Spin Structure Program at Jefferson Lab

Jian-ping Chen, Jefferson Lab, Virginia, USA

SPIN 2023, Duke University, Sept. 24-29, 2023

- **Introduction**
- **Highlights of JLab12 Spin Program**
  - **Spin structure in valence region**

    A1n@high-x in Hall C

    A1p@high-x: RGC@CLAS12
  - **quark-gluon correlations, twist-3 matrix element**

    d2n@medium-high Q^2 in Hall C
- **Spin Moments (Sum Rules and Polarizabilities) at Low-Q^2**

  Proton: g2p@Hall A (T) and EG4@Hall B (L)

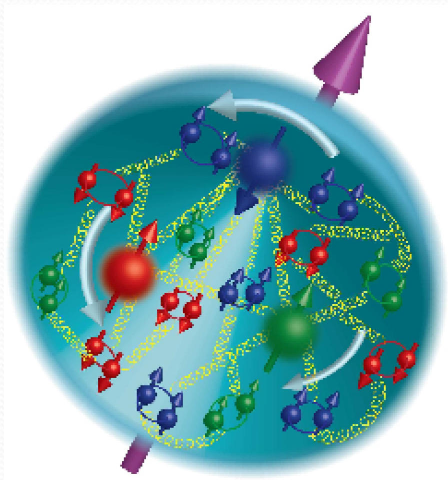
  Neutron: SAGDH@Hall A with pol. ^{3}He (both L/T)

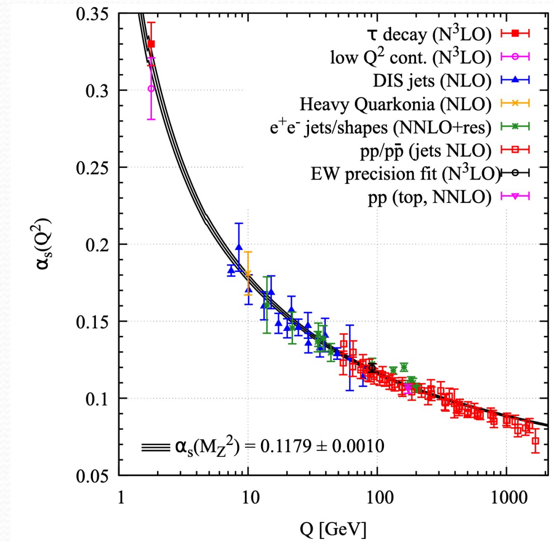
  Bjorken (p-n) Sum and (Effective) Strong Coupling
- **Summary**

Acknowledgment: Thanks to X. Zheng, M. Chen, B. Sawasky, J. Chen, A. Deur, K. Slifer, S. Kuhn, P. Pandey and collaborators for the work in this talk and for providing slides

Introduction

Nucleon Spin Structure and Strong Interaction,





Nucleon Structure and Strong Interaction/QCD

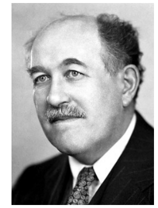
- **Nucleon Structure: discoveries**
  - -- anomalous magnetic moment (1943 Nobel)
  - -- elastic: form factors (1961 Nobel)
  - -- DIS: parton distributions (1990 Nobel)

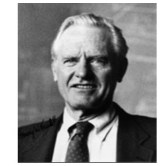
- **Strong interaction, running coupling ~1**
  - -- asymptotic freedom (2004 Nobel)
    perturbation calculation works at high energy
  - -- interaction significant at intermediate energy,
    quark-gluon correlations
  - -- interaction strong at low energy
    confinement

- **A major challenge in fundamental physics:**
  - -- Understand QCD in all regions, including strong (confinement) region

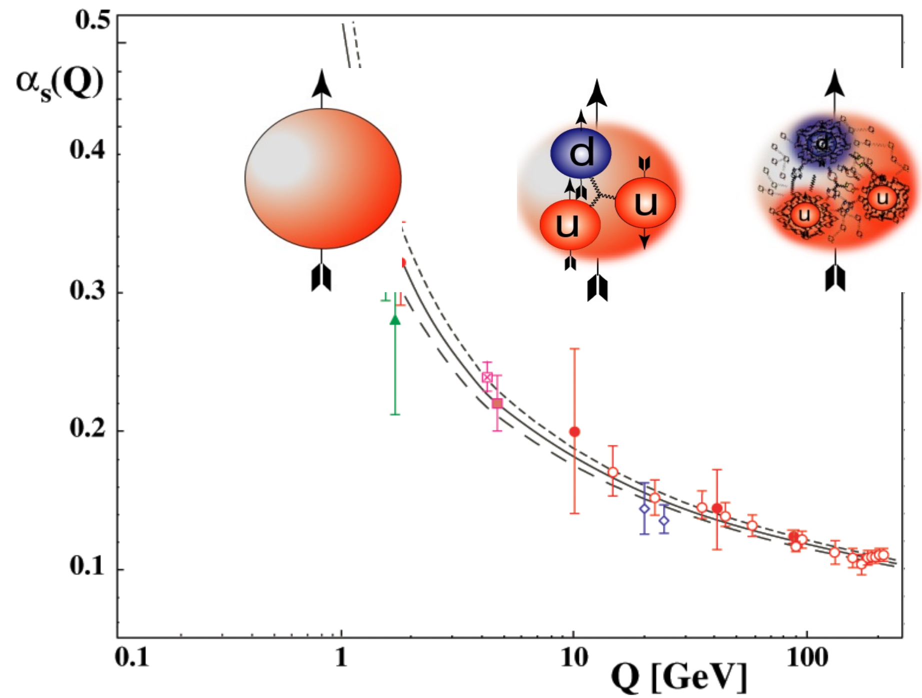
- **Nucleon: most convenient lab to study QCD**

- **Theoretical Tools:**
  pQCD, Lattice QCD, χEFT, Sum Rules, …

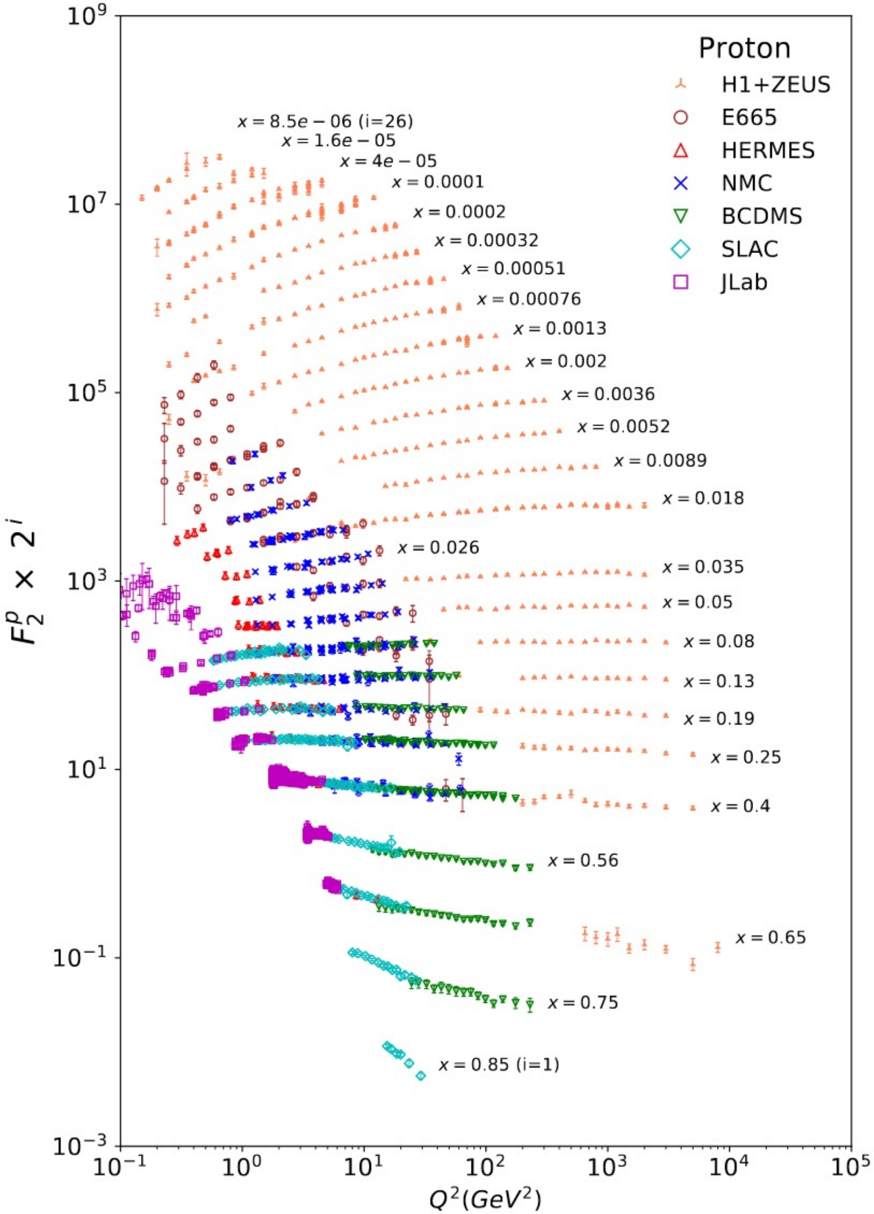


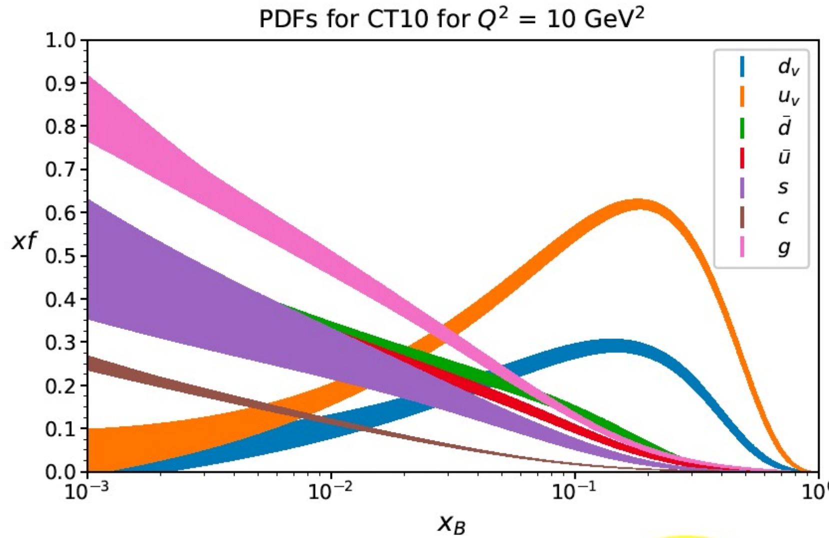



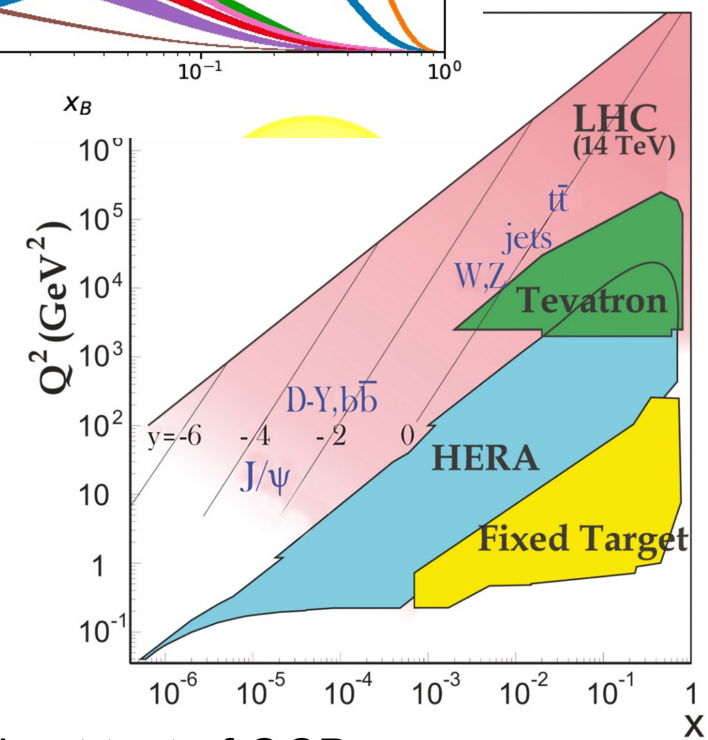

running coupling "constant"



