Experimental Spin Program at Jefferson Lab

Jian-ping Chen, Jefferson Lab, Virginia, USA

Diffraction2024, Palermo, Sicily, Sept. 8-15, 2024

- **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. Sawatzky, J. Chen, A. Deur, K. Slifer, S. Kuhn, P. Pandey and collaborators.

Nucleon Spin Structure Study

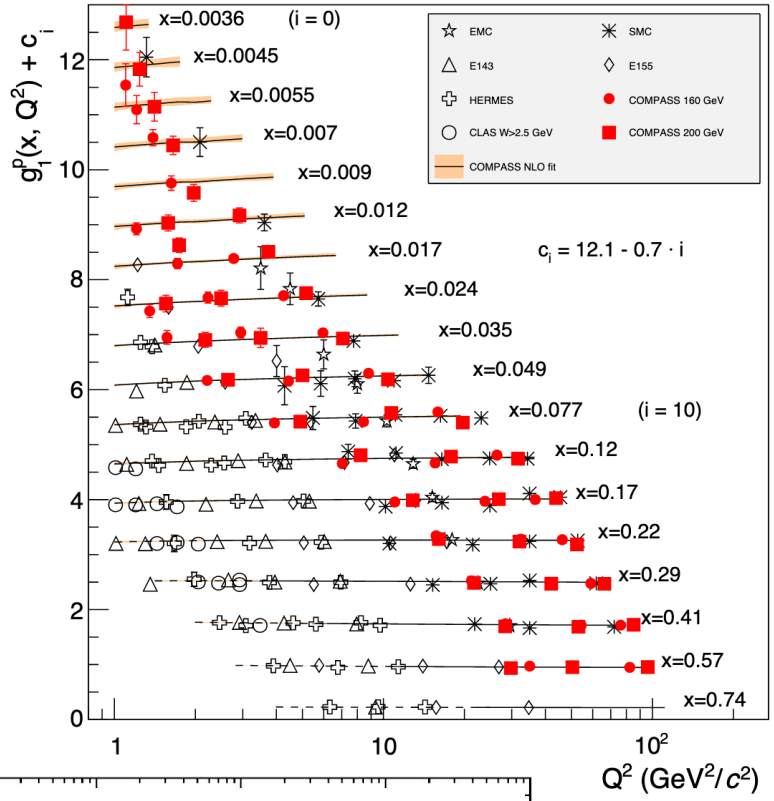
- 1980s: EMC (CERN) + early SLAC
  quark contribution to proton spin is very small
  $\Delta\Sigma = (12+-9+-14)\%$! 'spin crisis'
- 1990s-2000s: SLAC, SMC (CERN), HERMES (DESY)
  $\Delta\Sigma = 20-30\%$, the rest: gluon and quark orbital angular momentum
  $(1/2)\Delta\Sigma + L_q + \Delta G + L_G = 1/2$
  gauge invariant $(1/2)\Delta\Sigma + \mathcal{L}_q + J_G = 1/2$
  Bjorken Sum Rule verified to <10% level
- 2000s-2020s: COMPASS (CERN), HERMES (DESY), RHIC-Spin, JLab, … :
  $\Delta\Sigma \sim 30\%$; ΔG contributes (RHIC-Spin), orbital angular momentum significant

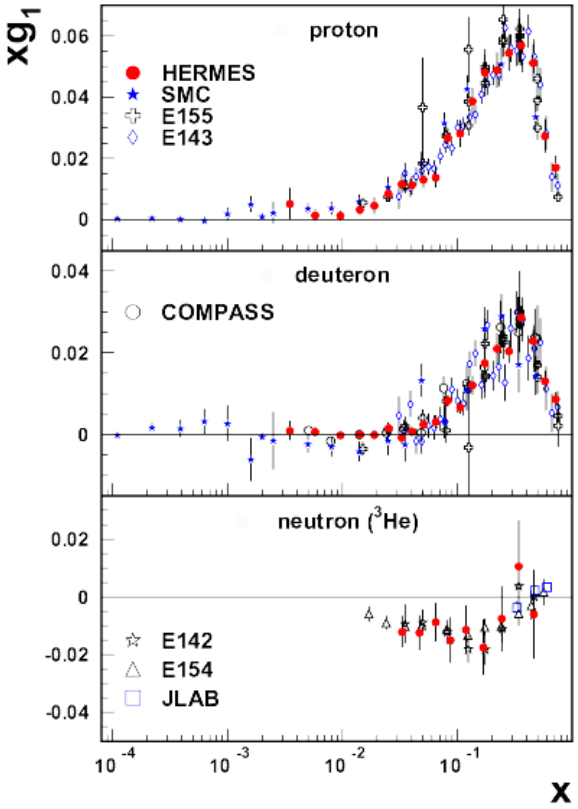
Needs full spin-flavor separation: valence quarks and sea quarks
spin moments (sum rules/polarizabilities) → test of QCD theoretic approaches

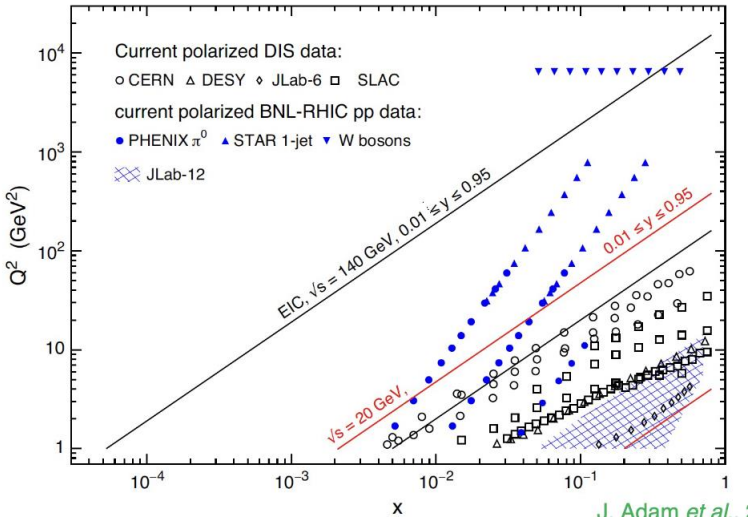
Reviews: Sebastian, Chen, Leader, arXiv:0812.3535, PPNP 63 (2009) 1;
Chen, arXiv:1001.3898, IJMPE 19 (2010) 1893; …

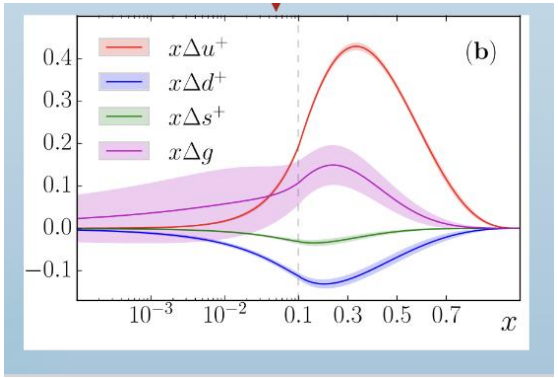
POLARIZED STRUCTURE FUNCTIONS

PDG
(online 2023)









JAM

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
Γ_1, $Q^2 << 1$ GeV^2	JLab EG4	JLab EG4	JLab E97-110
Γ_2, $Q^2 << 1$ GeV^2	JLab E08-027		JLab E97-110

JLab12
A1n
d2n
RGC

COMPASS
RHIC-Spin

SAGDH

g2p

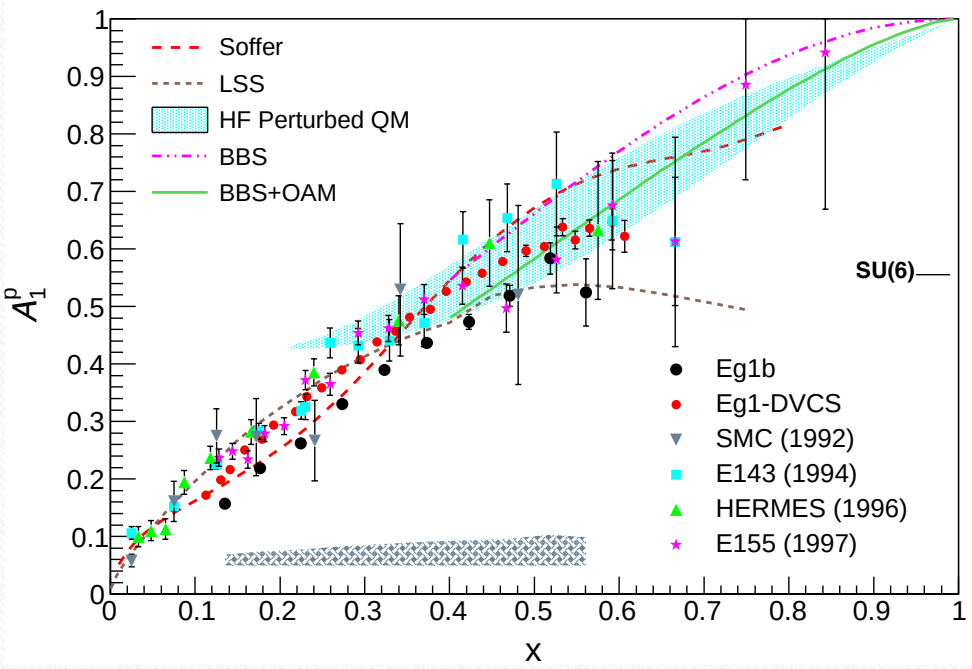
Highlights of JLab12 Spin Program I
Spin Structure in Valence Quark Region

