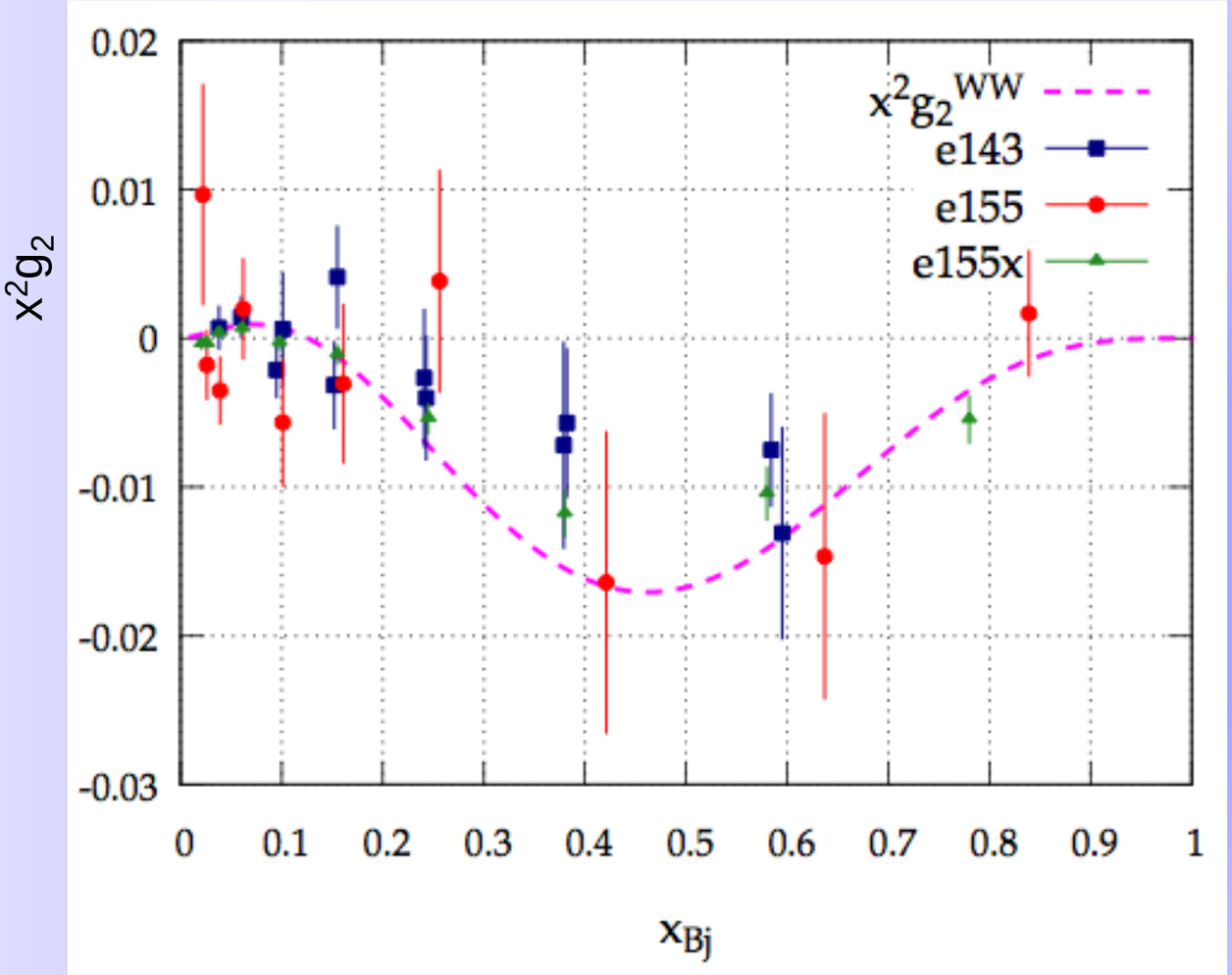
The main uncertainties originate from the proton polarizability, and from different values of the Zemach radius.

<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

Proton g_2 data from SLAC

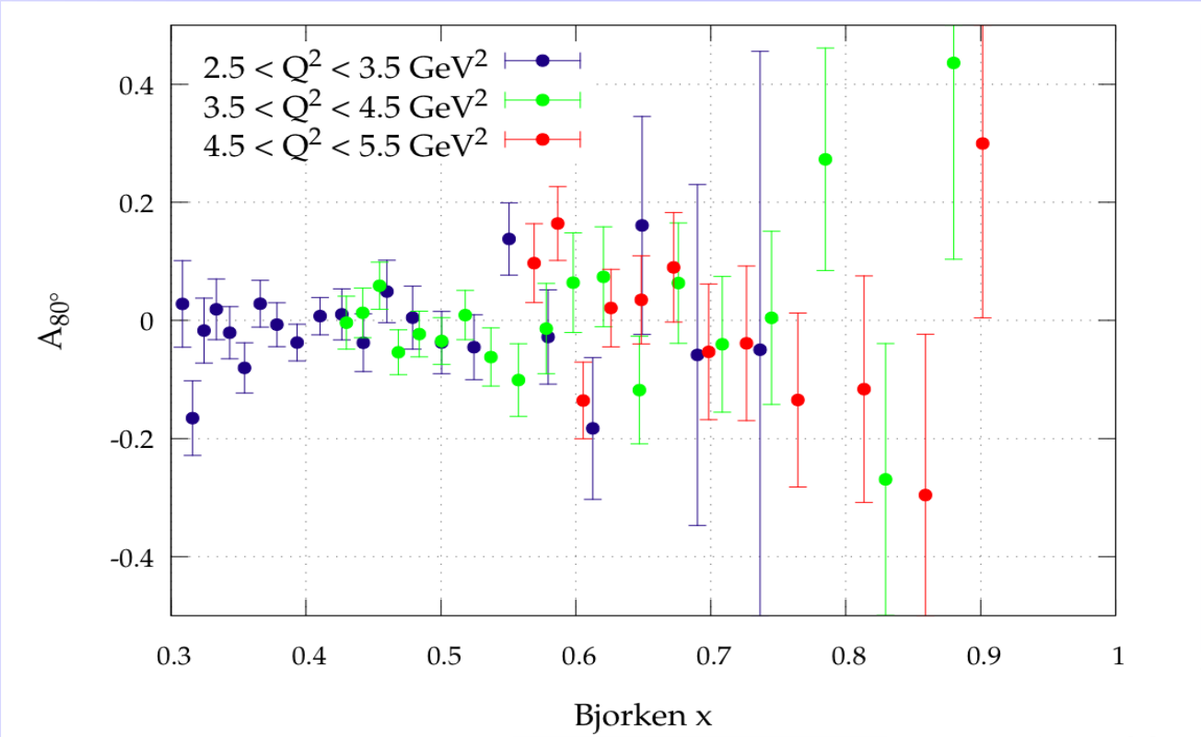


$Q^2 \approx 5\ GeV^2$

Leading Twist

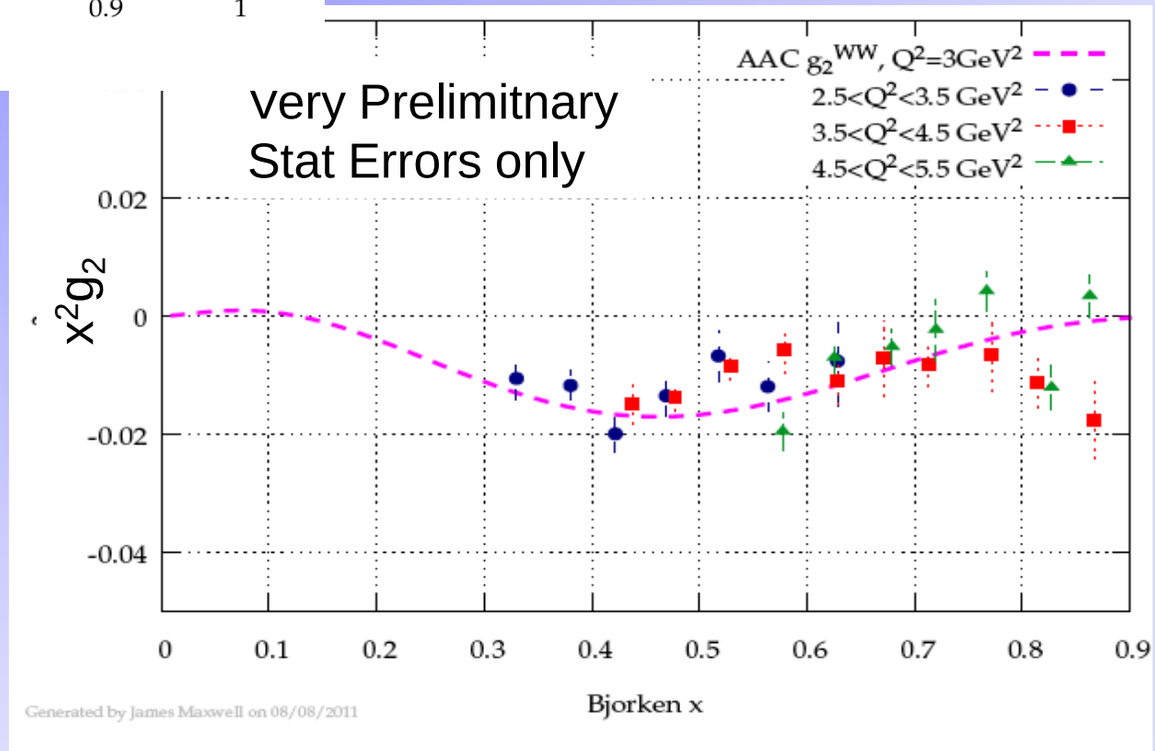
Precision does not allow unambiguous HT extraction

Proton g_2 data from JLAB SANE



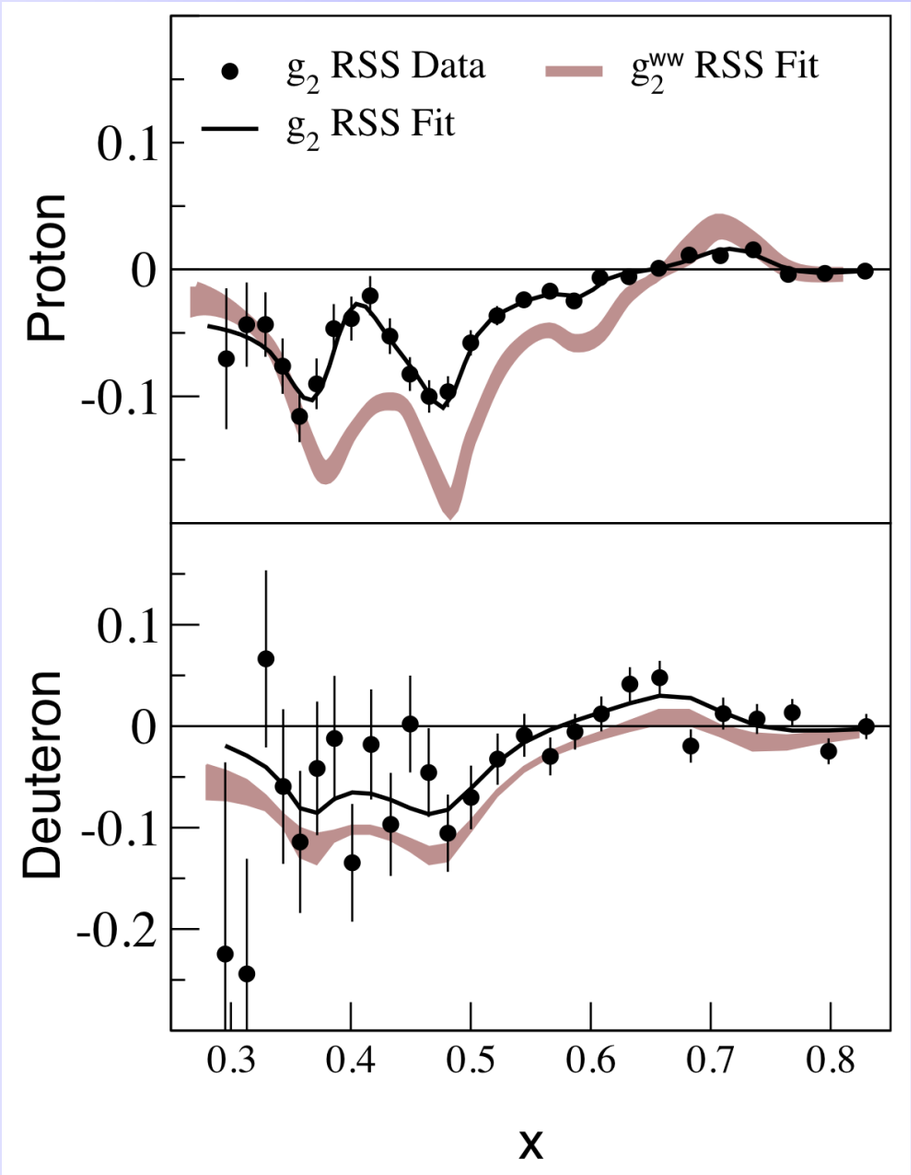
$Q^2 \approx 3\text{-}6\ \mathrm{GeV}^2$

Leading Twist



RSS Experiment (Spokesmen: Rondon and Jones)

