SPIN ASYMMETRIES OF THE NUCLEON EXPERIMENT (SANE E-07-003) HMS INCLUSIVE ANALYSIS

FOR THE SANE COLLABORATION
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UNIVERSITY OF VIRGINIA

USERS' MEETING
JANUARY 14, 2012

OUTLINE

- Goal of **SANE-HMS**
- Experiment
- Analysis
- Status
- Summary

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WHAT WE GET WITH HMS DATA

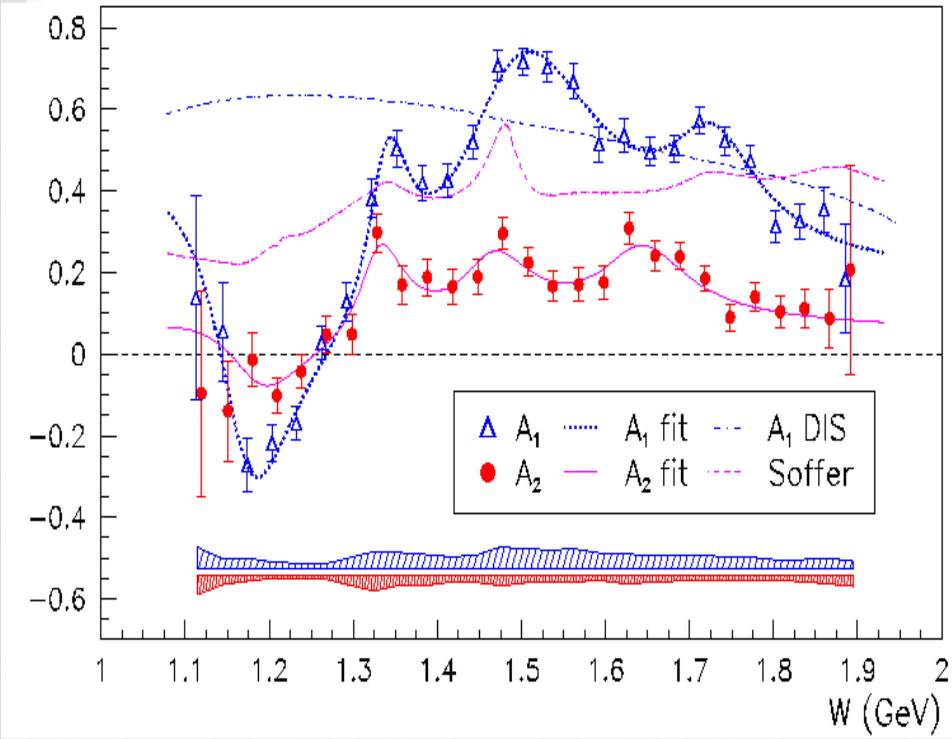
Of Course:

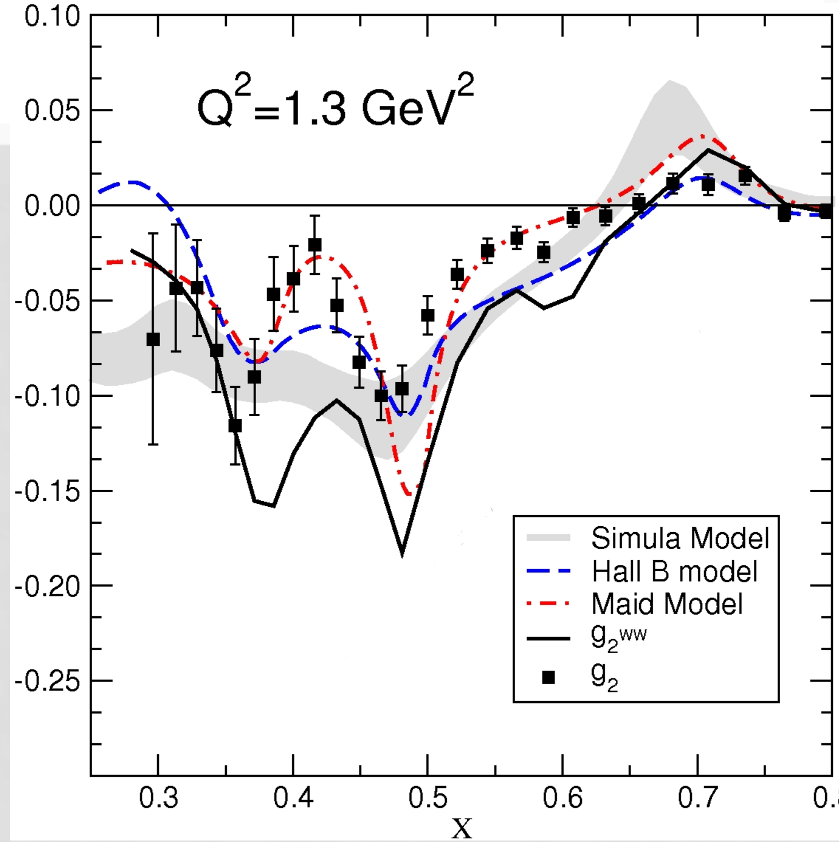
- C & C+He Yields for Packing Fractions; necessary for **SANE**.

Also:

- Inclusive Asymmetries; Q^2 of 0.8, 1.3, and 1.8 [GeV^2]
- Elastic Asymmetries (Single & Coincidence), at 80^0; Ratio of from-factors G_E^P/G_M^P (Anusha's Talk)

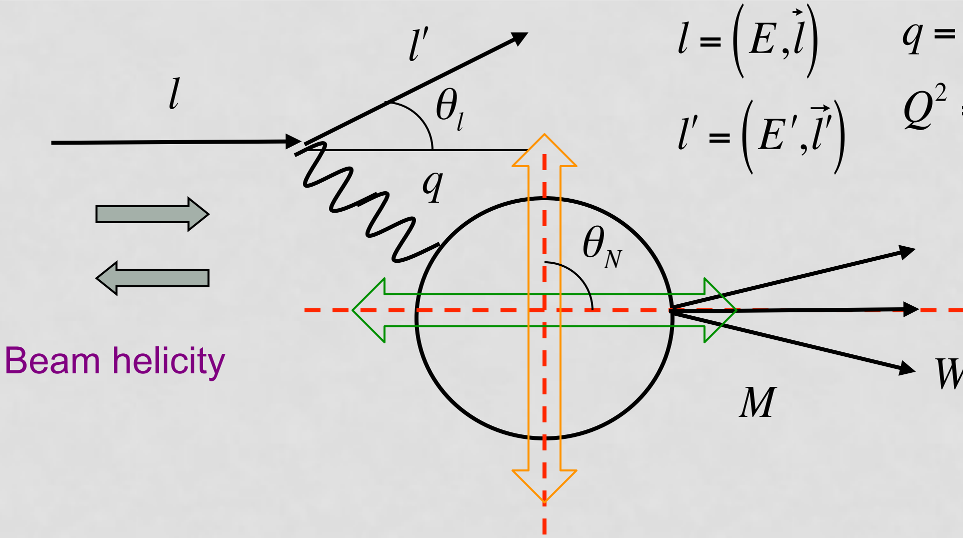
WHAT'S INTERESTING WITH SANE-HMS?





- Complementary to the previous Resonances Spin Structure (RSS) measurement.
- With the HMS, asymmetries were measured at Q^2 of 0.8, 1.3, and 1.8 [GeV^2].
- Q^2 = 0.8 & 1.3 taken to extend x range of RSS and allow better determination of the integral of g_2.
- The Q^2 = 1.8 data taken in the resonance region to study Q^2 dependence of A_1 and A_2

POLARIZED DIS



$l = (E, \vec{l})$

$l' = (E', \vec{l}')$

$q = l - l'$

$Q^2 = \vec{q}^{\,2} - \nu^2 = 2EE'(1 - \cos(\theta_{l'}))$

$x = \dfrac{Q^2}{2M\nu}$

$\nu = E - E'$

$y = \dfrac{\nu}{E}$

$W^2 = M^2 + 2M\nu - Q^2$

Longitudinal Target Polarization $\theta_N = 0$

Transverse Target Polarization $\theta_N = \pi/2$

Asymmetries in the scattering of polarized leptons on polarized nucleons most sensitive to spin structure functions g_1 and g_2

$$\frac{d^2\sigma^{\uparrow\Uparrow(\Downarrow)}}{d\Omega dE'} = \frac{d^2\sigma}{d\Omega dE'} - (+)\frac{2\alpha^2 E'}{Q^2 E}\left(\frac{E + E'\cos\theta}{M\nu} g_1(x,Q^2) - \frac{Q^2}{M\nu^2} g_2(x,Q^2)\right)$$

SPIN-STRUCTURE FUNCTIONS

- $g_1(x,Q^2)$ is sum of charge weighted helicities for each quark flavor $q^{+/-}(x,Q^2)$, in parton model

$$g_1(x,Q^2) = \frac{1}{2}\sum_i e_i^2\left[q_i^+(x,Q^2) - q_i^-(x,Q^2)\right]$$

- $g_2\,(x,Q^2)$ is more complex. Contains twist-2 part dependent on g_1 (g_2^{WW*}) and another on higher order terms

$$g_2(x,Q^2) = g_2^{WW}(x,Q^2) + \overline{g_2}(x,Q^2)$$

$$= -g_1(x',Q^2) + \int_x^1 g_1(x',Q^2)\frac{dx'}{x'} - \int_x^1 \frac{\partial}{\partial x'}\left[\frac{m}{M}h_T(x',Q^2) + \xi(x',Q^2)\right]\frac{dx'}{x'}$$

- h_T chiral-odd transversity term (twist-2), ξ involves quark-gluon correlations (twist-3).
- m (current) quark mass.

*Wandzura-Wilcek

OBTAINING QUANTITIES OF INTEREST

- Measured double-spin asymmetries

$$A_{\parallel} = A_{\perp} \cong \frac{1}{f P_B P_T} \frac{N^{\uparrow\downarrow} - N^{\downarrow\downarrow}}{N^{\uparrow\downarrow} + N^{\downarrow\downarrow}} + A_{RC}$$

f dilution factor: fraction of total rate from pol. nucleons

P_B Average Beam Polarization

P_T Average Target Polarization

A_{RC} Radiative Corrections (Proton only)

***For SANE:**

$$A_{\parallel} = A_{180}$$

$$A_{\perp} \cong A_{80}$$

- Calculate physics asymmetries using measured ones

$$A_1 = \frac{1}{D'(E+E')}\left(\left(E - E'\cos\theta\right)A_{180} - \frac{E'\sin\theta}{\cos\phi}A_{80}\,\frac{A_{180}\cos 80^0 + A_{80}}{\sin 80^0}\right)$$

$$A_2 = \frac{\sqrt{Q^2}}{2ED'}\left(A_{180} - \frac{E - E'\cos\theta}{E'\sin\theta\cos\phi}\,\frac{A_{180}\cos 80^0 + A_{80}}{\sin 80^0}\right)$$

