3He spin structure and intrinsic isobars

Vadim Guzey

Petersburg Nuclear Physics Institute (PNPI),
National Research Center "Kurchatov Institute",
Gatchina, Russia

Outline:

- Nuclear effects in He-3 spin structure function $g_1^{3He}(x,Q^2)$
- Possible presence of Δ(1232) isobar in He-3 wave function and $g_1^{3He}(x,Q^2)$
- Nuclear shadowing and antishadowing in $g_1^{3He}(x,Q^2)$
- Extraction of the neutron $g_{1n}(x,Q^2)$ from He-3 data
- Summary
- Based on Frankfurt, Guzey, Strikman, PLB 381 (1996) 379; Boros, Guzey, Strikman, Thomas, PRD 64 (2001) 014025; Bissey, Guzey, Strikman, Thomas, PRC 65 (2002) 064317

Exploring QCD with light nuclei at EIC, Stony Brook University, Jan 21-24, 2020 (remote presentation)

Nuclear effects in He-3 spin structure function $g_1^{3He}(x,Q^2)$

• Inclusive deep inelastic scattering (DIS) of longitudinally polarized leptons on longitudinally polarized targets (**p**, **D**, **He-3**, **Li-6**, **Li-7**) → spin structure function of the target $g_1(x,Q^2)$ → polarized quark and gluon distributions.

• Besides their own interest, polarized nuclear targets (D and He-3) are used as a source of polarized neutrons.

• The neutron $g_{1n}(x,Q^2)$ is needed for
- flavor separation of quark polarized distributions
- tests of various spin sum rules (Bjorken, Jaffe-Manohar, Burkhardt-Cottingham, Gerasimov-Drell-Hearn)

• Various nuclear effects make $g_{1n}(x,Q^2) \neq g_1^{3He}(x,Q^2)$. They include:
- nucleon spin depolarization
- nuclear binding and Fermi motion
- off-shell effects
- potential presence of $\Delta(1232)$ isobar in He-3 wave function
- nuclear shadowing and antishadowing

Standard picture of $g_1^{3He}(x,Q^2)$

• The effects of spin depolarization, binding and Fermi motion are traditionally described within the framework of the convolution approach:

$$g_1^{^3\mathrm{He}}(x,Q^2) = \int_x^3 \frac{dy}{y} \Delta f_{n/^3\mathrm{He}}(y) g_1^n(x/y,Q^2) + \int_x^3 \frac{dy}{y} \Delta f_{p/^3\mathrm{He}}(y) g_1^p(x/y,Q^2)$$

Nucleon light-cone momentum distributions from spectral functions = the probability to find spins of the nucleon and the nucleus aligned minus that to find their spins anti-aligned
Ciofi degli Atti, Scopetta, Pace, Salme, PRC 48 (1993) R968; Schulze, Sauer, PRC 48 (1993) 38; Bissey, Thomas, Afnan, PRC 64 (2001) 024004

Free, on-shell, nucleon structure function, Gluck, Reya, Stratmann, Wogelsang, PRD 63 (2001) 094005

• To a very good approximation, $\Delta f_{N/3He}(y)=P_N\delta(1-y)$,

$$g_1^{^3\mathrm{He}}(x,Q^2) = P_n g_1^n(x,Q^2) + 2P_p g_1^p(x,Q^2) \qquad \text{Eq. (2)}$$