- **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

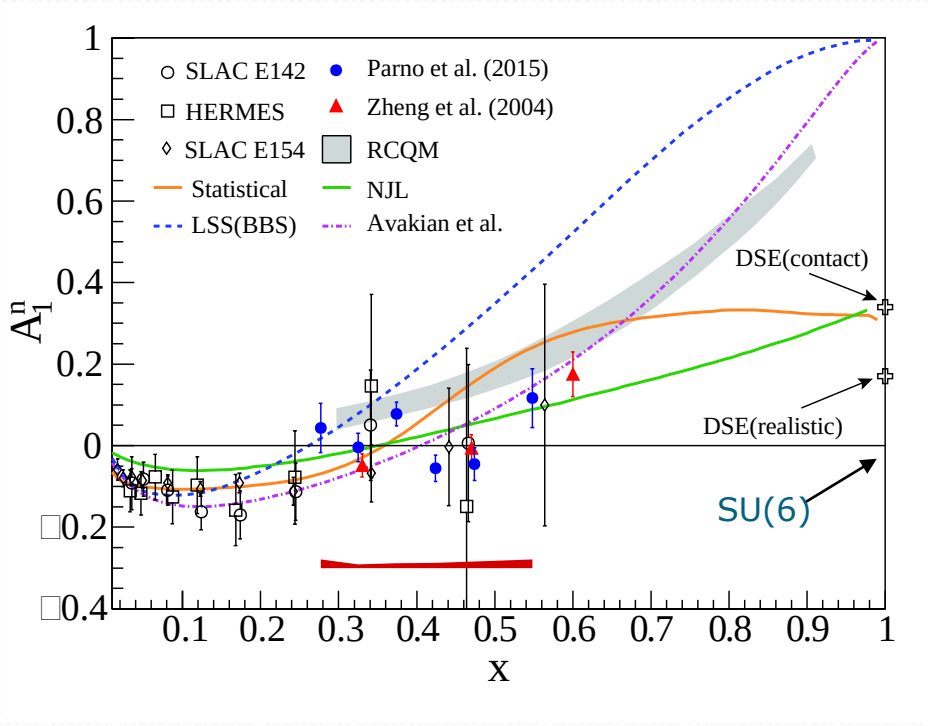
A_1 at High-x: World Data

- 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

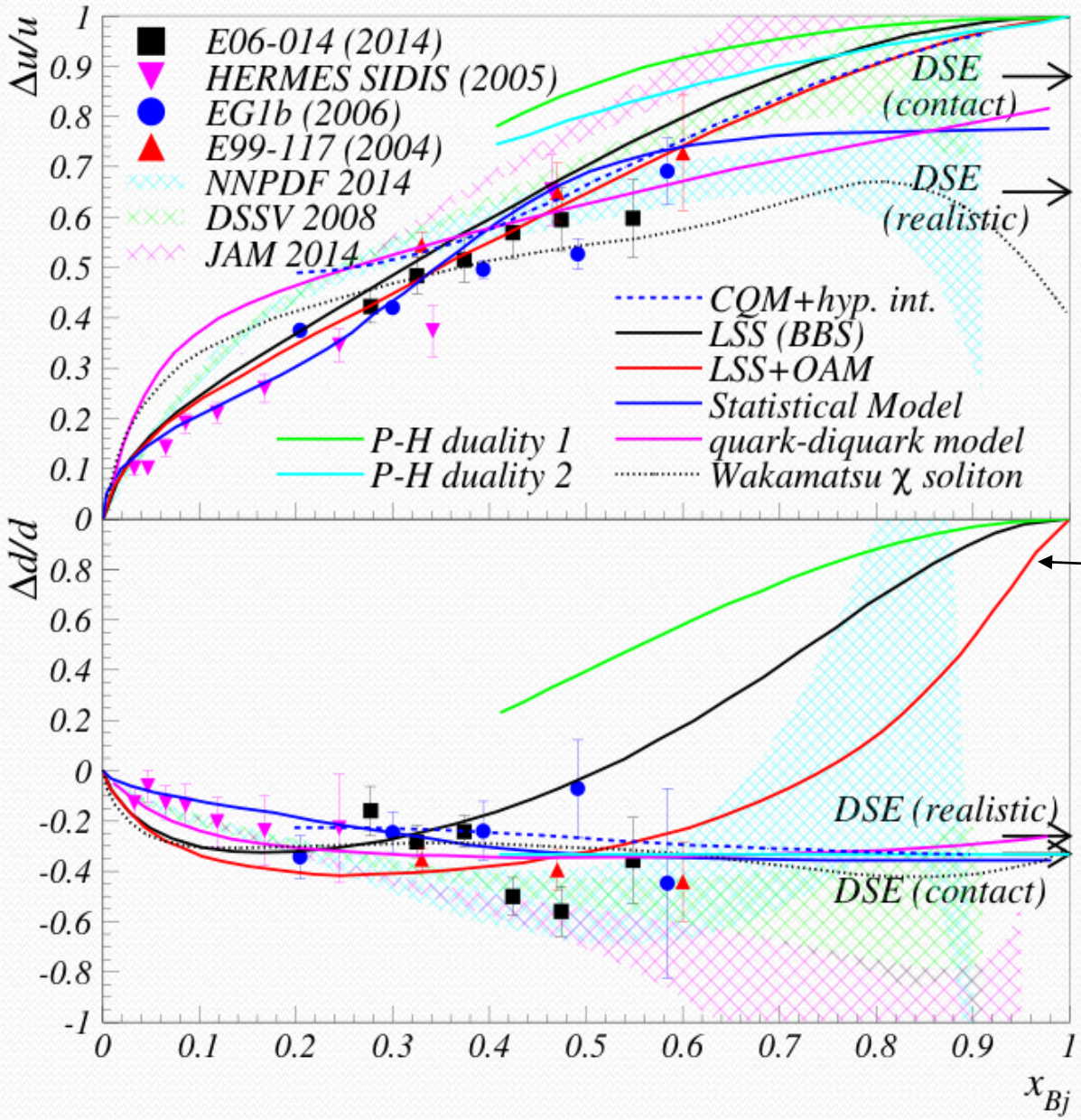
proton



neutron



Simple Spin-flavor Decomposition at High-x



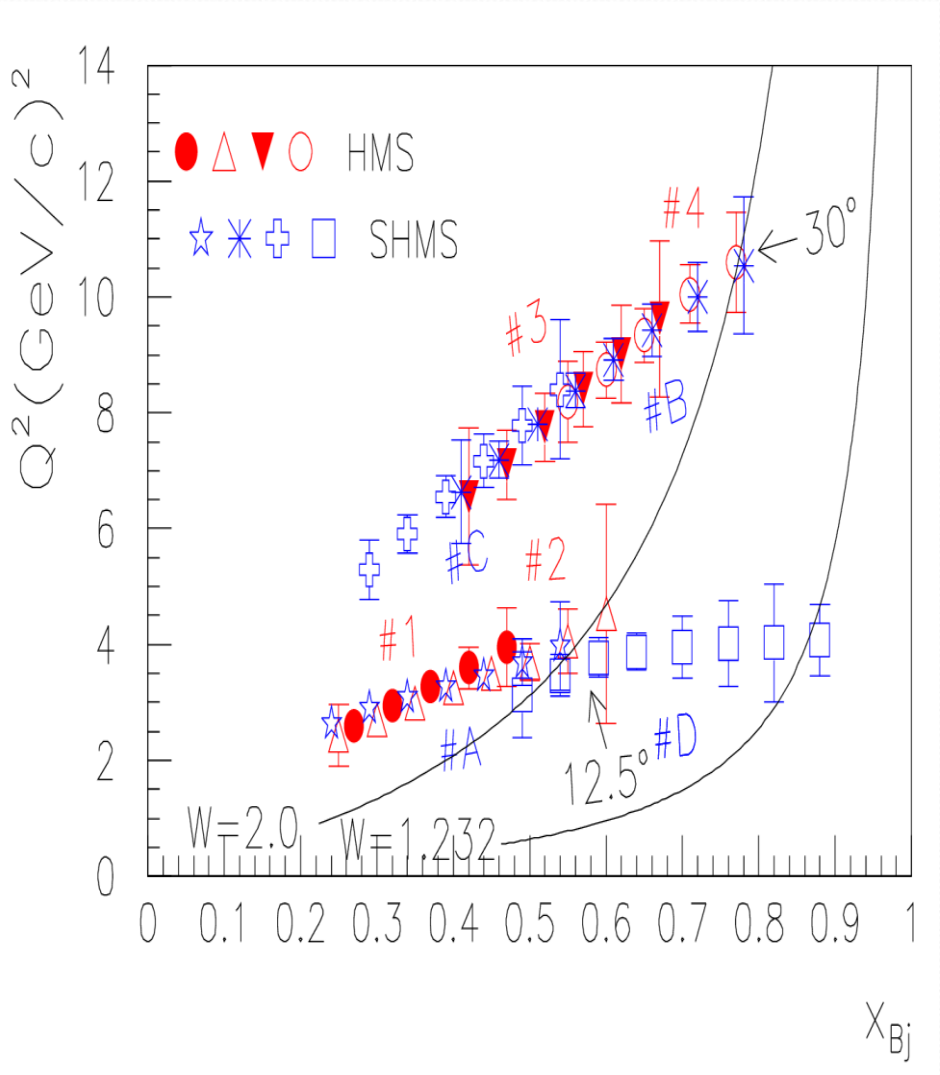
$$\frac{\Delta u+\Delta\bar{u}}{u+\bar{u}}=\frac{4}{15}\frac{g_1^p}{F_1^p}(4+R^{du})-\frac{1}{15}\frac{g_1^n}{F_1^n}(1+4R^{du})$$

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

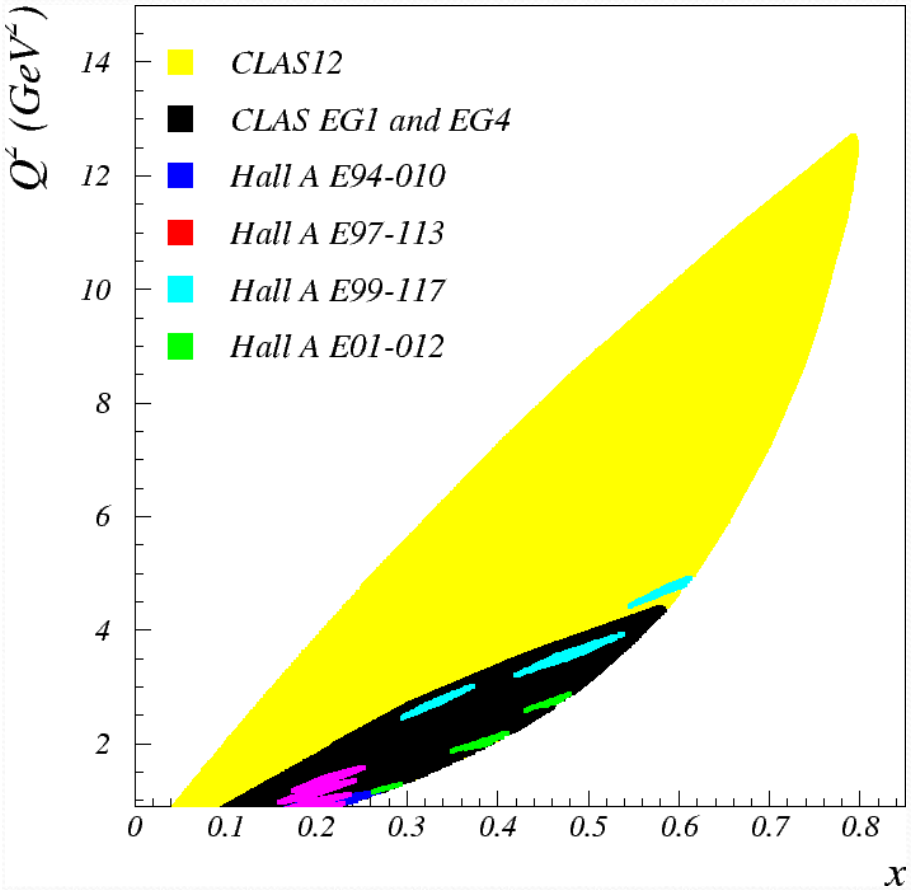
pQCD with quark OAM,

Reaching Deeper Valence Quark Region with 12 GeV

Hall C A_1^n Kinematics

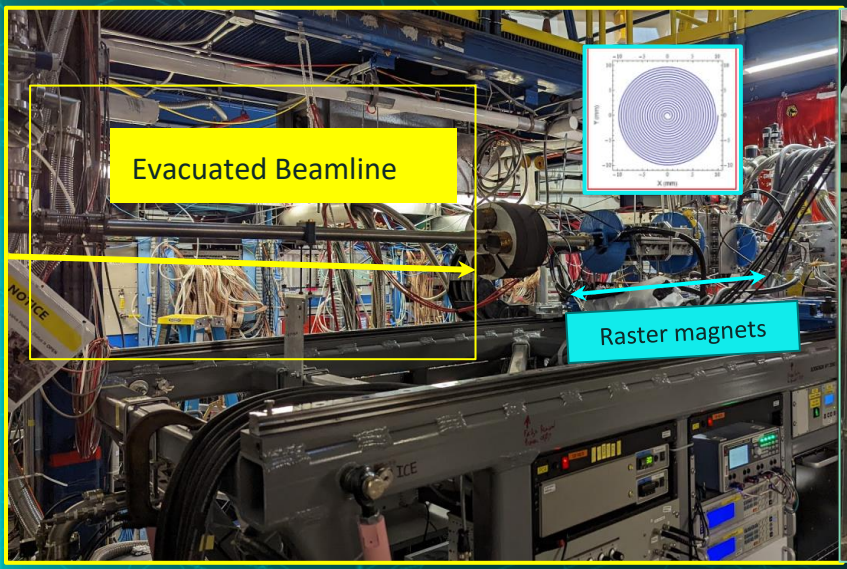


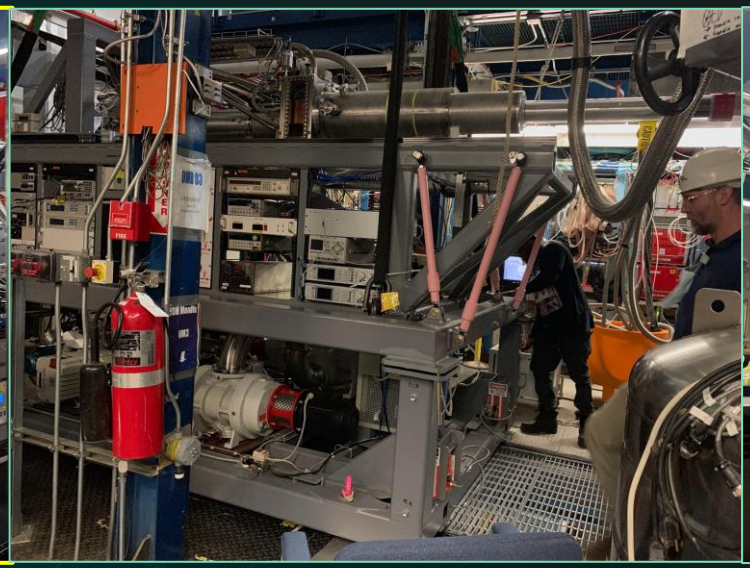
CLAS12 Kinematics



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

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

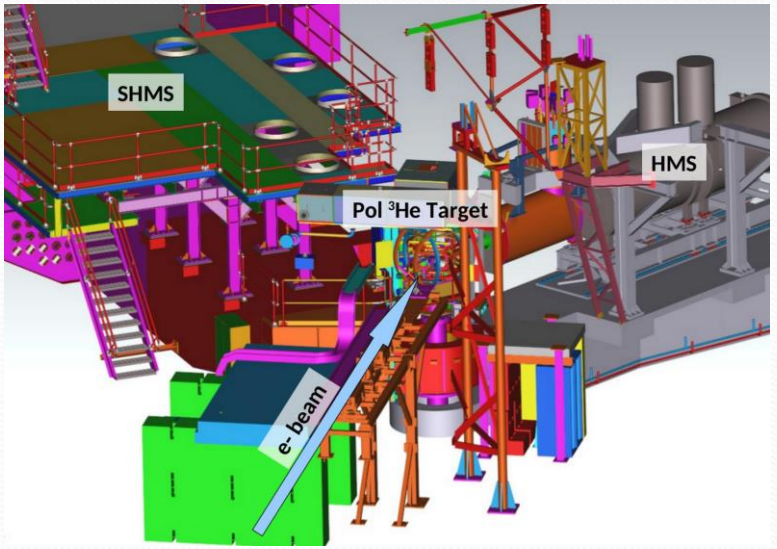
Spokespersons: X. Zheng, G. Cates, J. P. Chen, Z. E. Meziani

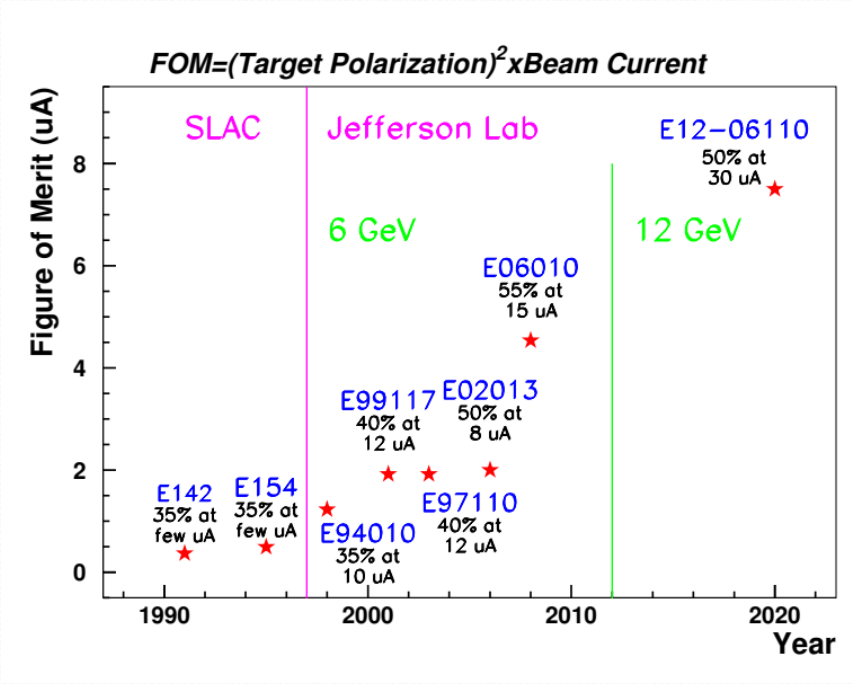
Ph.D Students: M. Chen, M. Rehfuss

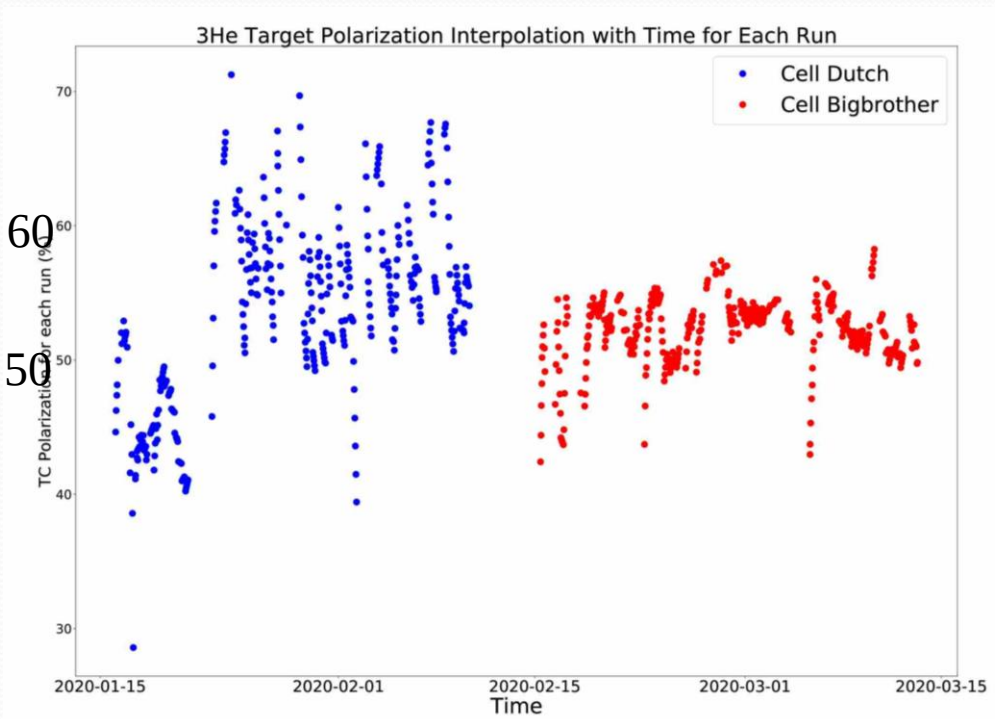
30 uA, 85% polarized 10.4 GeV electron beam

