Nucleon Spin Structure

Kees de Jager

Nucleon Spin Structure

- Introduction
- Q^2-evolution of GDH integral
- Nucleon Spin Structure at large x
- Quark-Hadron (Spin) Duality
- $R=\sigma_L/\sigma_T$ in Resonance Region
- Real Compton Scattering up to Large t-values
- Summary

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Spin Structure in Deep Inelastic Scattering

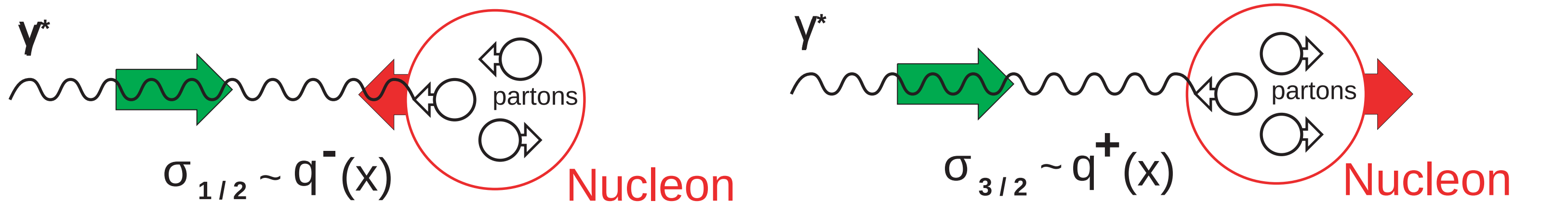
$$\langle S_z^N \rangle = \frac{1}{2} = J_q + J_g = \frac{1}{2}\Delta\Sigma + L_q + \Delta G + L_g$$

- Study of nucleon spin structure started with EMC (~'88):

  $\Delta\Sigma = \Delta d + \Delta u + \Delta s = 0.12 \pm 0.17$

- World-wide effort (SLAC, DESY, CERN) established that $\Delta\Sigma \sim 0.2 \dots 0.4$
- Focus shifted to other contributions to $\langle S_z \rangle$:
  - strange sea polarization — semi-inclusive DSA
  - gluon polarization — open charm, high p_T hadron pairs
  - orbital angular momentum — Generalized Parton Distributions

Spin Structure in Deep Inelastic Scattering



Partonic Interpretation

x = fraction of nucleon momentum carried by struck quark

$q^{+/-}$ quark helicity parallel/antiparallel to photon helicity

NO simple partonic picture of g_2

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

$$q(x) = q^+(x) + q^-(x)$$

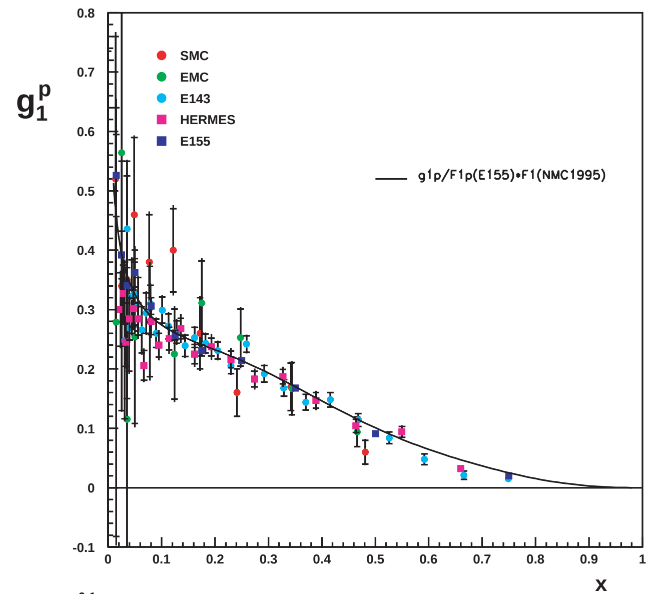
$$F_1(x) = \frac{1}{2}\sum_{flavor} e_f^2 q_f(x) \qquad F_2(x) = xF_1(x)$$

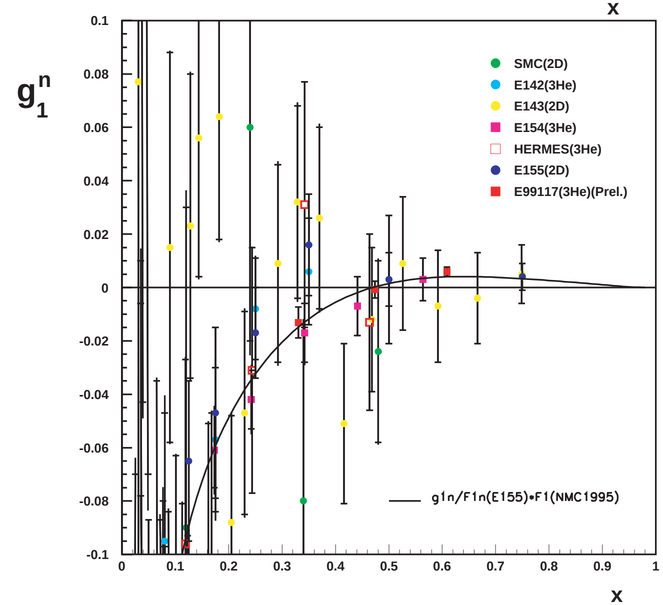
$$\Delta q(x) = q^+(x) - q^-(x) \qquad A_1(x) = \frac{g_1(x)}{F_1(x)}$$

$$g_1(x) = \frac{1}{2}\sum_{flavor} e_f^2 \Delta q_f(x) \qquad g_2(x) = 0$$

Nucleon Spin Structure

- Fairly extensive data set on $g_1(x)$, but only for $x < 0.3$
- Low-x region dominated by sea quarks, predictions difficult
- High-x region (a single quark carries most of the nucleon momentum) dominated by valence quarks, predictions feasible
- Accurate data will allow selection of models
- JLab unique combination of energy and luminosity





Bjørken Sum Rule

$$\Gamma_1^p(Q^2) - \Gamma_1^n(Q^2) = \int \{g_1^p(x,Q^2) - g_1^n(x,Q^2)\}\, dx = \frac{1}{6} g_A C_{NS}$$

g_A=1.2601 ± 0.0025 neutron β-decay coupling constant
C_{NS} Q^2-dependent QCD correction

Basic assumptions
- Isospin symmetry
- Current Algebra or Operator Product Expansion within QCD

Present status (at Q^2 = 5 $(GeV/c)^2$)
Experiment 0.176 ± 0.003 ±0.007
Theory 0.182 ± 0.005

- Combined world data are consistent with the Bjørken Sum Rule at 5 % level

Gerasimov-Drell-Hearn Sum Rule

$$\int_{\nu_{in}}^{\infty} \left(\sigma_{1/2}(\nu) - \sigma_{3/2}(\nu)\right)\frac{d\nu}{\nu} = -\frac{2\pi^2\alpha_{EM}}{M^2}\kappa^2$$

GDH Sum Rule

- The Gerasimov-Drell-Hearn Sum Rule (at $Q^2 = 0$) is a fundamental test of the relation between the nucleon resonance excitation and its anomalous magnetic moment
- Rests on basic physics principles (Lorentz invariance, gauge invariance, unitarity) and on dispersion relation applied to forward Compton amplitude
- Technical developments have only recently allowed first measurement of GDH integral for the proton up to 800 MeV (Mainz) and up to 3 GeV (Bonn)
- Results agree with sum rule with assumptions for contributions at higher energies
- Many facilities (GRAAL, SPring-8, LEGS, HIGS, JLab) geared for extensive studies
- Will include data for the neutron from polarized deuterium

Transition from Strong to Perturbative QCD

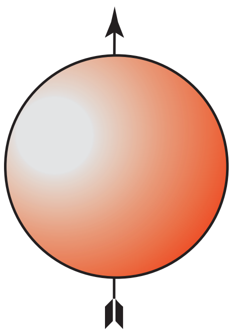
- Dispersion relations on Compton Scattering Amplitudes lead to extension of GDH sum rule valid at all Q^2 (Ji and Osborne)
- Q^2-evolution of Gerasimov-Drell-Hearn Sum Rule provides quantitative measure of transition from resonance (strong QCD) to DIS (pQCD) regimes
- Transition from Bjørken sum rule down to ~ 1 GeV^2 can be predicted using Operator Product Expansion of higher twist contributions
- Transition from GDH sum rule up to ~ 0.1 GeV^2 can be predicted using Chiral Perturbation Theory
- For intermediate region one awaits Lattice QCD calculations

Why is $I^{GDH}(Q^2)$ interesting?