UNPOLARIZED STRUCTURE FUNCTIONS

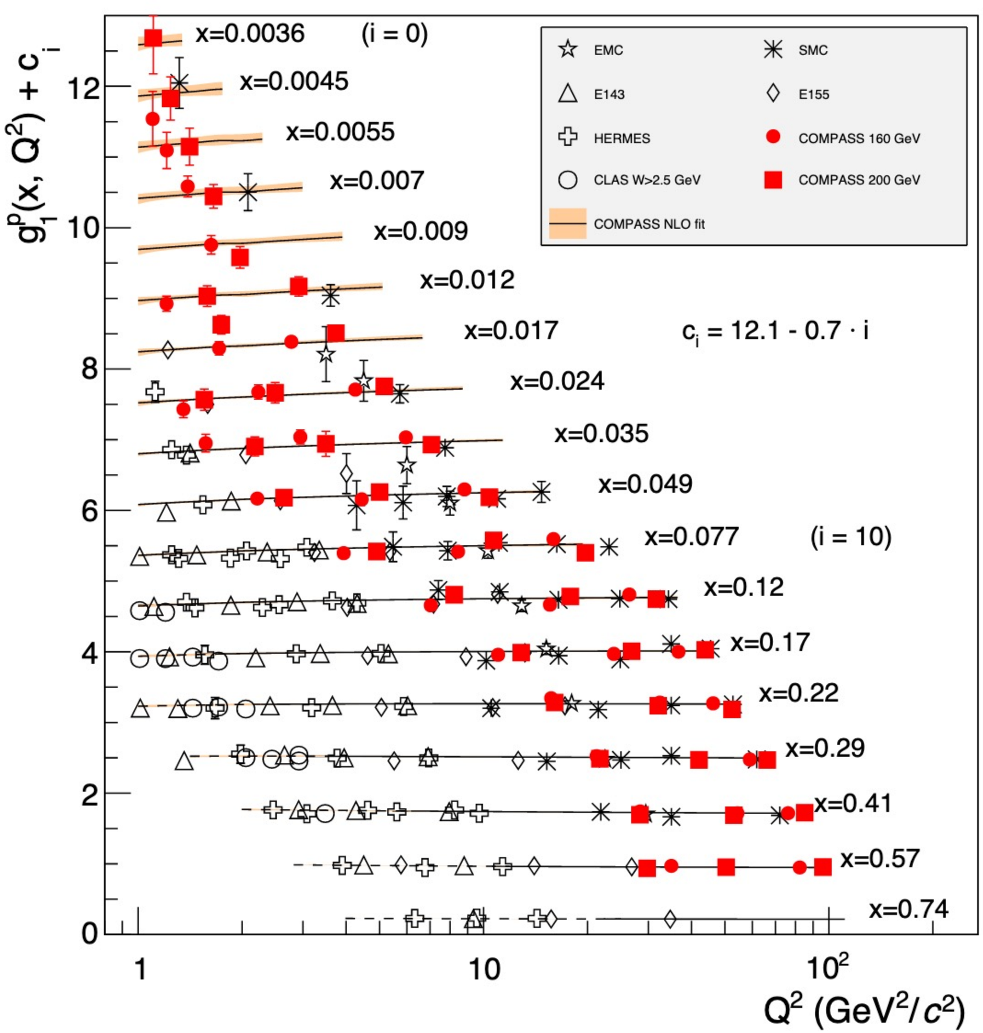




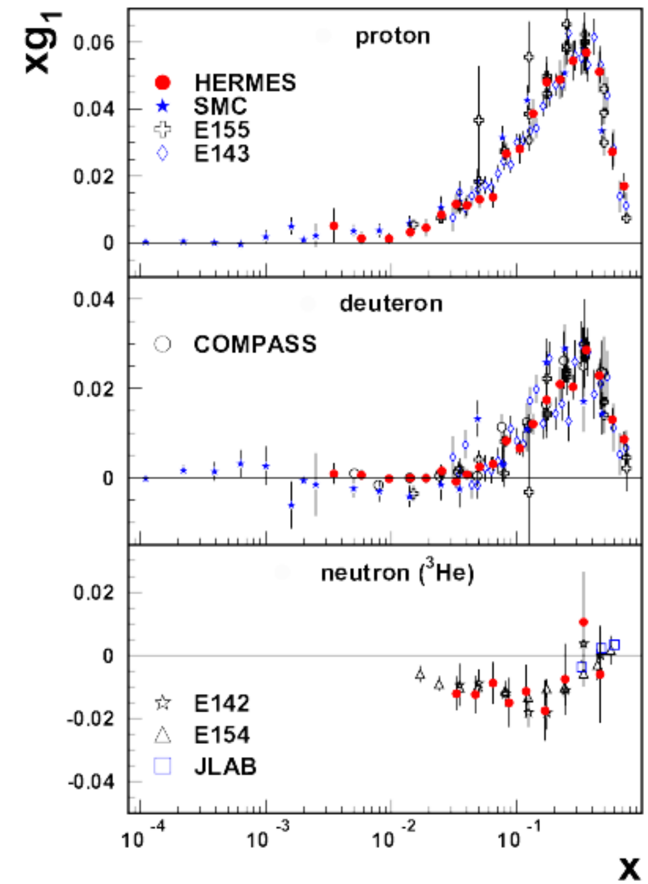


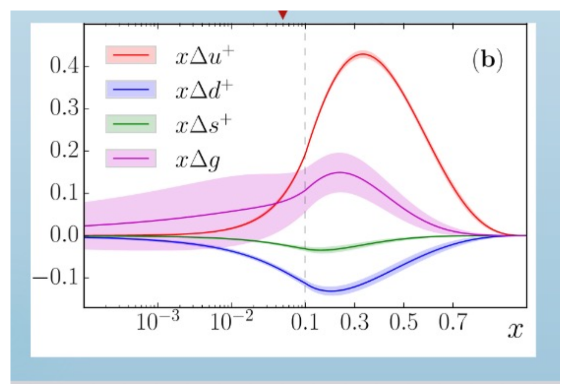
Q^2 evolution: the best test of QCD

POLARIZED STRUCTURE FUNCTIONS



PDG (online 2023)





JAM15

Nucleon Spin Structure Study

- 1980s: EMC (CERN) + early SLAC

  quark contribution to proton spin is very small

  $\Delta\Sigma$ = (12+-9+-14)% ! 'spin crisis'

- 1990s-2000s: SLAC, SMC (CERN), HERMES (DESY)

  $\Delta\Sigma$ = 20-30%, the rest: gluon and quark orbital angular momentum

  $$(1/2)\Delta\Sigma + L_q + \Delta G + L_G = 1/2$$

  gauge invariant $$(1/2)\Delta\Sigma + \mathcal{L}_q + J_G = 1/2$$

  Bjorken Sum Rule verified to <10% level

- 2000s-2010s: COMPASS (CERN), HERMES (DESY), RHIC-Spin, JLab, … :

  $\Delta\Sigma$ ~ 30%; ΔG contributes, orbital angular momentum significant

  Needs full spin-flavor separation: valence quarks and sea quarks

  spin moments (sum rules/polarizabilities) → test of QCD theoretic approaches

Reviews: Sebastian, Chen, Leader, arXiv:0812.3535, PPNP 63 (2009) 1;

Chen, arXiv:1001.3898, IJMPE 19 (2010) 1893; …

Summary of Spin Experiments

Observable	H target	D target	^{3}He target
g_1, g_2, Γ_1 & Γ_2 at high Q^2	SLAC JLAB SANE	SLAC	SLAC JLAB E97-117 JLAB E01-012 JLAB E06-014
g_1 & Γ_1 at high Q^2	SMC HERMES JLAB EG1	SMC HERMES JLAB EG1	HERMES
Γ_1 & Γ_2 at low Q^2	JLab RSS	JLab RSS	JLab E94-010 JLab E97-103
Γ_1 at low Q^2	SLAC HERMES JLAB EG1	SLAC HERMES JLAB EG1	HERMES
$\Gamma_1, Q^2 << 1$ GeV^2	JLab EG4	JLab EG4	JLab E97-110
$\Gamma_2, Q^2 << 1$ GeV^2	JLab E08-027		JLab E97-110

g2p

JLab12
A1n
d2n
RGC

COMPASS
RHIC-Spin

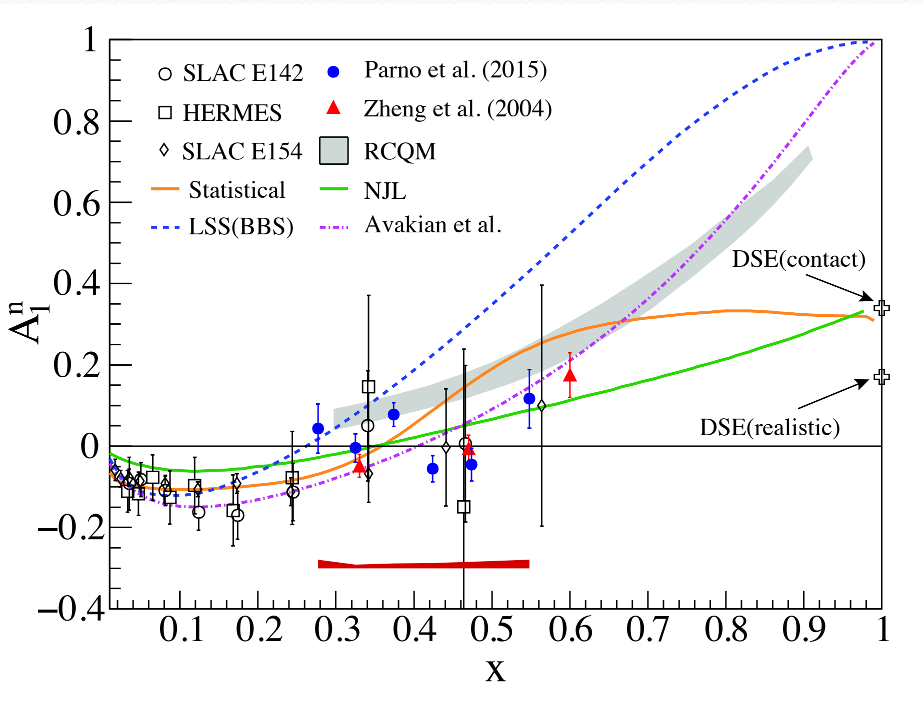
SAGDH

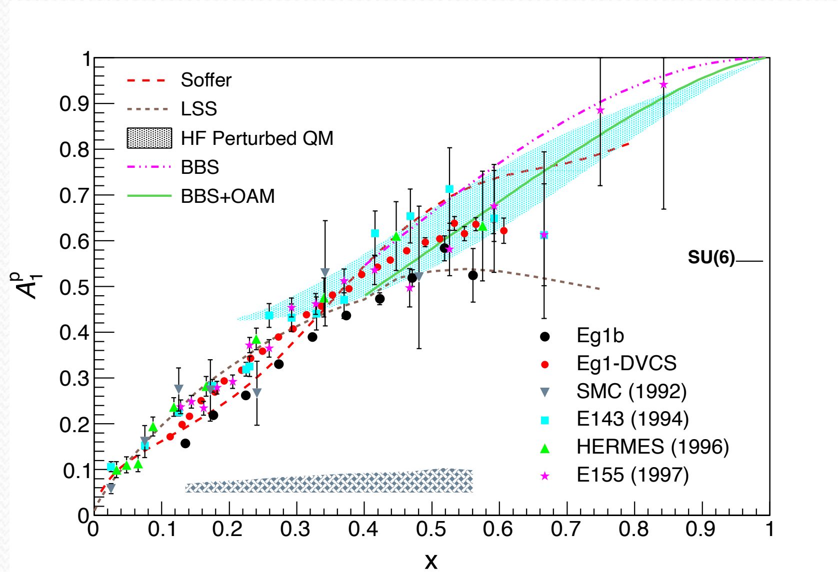
Highlights of JLab12 Spin Program I
Spin Structure in Valence Quark Region

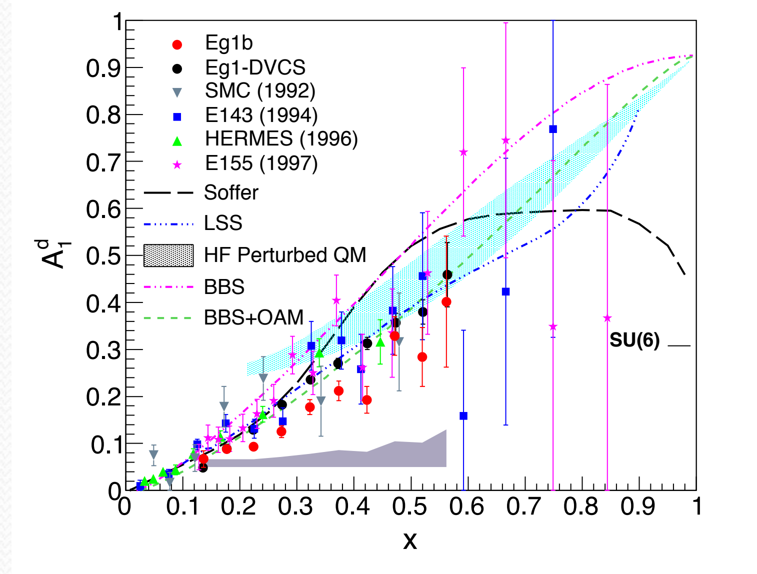
- **Preliminary results from A1n(^{3}He)@high-x:**
  spin structure in valence region
- **Overview of RGC@CLAS12: A1p (A1d) @high-x**
  spin structure with longitudinally polarized p and d

A_1 at High-x: World Data

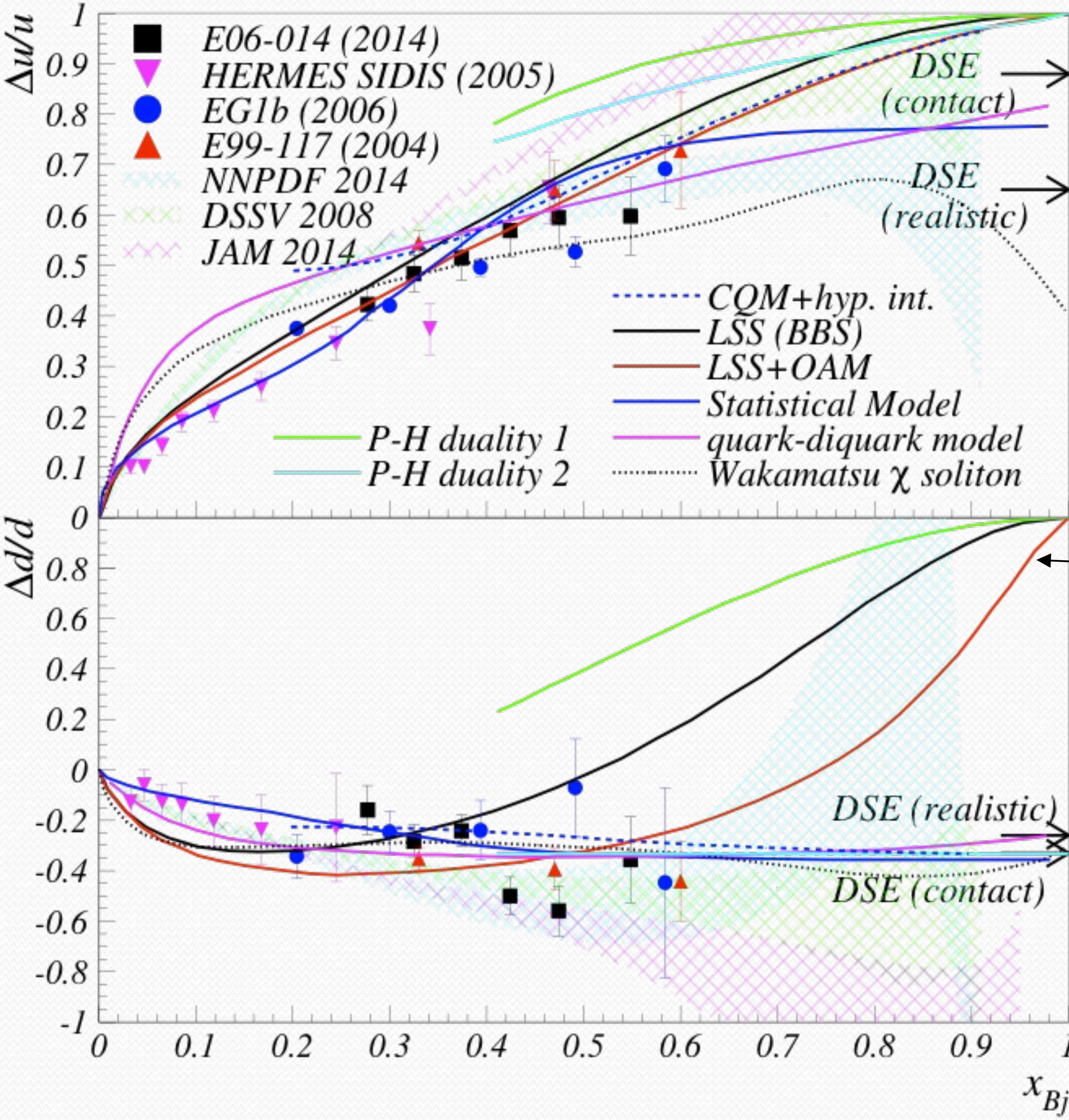
- a clean domain where QCD (and many other models) can make predictions for (the ratio of) structure functions
- ratios of pol/unpol pdfs at x→ 1 provide unambiguous, scale invariant, non-perturbative features of QCD