$D'(R,E',\theta)$ Depolarizing Factor, $R = \sigma_L / \sigma_T$

- Obtain SSFs from A_1 & A_2 and unpolarized structure-function $F_1(x)$

$$g_1 = \frac{F_1}{1+\gamma^2}\left(A_1 + \gamma A_2\right) \qquad g_2 = \frac{F_1}{1+\gamma^2}\left(\frac{A_2}{\gamma} - A_1\right)$$

$$\gamma = \frac{2xM}{\sqrt{Q^2}}$$

F_1 from F1F209 model

P. Bosted, E. Christy arXiv:0712.3731

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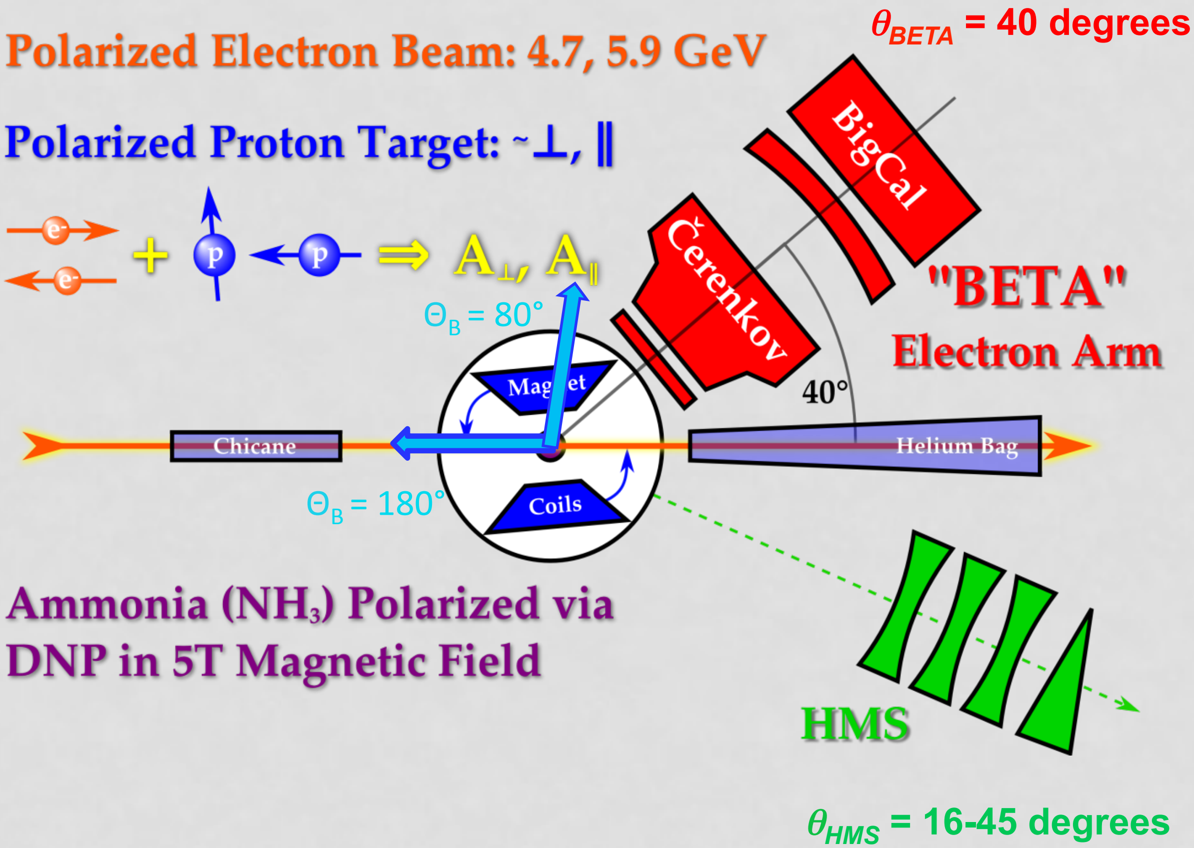
SANE SETUP AT JLAB



Target:
- UVa Polarized NH_3 target
- 5T Field

Beamline:
- Chicane
- He Bag (Miss. State Univ.)

Electron Arm:
- Tracker (Norfolk State ,Regina)
- Cerenkov (Temple)
- Lucite (NC A&T)
- BigCal (IHEP, Protvino, W&M, Lanzhou)

HMS:
- Hall-C Spectrometer
- Aux. Measurements
- Packing Fractions

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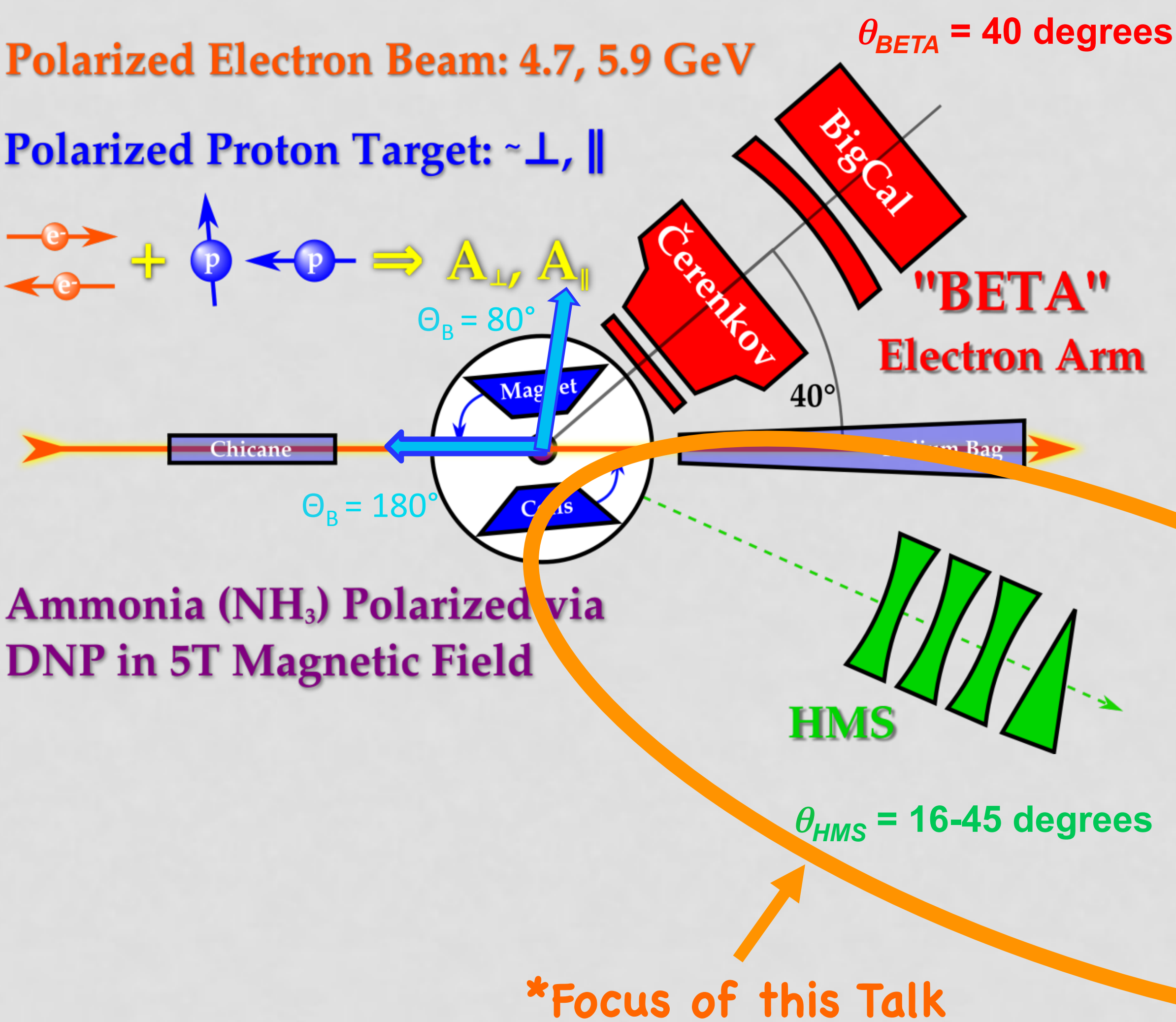

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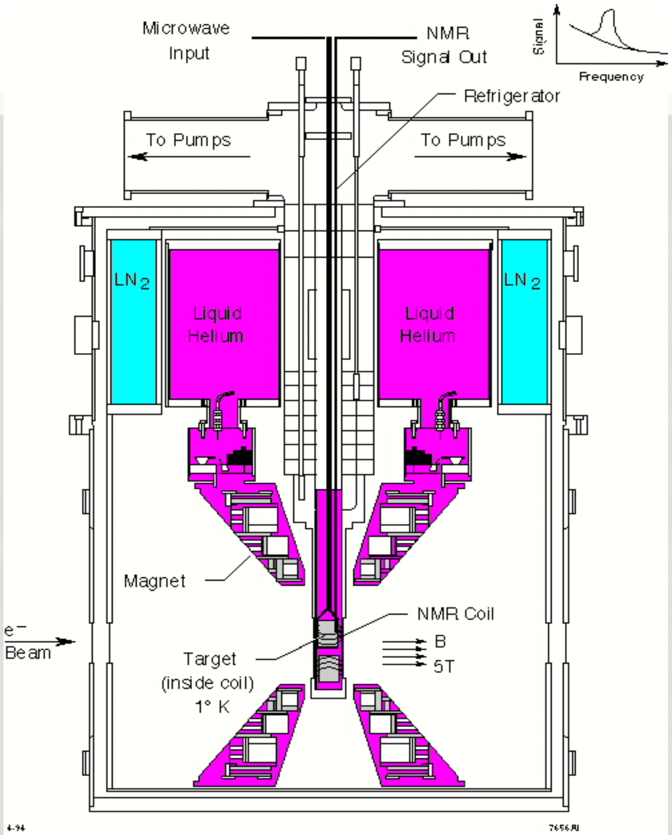
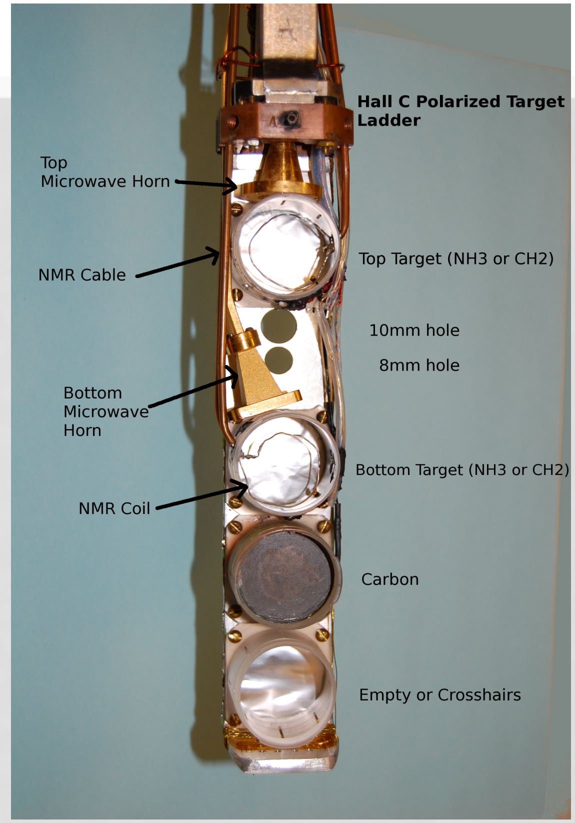
UVA TARGET





- Superconducting split Helmholtz pair magnet from Oxford Instruments. Produces 5 T field at 79 A.
- Polarizes via Dynamic Nuclear Polarization (DNP) with frequency 28 GHz/T at 5 T => 140 GHz.
- Polarization measured by NMR. Proton Larmor frequency 42.6 MHz/T in 5 T field => 213 MHz
- Used frozen solid NH_3 target, as well as C for Montecarlo calibration.

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RUN SUMMARY

- Data was taken Feb-March 2009 for 4.7 & 5.9 GeV with polarized beam and target in parallel and near-perpendicular fields.