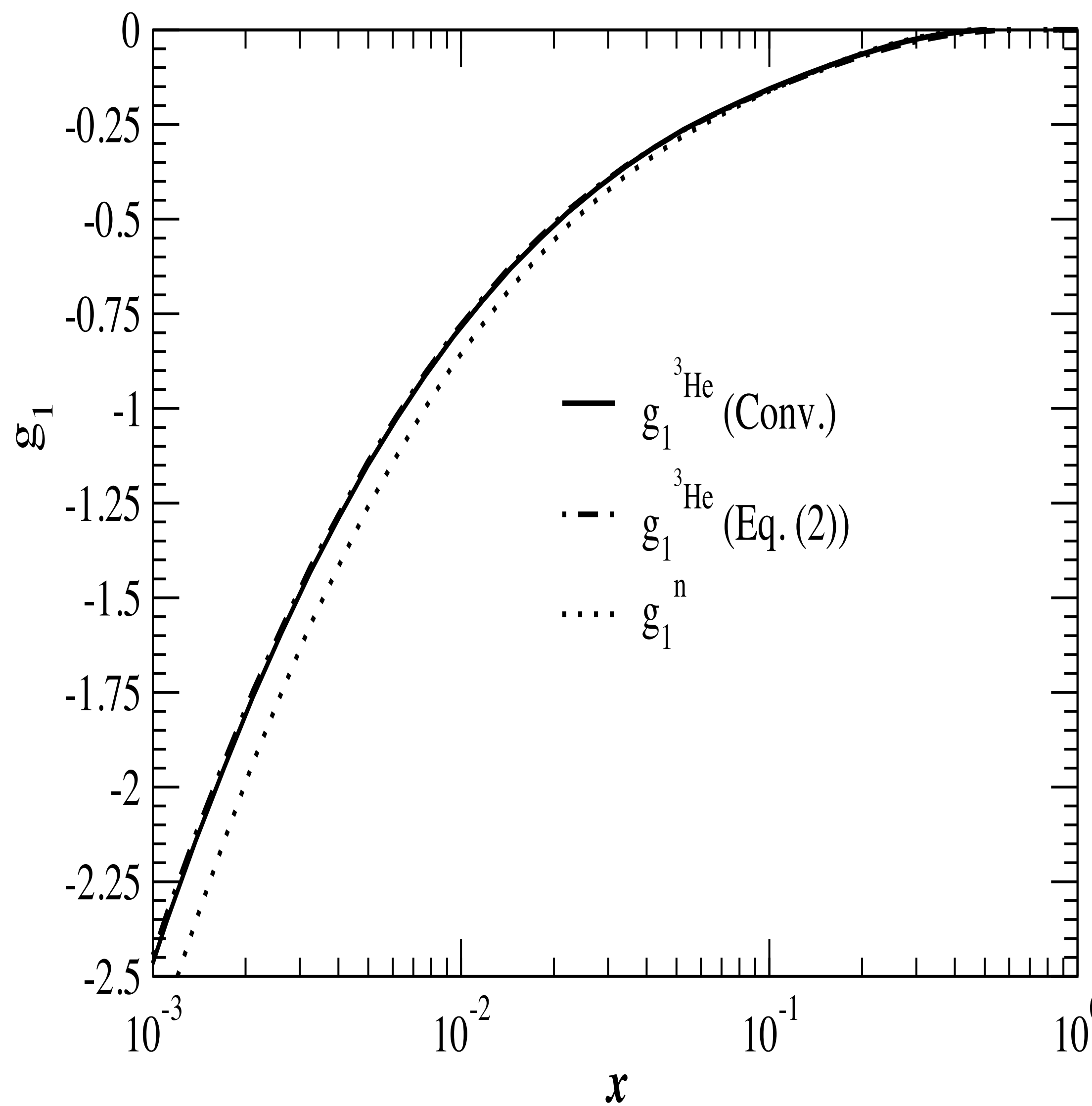
Effective n and p polarizations, include the effect of the tensor component of NN force: P_n=0.979 and P_p=-0.021.

Standard picture of $g_1^{3He}(x,Q^2)$ - Cont.

• Off-shell corrections for light nuclei are expected to be small. We used the results of the Quark-Meson Coupling model, Steffens, Tsushima, Thomas, Saito, PLB 447 (1999) 233.

• The spin structure function $g_1^{3He}(x,Q^2)$ at Q^2=4 GeV^2, Bissey, Guzey, Strikman, Thomas, PRC 65 (2002) 064317

• Eq. (2) approximates very well the full result for $x < 0.1$. For larger x, the differences are sizable.



Possible presence of Δ(1232) isobar in He-3 wave function

- The description of nuclei as collections of proton and neutrons may be incomplete.

- Consider the ratio of the Bjorken sum rules for the **A=3** and **A=1** systems:

$$\frac{\int_0^3 \left(g_1^{^3\mathrm{H}}(x,Q^2) - g_1^{^3\mathrm{He}}(x,Q^2)\right)dx}{\int_0^1 \left(g_1^p(x,Q^2) - g_1^n(x,Q^2)\right)dx} = \frac{g_A|_{triton}}{g_A} = \boxed{0.956 \pm 0.004}$$

From triton beta-decay, Budick, Chen, Lin, PRL 67 (1991) 2630

- Using the convolution formula:

$$\frac{\int_0^3 \left(g_1^{^3\mathrm{H}}(x,Q^2) - g_1^{^3\mathrm{He}}(x,Q^2)\right)dx}{\int_0^1 \left(g_1^p(x,Q^2) - g_1^n(x,Q^2)\right)dx} = \left(P_n - 2P_p\right)\frac{\tilde{\Gamma}_p - \tilde{\Gamma}_n}{\Gamma_p - \Gamma_n} = \boxed{0.921}\,\frac{\tilde{\Gamma}_p - \tilde{\Gamma}_n}{\Gamma_p - \Gamma_n}$$

- → a **3.5%** deficit!