One of the few opportunities to "zoom out" from tiny length scales (DIS) to large length scales

$I^{GDH}(Q^2)$

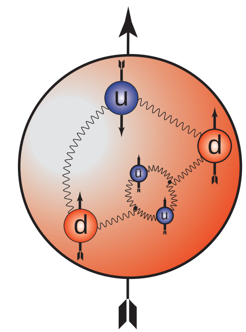
$$-\frac{2\pi^2\alpha}{M^2}\kappa^2 \quad \xleftarrow{\text{Chiral pert. theory}} \quad 2\pi^2\alpha S_1(0;Q^2) \quad \xrightarrow{\text{Higher twist corrections}} \quad \frac{16\pi^2\alpha}{Q^2}\Gamma_1$$



GDH

Non-perturbative, confinement

PQCD



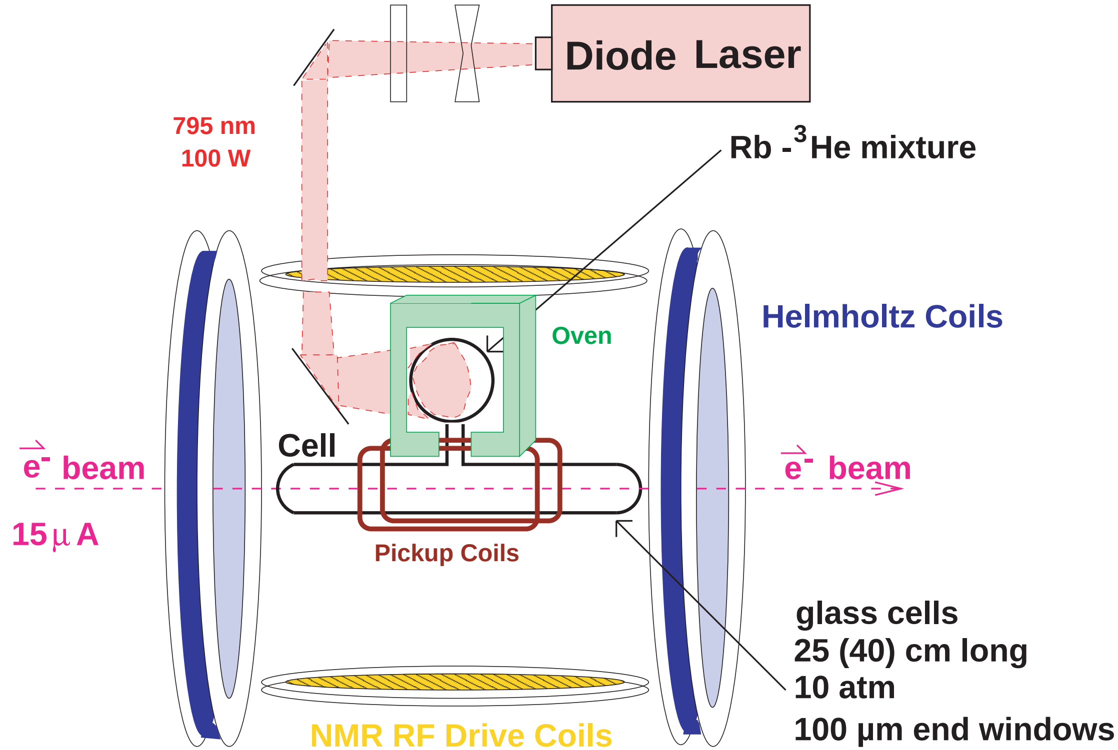
OPE, Bjorken, Ellis-Jaffe

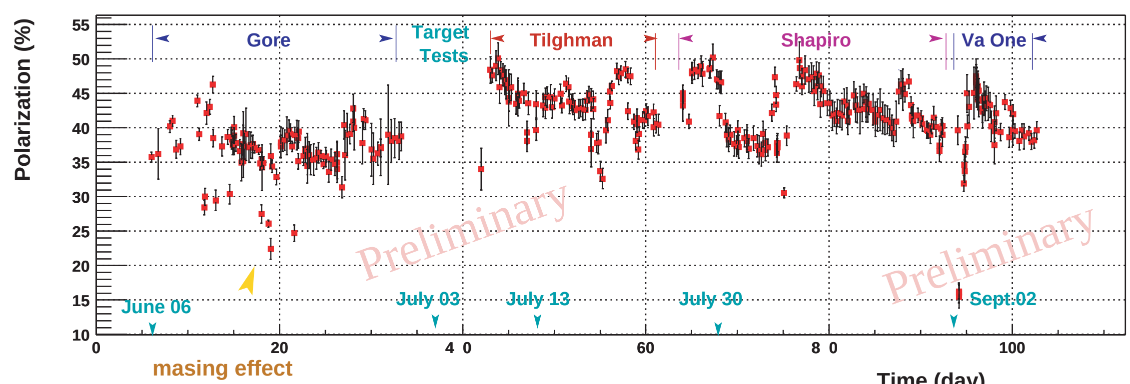
Many of the underlying assumptions are the same as those being tested in high-energy spin-structure tests

Polarized ^{3}He Target (Hall A)

- Polarized ^{3}He is best approximation of polarized neutron P_n=87 % and P_p=2.7 %
- Requires corrections for nuclear medium, investigated by many theorists
- Basic principle:

  Optical pumping of Rb, followed by polarization transfer to ^{3}He through spin-exchange collisions
- Target polarization measured by EPR/NMR

