Nucleon Resonances and Spin Structure

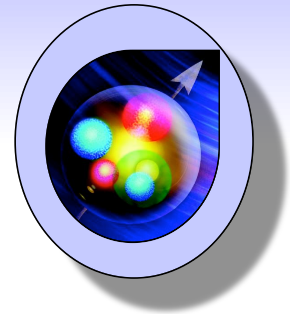
NSTAR 2011

The 8th International Workshop on the Physics of Excited Nucleons
May 17-20, 2011

K. Slifer, UNH

This talk

Brief overview of spin structure



Recent Results from JLab

Spin Duality (Hall A)

RSS (Hall C)

This talk

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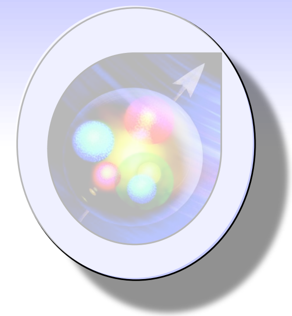

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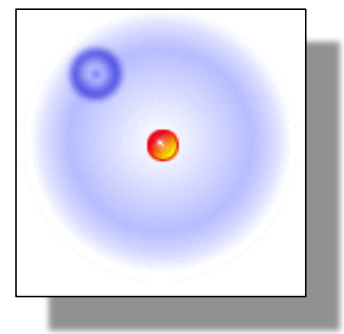

Finite Size effects in bound state Q.E.D.

Proton Charge Radius

Hydrogen HF splitting

Role of nucleon resonances

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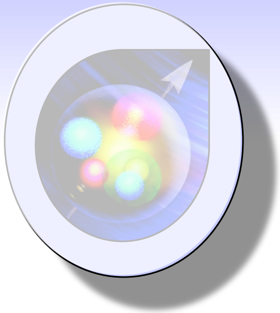

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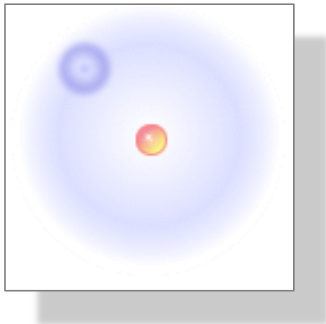

Finite Size effects in bound state Q.E.D.

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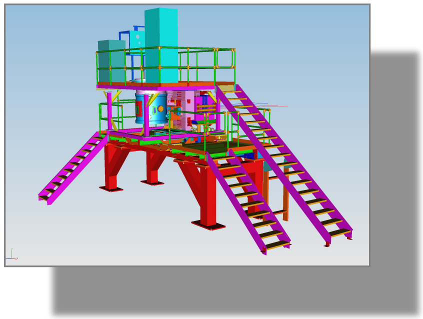
Role of nucleon resonances

Upcoming JLab Measurements

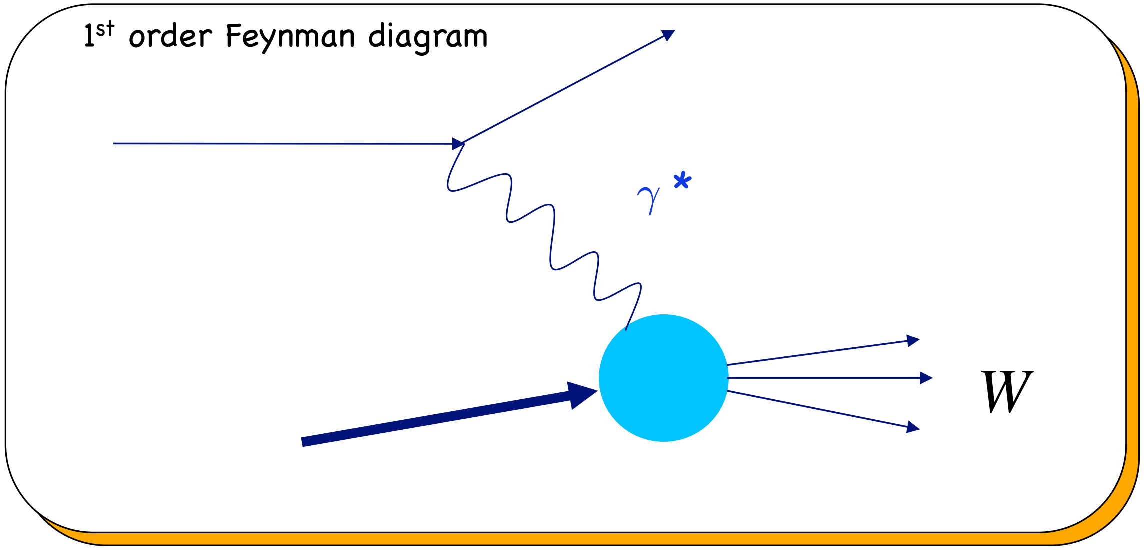
E08-027 and

E08-007

"g2p & gep"



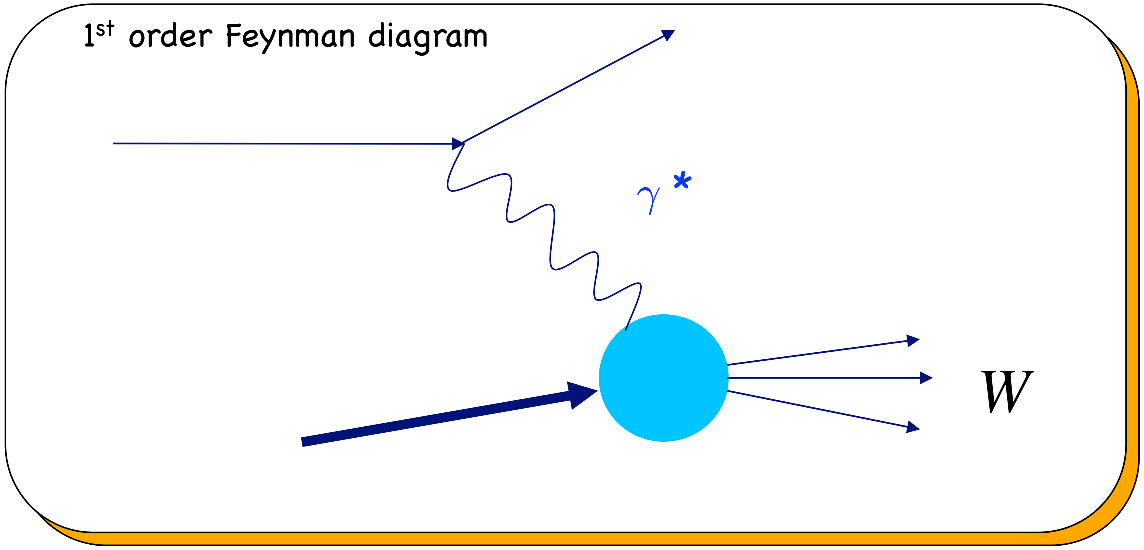
Inclusive Scattering



Kinematics

Q^2 : 4-momentum transfer
X : Bjorken Scaling var
W : Invariant mass of target

Inclusive Scattering



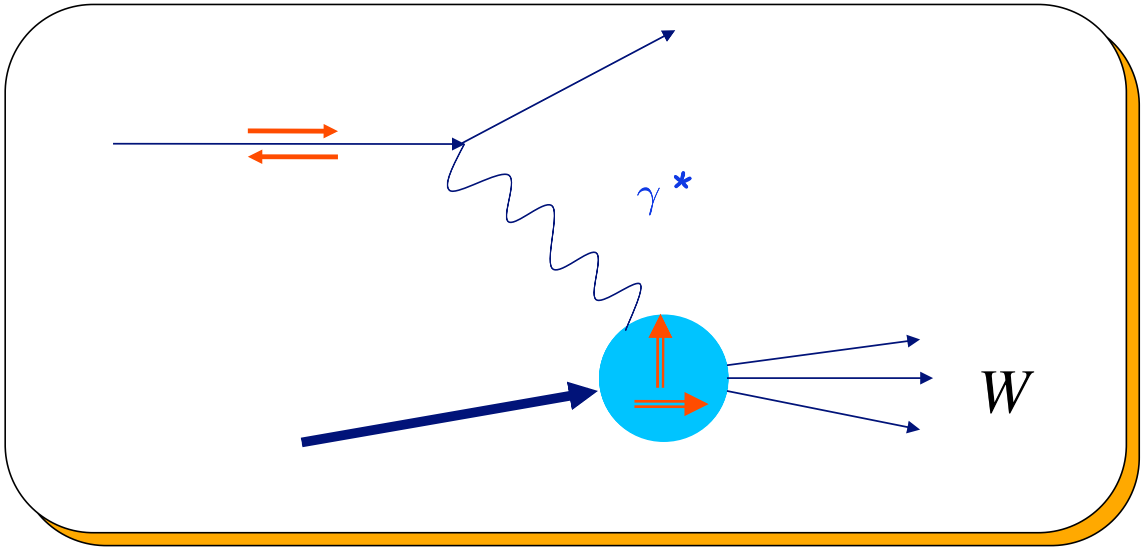
Q^2 : 4-momentum transfer
X : Bjorken Scaling var
W : Invariant mass of target

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

Inclusive Cross Section

deviation from point-like behavior
characterized by the Structure Functions

Inclusive Scattering



When we add spin degrees of freedom to the target and beam, 2 Additonal SF needed.

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

$$+\,\gamma\, g_1(x,Q^2) + \delta\, g_2(x,Q^2)$$

Inclusive **Polarized** Cross Section

SFs parameterize everything we don't know about proton structure

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"

How Big are Higher twist contributions at low X?

If we assume BC to hold,

we can learn something about the low x region

using only our high x measured data.

$$\Gamma_2 = \Gamma_2^{\rm ww} + \overline{\Gamma}_2 + \Gamma_2^{el}$$

HT

$$\Gamma_2 = \Gamma_2^{\rm ww} + \overline{\Gamma}_2 + \Gamma_2^{el}$$

0

leading twist part
satisfies BC exactly

HT

$$\Gamma_2 = \Gamma_2^{\mathrm{ww}} + \overline{\Gamma}_2 + \Gamma_2^{el}$$

0

well known

HT

$$\Gamma_2 = \overline{\Gamma}_2 + \Gamma_2^{el}$$

$$= \overline{\Gamma}_2^{u} + \overline{\Gamma}_2^{m} + \Gamma_2^{el}$$

HT

$$\Gamma_2 = \overline{\Gamma}_2 + \Gamma_2^{el}$$

$$= \overline{\Gamma}_2^{u} + \overline{\Gamma}_2^{m} + \Gamma_2^{el}$$

we can't access this low x contribution

we measure this

$$\Gamma_2 = \overline{\Gamma}_2 + \Gamma_2^{el}$$

$$= \overline{\Gamma}_2^{u} + \overline{\Gamma}_2^{m} + \Gamma_2^{el}$$

$$\Delta\overline{\Gamma}_2 = \Gamma_2 - \overline{\Gamma}_2^{u}$$

what we measure

$$\Gamma_2 = \overline{\Gamma}_2 + \Gamma_2^{el}$$

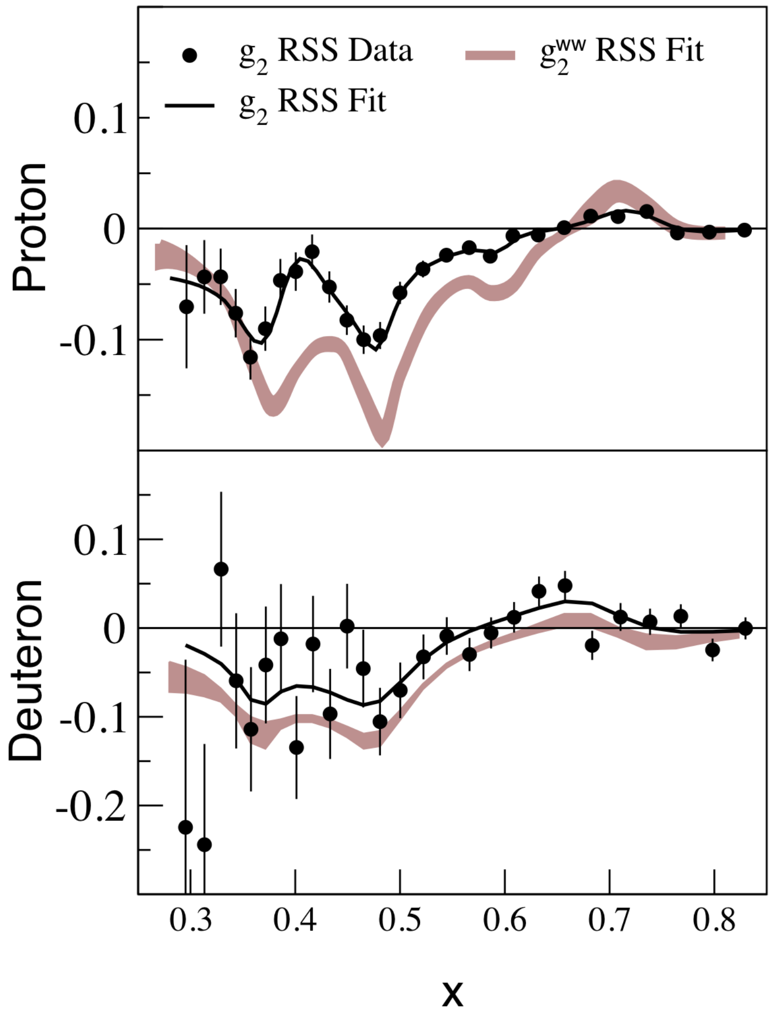
$$= \overline{\Gamma}_2^{u} + \overline{\Gamma}_2^{m} + \Gamma_2^{el}$$

$$\Delta\overline{\Gamma}_2 = \Gamma_2 - \overline{\Gamma}_2^{u}$$
$$= \overline{\Gamma}_2^{m} + \Gamma_2^{el}$$

what we measure places an upper limit on the low-x HT contribution to Γ_2

RSS Experiment (Spokesmen: Rondon and Jones)

