Nucleon spin in perspective

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Introduction

A Beautiful Spin (after X. Ji)

- Born with troubles (Stern & Gerlach (1922) vs Goudsmit & Uhlenbeck (1925))
- Is due to space–time symmetry
- Fundamental concept
- Laboratory to explore physics beyond the SM, e.g.:
  - Muon "$g - 2$" experiment @ BNL
  - Proton weak charge (Qweak exp @ JLAB)
  - Neutron EDM measurement ...

  Tool to measure observables hard to obtain otherwise, e.g:
  - Strangeness content of the nucleon from polarised parity–violating e–p scattering
  - Electromagnetic form factors of the nucleon from the recoil polarisation
  - Neutron density in large nuclei from parity–violating electron scattering
- and...

A Beautiful Spin (after X. Ji)...cont'd

- Probe to unravel the nonperturbative QCD dynamics, e.g.:
  - Nucleon spin–dependent structure functions, g_1 and $g - 2$
  - Quark helicity ($\Delta q(x)$) and transversity ($\Delta_T q(x)$) distributions
  - Gluon polarisation, $\Delta g(x)$
  - Generalised Parton Distributions, GPD
  - Semi–Inclusive Deep Inelastic Scattering, SIDIS
  - (Generalised) Drell–Hearn–Gerasimov–... sum rule
  - Single spin asymmetries

Cross section asymmetries $\Longrightarrow$ structure functions

- In a full analogy to spin–averaged DIS where

$$\sigma \sim F_1(x) = \frac{1}{2}\sum_f e_f^2 q_f(x) \quad \text{and} \quad F_2(x) \approx 2xF_1$$

we now have: $$\Delta\sigma = \sigma_{\leftrightarrows} - \sigma_{\leftleftarrows} \sim g_1(x) = \frac{1}{2}\sum_f e_f^2 \Delta q_f(x) \quad \text{and} \quad g_2(x)$$

where $$\Delta q(x) = q^+(x) - q^-(x)$$

- A direct observable, μ–p cross section asymmetry, $A^{\mu p}$:

$$A^{\mu d} = \frac{1}{f P_T P_B}\left(\frac{N_{\leftrightarrows} - N_{\leftleftarrows}}{N_{\leftrightarrows} + N_{\leftleftarrows}}\right); \quad f \sim 0.2, \quad P_T \sim 0.9, \quad P_B \sim -0.8$$

- is related to the longitudinal and transverse $\gamma^* p$ asymmetries:

$$\frac{A^{\mu p}}{D} = A_1^p + \eta A_2^p$$

- Longitudinal spin–dependent structure function:

$$g_1^p(x, Q^2) \approx A_1^p(x, Q^2)\frac{F_2^p(x, Q^2)}{2x(1 + R(x, Q^2))}$$

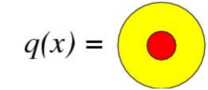
Cross section asymmetries $\Longrightarrow$ structure functions ...

- SIDIS asymmetry, e.g. A^-:

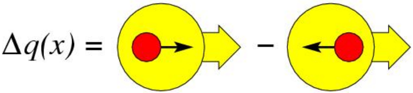
$$A^- = \frac{N^{h^-}_{\leftrightarrows} - N^{h^-}_{\leftleftarrows}}{N^{h^-}_{\leftrightarrows} + N^{h^-}_{\leftleftarrows}} \qquad \text{and} \qquad A_1^h = \frac{\sum_q e_q^2 \left(\Delta q D_q^h + \Delta\bar{q} D_{\bar{q}}^h\right)}{\sum_q e_q^2 \left(q D_q^h + \bar{q} D_{\bar{q}}^h\right)}$$

Partonic structure of the nucleon; distribution functions

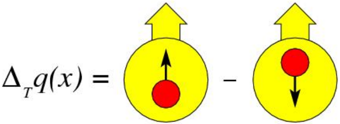
Three species of twist-two quark distributions in QCD (after integrating over the quark intrinsic k_t):



Quark momentum DF;
well known (unpolarised DIS $\longrightarrow F_{1,2}(x)$).



Difference in DF of quarks with spin parallel or antiparallel to the nucleon's spin;
known, helicity (polarised DIS $\longrightarrow g_1(x)$).



Difference in DF of quarks with spin parallel or antiparallel to the nucleon's spin in the transversely polarised nucleon;
unknown, transversity (polaris. SIDIS $\longrightarrow A_{Collins}$)

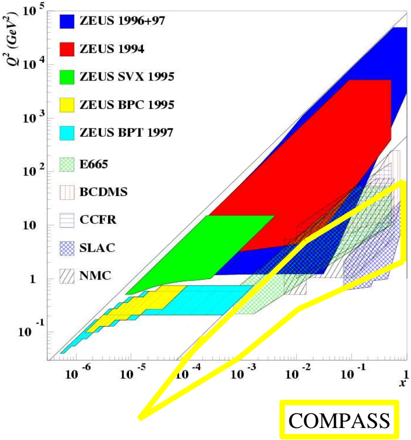
In the nonrelativistic approach $\Delta_T q(x)$ identical with $\Delta q(x)$.
$\Delta_T q(x)$ are C-odd and chiral-odd; may only be measured as $\Delta_T q(x) \otimes \Delta_T D_q^q$.

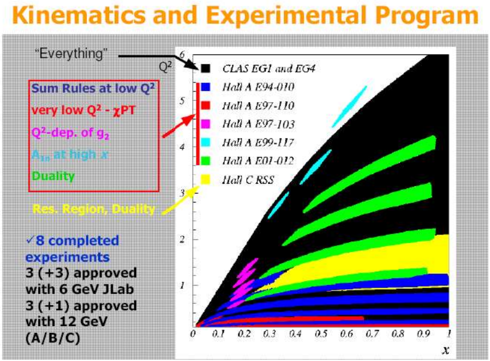
If the k_t taken into account $\Longrightarrow$ 8 TMD appear; one, $f_{1T}^{\perp}$ accessible through "Sivers asymmetry".