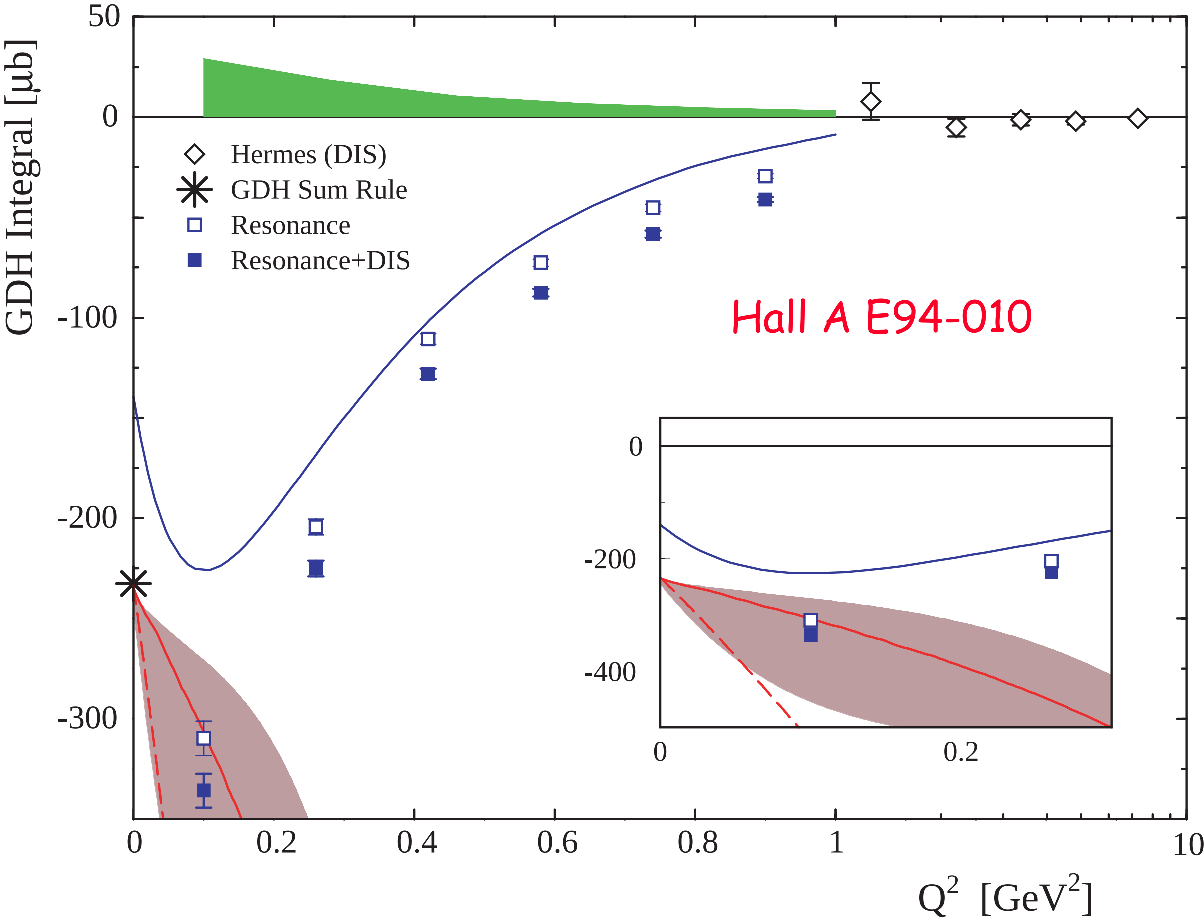




Q^2-Evolution of the Gerasimov-Drell-Hearn Integral

$$I_{GDH} = \int_{\nu_{in}}^{\infty} \left(\sigma_{1/2}(\nu,Q^2) - \sigma_{3/2}(\nu,Q^2)\right)\frac{d\nu}{\nu} = -2\int_{\nu_{in}}^{\infty} \sigma_{TT}\frac{d\nu}{\nu} = -\frac{8\pi^2\alpha}{MK}\int_{\nu_{in}}^{\infty}\left(g_1 - \frac{Q^2}{\nu^2}g_2\right)\frac{d\nu}{\nu}$$

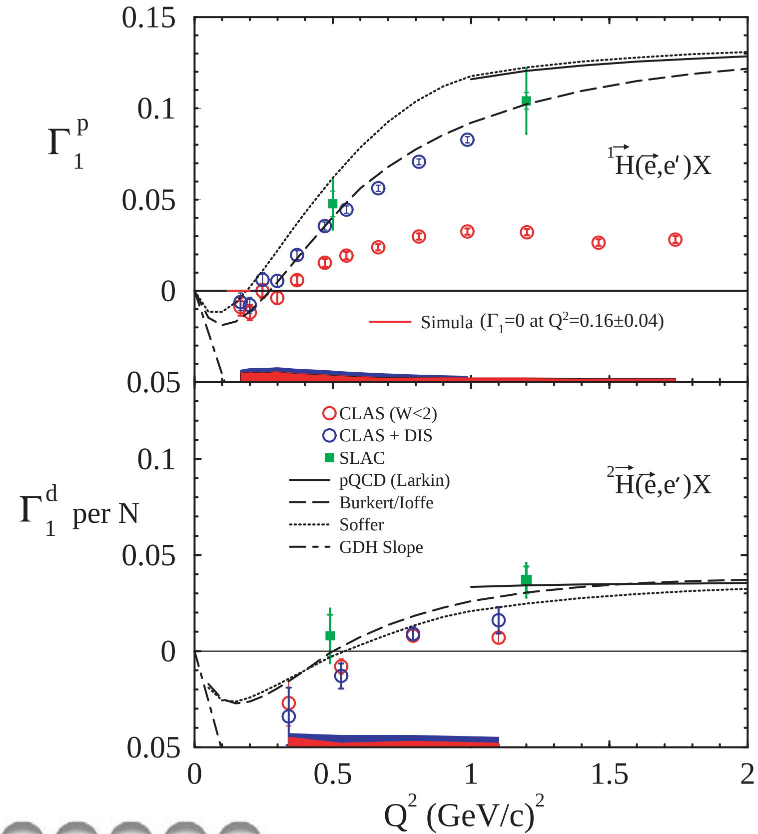
- Longitudinal and transverse target polarization allows separation of g_1 and g_2
- Kinematic coverage sufficient to integrate to W ≈ 2 GeV
- Nuclear medium corrections from Ciofi degli Atti and Scopetta
- Compared to calculations by Drechsel et al. which neglect contributions from DIS and by Ji and Bernard based on Chiral Perturbation Theory (band shows uncertainty in contribution from Δ-resonance)

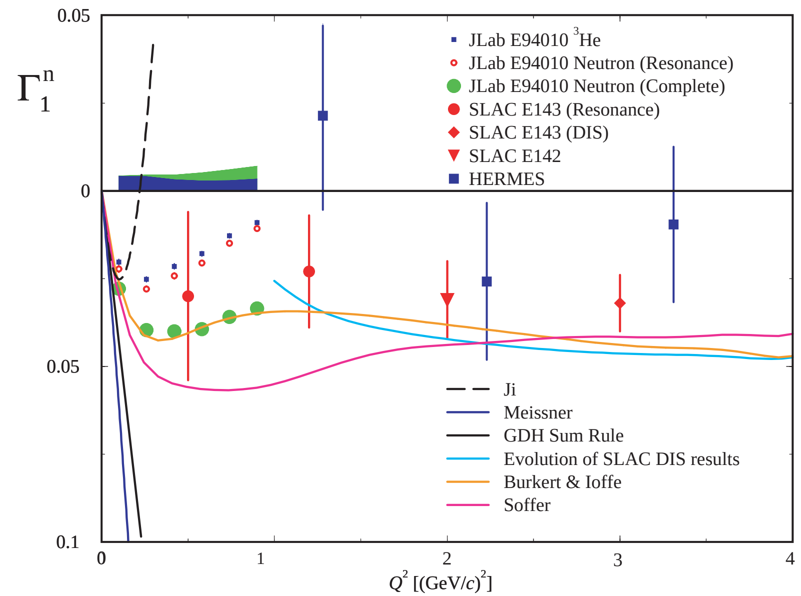


Q^2-Evolution of the Gerasimov-Drell-Hearn Integral (cont.)

$$\Gamma_1^{p/n} = \int_0^1 g_1^{p/n}(x_{Bj},Q^2)dx_{Bj} \propto \int_0^1 (A_{//} + \alpha A_\perp)F_1(x_{Bj},Q^2)dx_{Bj}$$