$Q^2 = 1.3\ GeV^2$



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

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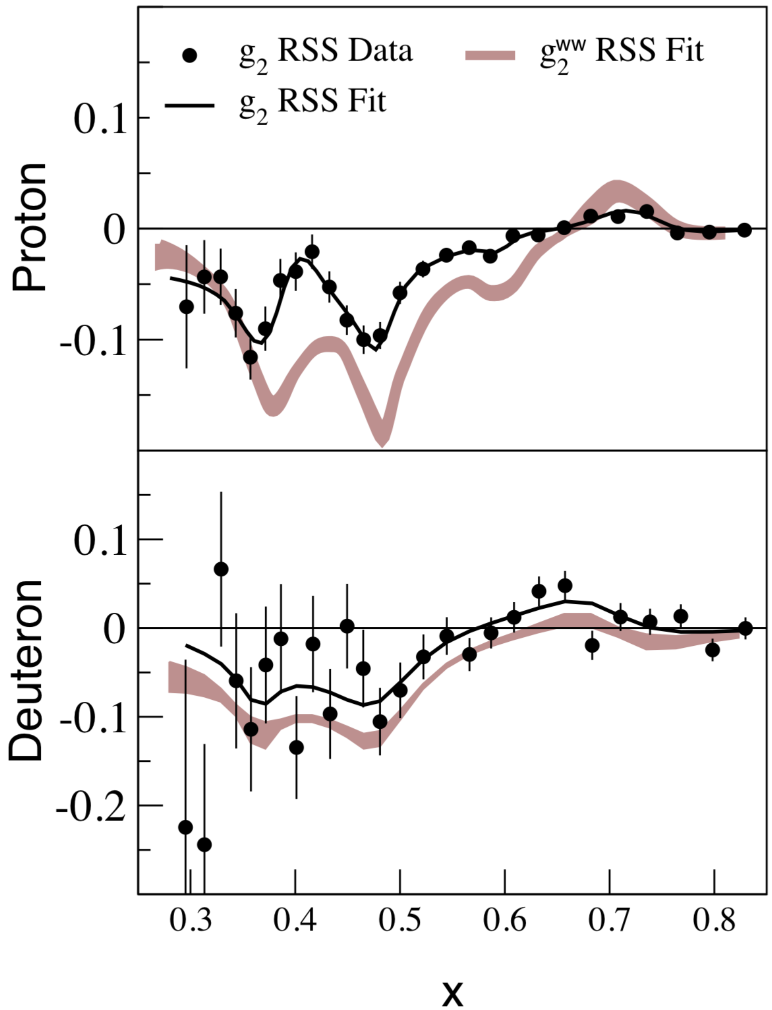

$$\overline{\Delta}\Gamma_2 = -0.0006 \pm 0.0021$$ (proton)

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

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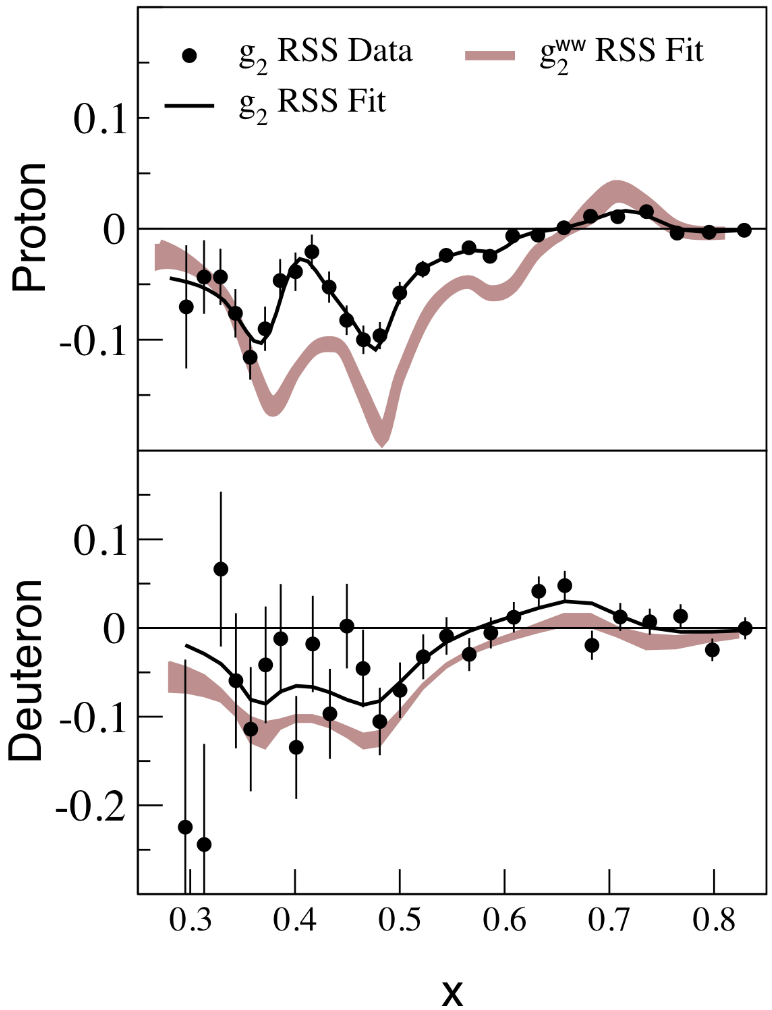


$$\overline{\Delta}\Gamma_2 = -0.0006 \pm 0.0021$$ (proton)

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

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

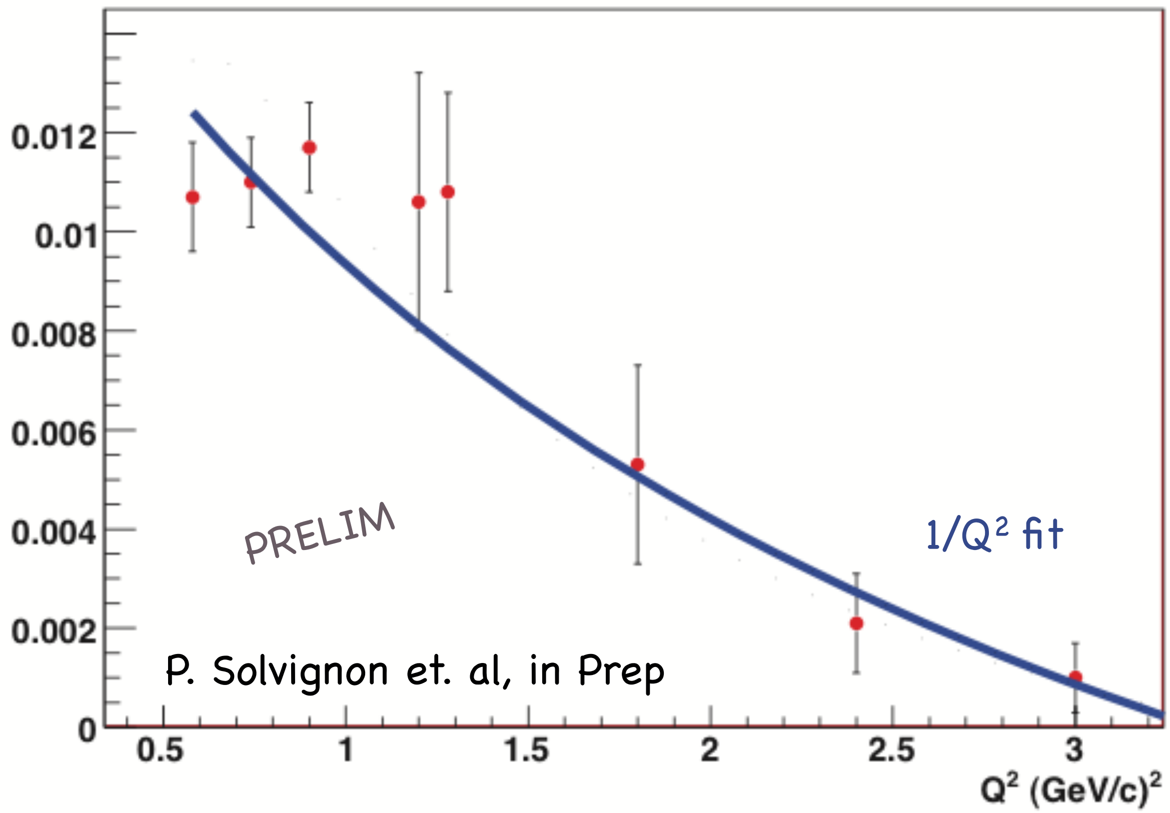
non-zero by 2.6σ

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

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

Neutron HT contribution to low x

Global Analysis of JLab Neutron g_2 Data



Plot courtesy of Nilanga Liyanage

Neutron HT contribution to low x

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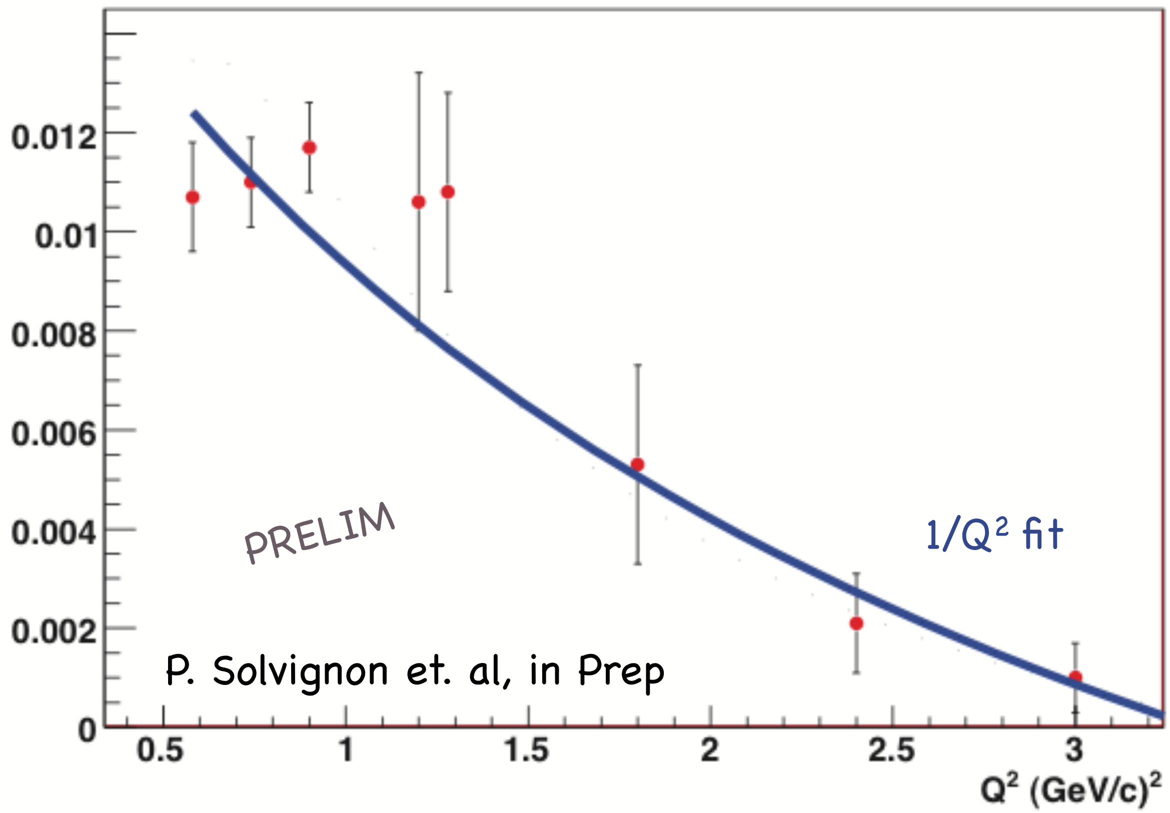


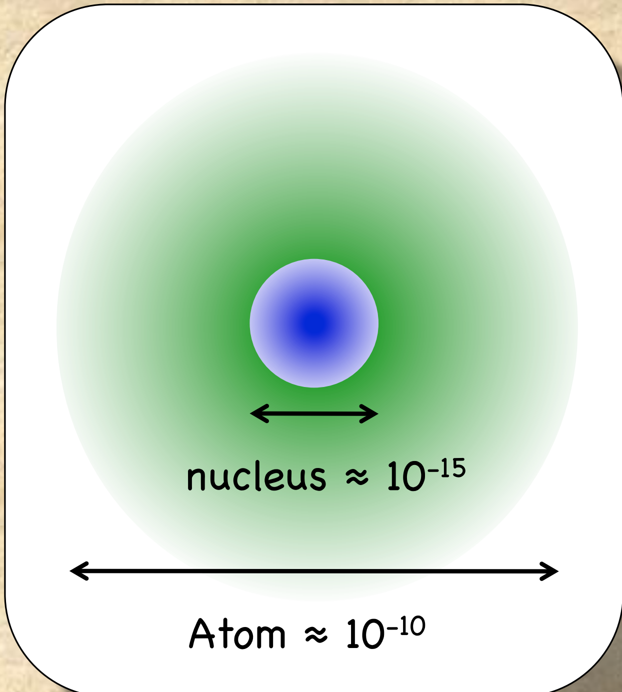
Consistency across all exps.
(E94010, RSS, E01012)

Follows rough $1/Q^2$ trend

HT contribution → 0
by about Q^2=3 GeV^2

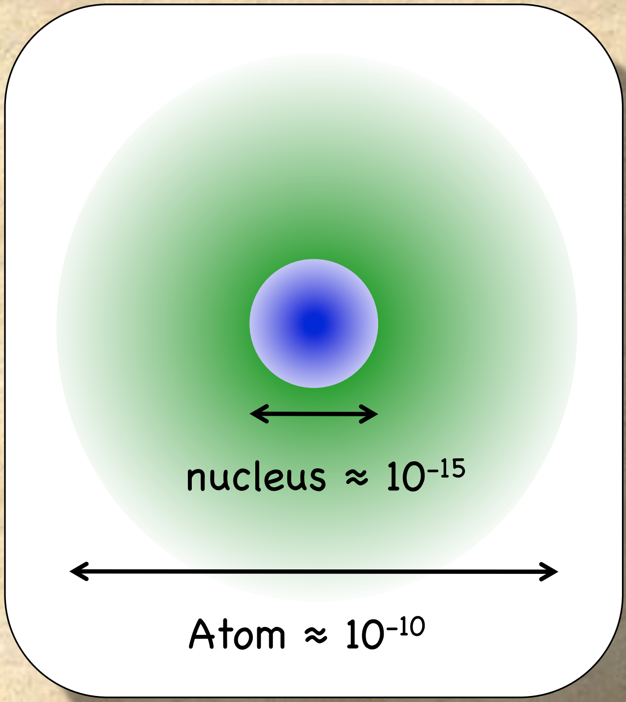
Plot courtesy of Nilanga Liyanage

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.



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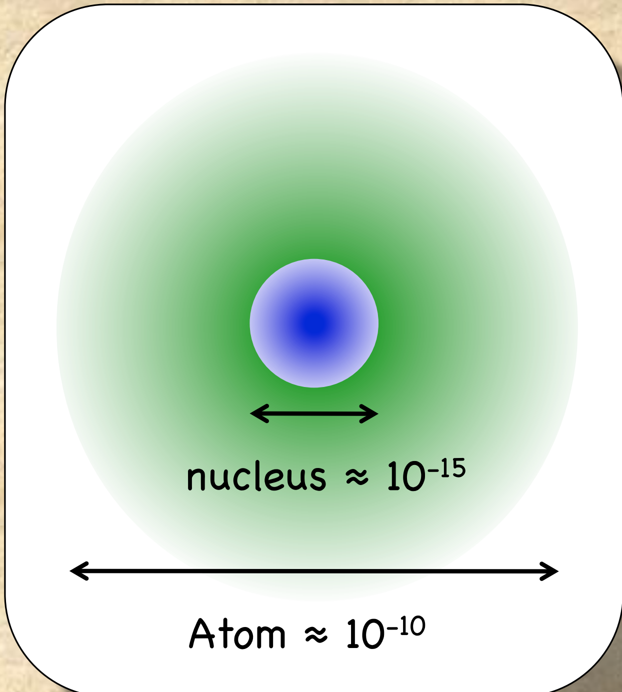
Hydrogen HF Splitting

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

Applications to Bound State Q.E.D.



