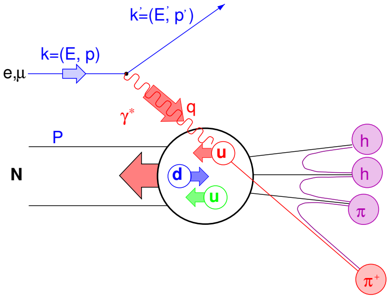
Polarised low x physics presently and on planned e-p machines

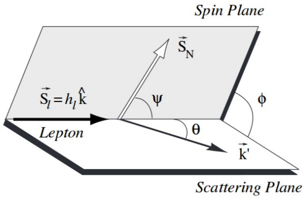
Barbara Badelek
University of Warsaw

Low x

Kyoto, June 17 – June 21, 2014

Nucleon spin structure in the electroproduction

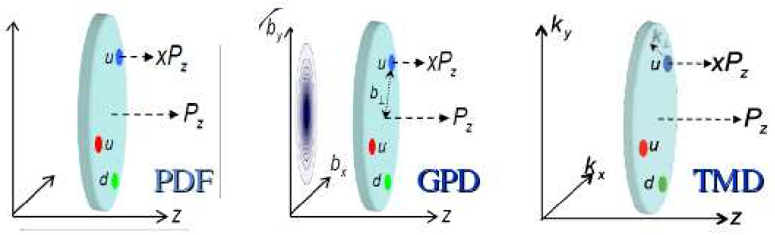




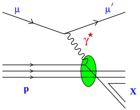
- $$\frac{d^2\sigma}{d\Omega dE'} = \frac{\alpha^2}{2Mq^4}\frac{E'}{E} L_{\mu\nu} W^{\mu\nu}$$
- Symmetric part of $W^{\mu\nu}$ – unpol. DIS, antisymmetric – polarised DIS
- Nominally $F_{1,2}, \quad q(x) \longrightarrow g_{1,2}, \quad \Delta q(x)$ but...
- ...anomalous gluon contribution to $g_1(x)$
- ...$g_2(x)$ has no interpretation in terms of partons.

$$\sigma = \bar{\sigma} - \frac{1}{2} h_l \left(\cos\psi \Delta\sigma_{\parallel} + \sin\psi \cos\phi \Delta\sigma_{\perp} \right)$$

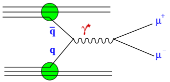
Transverse Momentum Dependent (TMD) distributions



- parton intrinsic k_{T} taken into account
- related to quark angular momentum, L!
- at COMPASS studied in 2 ways:
  - semi-inclusive DIS (polarised muons on unpolarised/transversely polarised target)
  - In the future: Drell-Yan process (π beam on unpolarised/transversely polarised tgt.)



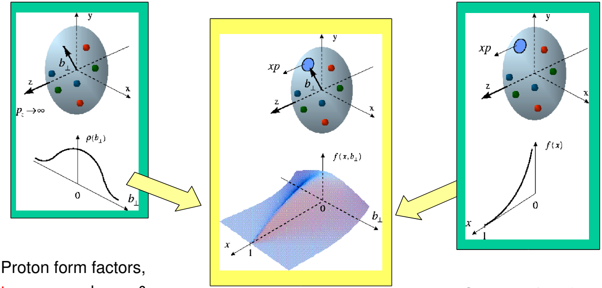
SIDIS



DY

3D picturing of the proton *via* GPD

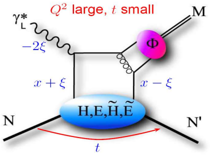
D. Mueller, X. Ji, A. Radyushkin, A. Belitsky, …
M. Burkardt, … Interpretation in impact parameter space



