Proton spin puzzles

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QCD: confinement and chiral symmetry inter-connected

Polarized DIS

→ Quarks spin contributes just ~ 33% of the proton's spin content

How to understand ? Valence quarks, sea, gluon, pion cloud, topology…

In medium proton spin structure

New: the high energy behavior of polarized photon-proton scattering

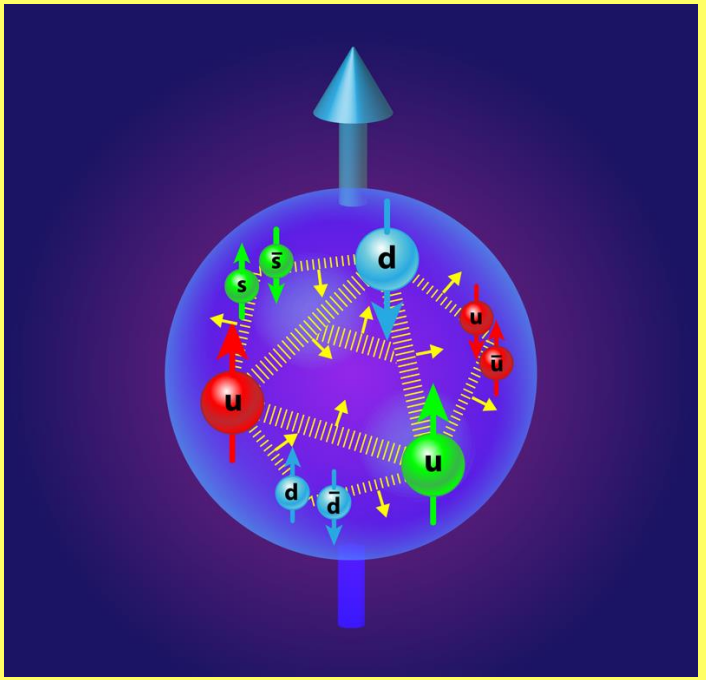
Challenge for models of spin dependent Regge theory

Kitzbühel Humboldt Kolleg, June 25 2019

Proton Spin Puzzles

In QCD hadrons are emergent from more fundamental quarks and gluons

- Protons including their mass, spin …
- Polarized deep inelastic scattering from polarized protons
- Measures the quark and gluon spin content of the proton
- Spin dependent parton distributions



$$g_1(x) = \frac{1}{2}\sum_q e_q^2 \Delta q(x).$$

- First moment ~ 33% quark spin content

$$\Delta q = \int_0^1 dx \ \Delta q(x)$$

$$2M s_\mu \Delta q = \langle p,s| \ \bar{q}\gamma_\mu\gamma_5 q \ |p,s\rangle$$

Deep Inelastic Spin Sum Rule

- Dispersion relation for polarized photon-nucleon scattering + operator product expansion → Sum Rule

$$\int_0^1 dx\; g_1^p(x,Q^2) \;=\; \left(\frac{1}{12}g_A^{(3)} + \frac{1}{36}g_A^{(8)}\right)\left\{1+\sum_{\ell\geq 1} c_{\mathrm{NS}\ell}\,\alpha_s^\ell(Q)\right\} + \frac{1}{9}g_A^{(0)}|_{\mathrm{inv}}\left\{1+\sum_{\ell\geq 1} c_{\mathrm{S}\ell}\,\alpha_s^\ell(Q)\right\} + \mathcal{O}(\frac{1}{Q^2})$$

$$\begin{aligned} g_A^{(3)} &= \Delta u - \Delta d \\ g_A^{(8)} &= \Delta u + \Delta d - 2\Delta s \\ g_A^{(0)} &= \Delta u + \Delta d + \Delta s \end{aligned}$$

- Here nature helps us (Bjorken):
  $g_A^{(3)}$ = 1.27 (same matrix element measured in neutron β decays)
  $g_A^{(8)}$ = 0.58 ± 0.03 (extracted from hyperon β decays + SU(3))
- Perturbative QCD corrections calculated to high precision (Larin et al)
- Guess (Ellis-Jaffe hypothesis): Strangeness contribution ~ 0