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





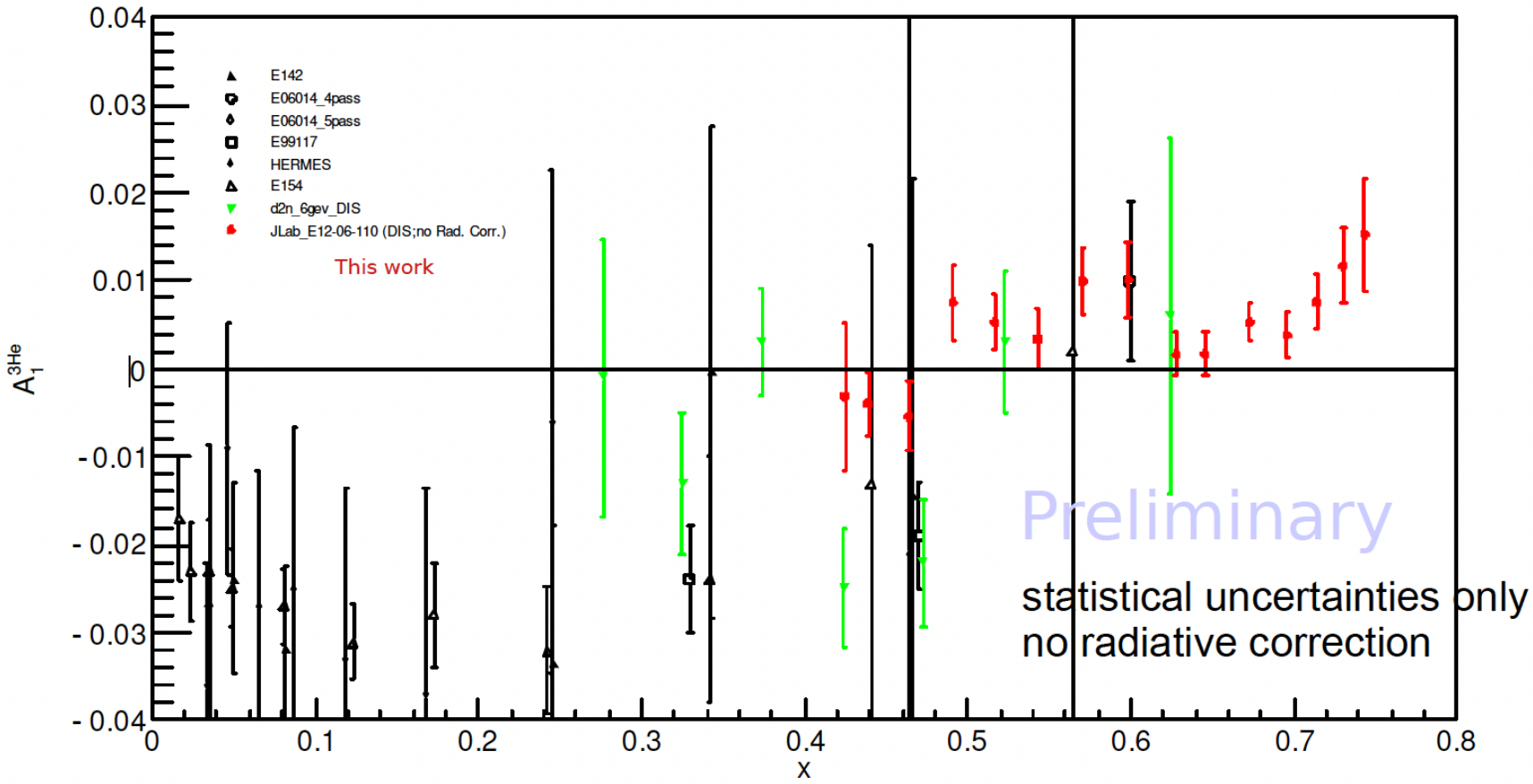


A1n@High-x: Preliminary Results

Asymmetry A_1^{3He}

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

with DIS W>2 GeV cut



- Credit to Mingyu Chen (UVA)

A1n@High-x: Preliminary Results

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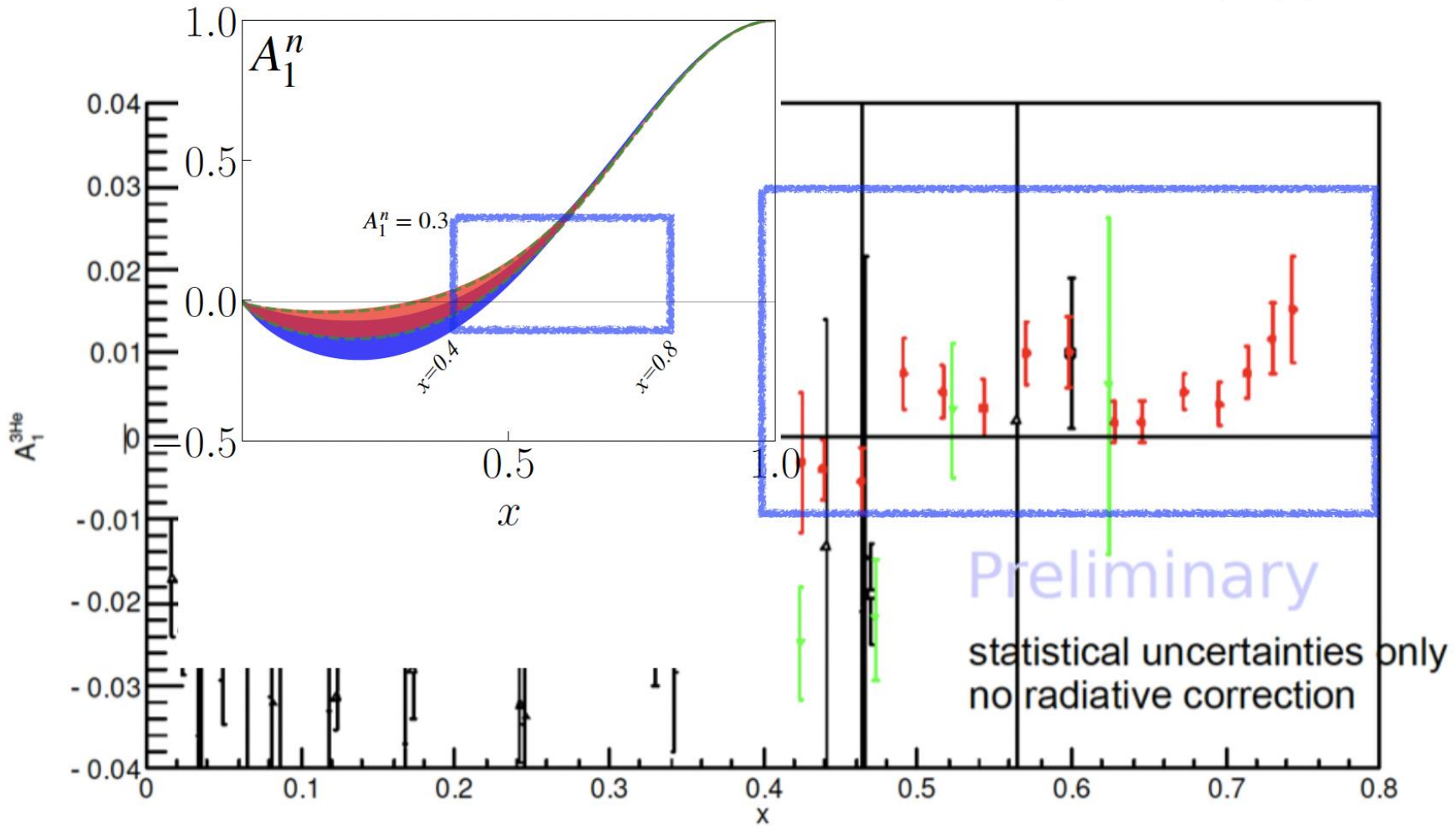


- Credit to Mingyu Chen (UVA)

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

Preliminary results from d2n(^{3}He) in Hall C:
twist-3 matrix element → quark-gluon correlations
(color polarizability/color Lorentz force)

6 GeV Results for d2 Moment

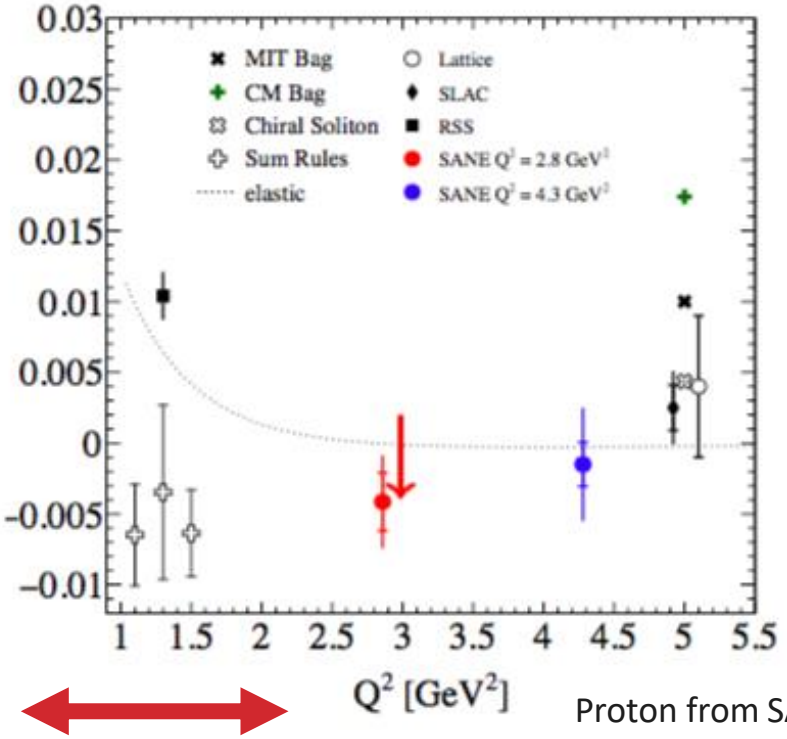
Dynamic twist-3 matrix element

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

Interpretations of d_2

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

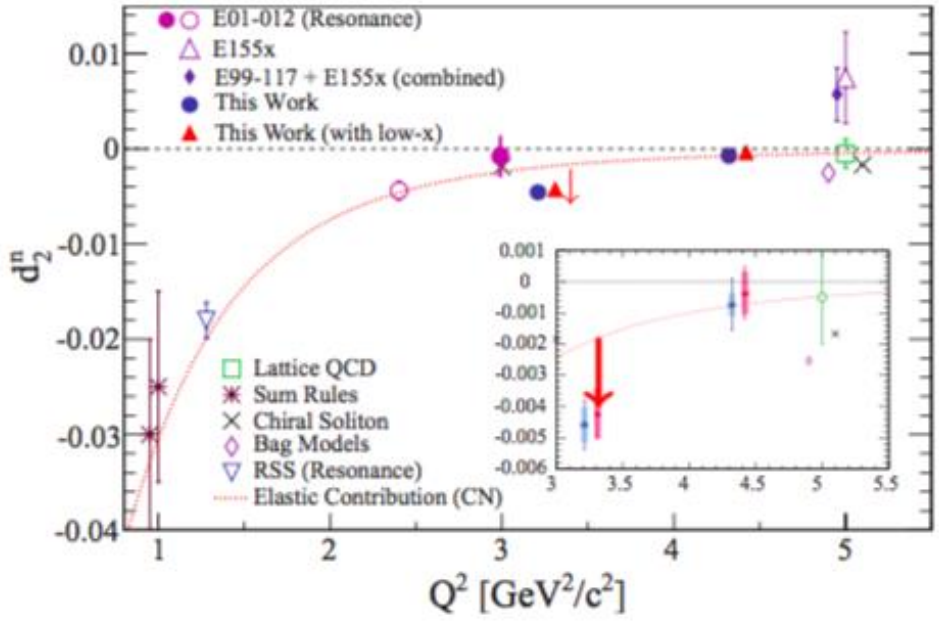
proton



g2p2 Proposal

Proton from SANE,
PRL 122, 022002 (2019)