Proton form factors, transverse charge & current densities

Correlated quark momentum and helicity distributions in transverse space - GPDs

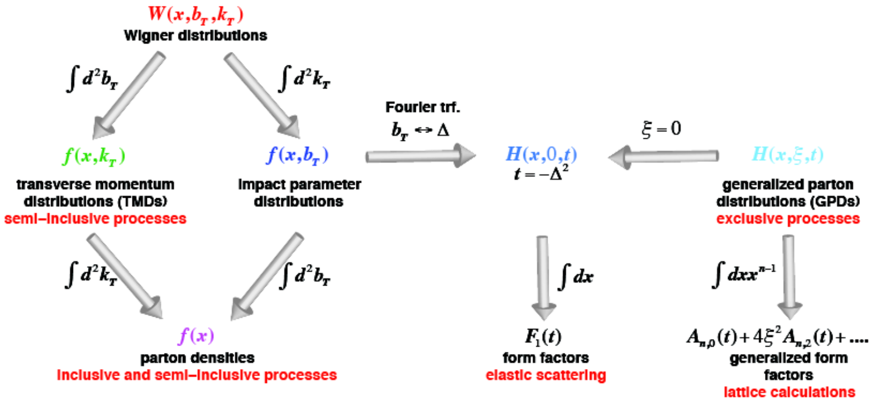
Structure functions, quark longitudinal momentum & helicity distributions



- Four GDPs $(H, E, \widetilde{H}, \widetilde{E})$ for each flavour and for gluons
- 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; $\widetilde{H}, \widetilde{E}$ refer to polarised distr.

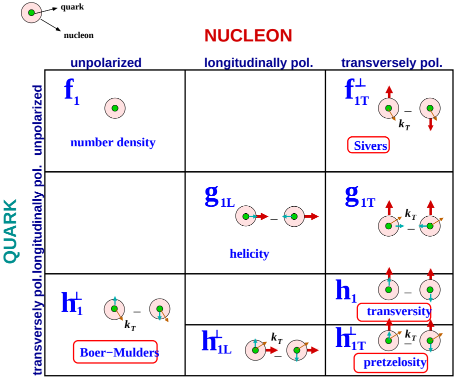
After V.D. Volker, LANL 2007

Descriptions of *pdf* ^{s} in the nucleon



From “White paper”, arXiv:1212.1701

Partonic structure of the nucleon; distribution functions



- In LT and considering k_{T}, 8 PDF describe the nucleon
- QCD-TMD approach valid $k_{\mathrm{T}} \ll \sqrt{Q^2}$
- After integrating over k_{T} only 3 survive: f_1, g_1, h_1
- TMD accessed in SIDIS and DY by measuring azimuthal asymmetries
- SIDIS: e.g. $A_{\mathrm{Sivers}} \propto$ PDF $\otimes$FF
- DY: e.g. $A_{\mathrm{Sivers}} \propto$ PDF$^{\mathrm{beam}} \otimes$ PDF$^{\mathrm{target}}$
- OBS! Boer-Mulders and Sivers PDF are T-odd, i.e. process dependent

$$h_1^{\perp}(\mathrm{SIDIS}) = -h_1^{\perp}(\mathrm{DY}) \qquad f_{1\mathrm{T}}^{\perp}(\mathrm{SIDIS}) = -f_{1\mathrm{T}}^{\perp}(\mathrm{DY})$$

- OBS! transversity PDF is chiral-odd (may only be measured with another chiral-odd partner, e.g. fragmentation function.
- Boer-Mulders, Sivers and transversity $(h_1^{\perp}, f_{1\mathrm{T}}^{\perp}, h_1)$ will be measured in COMPASS II

Nucleon spin structure: observables in $\vec{\mu}\vec{\mathrm{N}}$ scattering

- Inclusive asymmetry, A_{meas}:

$$A_{meas} = \frac{1}{f P_T P_B} \left(\frac{N^{\leftrightarrows} - N^{\leftleftarrows}}{N^{\leftrightarrows} + N^{\leftleftarrows}} \right) \approx D A_1 = D \, \frac{g_1(x,Q^2)}{F_1(x,Q^2)} = D \, \frac{\sum_q e_q^2 \Delta q(x,Q^2)}{\sum_q e_q^2 q(x,Q^2)}$$