Beam:

Energy/field	$<P_{beam}>$*	Proposed/FOM**
4.7 GeV Parallel	~66%	~39%
5.9 GeV Parallel	~88%	~35%
4.7 GeV Perp	~85%	~58%
5.9 GeV Perp	~71%	~62%

**$FOM=(P_{Targ}*P_{Beam})^2*I_{Beam}$

Target:

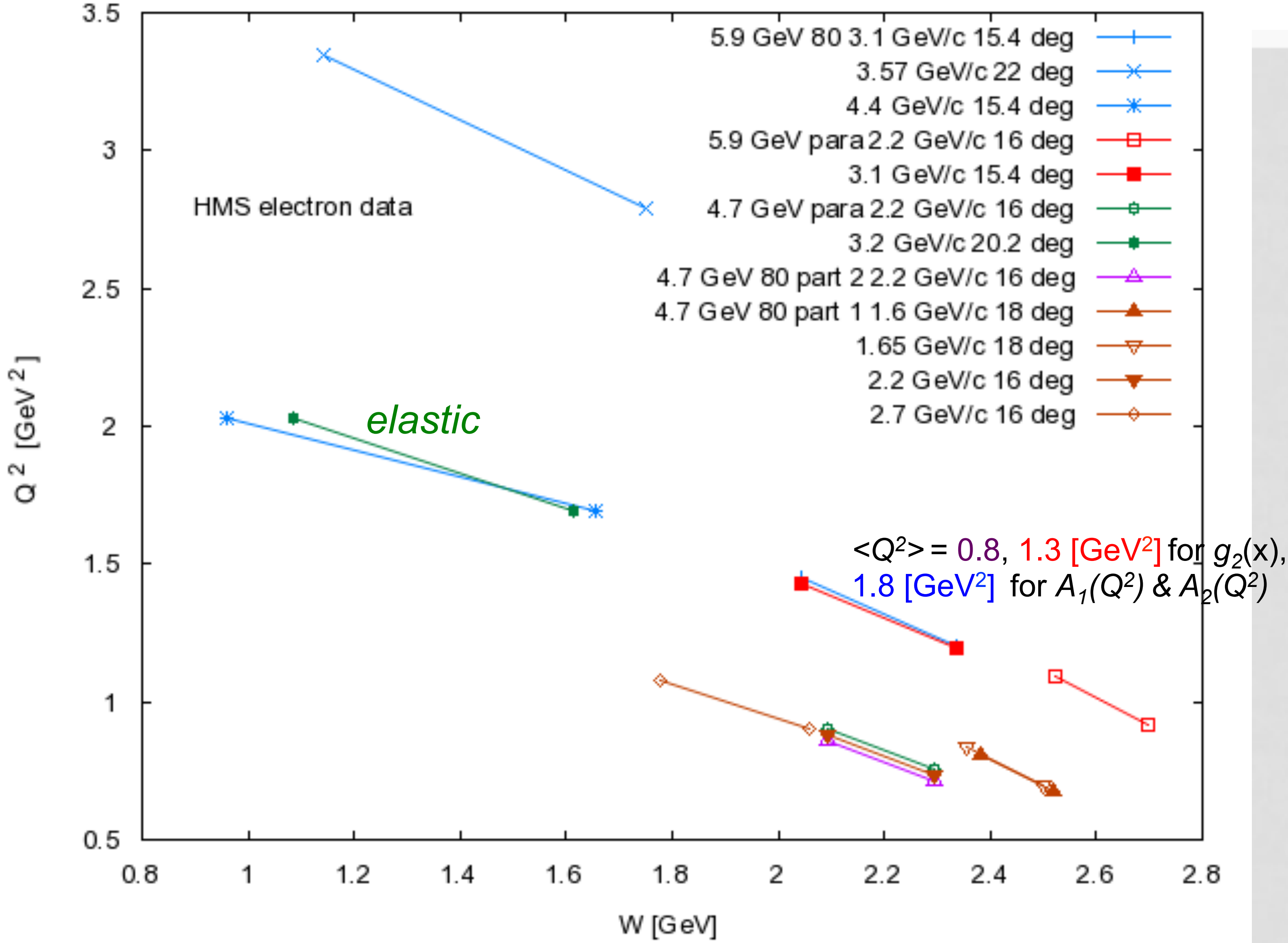
$<P_{Targ}> \sim 69\%$

(*) Measured by Moller polarimeter

(**) $FOM=(P_{targ}*P_{Beam})^2 * I_{Beam}$

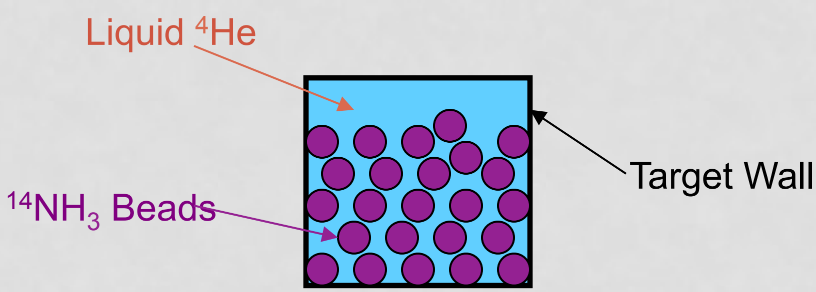
*Thanks to D. Gaskell

SANE-HMS DATA (PLOTTED)

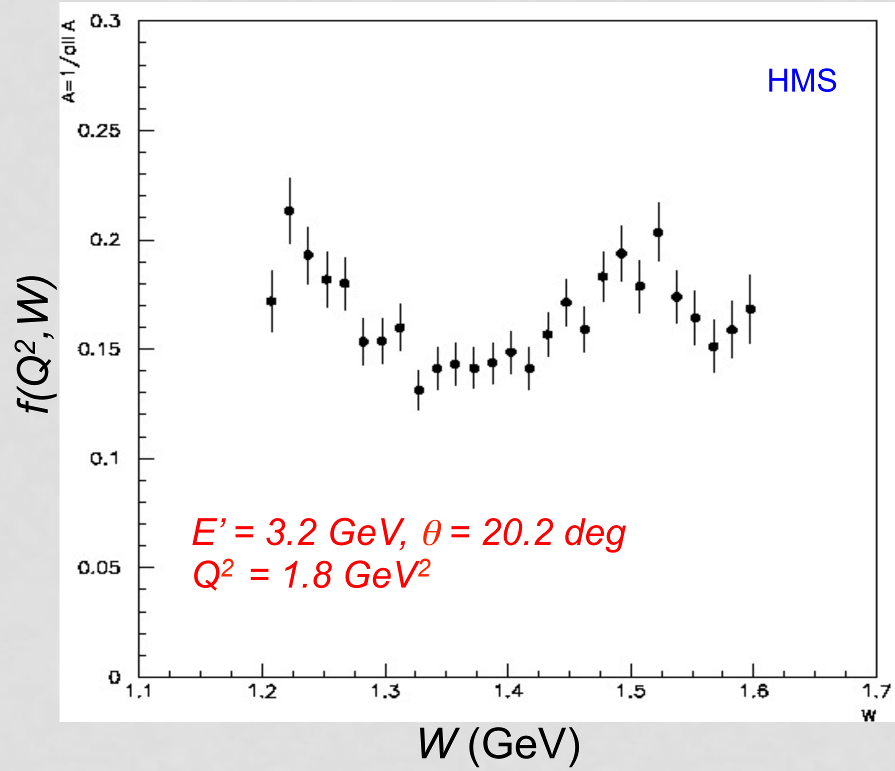


PACKING FRACTIONS AND DILUTION FACTORS

- Packing Fraction essentially amount of material in target cup. This is a number.
- Dilution Factor (f) ratio of rates of free polarizable nucleons (proton) to all nucleons composing the target sample (nitrogen, NMR coils, …). This is kinematics dependant.
- Need Packing Fraction and Dilution Factor for each target load used during running of experiment.



4.7 GeV Parallel Field



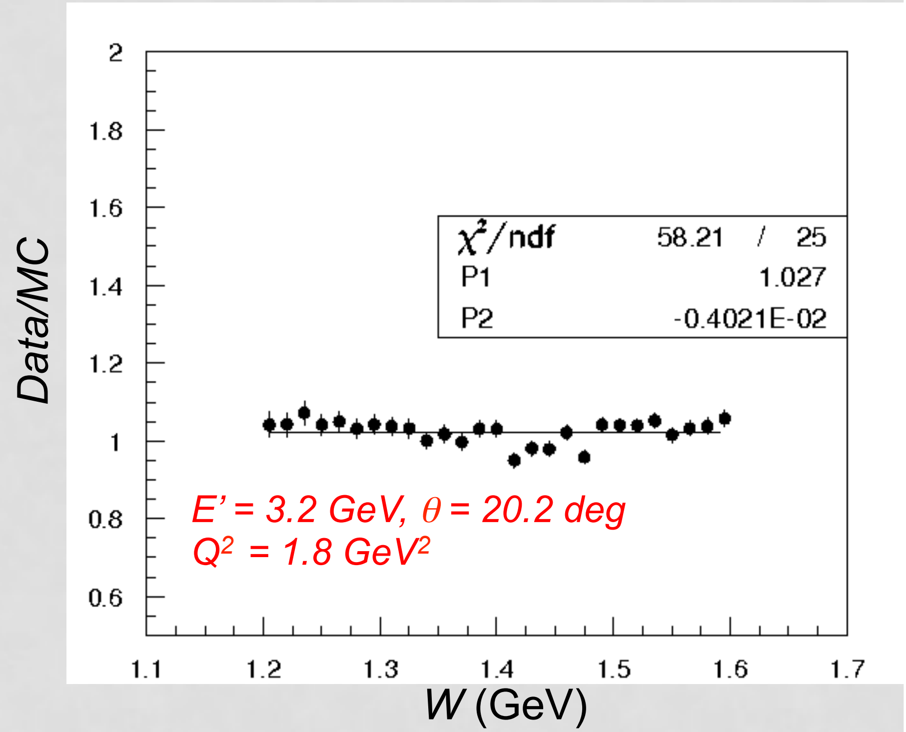
$$f\left(Q^2,W\right)=\frac{N_1\sigma_1\left(Q^2,W\right)}{N_1\sigma_1(Q^2,W)+N_4\sigma_4(Q^2,W)+N_{14}\sigma_{14}\left(Q^2,W\right)+\sum N_A\sigma_A\left(Q^2,W\right)}$$

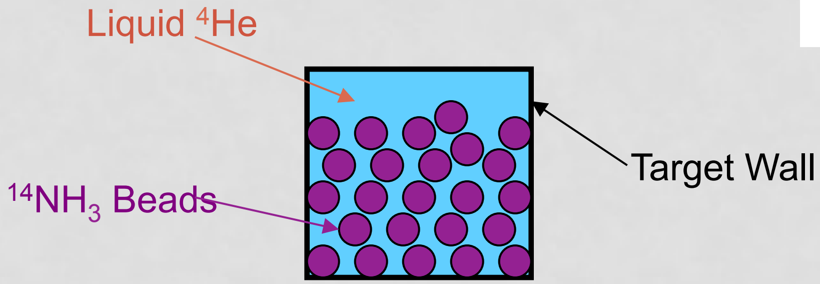
H. Kang

OBTAINING THE PACKING FRACTIONS

- Take ratio of data to Monte Carlo to get agreement (flat ratio).
- Utilize Carbon data.
- MC NH_3 at 50% & 60% pf's vs. data
- Determined via $Y_T = mpf + b$, $Y_T \sim 1$.
- Expecting *pf* ~ 0.55 +/- 0.02.
- F1F209 Cross-section model used.
- Mostly done!