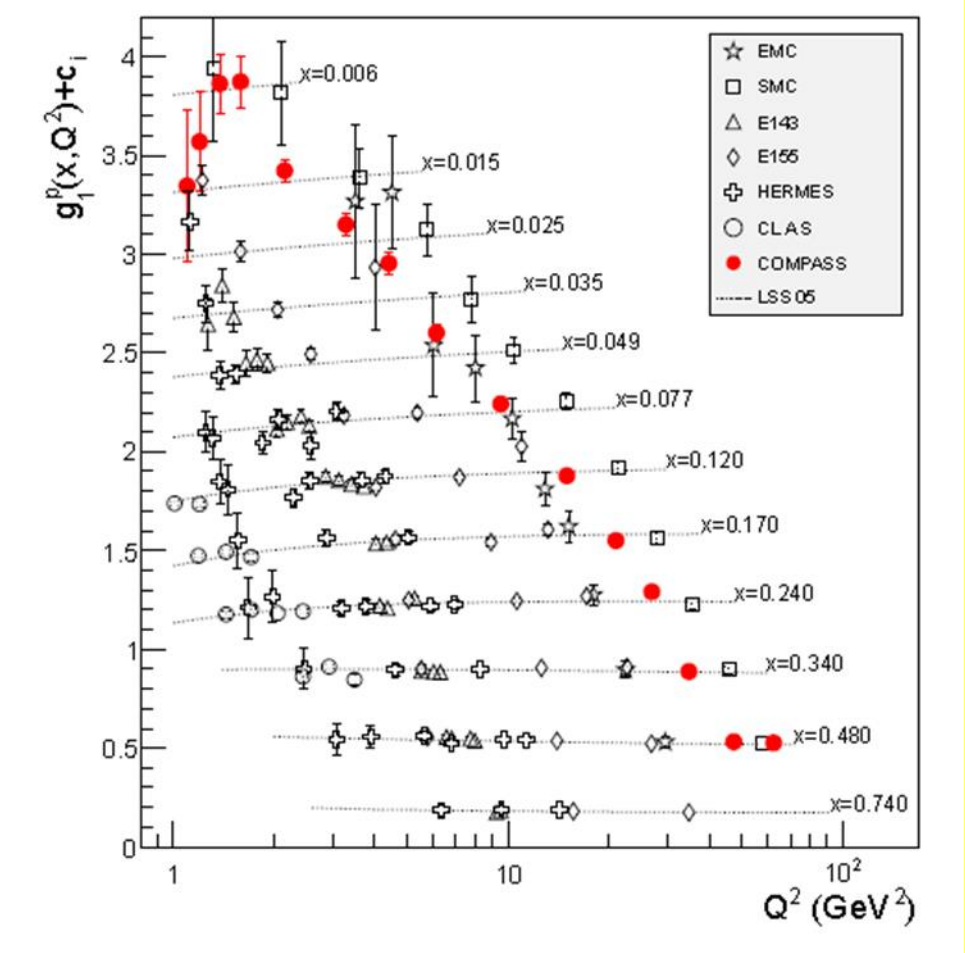
  → $g_A^{(8)} = g_A^{(0)} \sim 0.6$

TEST THIS IN EXPERIMENT

Proton spin puzzles

Quark spin content determinations

Assumes SU(3) value of $g_A^{(8)}$



$$g_A^{(0)}|_{\mathrm{pDIS},Q^2\to\infty} = 0.33 \pm 0.03(\mathrm{stat.}) \pm 0.05(\mathrm{syst.})$$

$$\Delta s_{Q^2\to\infty} = \frac{1}{3}(g_A^{(0)}|_{\mathrm{pDIS},Q^2\to\infty} - g_A^{(8)}) = -0.08 \pm 0.01(\mathrm{stat.}) \pm 0.02(\mathrm{syst.})$$