Simple Spin-flavor Decomposition at High-x



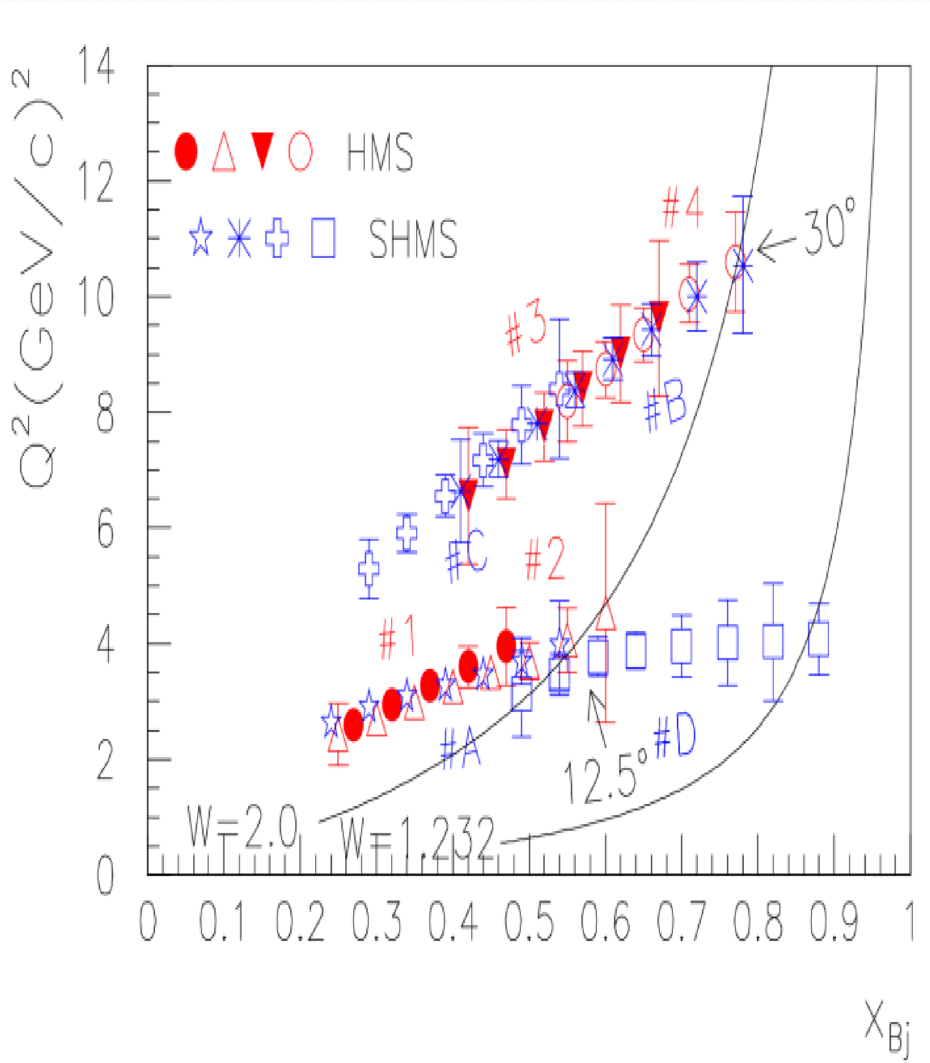
$$\frac{\Delta u+\Delta\bar{u}}{u+\bar{u}}=\frac{4}{15}\frac{g_1^p}{F_1^p}(4+R^{du})-\frac{1}{15}\frac{g_1^n}{F_1^n}(1+4R^{du})$$

$$\frac{\Delta d+\Delta\bar{d}}{d+\bar{d}}=\frac{-1}{15}\frac{g_1^p}{F_1^p}\left(1+\frac{4}{R^{du}}\right)+\frac{4}{15}\frac{g_1^n}{F_1^n}\left(4+\frac{1}{R^{du}}\right)$$

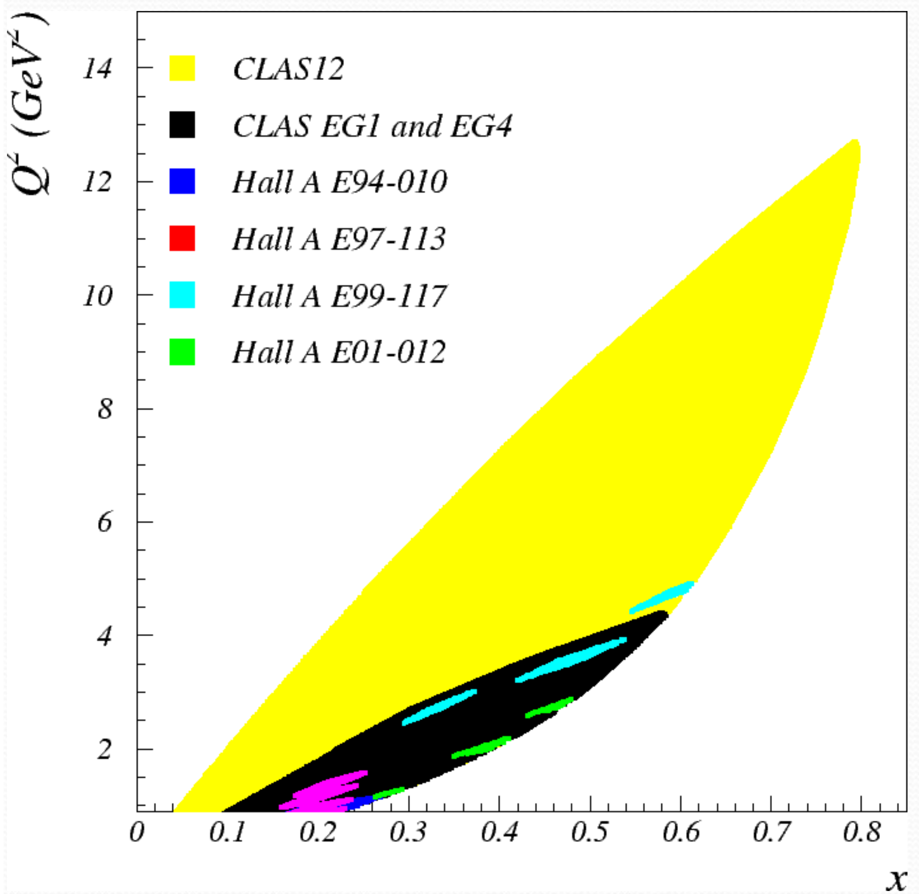
pQCD with quark OAM,

Reaching Deeper Valence Quarks Region with 12 GeV

Hall C A_1^n Kinematics

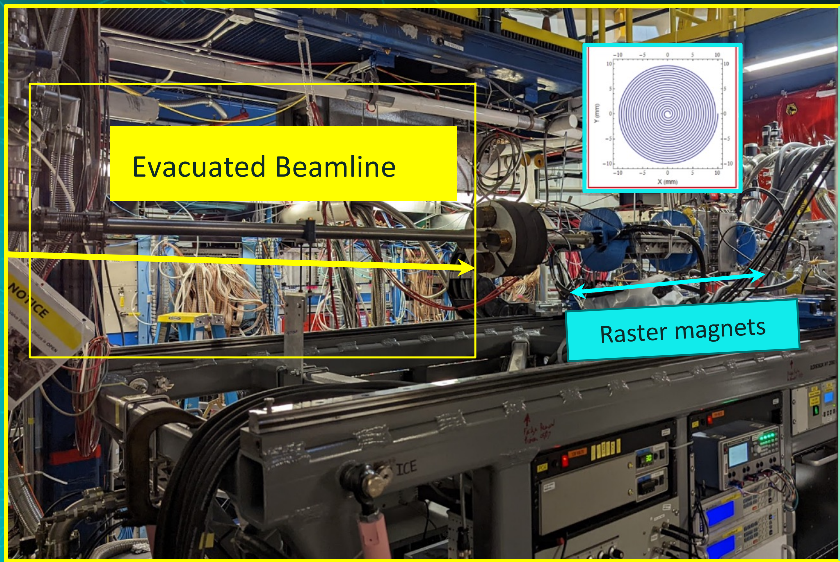


CLAS12 Kinematics



RGC@CLAS12 with Longitudinally Polarized proton/deuteron Targets

P. Pandey



RGC scheduled for 9 calendar months (240 calender days), data collected for 190 days, 80% of allotted beam time.

Collected data from 06/11/2022 to 03/20/2023 with some breaks due to Magnet power supply failure (firmware issue) and configuration changes.

Proposal ID	Title
E12-06-109	Longitudinal Spin Structure of the Nucleon
E12-06-109A	DVCS on the Neutron with Polarized Deuterium Target
E12-06-119(b)	DVCS on Longitudinally Polarized Proton Target
E12-07-107	Spin-Orbit Correlations with Longitudinally Polarized Target
E12-09-007(b)	Study of Partonic Distributions using SIDIS K Production
E12-09-009	Spin-Orbit Correlations in K Production with Polarized Targets

See G. Matousek's talk

A1n@High-x: E12-06-110 in Hall C

X. Zheng's talk

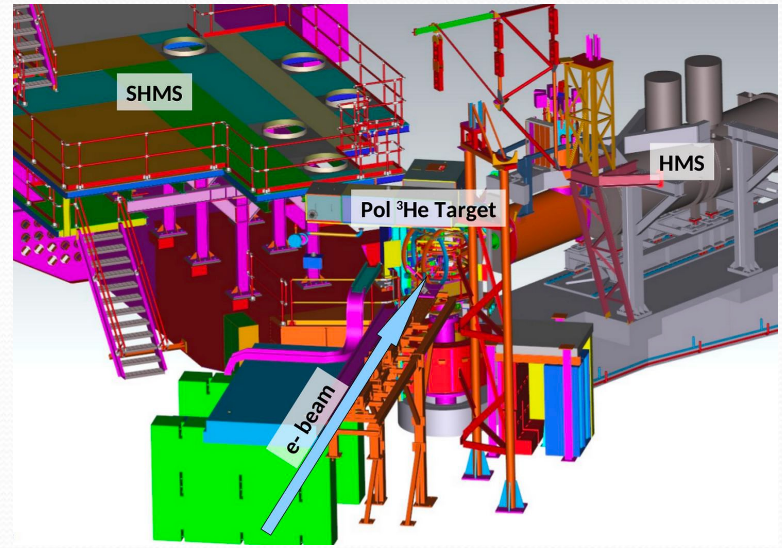
Spokespersons: X. Zheng, G. Cates, J. P. Chen, Z. E. Meziani

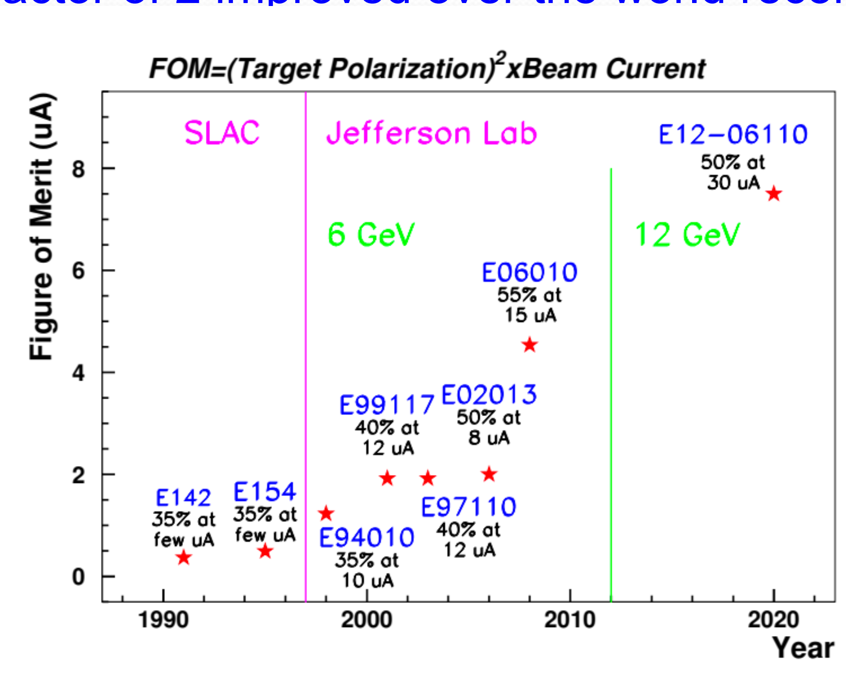
Ph.D Students: M. Chen, M. Rehfuss

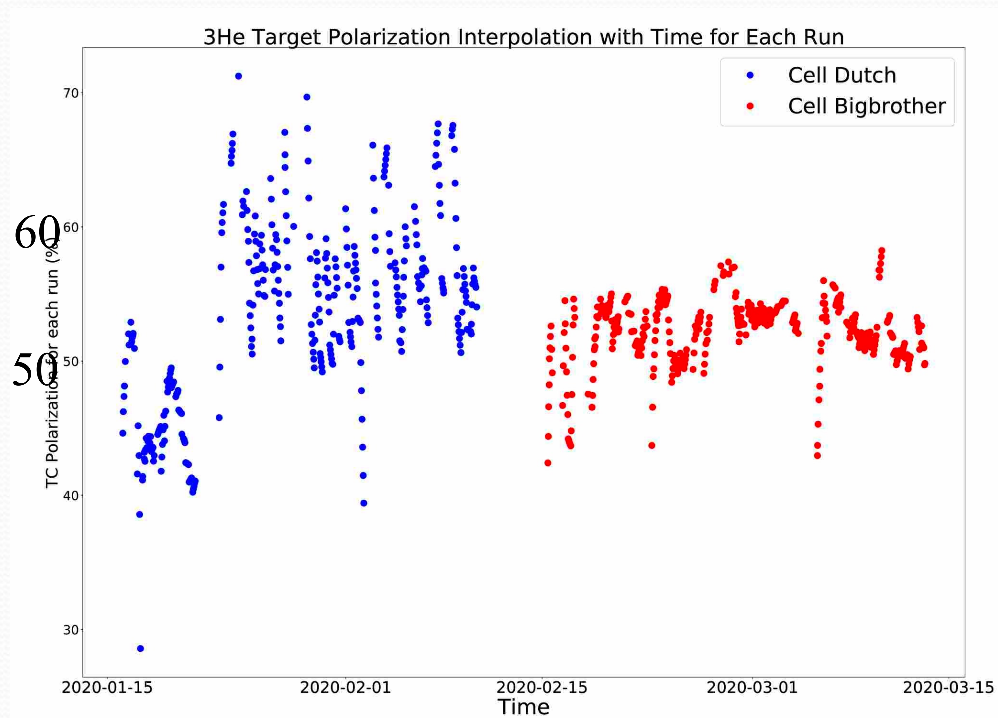
30 uA, 85% polarized 10.4 GeV electron beam

40 cm L/T polarized ^{3}He with in-beam polarization reach up to 60% (average ~ 50-55%)

luminosity (2×10^{36} cm^{-2}s^{-1}) and FOM are a factor of 2 improved over the world record