neutron

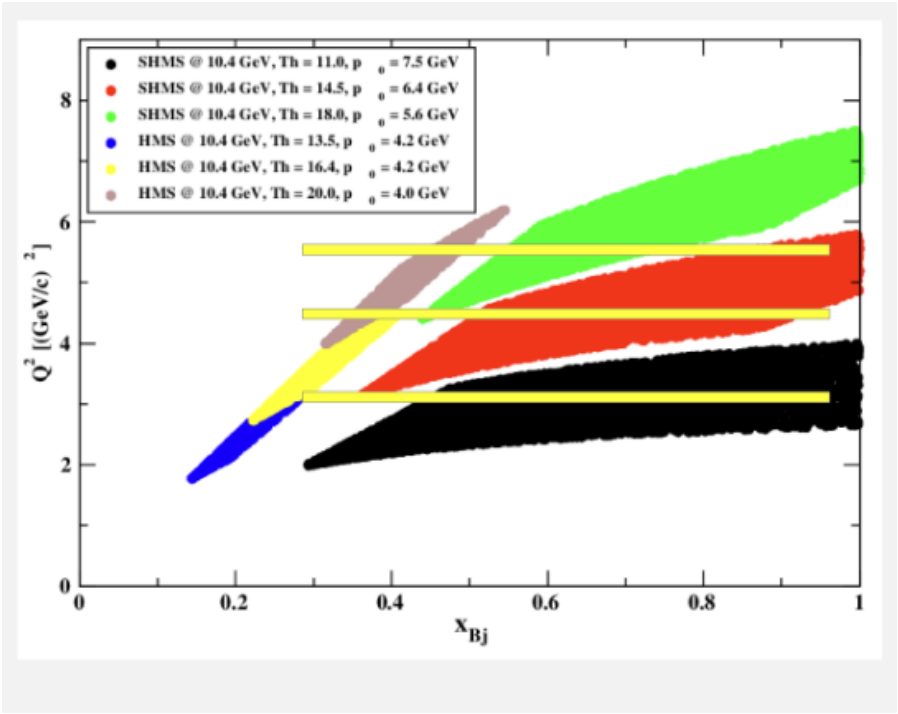


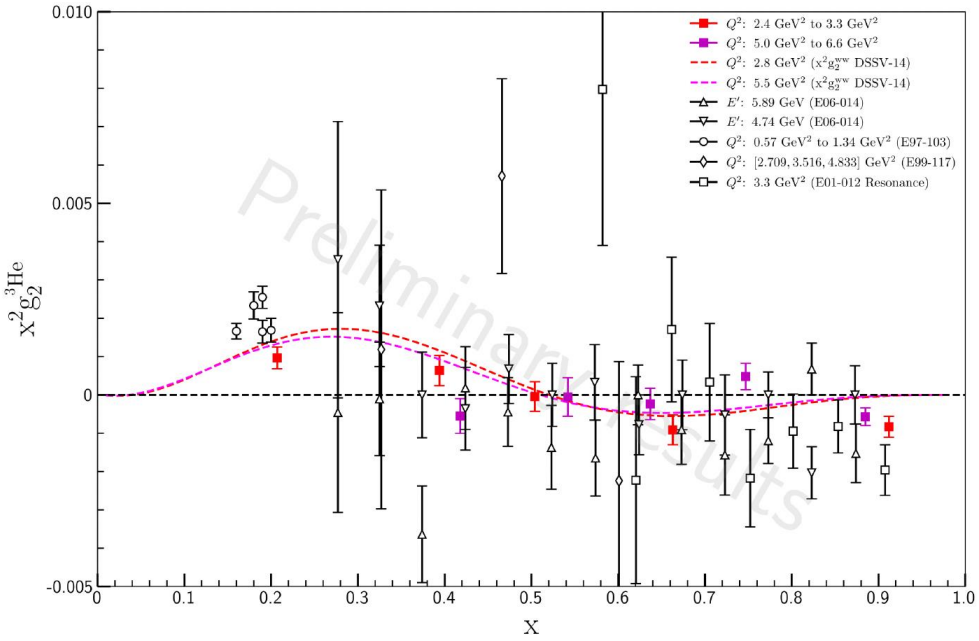
Neutron from d_2^n experiment: D.Flay, et.al.
PRD.94(2016)no.5,052003

12 GeV d_2^n

12 GeV d_2^n: Color Polarizability/Lorentz Force

- 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 ^{3}He target
- Study quark-gluon correlations (twist-3) and provide a benchmark test of LQCD calculations.
- Data taking completed, analysis on-going





preliminary results on $g_2n/g_2{}^3He$ (J. Chen)

Recent Published Results on Spin Moments: Sum Rules and Polarizibilities @ Low-Q

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 study/understand Strong QCD

Bjørken Sum Rule, GDH Sum Rule, Generalized Sum Rule

Bjørken Sum Rule (high Q^2)

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

GDH Sum Rule Real photon ($Q^2=0$)

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

Generalized GDH Sum Rule

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

- Q^2-dependence 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 : $S_1(p-n) \sim g_A$ → Bjorken

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

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

- B-C Sum Rule:

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

Spin Polarizabilities (higher moments)

- Polarizibilities @ low Q^2

Generalized forward spin polarizability:

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

Longitudinal-Transverse polarizability:

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

They can be calculated with χEFT and Lattice QCD (4-point functions)

- Polarizibilities @ Intermediate-to-high Q^2

Color polarizability (X. Ji)
Color Lorentz force (M. Burkardt)

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

Dynamic twist-3 matrix element: quark-gluon correlations
Lattice QCD calculations

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 α_{g1}: **A. Deur, et al., Particles, 5-171 (2022)**

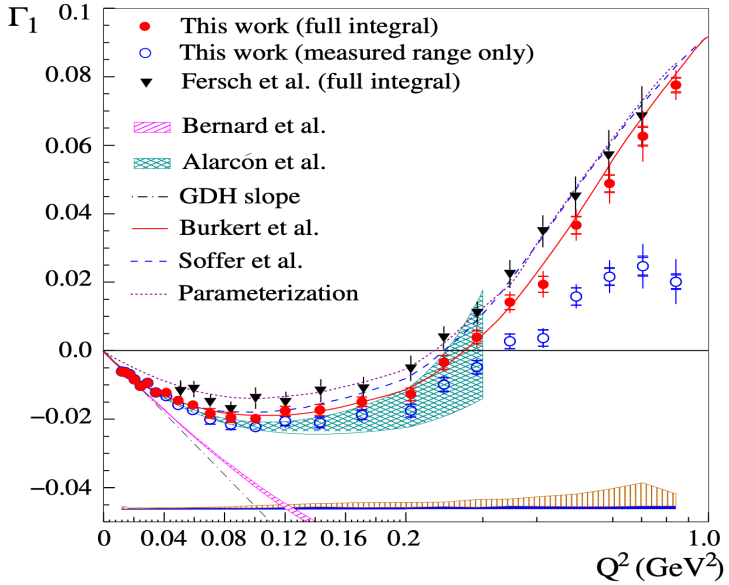
Low-Q workshop at Crete, Greece, May 2023 (https://sites.temple.edu/lowq/)

low-Q Γ_1, Γ_2 (spin sums) for proton and neutron

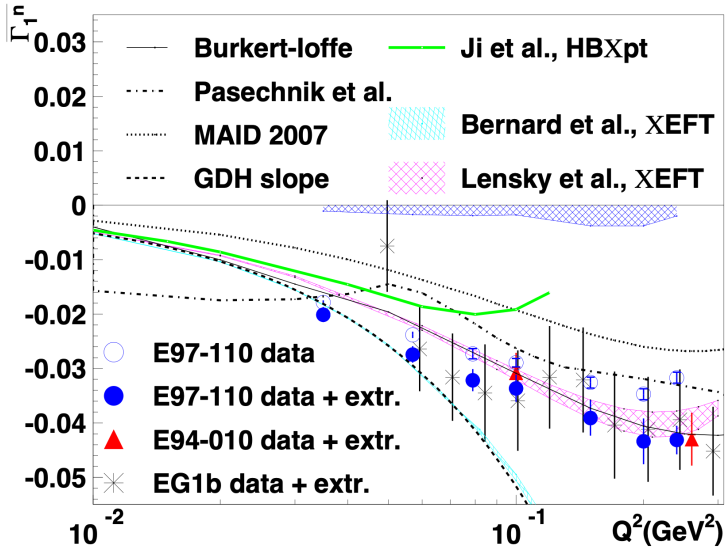
proton

neutron

Γ_1



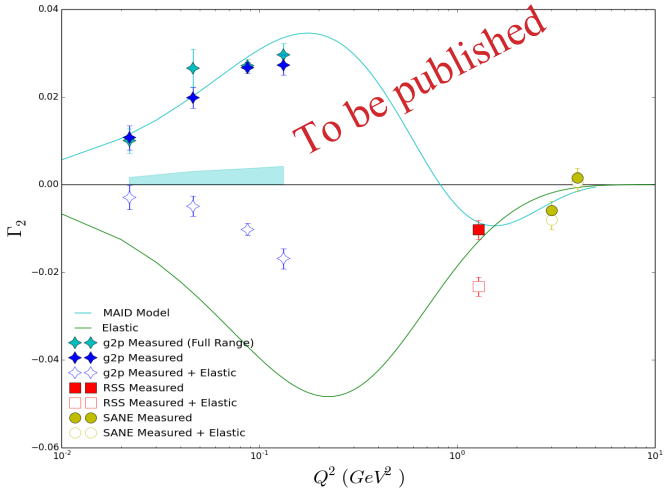
Nature Physics 17, 736 (2021)

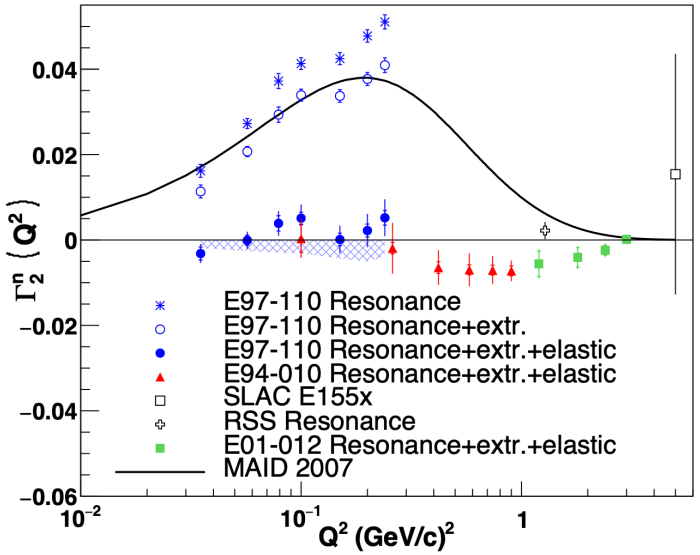


PLB 805, 135428 (2020)

Γ_2

Preliminary results from JLab g2p experiment (D. Ruth)



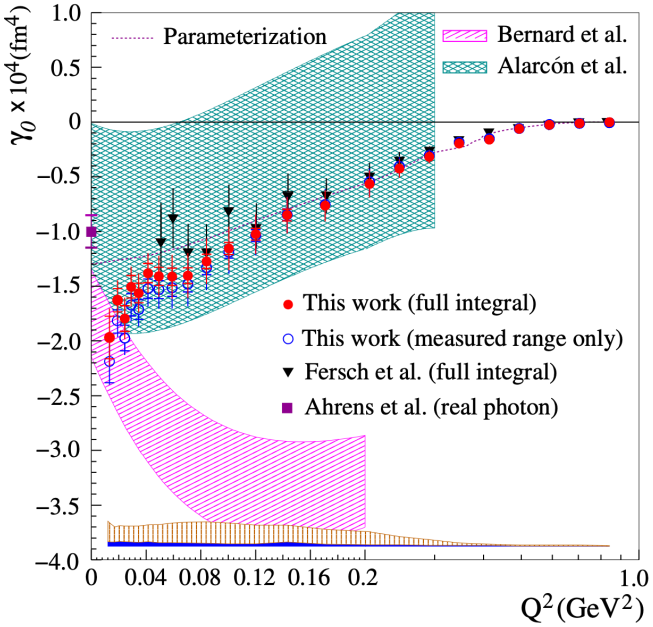


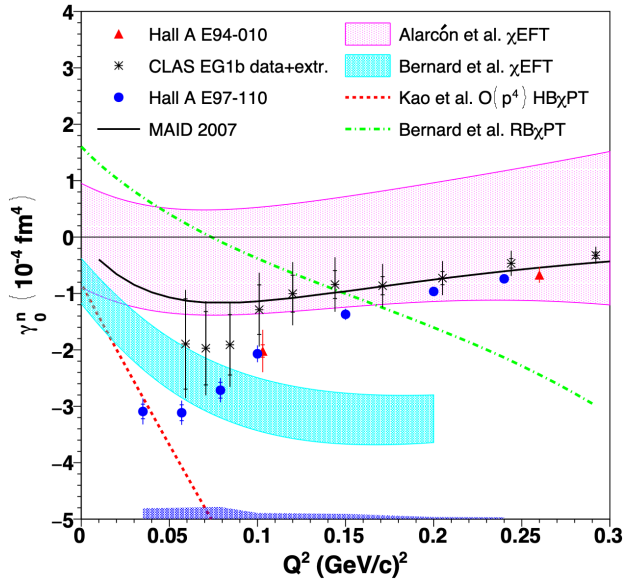
low-Q γ_0, δ_{LT} (spin polarizabilities) or proton and neutron

proton **neutron**

γ_0

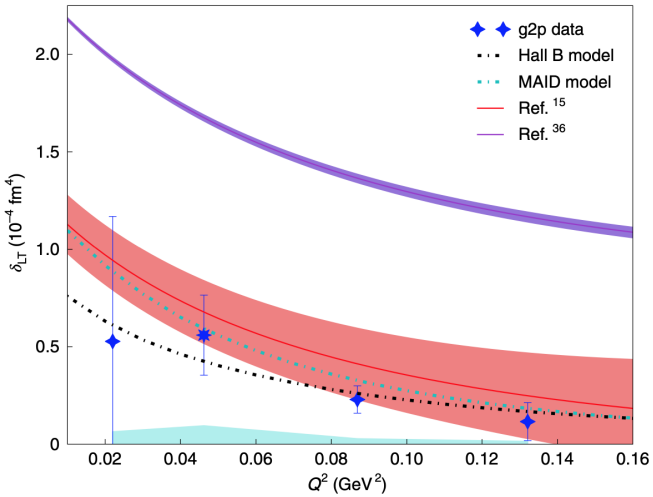
Nature Physics 17, 736 (2021)