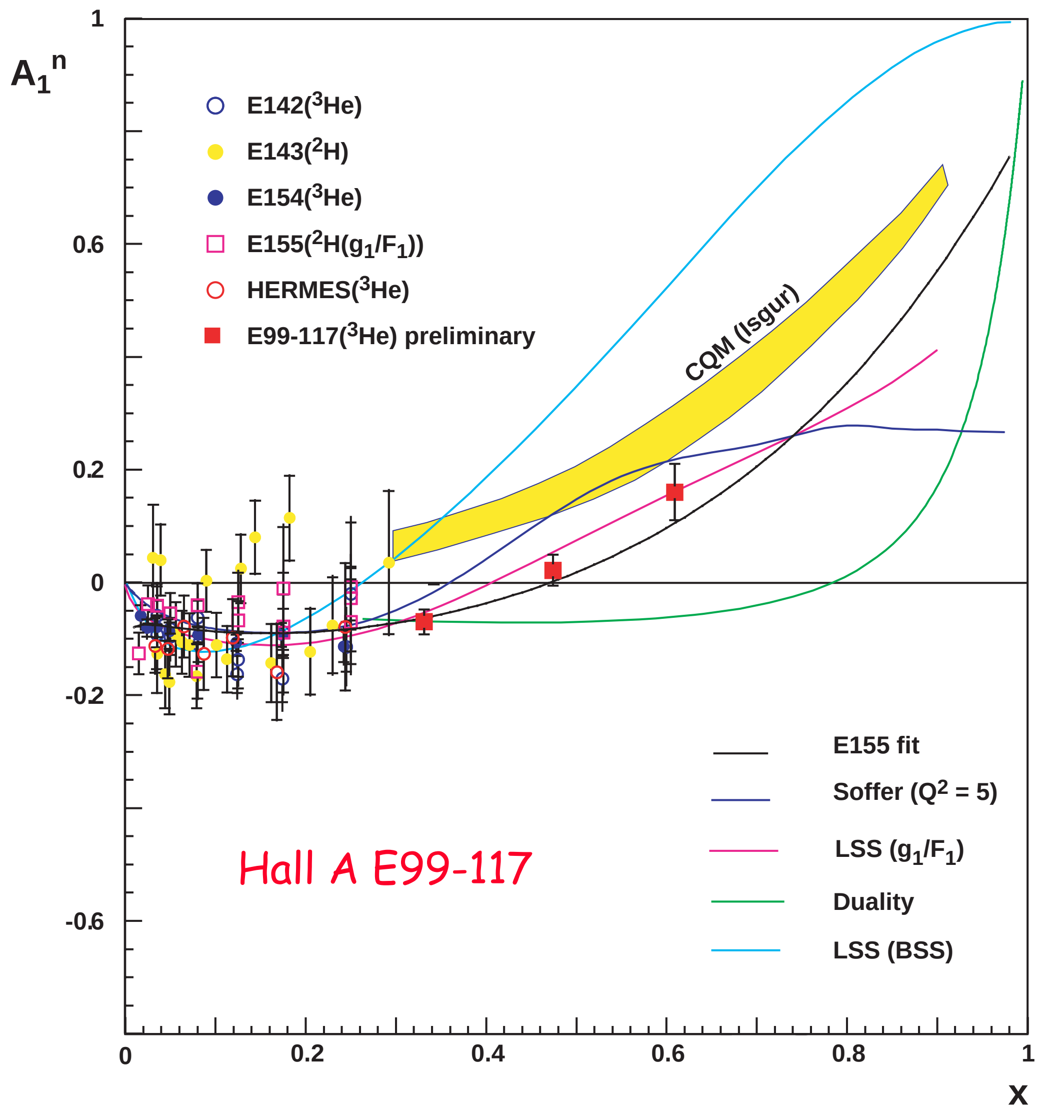
Hall B E91-023





The neutron A_1^n spin structure function

- Naïve SU(6) predictions:
  $A_1^p = 5/9$, $A_1^n = 0$
- Broken SU(6):
  A_1^n -> 1 as x -> 1
  CQM: hyperfine perturbed with simple model for d/u
  LSS: NLO polarized parton densities
  Soffer: global NLO analysis of (un)polarized DIS
  Duality: local QHD using available G_E, G_M data

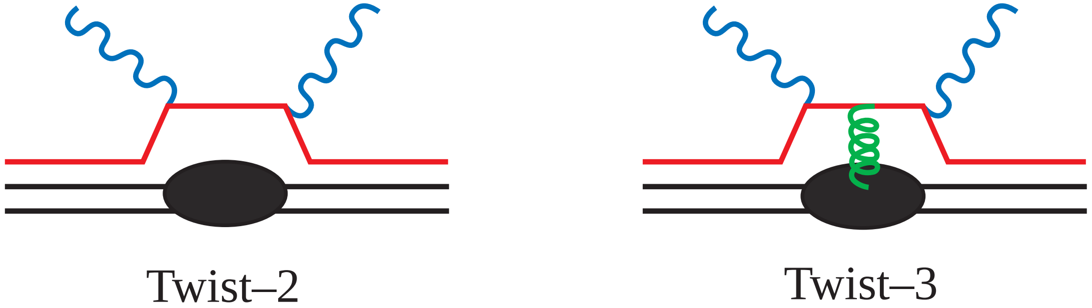


Quark-Gluon Correlations

$$g_2(x,Q^2) = g_2^{WW}(x,Q^2) + \overline{g}_2(x,Q^2)$$

$$g_2^{WW}(x,Q^2) = -g_1(x,Q^2) + \int_x^1 g_1(y,Q^2)\frac{dy}{y}$$

- In simple partonic picture $g_2(x)=0$
- Wandzura and Wilczek have shown that g_2 can be written in two parts:
  - one given by g_1 in twist-2 contributions
  - the other originating solely from quark-gluon correlations (twist-3)