Convergence of the first moment integrals

Isosinglet integral converges at x ~ 0.03

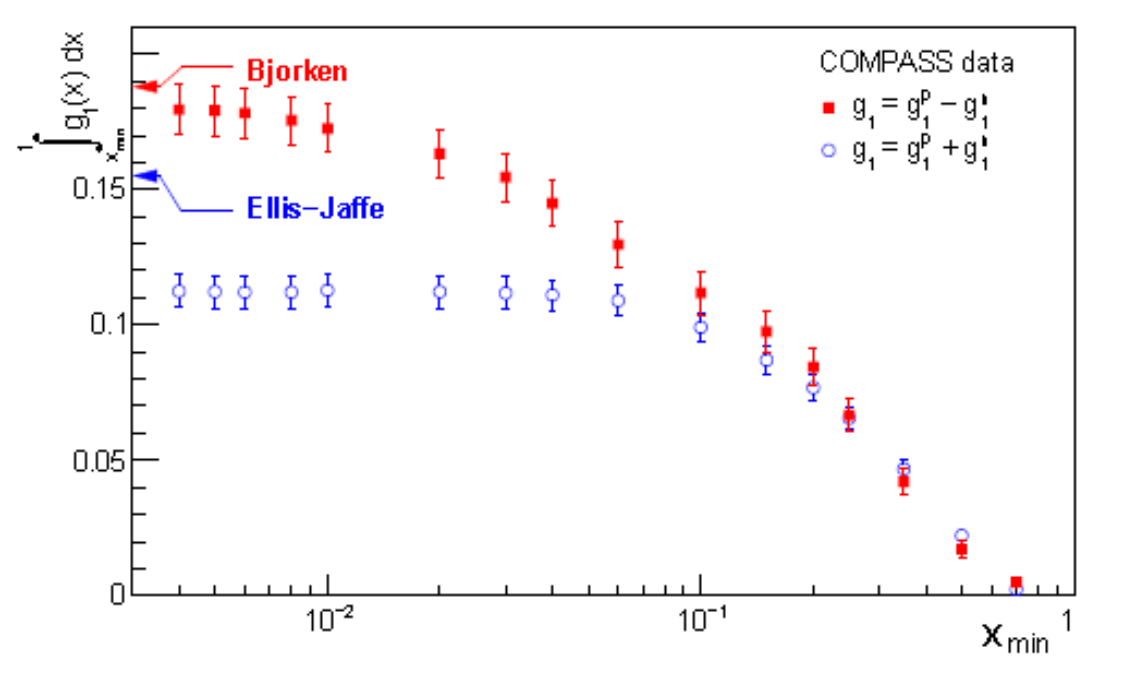
Spin problem associated with „collapse" of the singlet structure function at small x

Saturation of isosinglet g_1 integral

Bjorken Sum Rule for g_1^{p-n} works: COMPASS result

$g_A^{(3)} \sim 1.29 \pm 0.05 \pm 0.10$

Cf. Neutron β decays $g_A^{(3)} \sim 1.27$



$$g_1^{p-n} \sim x^{-0.22\pm0.07}$$

$$2Mg_A^{(3)} = f_\pi g_{\pi NN}$$

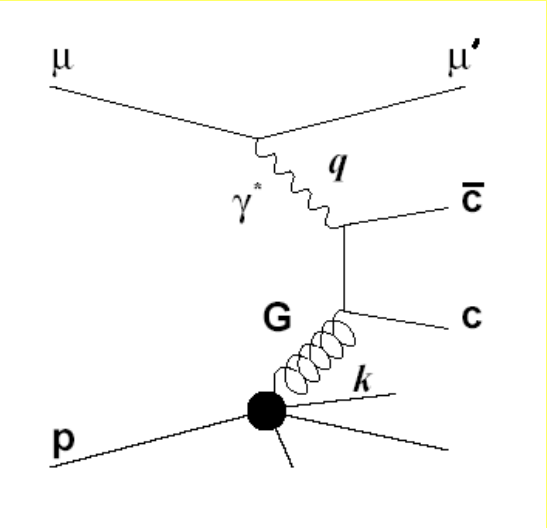
Polarized glue and sea in QCD

- Attempts to understand the polarized DIS values of $g_A^{(0)}$ and Δs
  - Gluon polarization
  - Sea and valence quark polarization

  → measure through hard processes in (semi-inclusive) DIS, jets, polarized pp collisions at RHIC …

$$g_A^{(0)} = \left(\sum_q \Delta q - 3\frac{\alpha_s}{2\pi}\Delta g \right)_{\text{partons}} + C_\infty$$