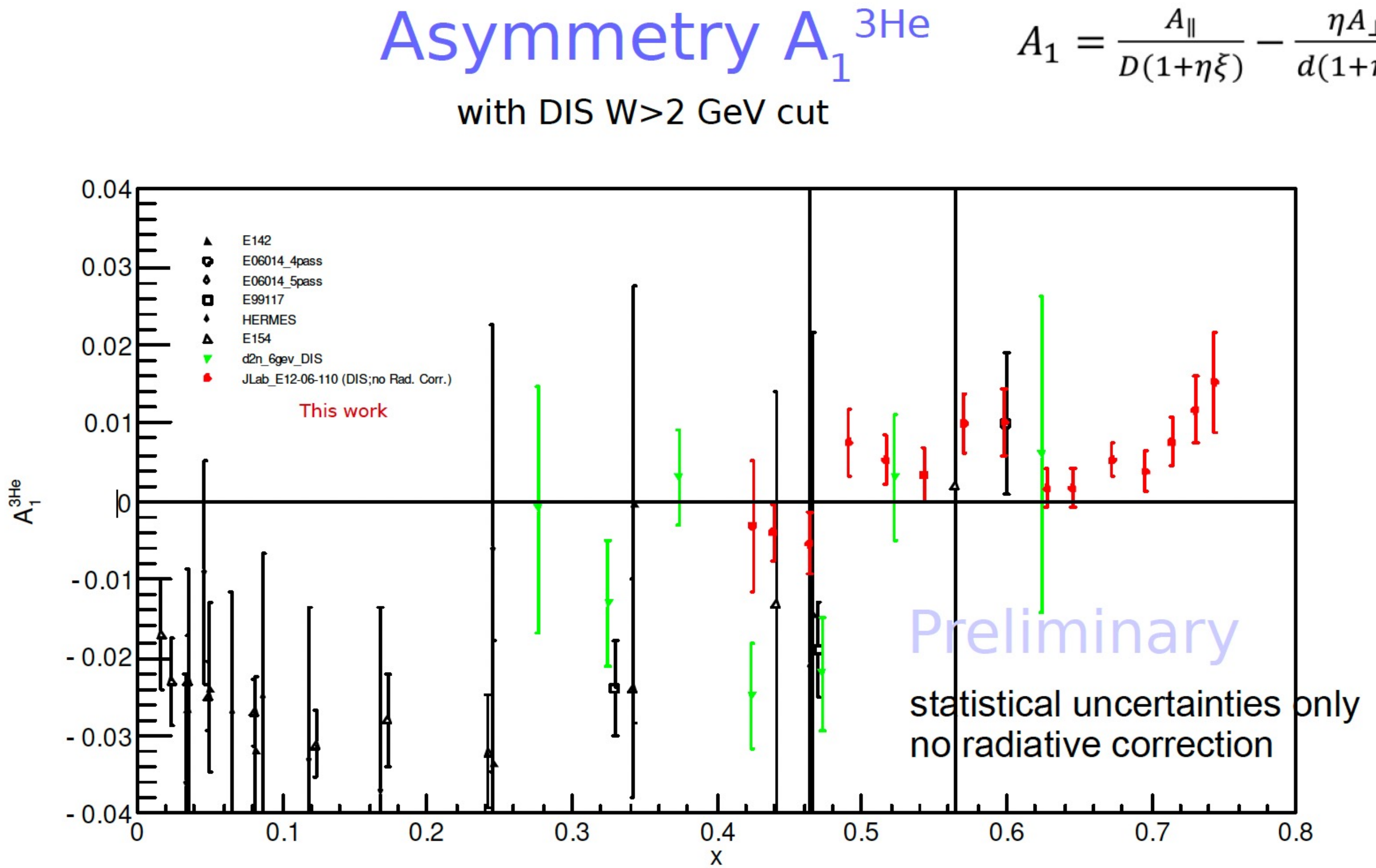




Further improvement for the ongoing GEn experiment, See C. Jantzi and A. Tadeoalli's talks

A1n@High-x: Preliminary Results

$$A_1 = \frac{A_\parallel}{D(1+\eta\xi)} - \frac{\eta A_\perp}{d(1+\eta\xi)}$$



- Credit to Mingyu Chen (UVA)

Highlights of JLab12 Spin Program II
Spin Moments @ Intermediate Q^2

Preliminary results from d2n(^3He) in Hall C:

twist-3 matrix element → quark-gluon correlations
(color polarizability/color Lorentz force)

6 GeV Results for d2 Moment

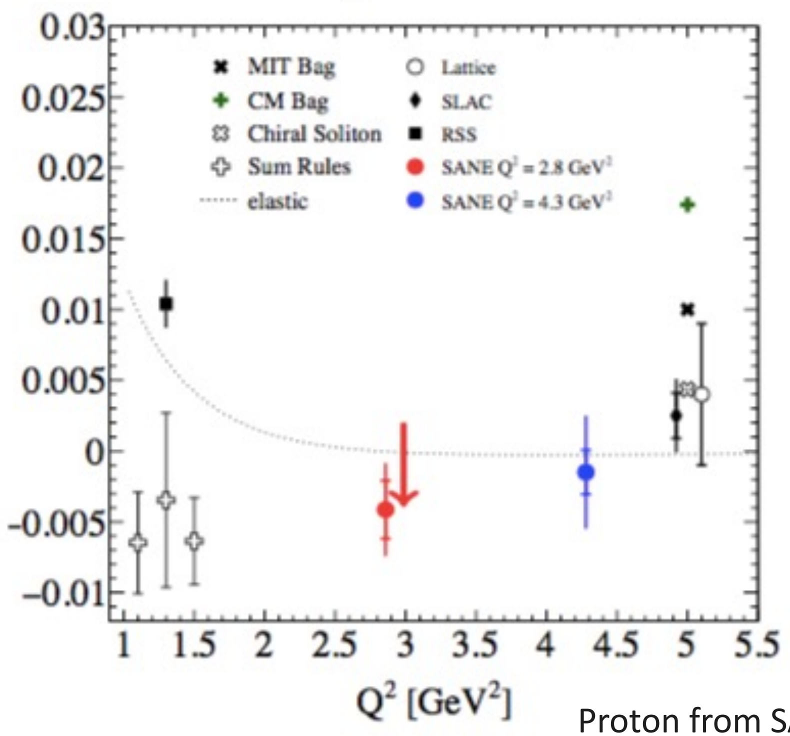
Dynamic twist-3 matrix element

$$\int_0^1 x^2\{2g_1 + 3g_2\}dx = d_2$$

Interpretations of d_2

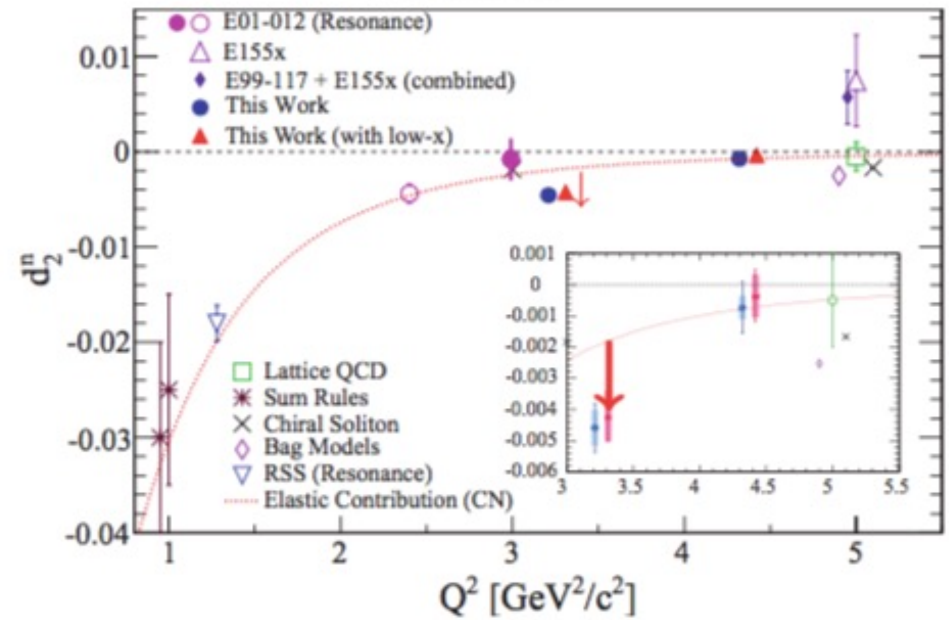
- Color Polarizabilities (X.Ji 95, E. Stein et al. 95)
- **Average Color Lorentz force** (M.Burkardt)

proton



Proton from SANE, PRL 122, 022002 (2019)

neutron



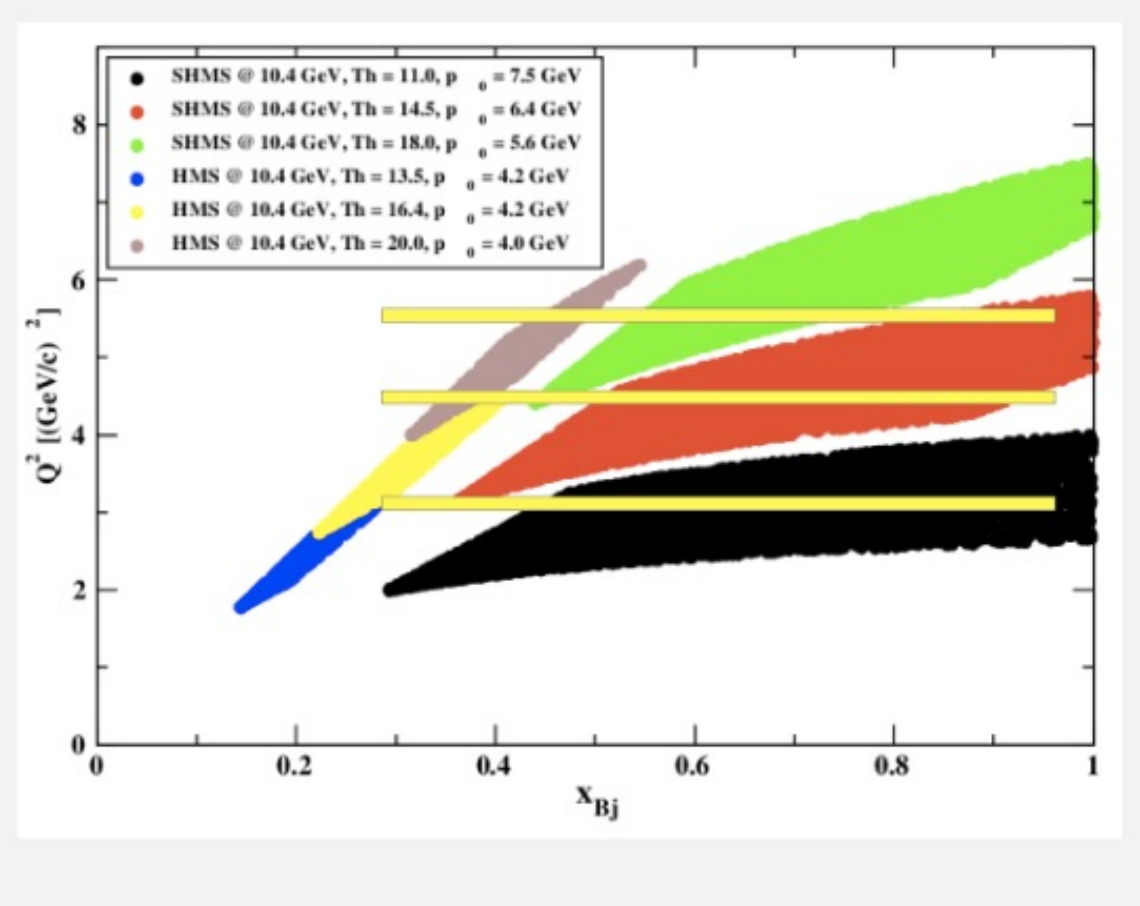
Neutron from d_2^n experiment: D.Flay, et.al. PRD.94(2016)no.5,052003

12 GeV d_2^n

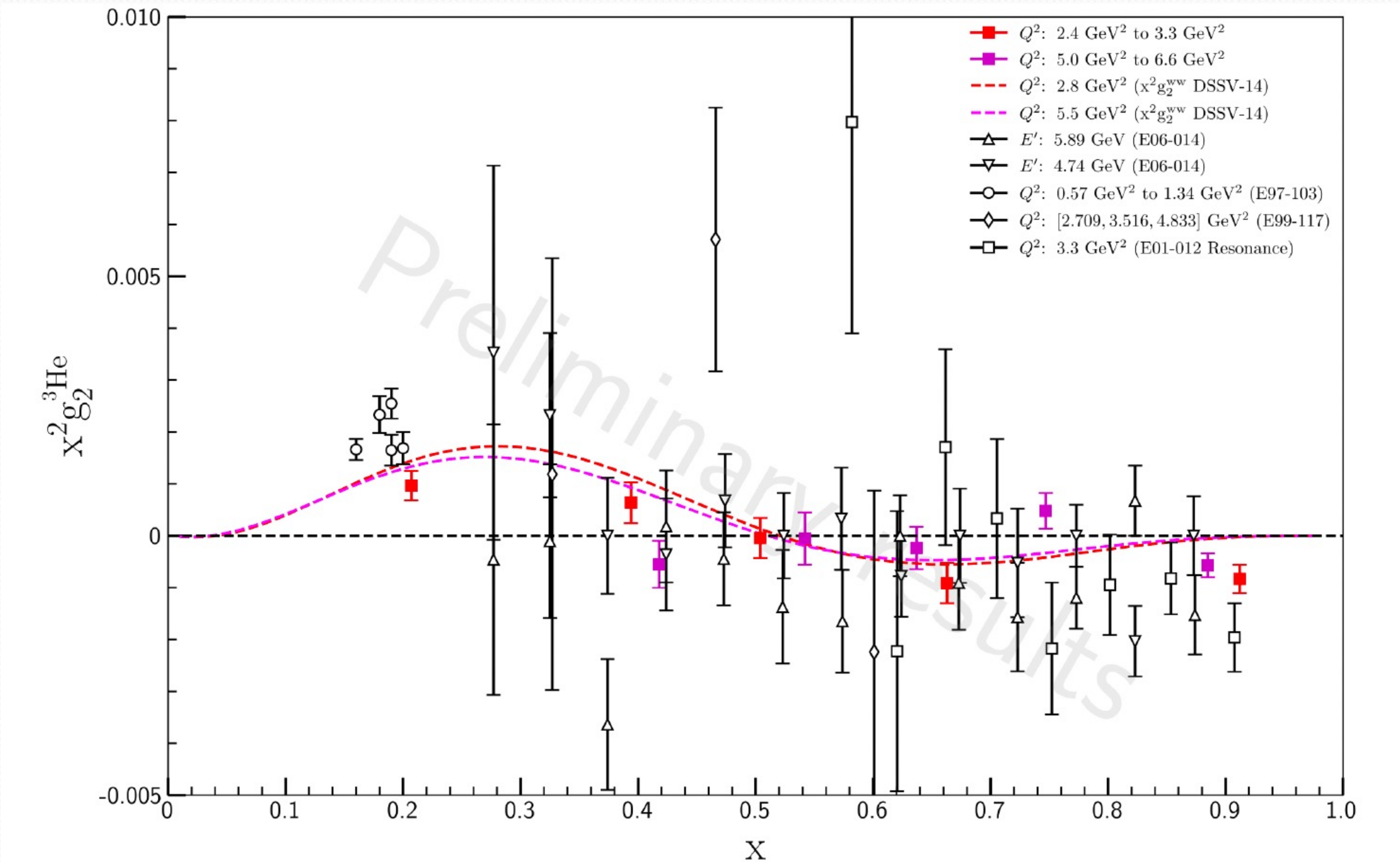
12 GeV d_2^n: Color Polarizability/Lorentz Force

Spokesmen: T. Averett, W. Korsch, Z.-E. Meziani, B. Sawatzky
PhD Students: J. Chen, M. Roy

- Measurement of g_1 and g_2 structure functions and d_2 moments at 3 $GeV^2 < Q^2 <$ 5.5 GeV^2 for the neutron using a polarized ^3He target
- Study quark-gluon correlations (twist-3) and provide a benchmark test of LQCD calculations.
- Completed data taking in 2020



Preliminary Results on g2n



Spin Sum Rules and Q^2 dependence

Sum Rules

Nucleon Structure ←→ Global Properties

mass, spin, magnetic moment, polarizabilities, …

How the structure is related (gives rise) to the global properties?
How the global properties emerging from the structure?