$Q^2 = 1.3\ GeV^2$



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

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

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

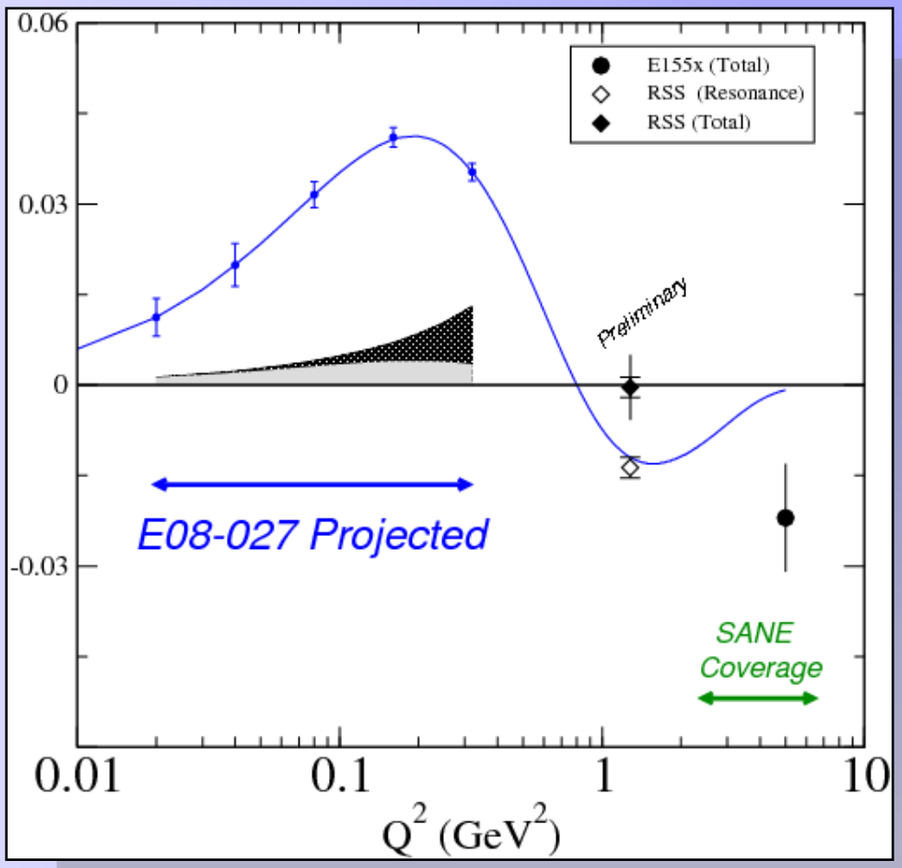
non-zero by 2.6σ

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

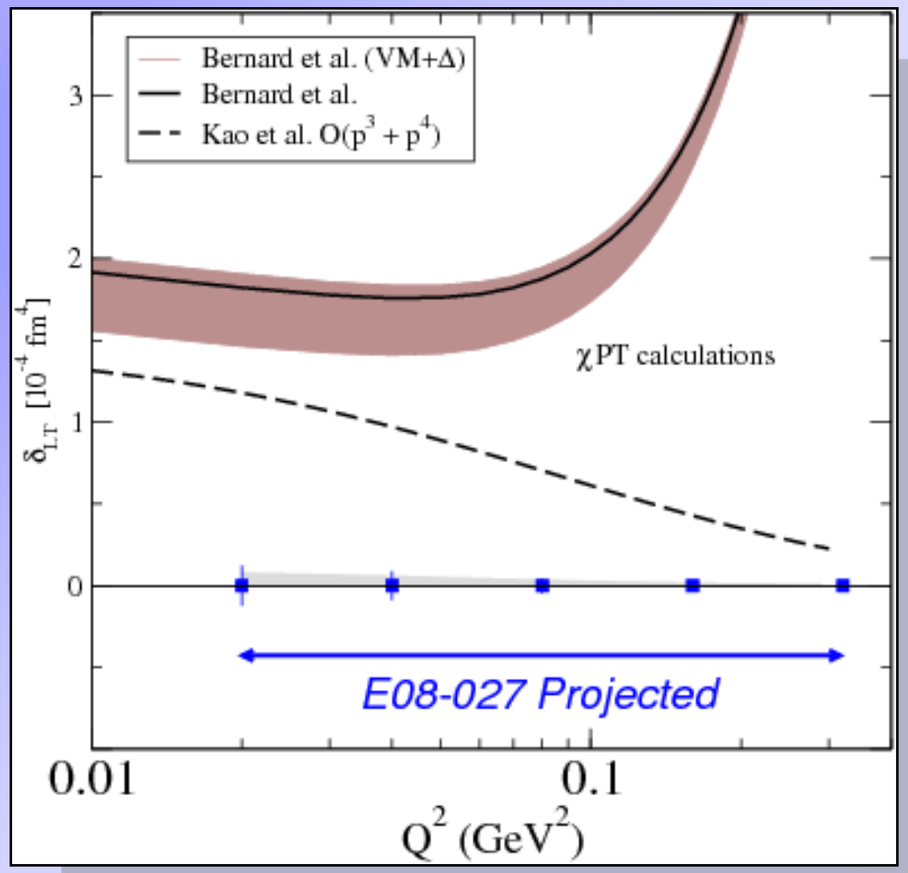
K.S., O. Rondon *et al*.
PRL 105, 101601 (2010)

Projected Results

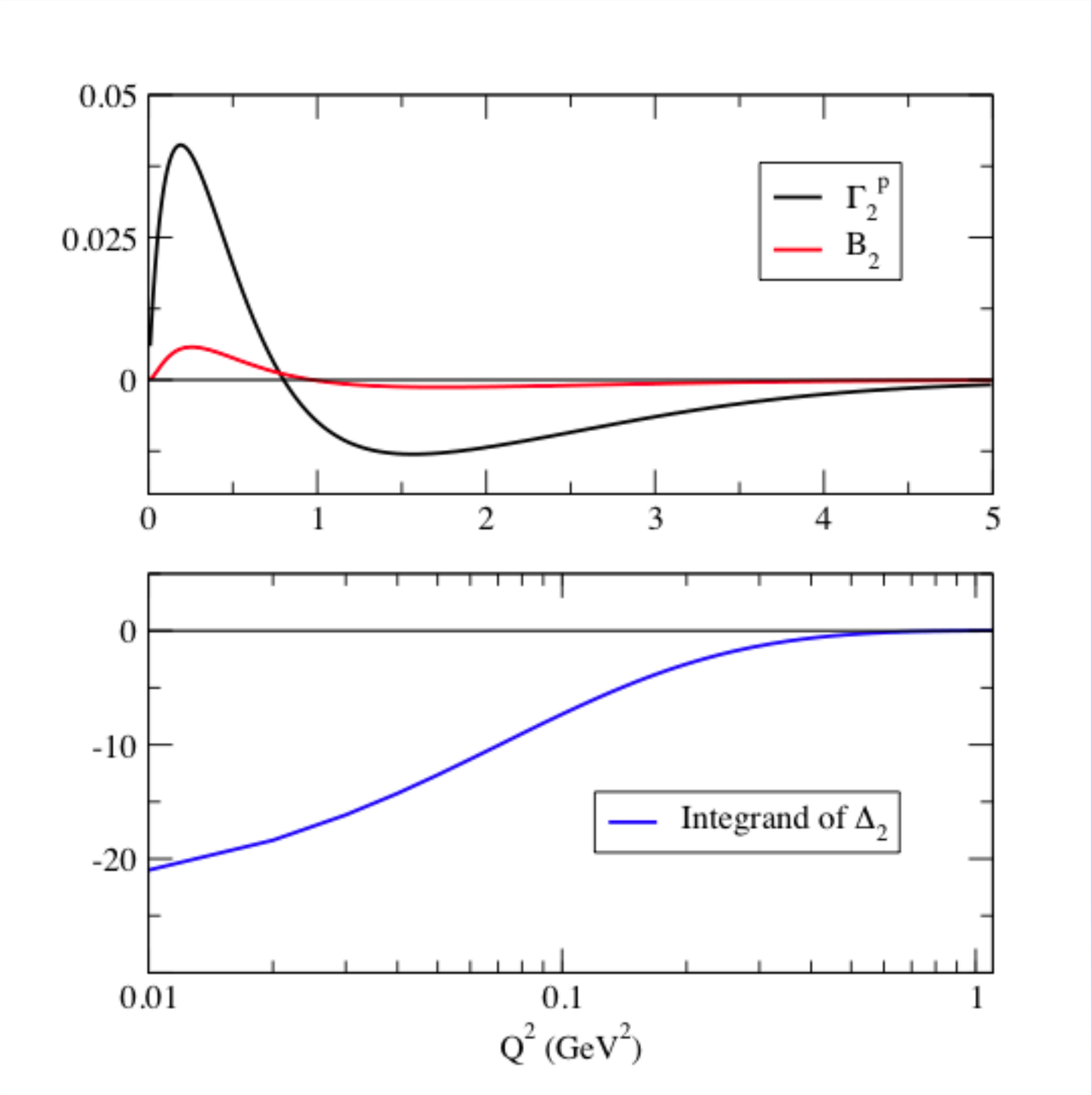
BC Sum Rule



Spin Polarizability δ_{LT}

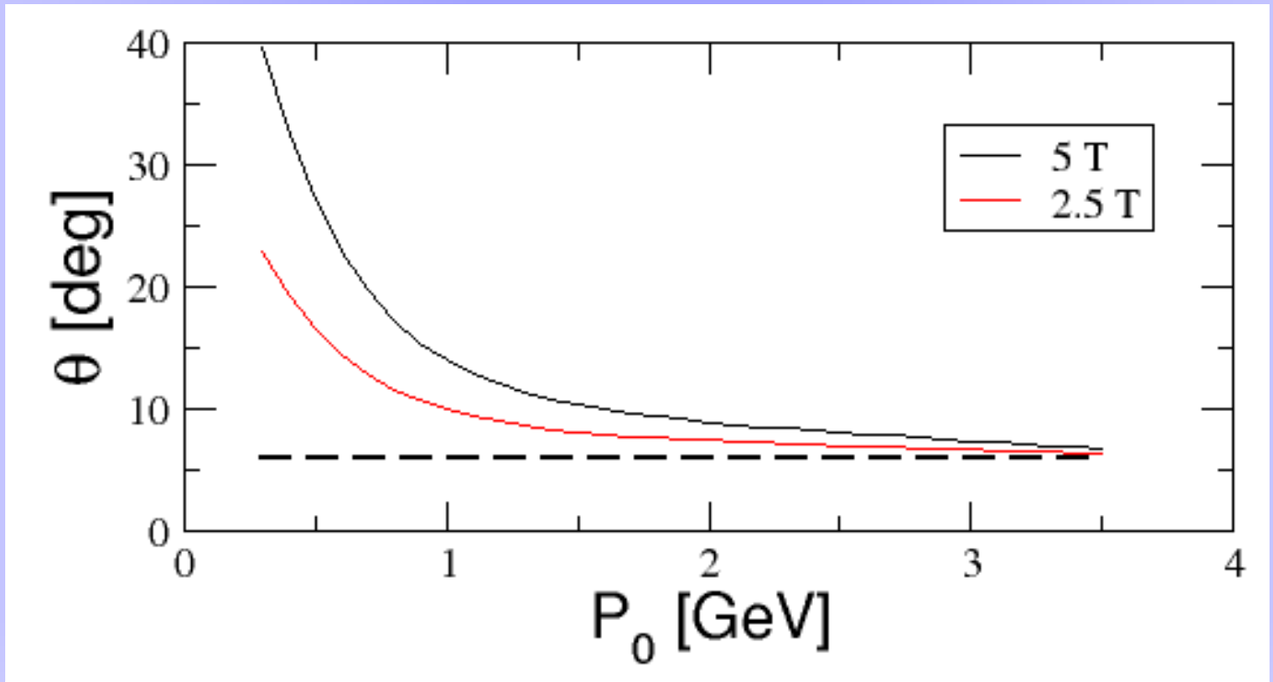


Contribution to Hyperfine Splitting



Out of plane scattering angle

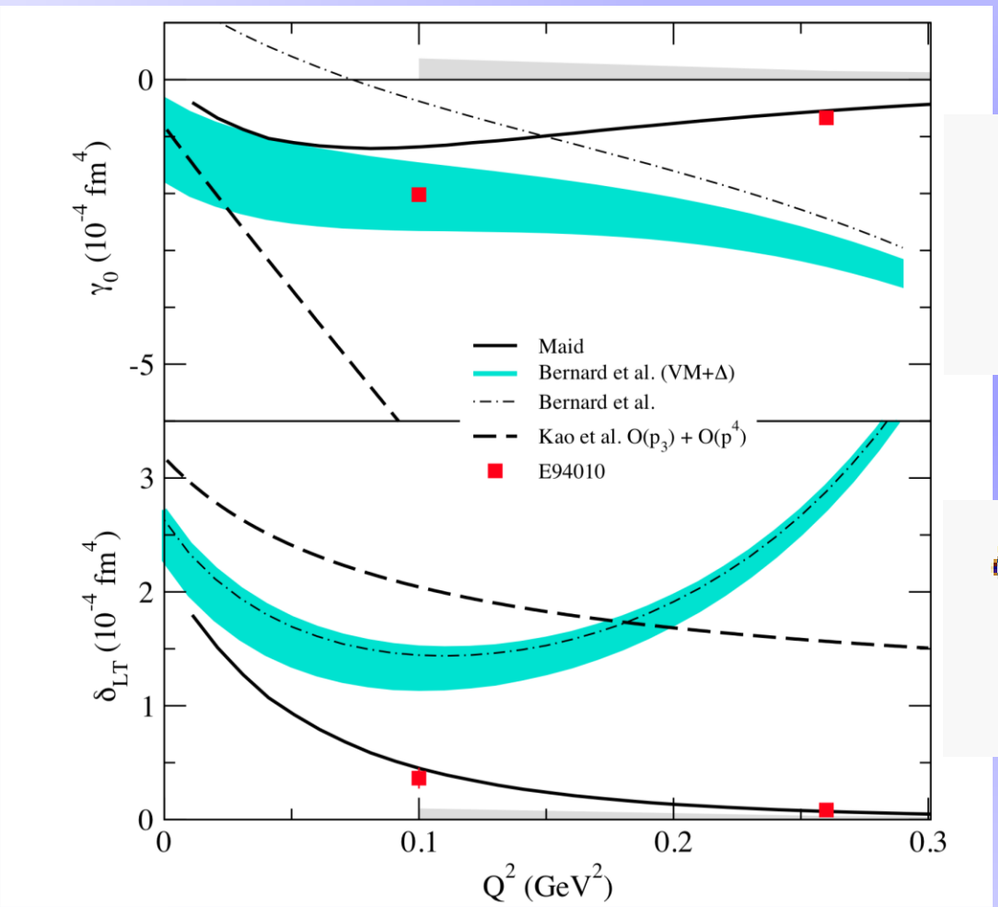
The 5T magnet field distorts the scattering plane much more than initial simulations revealed, especially at low momentum