Recent and ongoing spin experiments

- CERN: EMC, SMC, COMPASS
- DESY: HERMES
- SLAC (completed): E142, E143, E154, E155, E156
- BNL (RHIC): STAR, PHENIX, BRAHMS

Acceptance of electroproduction experiments





JLAB

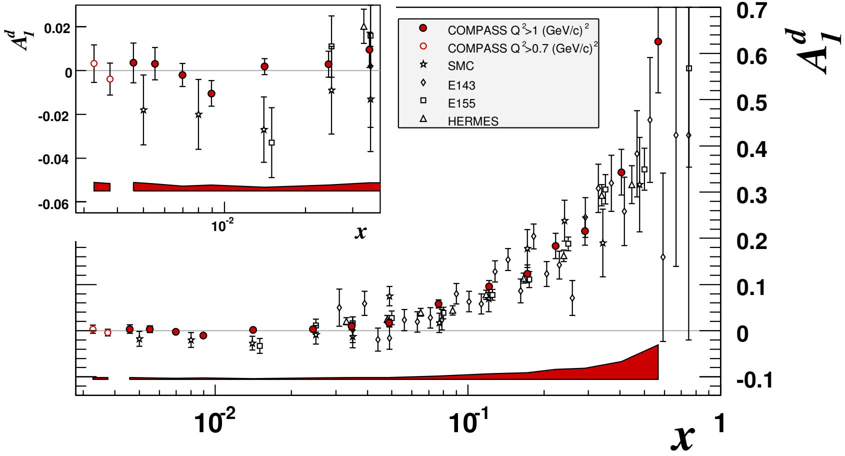
Figure from: N. D'Hose, Villars 2004

Figure from: R. Carlini

Longitudinal spin structure

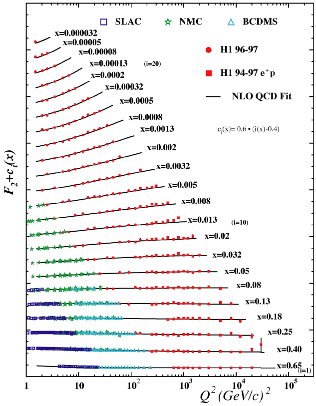
World data on $A_1^d(x)$

V.Yu. Alexakhin (COMPASS) *et al.* Phys. Lett. B **647** (2007) 8



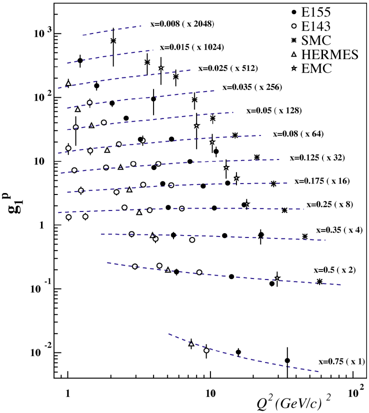
World data on the g_1^p (high energy experiments...)

World data on F_2^p



→ *50% of momentum carried by gluons*

World data on g_1^p



→ *20% of proton spin carried by quark spin*

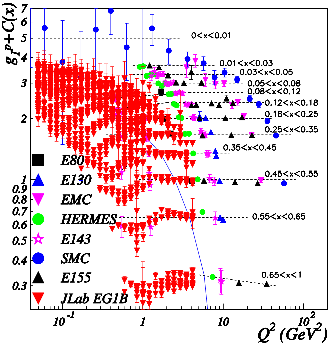
Figure from R.Ent, DIS2006

World data on the g_1^p (...and JLAB)

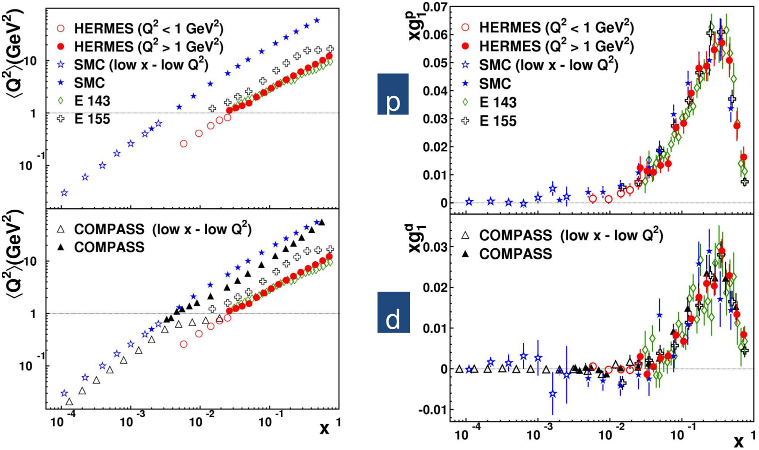
World data on polarized structure function $g_{1p}(x,Q^2)$

CLAS provides a large body of precise g_1 data in the DIS and transition regions that can be used to improve knowledge of twist-2 PDFs.

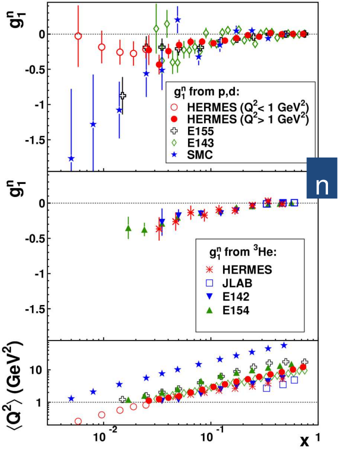
Phys. Rev.C75:035203, 2007
Phys. Lett. B 641, 11 (2006)



World data on the nucleon g_1



World data on the nucleon g_1...cont'd



from p and d

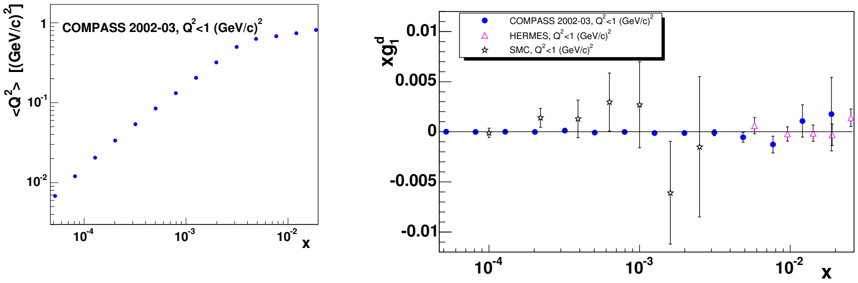
$$g_1^n = \frac{2}{1 - \frac{3}{2}\omega_D} g_1^d - g_1^p$$

from ^{3}He

G. Mallot, APS, May 2008

g_1^d in the nonperturbative ($Q^2 < 1$ (GeV/c)^2 region)

V.Yu. Alexakhin (COMPASS) *et al.* Phys. Lett. B **647** (2007) 330

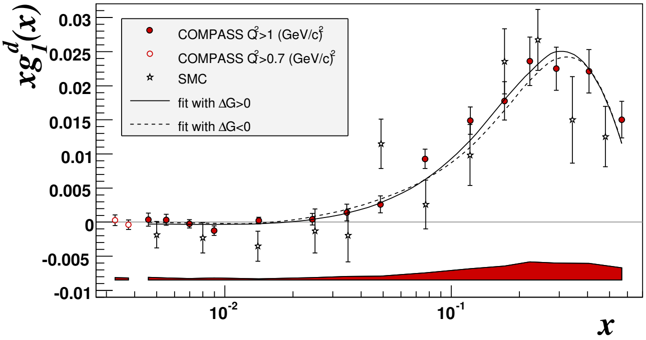


- Order of magnitude improvement over the statistical precision of the SMC.
- Interplay between perturbative and nonperturbative mechanisms.
- Spin effects in g_1^d at low x and Q^2 absent ?