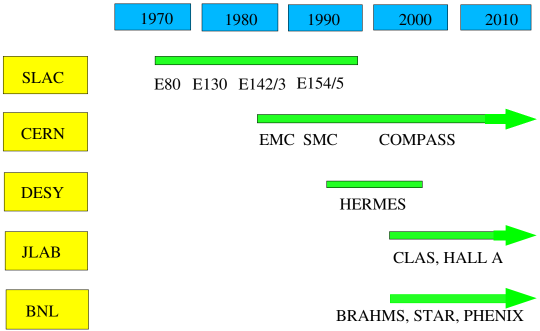
$$\Delta q = q^+ - q^-, \quad q = q^+ + q^-, \qquad g_1^d = g_1^N (1 - \frac{3}{2}\omega_D) = \frac{g_1^p + g_1^n}{2}(1 - \frac{3}{2}\omega_D);$$

$$\omega_D = 0.05 \pm 0.01$$

- At LO, semi–inclusive asymmetry, A_1^h:

$$A_1^h(x,z,Q^2) \approx \frac{\sum_q e_q^2 \Delta q(x,Q^2) D_q^h(z,Q^2)}{\sum_q e_q^2 q(x,Q^2) D_q^h(z,Q^2)} \qquad z = \frac{E_h}{\nu} \qquad D_q^h \neq D_{\bar{q}}^h$$

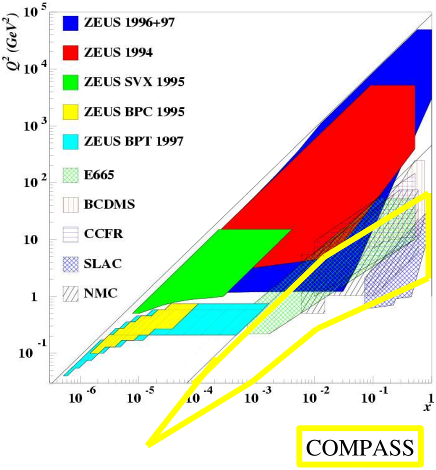
Experiments



Experiment	Polarised beam	Polarised target	Energy (GeV)
SLAC	e	p, n, d	$\lesssim 50$
CERN/EMC	μ	p	100–200
CERN/SMC	μ	p, d	100, 190
DESY/HERMES	e	p, n, d	27.5
CERN/COMPASS	μ	p, d	160, 200
JLAB	e	p, n, d	$\lesssim 6$
BNL/RHIC	p	p	$\lesssim 250{+}250$

After G.Mallot, COMPASS

Acceptance of high energy electroproduction experiments



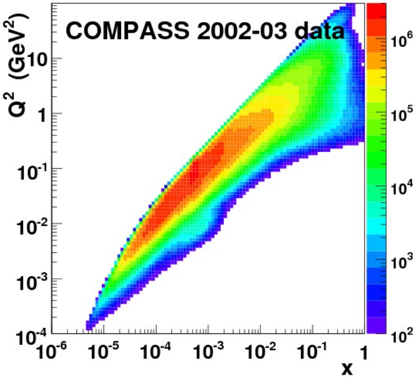
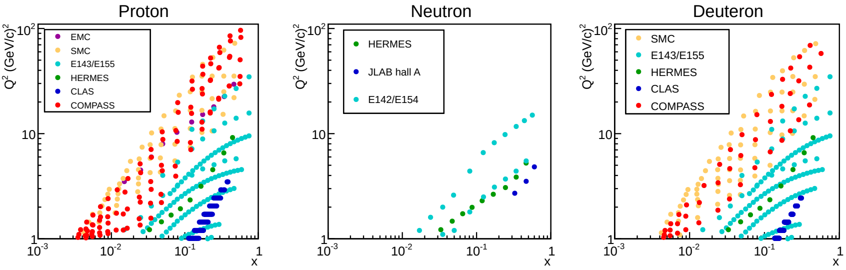


Figure from: N. D'Hose, Villars 2004

Acceptance of spin experiments: different targets

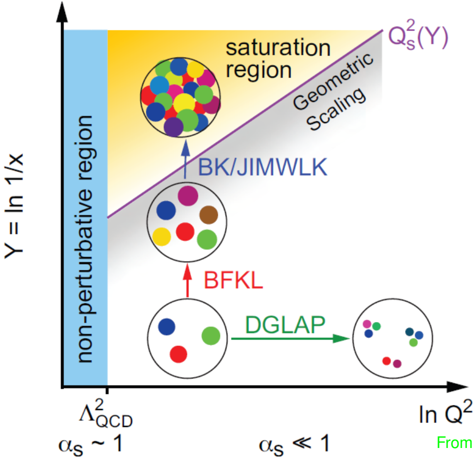
$$Q^2 > 1 \text{ GeV}^2$$



From M. Wilfert, DIS2014

Why is low x needed?