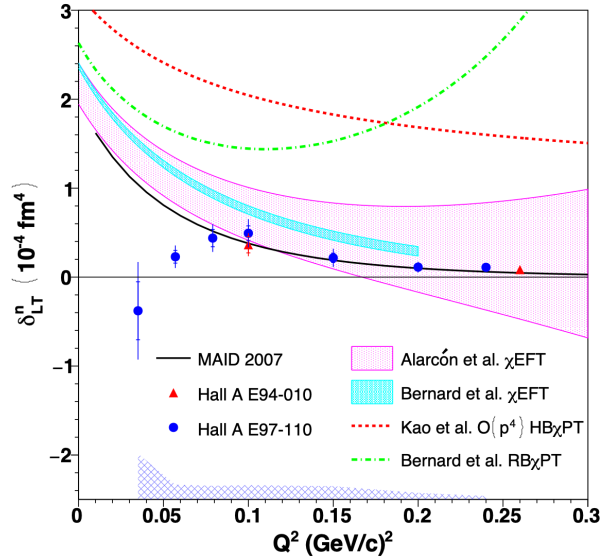




Nature Physics 17 687 (2021)

Nature Physics 18, 1441 (2022) δ_{LT}



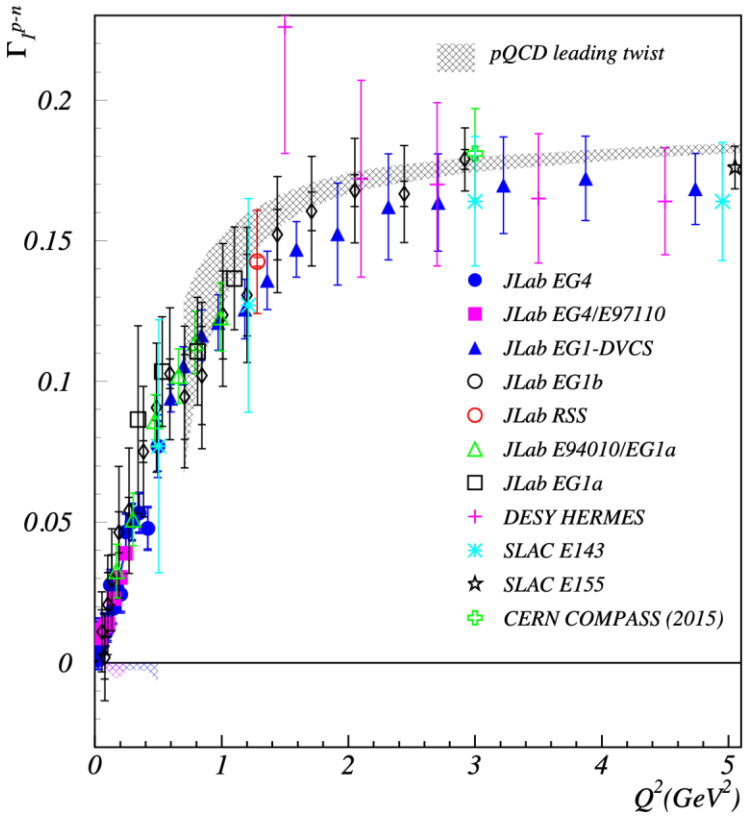


Comparisons with χEFT calculations: favor Alarcon *et al.*, strong disagreement with Bernard *et al.*

"$\delta_{LT}^n(Q^2)$ puzzle" remains!

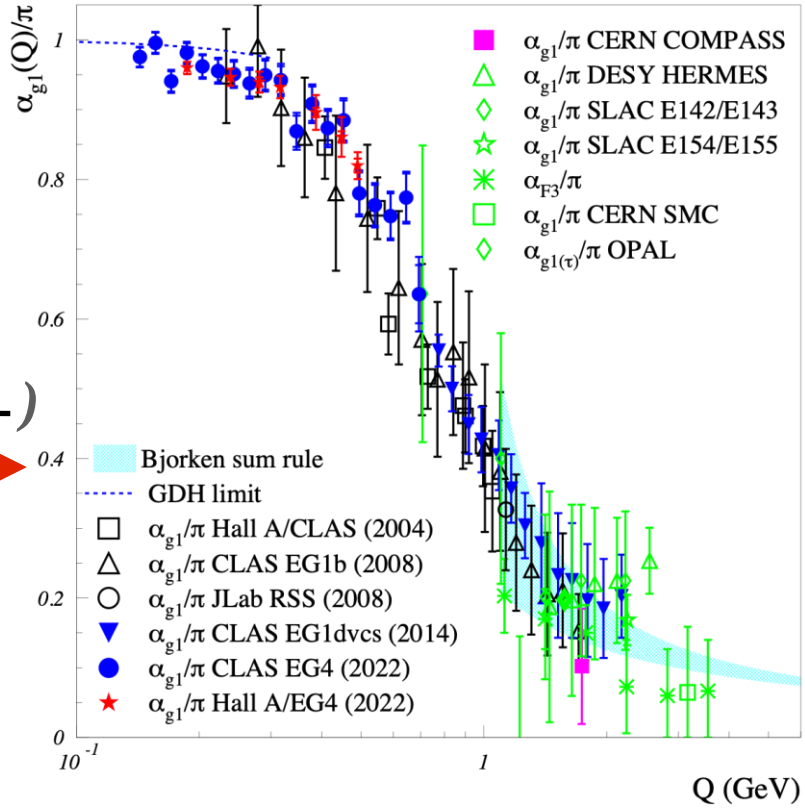
α_{g1} Extracted from the Bjorken Sum data

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 α_{g1}



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

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

- Generalized Spin Sum Rules/Polarizabilities

  → clean means to study 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, …

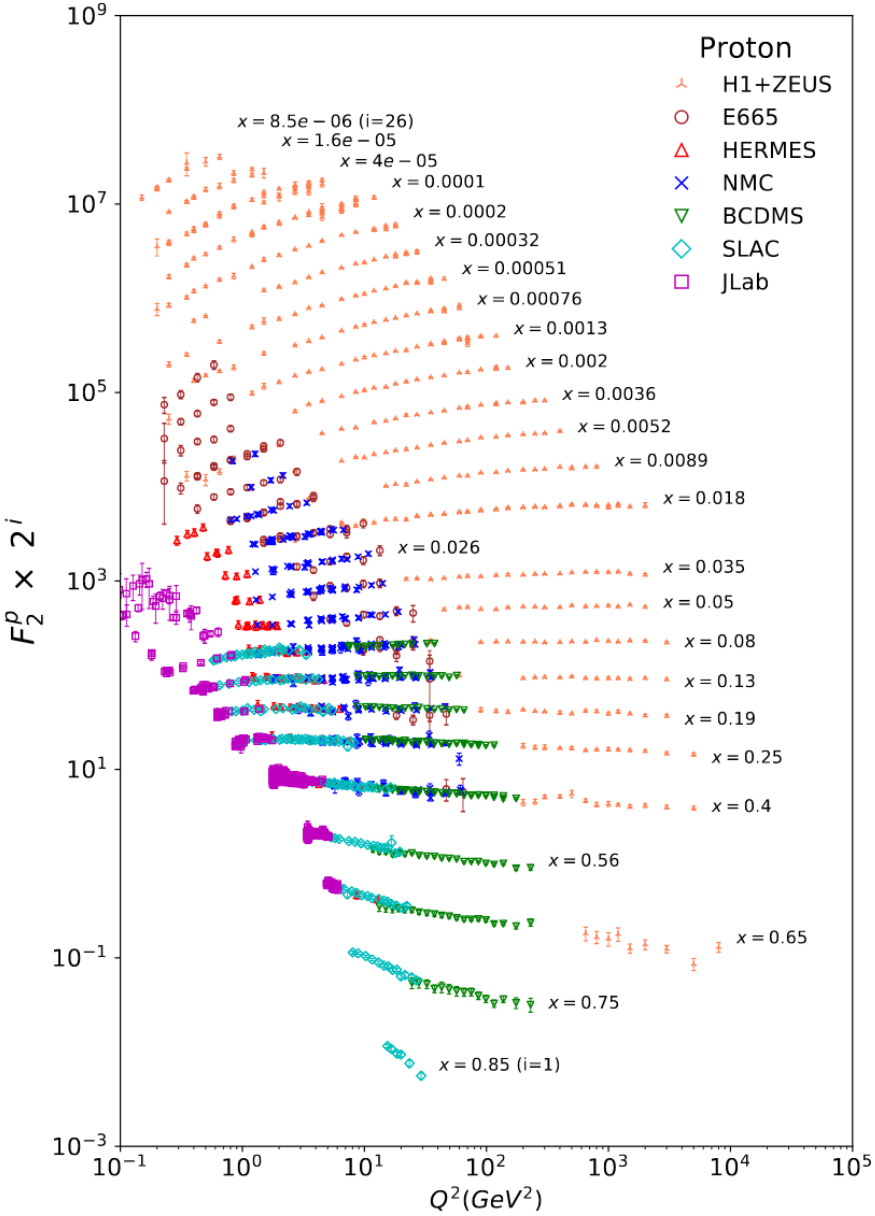
  g2p2 (spin moments/d2p) proposal in Hall C

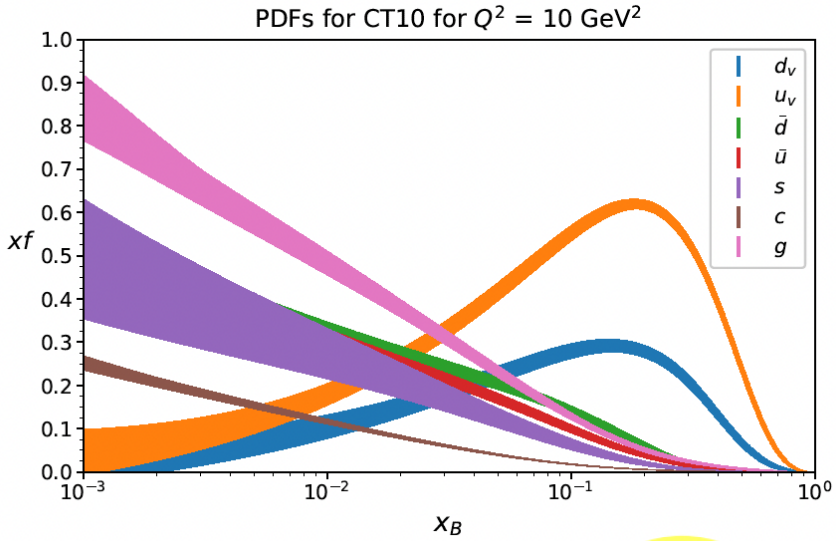
  Bjorken sum and α_s extraction @ JLab22 …

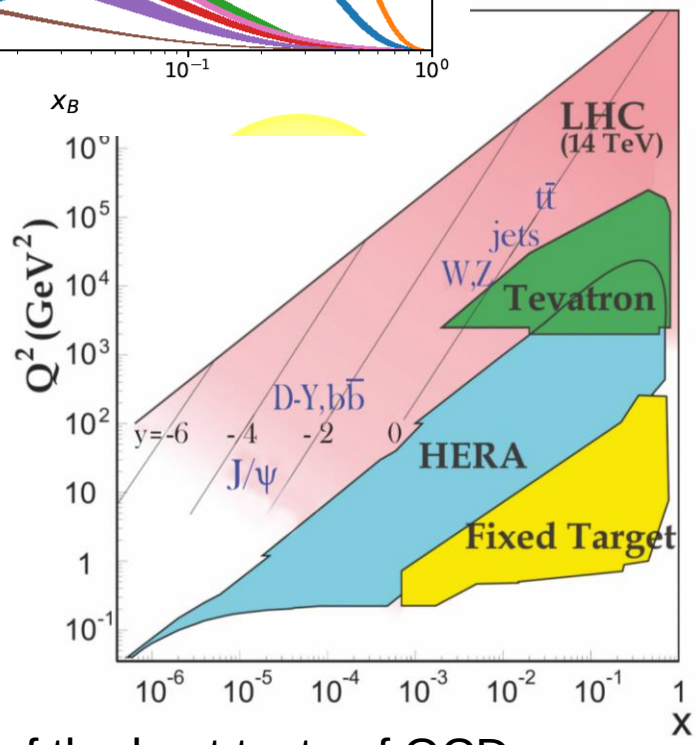
  3-D spin structure (TMDs, GPDs) (not covered in this talk)