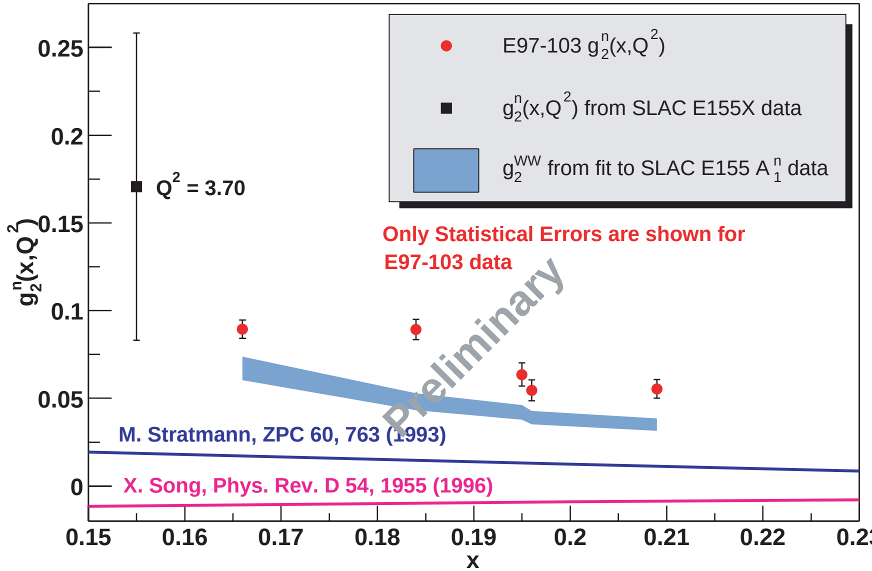


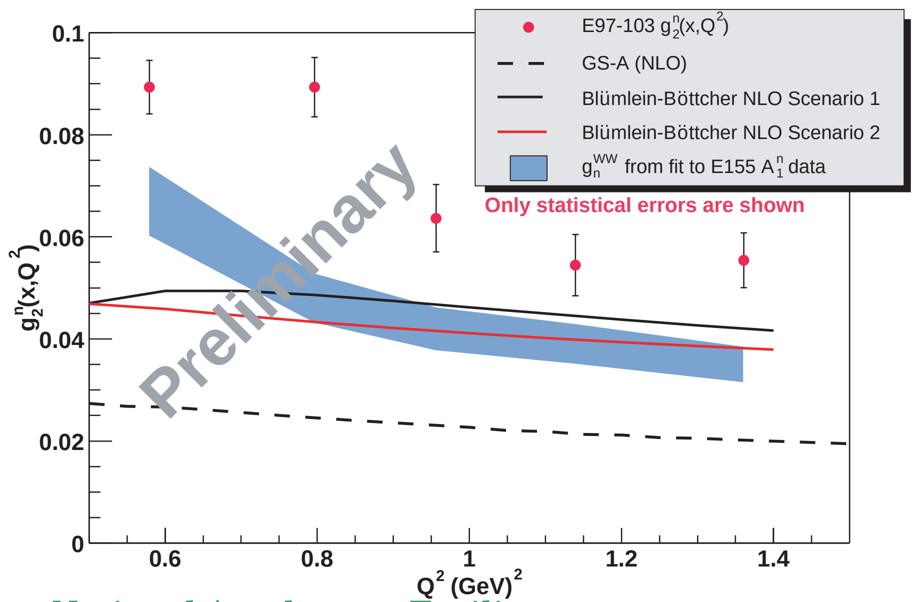
$$d_2^n(Q^2) = \int_0^1 x^2\left[2g_1^n(x,Q^2) + 3g_2^n(x,Q^2)\right]dx \qquad d_2 = (2\chi_B + \chi_E)/3$$

The neutron g_2 structure function

- First measurements of g_2 in Hall A order of magnitude improvement in accuracy over SLAC E155X
- Preliminary data indicate significant excess over simple prediction
- First quantitative information(?) of twist-3 effects

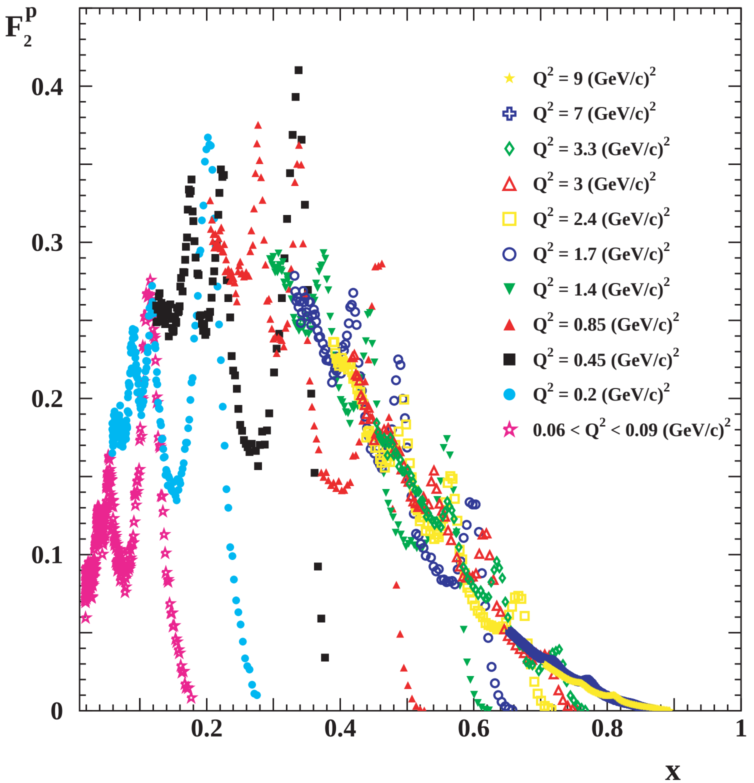
Hall A E97-103





Quark-Hadron Duality

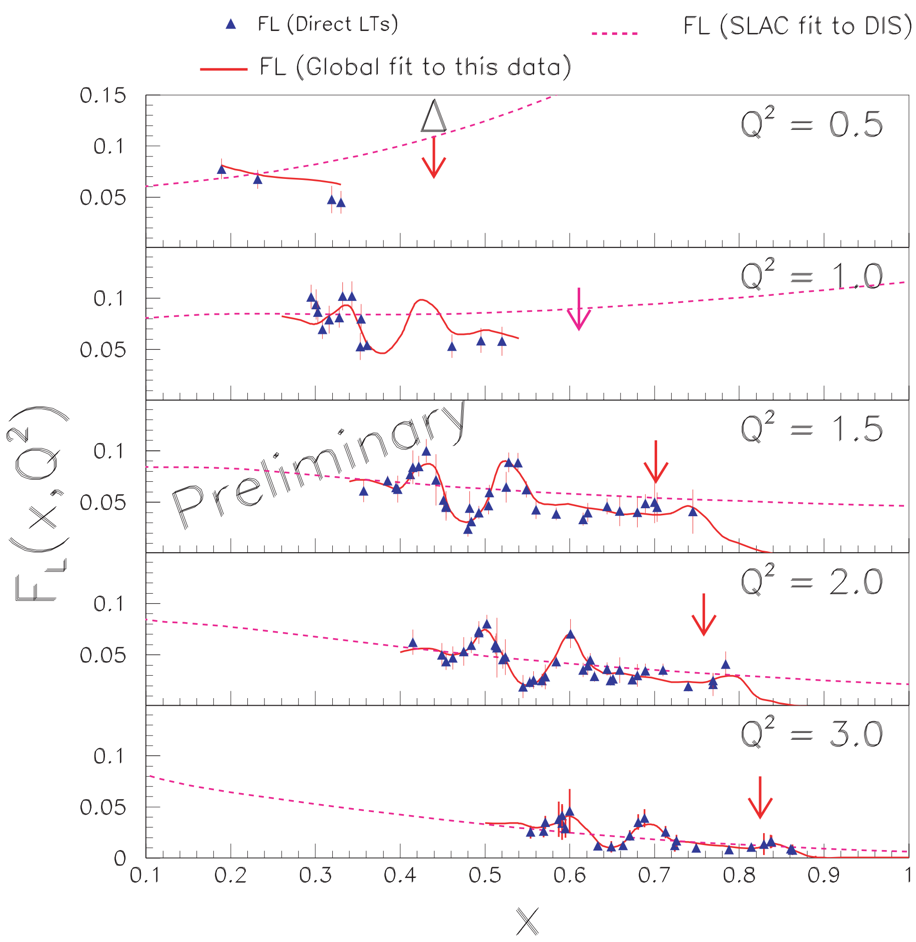
- Quark-Hadron Duality implies that properly averaged hadronic observables can be described by perturbative QCD in a certain kinematic regime
- QHD must hold in the scaling region
- QHD must break down at very low Q^2
- Extensive data set from Hall C shows that QHD works well down to $Q^2 \sim 0.5\ GeV^2$
- Once QHD has been verified, it provides a relation between the resonance region and the DIS region