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

Hydrogen HF Splitting

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

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

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)

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

Elastic piece larger but with similar uncertainty

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

integral of g1 & F1

pretty well determined from F_2, g_1 JLab data

Structure dependence of Hydrogen HF Splitting

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Elastic piece larger but with similar uncertainty

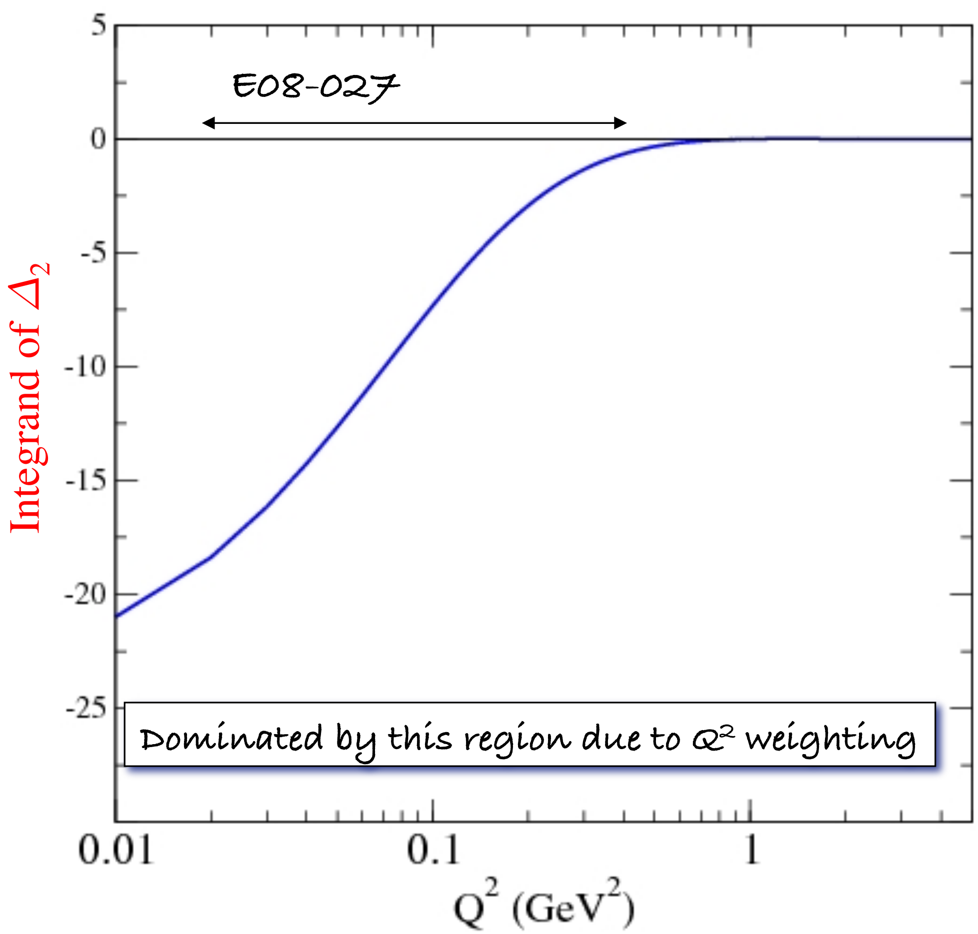
$$\Delta_{POL} = 0.2265 \quad (\Delta_1 + \Delta_2)\text{ppm}$$

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

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

weighted heavily to low Q^2

Hydrogen Hyperfine Structure

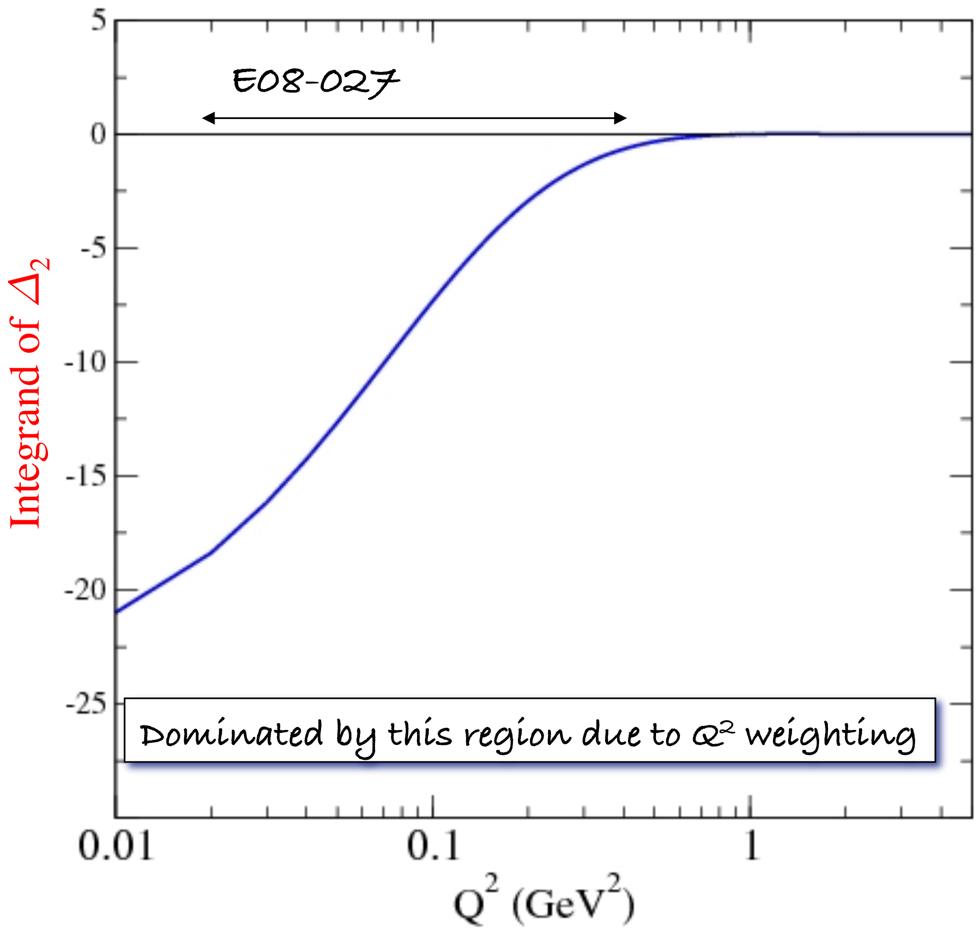


$$\Delta_2 = -24 m_p^2 \int_0^\infty \frac{dQ^2}{Q^4} B_2(Q^2)$$

$$= -0.57 \pm 0.57$$

assuming CLAS model with 100% error

Hydrogen Hyperfine Structure



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$$= -0.57 \pm 0.57$$

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

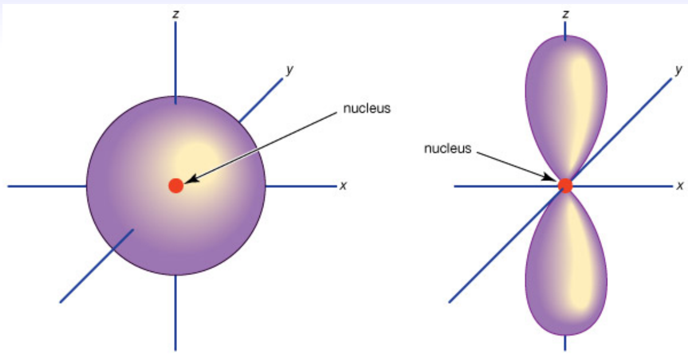
Proton Charge Radius from μP lamb shift disagrees with eP scattering result by about 6%

$\langle r_p \rangle = 0.84184 \pm 0.00067$ 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

R. Pohl *et al.* Nature, 2010

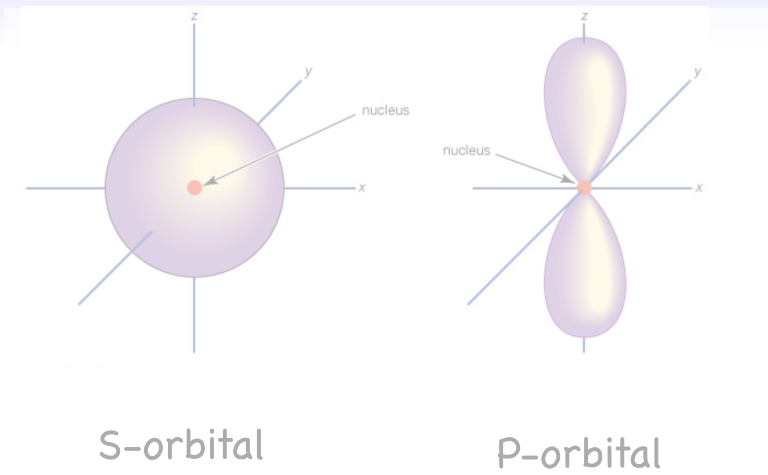
Lamb Shift

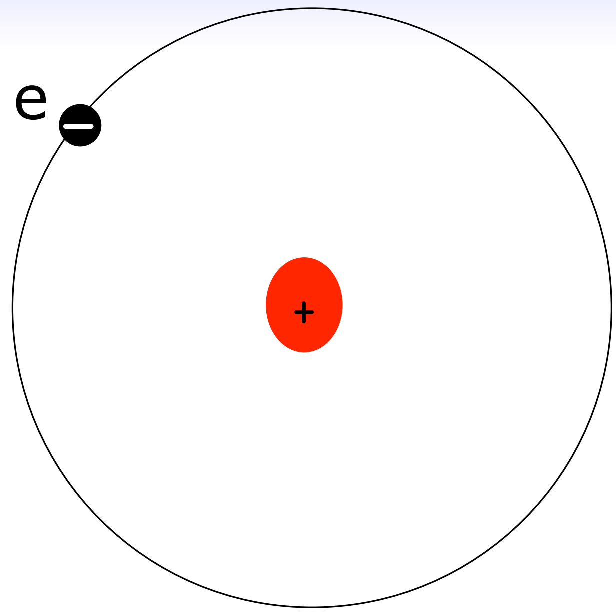


S-orbital P-orbital

Energy difference between the 2s and 2p levels

Lamb Shift



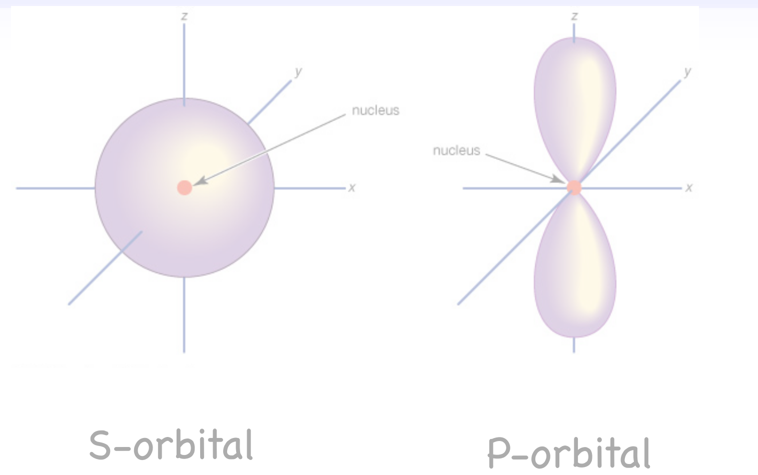


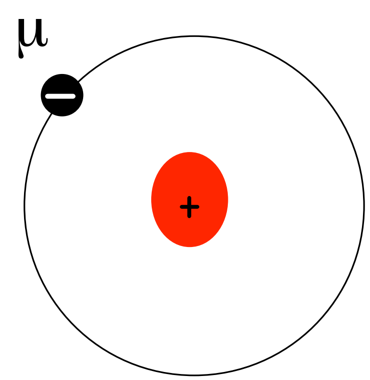
Hydrogen

radial distance in hydrgenic atom depends inversely on mass

$$r = \frac{\hbar}{mc\alpha}$$

Lamb Shift



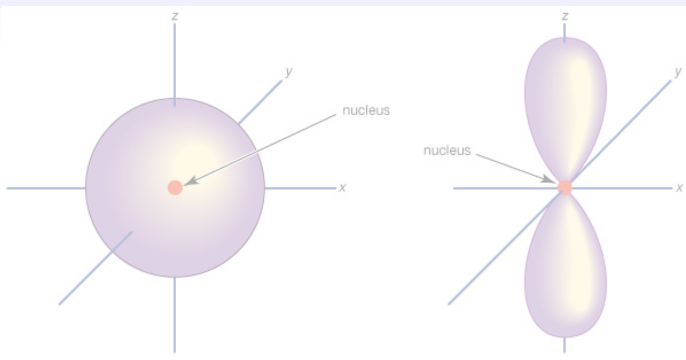


muonic Hydrogen

muon is about 200 times heaviear than electron

1st Bohr radius is about 200 times smaller

Lamb Shift



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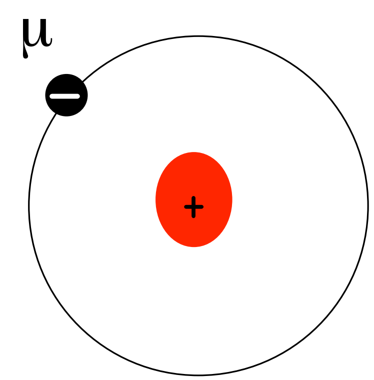