Backup Slides

UNPOLARIZED STRUCTURE FUNCTIONS



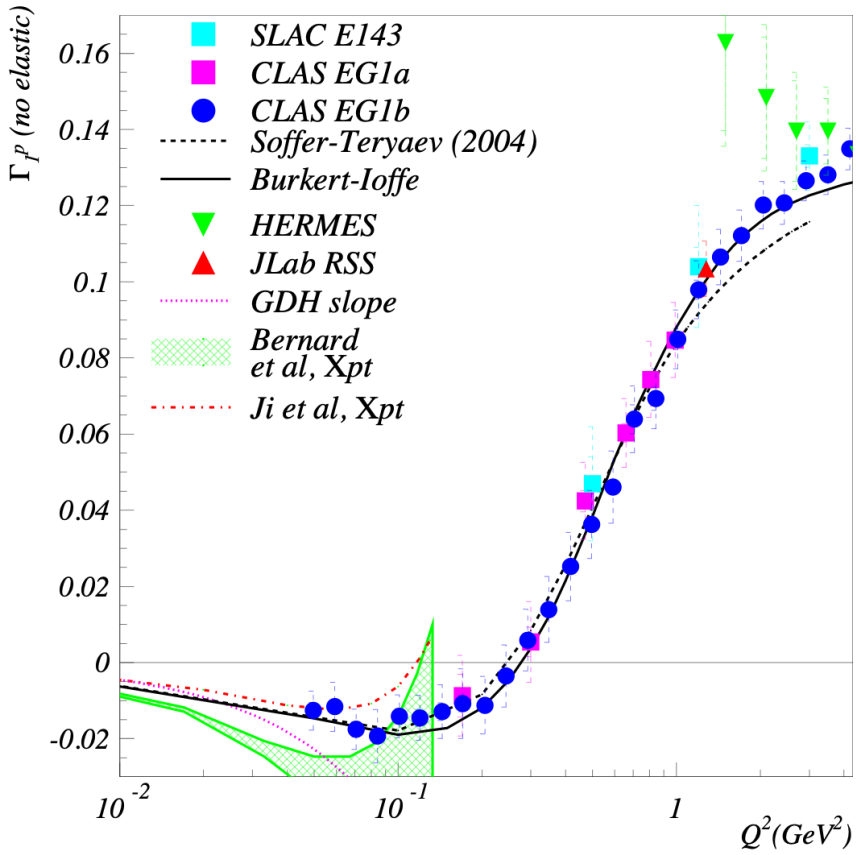




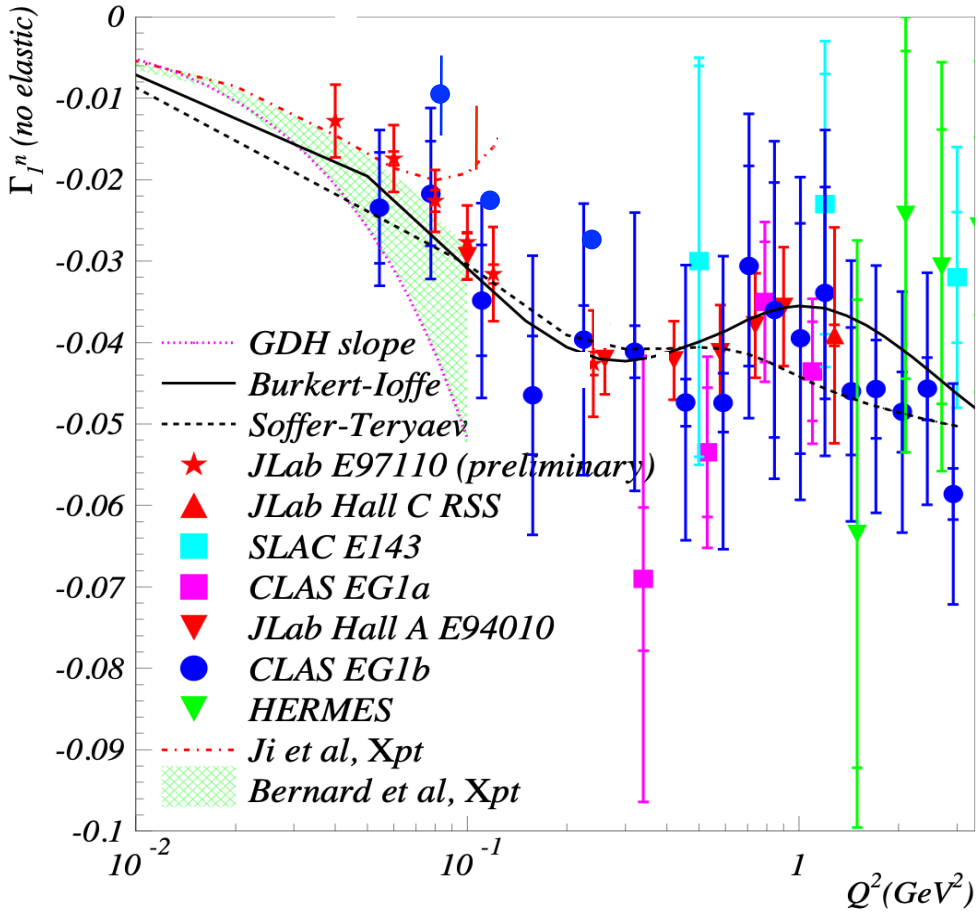
Q^2 evolution: one of the best tests of QCD

Previous world Γ_1 data before low-Q experiments

Proton



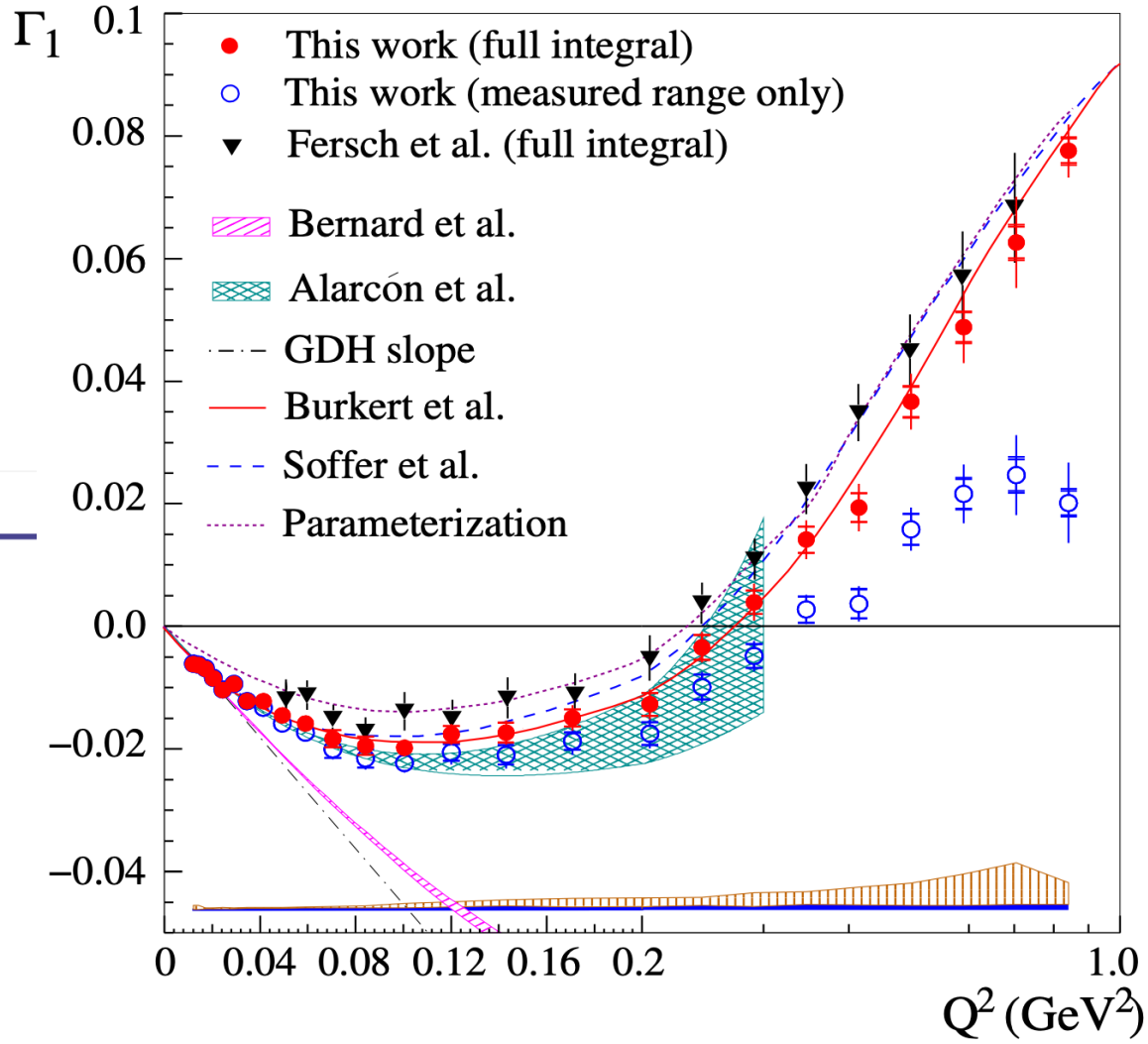
Neutron



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

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



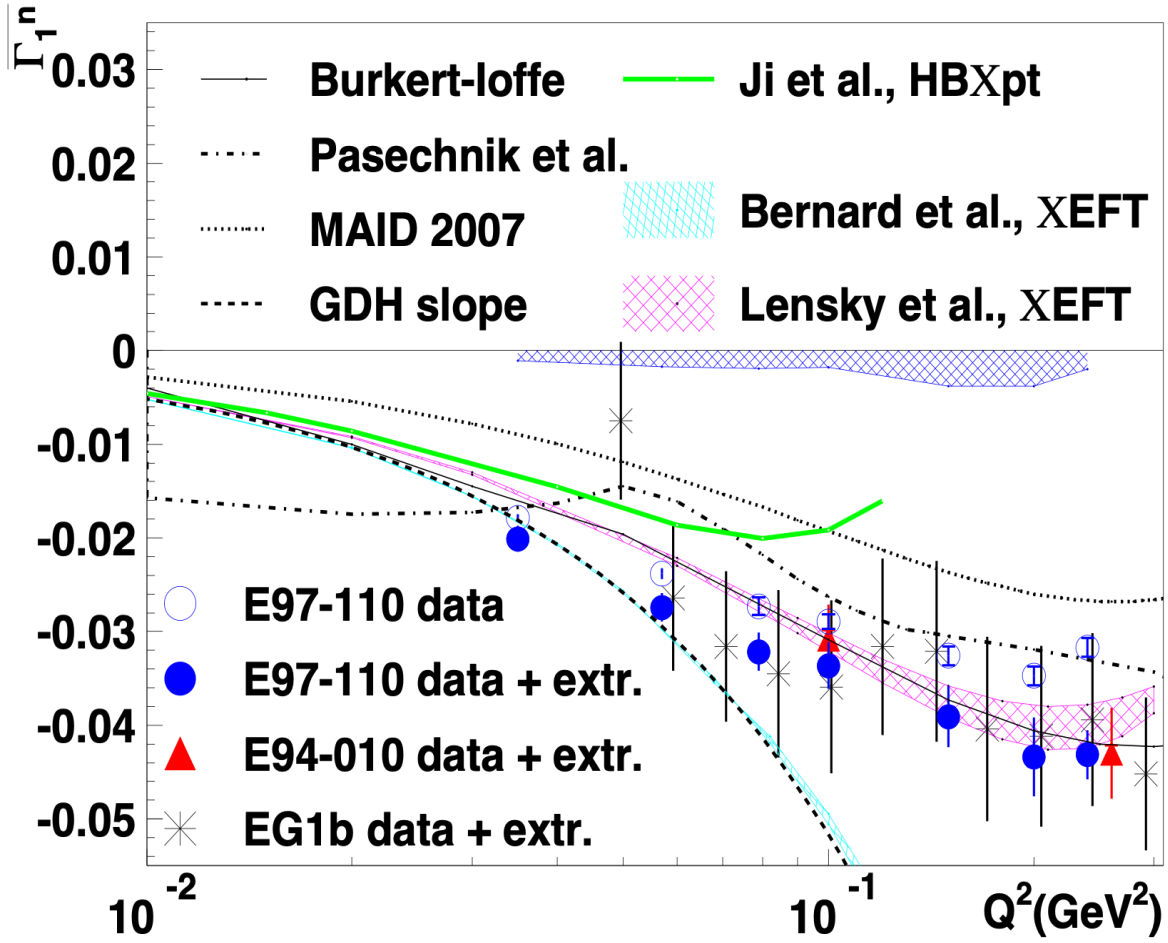
- *Slight tension between EG4 and EG1 above Q^2 ~0.1 GeV^2.*
- *EG4 and χEFT agree up to Q^2 ~0.04 GeV^2 (Bernard et al) or Q^2 >0.2 GeV^2 (Alarcón et al.)*
- *Phenomenological models (Pasechnik et al, Burkert-Ioffe) agree well.*

SAGDH: new low-Q data on Γ_1 for neutron

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

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

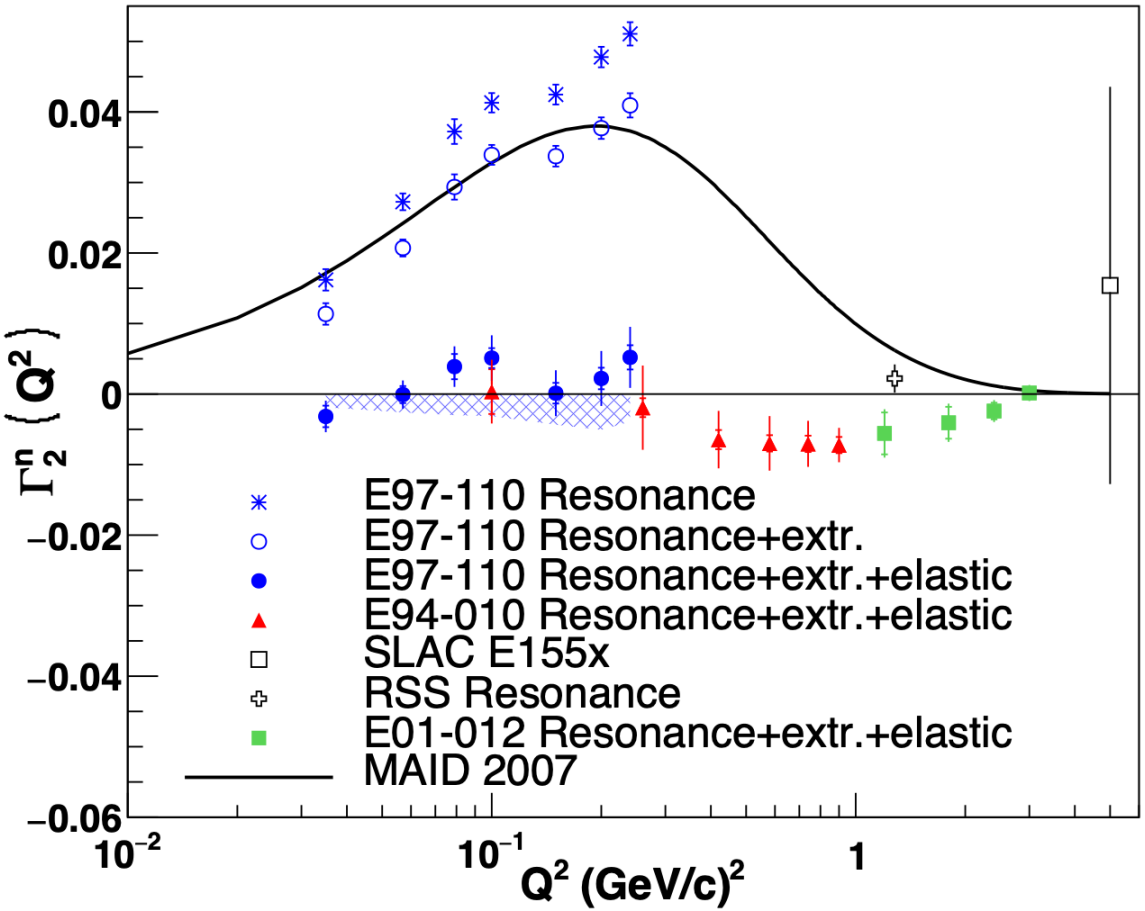


- *E97-110 agree with existing data at larger Q^2 (EG1b, E94-010).*
- *E97-110 and χEFT agree up to Q^2 ~0.06 GeV^2 (Bernard et al) or Q^2 >0.08 GeV^2 (Lensky et al.)*
- *Some phenomenological models (Burkert-Ioffe) agree well with data, other (MAID, Pasechnik et al) not as much.*