COMPASS QCD analysis of inclusive g_1^d

V.Yu. Alexakhin (COMPASS) *et al.* Phys Lett B**647** (2007) 8

- Two programs: DGLAP evolution of structure functions and evolutions of moments
- NLO $\overline{MS}$ scheme
- World data: 9 experiments, 230 data points (43 from COMPASS)
- Two solutions, $\Delta G > 0$ and $\Delta G < 0$ describe data equally well.

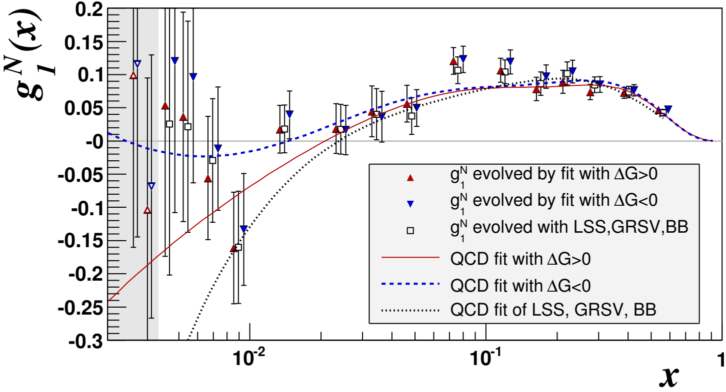


Quark polarisation from COMPASS data only (@ Q^2 = 3 GeV^2):

$a_0 = 0.35 \pm 0.03(\text{stat.}) \pm 0.05(\text{syst.})$ and gluon polarisation: $|\Delta G| \approx 0.2 - 0.3$

COMPASS QCD analysis of g_1^d...cont'd

V.Yu. Alexakhin (COMPASS) *et al.* Phys Lett B**647** (2007) 8



COMPASS g_1^N evolved to Q^2 = 3 GeV^2; LSS, GRSV, BB are NLO fits to world (but no COMPASS) data.

Low x data prefer $\Delta G < 0$??? Sign of ΔG not fixed by the g_1 measurements...

Gluon polarisation from QCD evolution

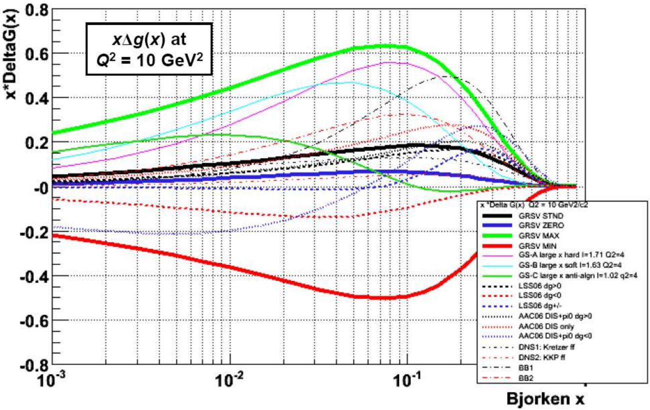


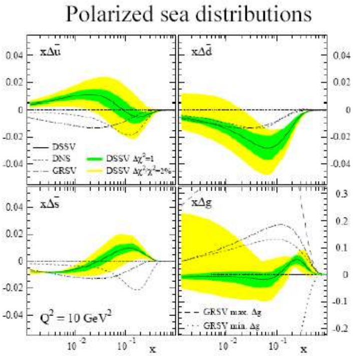
Figure from C. Gagliardi, DIS2008

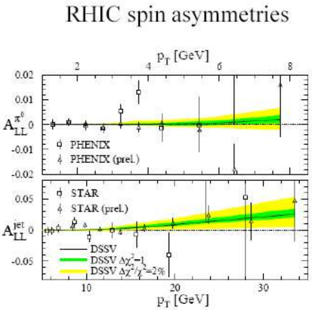
Carl Gagliardi – DIS2008 – Jets in pp at RHIC

NLO QCD analysis of world data

Analysis of worls data by several groups, e.g. the recent ones:

- Leader–Sidorov–Stamenov, LSS06, including COMPASS g_1^d
- De Florian–Sassot–Stratmann-Vogelsang, DSSV08, including RHIC $\vec{p}\vec{p}$ →jets+... data





NLO QCD analysis of world data...cont'd

TABLE II: First moments $\Delta f_j^{1,[x_{\min}-1]}$ at $Q^2 = 10\,\mathrm{GeV}^2$.

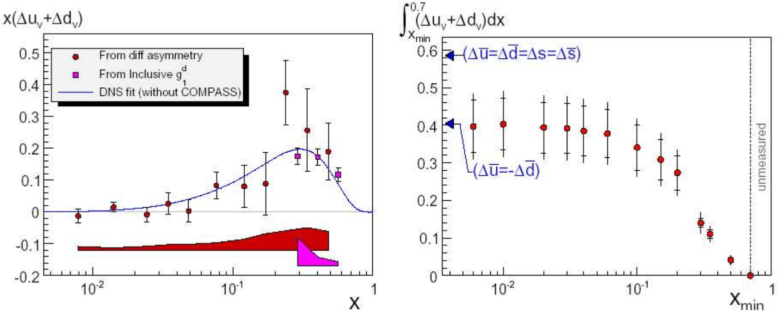
	$x_{\min}=0$	$x_{\min}=0.001$	
	best fit	$\Delta\chi^2=1$	$\Delta\chi^2/\chi^2=2\%$
$\Delta u+\Delta\bar{u}$	0.813	$0.793\ ^{+0.011}_{-0.012}$	$0.793\ ^{+0.028}_{-0.034}$
$\Delta d+\Delta\bar{d}$	-0.458	$-0.416\ ^{+0.011}_{-0.009}$	$-0.416\ ^{+0.035}_{-0.025}$
$\Delta\bar{u}$	0.036	$0.028\ ^{+0.021}_{-0.020}$	$0.028\ ^{+0.059}_{-0.059}$
$\Delta\bar{d}$	-0.115	$-0.089\ ^{+0.029}_{-0.029}$	$-0.089\ ^{+0.090}_{-0.080}$
$\Delta\bar{s}$	-0.057	$-0.006\ ^{+0.010}_{-0.012}$	$-0.006\ ^{+0.028}_{-0.031}$
Δg	-0.084	$0.013\ ^{+0.106}_{-0.120}$	$0.013\ ^{+0.702}_{-0.314}$
$\Delta\Sigma$	0.242	$0.366\ ^{+0.015}_{-0.018}$	$0.366\ ^{+0.042}_{-0.062}$

- First moment of the singlet distribution $\sim$0.25 !
- Gluon polarisation small (with lare errors!)