→ Help understand Strong QCD

GDH Sum Rule and Generalization

Circularly polarized photon on longitudinally polarized nucleon

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

- A fundamental relation between the nucleon spin structure and its anomalous magnetic moment
- Based on **general** physics principles
  - Lorentz invariance, gauge invariance → low energy theorem
  - unitarity → optical theorem
  - casuality → unsubtracted dispersion relation applied to forward Compton amplitude
- Generalized GDH Sum Rule. (Ji and Osborne (J. Phys. G27, 127, 2001):

Compton Amplitude S_1

$$S_1(Q^2) = 4\int_{el}^{\infty}\frac{G_1(Q^2,\nu)d\nu}{\nu}$$

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: axial charge (from neutron β-decay)
C_{NS}: Q^2-dependent QCD corrections (for flavor non-singlet)

- A fundamental relation relating an integration of spin structure functions to axial-vector coupling constant (axial charge)
- Based on Operator Product Expansion within QCD or Current Algebra
- Valid at large Q^2 (higher-twist effects negligible)
- Data are consistent with the Bjørken Sum Rule at 5-10 % level

Connecting GDH with Bjorken Sum Rules

- Q^2-evolution of GDH Sum Rule provides **a bridge linking strong QCD to pQCD**
  - Bjorken and GDH sum rules are two limiting cases

    High Q^2, Operator Product Expansion : $S_1(p\text{-}n) \sim g_A$ → Bjorken

    $Q^2 \rightarrow 0$, Low Energy Theorem: $S_1 \sim \kappa^2$ → GDH

  - High Q^2 (> ~1 GeV^2): Operator Product Expansion
  - All Q^2 region: Lattice QCD calculations
  - Low Q^2 region (< ~0.1 GeV^2): Chiral Effective Field Theory (χEFT)

Calculations: BχPT: Ji, Kao,…,Vanderhaeghen,…

Lensky, Alarcon & Pascalutsa

Bernard, Hemmert, Meissner

Spin Polarizabilities Sum Rules

Spin polarizability sum rules involve higher moments:

Generalized forward spin polarizability:

$$\gamma_0 = \frac{4e^2M^2}{\pi Q^6} \int x^2 (g_1 - \frac{4M^2}{Q^2} x^2 g_2) dx$$

Longitudinal-Transverse polarizability:

$$\delta_{LT} = \frac{4e^2M^2}{\pi Q^6} \int x^2 (g_1 + g_2) dx$$

We do not know how to measure directly generalized spin polarizabilities. The spin polarizability sum rules are used to access them.
They can be calculated with χEFT and Lattice QCD

News: Lattice QCD started calculations with 4-point functions on polarizabilities

F. Lee *et al*. (U. George Washington); X. Feng *et al*. (Peking U.)

Low-Q Spin Experiments @ JLab

- **Hall B EG4: proton g_1:** Spokespeople: M. Ripani, M. Battaglieri, A. Deur, R. de Vita
  Students: H. Kang, K. Kovacs
  X. Zheng et al., Nature Physics, vo. 17 736-741 (2021)
- **Hall A g2p: proton g_2:** Spokespeople: K. Slifer, J. P. Chen, A. Camsonne, D. Crabb
  Students: D. Ruth, R. Zielinski, C. Gu, M. Allada (Cummings), T. Badman, M. Huang, J. Liu, P. Zhu
  D. Ruth et al, Nature Physics 18, 1441 (2022)
- **Hall A SAGDH: neutron g_1 and g_2 with L/T polarized ^{3}He**

Spokespeople: J. P. Chen, A. Deur, F. Garibaldi.

Students: V. Sulkosky, C. Peng, J. Singh,V. Laine, N. Ton, J. Yuan.

V. Sulkosky et al., Nature Phys., 17 687 (2021)
V. Sulkosky et al., PLB 805 135428 (2020)

Combining EG4 and SAGDH to form Bjorken Sum: **A. Deur et al., Phys. Lett. B 825 (2022) 136878**
Extracting effective coupling a_{g1}: **A. Deur, et al., Particles, 5-171 (2022)**

Talk by A. Deur on Wednesday
Low-Q workshop at Crete, Greece, May 2023 (https://sites.temple.edu/lowq/)

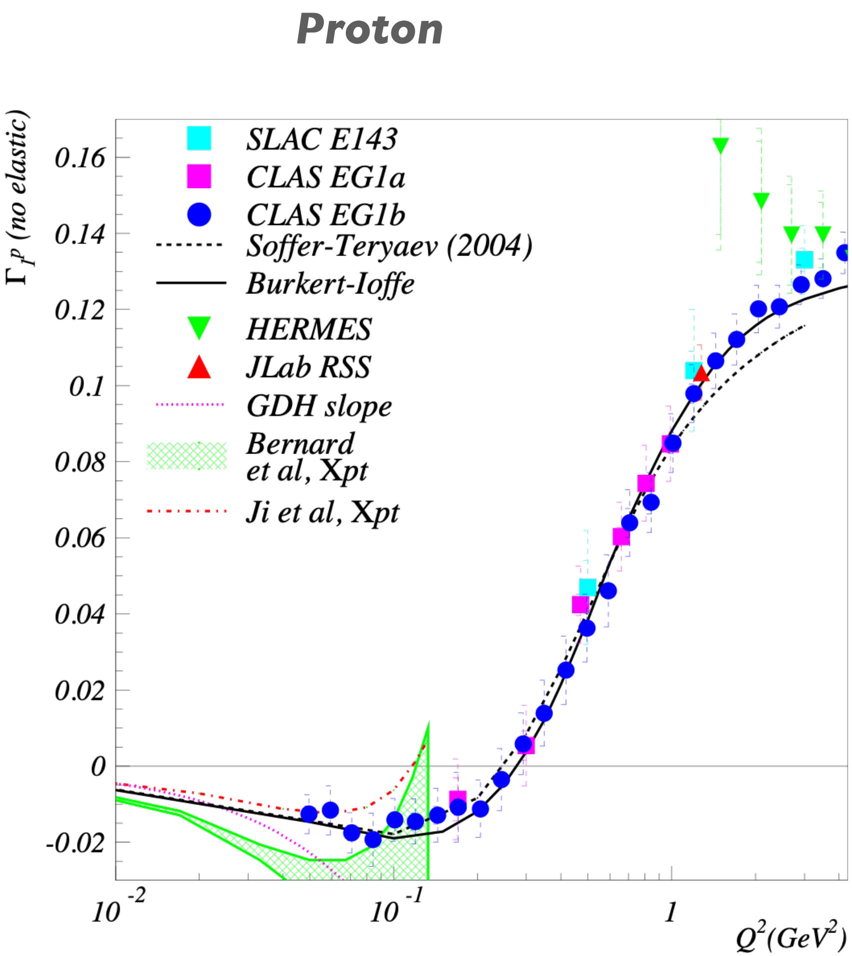
Measurement of Low-q Spin Sum Γ_1 and Γ_2 for proton and neutron

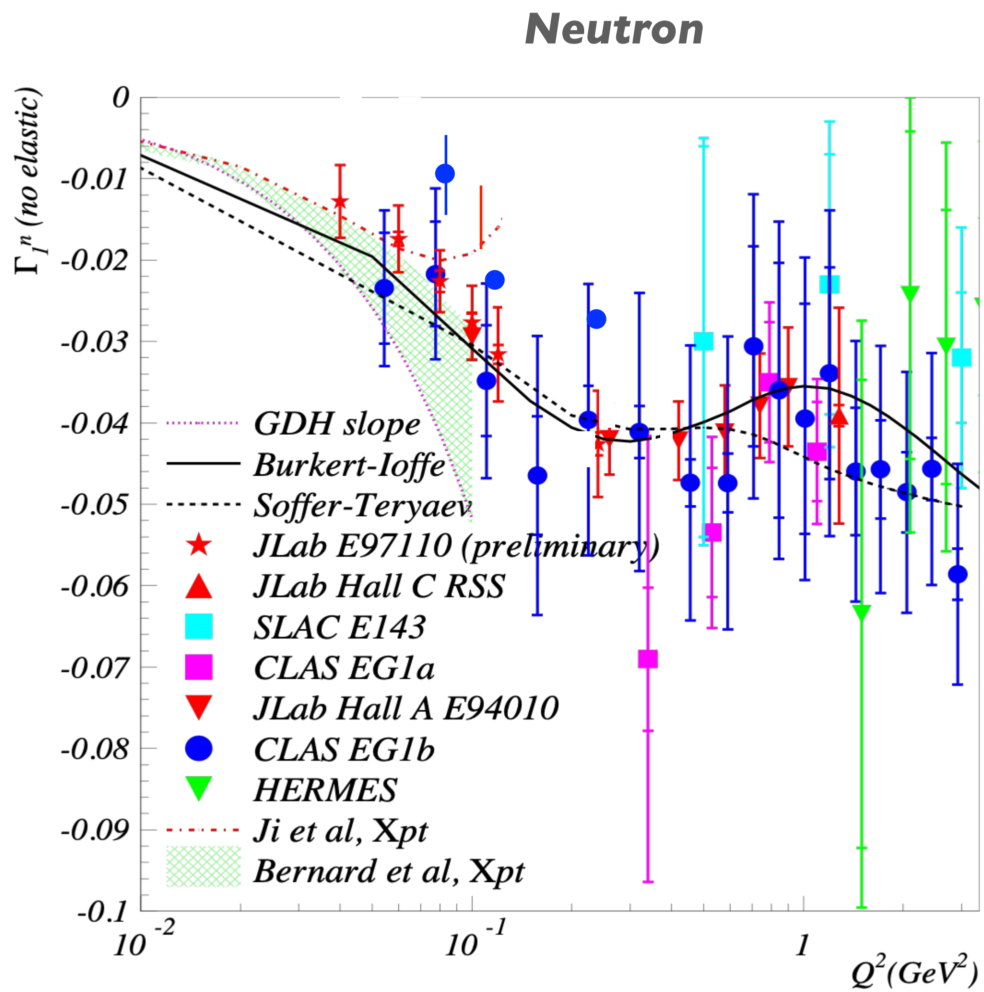
Testing χEFT and study strong QCD

X. Zheng et al., Nature Physics, 17, 736-741 (2021)

V. Sulkosky et al., Physics Letter B 805, 135428 (2020)

Previous world Γ_1 data before low-Q experiments



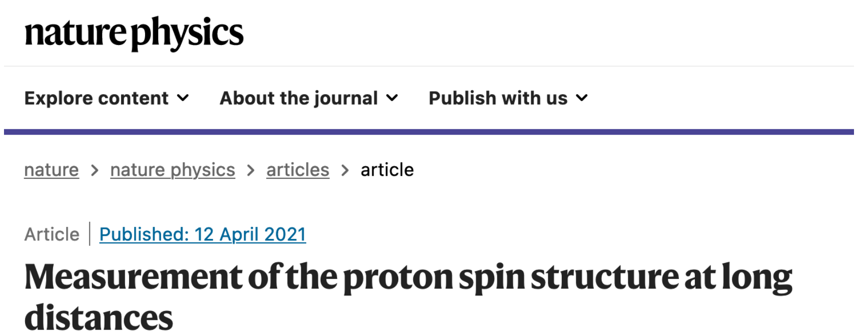


Precise mapping of spin structure function moments in intermediate Q^2 region
PQCD, models and data agree.
How about χEFT predictions? Not clear.