Effect discovered by **Jixie Zhang** (Geant4).
confirmed by Min Huang (Snake), John Lerose

Spin Polarizabilities

Major failure (>8σ) of χPT for neutron δ_{LT}. Need g_2 isospin separation to solve.



$$\gamma_0(Q^2) = \left(\frac{1}{2\pi^2}\right)\int_{\nu_0}^{\infty}\frac{K(\nu,Q^2)}{\nu}\frac{\sigma_{TT}(\nu,Q^2)}{\nu^3}d\nu = \frac{16\alpha M^2}{Q^6}\int_0^{x_0} x^2\left[g_1(x,Q^2) - \frac{4M^2}{Q^2}x^2 g_2(x,Q^2)\right]dx.$$

$$\delta_{LT}(Q^2) = \left(\frac{1}{2\pi^2}\right)\int_{\nu_0}^{\infty}\frac{K(\nu,Q^2)}{\nu}\frac{\sigma_{LT}(\nu,Q^2)}{Q\nu^2}d\nu = \frac{16\alpha M^2}{Q^6}\int_0^{x_0} x^2\left[g_1(x,Q^2) + g_2(x,Q^2)\right]dx.$$

this is the region we should start to be able to trust χPT

Burkhardt-Cottingham Sum Rule

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

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

predicted to vanish for all Q^2

Assumptions:

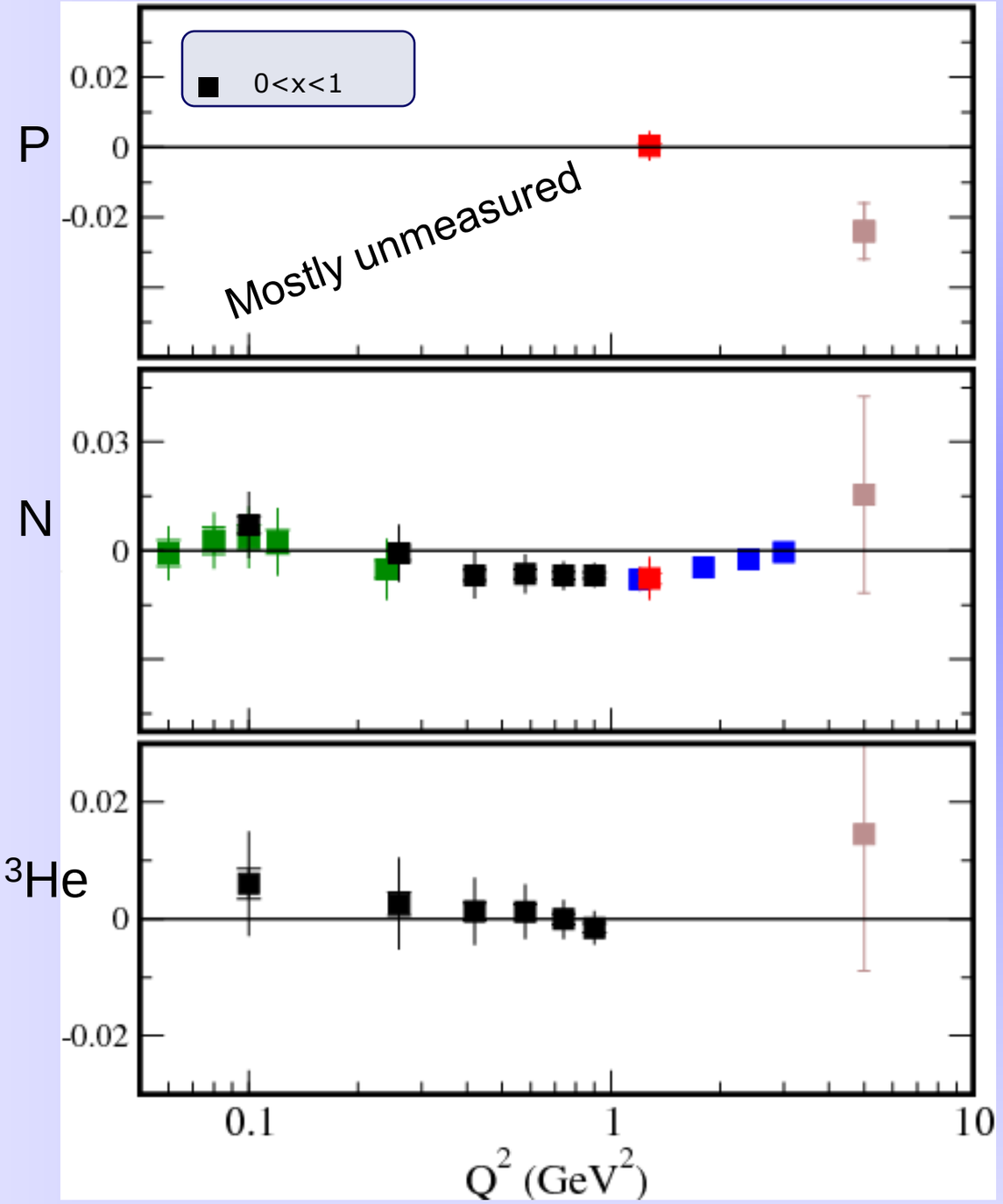
the virtual Compton scattering amplitude S_2 falls to zero faster than $1/x$
g_2 does not behave as $\delta(x)$ at $x=0$.

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



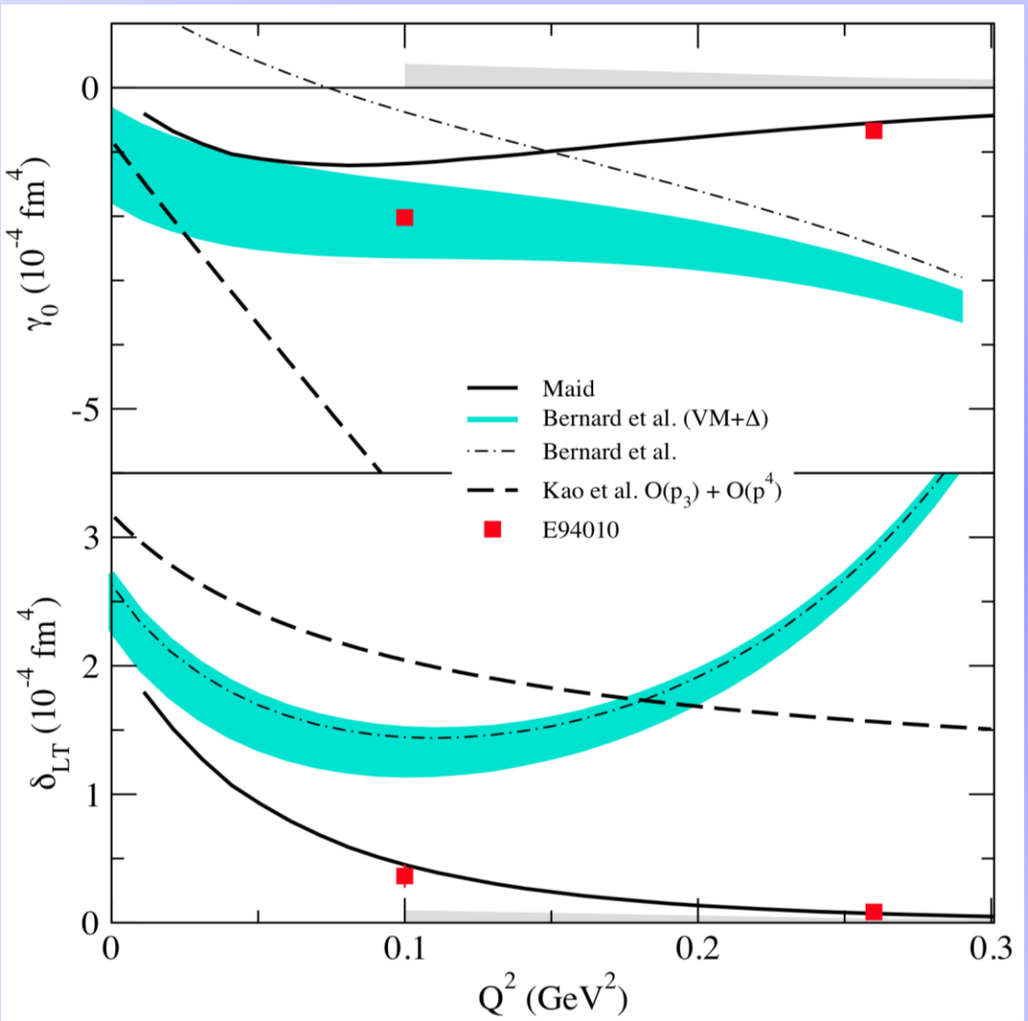
BC satisfied w/in errors for JLab Proton
2.8σ violation seen in SLAC data