$$\alpha_s \Delta g \sim \text{constant}, \quad Q^2 \to \infty$$

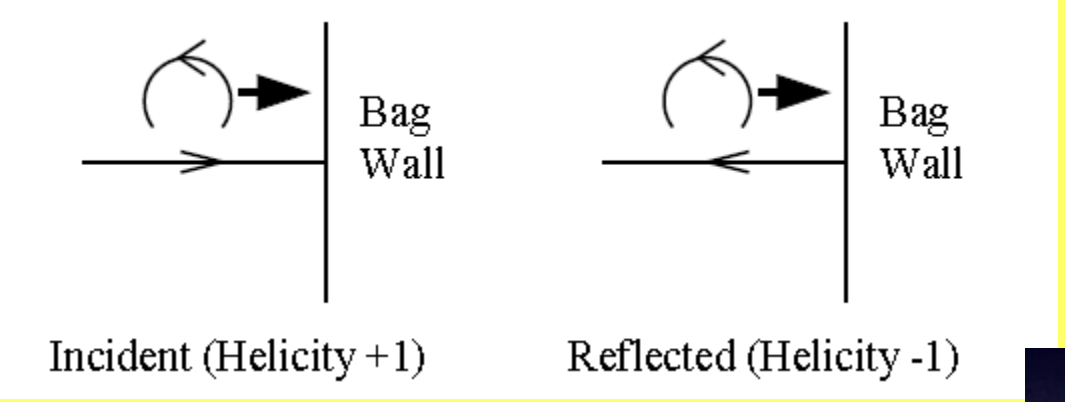


- Measurements at COMPASS, RHIC, HERMES: $\Delta g < 0.5$, $Q^2 \sim 3$ GeV^2
- No evidence of negative strangeness polarization

$\Delta s = -0.02 \pm 0.02 \pm 0.02$ @ $0.003 < x < 0.3$

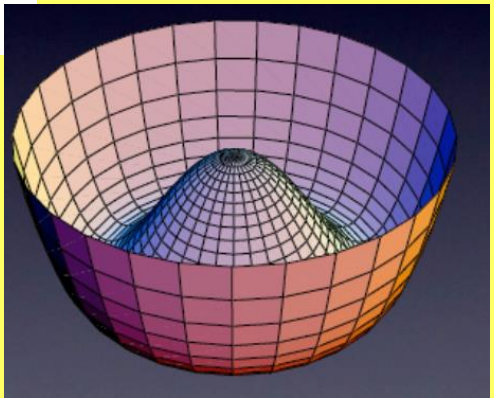
Confinement and chiral symmetry

- Scalar confinement dynamically breaks chiral symmetry
  - Bag wall connects left and right handed quarks
  - Quark – pion coupling and the pion cloud of the nucleon
- Pions, kaons, eta ... as Goldstone bosons



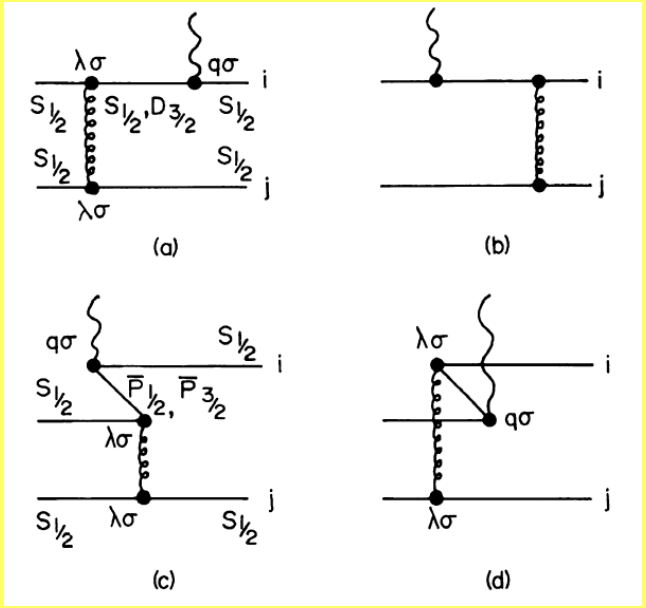
- OGE as residual vector (colour hyperfine) interaction