EG4: new low-Q data on Γ_1 for proton

A. Deur's talk

X. Zheng et al., Nature Physics, 17, 736-741 (2021)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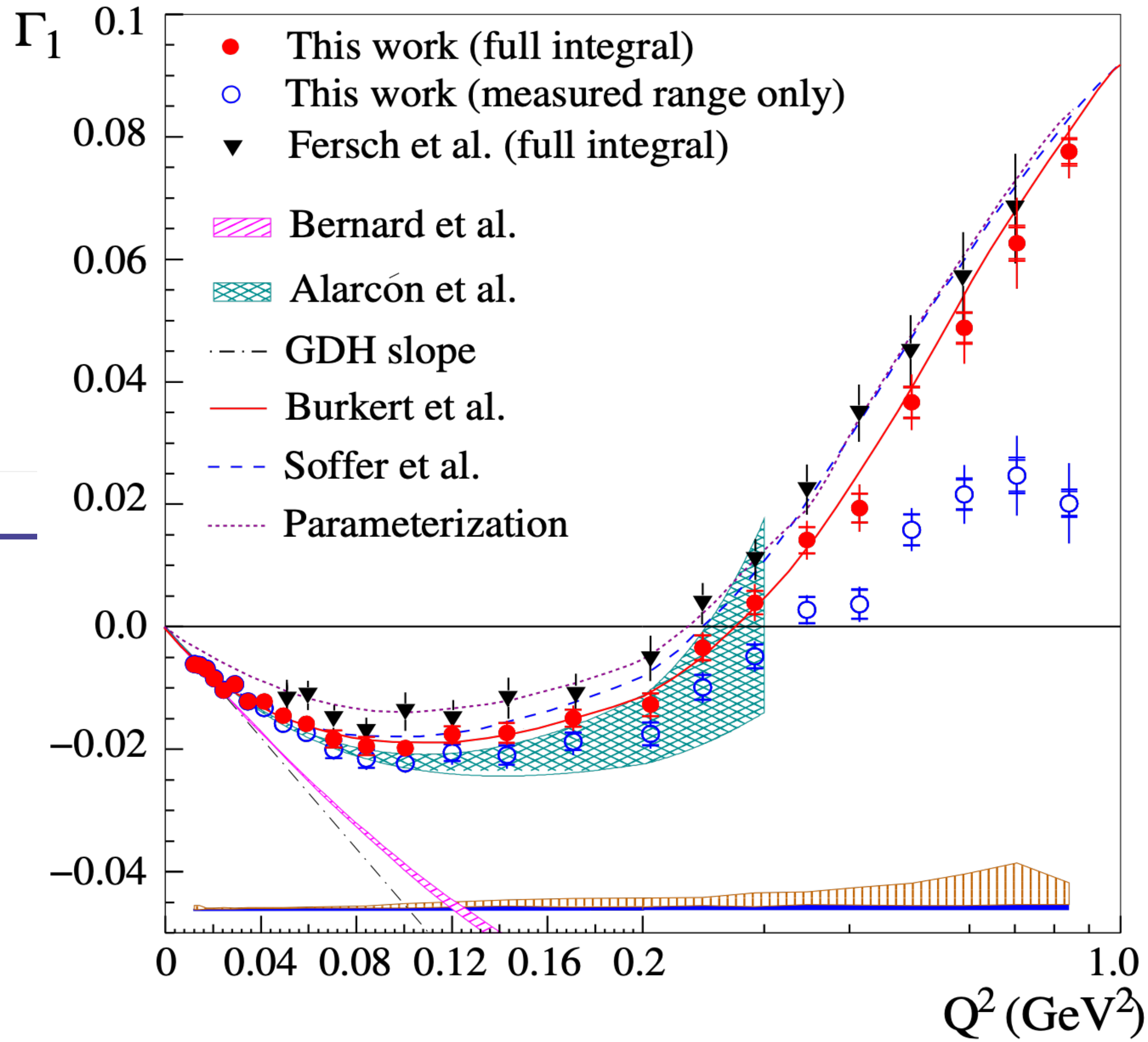
Article | Published: 12 April 2021

Measurement of the proton spin structure at long distances



- *Slight tension between EG4 and EG1 above Q^2 ~0.1 GeV^2.*
- *EG4 and χEFT agree up to Q^2 ~0.04 GeV^2 (Bernard et al) or Q^2 >0.2 GeV^2 (Alarcón et al.)*
- *Phenomenological models (Pasechnik et al, Burkert-Ioffe) agree well.*

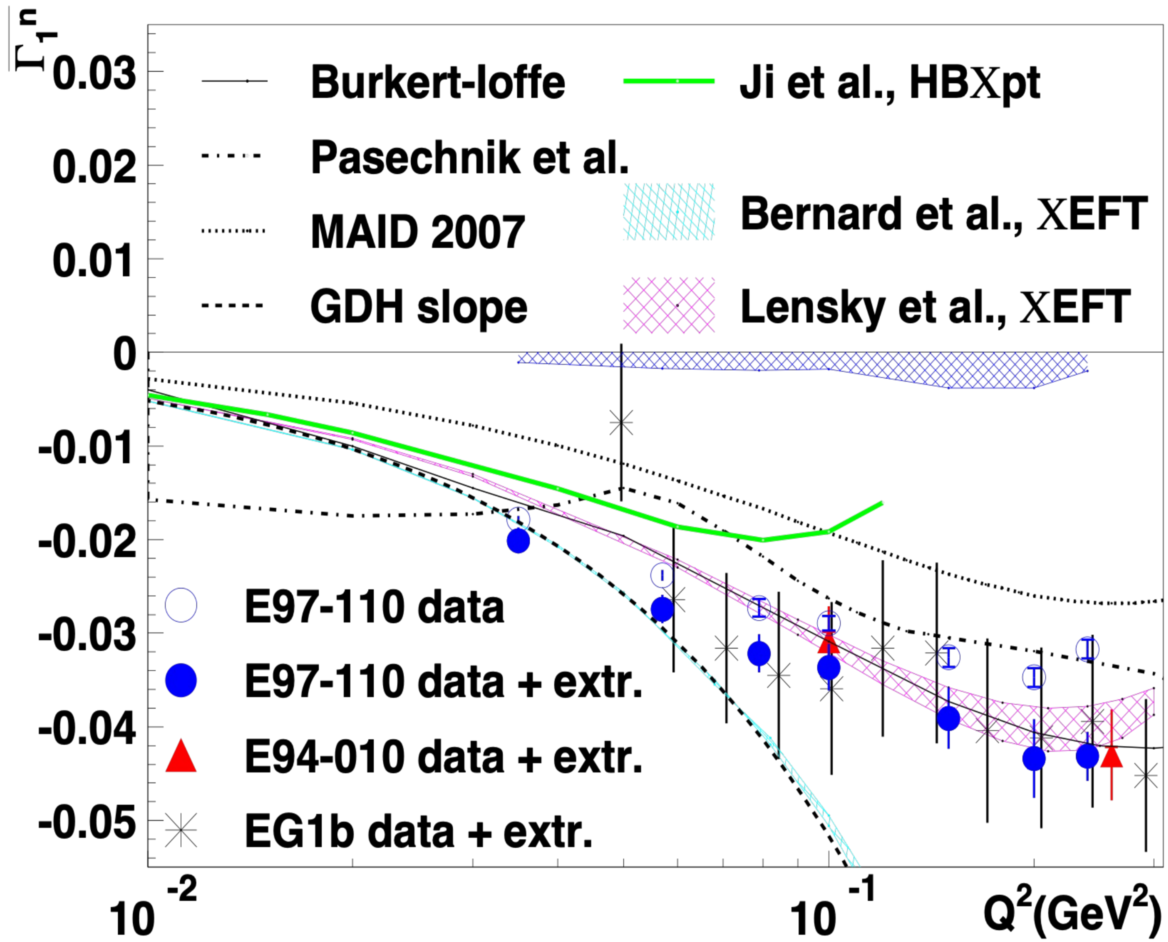
SAGDH: new low-Q data on Γ_1 for neutron

V. Sulkosky et al., Physics Letter B 805, 135428 (2020)

ELSEVIER

Physics Letters B
Volume 805, 10 June 2020, 135428

Measurement of the ^{3}He spin-structure functions and of neutron (^{3}He) spin-dependent sum rules at $0.035 \le Q^2 \le 0.24$ GeV^2



- *E97-110 agree with existing data at larger Q^2 (EG1b, E94-010).*
- *E97-110 and χEFT agree up to Q^2 ~0.06 GeV^2 (Bernard et al) or Q^2 >0.08 GeV^2 (Lensky et al.)*
- *Some phenomenological models (Burkert-Ioffe) agree well with data, other (MAID, Pasechnik et al) not as much.*

Generalized Spin Polarizibilities: γ_0 and δ_{LT}

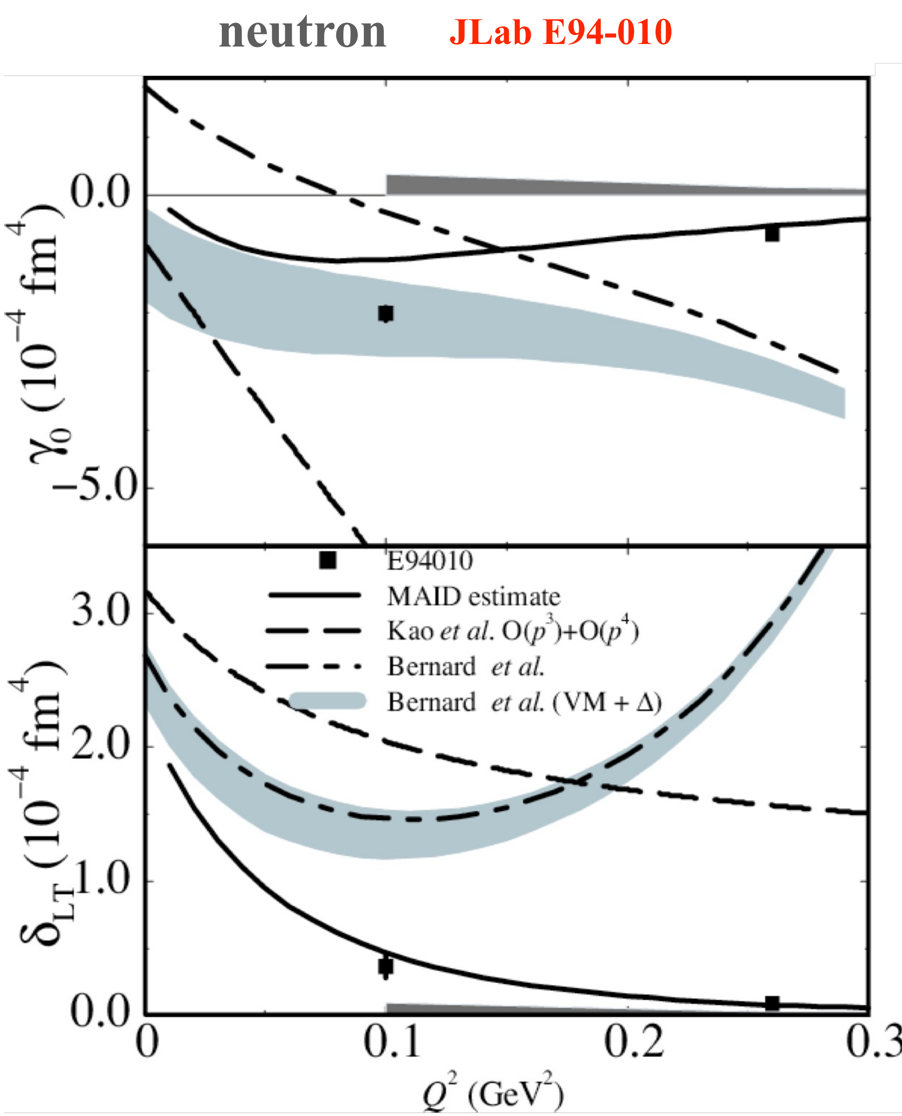
Testing χEFT and study strong QCD

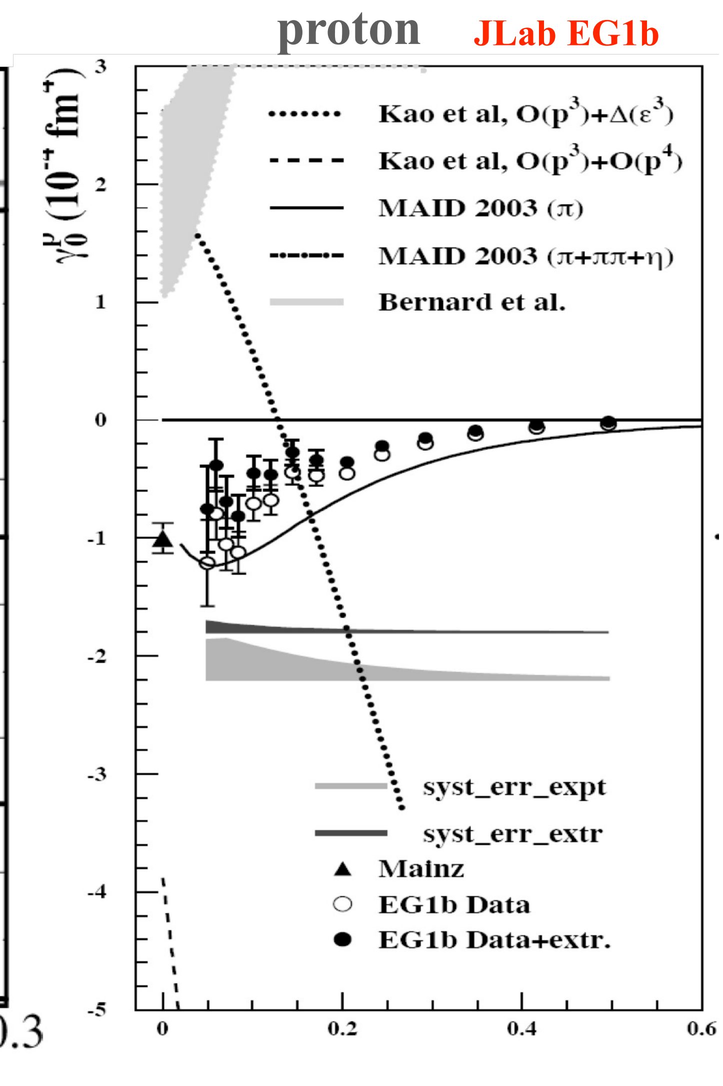
X. Zheng et al.,
Nature Physics,
17, 736-741 (2021)

V. Sulkosky et al.,
Nature Physics,
17, 736-741 (2021)

D. Ruth et al,
Nature Physics
18, 1441 (2022)

Previous JLab spin polarizabilities data before low-Q experiments





Strong disagreement with χEFT predictions available at that time: **"δ_{LT} puzzle"**

EG4 results on $\gamma_0^p(Q^2)$

A. Deur's talk

X. Zheng et al.,
Nature Physics,
17, 736-741 (2021)

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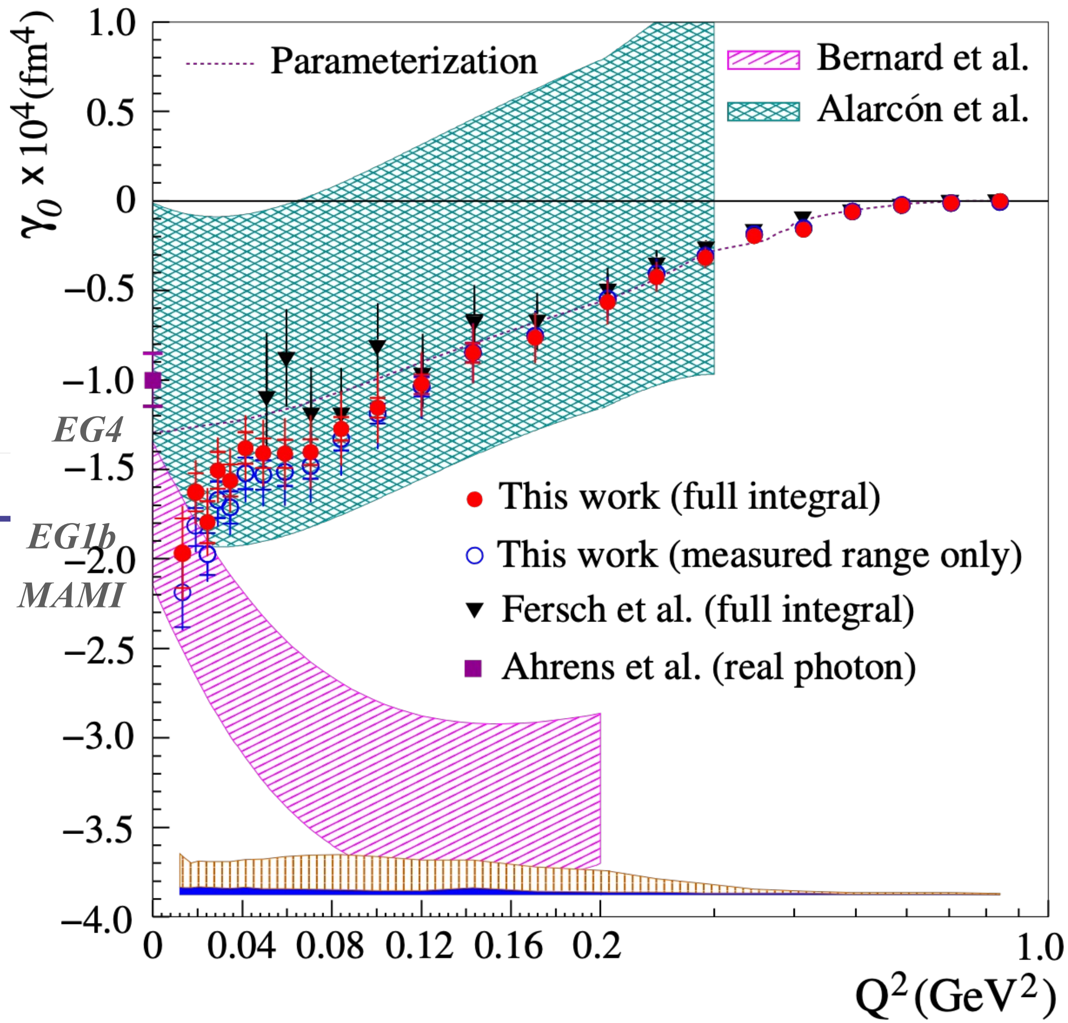
Measurement of the proton spin structure at long distances



- χEFT result of Alarcón et al agrees with data.
- Bernard et al. χPT calculation agrees for lowest Q^2 points.