4.7 GeV Parallel Field

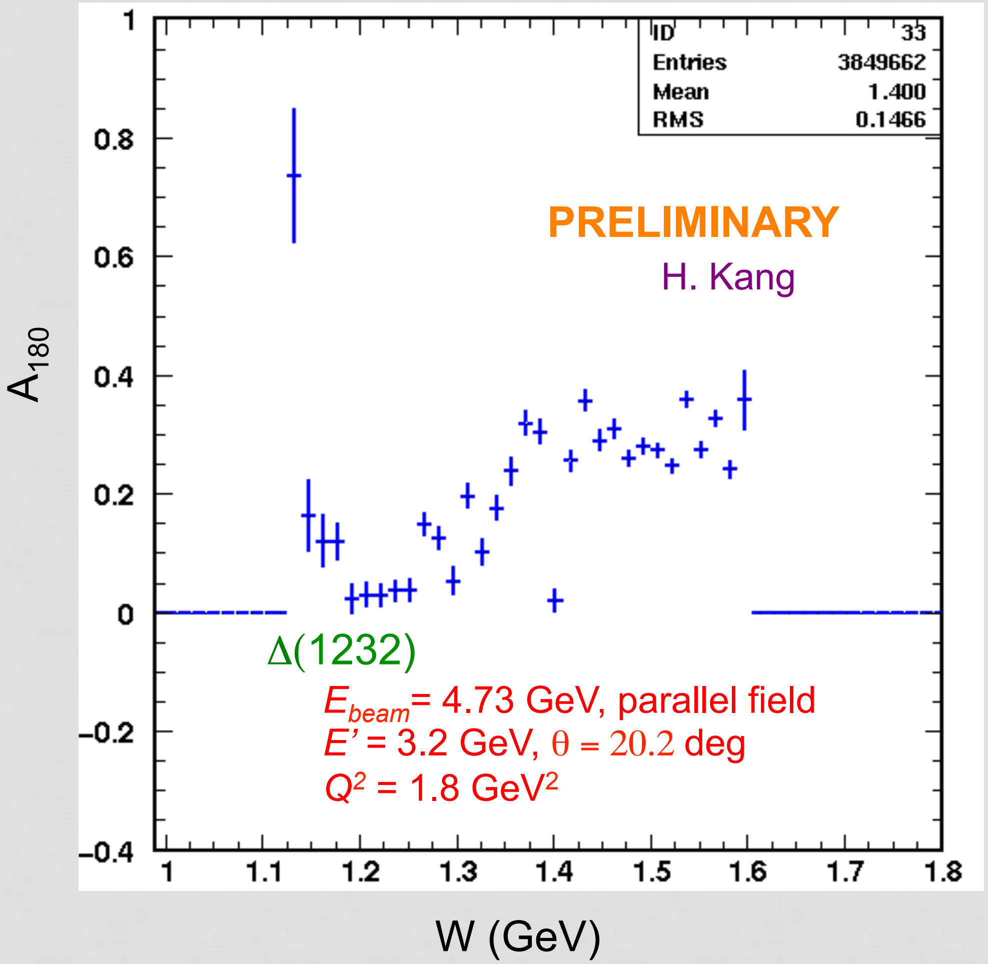




H. Kang

ASYMMETRIES: HMS

- A_{180} for a considerable portion of the parallel field data.
- Corrected for beam and target polarizations, dilution factors, and charge.
- Radiative corrections in progress.
- A_{80} in progress.
- Systematics to follow.

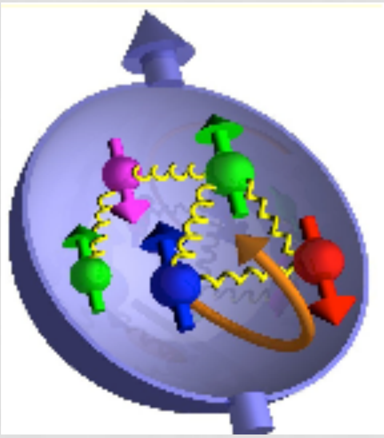


SUMMARY

- **SANE** measures double polarization inclusive scattering to obtain g_2, A_1, & A_2 .
- **HMS** data will provide interesting extension to previous results
- Data was taken Feb-March 2009 for 4.7 & 5.9 GeV with polarized beam and target in parallel and near-perpendicular fields
- Packing-fractions and dilutions factors well in progress.
- Have preliminary asymmetries.
- In process of applying corrections and obtaining systematics, to finalize.

"Polarization data has often been the graveyard of fashionable theories. If theorists had their way, they might just ban such measurements altogether out of self-protection."
- J. D. Bjorken (1987)

SUPPORT SLIDES

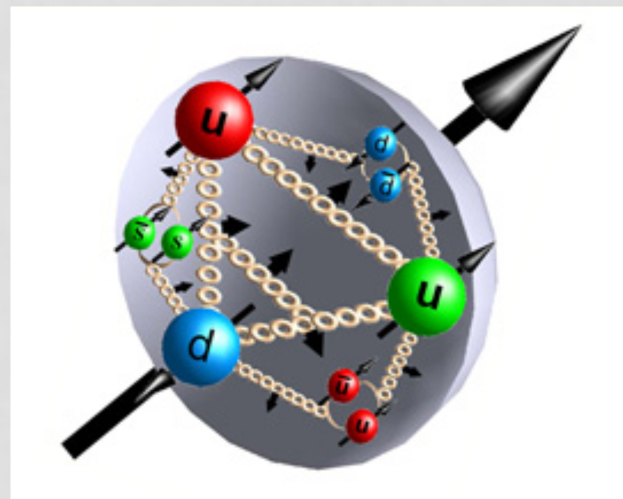


Motivation: Spin Structure

- The spin plays a paramount role in studies of fundamental symmetries, interactions, particle properties, and hadron structure.
- Similarly, spin physics provides decisive progress in the understanding of nuclear reaction dynamics and of the structures of hadron-nucleon many body systems.

Ellis-Jaffe Spin Sum Rule:

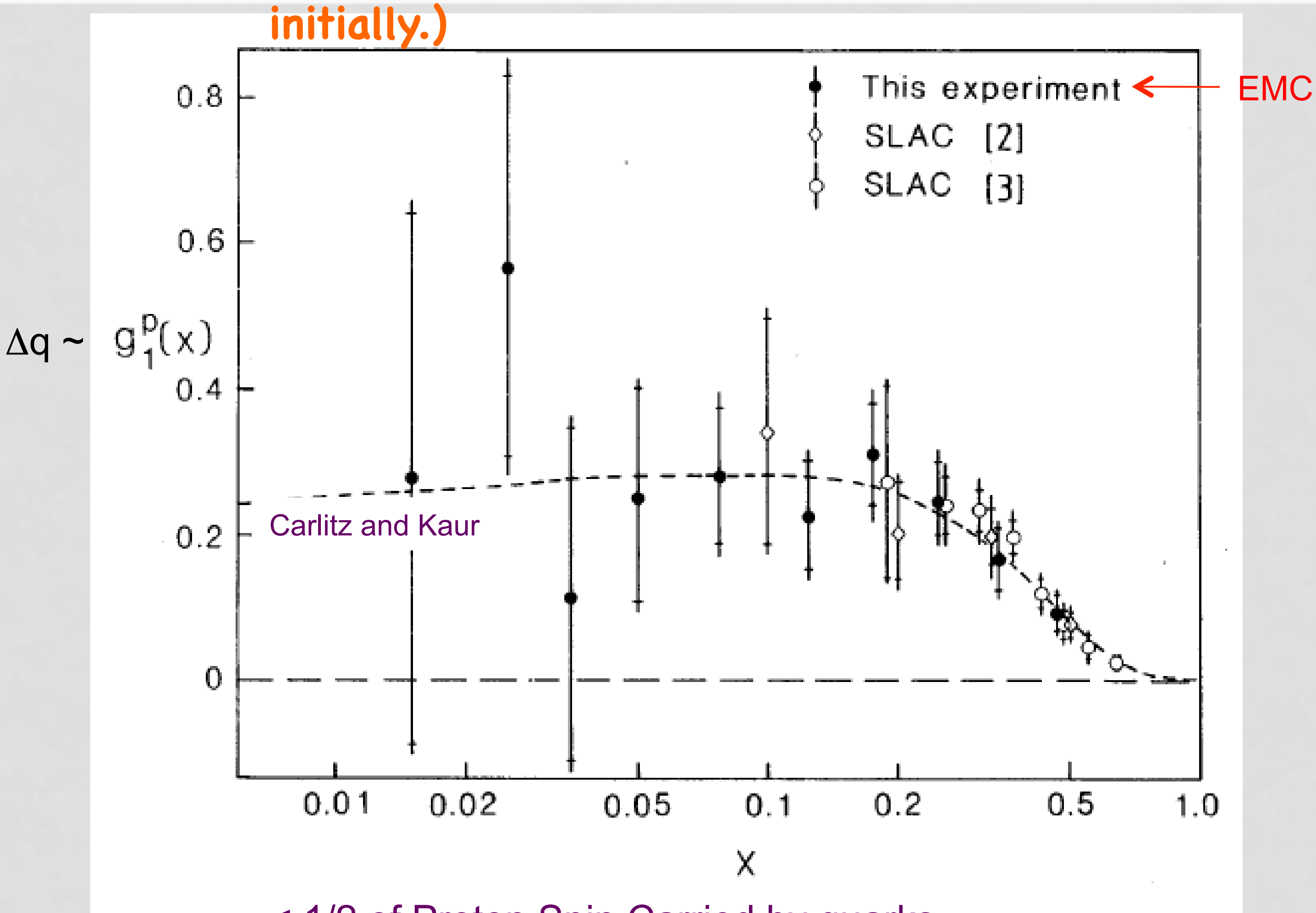
$$S_p = \frac{1}{2} = \frac{1}{2}\underbrace{\sum_q \Delta q}_{\Delta\Sigma} + \Delta G + L_q + L_G$$



(So, this is what we expect.)

Motivation: EMC, SLAC Results

(Instead, this is what we got, initially.)



< 1/2 of Proton Spin Carried by quarks

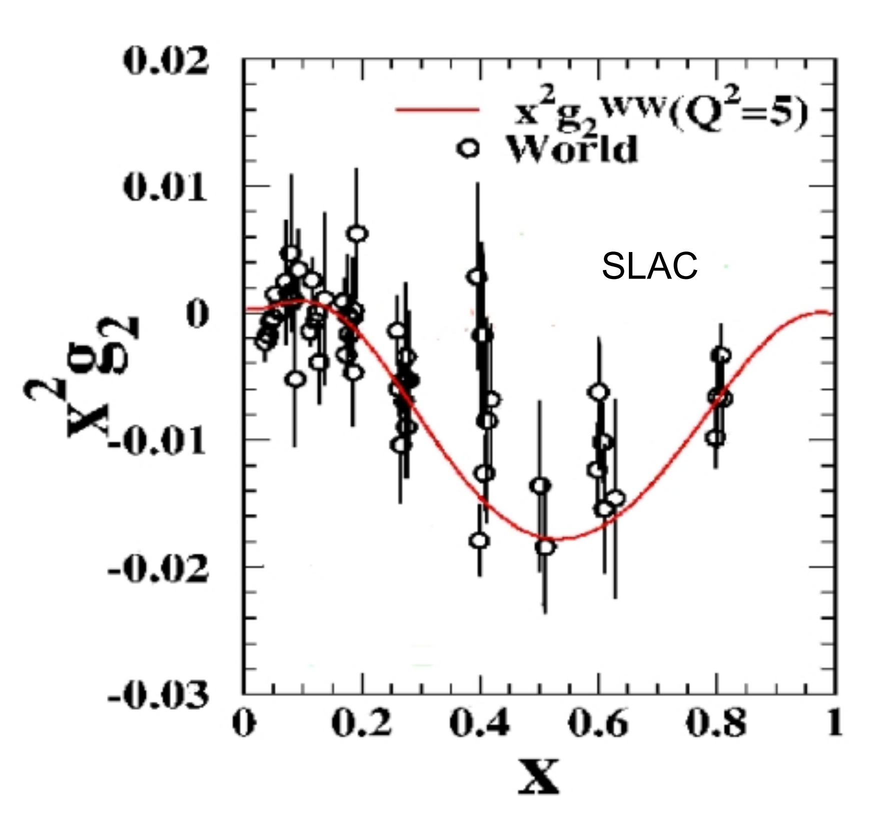
Motivation: "Spin Crisis"