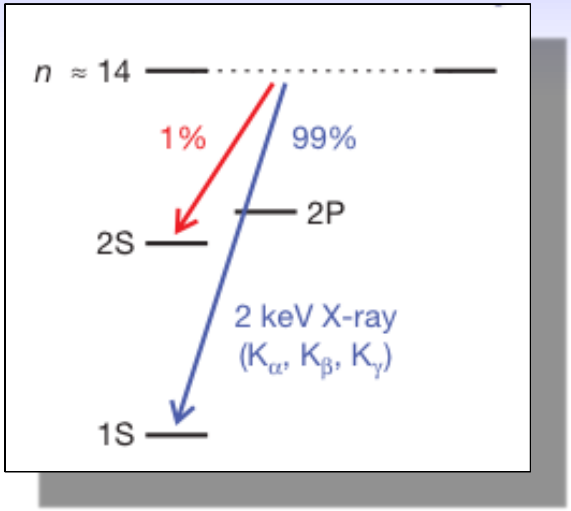
muonic Hydrogen

muon is about 200 times heaviear than electron

1st Bohr radius is about 200 times smaller

so Lamb shift is enhanced by about 200 compared to eH

PSI results on Muonic Hydrogen



Muon Beam incident on H gas

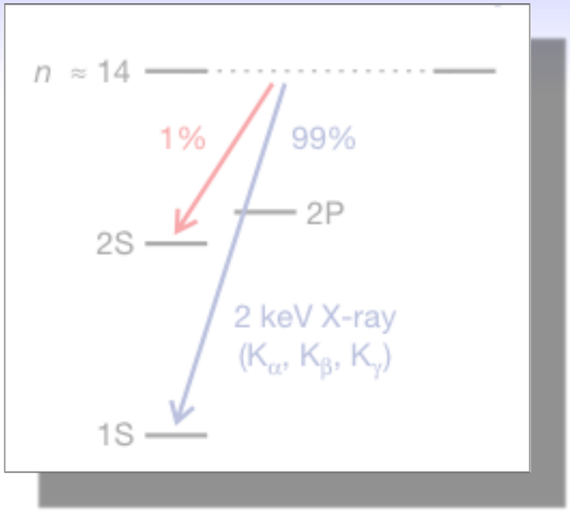
μH formed in highly excited state

most decay directly to ground 1S state

small fraction of μ decay to the 2s level

reproduced from R. Pohl *et al.* Nature, 2010

PSI results on Muonic Hydrogen



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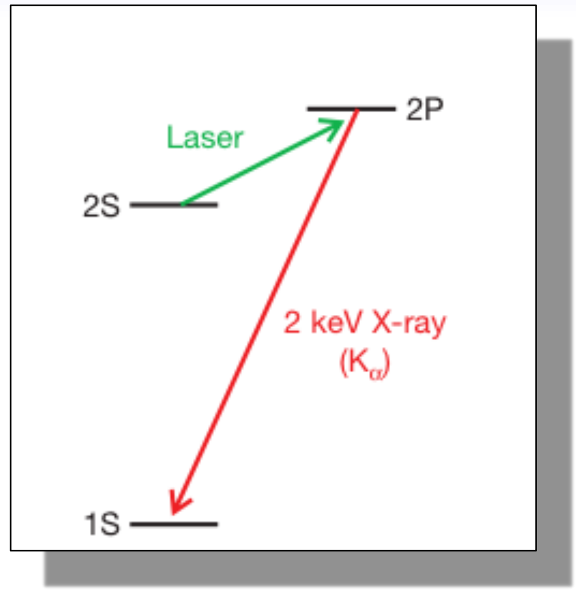


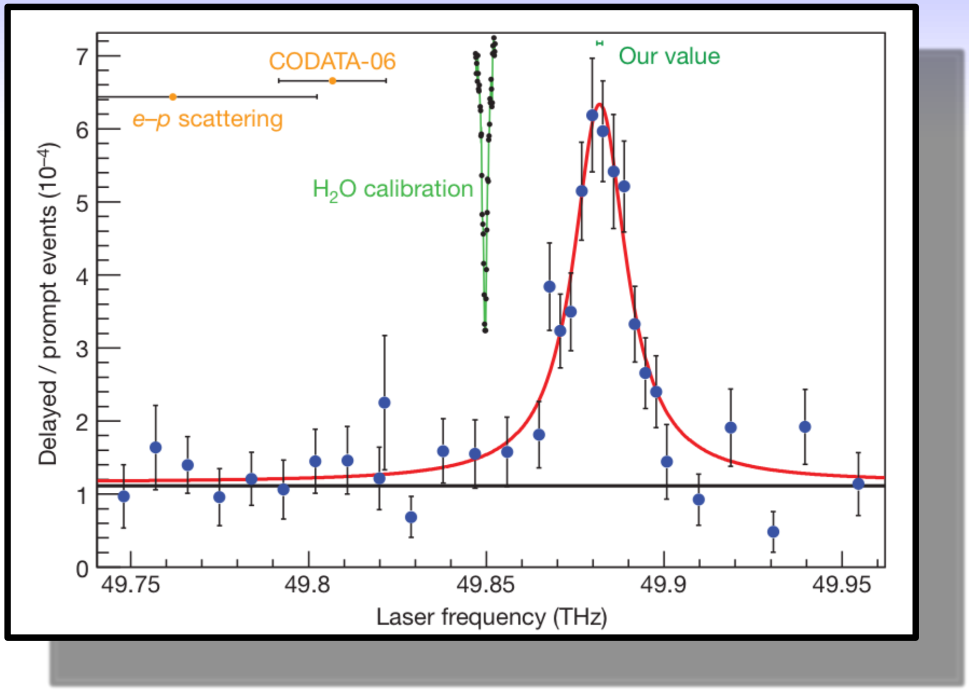
Stimulate transitions from 2S-2P

observe increase in decay from 2P-1S

xray of 2 keV

reproduced from R. Pohl *et al.* Nature, 2010

PSI results on Muonic Hydrogen



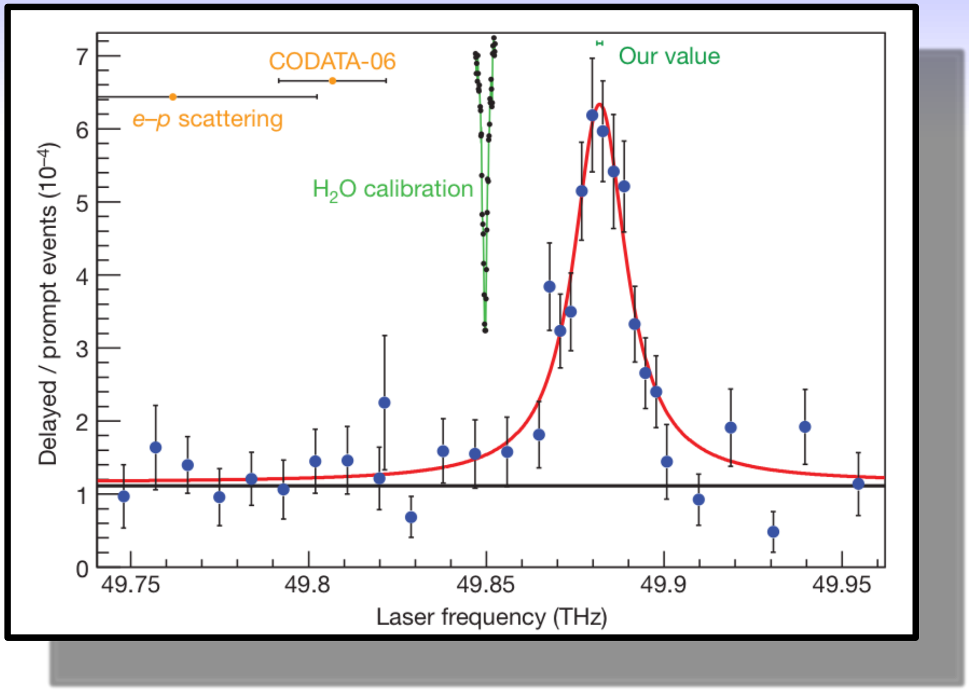
Scan the probe laser frequency

At resonance, stimulating 2S -> 2P transistions

so see an increase in the 2P -> ground state xrays

reproduced from R. Pohl *et al.* Nature, 2010

PSI results on Muonic Hydrogen

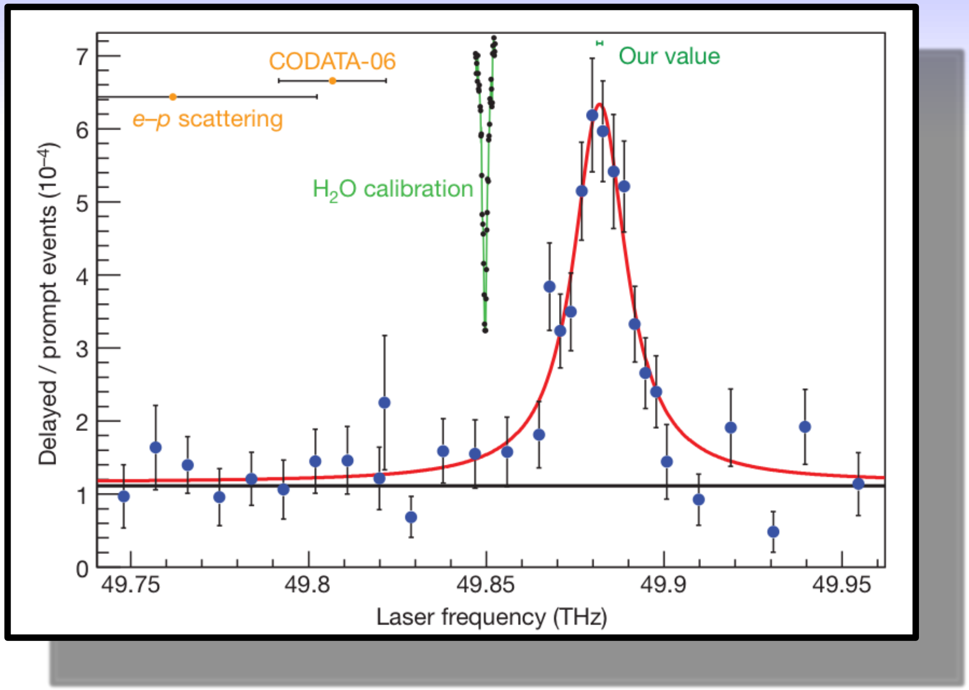


Observed ν=49.882 THz (= 206.295 meV)

gives r_p = 0.84184 ± 0.00067 fm

reproduced from R. Pohl *et al.* Nature, 2010

PSI results on Muonic Hydrogen



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from e-p scattering

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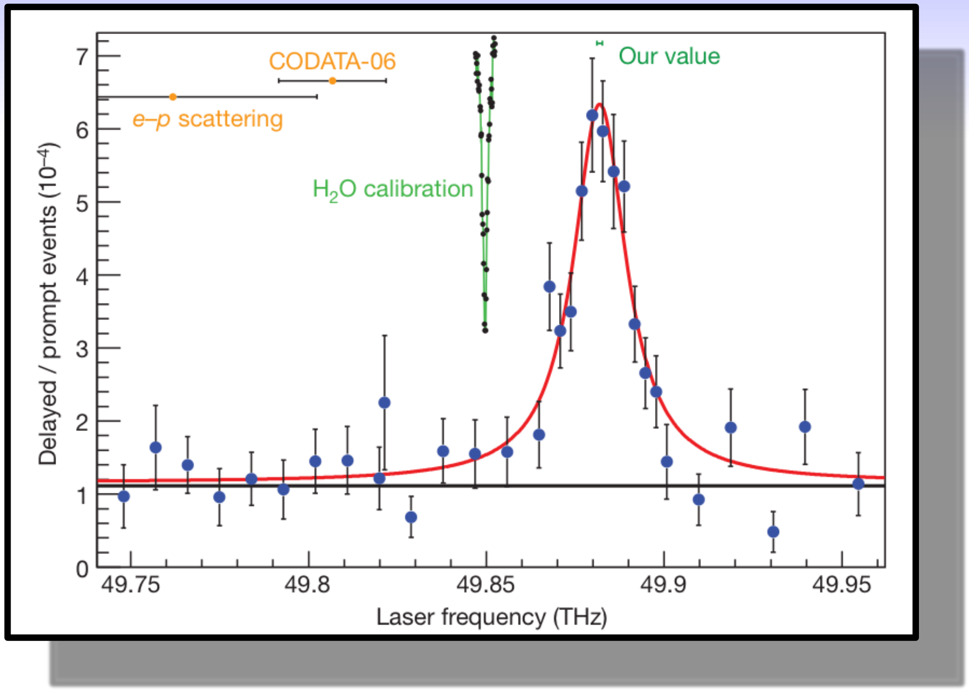

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r_p = 0.897 ± 0.018 fm Sick (3σ)

r_p = 0.8768 ± 0.0069 fm CODATA (5σ)

from H spectroscopy

reproduced from R. Pohl *et al.* Nature, 2010

What could solve the discrepency?

r_p = 0.84184 ± 0.00067 fm PSI

r_p = 0.8768 ± 0.0069 fm CODATA (5σ)

What could solve the discrepency?

NYT : July 12, 2010
For a Proton, a Little Off the Top (or Side) Could Be Big Trouble

r_p = 0.84184 ± 0.00067 fm PSI

r_p = 0.8768 ± 0.0069 fm   CODATA (5σ)

Miscalibration of PSI frequency? Very unlikely

QED wrong? Exciting! but unlikely ☹

Calculations incorrect? maybe missing some terms… (muon mass)

Uncertainty underestimated? This is where SSF program can play a role.


WARNING
EXPERIMENTALIST
Interpreting
Theory
ahead

Splitting of 2S and 2P level is sensitive to r_p

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

Splitting of 2S and 2P level is sensitive to r_p

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

2% effect
200X bigger than in eH

Splitting of 2S and 2P level is sensitive to r_p

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

Total observed shift is combination of

Lamb Shift

$$\Delta E_{LS} = 206.0573(45) - 5.2262\,r_p^2 + 0.0347\,r_p^3\ \text{meV},$$

Splitting of 2S and 2P level is sensitive to r_p

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Fine structure $\Delta E_{FS} = 8.352082\ \text{meV},$

Splitting of 2S and 2P level is sensitive to r_p

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Lamb Shift	$\Delta E_{LS} = 206.0573(45) - 5.2262\, r_{\mathrm{p}}^2 + 0.0347\, r_{\mathrm{p}}^3$ meV,
Fine structure	$\Delta E_{FS} = 8.352082$ meV,
2P Hyperfine structure	$\Delta E_{HFS}^{2P_{3/2}} = 3.392588$ meV.
2S Hyperfine structure	$\Delta E_{HFS}^{2S} = 22.8148\,(78)$ meV.

Splitting of 2S and 2P level is sensitive to r_p

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2S Hyperfine splitting	$\Delta E_{HFS}^{2S} = 22.8148\,(78)\ \text{meV}.$

mostly negligible uncertainty

Explicit dependence on r_p comes from the **Lamb shift** term

$$\Delta E_{LS} = 206.0573(45) - 5.2262\, r_p^2 + 0.0347\, r_p^3 \text{ meV},$$

several dozen terms contribute to the Lamb shift, but only a few are really significant:

Explicit dependence on r_p comes from the **Lamb shift** term

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several dozen terms contribute to the Lamb shift, but only a few are really significant:

≈205 meV : Relativ. one loop vacuum polarization

≈1.5 meV : NR two loop vacuum polarization

negligible uncertainty

Explicit dependence on r_p comes from the **Lamb shift** term

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several dozen terms contribute to the Lamb shift, but only a few are really significant:

≈205 meV : Relativ. one loop vacuum polarization

≈1.5 meV : NR two loop vacuum polarization

negligible uncertainty

0.015 ± 0.004 meV : Nuclear Structure correction ("Proton Polarizability")

82% of the total error on the PSI value comes from this term

Proton Polarizability term

0.015 ± 0.004 meV : Nuclear Structure correction

E. Borie Phys.ReV.A (2005)

"This uncertainty is probably underestimated"

27% relative uncertainty

Proton Polarizability term

0.015 ± 0.004 meV : Nuclear Structure correction
E. Borie Phys.ReV.A (2005)
"This uncertainty is probably underestimated"

In fact its the simple average of several different calculations:

0.0174 ± 0.004 meV Rosenfelder 1999 *
0.012 ± 0.002 meV Pachuki 1999
0.016 ± ? Faustov, Martynenko 2001

this uncertainty is probably not very well constrained by SF data (1999)

How much would this term have to shift to get agreement?