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

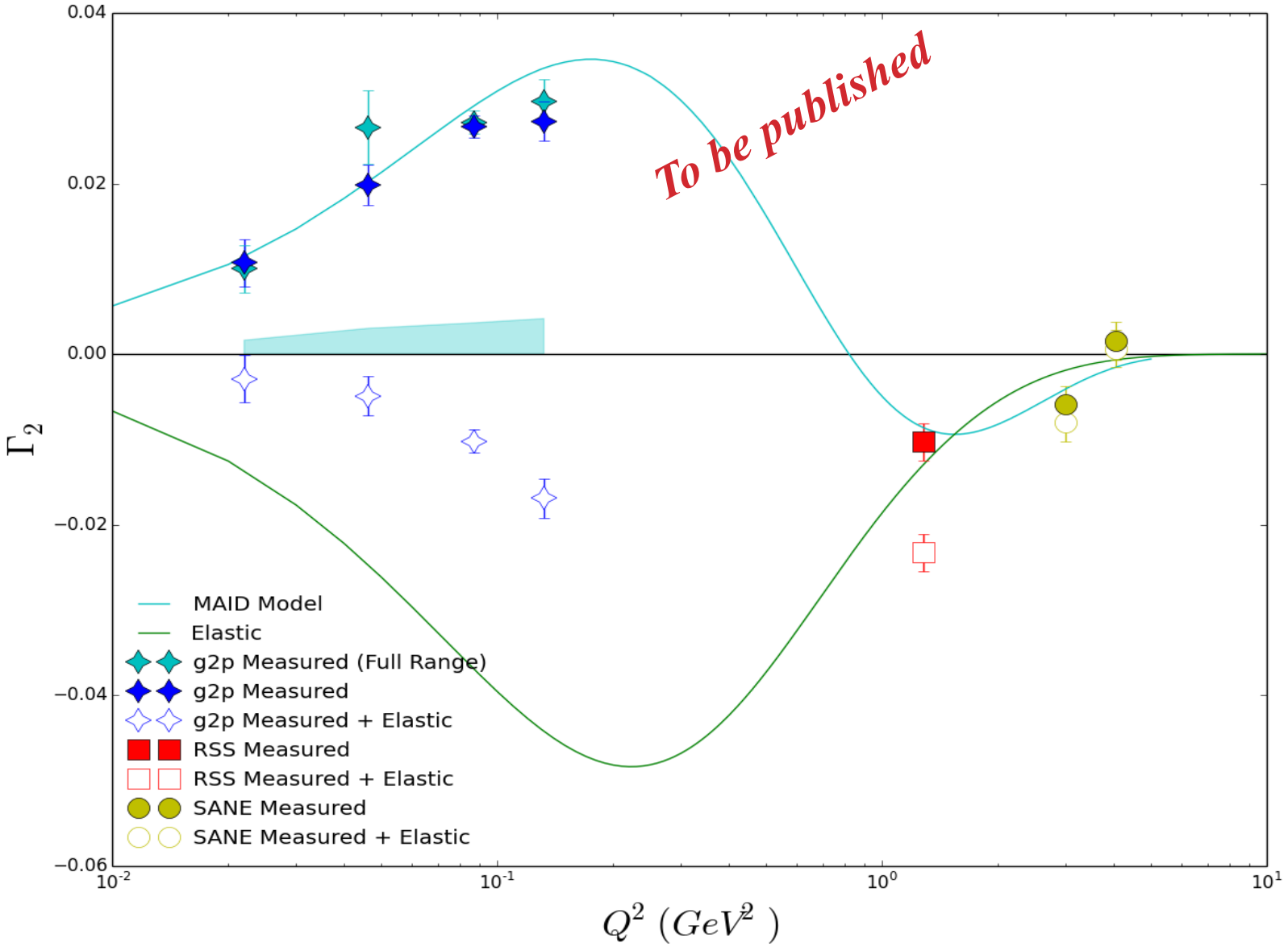
$$\Gamma_2(Q^2) \equiv \int_0^1 g_2 dx = 0$$

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

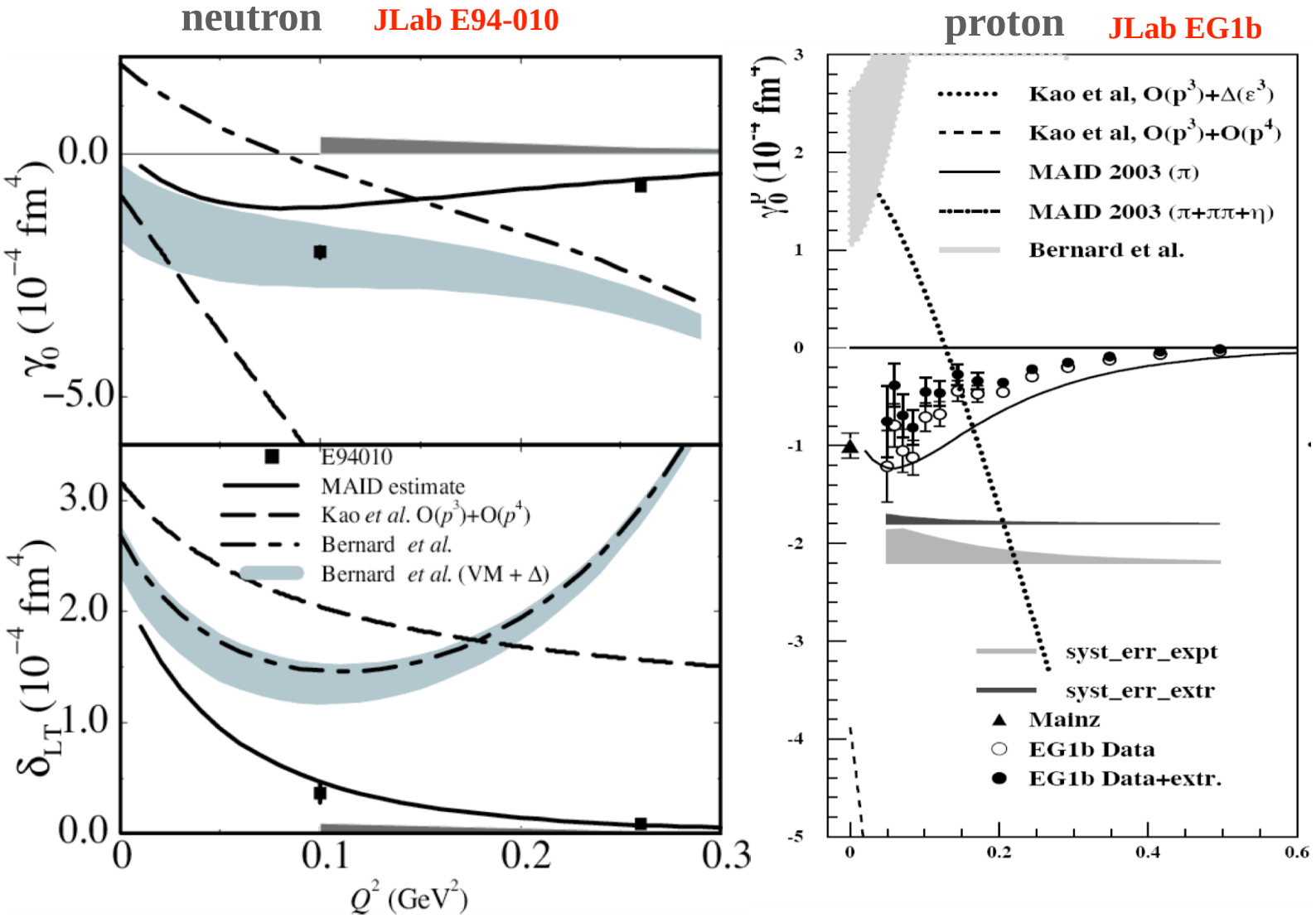


E97-110 verifies the B-C sum rule at low Q^2. Older experiments at higher Q^2 also verify it.

g2p: new Γ_2 data on proton: BC Sum Rule



Previous JLab spin polarizabilities data before low-Q experiments



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

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

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

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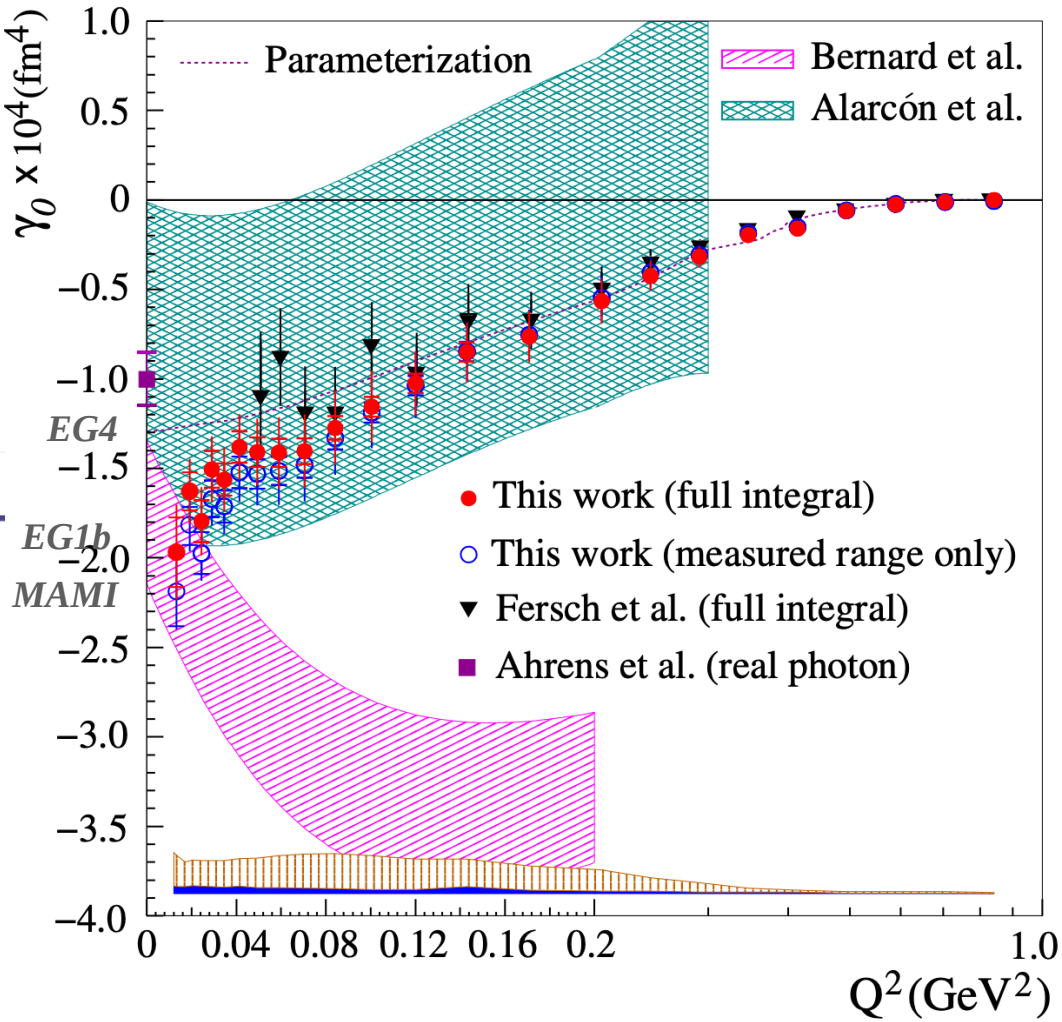
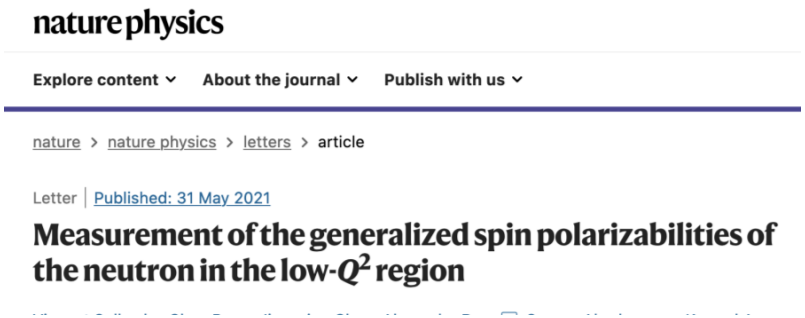
Measurement of the proton spin structure at long distances