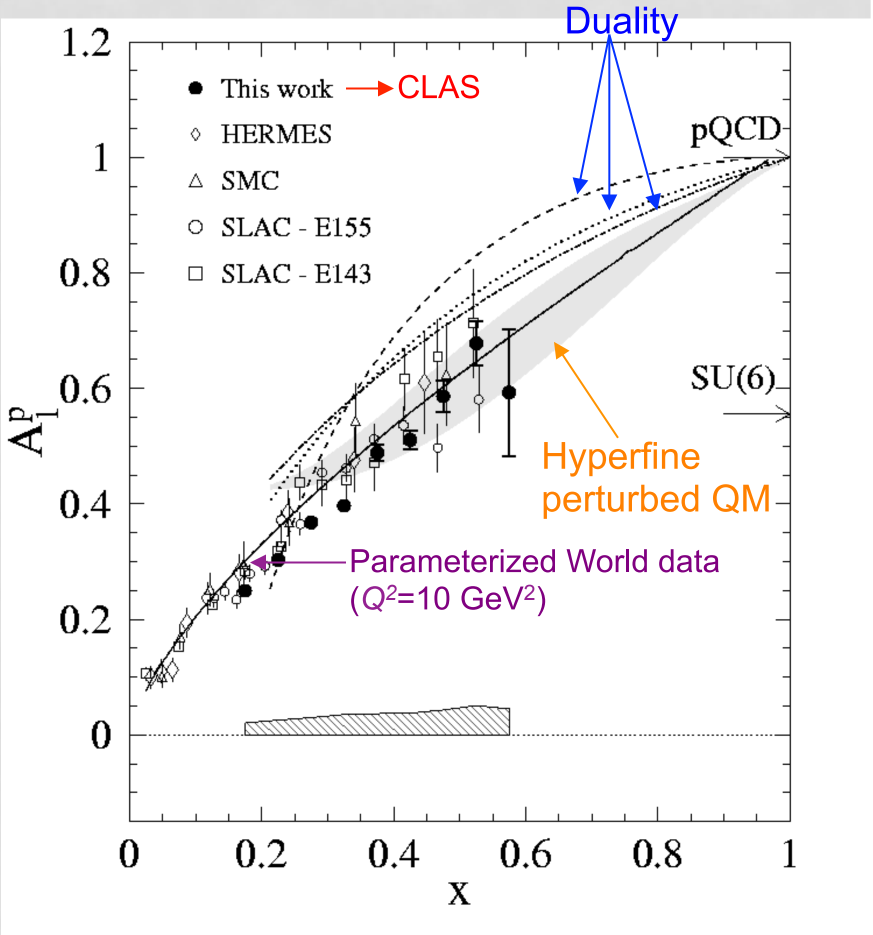
Need to explain 2 things:

- Why is $\Delta\Sigma$ so small (30% +/- 10%) ?
  - Suppression of valence quark spins?
  - Negatively polarized sea? In particular, $\Delta s < 0$?
- What else carries the spin of the proton?
  - Gluons?
  - Orbital angular momentum of quarks?

Motivation: World Data

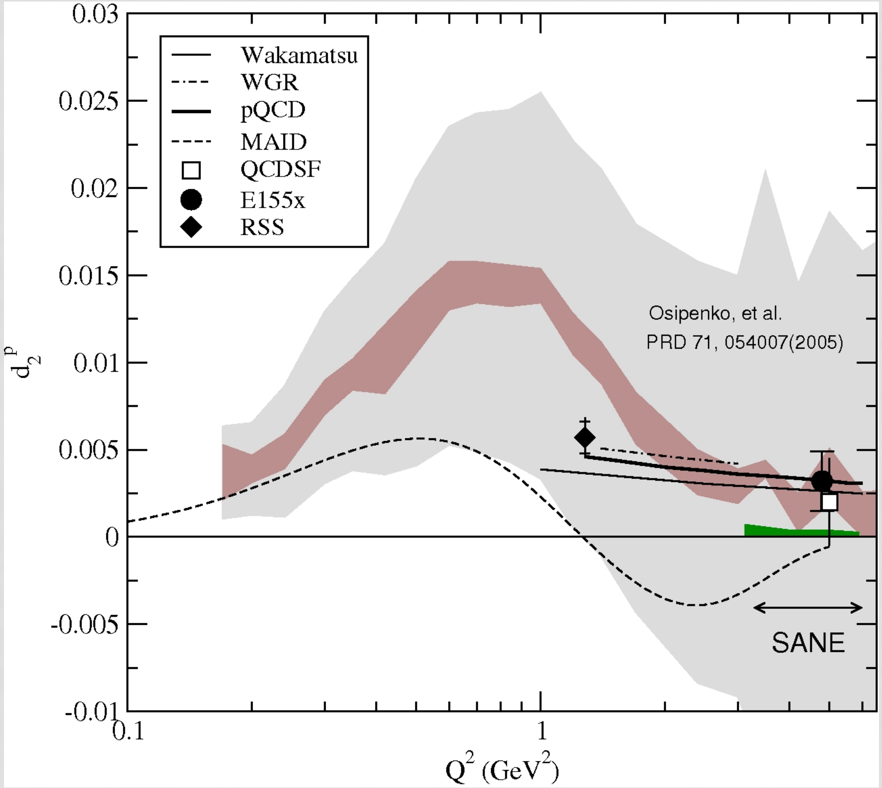
- Limited precision data for g_2^p
- Further constrain A_1^p data.
- Limited A_{perp} data.





Motivation: World Data (Cont'd)

- Little info on d_2^p
- Recent Data from RSS



SPIN-STRUCTURE SUM RULES

- OPE: moments of g_1 & g_2 related to twist-2 (a_N) and twist-3 (d_N) matrix elements

$$\int_0^1 x^N g_1(x,Q^2)dx = \frac{1}{2}a_N + O(M^2/Q^2), \quad N = 0,2,4,...$$

$$\int_0^1 x^N g_2(x,Q^2)dx = \frac{N}{2(N+1)}(d_N - a_N) + (M^2/Q^2), \quad N = 2,4,...$$

- d_N measure twist-3 contributions ($m << M$, h_T not very large)

$$d_N(Q^2) = \frac{2\left(N+1\right)}{N}\int_0^1 x^N \overline{g}_2(x,Q^2)\,dx$$

- Burkhardt-Cottingham (Expected to be valid for all Q^2) $\int_0^1 g_2(x,Q^2)dx = 0$

- Efremov-Leader-Teryaev (Valid in valence region) $\int_0^1 x\left(g_1(x) + 2g_2(x)\right)dx = 0$

SIMPLE QUARK MODEL

- SU(6)-symmetric wave function of the proton in the quark model:

$$|p\uparrow\rangle = \frac{1}{\sqrt{18}}\left(3u\uparrow[ud]_{S=0} + u\uparrow[ud]_{S=1} - \sqrt{2}u\downarrow[ud]_{S=1} - \sqrt{2}d\uparrow[uu]_{S=1} - 2d\downarrow[uu]_{S=1}\right)$$

- In this model: d/u = 1/2, Δu/u = 2/3, Δd/d = -1/3 for all x ⇒

$$\sum_q \Delta q = 1 \quad \Rightarrow \quad S_p = \frac{1}{2}\sum_q \Delta q = \frac{1}{2}\Delta\Sigma; \quad g_A{}^{(3)} = \Delta u - \Delta d = 5/3; \quad g_A{}^{(8)} = \Delta u + \Delta d - 2\Delta s = 1$$

- Relativistic Correction: lower component reduces axial charge, adds to orbital angular momentum (p-wave) ⇒

$$\sum_q \Delta q = \Delta\Sigma \approx 60\%; \quad g_A{}^{(3)} = \Delta u - \Delta d \approx 1.26; \quad g_A{}^{(8)} = \Delta u + \Delta d - 2\Delta s \approx 0.6$$

QUARK MODEL

- SU(6)-symmetric wave function of the proton in the quark model:

$$|p\uparrow\rangle = \frac{1}{\sqrt{18}}\left(3u\uparrow[ud]_{S=0} + u\uparrow[ud]_{S=1} - \sqrt{2}u\downarrow[ud]_{S=1} - \sqrt{2}d\uparrow[uu]_{S=1} - 2d\downarrow[uu]_{S=1}\right)$$

- In this model: d/u = 1/2, Δu/u = 2/3, Δd/d = -1/3 for all x
  => A_{1p} = 5/9, A_{1n} = 0, A_{1D} = 1/3 *)

- Hyperfine structure effect: S=1 suppressed => d/u = 0, Δu/u = 1, Δd/d = -1/3
  for x -> 1 => A_{1p} = 1, A_{1n} = 1, A_{1D} = 1

- pQCD: helicity conservation (q↑↑p) => d/u =2/(9+1) = 1/5, Δu/u = 1, Δd/d = 1
  for x -> 1

- Wave function of the neutron via isospin rotation:
  replace u -> d and d -> u => using experiments with protons and neutrons one can extract information on u, d, Δu and Δd in the valence quark region.

*) $$A_{1p} = \frac{4/9\cdot u\cdot \Delta u/u + 1/9\cdot d\cdot \Delta d/d}{4/9\cdot u + 1/9\cdot d} = \frac{4\cdot \Delta u/u + (d/u)\cdot \Delta d/d}{4 + (d/u)}$$

OBTAINING QUANTITIES OF INTEREST

$$A_{80} \sim [(\cos(\theta_0)\cos(80) + \sin(80)\sin(\theta_0)\cos(\phi))E' + \cos(80)E]M_p G_1 + 2[\cos(\theta_0)\cos(80) - \cos(80) + \sin(80)\sin(\theta_0)\cos(\phi)]E'EG_2$$

$$A_{180} \sim ((\cos(\theta_0)E' + E)M_p G_1 - Q^2 G_2)$$

Solve for $\frac{M_p \cdot G_1}{W_1}, \frac{G_2}{W_1}$ which can be used to extract A_1 and A_2

$$A_1 = \nu \cdot \frac{M_p \cdot G_1}{W_1} - Q^2 \cdot \frac{G_2}{W_1} \qquad g_1 = \frac{(E - E')}{M_p} G_1$$

$$A_2 = \sqrt{Q^2}\left(\frac{M_p \cdot G_1}{W_1} + \nu \cdot \frac{G_2}{W_1}\right) \qquad g_2 = \frac{(E - E')^2}{M_p^2} G_2$$

A_1 and A_2 are obtained in model independent way using experimental asymmetries only

M. Anselmino, A. Efremov, E. Leader arXiv:9501369

PHYSICS ASYMMETRY A_1

- **SU(6)**

$$A_1^p = \frac{5}{9}, \quad A_1^n = 0$$

- **Hyperfine perturbed QM**
  - makes S=1 pairs more energetic than S=0 pairs
  - At large x struck quark carry the spin of the nucleon