0.015 ± 0.004 meV

PSI results would need to shift by about 3σ to coincide with CODATA

How much would this term have to shift to get agreement?

0.015 ± 0.004 meV

PSI results would need to shift by about 3σ to coincide with CODATA

i.e. need a shift of about 0.187 meV in the predicted splitting

which would mean the proton polarizability term is incorrect by an order of magnitude.

This is unlikely

but,

given the poor state of knowledge of SSF and FF at very low Q^2...

Upcoming Experiments/Results

E08-027 : Proton g2 Structure Function

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

Primary Motivation

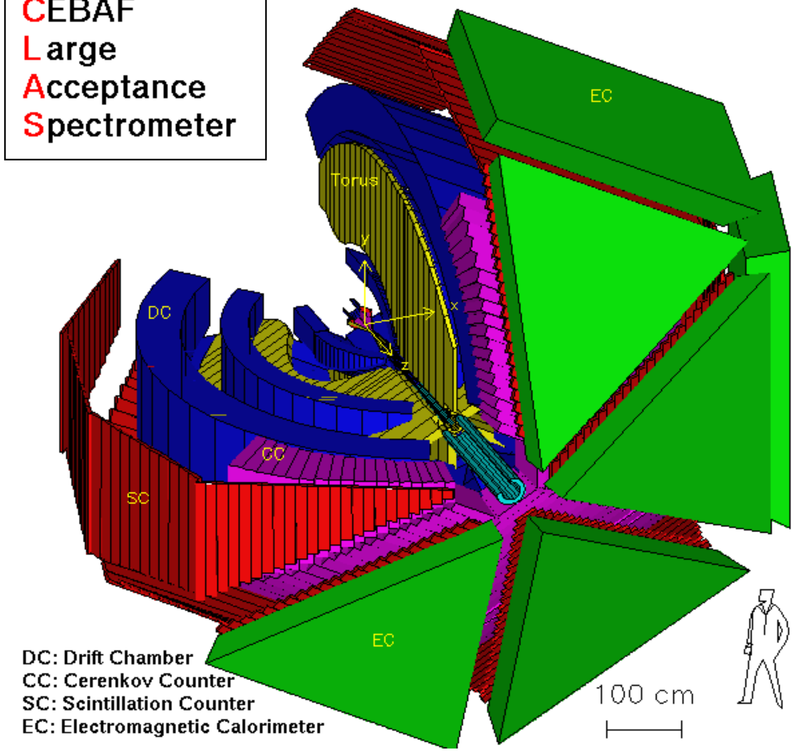
Proton g_2 structure function has never been measured at low or moderate Q^2.

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

This will help to clarify several outstanding puzzles

EG4

CEBAF
Large
Acceptance
Spectrometer



Ran in 2006

Measurement of g_1 at low Q^2

Test of ChPT as $Q^2 \rightarrow 0$

Measured Absolute XS differences

Goal : Extended GDH Sum Rule
Proton
Deuteron

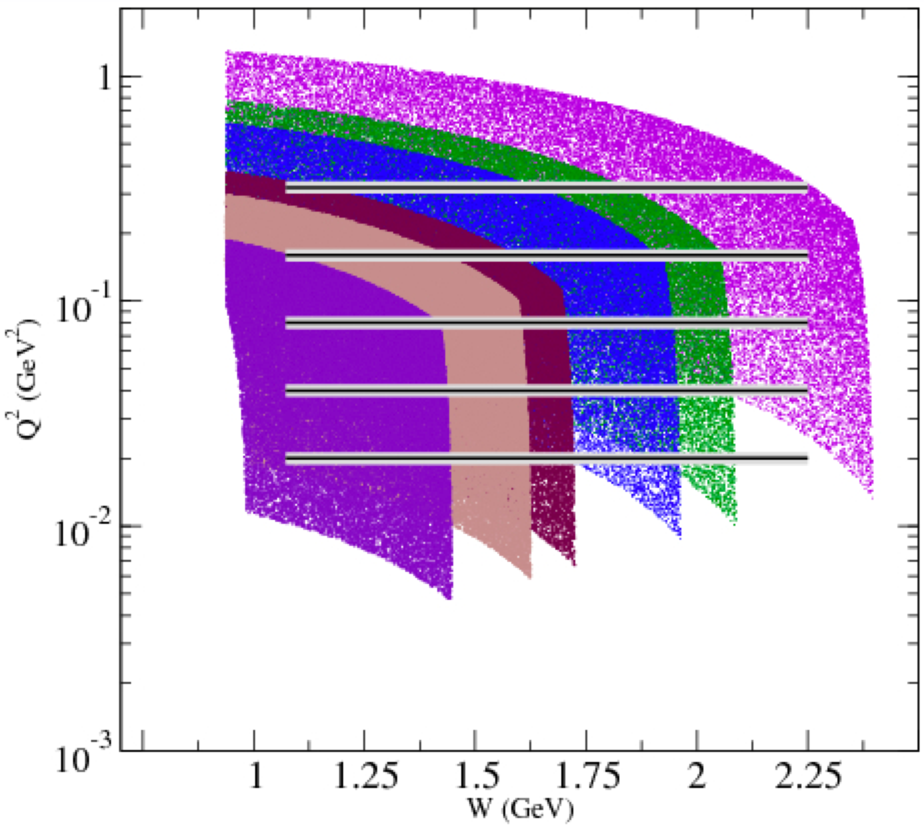
Spokespersons

NH_3: M. Battaglieri, A. Deur, R. De Vita, M. Ripani (Contact)
ND_3: A. Deur(Contact), G. Dodge, K. Slifer

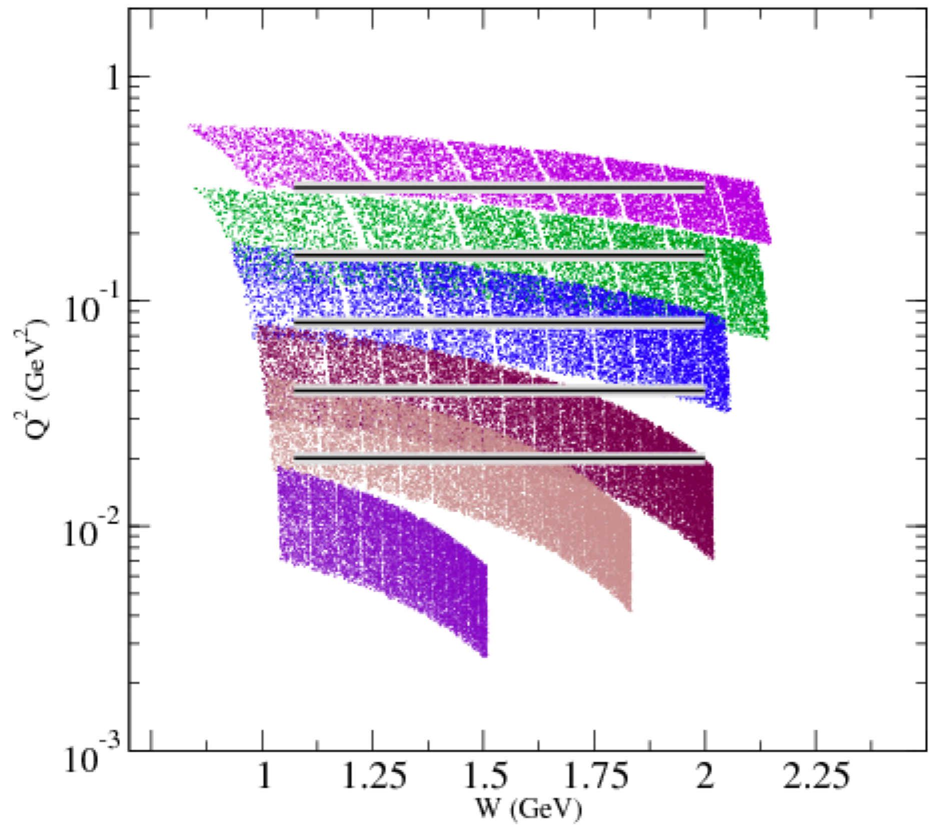
PhD. Students
K. Adhikari, H. Kang, K. Kovacs

Low Q^2 SSF measurements

EG4: g1p



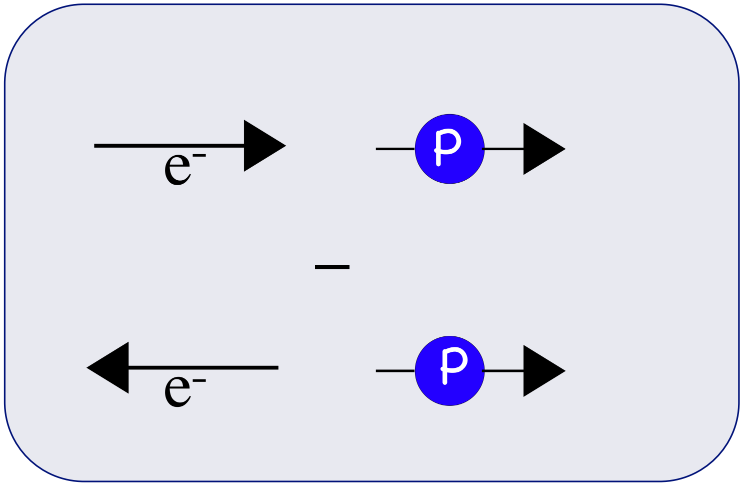
E08-027 : g2p



$0.02 < Q^2 < 0.5$ GeV^2

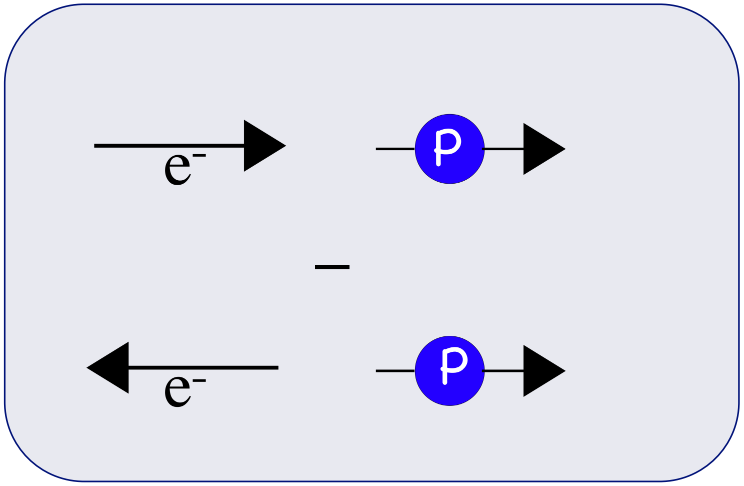
Resonance Region

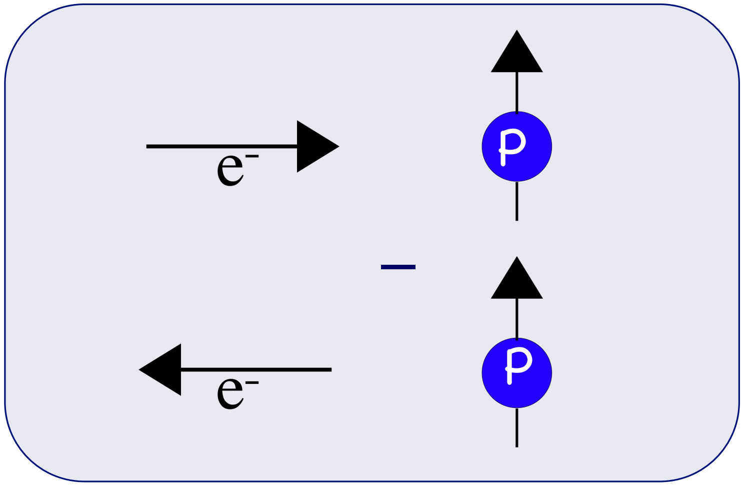
Experimental Technique



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

Experimental Technique





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

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

Experimental Technique

Inclusive Polarized Cross Section differences

We Need:

Polarized proton target

- upstream chicane
- downstream local dump

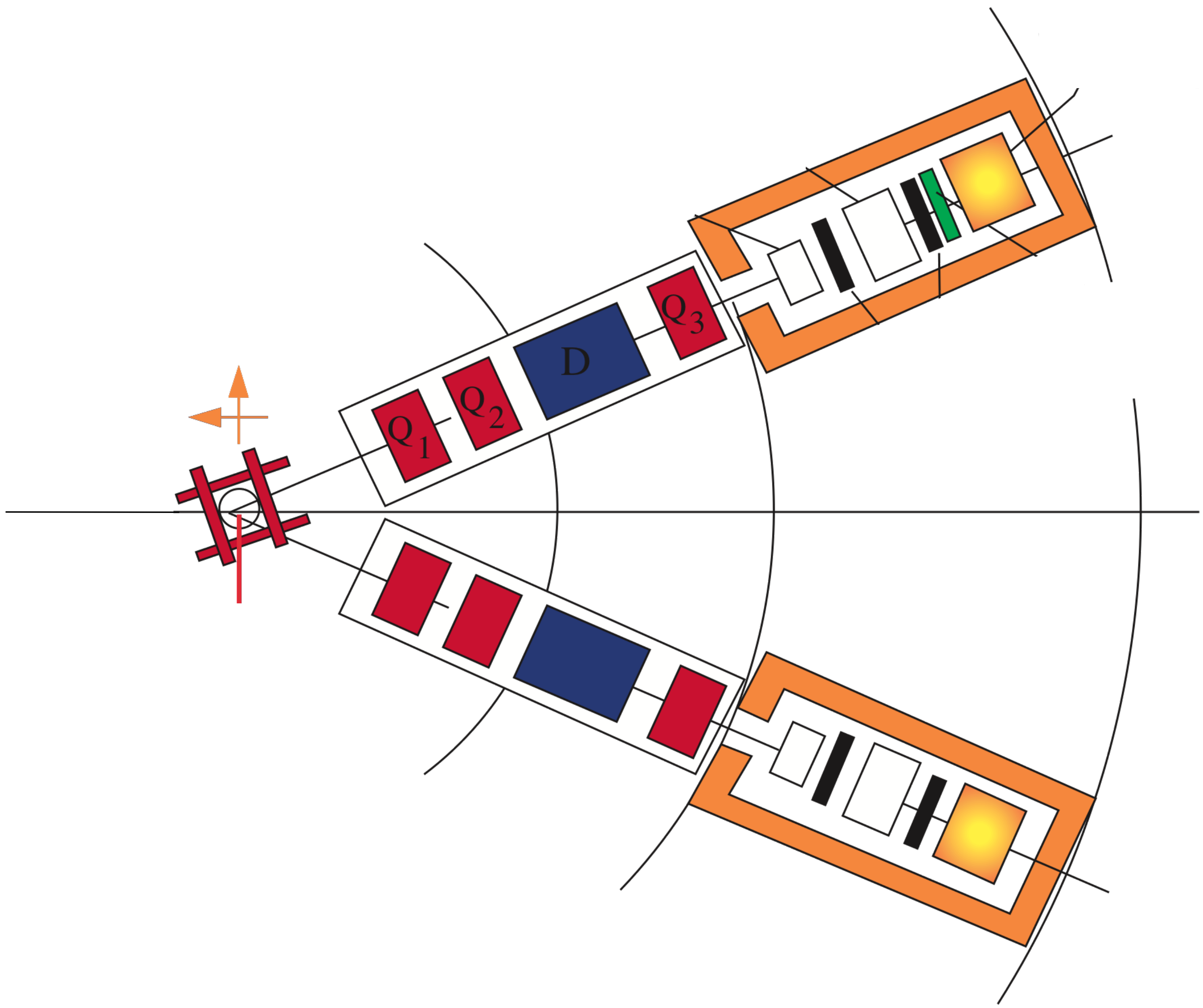
Low current polarized beam

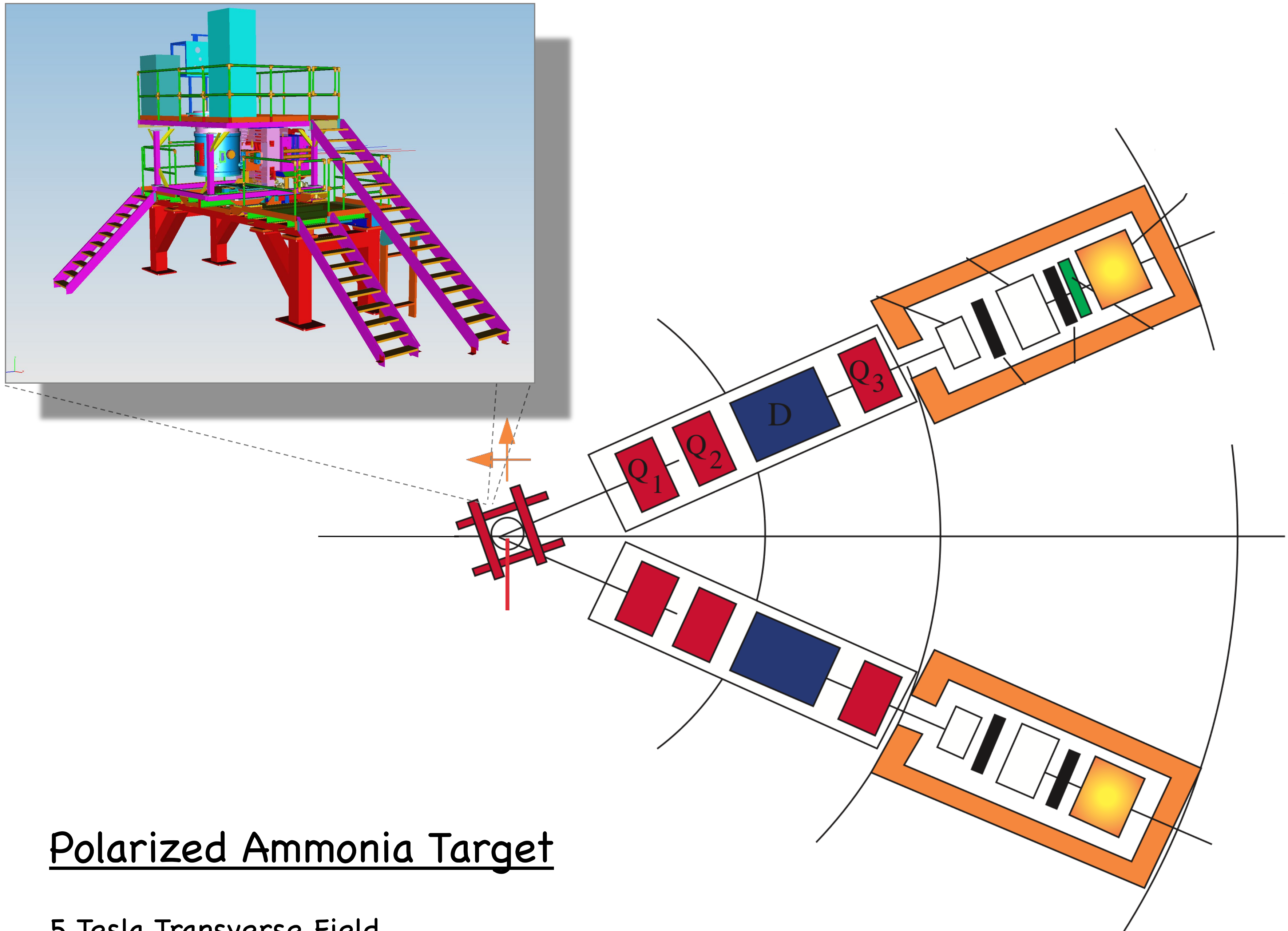
- Upgrades to existing Beam Diagnostics to work at 85 nA

Lowest possible Q^2 in the resonance region

- Septa Magnets to detect forward scattering

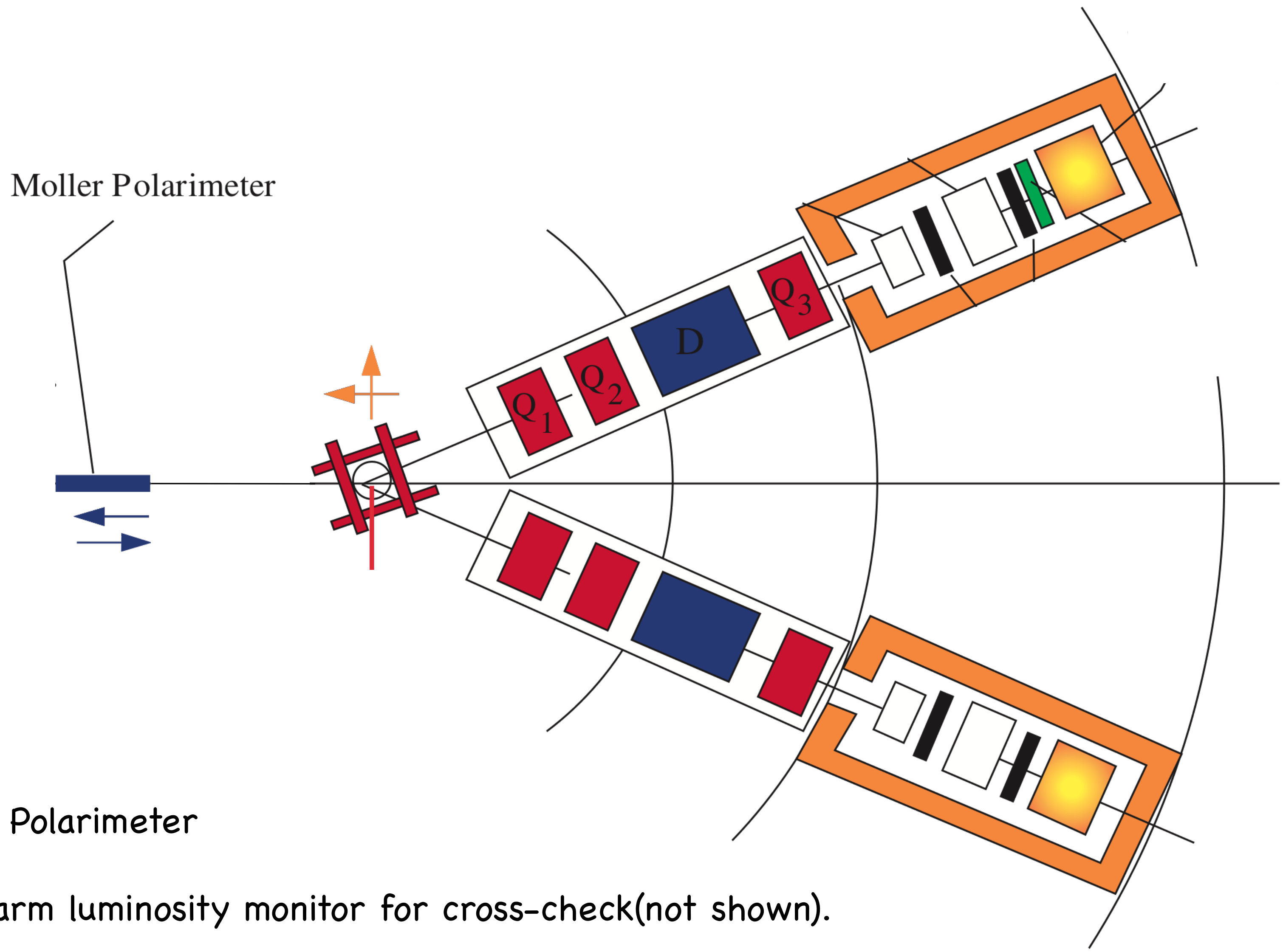
Hall A E08-027 configuration





Polarized Ammonia Target

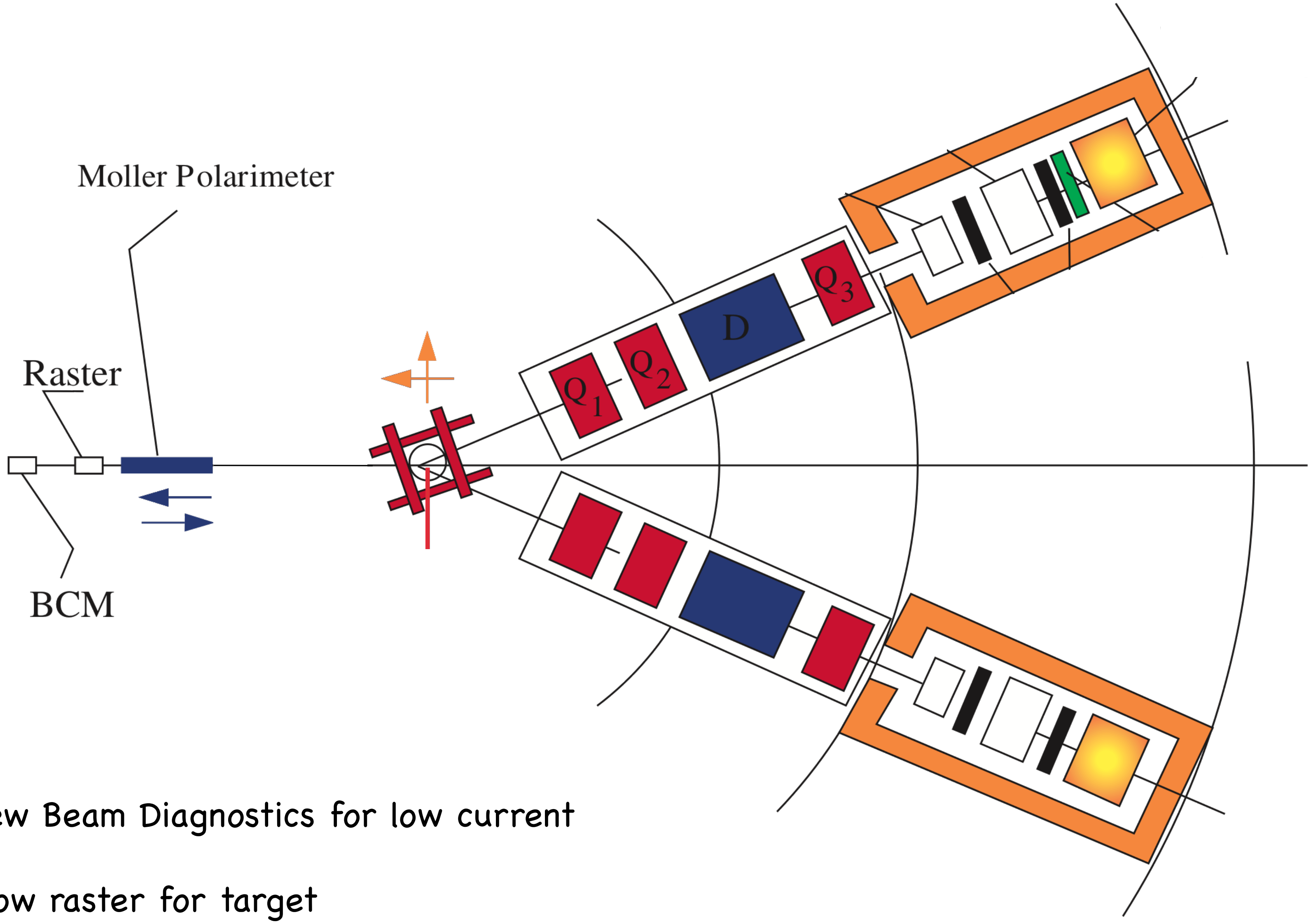
5 Tesla Transverse Field
Current = 85 nA