Sea quark polarisation

M. Alekseev *et al.* (COMPASS), Phys. Lett. **B660** (2008) 458.

- Difference asymmetry: $A^{h^+-h^-}$: $A_d^{\pi^+-\pi^-} = A_d^{K^+-K^-}$
- At LO, the fragmentation functions drop out



$$\int_{0.006}^{0.7} (\Delta u_v + \Delta d_v)\mathrm{d}x = 0.40 \pm 0.07 \pm 0.05$$

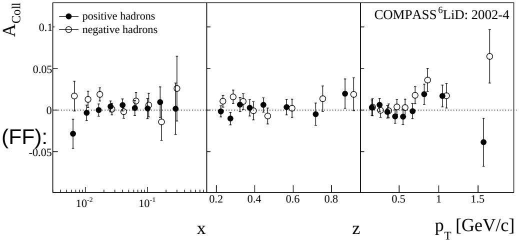
- Unmeasured regions contribute neligibly.
- Non-symmetric sea preferred ?
- Next step: determine Δs from $K^{\pm}$ asymmetries.

Transversity

Results for the Collins and Sivers asymmetries

Deuteron target; all hadrons: positive and negative

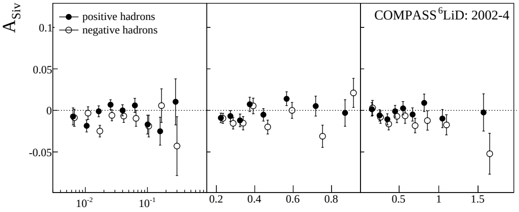
E.S. Ageev *et al.* (COMPASS) Nucl.Phys.B **765**(2007) 31



(FF):

Collins asymmetries very small.
These data + Hermes + Belle

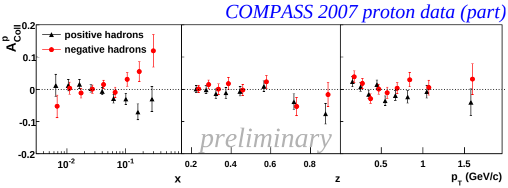
$\Longrightarrow \Delta_T u + \Delta_T d \sim 0$



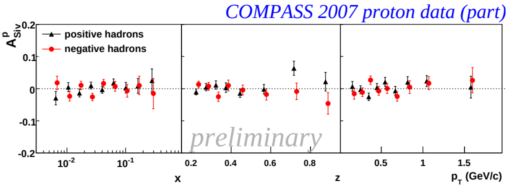
Sivers asymmetries very small.
S.Brodsky & S. Gardner (2006): no gluon orbital angular momentum in the nucleon?

Results for the Collins and Sivers asymmetries...cont'd

Proton target; all hadrons: positive and negative



Asymmetries nonzero at $x \gtrsim 0.1$.



Sivers asymmetries very small.

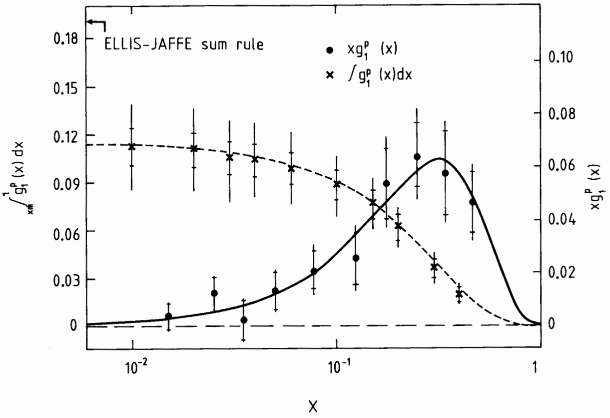
Gluon polarisation

Nucleon spin decomposition

$$\frac{\hbar}{2} = J_q + J_g = \left(\frac{1}{2}\Delta\Sigma + L_q\right) + \left(\Delta G + L_g\right)$$

- Observe! each term is μ^2 dependent;
  decomposition $J_g = \Delta G + L_g$ is NOT gauge–invariant.
- EMC (1988): $a_0 = \Delta\Sigma$ =0.12 $\pm$ 0.09 $\pm$0.14 (expected: $\sim$0.6 if Δs = 0).
  Here $\Delta\Sigma = \Delta u + \Delta d + \Delta s$ and $\Delta q = \int \Delta q(x)dx$, $\Delta G = \int \Delta G(x)dx$
- COMPASS @ 3 GeV^2: $a_0 = 0.35 \pm 0.03 \pm 0.05$
- But as a consequence of the “axial anomaly” (axial vector current not conserved) the measured quantity is:
  $$a_0(Q^2) = \Delta\Sigma^{AB} - (\frac{n_f \alpha_s}{2\pi})\Delta G(Q^2)$$
  and the “spin crisis” can be solved ($\Delta\Sigma$ $\sim$0.6) if ΔG $\sim$2.2 (and $L \sim -2$) at Q^2 = 3 GeV^2.
- Impressive spin-off since 1988: SLAC (E142, E143, E155, E156), SMC, HERMES, JLAB, COMPASS, RHIC Spin.
- Need to measure ΔG (and L)!

“Spin puzzle”: 20 years



European Muon Collaboration, J.Ashman *et al.* Phys. Lett. **B206** (1988) 364

$\Gamma_1^p = 0.123 \pm 0.013 \pm 0.019$ $\Delta\Sigma = a_0 = 0.12 \pm 0.17$

Ways of measuring the ΔG

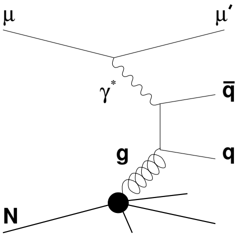
- Scaling violation of g_1 (QCD fits, world data).
- Direct measurements
  - Cross section asymmetry for the photon–gluon fusion (PGF) with subsequent fragmentation into the charm mesons (max. @ low Q^2, perturbative scale: e.g. mass of the charm quark).
  - Cross section asymmetry for the photon–gluon fusion (PGF) with subsequent fragmentation into a pair of hadrons of large p_T, separately for low- and high Q^2 (perturbative scale: e.g. p_T).