Generalized forward spin polarizability γ_0^n from SAGDH

V. Sulkosky et al., Nature Physics, 17, 736-741 (2021)

nature physics

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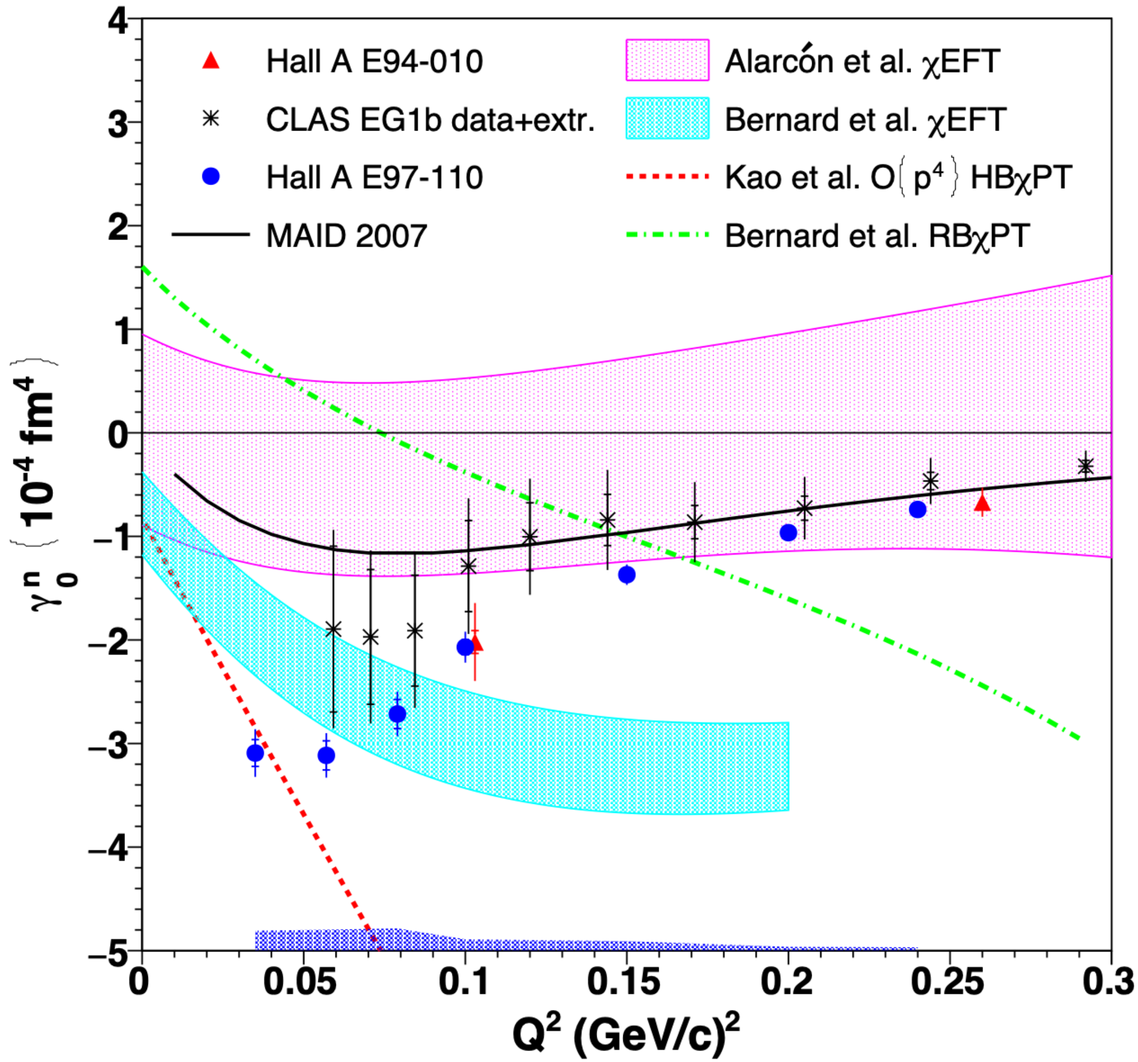
Letter | Published: 31 May 2021

Measurement of the generalized spin polarizabilities of the neutron in the low-Q^2 region



- E97-110 agree with older data at larger Q^2 (EG1b, E94-010). Maid disagrees with the data.
- χEFT result of Alarcón et al disagrees with data.
- Bernard et al. χPT calculation agrees for lowest Q^2 points.

Generalized Interference Spin Polarizability δ_{LT} from SAGDH

V. Sulkosky et al., Nature Physics, 17, 736-741 (2021)

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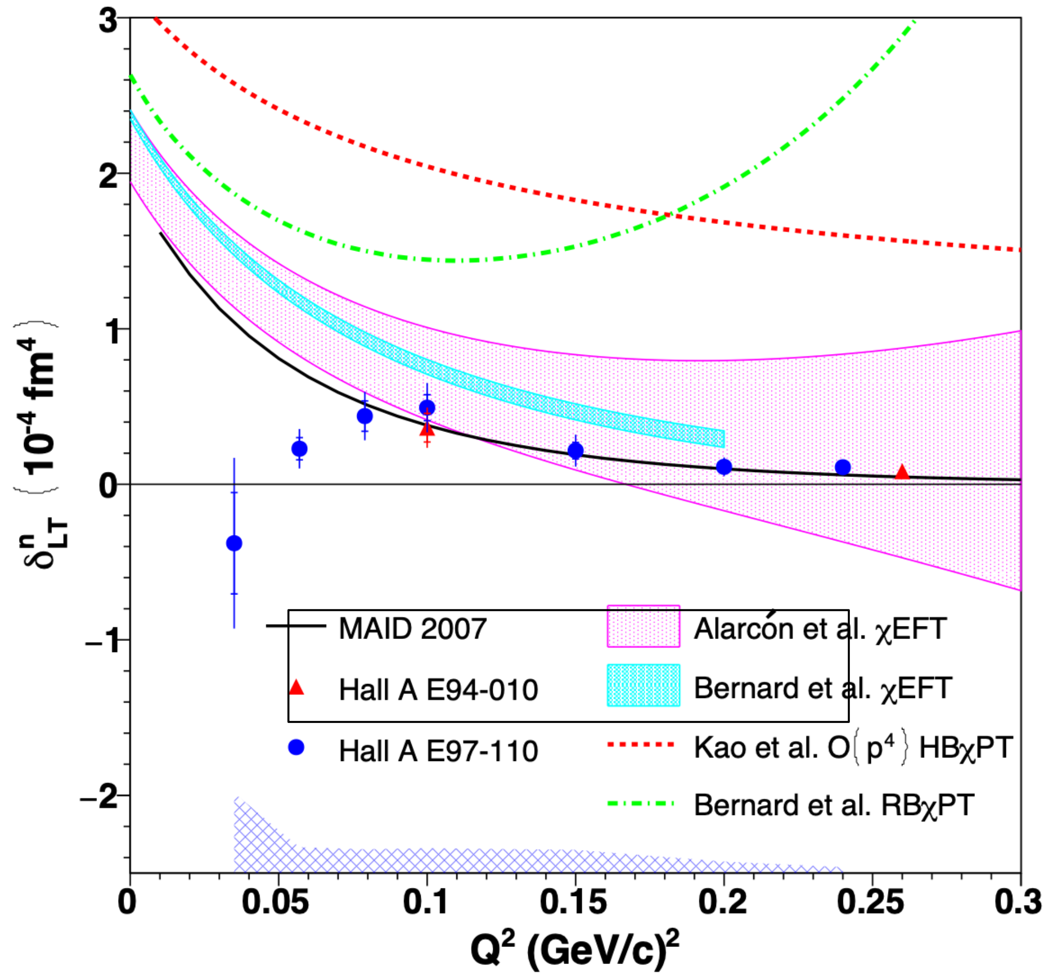
Measurement of the generalized spin polarizabilities of the neutron in the low-Q^2 region



- Good agreement with older data at larger Q^2 and with χEFT & MAID there.
- Disagreement at lower Q^2 (opposite trend)
- **“ $\delta^n_{LT}(Q^2)$ puzzle” remains!**

δ_{LT} for Proton from g2p

D. Ruth et al, Nature Physics 18, 1441 (2022)

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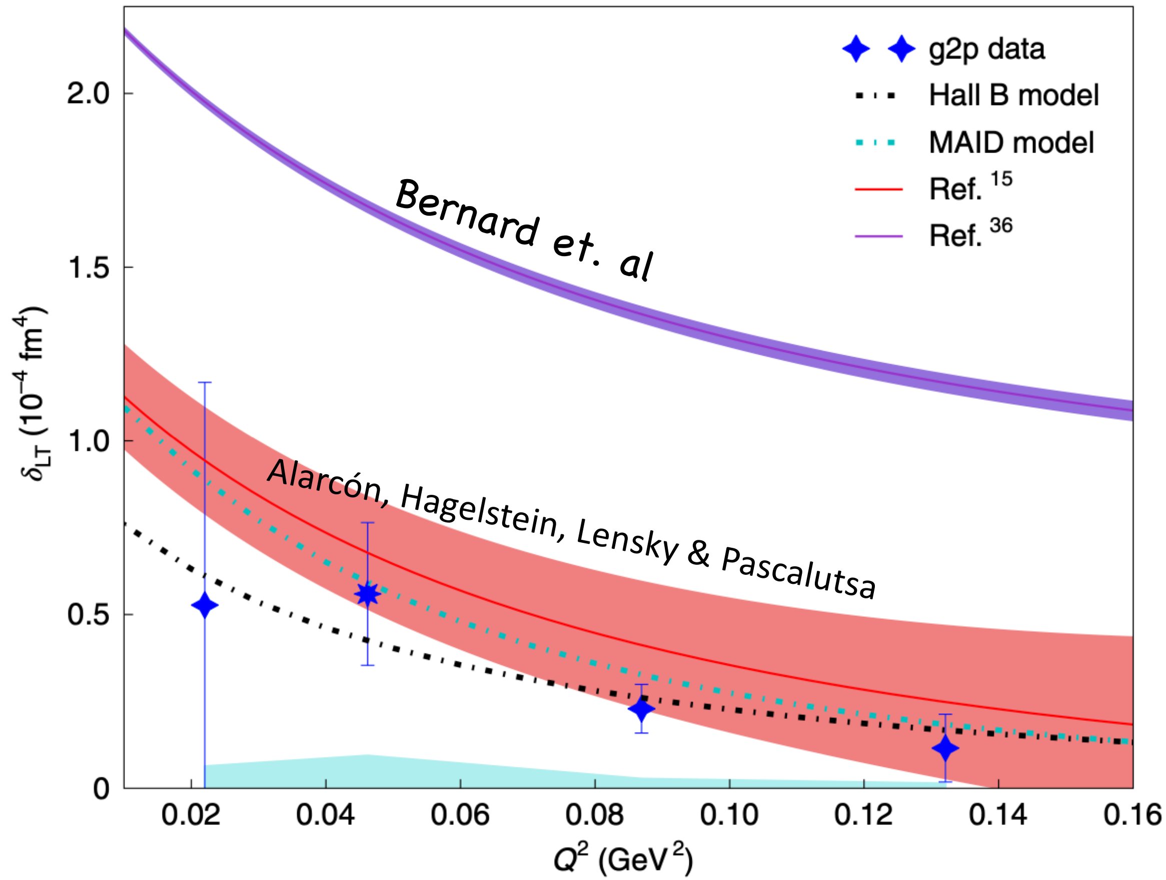
Article | Published: 13 October 2022

Proton spin structure and generalized polarizabilities in the strong quantum chromodynamics regime



- Comparisons with χEFT calculations: favor Alarcon *et al.*, strong disagreement with Bernard *et al.*

Bjorken Sum at Low-Q and Effective α_s

A. Deur, ***et al.***
Physics Letter B 825 (2022) 136878

A. Deur, V. Burkert, J. P. Chen and W. Korsch
Particles, 5-171 (2022)

Bjorken Sum: Γ_1 of *p-n* (EG4 and SAGDH)

A. Deur, *et al.*
Physics Letter B
825 (2022) 136878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Physics Letters B