Moller Polarimeter

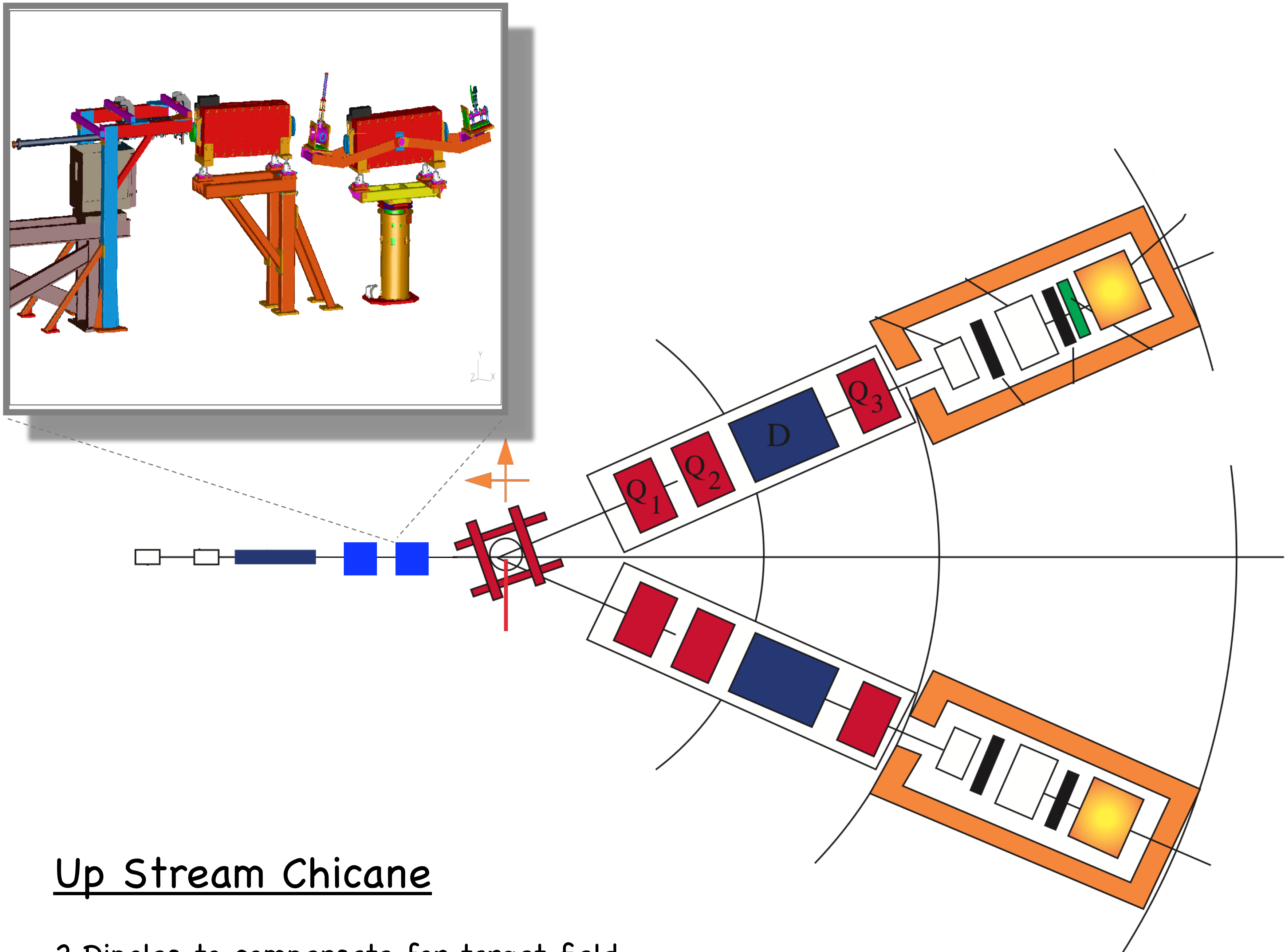
Third arm luminosity monitor for cross-check(not shown).

Compton will not be used.



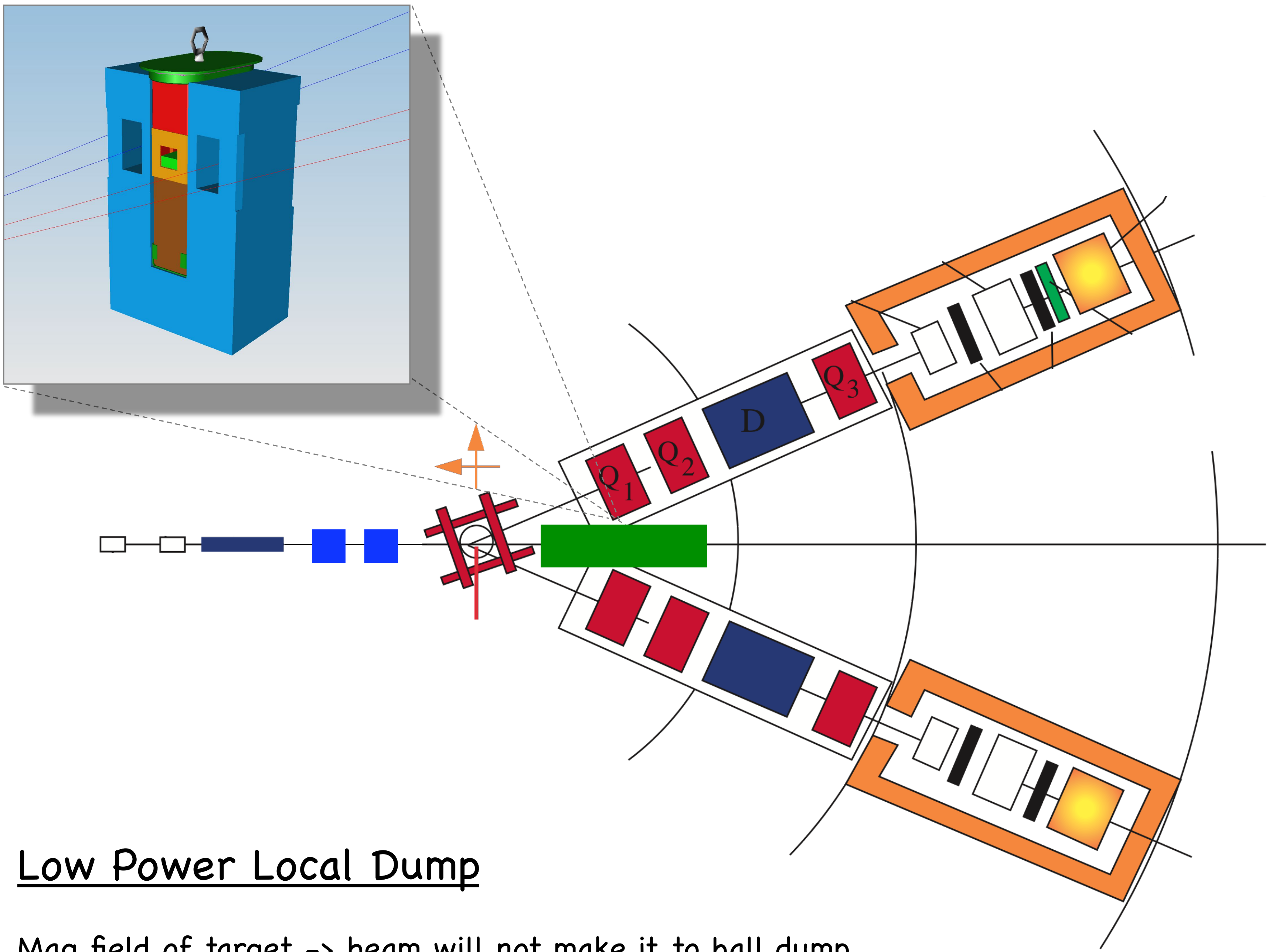
New Beam Diagnostics for low current

Slow raster for target



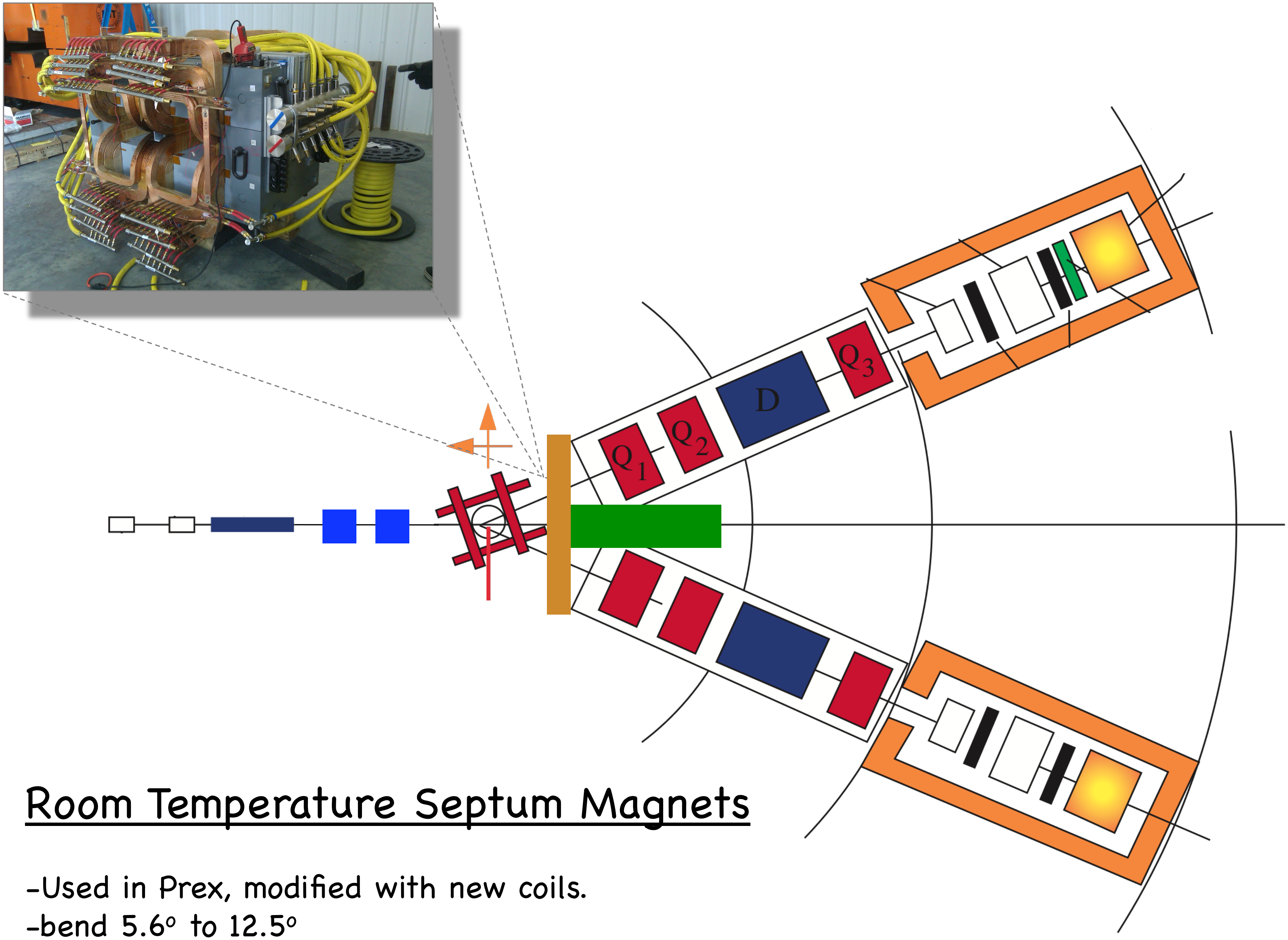
Up Stream Chicane

2 Dipoles to compensate for target field
Magnets on loan from Hall C



Low Power Local Dump

Mag field of target -> beam will not make it to hall dump



Room Temperature Septum Magnets

- -Used in Prex, modified with new coils.
- -bend 5.6° to 12.5°
- -allow access to lowest possible Q^2

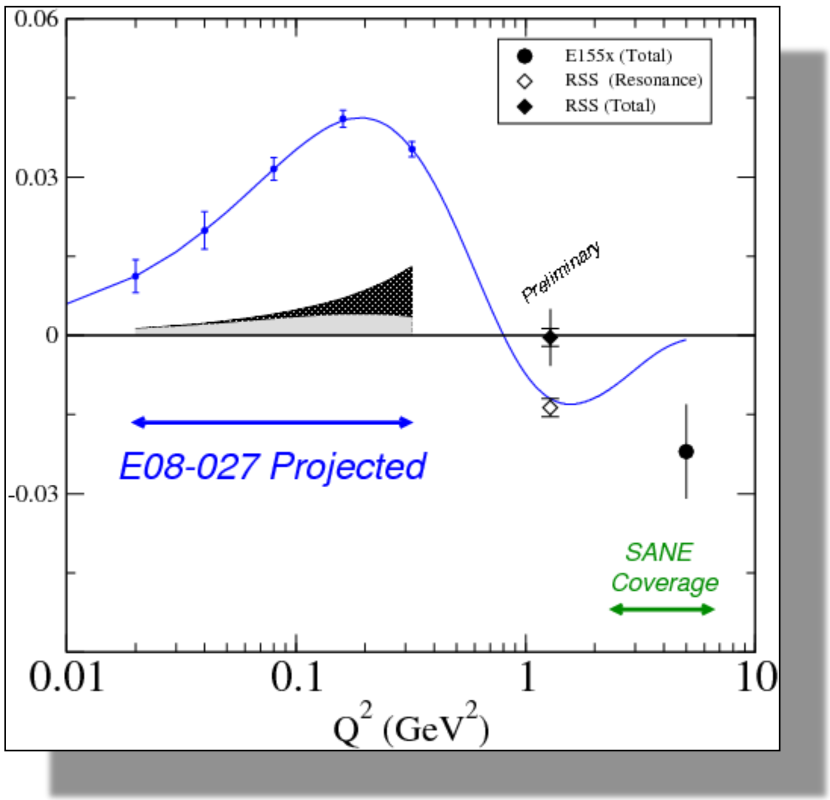
Systematic Error Budget

Source	(%)
Cross Section	5-7
$P_b P_T$	4-5
Radiative Corrections	3
Parallel Contribution	<1
Total	7-9

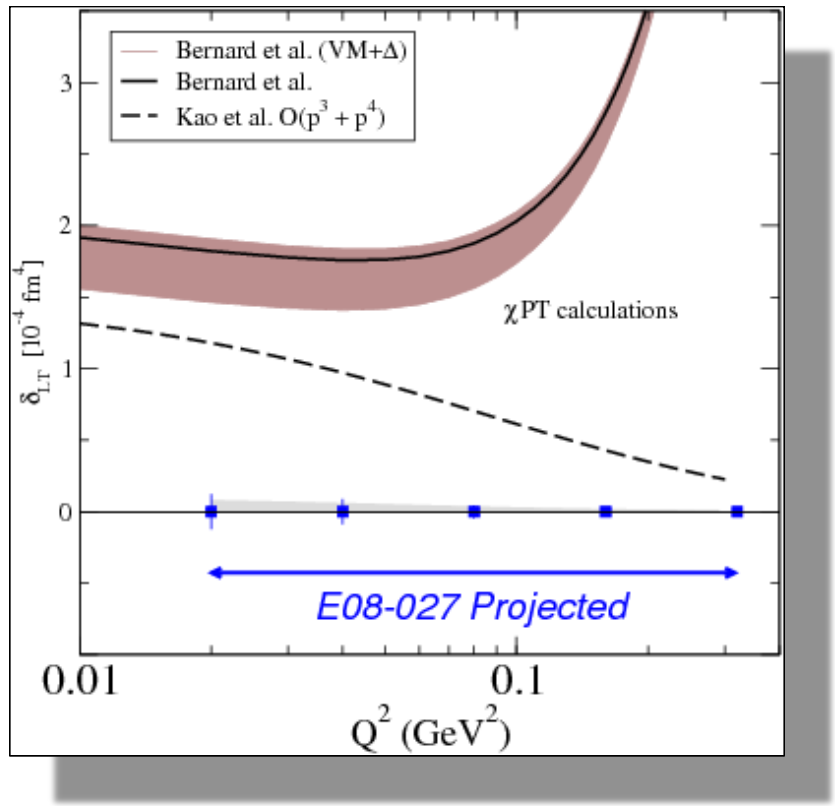
Statistical error to be equal or better at all kins