Direct $\Delta G/G$ measurements

Mechanism employed: photon–gluon fusion. Observable: asymmetry in the hadron production

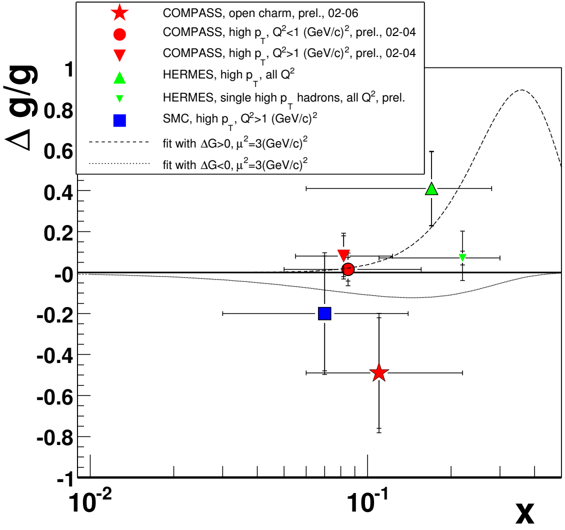
$$A_{\gamma N}^{PGF} = \frac{\int d\hat{s}\Delta\sigma^{PGF}\Delta G(x_g,\hat{s})}{\int d\hat{s}\sigma^{PGF} G(x_g,\hat{s})}$$

$$\approx \langle a_{LL}^{PGF}\rangle \frac{\Delta G}{G}$$



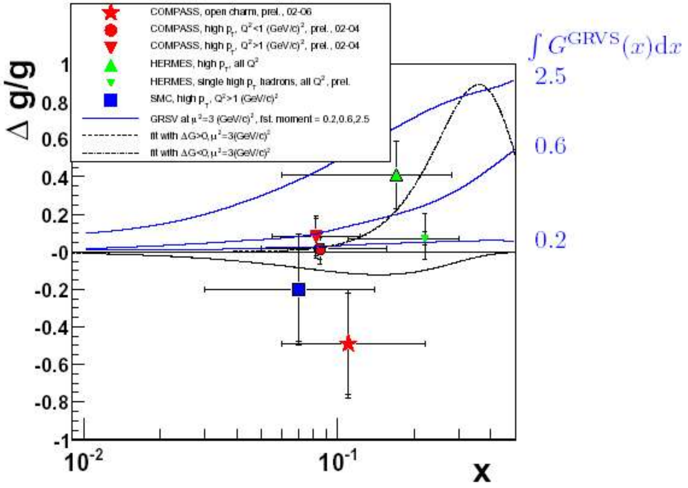
- If q≡ c $\Longrightarrow$ a pair of charmed mesons (we demand only one) in the final state;
  - measurement difficult (low statistics),
  - NLO corrections may be important.
- If q≡ u,d,s $\Longrightarrow$ a pair of jets or (in COMPASS) of high-p_T hadrons;
  - measurement simple (high statistics),
  - strong physics background, MC – dependence.

Summary of the gluon polarisation measurements



At $x_g \sim 0.1$, $\Delta G/G$ is compatible with zero! Qualitative agreement with RHIC results.

Summary of the gluon polarisation measurements



- Restoration of ΔΣ=0.6 via the axial anomaly improbable.
- Independent measurement of orbital momentum necessary!

Orbital angular momentum in the proton

Ways of constraining the orbital angular momentum

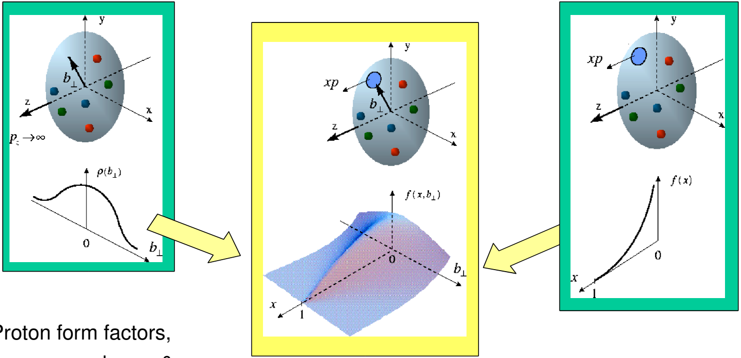
- Extract from the full, 3D decription of the proton $\Longrightarrow$ GPDs
- Measurement of asymmetries sensitive to e.g. the k_T of the partons (Sievers, Cahn ???)
- QCD calculations on the lattice
- X. Ji: evolution equations for J_q and J_g give the asymptotic solutions:

$$J_q(\mu^2 \to \infty) = \frac{1}{2}\frac{3n_f}{16+3n_f}, \qquad J_g(\mu^2 \to \infty) = \frac{1}{2}\frac{16}{16+3n_f}$$

L cannot be negligible!

3D picturing of the proton *via* GPD

D. Mueller, X. Ji, A. Radyushkin, A. Belitsky, …
M. Burkardt, … Interpretation in impact parameter space



Proton form factors, transverse charge & current densities

Correlated quark momentum and helicity distributions in transverse space - GPDs

Structure functions, quark longitudinal momentum & helicity distributions

Slide from V.D. Volker, LANL 2007

Access GPD through the DVCS mechanism

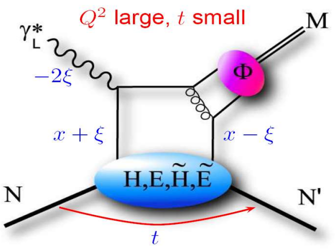


Figure from A. Sandacz, EINN, 2007

- Four GDPs $(H, E, \widetilde{H}, \widetilde{E})$ for each flavour and for gluons
- Factorisation proven for σ_L only
- All depend on 3 variables: x, ξ, t;   DIS @ $\xi = t = 0$
- $H, \widetilde{H}$ conserve nucleon helicity
  $E, \widetilde{E}$ flip nucleon helicity
- H, E refer to unpolarised distributions
- $H^q(x,0,0) = q(x)$, $\widetilde{H}^q(x,0,0) = \Delta q(x)$
  $\widetilde{H}, \widetilde{E}$ refer to polarised distributions

- H, E accessed in vector meson production *via* A_{UT} asymmetries
- $\widetilde{H}, \widetilde{E}$ accessed in pseudoscalar meson production *via* A_{UT} asymmetries
- All 4 accessed in DVCS (γ production) in $A_C, A_{LU}, A_{UT}, A_{UL}$
- Integrals of $H, E, \widetilde{H}, \widetilde{E}$ over x give Dirac–, Pauli–, axial vector– and pseudoscalar vector form factors resp.
- Important: $J^q_z = \frac{1}{2}\int dx\, x\, [H^q(x,\xi,t=0) + E^q(x,\xi,t=0)] = \frac{1}{2}\Delta\Sigma + L^q_z$ (X. Ji)