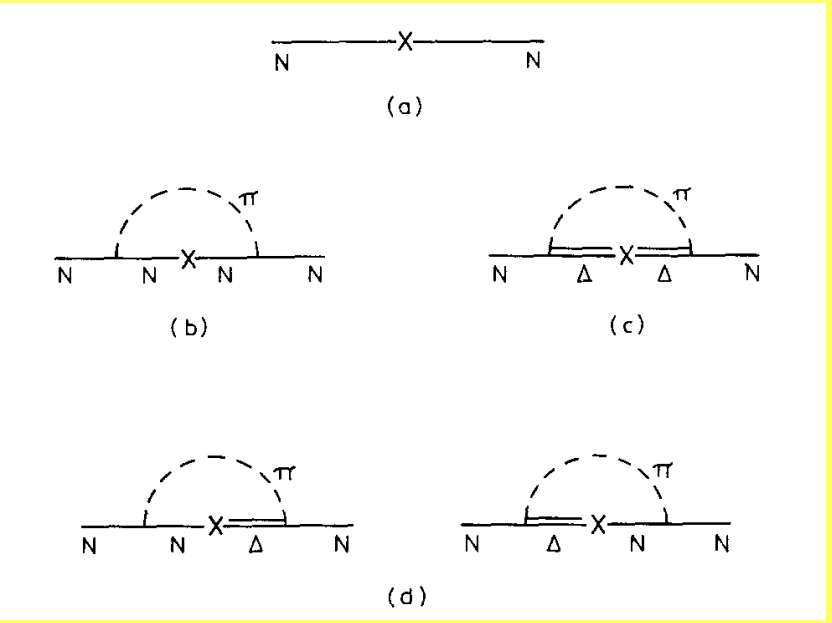
$$E(R) = \sum_i \frac{\omega_i}{R} + \frac{4}{3}\pi R^3 B + \Delta E_M^q - \frac{Z}{R}$$



Modelling the spin

- Colour hyperfine interaction (OGE) and the pion cloud shifts total angular momentum into orbital angular momentum





- Cloudy Bag, pion cloud violates SU(3)

$$g_A^{(8)} = 0.46 \pm 0.05$$

$$\Delta s \sim -0.03 \pm 0.03.$$

Proton spin in medium

- The proton's axial charge is medium dependent

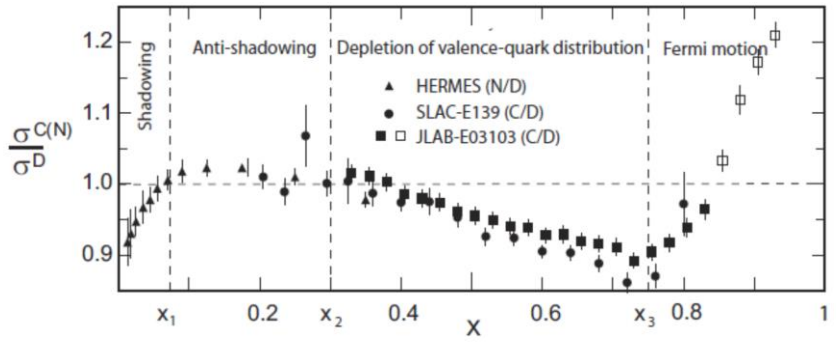
- $g_A^{(3)}$ is quenched by about 10% at nuclear matter density
- Gamow-Teller transitions (M. Ericson, Acta Phys. Pol B29 (1998) 2349)

- Through Bjorken Sum Rule, quark spin structure modified in medium

- Isosinglet axial charges still to be calculated (pions, glue...)
  - Pions not significantly enhanced in nuclei ← nuclear Drell-Yan

- Hadrons in medium ← partial restoration of chiral symmetry (Metag talk)

- Spin version of EMC nuclear effect
  - Jlab experiment with ^{7}Li
  - Future EIC



Mesons and protons in medium

- Effective mass of the η´ changes by ~ -40 MeV at ρ_0
  - From coupling of light-quark part of the η´ to the sigma mean field in the nucleus, with -20 degrees mixing angle
- Glue important in η´
  - Otherwise a strange quark state (no interaction with sigma mean field)

QMC prediction SDB and AW Thomas, PLB 2006

Experimental discovery: Nanova, Metag et al., PLB 2013

- Partial restoration of chiral symmetry
  - $F_\pi^{*2}/F_\pi^2 = 0.64 \pm 0.06$ at ρ_0 from pionic atoms
  - Pion masses shifted few MeV
  - Antiproton effective mass shifted by -100 to -150 MeV
  - K^- effective mass ~ 270 MeV at 2 ρ_0
- 30% of nucleons as excited resonances at 3 ρ_0

Spin dependent Regge intercepts

- Close to photoproduction, $Q^2 = 0$, high energy behaviour of photoabsorption cross sections given expected by Regge phenomenology

$$(\sigma_A - \sigma_P)^{(p-n)} \sim \sum_i N_i^{(3)} s^{\alpha_{a_i}-1},$$

$$(\sigma_A - \sigma_P)^{(p+n)} \sim \sum_i N_i^{(0)} s^{\alpha_{f_i}-1} + N_g \frac{\ln s/\mu^2}{s}$$

$$(\sigma_A - \sigma_P) \simeq \frac{4\pi^2 \alpha_{\rm QED}}{pq} g_1$$

- (Parallel) Straight line Regge trajectories,
  - » intercept between -0.25 and -0.4
  - » a_1 (soft/hard) pomeron cut -0.17 and +0.15