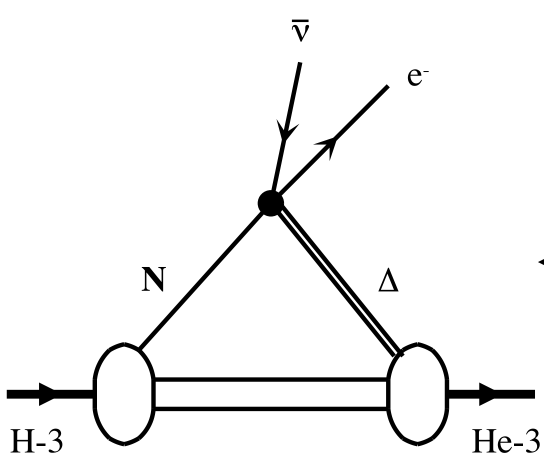
Possible presence of Δ(1232) isobar in He-3 (2)

• Is has been known for a long time that non-nucleonic dof's (pions, vector mesons, Δ) play important role in calculations of low-energy nuclear physics.

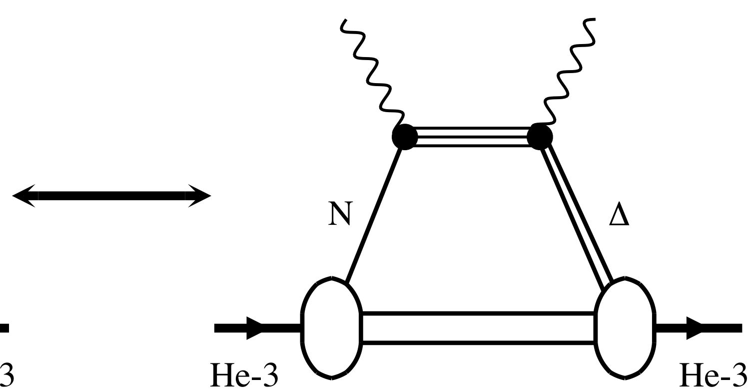
• In particular, two-body exchange currents involving Δ(1232) increase the theoretical description for the axial-vector coupling constant of triton by ~4%,

Saito, Wu, Ishikawa, Sasakawa, PLB 242 (1990) 12; Carlson, Riska, Schiavilla, Wiringa, PRC 44 (1991) 619

• → it is natural to assume that the same mechanism is present also in polarized DIS on 3He and 3H, Frankfurt, Guzey, Strikman, PLB 381 (1996) 379



Triton beta decay



Polarized DIS on He-3

Possible presence of Δ(1232) isobar in He-3 (3)

- The contribution of Δ-isobar to $g_1^{3He}(x,Q^2)$:

$$g_1^{^3\mathrm{He}} = \int_x^3 \frac{dy}{y} \Delta f_{n/^3\mathrm{He}}(y) \tilde{g}_1^n(x/y,Q^2) + \int_x^3 \frac{dy}{y} \Delta f_{p/^3\mathrm{He}}(y) \tilde{g}_1^p(x/y,Q^2)$$
$$+ \; 2P_{n\to\Delta^0} g_1^{n\to\Delta^0} + 4P_{p\to\Delta^+} g_1^{p\to\Delta^+}$$

- The new interference structure functions can be estimated using SU(6) wave functions, Close, Thomas, PLB 212 (1988) 227; Boros, Thomas, PRD 60 (1999) 074017