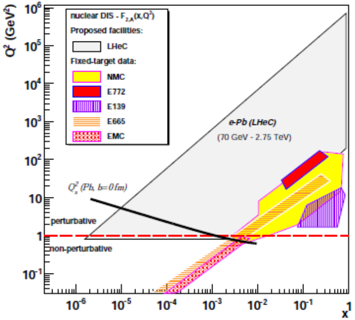
- Manifestation of new dynamics
- Problem with truncated sum rules...



From “White paper”, arXiv:1212.1701

A Large Hadron Electron Collider (LHeC) at CERN

- Symposium on the European Strategy for Partice Physics, Cracow, 2012 arXiv:12111.483
- Two options: ring–ring (RR) and linac–ring (LR). Basic beam design:



electron beam 60 GeV	Ring	Linac
e^- (e^+) per bunch N_e [10^9]	20 (20)	1 (0.1)
e^- (e^+) polarisation [%]	40 (40)	90 (0)
bunch length [mm]	6	0.6
tr. emittance at IP $\gamma\epsilon^e_{x,y}$ [mm]	0.59, 0.29	0.05
IP β function $\beta^*_{x,y}$ [m]	0.4, 0.2	0.12
beam current [mA]	100	6.6
energy recovery efficiency [%]	–	94
proton beam 7 TeV		
protons per bunch N_p [10^{11}]	1.7	1.7
transverse emittance $\gamma\epsilon^p_{x,y}$ [μm]	3.75	3.75
collider		
Lum e^-p (e^+p) [10^{32}cm^{-2}s^{-1}]	9 (9)	10 (1)
bunch spacing [ns]	25	25
rms beam spot size $\sigma_{x,y}$ [μm]	45, 22	7
crossing angle θ [mrad]	1	0
$L_{eN} = A\ L_{eA}$ [10^{32}cm^{-2}s^{-1}]	0.45	1

- The “Strategy” has not recommended a continuation of R&D for LHeC!

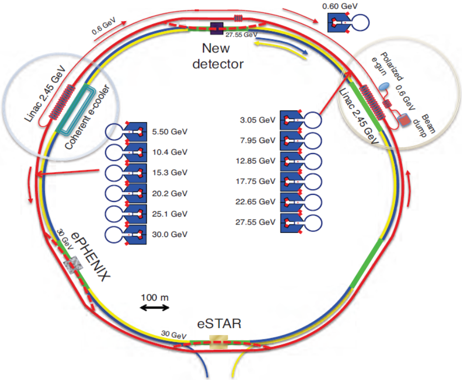
e-p machine, EIC, planned at BNL or JLab

BNL

Electron beam facility needed
(inside RHIC tunnel)

JLab

ELIC + injector needed



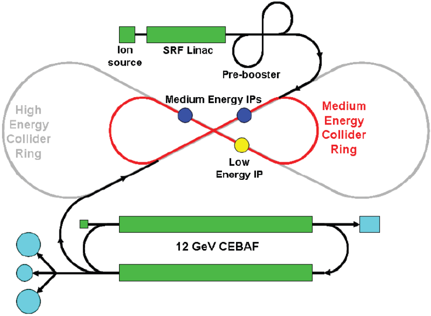
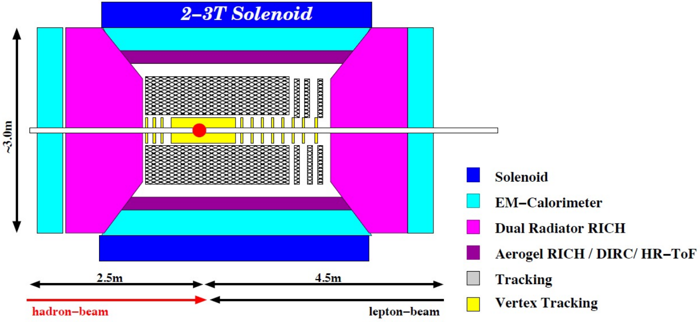


figure from The White Paper, arXiv:1212.1701

A dedicated EIC detector



- Acceptance -5 $< \eta <$ 5 (large, comparable to CMS forward)
- PID: π, K, p, leptons
- Low material density (minimal multiple scattering and bremsstrahlung)
- Hadron beams: proton to lead