BC satisfied w/in errors for Neutron

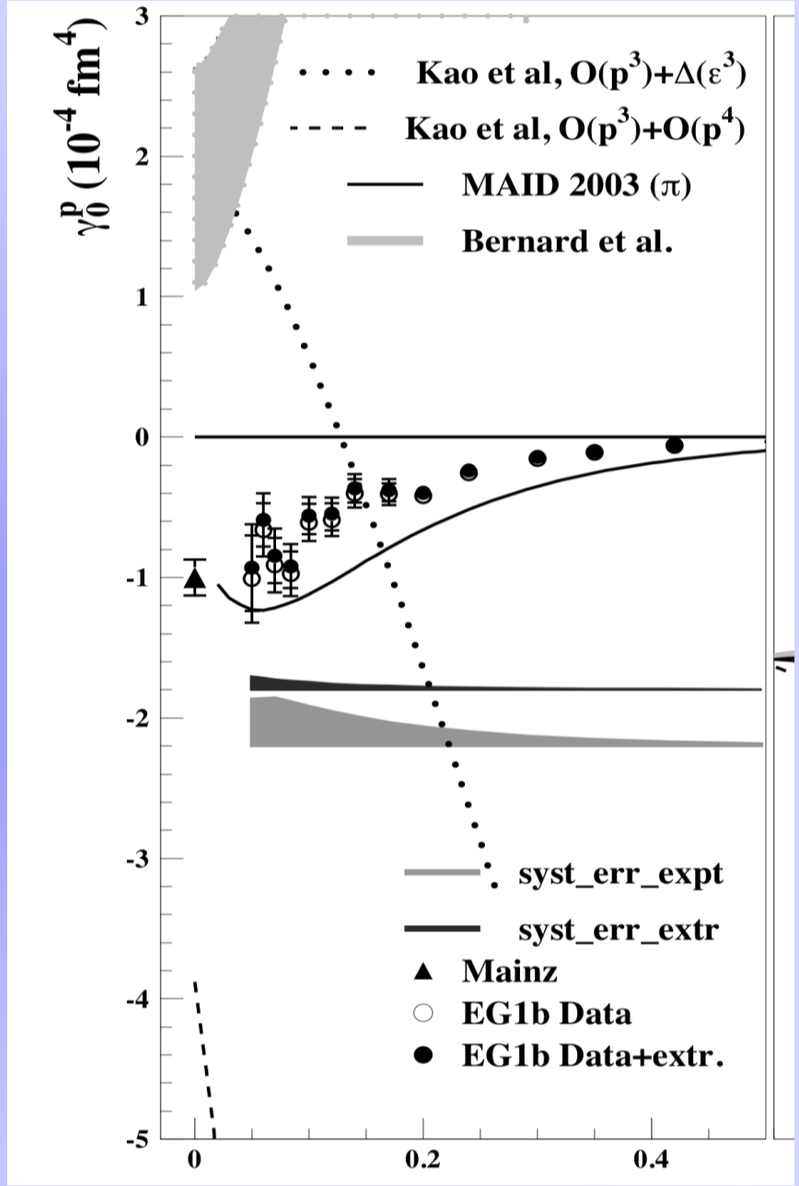
BC satisfied w/in errors for ^{3}He

Spin Polarizabilities

Major failure (>8σ) of χPT for neutron δ_{LT}



similar problem for proton γ_0

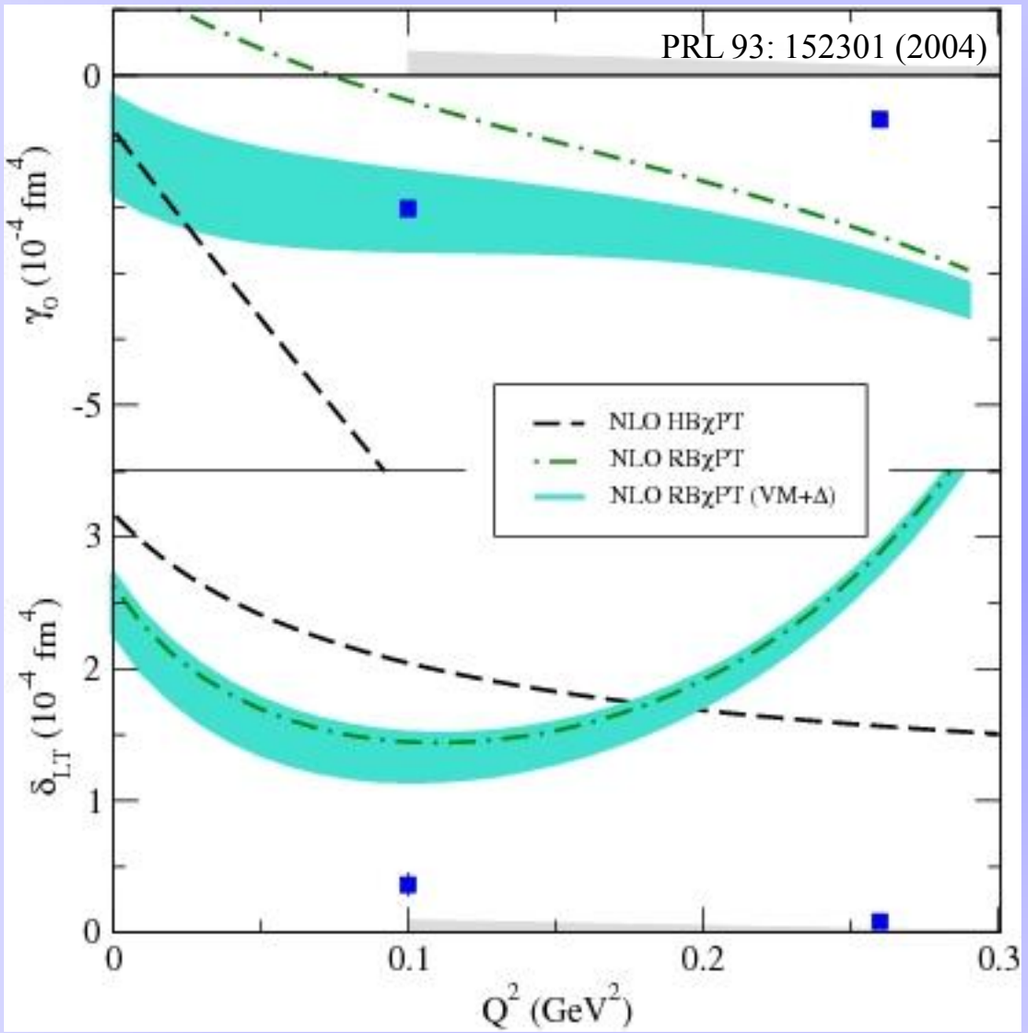


$$\gamma_0 = \frac{16\alpha M^2}{Q^6}\int_0^{x_0} x^2\left[g_1 - \frac{4M^2}{Q^2}x^2 g_2\right]$$

Low Q^2 region is the one we should start to be able to trust χPT

Spin Polarizabilities

Neutron



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

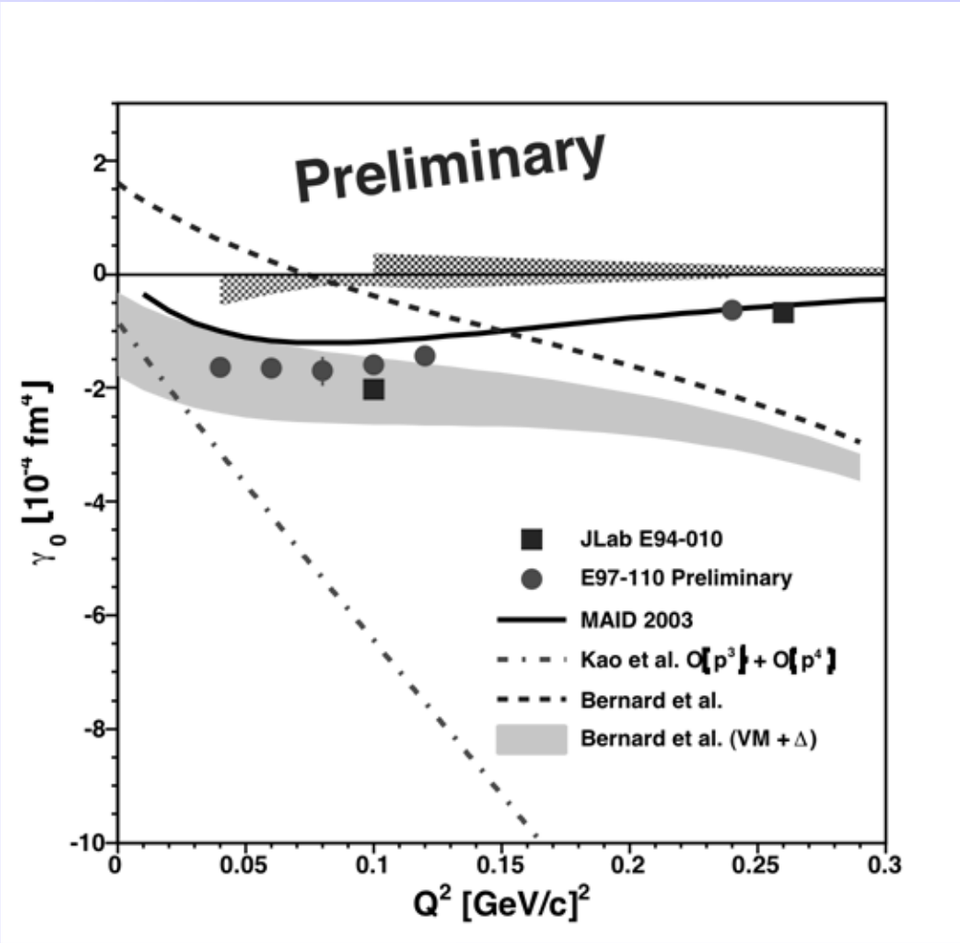
$$\delta_{LT} = \frac{16\alpha M^2}{Q^6}\int_0^{x_0} x^2\left[g_1 + g_2\right]$$