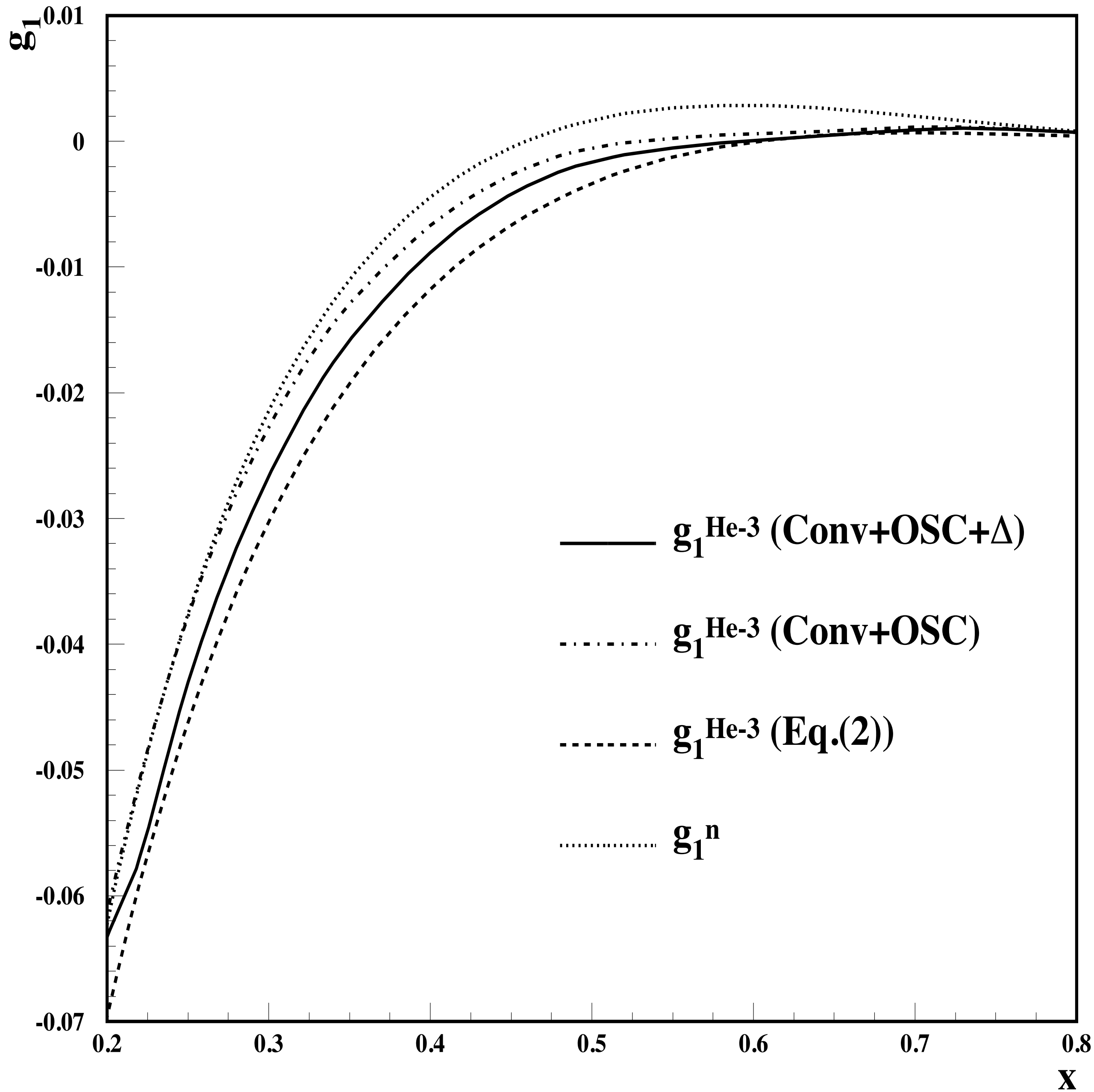
$$g_1^{n\to\Delta^0} = g_1^{p\to\Delta^+} = \frac{2\sqrt{2}}{5}\left(g_1^p - 4g_1^n\right)$$

- Requiring that theory reproduces the experimental value of $g_{A|triton}/g_A$, we determine the effective polarizations: $2\left(P_{n\to\Delta^0} + 2P_{p\to\Delta^+}\right) = -0.025$

- $g_1^{3He}(x,Q^2)$ including the effects of the nucleon spin depolarization, binding, Fermi motion, off-shellness, and the intrinsic Δ-isobar:

$$g_1^{^3\mathrm{He}} = \int_x^A \frac{dy}{y} \Delta f_{n/^3\mathrm{He}}(y) \tilde{g}_1^n(x/y,Q^2) + \int_x^A \frac{dy}{y} \Delta f_{p/^3\mathrm{He}}(y) \tilde{g}_1^p(x/y,Q^2)$$
$$- \; 0.014\left(\tilde{g}_1^p(x,Q^2) - 4\tilde{g}_1^n(x,Q^2)\right) .$$

Possible presence of Δ(1232) isobar in He-3 (4)



Bissey, Guzey, Strikman, Thomas, PRC 65 (2002) 064317

Nuclear shadowing in $g_1^{3He}(x,Q^2)$

• The small-x coherent nuclear effects of shadowing and antishadowing have so far been ignored in analyses of DIS of polarized nuclear targets.