DVCS data taken or expected soon; future projects

- Data being analysed:
  - Z1 and ZEUS: cross section for ρ^0, ϕ, J/ψ, Υ production
  - HERMES: cross section for ρ^0, ϕ, BCA, BSA, TSA (π^+)
  - CLAS: cross section for $\rho^+, \phi, \pi^+, \pi^0, \eta$
- Data taken or expected
  - DVCS Coll. (JLAB, Hall A): cross section for π^0 (2009)
  - CLAS: BSA, TSA (2009)
  - COMPASS: muoproduction of ρ^0 on the proton (2007 data)
- Future
  - COMPASS upgrade for DVCS, DVMP ($\sim$ 2010)
  - JLAB 12 GeV upgrade ($\gtrsim$ 2014)
  - PANDA @ FAIR ($\gtrsim$ 2014)
  - EIC/ELIC ($\gtrsim$??)
- First results constraining *E* and *H* (and thus orbital momentum) and DVMP models; L_q close to zero ?

Orbital angular momentum in the proton: results from lattice QCD

- In the sum rule: $\frac{1}{2} = J_q + J_g = \frac{1}{2}\Delta\Sigma + L_q + \Delta G + L_g$

- total spin: $J_q^u = 0.22 \pm 0.02, \qquad J_q^d = 0.00 \pm 0.02$
- *OAM* : $L^u = 0.20 \pm 0.04, \qquad L^d = –0.20 \pm 0.04$

$$\Longrightarrow \quad L_q = 0 \text{ ?}$$

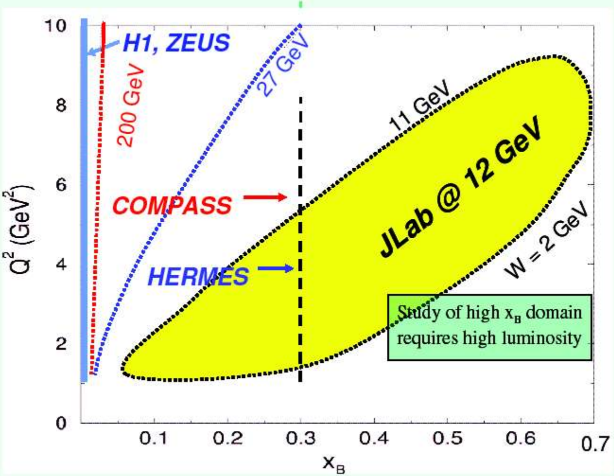
- Errors do not contain the systematic part (hard to estimate) !
- Results on L_q in line with the DVCS results of HERMES, JLAB.

P. Hägler, DIS2008

Future

CEBAF 12 GeV upgrade

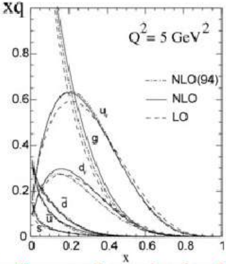
Deeply Virtual Exclusive Processes -
Kinematics Coverage of the 12 GeV Upgrade



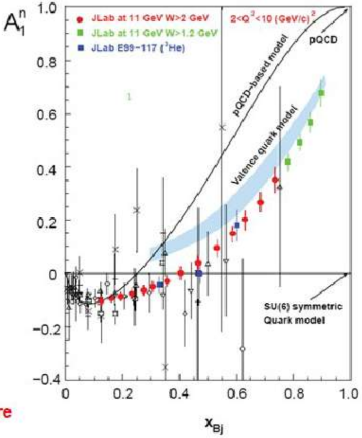
Future: high x structure functions at JLAB 12 GeV

REQUIRES:

- High beam polarization
- High electron current
- High target polarization
- Large solid angle spectrometers



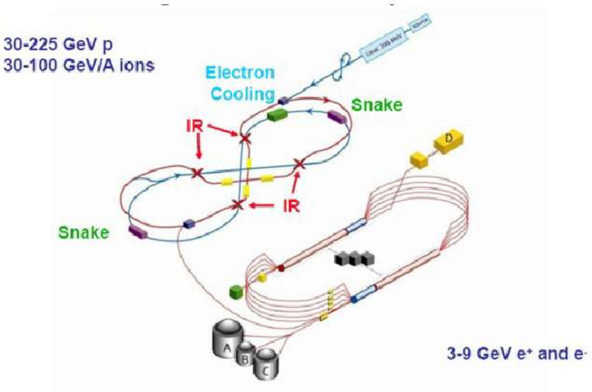
12 GeV will access the regime (x > 0.3), where valence quarks dominate



Slide from H. Montgomery, SPIN 2008

Future: Electron–Ion Collider, EIC

- LHeC @ CERN
- eRHIC @ BNL
- ELIC @ JLAB
- MANUEL @ FAIR (GSI)



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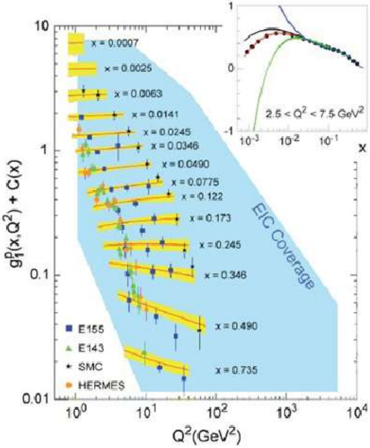
Future: Electron–Ion Collider, EIC,...cont'd



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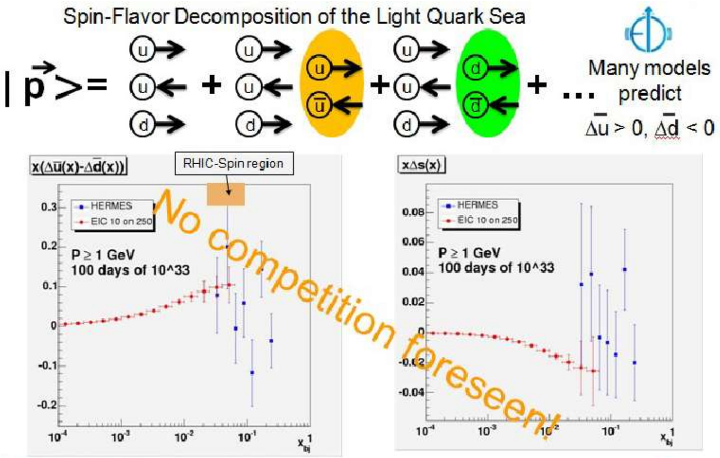
Future: Electron–Ion Collider, EIC,...cont'd



Slide from H. Montgomery, SPIN 2008

Outline

1. Introduction
2. Longitudinal spin structure
3. Transversity
4. Gluon polarisation
5. Orbital angular momentum in the proton
6. Future
7. **Outlook**

Outlook

- We have learned a lot about the polarised PDFs (helicity, transversity) in the last 20 years.
- "Spin puzzle": restoration of $\Delta\Sigma = 0.6$ via the axial anomaly improbable. Significant orbital angular momentum in the proton expected; must find a way to expose it $\Longrightarrow$ DVCS!
- Much experimental and theoretical progress in analysing the physics mechanism of the Single–Spin–Asymmtries.
- More data await analysis (HERMES, COMPASS, RHIC, JLAB); new data come (COMPASS, RHIC); new experiments soon (COMPASS II (2010), JLAB 12 (2014)).
- Polarised EIC badly needed!