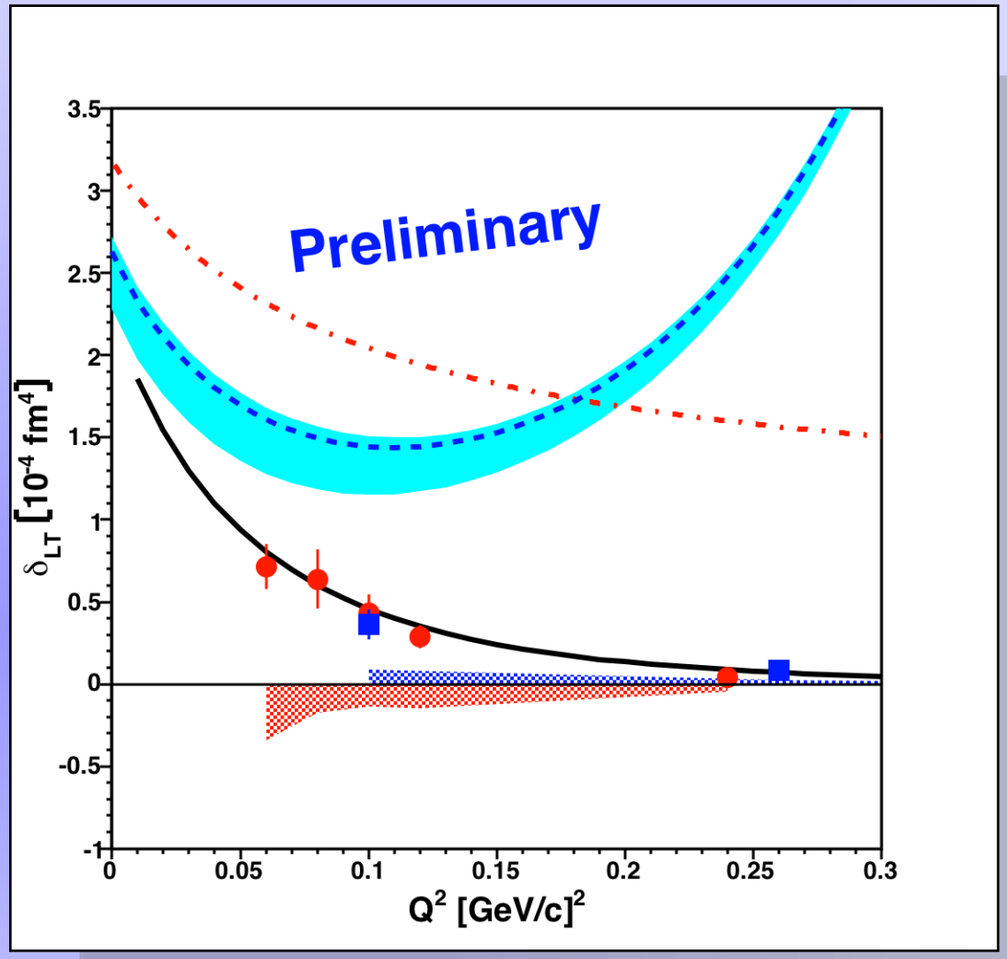
Dramatic Failure of ChiPT

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

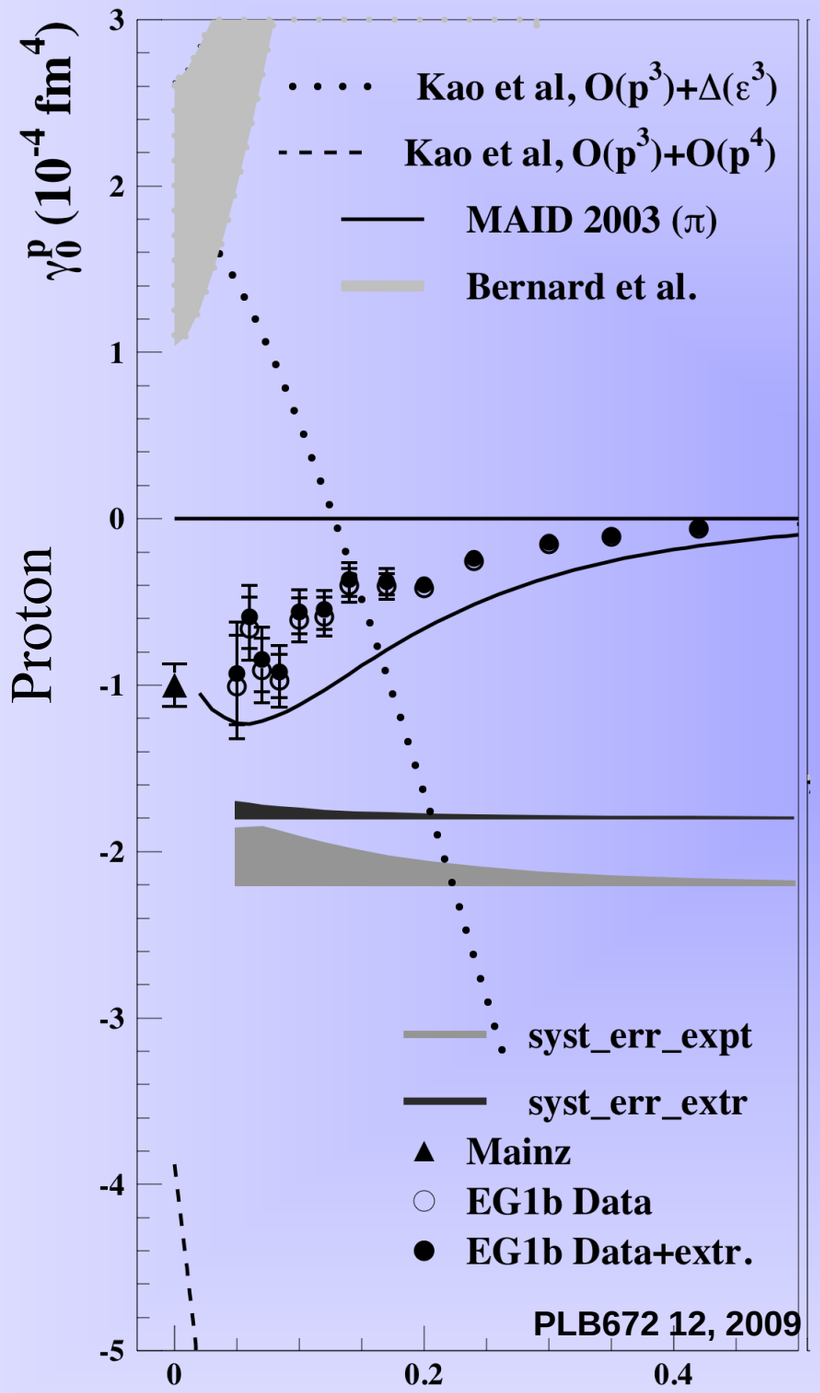




Large discrepency with δ_{LT} remains

Plots courtesy of V. Sulkosky

Proton γ_0



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

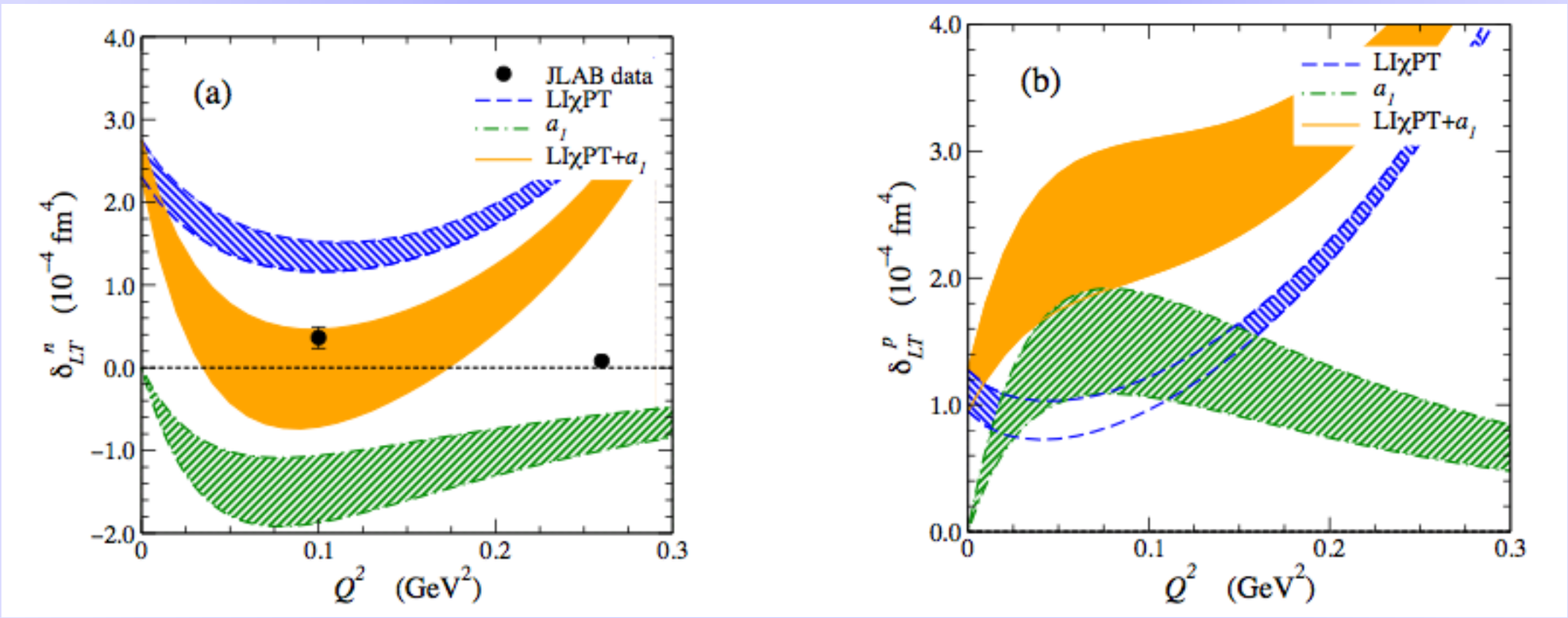
Calculations also fail for proton γ_0

LT Spin Polarizability

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

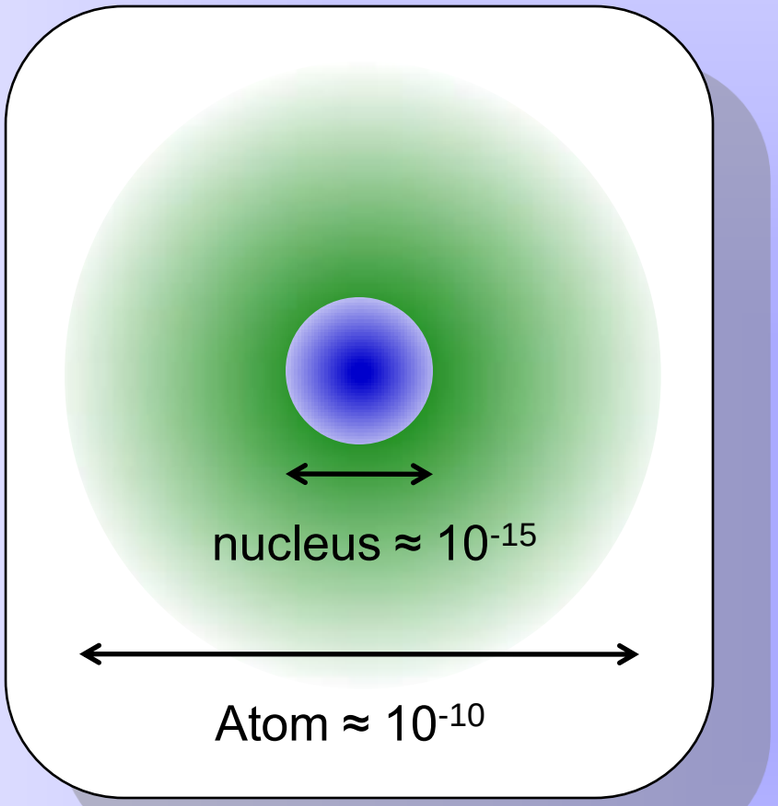
Neutron

Proton



No data yet on proton LT polarizability

Applications to Bound State Q.E.D.



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

Hydrogen HF Splitting

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

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

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

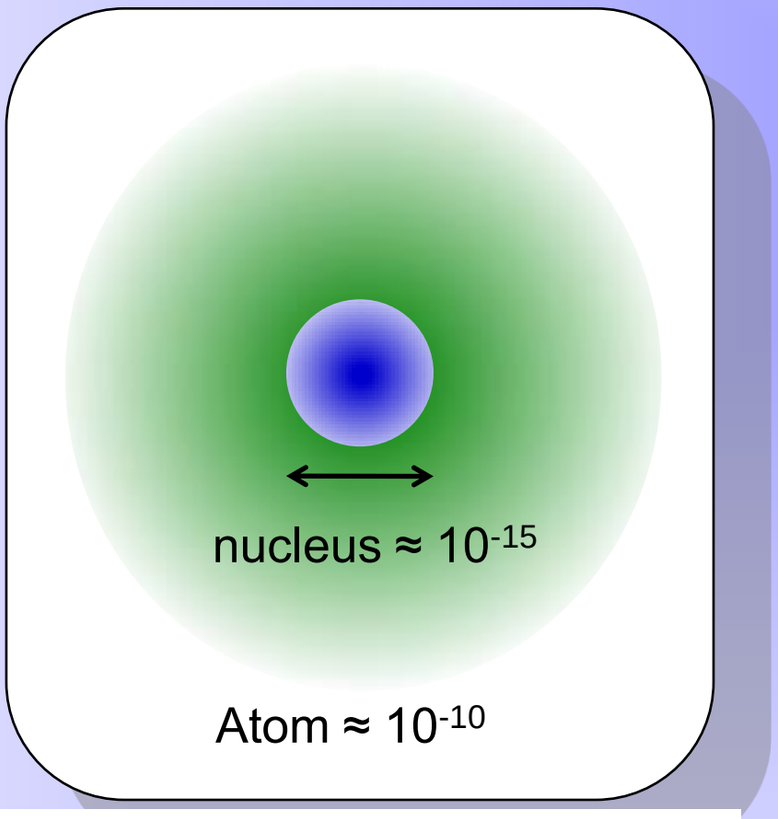
Finite Size Effects

Hydrogen HyperFine Splitting :

Lack of knowledge of g_2 at low Q^2 is one of the leading uncertainties.

Proton Charge Radius :

One of the leading uncertainties in extraction of $<R_p>$ from μ–H Lamb shift.



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

The finite size of the nucleon (QCD) plays a small but significant role in calculating atomic energy levels in QED.

Hydrogen HF Splitting

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

Inelastic

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

Δ_Z=-41.0$\pm$0.5ppm

Δ_{pol}≈ 1.3$\pm$0.3 ppm

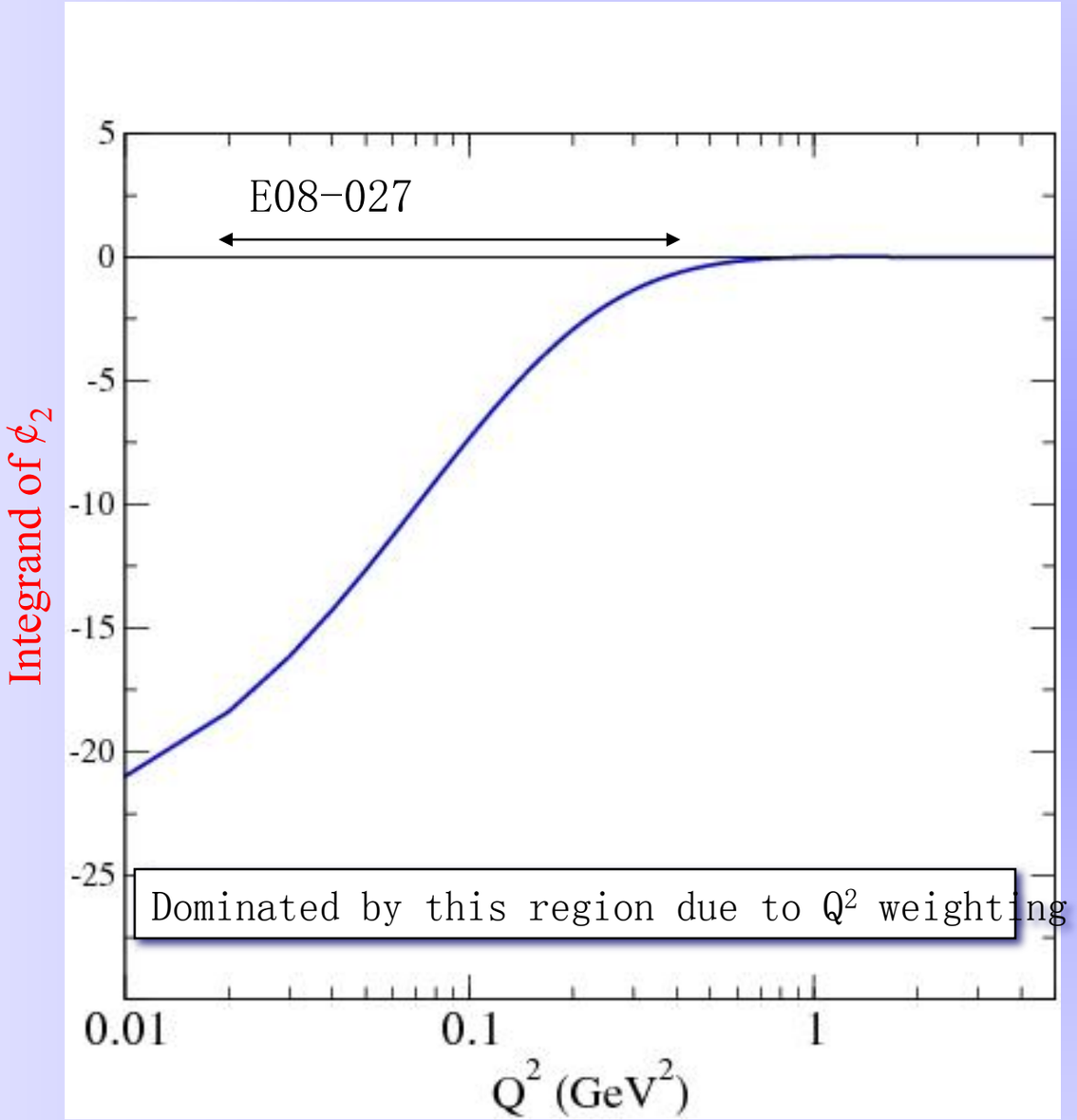
Elastic piece larger but with similar uncertainty

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

integral of g1 & F1

pretty well determined from F_2, g_1 JLab data

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).