• In the target rest frame, the photon interacts coherently with all target nucleons by fluctuating into h_{eff} → the destructive interference of scattering amplitudes with N=1, 2, and 3 nucleons leads to the suppression of the nuclear cross section:

$$g_1^{^3\mathrm{He}} \propto \sigma_{\gamma^* A}^{\uparrow\downarrow} - \sigma_{\gamma^* A}^{\uparrow\Downarrow} \propto \sigma_{h_{eff}A}^{\uparrow\uparrow} - \sigma_{h_{eff}A}^{\uparrow\downarrow}$$

• Using the Gribov-Glauber shadowing formalism:

$$\Delta\sigma_{h_{eff}A} \equiv \sigma_{h_{eff}A}^{\uparrow\uparrow} - \sigma_{h_{eff}A}^{\uparrow\downarrow} = P_n \Delta\sigma_n + 2P_p \Delta\sigma_p$$
$$-\frac{\sigma_{eff}}{4\pi B}\Big(\Delta\sigma_n \Phi_n + \Delta\sigma_p \Phi_p\Big) + \frac{\sigma_{eff}^2}{48\pi^2(\alpha_{^3\mathrm{He}} + B)^2}\Delta\sigma_n$$

Effective cross section driven by spin-dependent diffraction or diffraction due to Pomeron-Reggeon interference - unknown

Calculated using the ground-state 3He wf

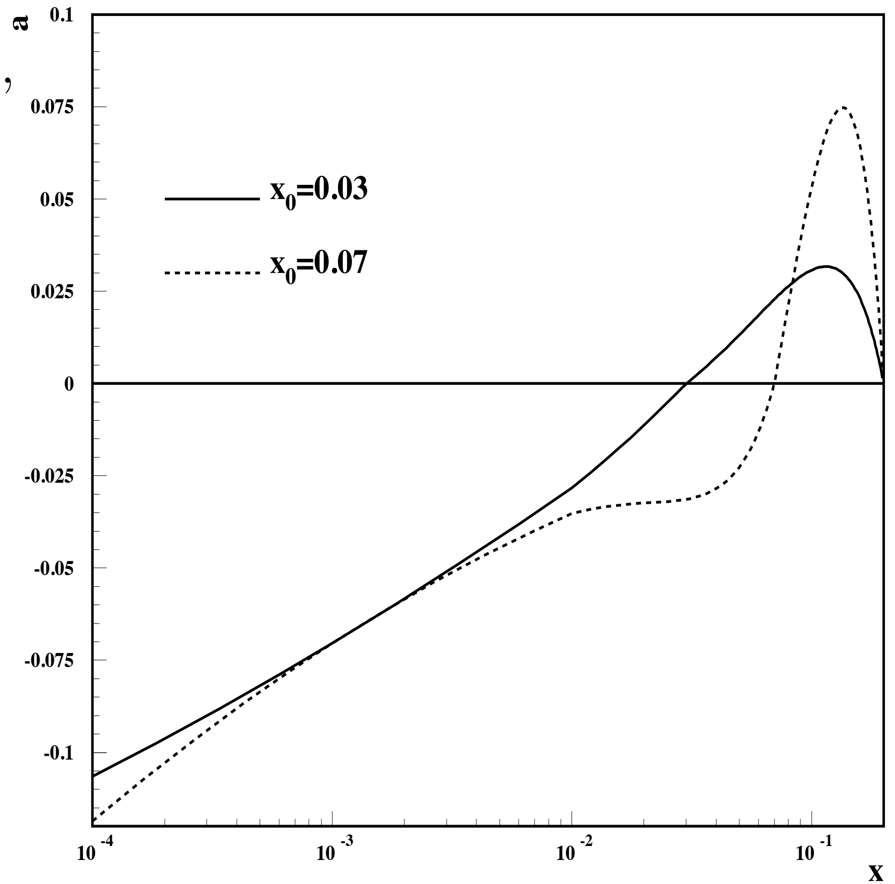
Nuclear antishadowing in $g_1^{3He}(x,Q^2)$

- In unpolarized DIS on nuclear targets, the suppression of the nuclear cross section due to shadowing is followed by some enhancement (antishadowing).

- We assume the same for $g_1^{3He}(x,Q^2)$ and requite that both effects compensate each other in the Bjorken sum rule:

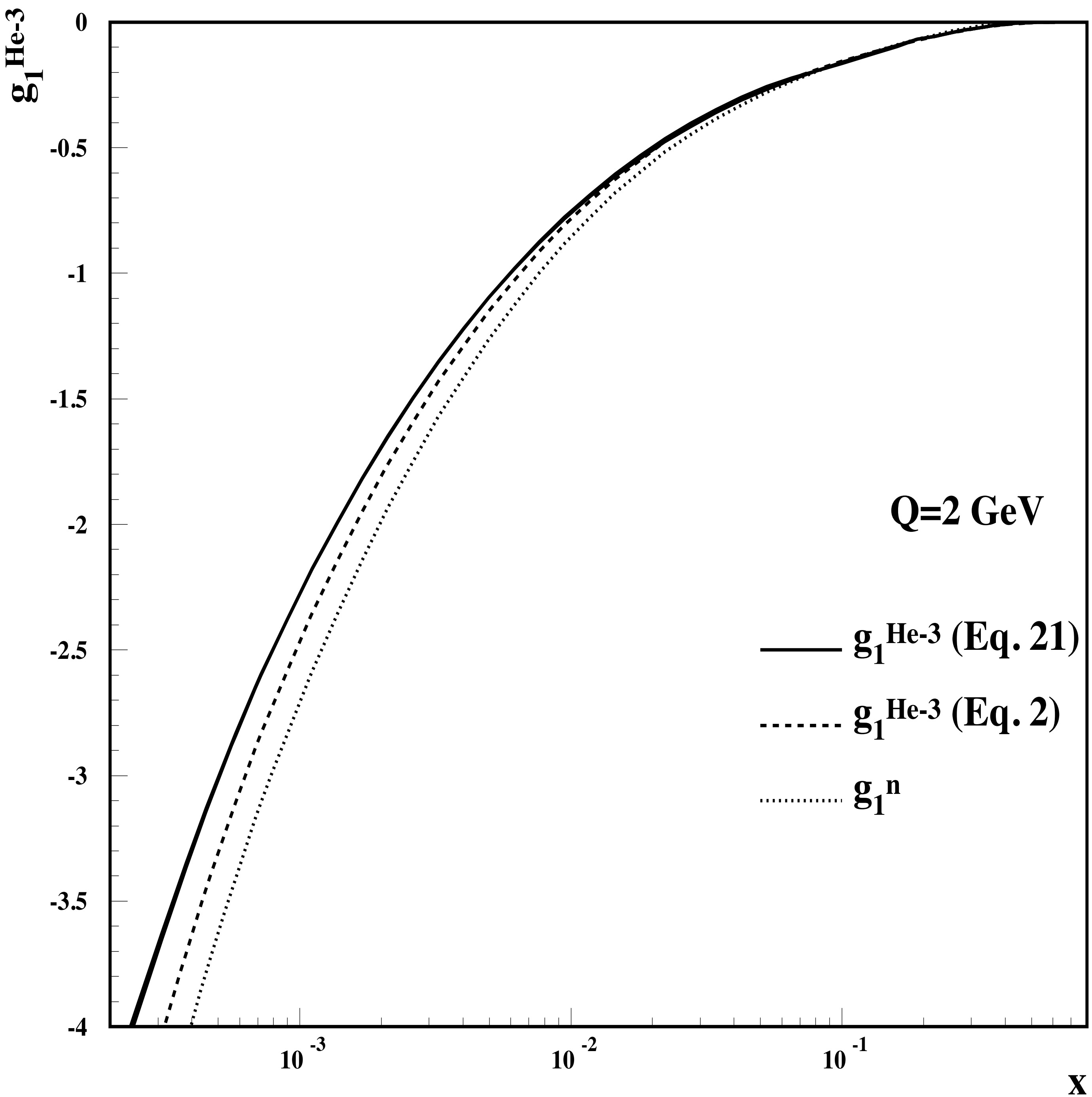
$$g_1^{^3\mathrm{He}} = \int_x^3 \frac{dy}{y} \Delta f_{n/^3\mathrm{He}}(y) \tilde{g}_1^n(x/y) + \int_x^3 \frac{dy}{y} \Delta f_{p/^3\mathrm{He}}(y) \tilde{g}_1^p(x/y)$$
$$-0.014\Big(\tilde{g}_1^p(x) - 4\tilde{g}_1^n(x)\Big) + a(x) g_1^n(x) + b(x) g_1^p(x) \,,$$

Calculated using Gribov-Glauber model for small x < 0.03-0.07 and modeled for large x →



The hight and shape of antishadowing depends on the assumed cross-point x_0.