THANKS, Jan!

SPARE

Spin applications...

Fluctuations and Market Friction in Financial Trading

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(May 15, 2006)

We study the relation between stock price changes and the difference in the number of sell and buy orders. Using a soft spin model, we describe the price impact of order imbalances and find an analogy to the fluctuation-dissipation theorem in physical systems. We empirically investigate fluctuations and market friction for a major US stock and find support for our model calculations.

PACS numbers: 05.45.Tp, 89.90.+n, 05.40.-a, 05.40.Fb

The unpredictable up and down movements in the stock market have always captured the interest and imagination of investors. The scientific investigation of these phenomena started with Bachelier's comparison of stock price dynamics with a random walk [1]. This study has been refined in many respects [2]. Interest has been devoted to the precise shape of the distribution of returns (difference of the logarithm of stock prices at different times), which is characterized by a high probability for large fluctuations [3–6].

After it was realized that large price fluctuations tend to cluster together in time, stock price returns were described by models of volatility (standard deviation of returns) changing in time [7,8]. This effect is captured in time series models, in which the volatility at a given time depends on the magnitude of previous returns [9,10]. It has been actively investigated how the stochastic properties of price dynamics can be related to the market microstructure, i.e. the rules and motivations according

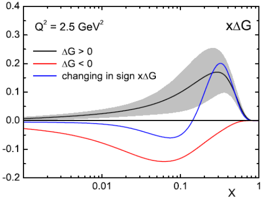
sell orders (order imbalance), which acts as an external force. We study the dependence of stock price changes on order imbalance empirically by using the method of data analysis and some of the results of [21,22]. We find that the empirical results agree well with our model.

Model calculation: The observable quantity we are interested in is the logarithmic stock price changes within a time interval Δt

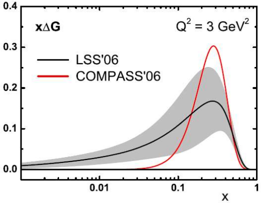
$$G_{\Delta t}(t) = \ln S(t) - \ln S(t - \Delta t) \ , \qquad (1)$$

where $S(t)$ is the price of a given stock at time t. Transaction prices at a stock exchange lie usually in a finite interval between the bid price (the price a trader offers to pay for a stock) and the ask price (the price at which a dealer is willing to buy the stock). In addition, the historical prices studied take only discrete (tick) values. This motivates to model price changes by a spin model, and for the virtue of easier analytical calculations by a

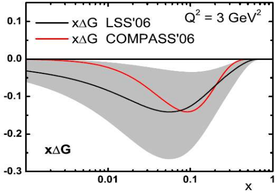
Gluon polarisation from QCD evolution, cont.'d



$\Delta G > 0$



$\Delta G < 0$



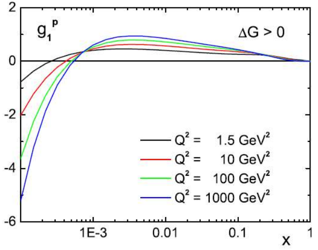
Can we ever tell the sign of ΔG ?

Figures from E. Leader, DIS2008

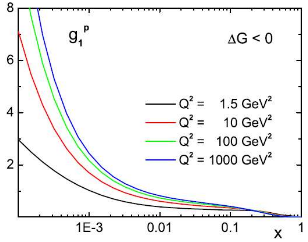
Gluon polarisation from QCD evolution,cont.'d

... except at an ep collider ?

LSS06, $\Delta G > 0$

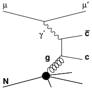


LSS06, $\Delta G < 0$

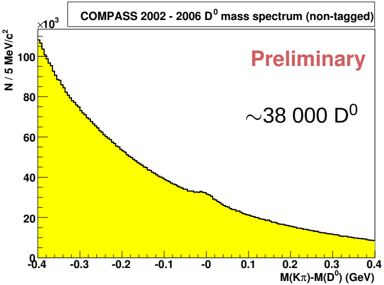


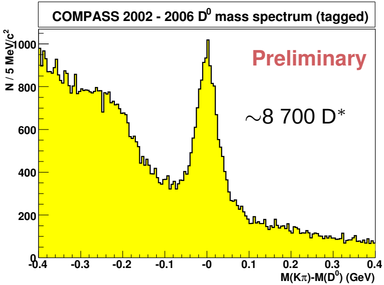
Figures from E. Leader, DIS2008

Direct $\Delta G/G$ measurements; open charm production



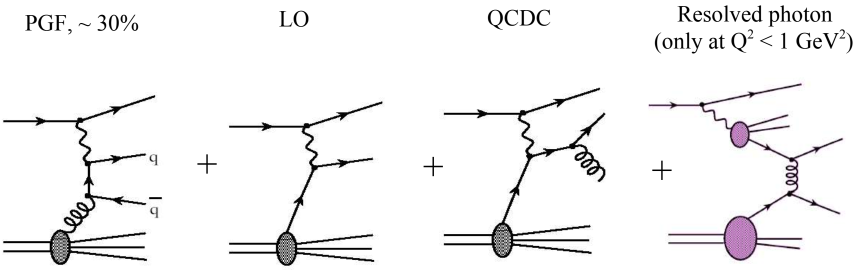
$$D^0 \rightarrow K + \pi, \qquad D^* \rightarrow D^0 + \pi_s \rightarrow K + \pi + \pi_s$$





- Choose $D^0 \rightarrow K\pi$ (BR∼4%); pions and kaons identified by RICH.
- Clean sample of the PGF events (but low statistics); little physics background.
- Combinatorial background significantly reduced for the $D^* \rightarrow D^0 + \pi_s \rightarrow K + \pi + \pi_s$.
- Charm in the nucleon neglected.
- Weak dependence on the MC in the analysis.
- A weighting method used to optimise the $\Delta G/G$ extraction $\Longrightarrow$ C. Quintans' talk