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

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*
$\langle R_p \rangle = 0.897 \pm 0.018$ fm	World analysis of eP scattering *I. Sick PLB, 2003*
$\langle R_p \rangle = 0.8768 \pm 0.0069$ fm	CODATA world average

I. Sick (Basel) : "*What gives? I don't know". "Serious discrepency*" [*ELBA XI, Nature.com*]

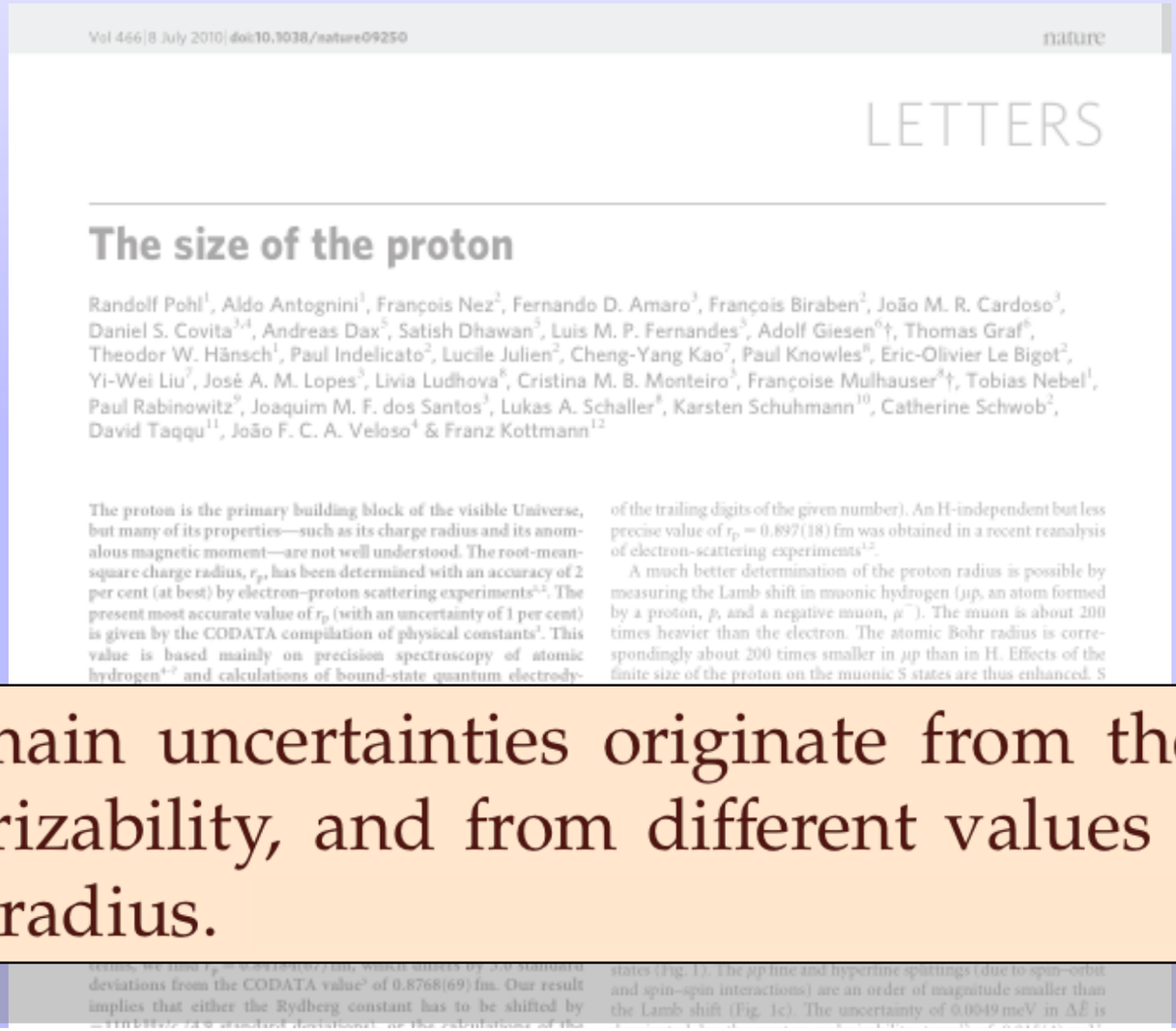
C. Carlson (W&M) : "*Something is missing, this is very clear*." [*Nature.com*]

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[1], 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 electrody-

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

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

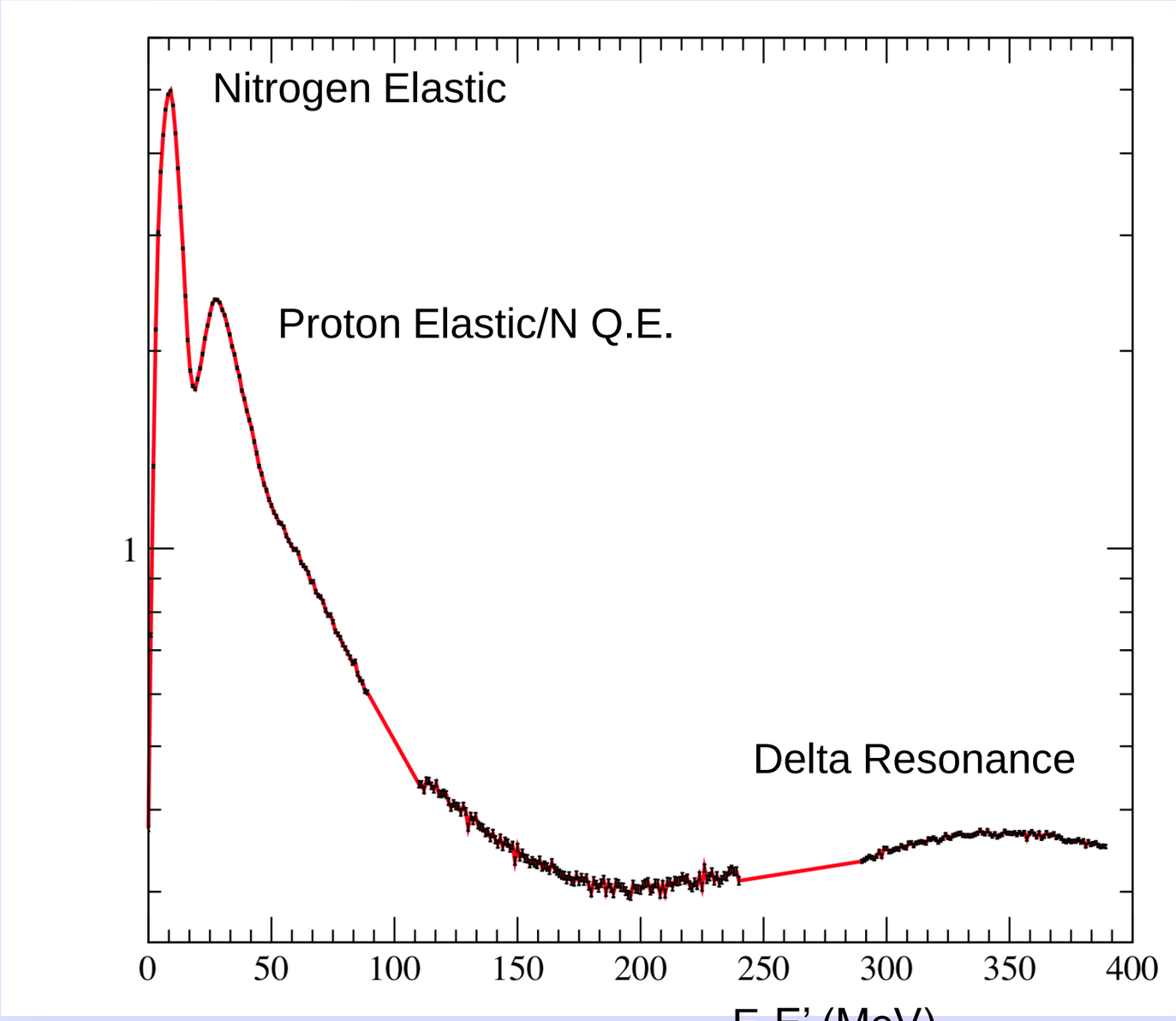
<u>Polarizability</u> : Integrals of g_1 and g_2 weighted by $1/Q^4$