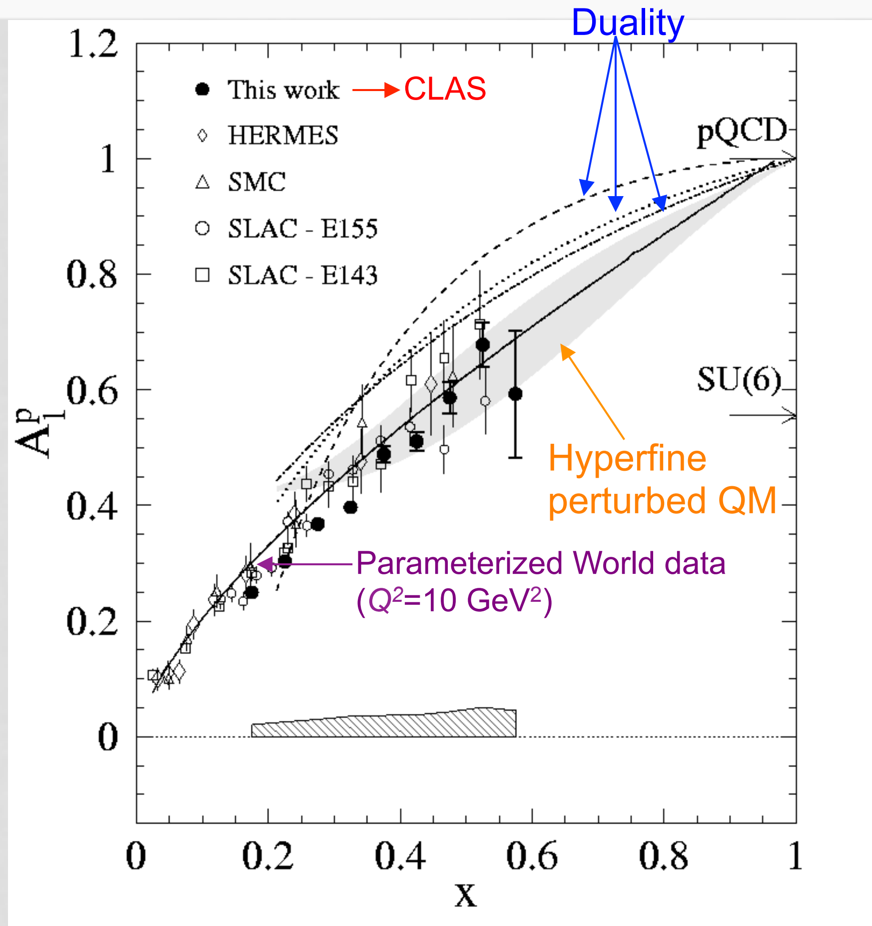
N. Isgur, Phys. Rev. D 59, 34013

- **Duality**
  suppress transitions to specific resonances in the final state

$$\gamma^* + N \to N^*$$

states in 56^+ and 70^-

F. Close and W. Melnitchouk Phys. Rev. C 68, 035210



SANE-HMS DATA

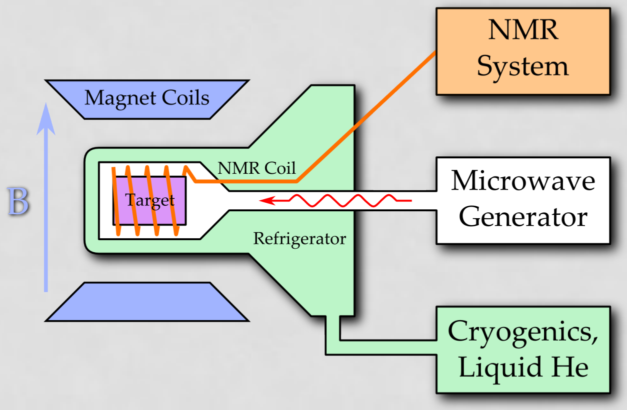
HMS data

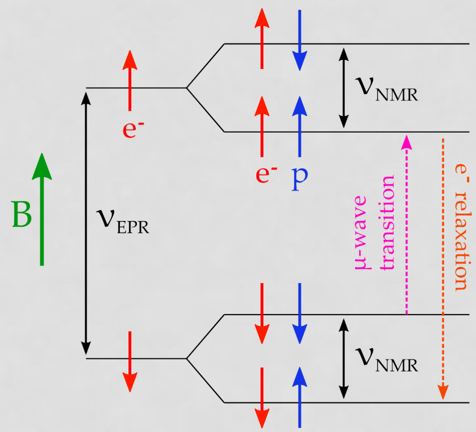
Setting	Runs	HMS_p	HMS_theta	Q2	W	Wmin	Wmax
5.9 80	87	3.1	15.4	1.313	2.196	2.044	2.337
	5	3.57	22	3.067	1.478	1.143	1.751
	173	4.17	22	3.583	0.738	→ elastic	1.253
	16	4.4	15.4	1.864	1.353	0.959	1.656
5.9 para	16	2.2	16	1.006	2.611	2.521	2.698
	31	3.1	15.4	1.313	2.196	2.044	2.337
4.7 para	17	2.2	16	0.806	2.196	2.092	2.295
	45	3.2	20.2	1.862	1.375	1.087	1.612
4.7 80 part 2	16	2.2	16	0.806	2.196	2.092	2.295
	39	3.585	22.3	2.536	0.702	→ elastic	1.152
4.7 80 part 1	6	1.6	18	0.741	2.452	2.383	2.52
	1	1.65	18	0.764	2.428	2.356	2.499
	94	2.2	16	0.806	2.196	2.092	2.295
	52	2.7	16	0.989	1.924	1.776	2.06

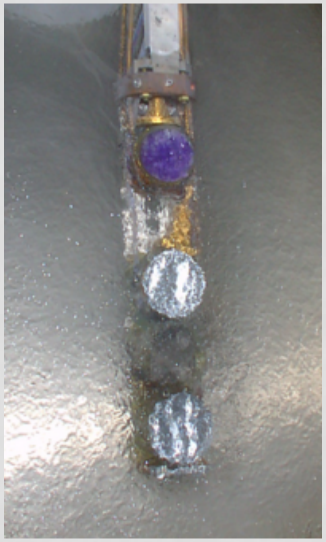
$\langle Q^2 \rangle$ = 0.8, 1.3 [GeV^2] for $g_2(x)$, 1.8 [GeV^2] for $A_1(Q^2)$ & $A_2(Q^2)$

Data with W_{min} = *elastic* for A_{el}

UVA TARGET

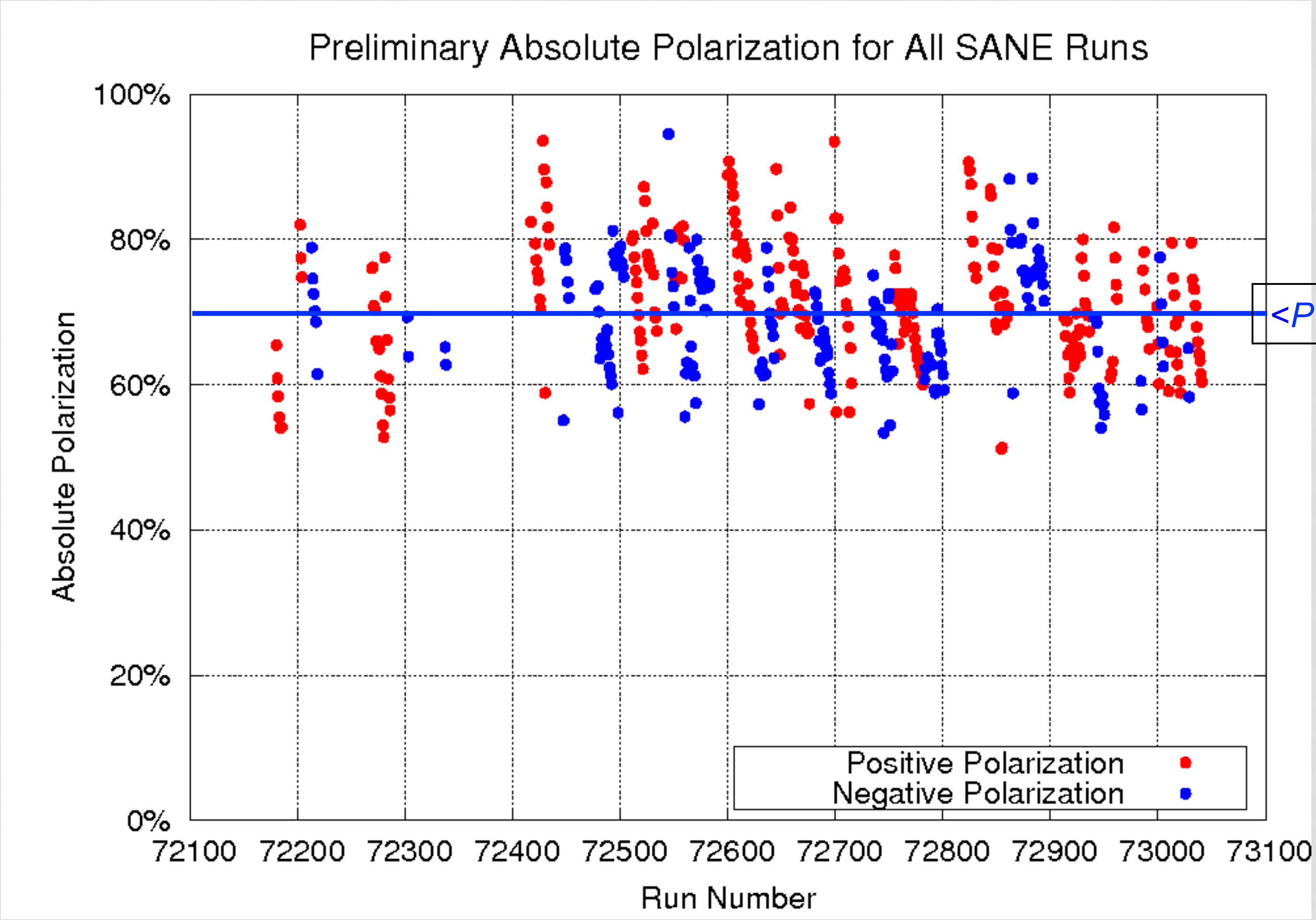






- Operates via dynamic nuclear polarization (DNP), which leverages hyperfine splitting of electron-proton pairs in a strong magnetic field (~5T) at very low temperatures (~1K).
- Using microwaves of specific frequency, spin flips are induced to transfer the high polarization of the electrons in to the protons.
- “Proton” target ammonia ($^{14}NH_3$) doped with paramagnetic centers via irradiation.
- Split Helmholtz pair, which allows target polarization axis to be oriented both parallel and perpendicular to the beam.

TARGET PERFORMANCE



$<P_T> \sim 69\%$

J. Maxwell

DYNAMIC NUCLEAR POLARIZATION

- Employs paramagnetic radicals, which provide electron-proton hyperfine splitting in a high magnetic field at moderate-low temperature
- Microwaves drive “forbidden transitions” to propagate polarization.

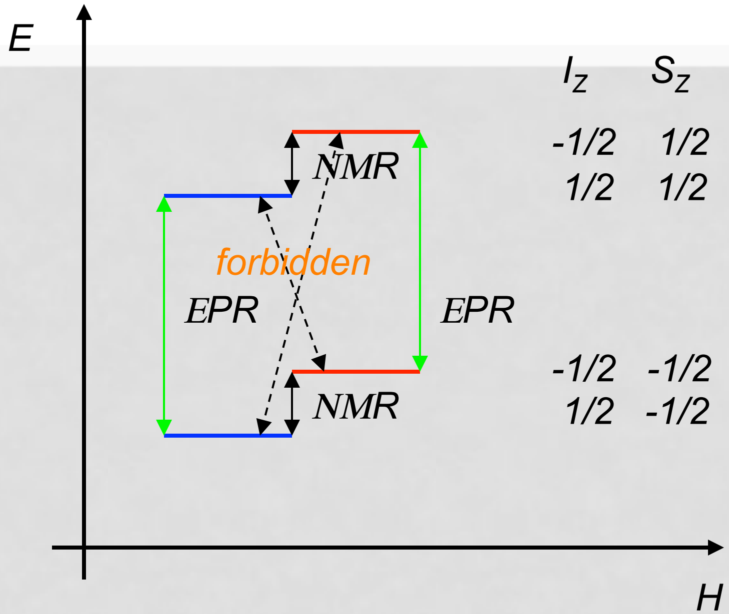
- Refrigerator 0.25-1.0 K
- Magnetic Field 2-6 T
- Microwaves 55-165 GHz
- NMR

Polarization

Protons: 70-100%

Deuterons: 20-50%

FORBIDDEN TRANSITIONS



The desired transitions -- <-> ++ and -+ <-> +- are forbidden.