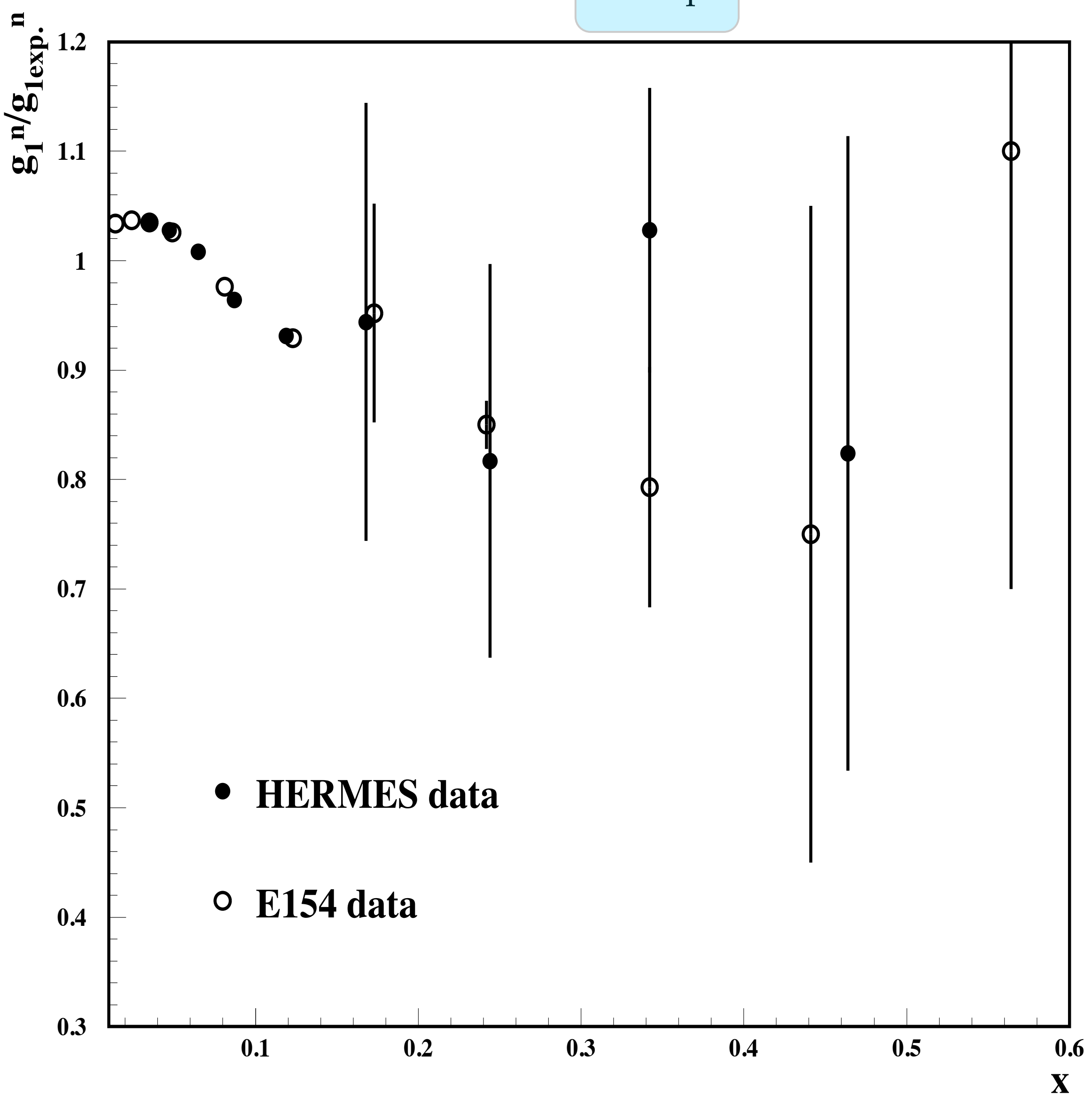
Full result for $g_1^{3He}(x,Q^2)$



Extraction of neutron $g_{1n}(x,Q^2)$ from 3He data

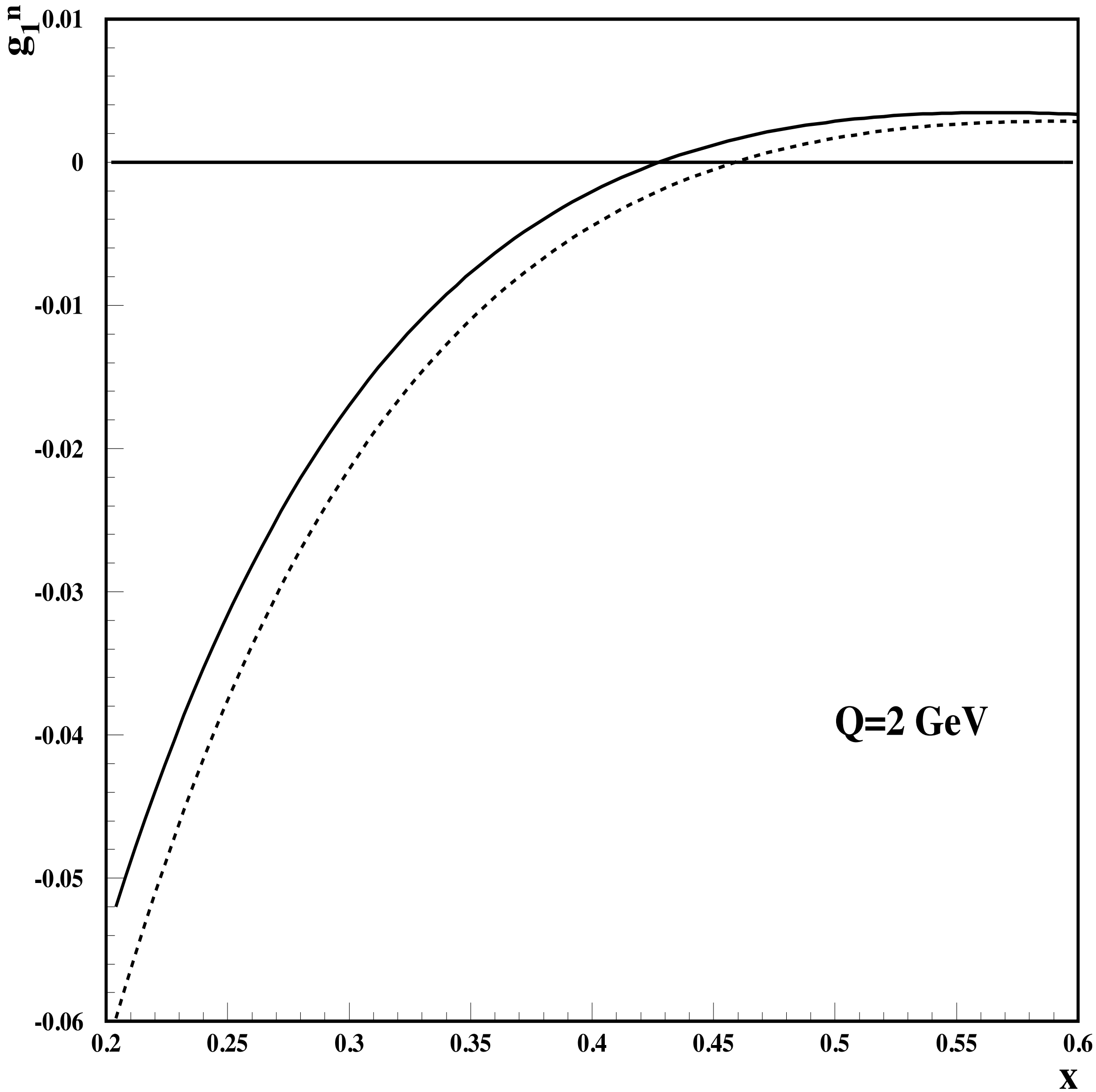
- Correction factor due to Δ isobar, shadowing and antishadowing:

$$\frac{g_1^n}{g_{1\,\mathrm{exp}}^n} = \frac{P_n + g_1^p/g_{1\,\mathrm{exp}}^n\left(0.014 - b(x)\right)}{P_n + 0.056 + a(x)}$$



Extraction of neutron $g_{1n}(x,Q^2)$ from 3He data (2)

- $g_{1n}(x,Q^2)$ from $$\frac{g_1^n}{g_{1\,\mathrm{exp}}^n} = \frac{P_n + g_1^p/g_{1\,\mathrm{exp}}^n\Big(0.014 - b(x)\Big)}{P_n + 0.056 + a(x)}$$



Solid $g_{1n}(x,Q^2)$
Dotted $g_{1n}^{exp}(x,Q^2)$

Summary

• Comprehensive picture of nuclear effects in DIS on polarized He-3 over a wide range of x, $10^{-4} < x < 0.8$: nucleon spin depolarization, presence of Δ isobar, Fermi motion and binding, nuclear shadowing and antishadowing.

• **Nucleon spin depolarization**, present for all x. Especially important at x=0.4-0.5, where $g_{1n} \approx 0$. Well-understood and used in analyses of He-3 data to extract the neutron g_{1n}.

• **Presence of Δ isobar**, present for all x, but modeled here only for valence quarks, $0.2 < x < 0.8$: 15-25% effect on g_1^{3He} and g_{1n} ; lowers x, where g_{1n} changes sign.

• **Shadowing,** $10^{-4} < x < 0.03$-0.07, by analogy with unpolarized DIS: 10% effect on g_1^{3He} at 10^{-4} and 4% effect on g_{1n} at x=0.01.

• **Antishadowing,** 0.03-$0.07 < x < 0.2$, modeled to preserve Bjorken sum rule, depends on the cross-over point x_0, 7% effect on g_1^{3He} and g_{1n} at x=0.12-013.

• **Fermi motion and binding** become sizable for x > 0.1 (c,f. Ciofi degli Atti, Scopetta, Pace, Salme, PRC 48 (1993) R968) and very significant for x > 0.8.