(c) Ioana Niculescu 02/02/00

$R=\sigma_L/\sigma_T$ in Resonance Region

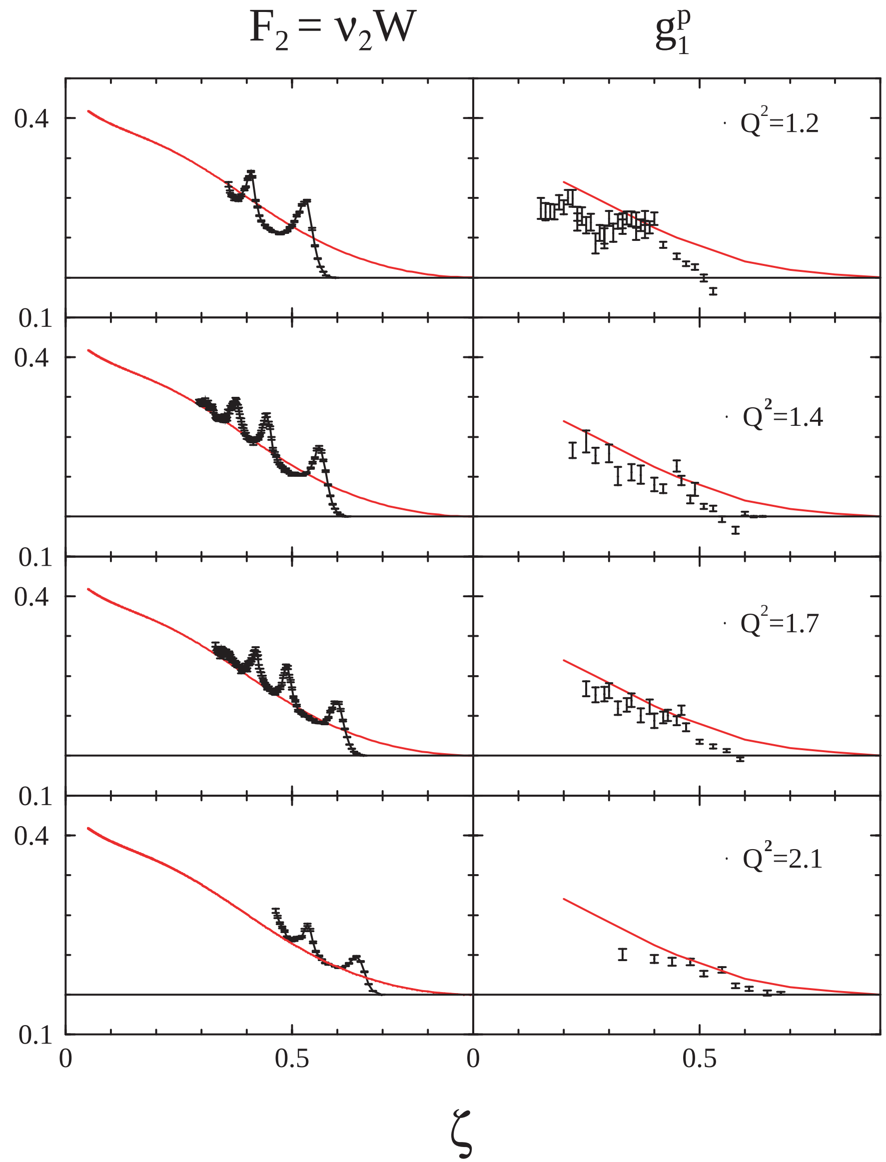
- First measurements of R (yielding the longitudinal structure function F_L) in the resonance region
- Surprisingly strong resonance structure evident in F_L
- Allows test of QHD in F_L
- Moments of F_L can be directly compared to Lattice Gauge Theory calculations



Hall C E94-110

Spin Duality

- First preliminary results of measurements of g_1^p in the resonance region
- Spin duality appears to set in at $Q^2 > 1.5$ GeV^2
- Opens possibility to extend measurements of spin structure functions to smaller values of W (larger values of x, shown is the Nachtmann variable ξ, which is x with a target mass correction)



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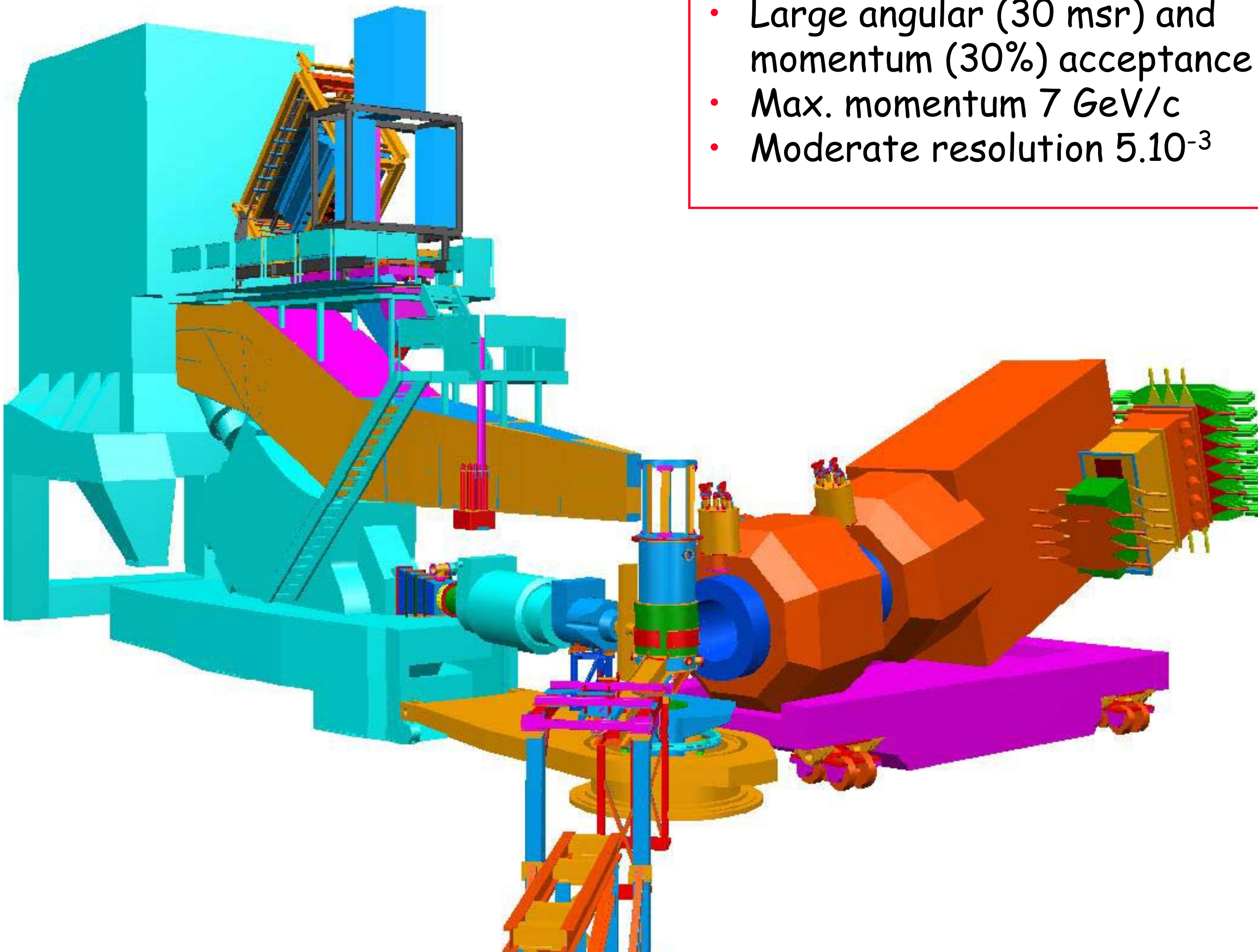
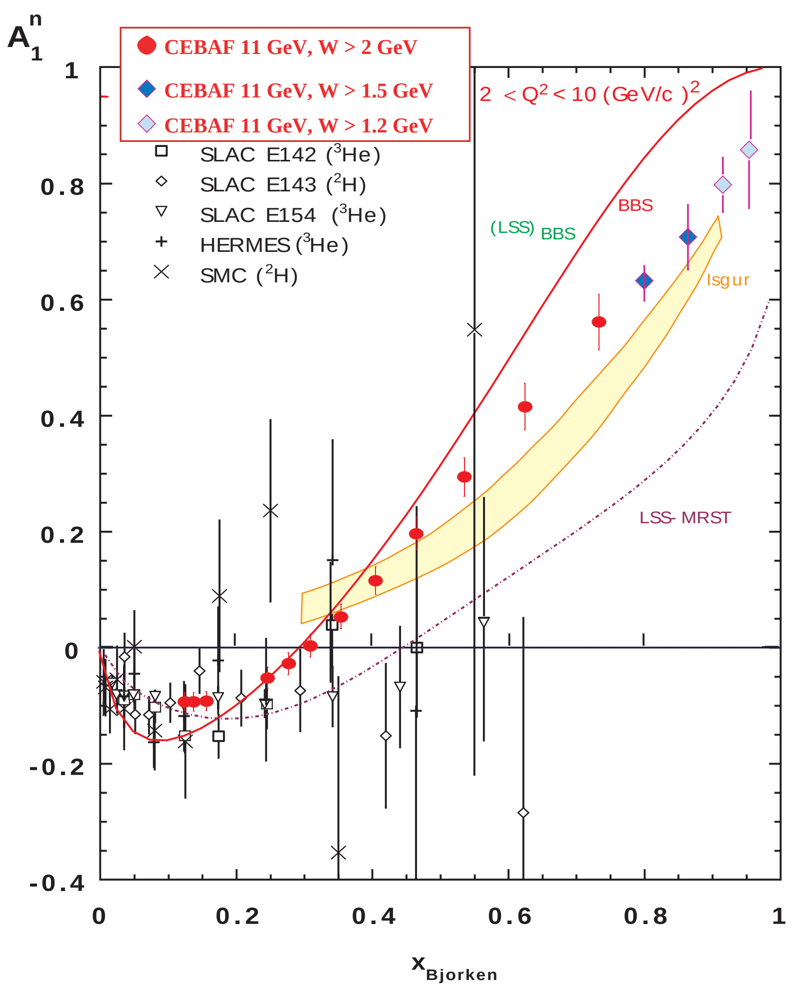
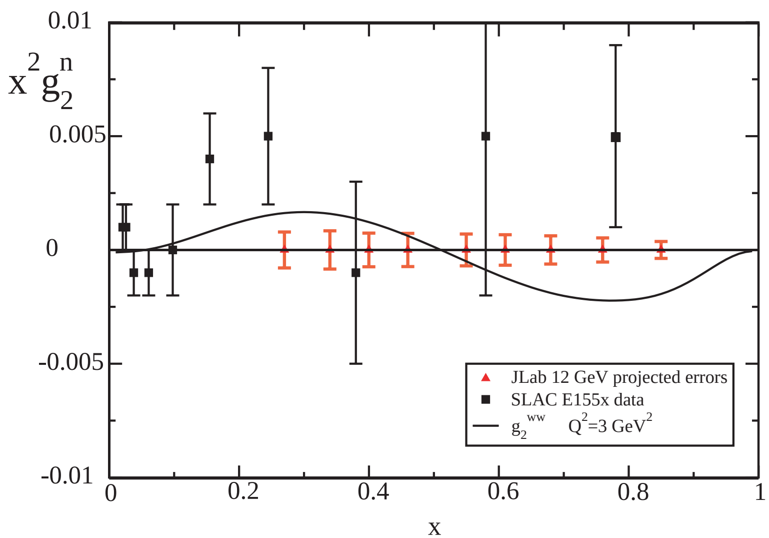
MAD Spectrometer in Hall A