- Deep inelastic

$$g_1^{p-n} \sim x^{-0.22\pm0.07}$$

$$\alpha_{a_1}(Q^2) = 0.22 \pm 0.07$$

$$Q^2 = 3\,\mathrm{GeV}^2,$$

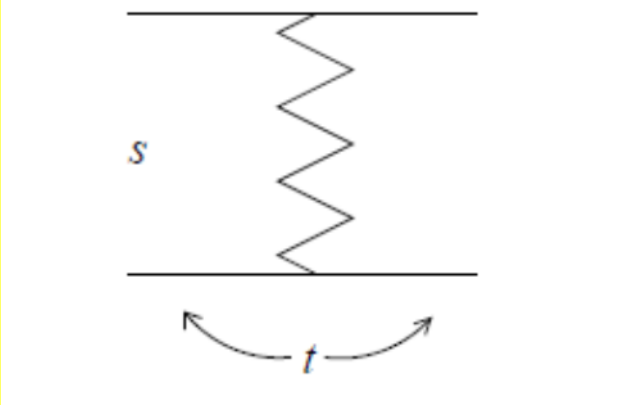
Rising behaviour needed to get large area under Bj Sum Rule

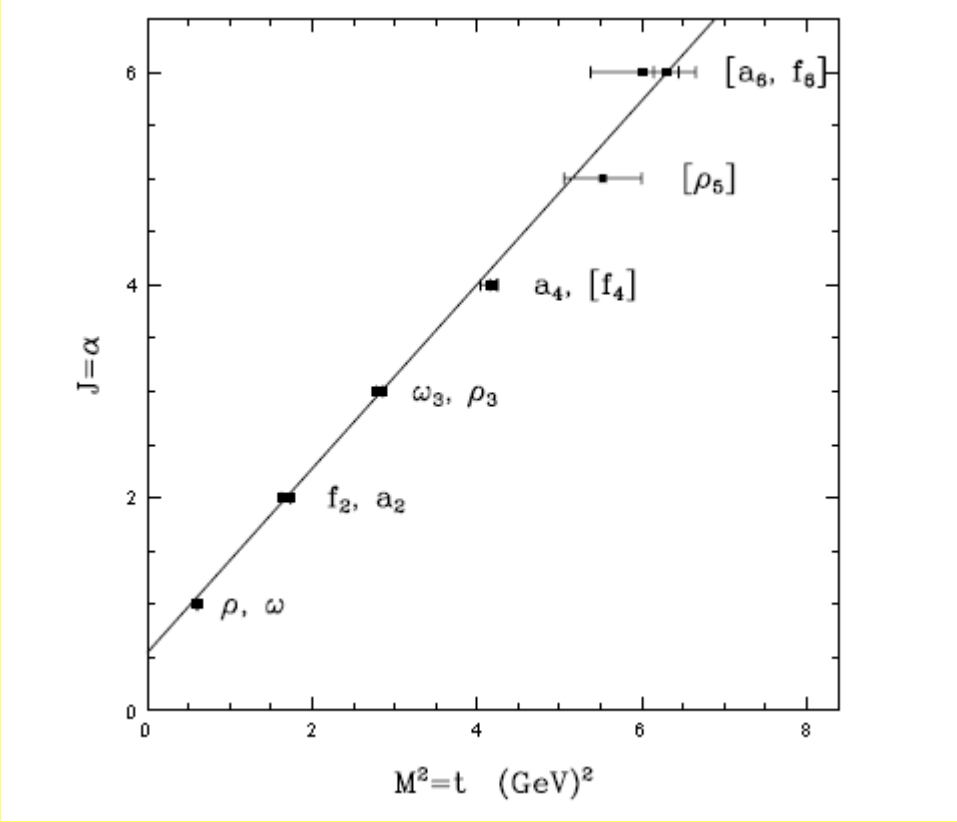
Regge trajectories

- Unpolarised Regge trajectories
  - Straight line, parallel trajectories from linear confinement potential with quark and antiquark pair connected by confining string