Using the fact that the dipole-dipole interaction exists:

2 distant magnetic moments => dipole-dipole interaction << Zeeman splitting

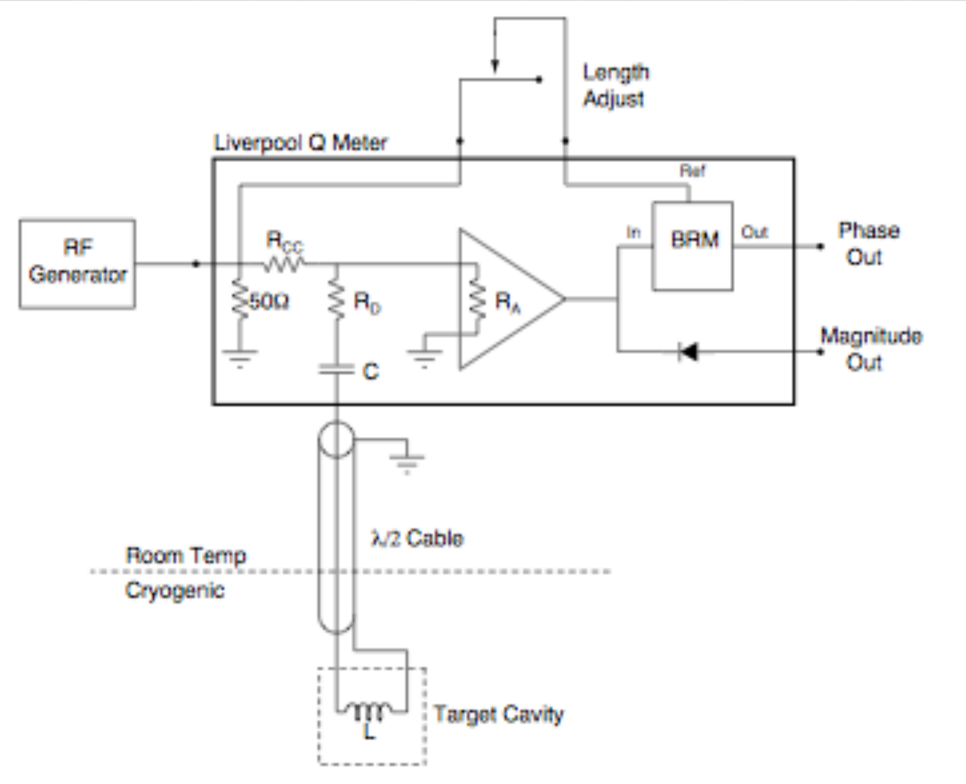
This results in a mixing of nuclear states, allowing for the desired interactions, though with a much less probability than those allowed (10^{-4}).

MEASUREMENT OF POLARIZATION

A Q-meter is connected in series to the NMR coil with inductance L_C and resistance r_C, which is imbedded in the target sampling. The impedance Z_C of this circuit is written

$$Z_C = r_C + i\omega L_C\left(1 + 4\pi\eta\chi(\omega)\right)$$

where η is the filling factor of the coil.



Q-METER

Piece of equipment used in testing of rf circuits.

Measures Q "Quality-factor" of a circuit, or how much how much energy is dissipated per cycle in a non-ideal reactive circuit.

$$Q = 2\pi \times \frac{Peak\ Energy\ Stored}{Energy\ dissipated\ per\ cycle}$$

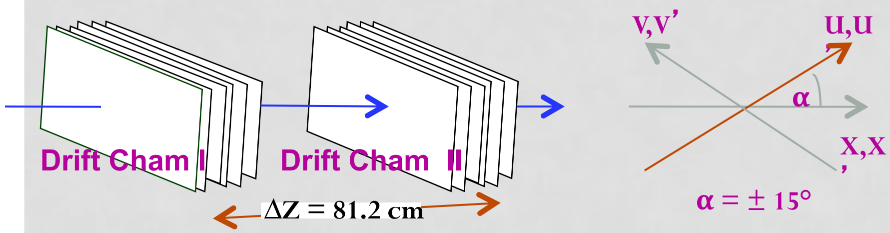
For inductors

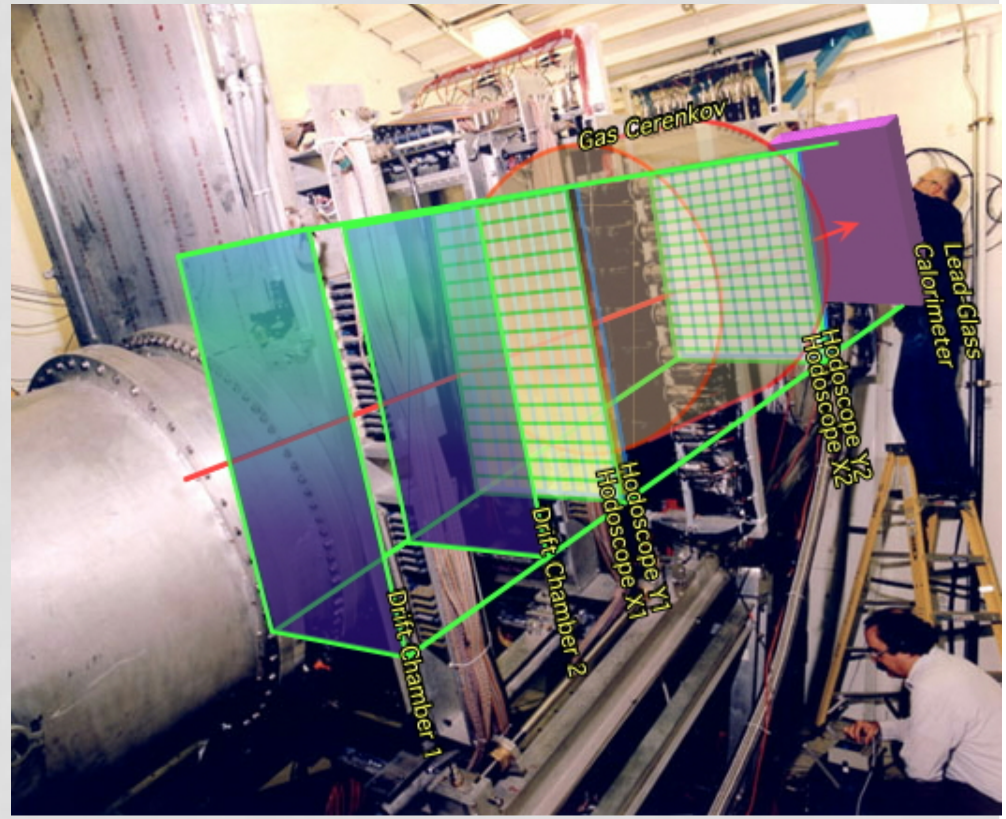
$$Q = \frac{\omega L}{R}$$

High Momentum Spectrometer – HMS

Drift Chambers:

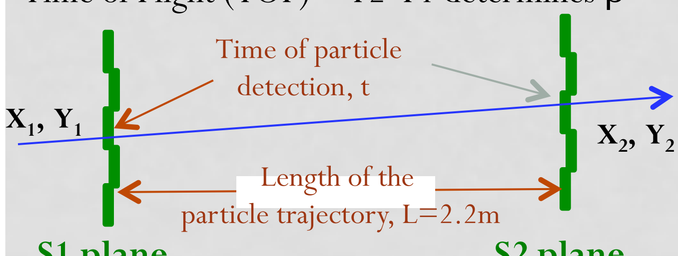
- Each plane has a set of alternating field and sense wires
- Filled with an equal parts Argon-Methane mixture
- Track particle trajectory by multiple planes.
- χ^2 fitting to determine a straight trajectory.





Hodoscopes:

- Each plane contains 10 to 16 Scintillator paddles with PMTs on both ends
- Each Paddle is 1.0 cm thick and 8.0 cm wide
- Fast position determination & triggering
- Time of Flight (TOF) = T2-T1 determines β



($\beta = L/c \times TOF$)

Gas Cerenkov:

- Two mirrors (top & bottom) connected to two PMTs
- Used as a Particle ID; in trigger to cut out π^-

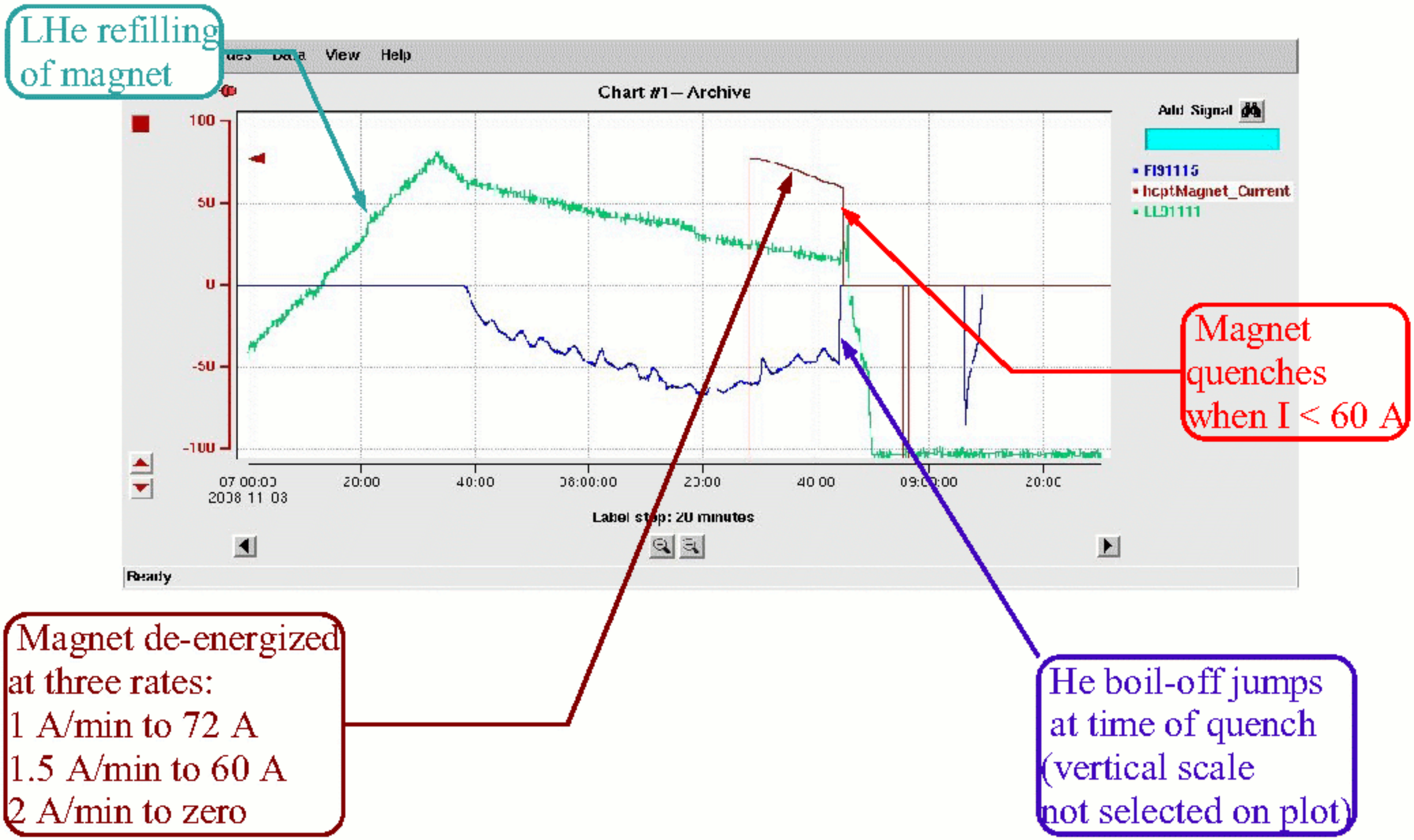
Lead Glass Calorimeter:

- 4 layers of 10 cm x 10cm x70cm blocks stacked 13 high.
- Used as a Particle ID; cut used for separating e^-/π^-

QUENCHES

- Several quenches occurred in late October and early November of 2008, which caused the magnet to be inoperable.
- This was diagnosed and fixed by the Hall C staff, target group, and an Oxford Instruments Specialist. The magnet was then placed back in the beam-line December 2008.
- Since then there were some spontaneous quenches that did not damage the magnet, due to the new protection circuits working.
- Detailed procedures were implemented to minimize occurrences.

QUENCH OF 11/03/08 AM



Important Criteria:

Degree of Polarization *P*.

Dilution factor *f*, ratio of free polarizable nucleons to the total amount of nucleons in the sample and is dependant on kinematics.

$$f = \frac{N_1\sigma_1}{N_{14}\sigma_{14} + N_1\sigma_1 + \sum N_A\sigma_A}$$

Here *P* and *f* correct for the fact that the target is not 100% polarized and contains other materials.