Direct $\Delta G/G$ measurements; high p_T hadrons



$$A_{LL}^{2h}(x) = R_{pgf} \cdot a_{LL}^{pgf} \cdot \frac{\Delta G}{G}(x_g) + R_{LO} \cdot D \cdot A_1^{LO}(x) + R_{QCDQ} \cdot a_{LL}^{QCDQ} \cdot A_1^{LO}(x_c)$$

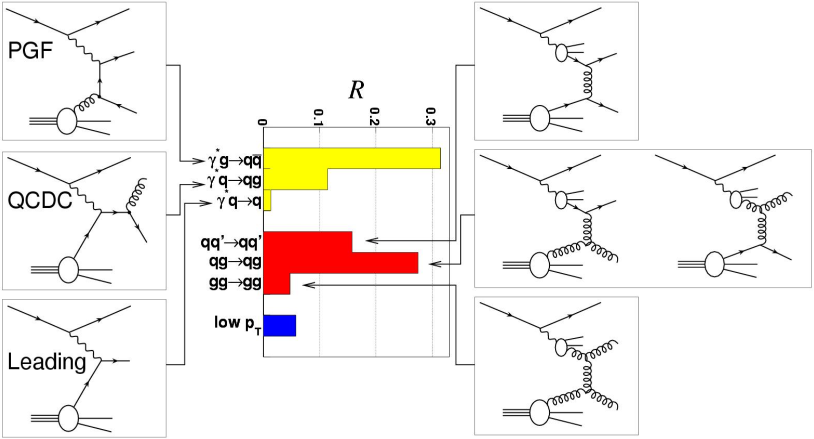
$\frac{\Delta G}{G}$ evaluated from $A_{LL}^{2h} = A_{meas}/(P_b P_T f)$ and from inclusive asymmetries, $A_1 = A_{meas}^{incl}/D$ if contributions of PGF and of background processes (LO, QCDQ) taken from MC

$\Longrightarrow$ C. Quintans' talk.

Direct $\Delta G/G$ measurements; high p_T hadrons @ $Q^2 < 1$ GeV^2

E.S. Ageev (COMPASS) *et al.* Phys. Lett. B **633** (2006) 25

Resolved photons



Summary of the gluon polarisation measurements

...cont'd

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L$$

Are we approaching the solution of the "proton spin puzzle"?

- Restoration of $\Delta\Sigma$=0.6 via the axial anomaly improbable.
- Global, consistent NLO analysis of ΔG needed.
- Independent measurement of L necessary.

Properties of transversity

Properties of $\Delta_T q(x)$:

- is chiral–odd $\Longrightarrow$ hadron(s) in final state needed to be observed
- simple QCD evolution since no gluons involved
- related to GPD
- sum rule for transverse spin
- first moment gives "tensor charge" (now being studied on the lattice)

Asymmetry measured *e.g. via* the Collin's asymmetry (asymmetry in the distribution of hadrons):

$$N_h^{\pm}(\phi_c) = N_h^0\,[1 \pm p_T D_{NN} A_{Coll} \sin\phi_c]$$

which in turn gives at LO:

$$A_{Coll} \sim \frac{\sum_q e_q^2 \cdot \Delta_T q \cdot \Delta_T^0 D_q^h}{\sum_q e_q^2 \cdot q \cdot D_q^h}$$

But transverse fragmentation functions $\Delta_T^0 D_q^h$ needed to extract $\Delta_T q(x)$ from the Collin's assymmetry! Recently those FF measured by BELLE.

Properties of the Sivers process:

it is related to L_q in the proton. Fundamental !

Link to DIS and elastic form factors

DIS at $\xi = t = 0$

$$H^q(x,0,0) = q(x)$$

$$\tilde{H}^q(x,0,0) = \Delta q(x)$$

Form factors (sum rules)

$$\int_{-1}^{1} dx \sum_q \left[H^q(x,\xi,t)\right] = F_1(t) \quad \text{Dirac f.f.}$$

$$\int_{-1}^{1} dx \sum_q \left[E^q(x,\xi,t)\right] = F_2(t) \quad \text{Pauli f.f.}$$

$$\int_{-1}^{1} dx\, \tilde{H}^q(x,\xi,t) = G_{A,q}(t), \quad \int_{-1}^{1} dx\, \tilde{E}^q(x,\xi,t) = G_{P,q}(t)$$

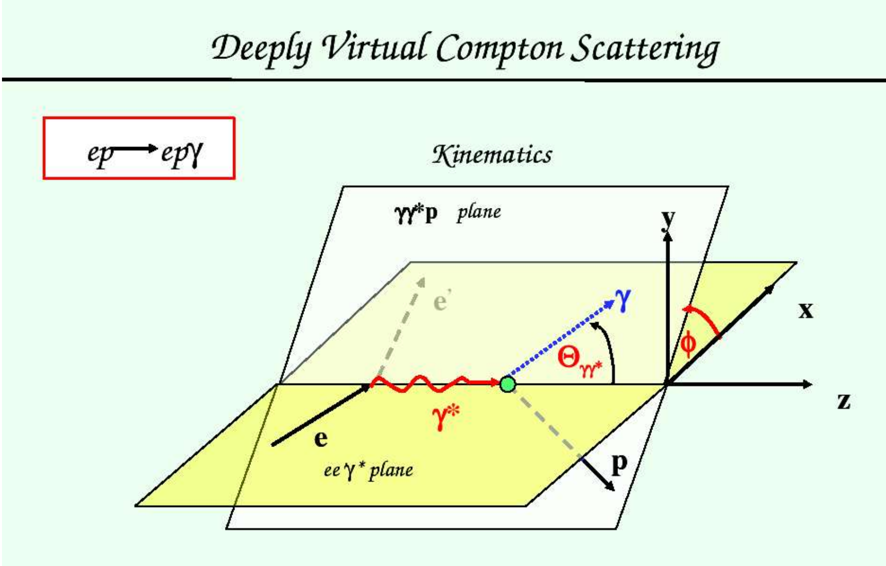
$$H^q, E^q, \tilde{H}^q, \tilde{E}^q(x,\xi,t)$$

Angular Momentum Sum Rule

$$J^q = \frac{1}{2} - J^G = \frac{1}{2}\int_{-1}^{1} x\,dx \left[H^q(x,\xi,0) + E^q(x,\xi,0)\right]$$

X. Ji, Phy.Rev.Lett.78,610(1997)

Slide from V.D. Volker, LANL 2007



Slide from V.D. Volker, LANL 2007