<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

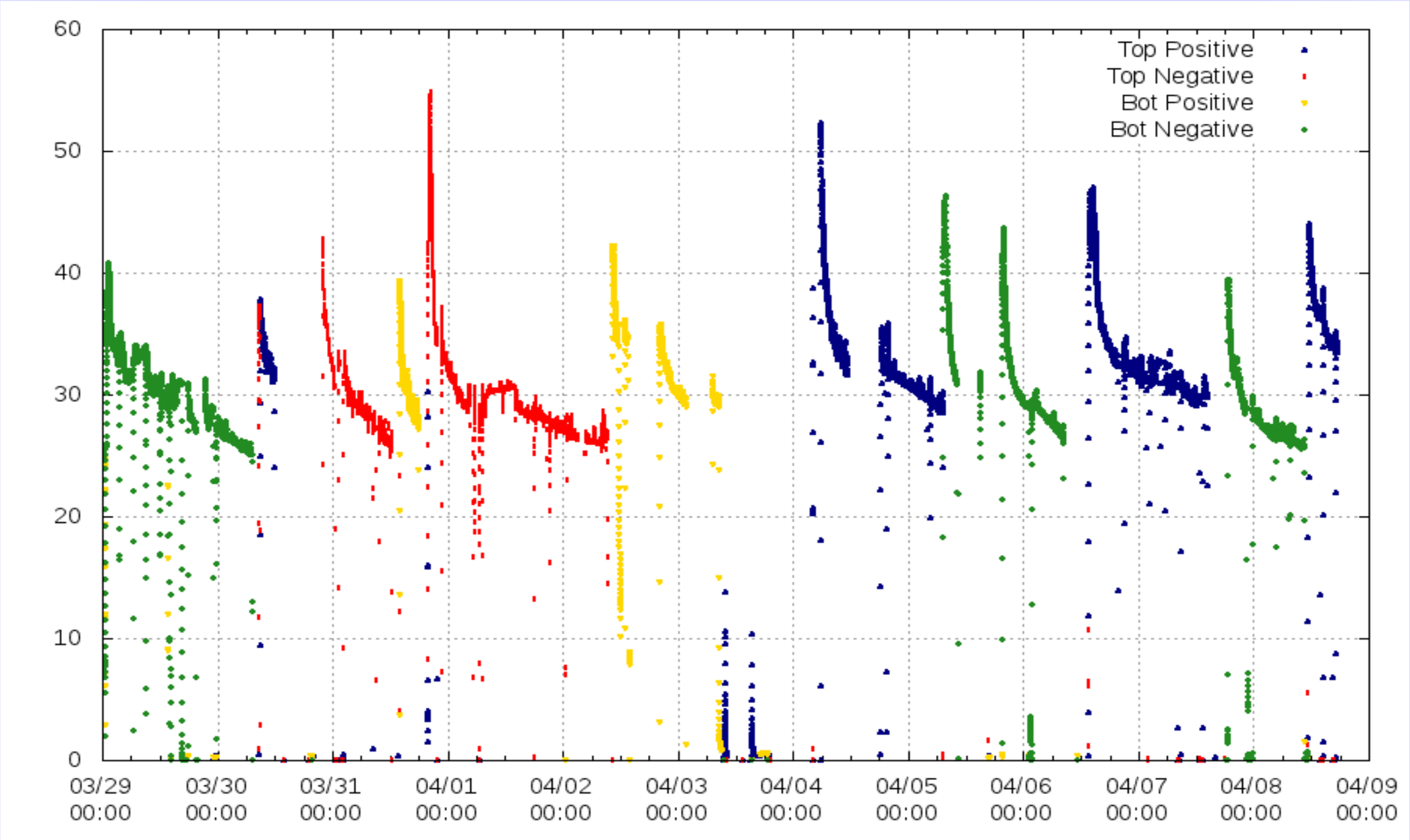
Normalized Yields

E=2.2 GeV Left Arm



courtesy Ryan Zielinski

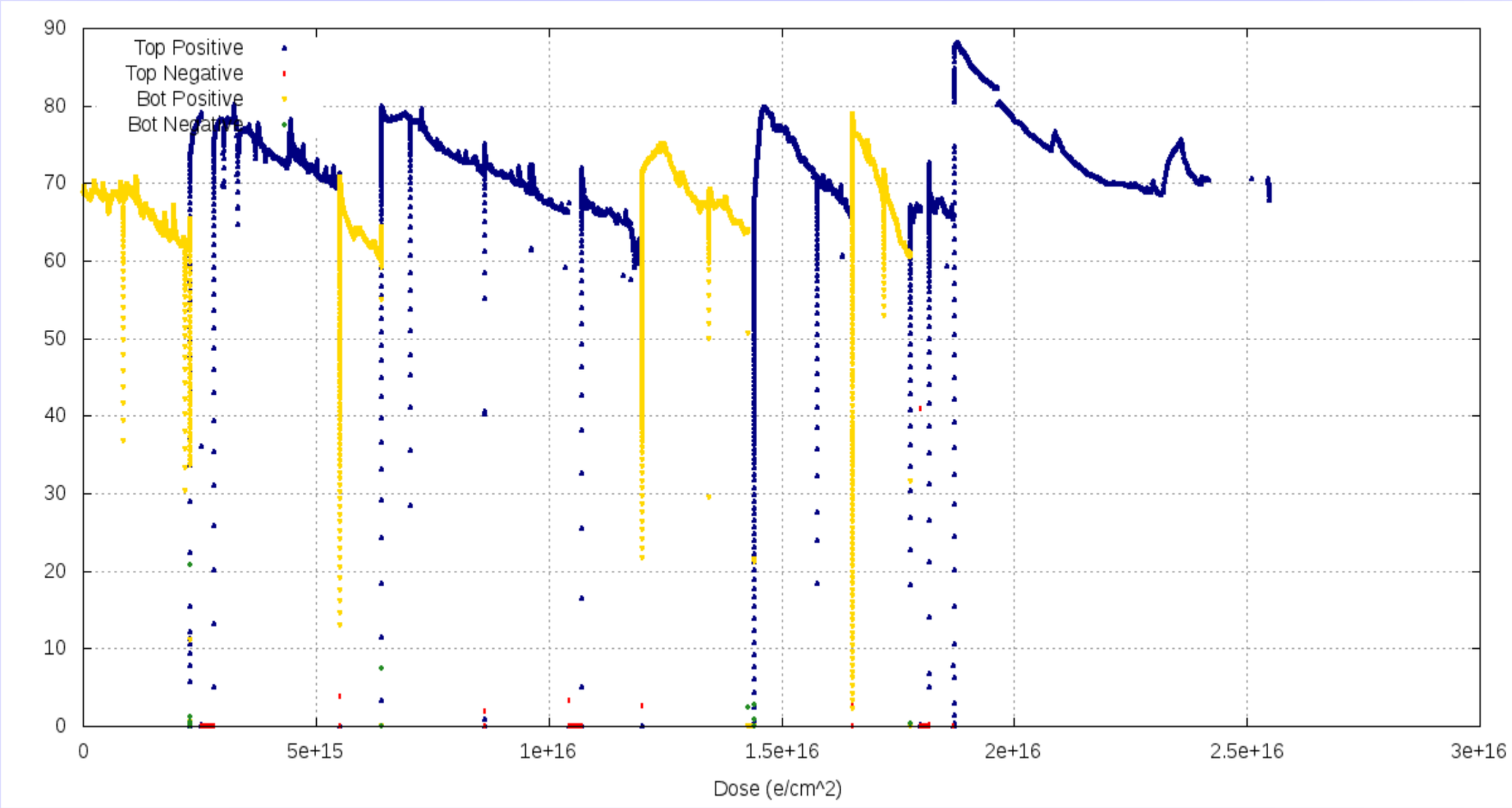
Target polarization @ 2.5T



Average Polarization >30% at 2.5 Tesla/70 GHz

courtesy James Maxwell

Target Poarizazion @ 5T



Average Polarization >75% at 5.0 Tesla/140 GHz

courtesy James Maxwell

Beamline Diagnostics

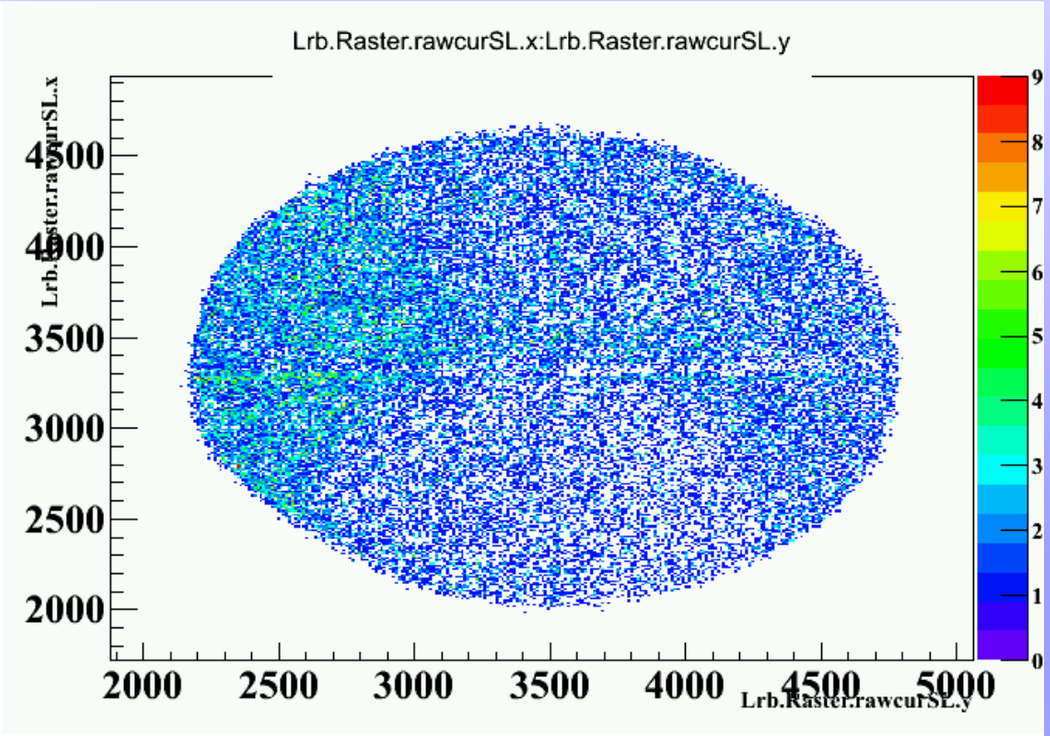
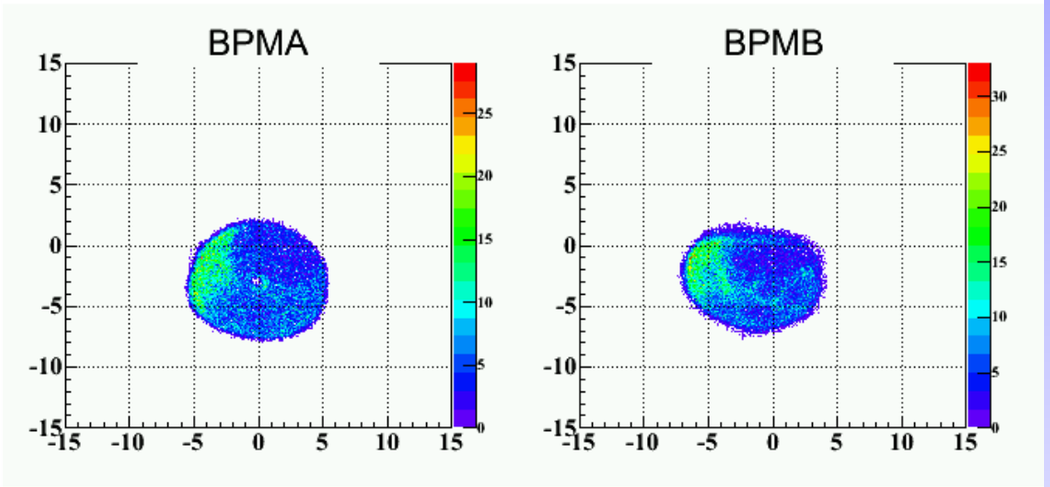
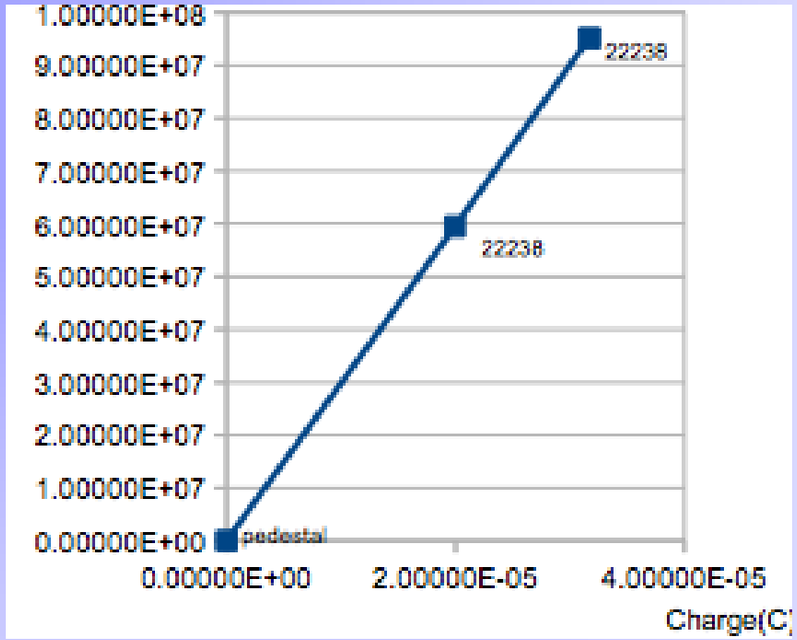