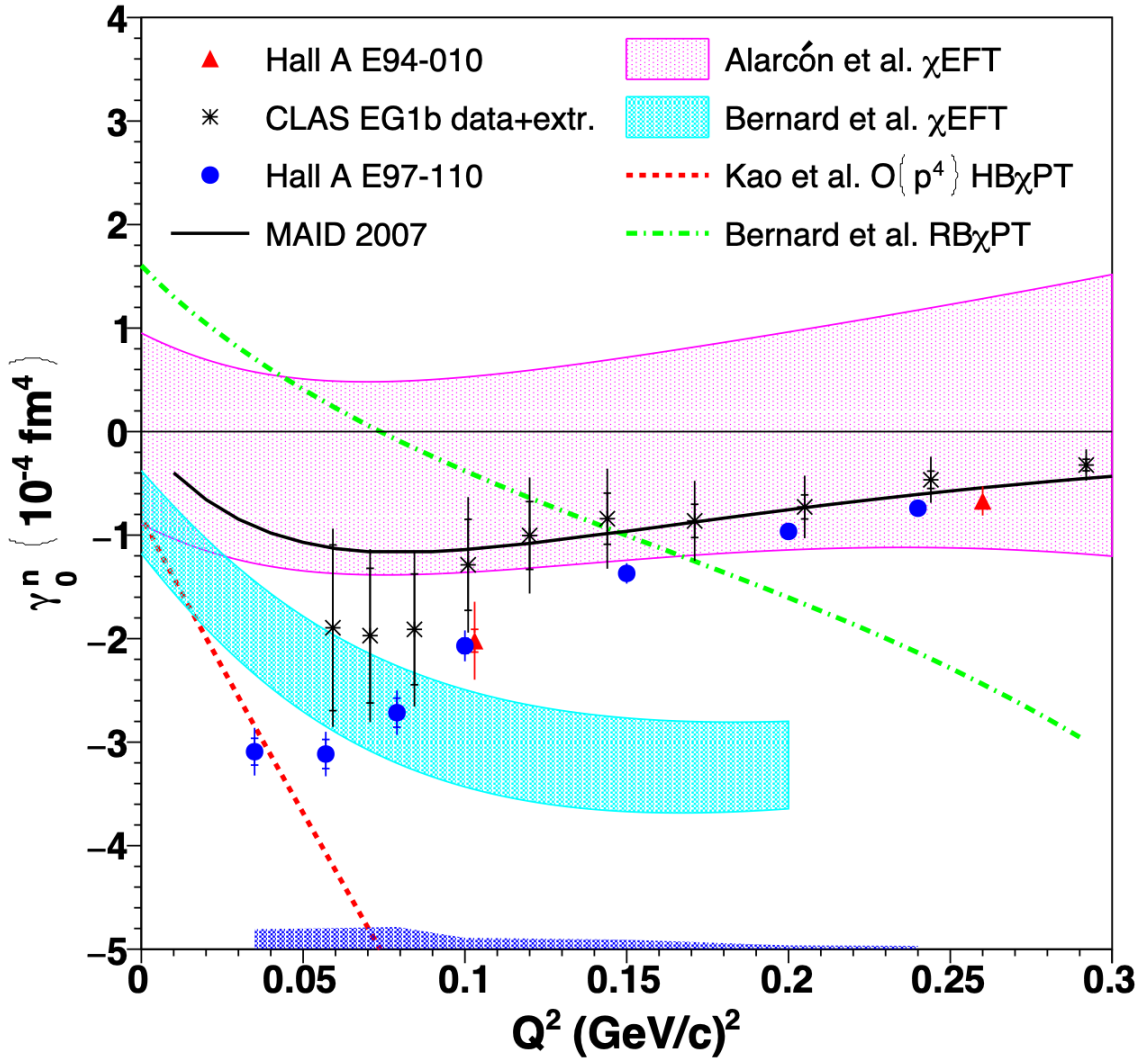


- χEFT result of Alarcón et al agrees with data.
- Bernard et al. χPT calculation agrees for lowest Q^2 points.

Generalized forward spin polarizability γ_0^n from SAGDH

V. Sulkosky et al.,
Nature Physics,
17, 687 (2021)

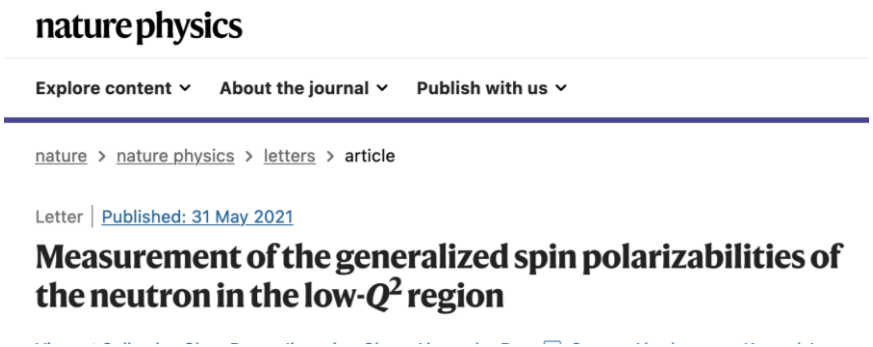


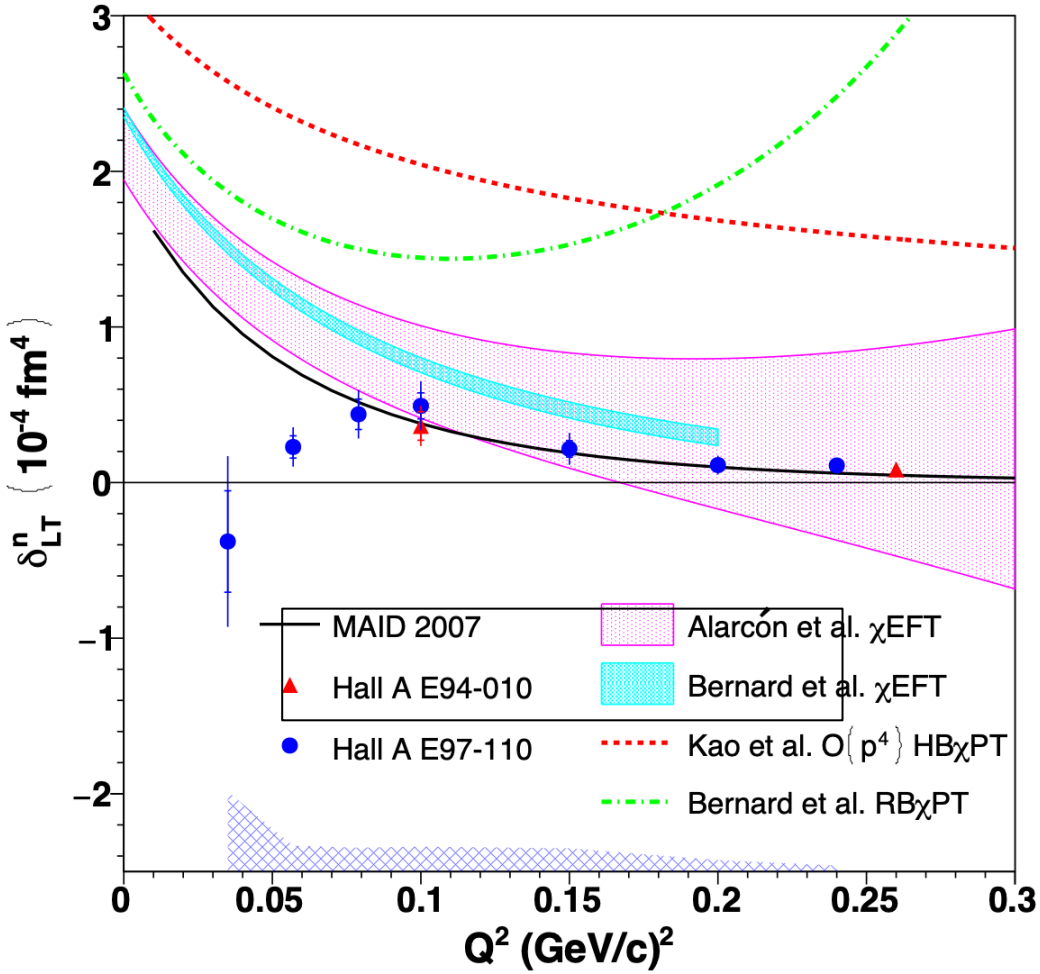


- E97-110 agree with older data at larger Q^2 (EG1b, E94-010). Maid disagrees with the data.
- χEFT result of Alarcón et al disagrees with data.
- Bernard et al. χPT calculation agrees for lowest Q^2 points.

Generalized Interference Spin Polarizability δ_{LT} from SAGDH

V. Sulkosky et al.,
Nature Physics,
17, 687 (2021)





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

δ_{LT} for Proton from g2p

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

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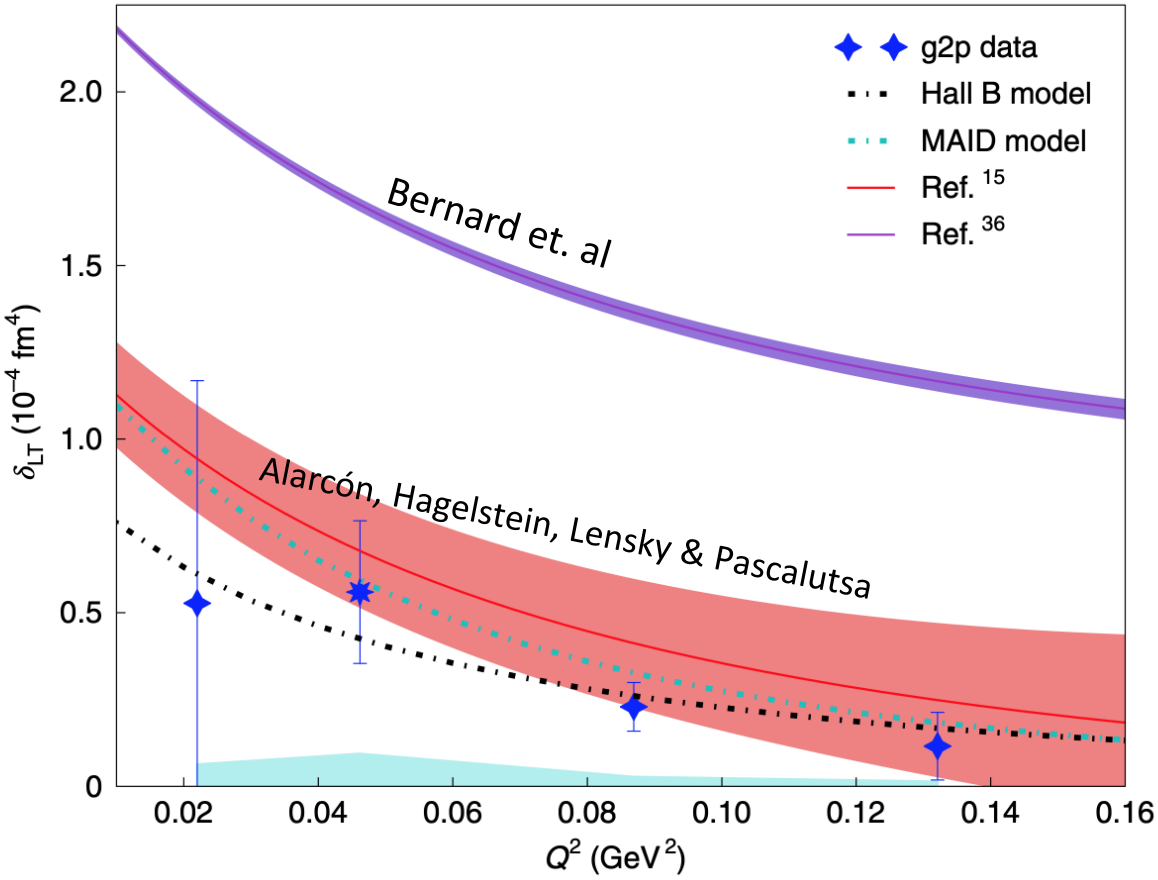
Article | Published: 13 October 2022

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: Γ_1 of *p-n* (EG4 and SAGDH)

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

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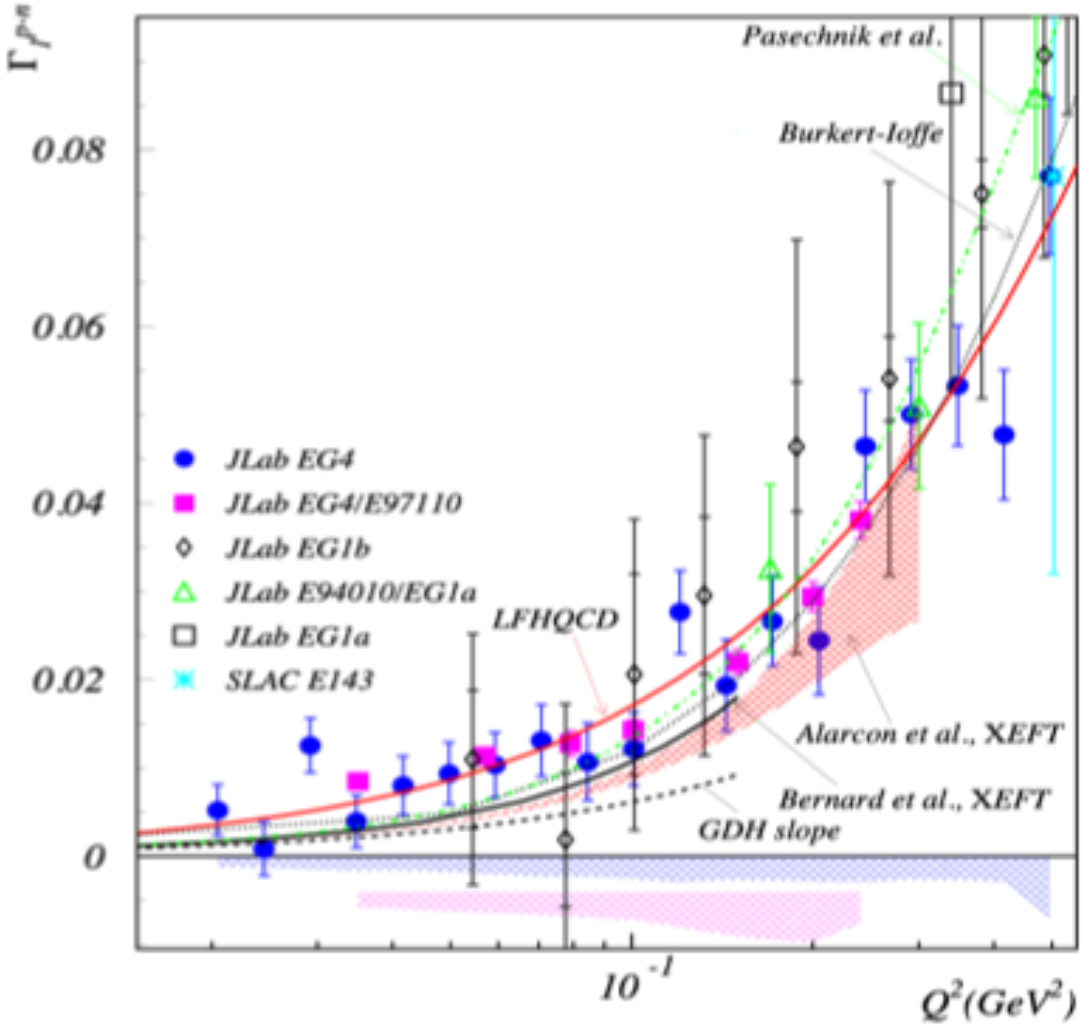
Experimental study of the behavior of the Bjorken sum at very low Q^2



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Impact on:
hadron spectroscopy
PDFs and GPDs
quark mass functions
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scale of QCD, Λ_s
QCD Phase/Hot QCD
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A. Deur, V. Burkert, J. P. Chen and W. Korsch
Particles, 5-171 (2022)