$$\mathcal{A}(s,t) \sim \beta(t) s^{\alpha(t)}$$

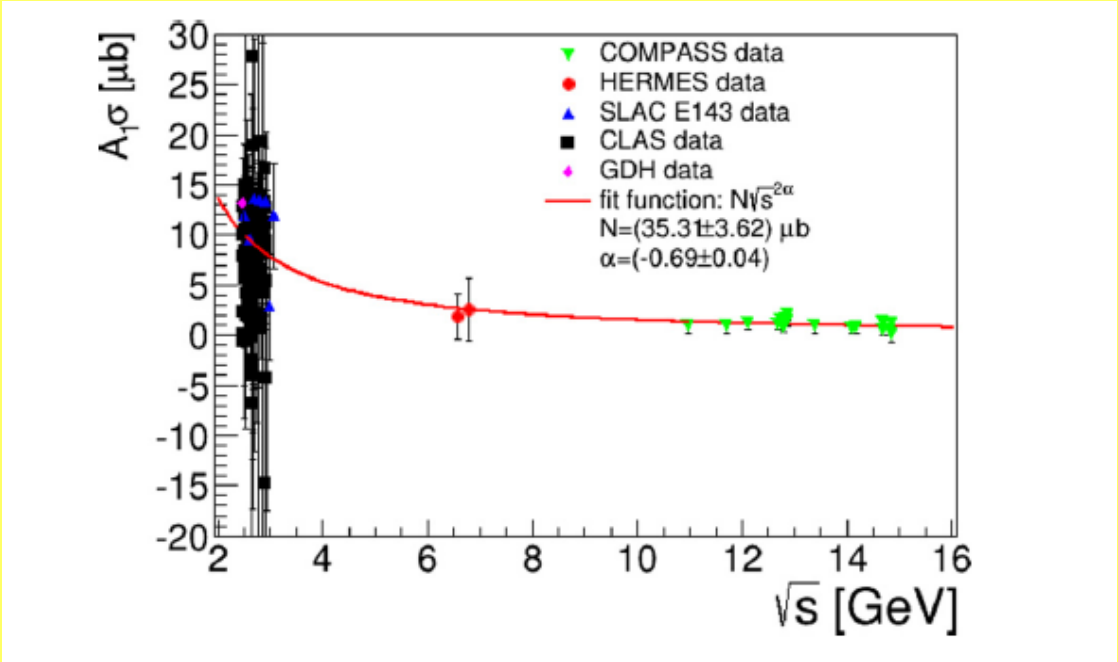
$$\alpha(t) = \alpha_0 + \alpha' t$$





Low Q^2 asymmetries

- Keep Q^2 < 0.5 GeV^2 and centre of mass energy > 2.5 GeV



$$(\sigma_A + \sigma_P) = 67.7\, s^{+0.0808} + 129\, s^{-0.4545}$$

$$(\sigma_A - \sigma_P) = (35.3 \pm 3.6)\, s^{-0.69\pm0.04}\ \mu\text{b}$$

$$\alpha_{a_1} = +0.31 \pm 0.04$$

[SDB, Skurzok, Moskal, PRC 2018]

High energy part of GDH sum rule

- Fundamental GDH – Gerasimov Drell Hearn – sum rule for polarised photoabsorption with real photons

- Fit predicts high energy part $\sqrt{s} \geq 2.5$ GeV

$$\int_{s_0}^{\infty} \frac{ds}{s - M^2}(\sigma_P - \sigma_A) = -15 \pm 2\ \mu\text{b}.$$

- Adding in with lower energy measurements from ELSA and MAMI (Helbing)

$$\int_{M^2}^{\infty} \frac{ds}{s - M^2}(\sigma_P - \sigma_A) = 211 \pm 13\ \mu\text{b}$$

- Theoretical prediction is $2\pi^2 \alpha_{\text{QED}} \kappa^2 / M^2 = 205\ \mu\text{b}$

Understanding the proton spin

- Non-perturbative physics is important !
  - SU(3) breaking through pion cloud
  - Role of gluon topology in dynamical symmetry breaking and the transition from current to constituent quarks
- SIDIS data + RHIC Spin → Glue and sea polarization appears small
- Proton spin puzzle is „valence like" connected with chiral dynamics and complex vacuum structure of QCD in (iso-)singlet channel
- Medium dependence
- Spin dependent Regge intercept evidence for QCD physics beyond simple straight line trajectory: glue and/or chiral dynamics in the a_1 trajectory