FIGURE 2



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

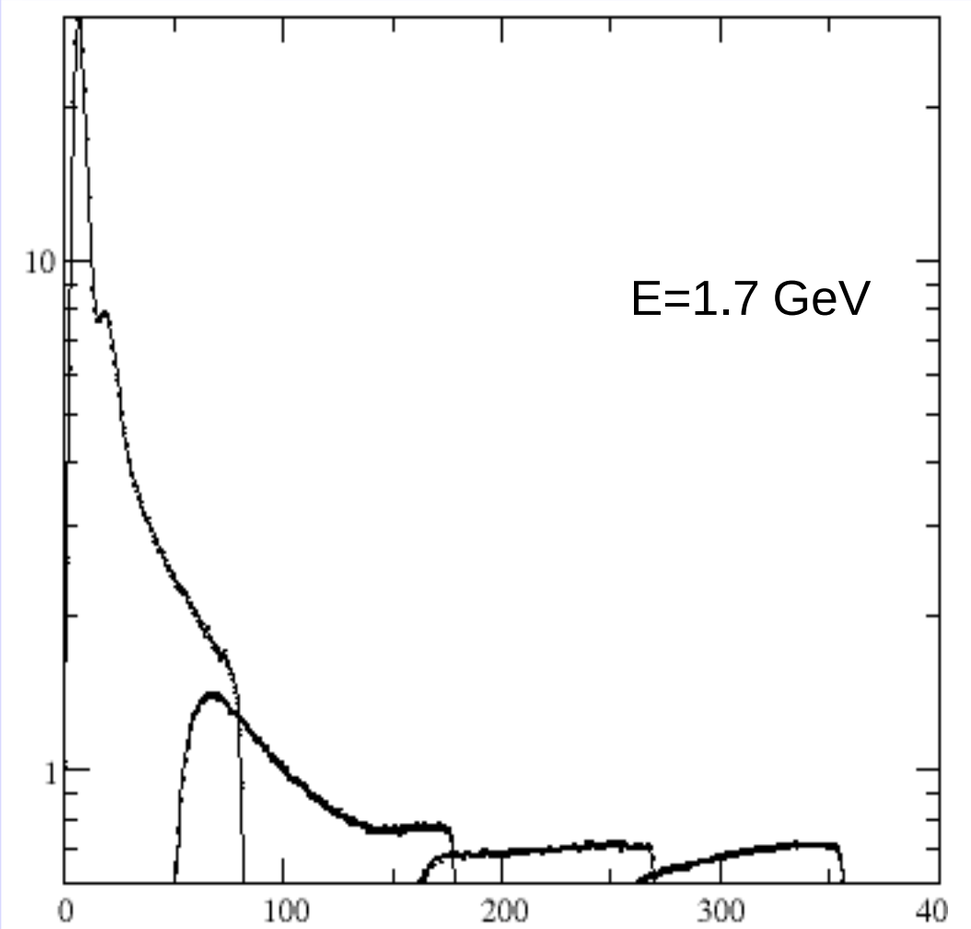
to operate Hall a beam at < 100 nA

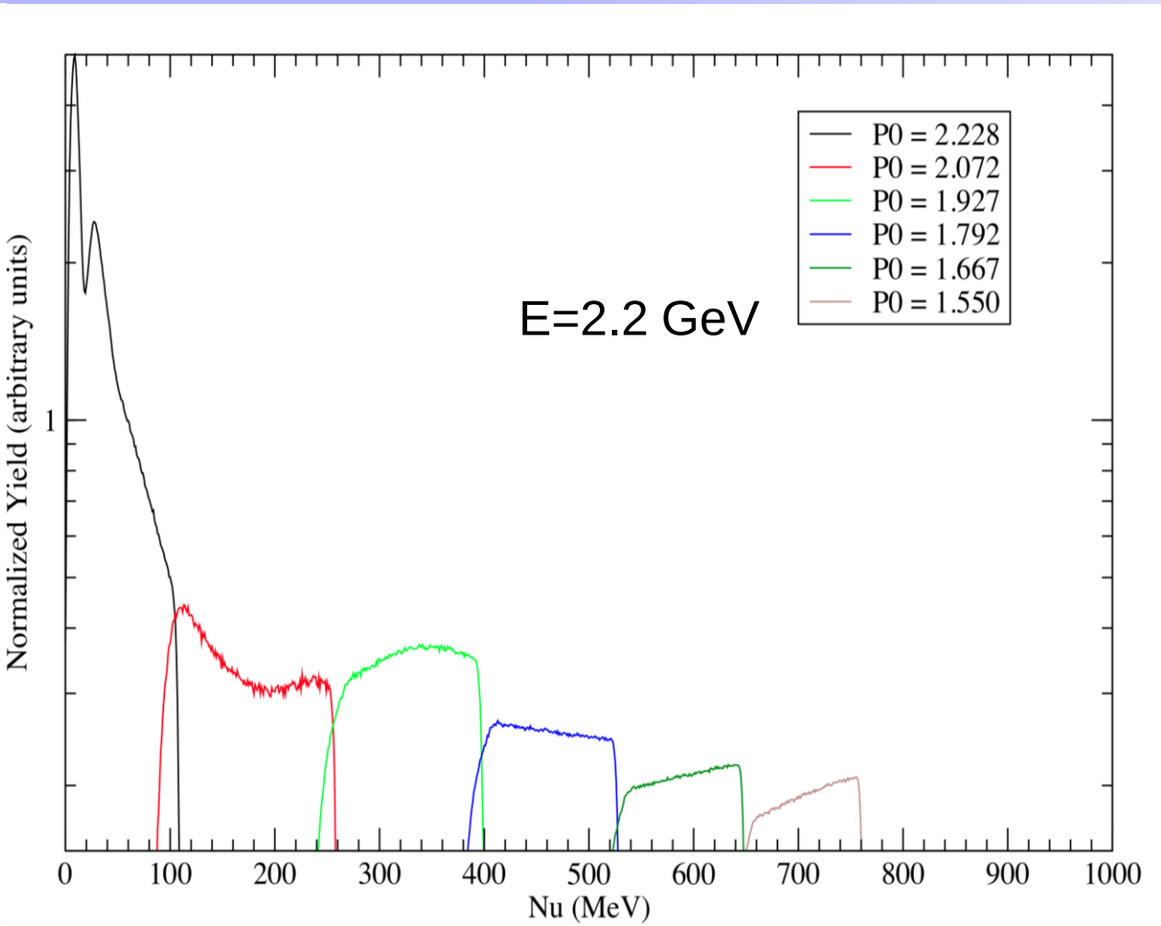


courtesy Pengia Zhu

Normalized Yields

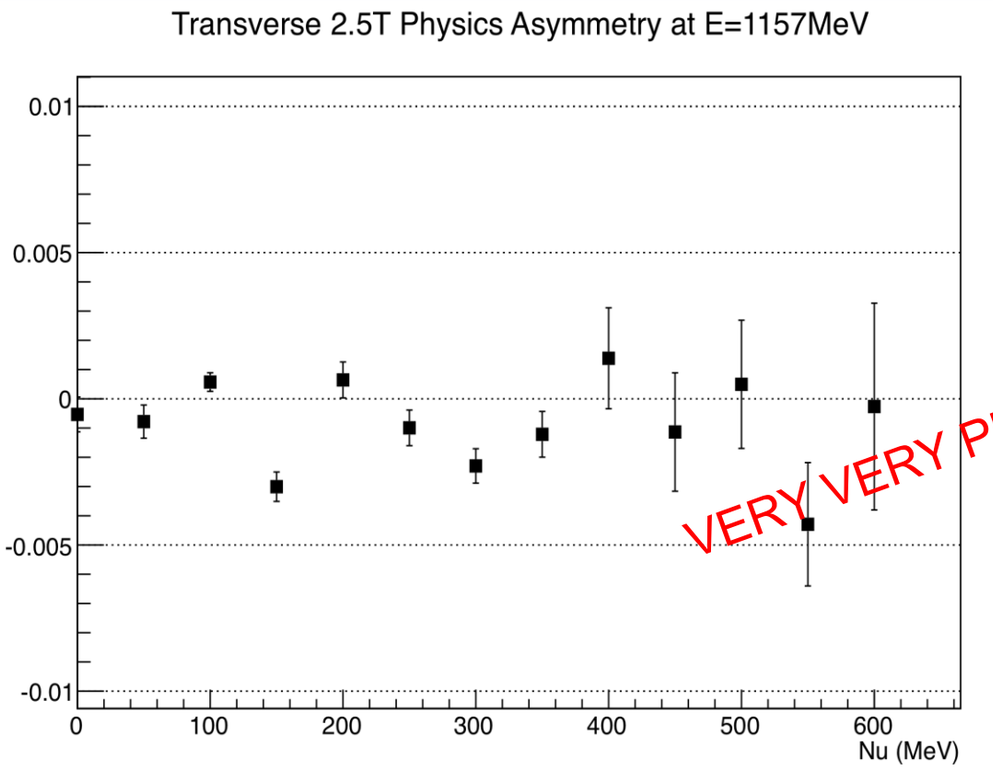
Acceptance effects becomes much more pronounced at low momentum

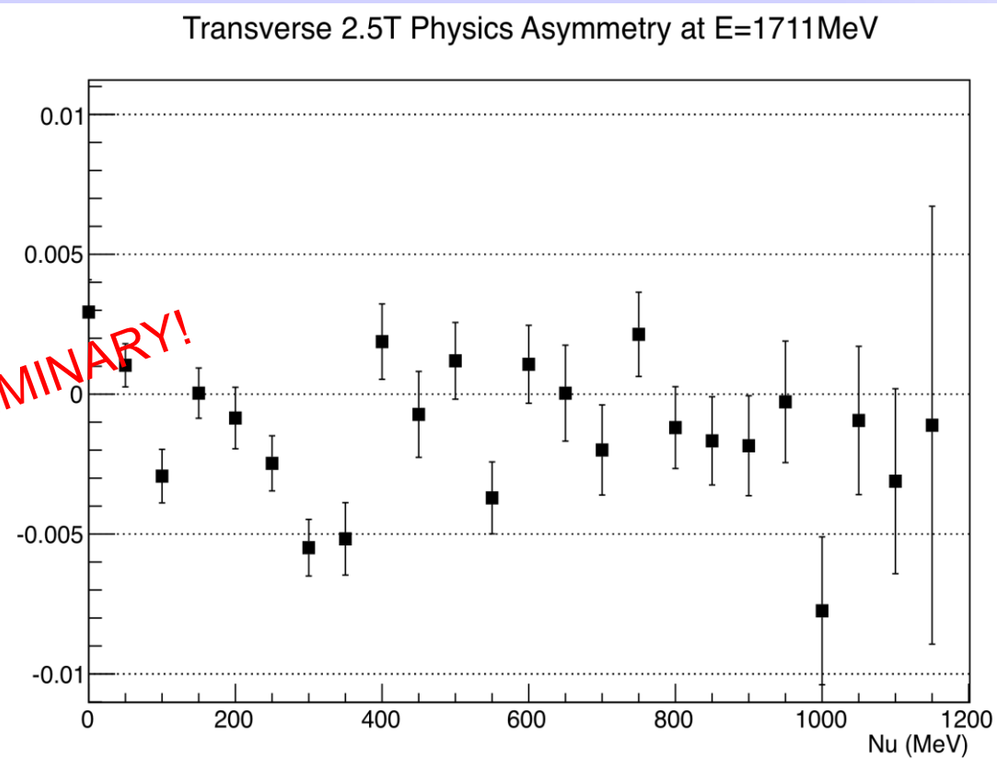




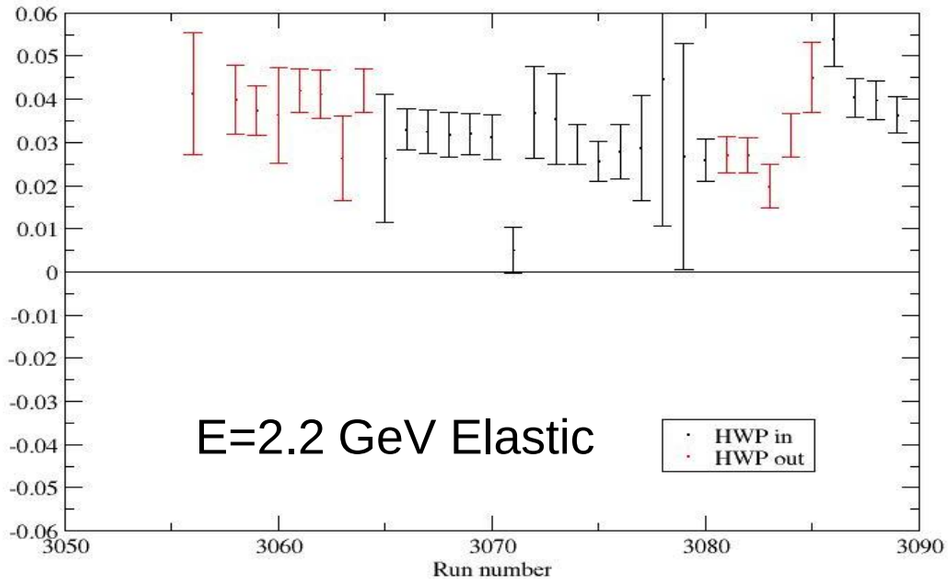
courtesy Ryan Zielinski

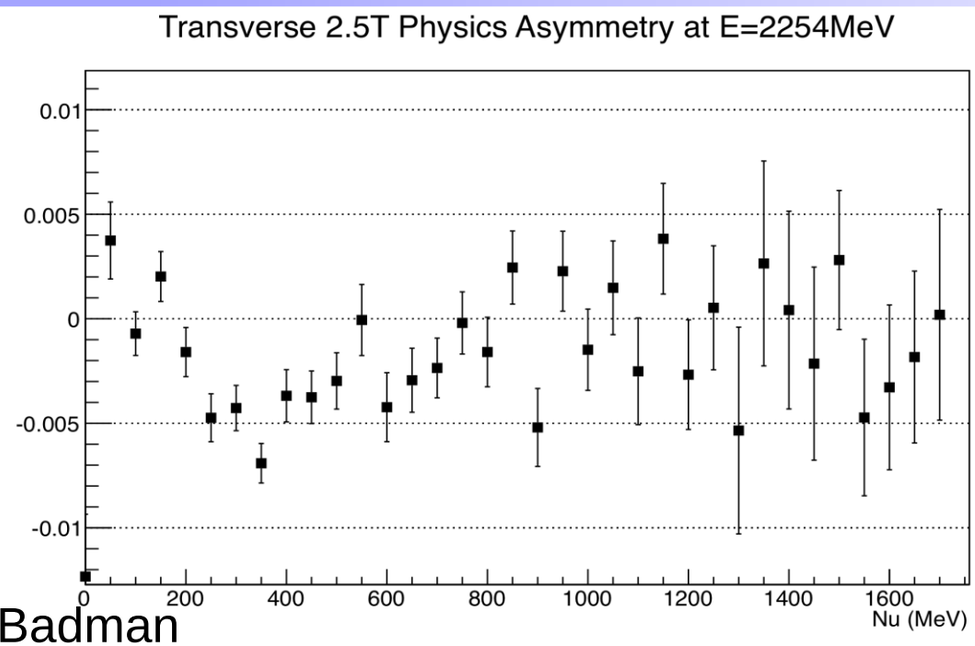
Asymmetries



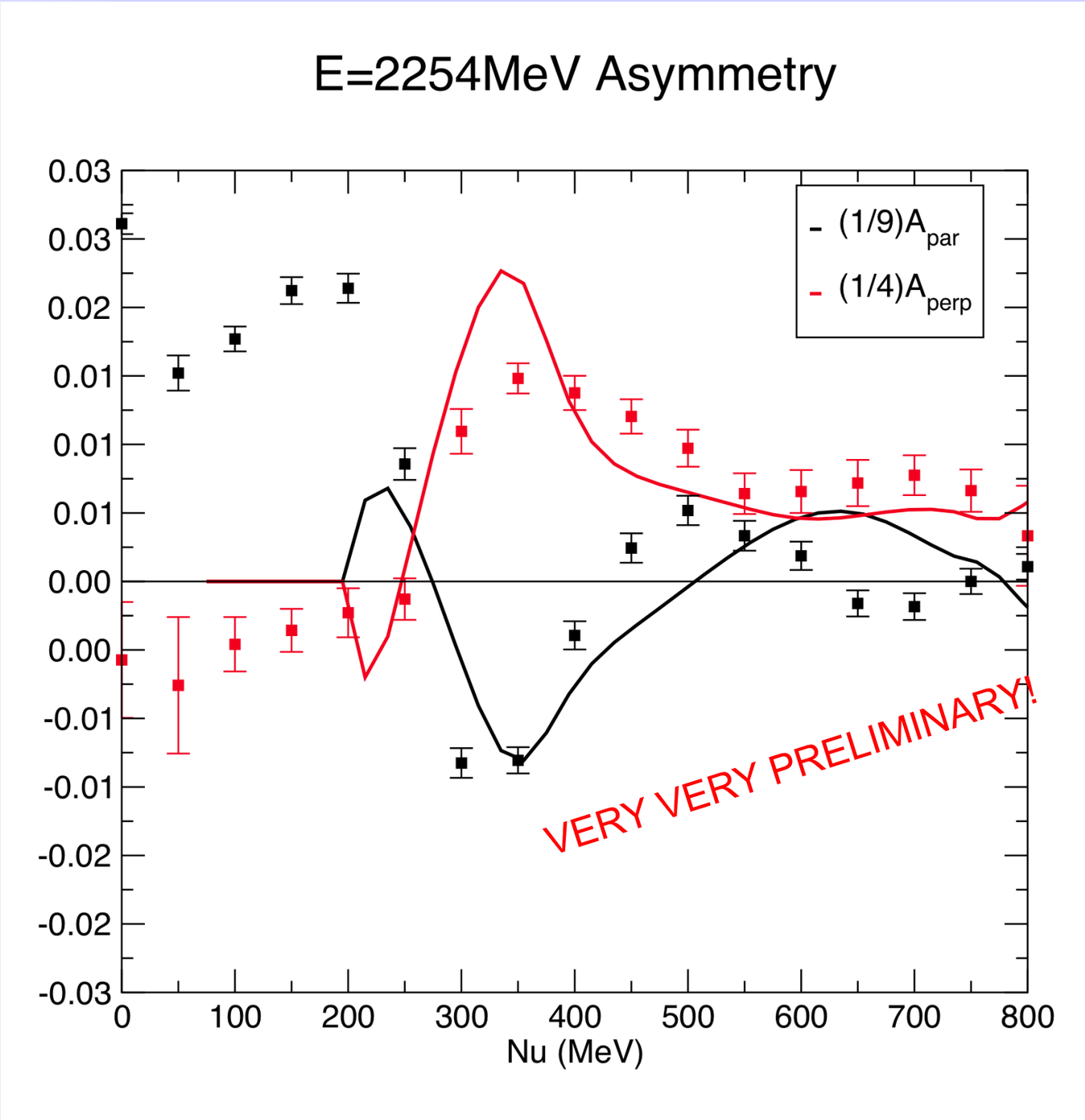


VERY VERY PRELIMINARY!





courtesy Toby Badman



courtesy Toby Badman