The (raw) asymmetry is then expressed as

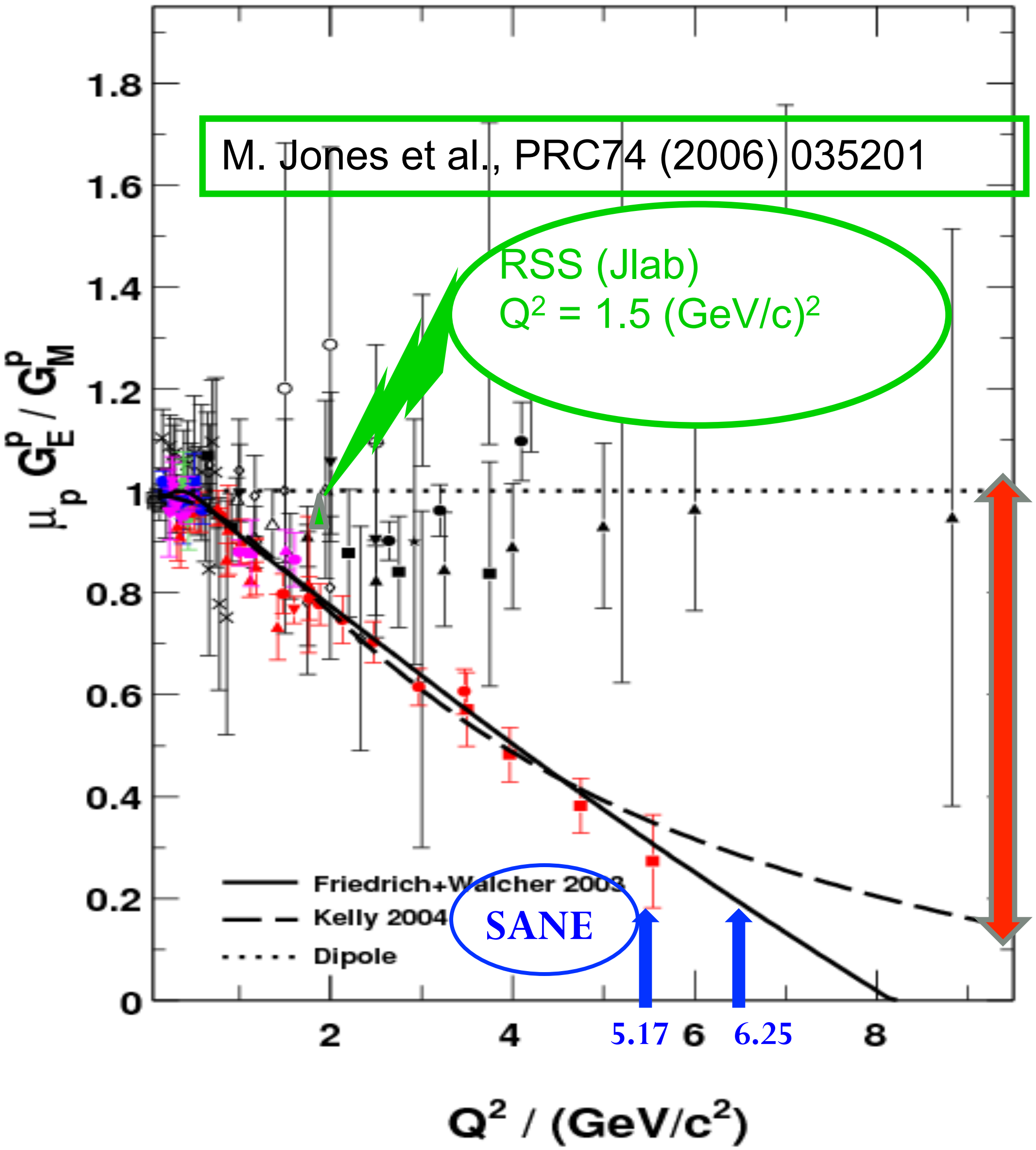
$$A_{\parallel} = A_{\perp} = \frac{1}{Pf}\frac{N^{\uparrow\downarrow} - N^{\downarrow\downarrow}}{N^{\uparrow\downarrow} + N^{\downarrow\downarrow}}$$

The amount of beam-time needed *t* to obtain a statistical error *ΔA* has the dependency

$$t \propto \frac{1}{\rho(Pf)^2}$$

Where ρ is the density of the material.

Form-Factor Ratio



- Dramatic discrepancy between Rosenbluth and recoil polarization technique.
- Multi-photon exchange considered the best candidate for the explanation

Dramatic discrepancy !

MEASURING THE FORM-FACTOR RATIO

The raw asymmetry,

$$A_m = \frac{N^+ - N^-}{N^+ + N^-}$$

N^+ = Helicity + Counts
N^- = Helicity - Counts

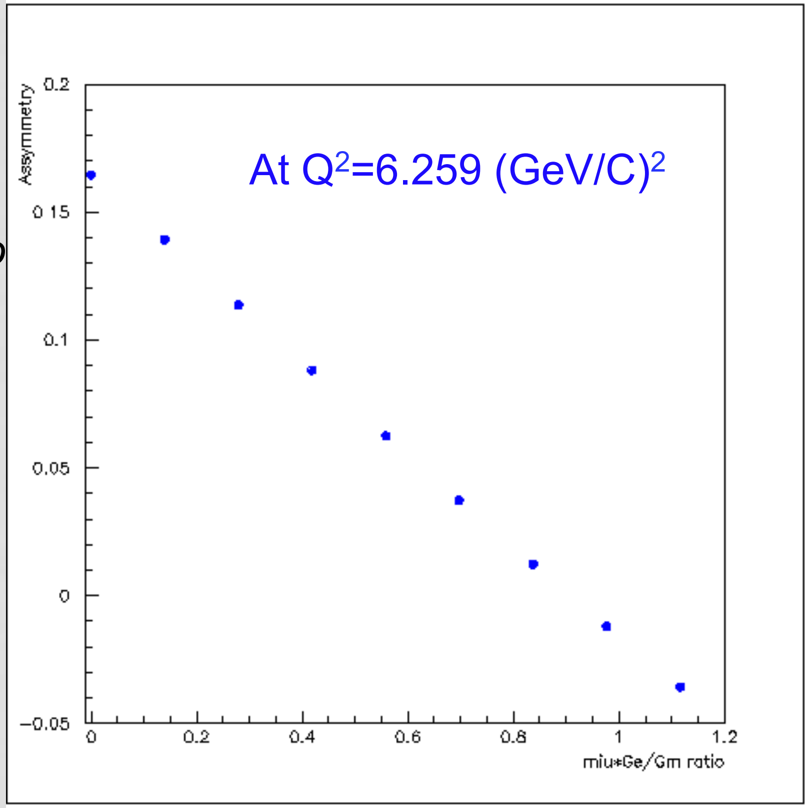
The elastic asymmetry,

$$A_P = \frac{A_m}{f P_B P_T} + Nc$$

P_B, P_T = Beam & Target Po
f = Dilution Factor
Nc = A Correction Term

P_T+ = ~71.0% , P_T- = ~-65.0%, P_B = ~73.0%,

Calculated asymmetry vs $\mu G_E^P/G_M^P$



The beam-target asymmetry,

$$A_p = \frac{- br\, Sin\Theta^* Cos\,\Phi^* - aCos\Theta^*}{r^2 + c}$$

Here,

$r = G_E^P / G_M^P$
a, b, c = kinematic factors
Θ^*, Φ^* = pol. and azi. Angles between $\bar{q}$ and $\bar{S}$

$\Theta^* \approx 102°$ and $\Phi^* = 0$
From the HMS kinematics, r2 << c

$$A_p = \frac{- bSin\Theta^* Cos\,\Phi^*}{c}\, r - \frac{aCos\Theta^*}{c}$$

Error Propagation From The Experiment

$$A_P = \frac{-bSin\theta^* Cos\Theta^* r}{c} - \frac{aCos\theta^*}{c}$$

$$\Delta A_P = \left| \frac{bSin\theta^* Cos\Theta^*}{c} \right| \Delta r$$

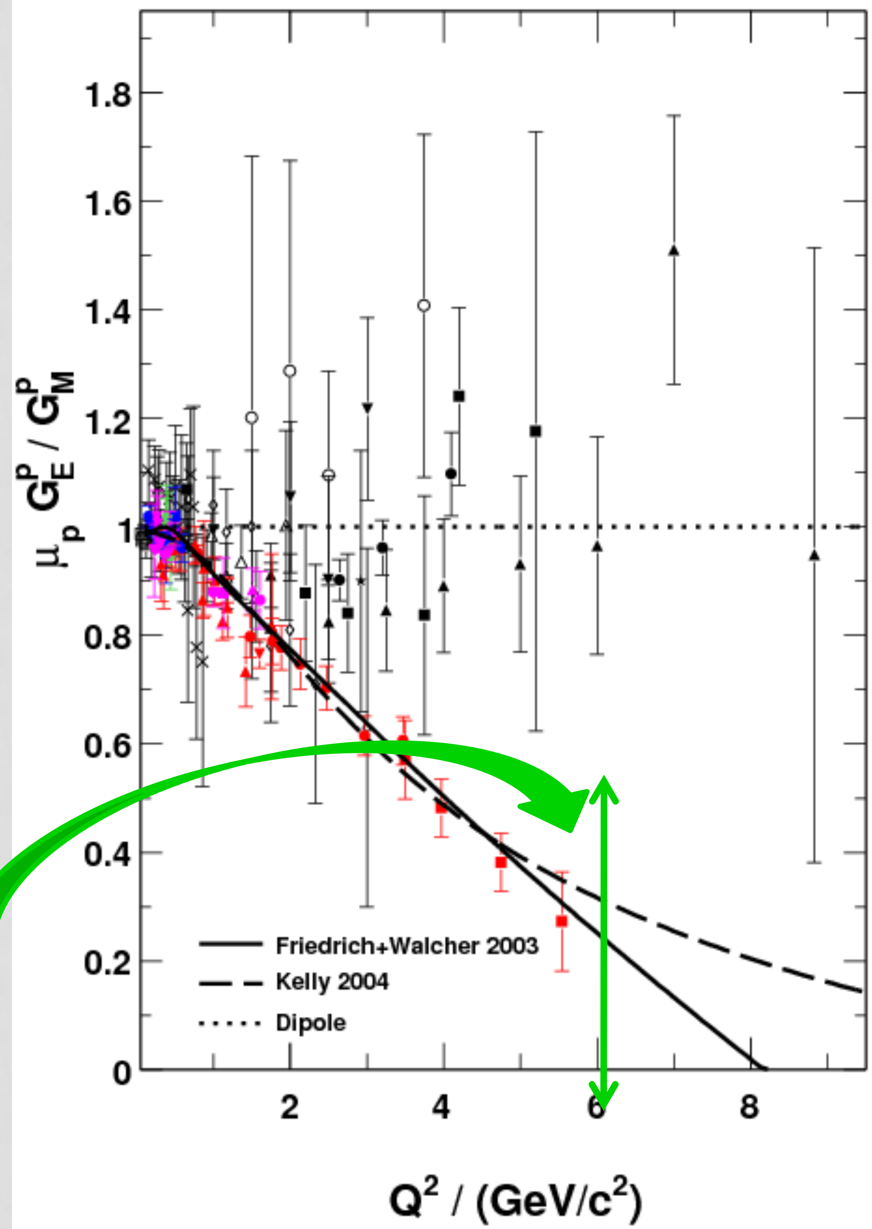
Using the experimental data at Q^2=6.259 $(GeV/C)^2$,

Δr = 0.118

$\mu\, \Delta r$ = 2.79 x 0.118

$\mu\, \Delta r$ = 0.3

Where, μ – Magnetic Moment of the Proton



The error on the $\mu\, \Delta r$ from the experimental data with total ep events ~1000,

$\mu\, \Delta r$ = 0.3