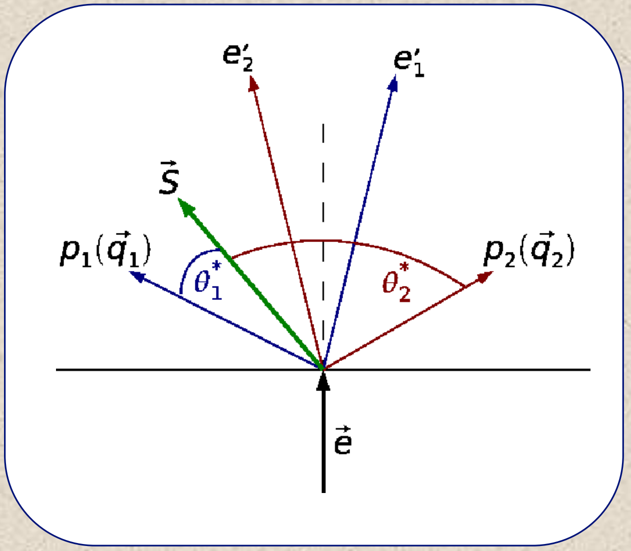
Projected Results

BC Sum Rule



Spin Polarizability δ_{LT}





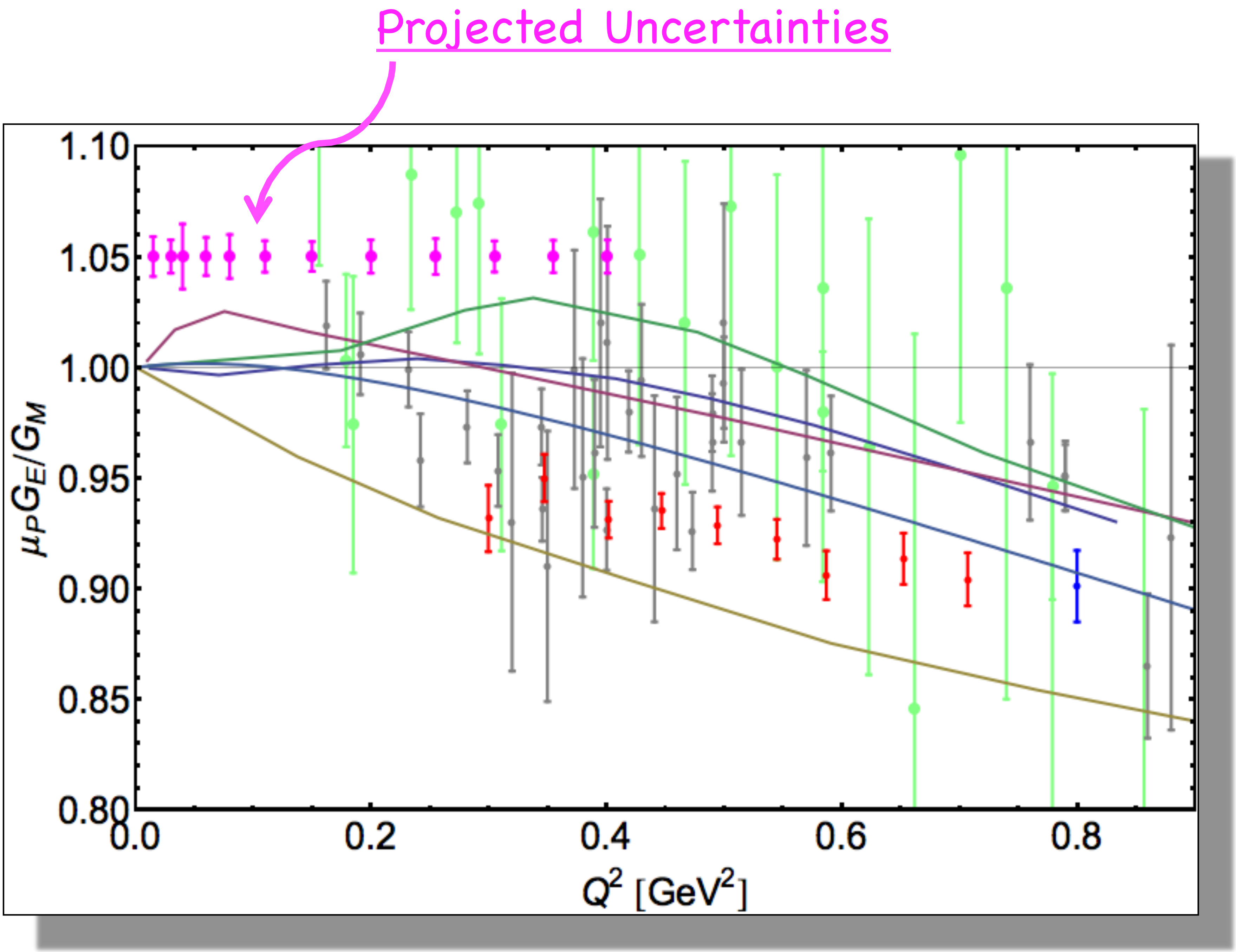
E08-007 : G_E/G_M

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

Measure asym in both HRS simultaneously

Form 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 Uncertainties
1.10
1.05
1.00
0.95
0.90
0.85
0.80
$\mu_P G_E/G_M$
0.0
0.2
0.4
0.6
0.8
Q^2 [GeV^2]

Summary

Assuming BC sum rule holds allows extraction of higher twist contribution in DIS

Data consistent across RSS, E01-012, E94010

g1 & g2 play significant role in bound state Q.E.D. calculations

E08-027 and E08-007 now being installed in Hall A for run beginning in the Fall

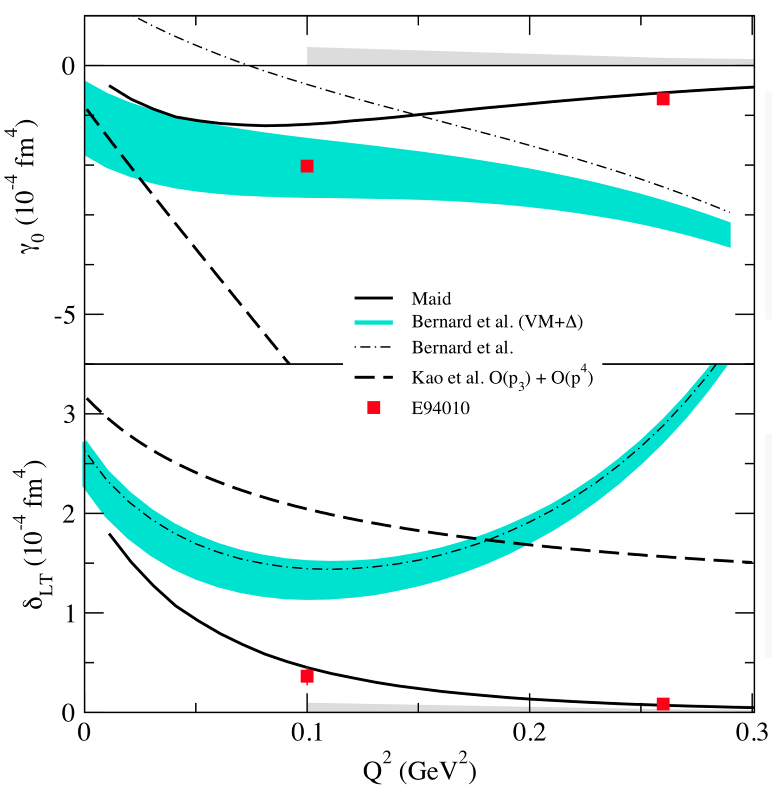
will provide definitive measurement of g_2 and G_E/G_M at low Q^2

Backup slides

NSTAR
ELECTRIC
GAS

Spin Polarizabilities

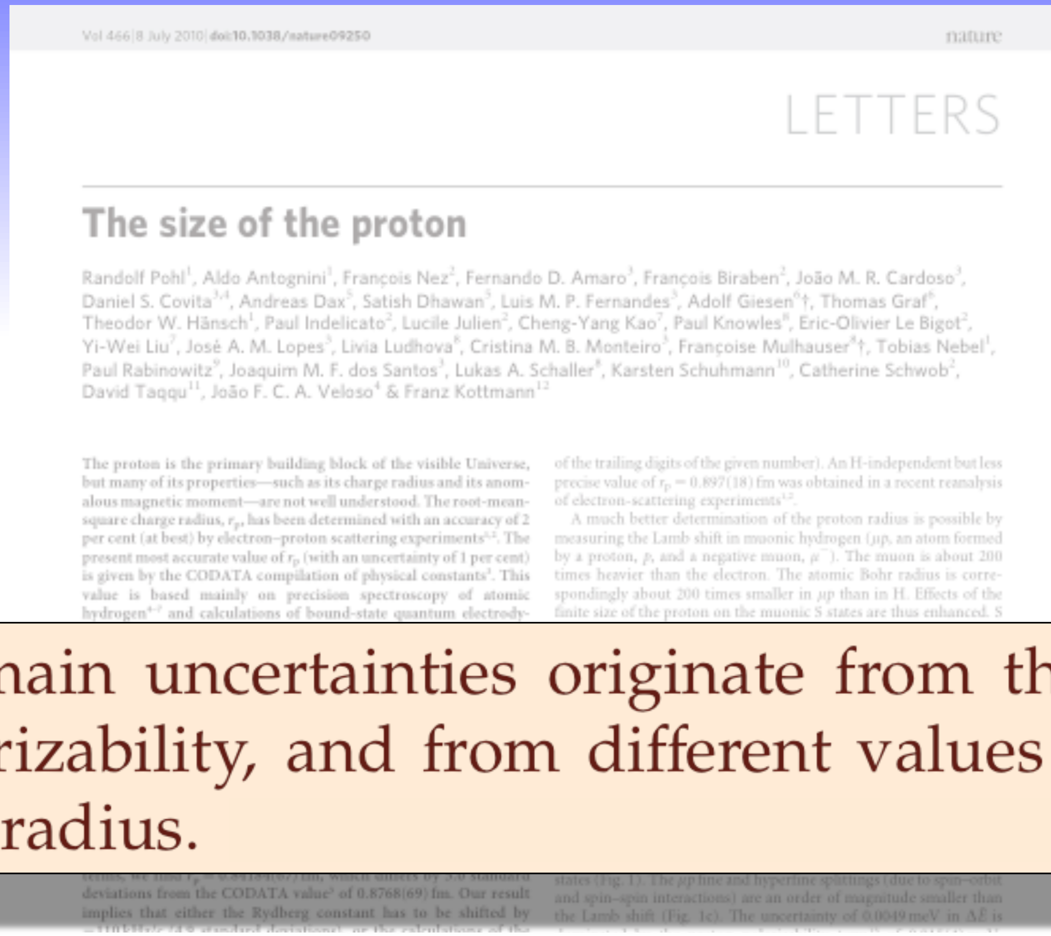
Major failure (>8σ) of χPT for neutron δ_{LT}. Need g_2 isospin separation to solve.



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

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

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


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

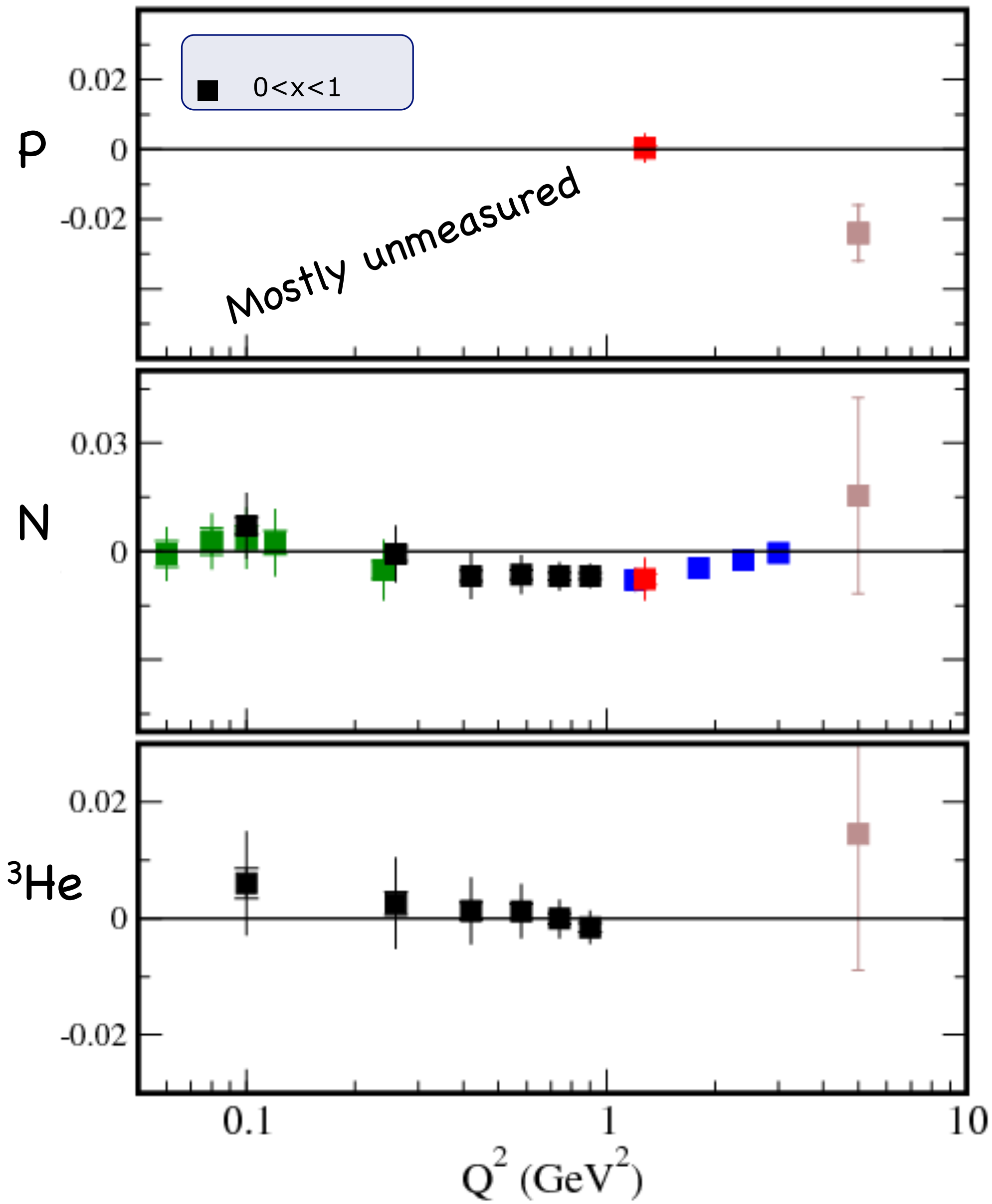
The main uncertainties originate from the proton polarizability, and from different values of the Zemach radius.

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

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

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

BC Sum Rule



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