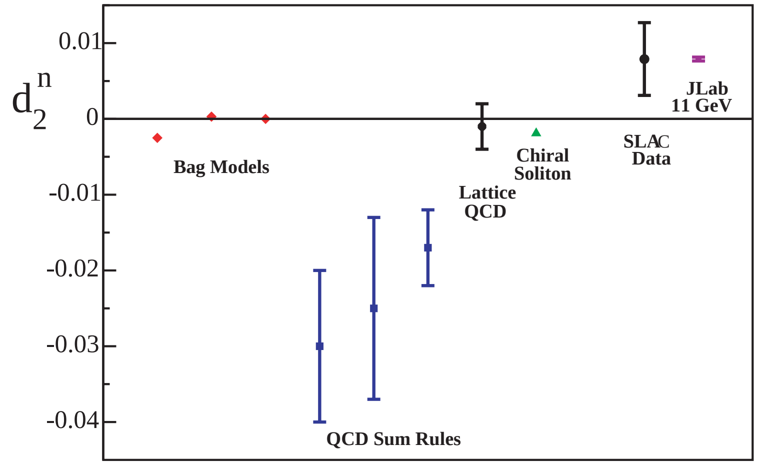
- Large angular (30 msr) and momentum (30%) acceptance
- Max. momentum 7 GeV/c
- Moderate resolution 5.10^{-3}



Expected results with 12 GeV upgrade

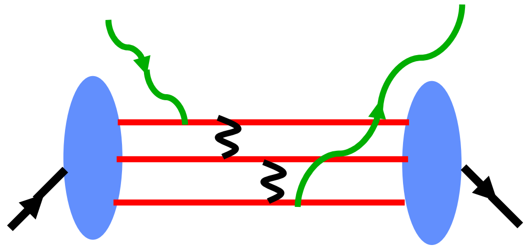




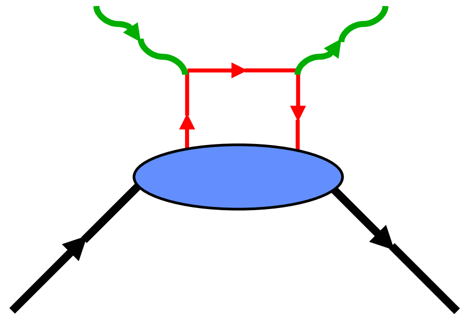


Real Compton Scattering

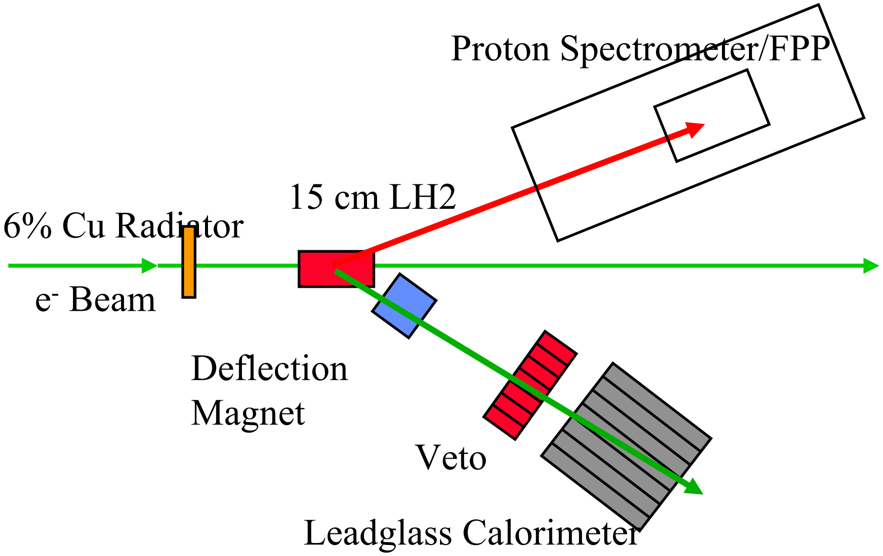
- Wide-Angle Compton Scattering (WACS) provides information on the partonic structure of the nucleon through the moments of the Generalized Parton Distributions
- First, the dominant mechanism of Real Compton Scattering at large values of s and t (~10 GeV^2) has to be established:
  - pQCD
    - momentum shared by hard gluon exchange
    - 3 active quarks
    - valence configuration dominates
    - scaling: $d\sigma/dt = f(\theta_{CM})/s^6$