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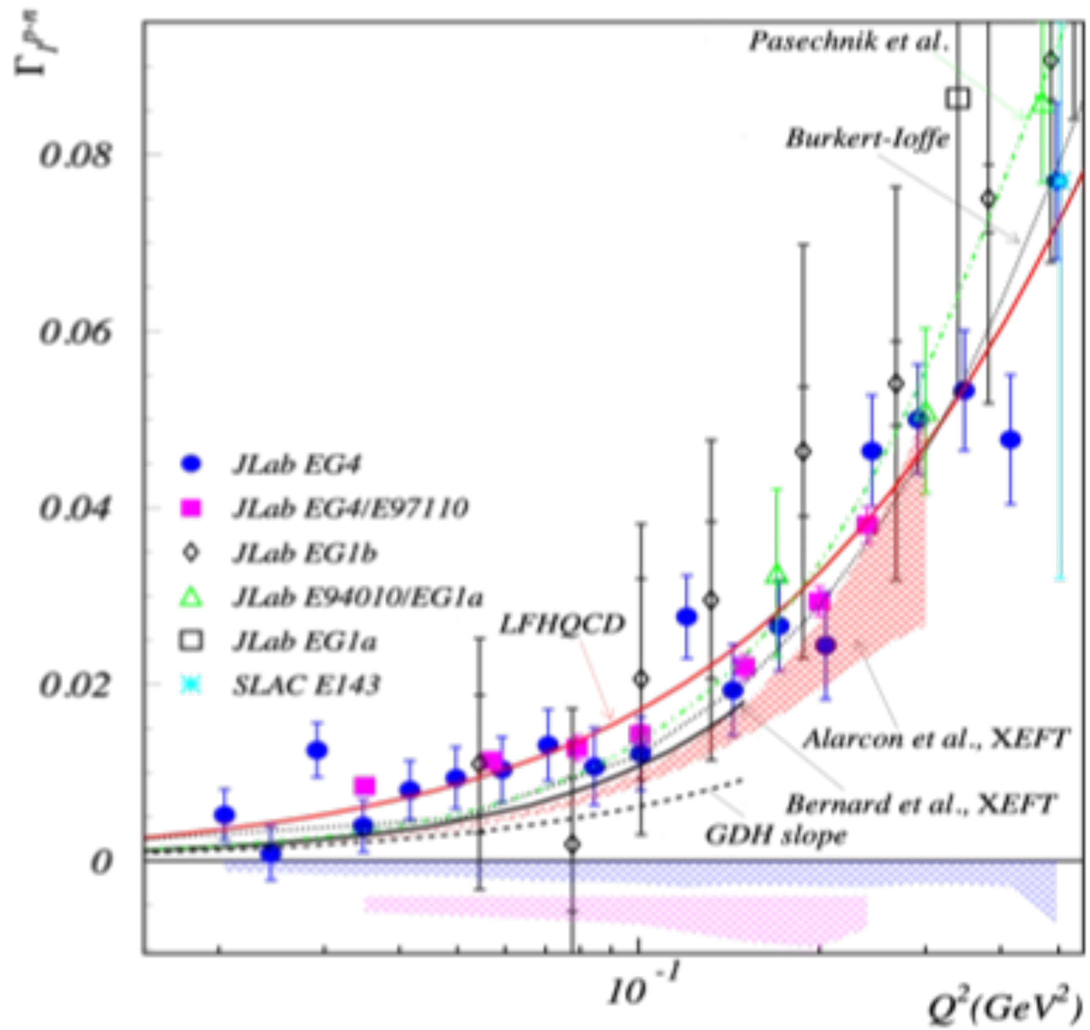
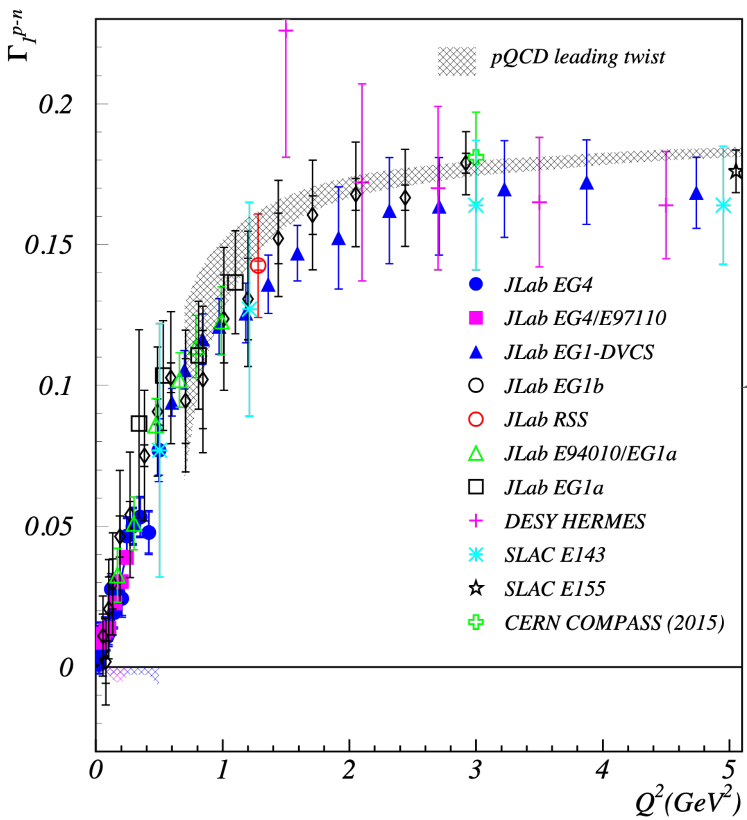
Experimental study of the behavior of the Bjorken sum at very low Q^2

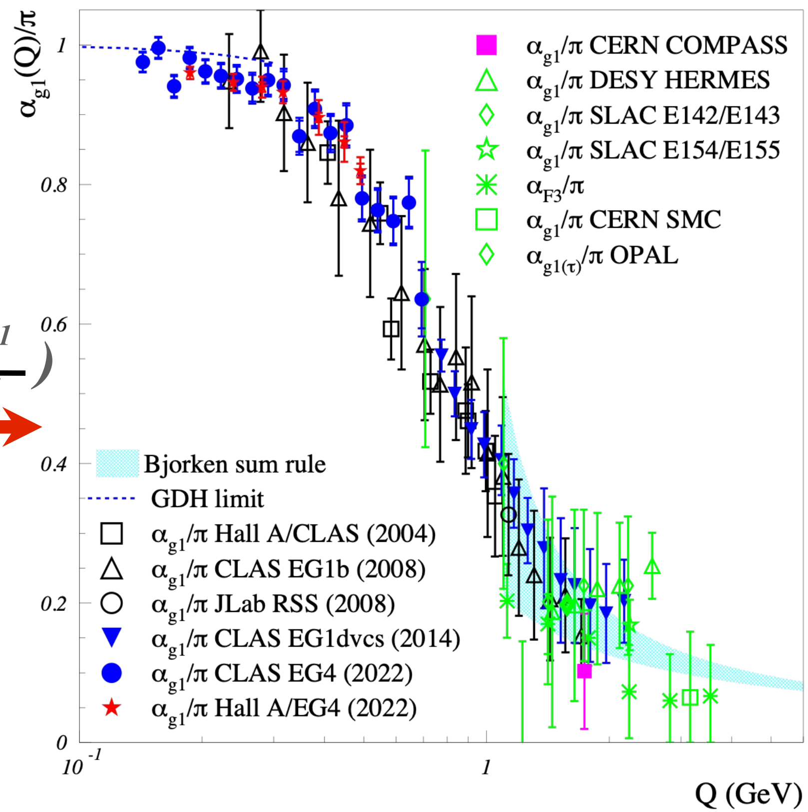


α_{g1} Extracted from the Bjorken Sum data

Bjorken sum Γ_1^{p-n} measurements



$$\Gamma_1^{p-n} = \frac{1}{6} g_A \left(1 - \frac{\alpha_{g1}}{\pi}\right)$$

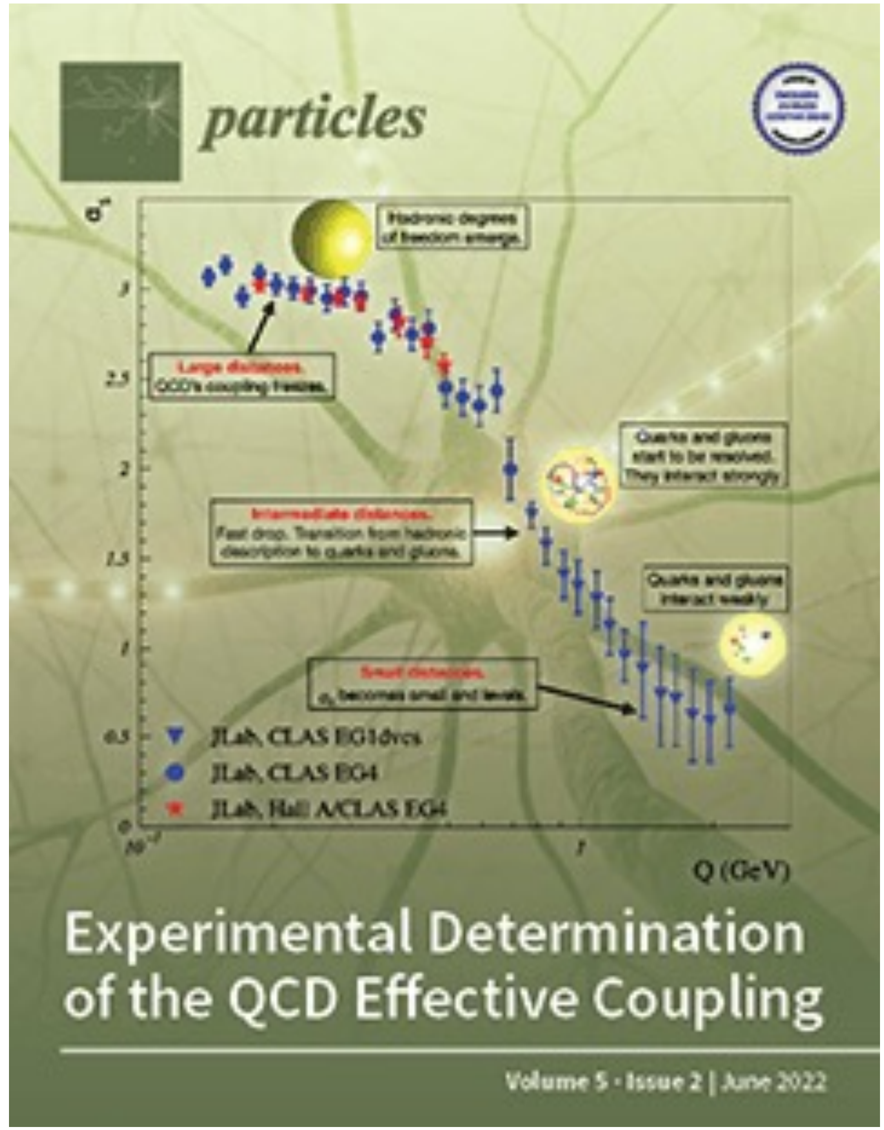


Effective Coupling and Impact

Featured as Cover
Featured in JLab News
https://phys.org/news/2022-08-strength-strong.html
Featured in YouTube
https://www.youtube.com/watch?v=8BTZOz850GI&t=497s

Base for understanding of emergence of hadron properties
Impact on:
hadron spectroscopy
PDFs and GPDs
quark mass functions
pion decay constant
scale of QCD, Λs
QCD Phase/Hot QCD
…

A. Deur, V. Burkert, J. P. Chen and W. Korsch
Particles, 5-171 (2022)



Summary and Outlook

- Highlights of Spin structure study @ JLab12:

  Preliminary results on A1n @ high-x in Hall C: valence behavior

  Data taking complete for A_1(p/D)@CLAS12

  Preliminary results on d2n in Hall C: twist-3, q-g correlations, LQCD calculations
- Generalized Spin Sum Rules/Polarizabilities

  → clean means to study of QCD over full range of Q2
- Exciting results from 3 JLab low-Q spin experiments

  Γ_1, Γ_2, γ_0, δ_{LT} for proton and neutron

  results in 3 *nature physics*, 1 *PRL*, 1 *PLB,* + *more*

  combined results (Bjorken sum) in 1 PLB, α_{g1} extraction in *1 Particle*
- Extensive tests of χEFT calculations

  Lattice QCD predictions becoming available
- Future: real photon GDH@Hall D, d2n@SoLID, …

  g2p2 (spin moments/d2p) proposal in Hall C

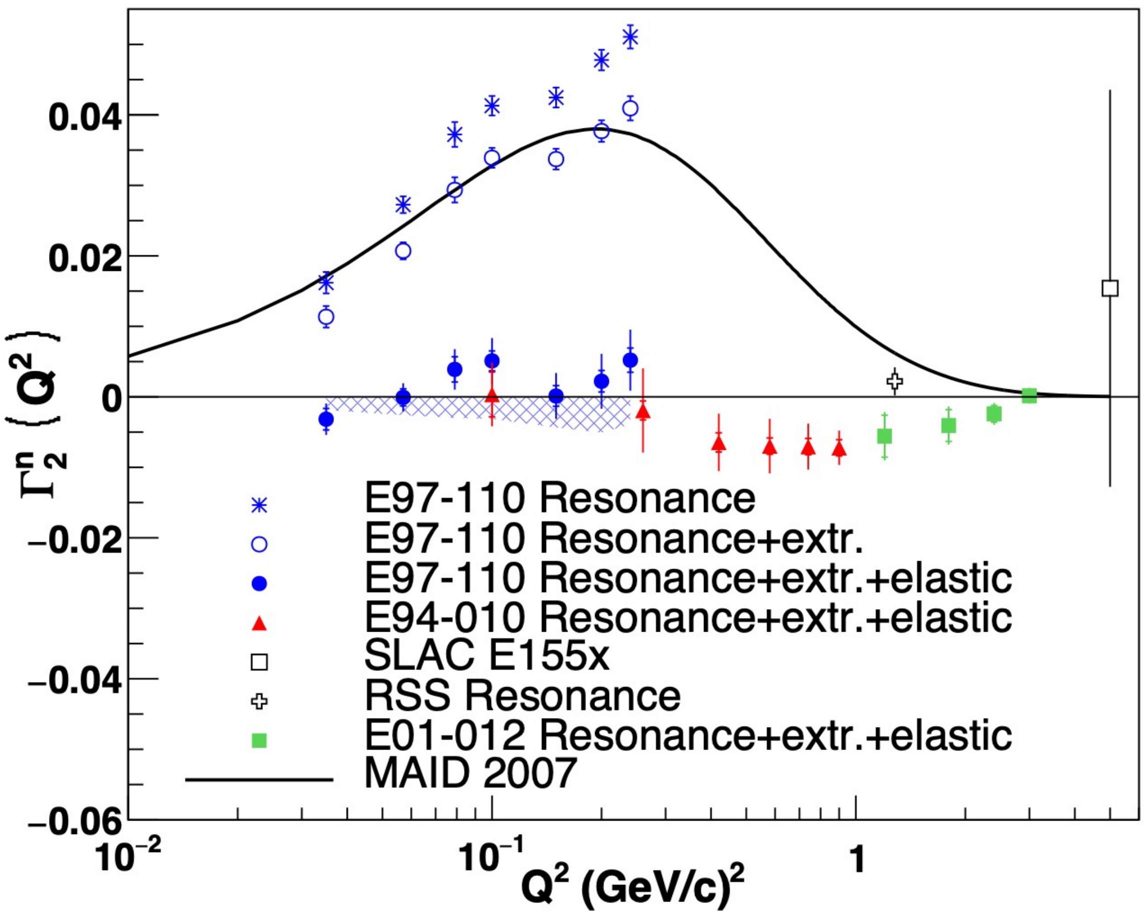
  Bjorken sum and α_s extraction @ JLab22 (A. Deur, JLab22 whitepaper)

  …

SAGDH: new Γ_2 data for neutron: Burkhardt–Cottingham sum rule

$$\Gamma_2(Q^2) \equiv \int_0^1 g_2 dx = 0$$

V. Sulkosky et al., Physics Letter B 805, 135428 (2020)



E97-110 verifies the B-C sum rule at low Q^2. Older experiments at higher Q^2 also verify it.

g2p: new Γ_2 data on proton: BC Sum Rule