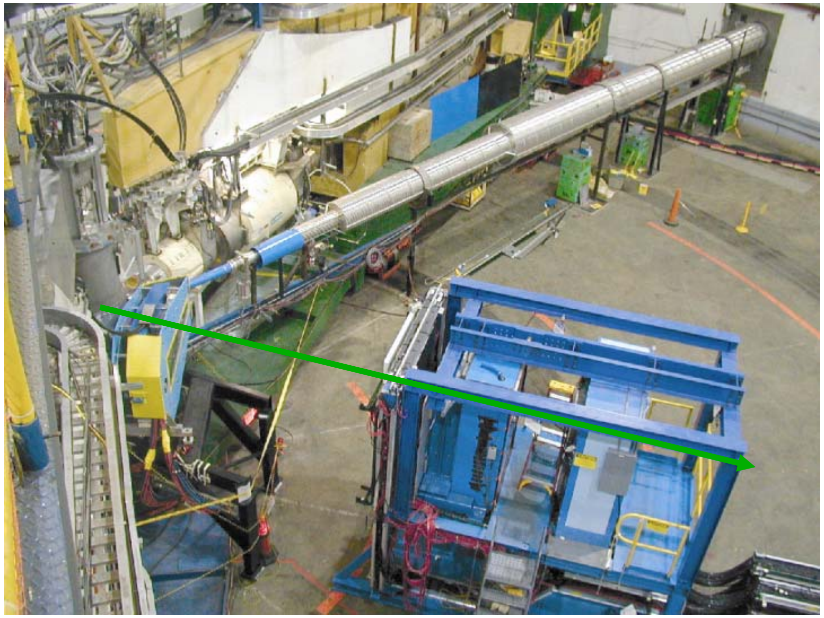


  - Handbag diagram
    - hard scattering from single quark
    - momentum shared by soft overlap
    - 1-body form factor
    - soft gluon exchange neglected



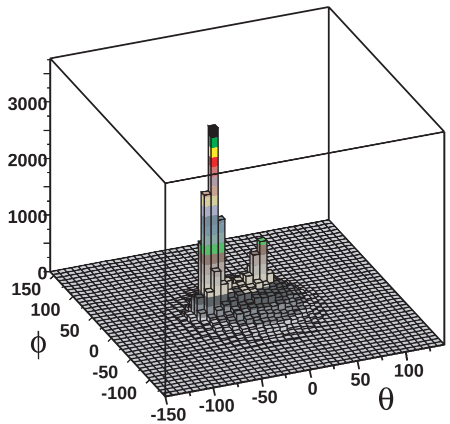
Real Compton Scattering (cont.)

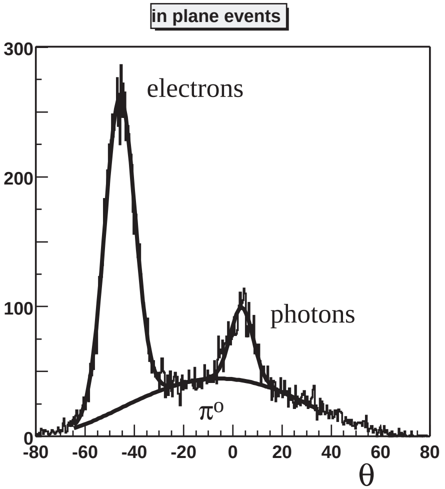




"Sweep" magnet essential for electron/photon separation

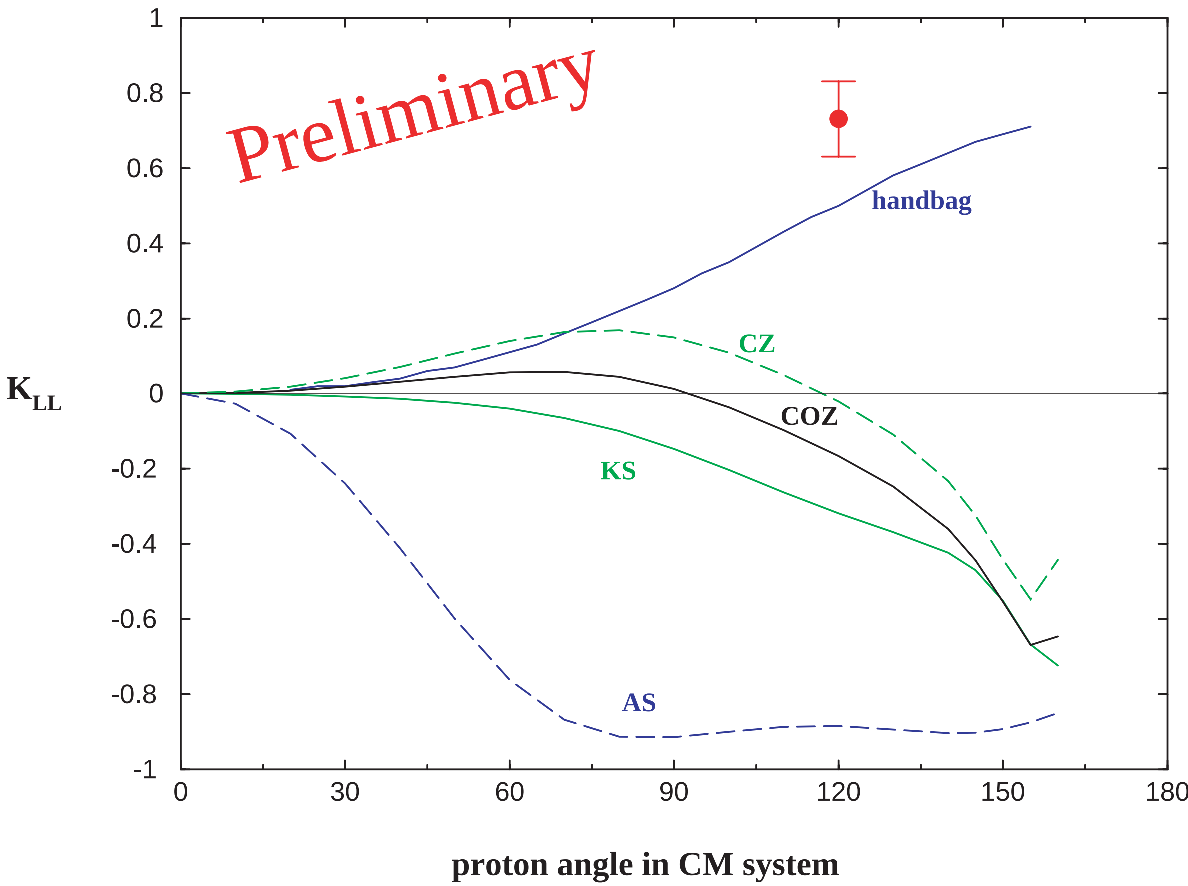
Hall A E99-114





Real Compton Scattering (cont.)

- On-line analysis of ~60 % of data
- Demonstrates feasibility of WACS at high luminosity (three orders higher than at Cornell)
- Proves dominance of soft-overlap mechanism (handbag)
- AS, KS, COZ, CZ:
  variety of pQCD calculations



Summary

- Study of Nucleon Spin Structure provides fascinating insight into the partonic structure of the nucleon
- Recent results from Jefferson Lab have contributed significantly to this field in a wide variety of aspects
  - Sensitive measurements of the Q^2-evolution of the GDH integral
  - First accurate measurements of A_1^n at large x and of g_2^n
  - First L/T separation in the resonance region
  - First high-luminosity measurement of Wide Angle Compton Scattering
  - ……………………
- These studies will continue and be expanded strongly with the 12 GeV upgrade

Proton