From "White paper", arXiv:1212.1701

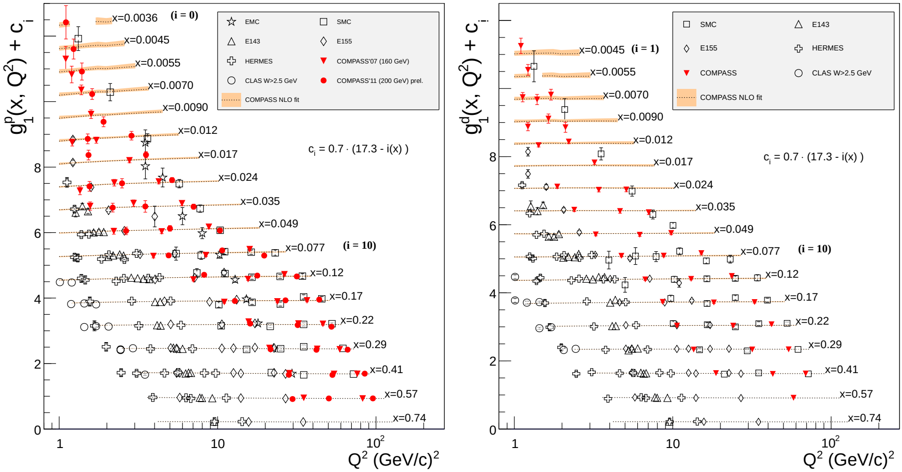
EIC: main features

- Highly polarised ($\sim$ 70%) e, N beams
- ions from deuteron to uranium (lead ?)
- variable $\sqrt{s}$ from $\sim$ 20 GeV to $\sim$ 100 (150) GeV
- high luminosity: $\sim 10^{33-34}$ cm^{-2} s^{-1} (cooling of hadronic beam !)
- more than one interaction rregion
- limits of current technology $\Longrightarrow$ R & D!
- staged realisation; first stage: $\sqrt{s}$ = 60 - 100 GeV
  and high luminosity.

Perturbative ($Q^2 > 1$ GeV^2) region

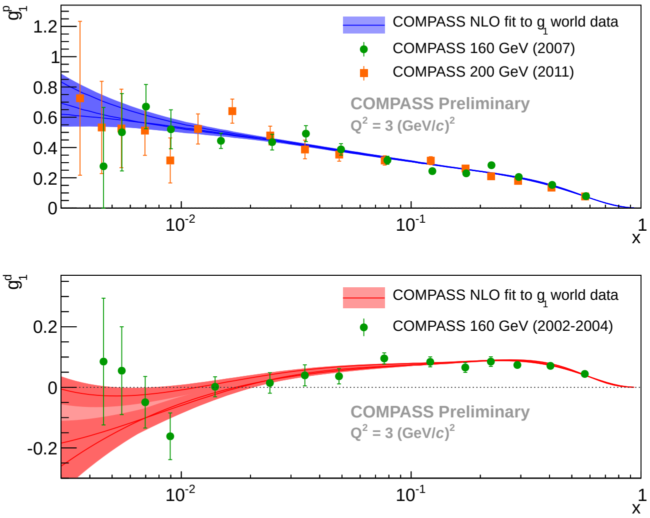
$g_1^p(x)$ and $g_1^d(x)$

NEW: COMPASS proton data 2011 (prelim.); full deuteron statistics



COMPASS measurements at high Q^2 important for the QCD analysis! but little sensitive to Δg

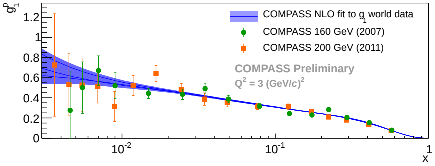
COMPASS NLO fit to g_1 world data; $Q^2 = 3\ (\mathrm{GeV}/c)^2$

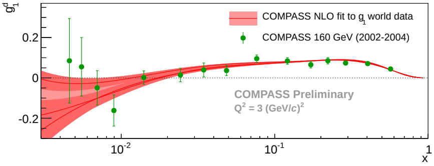


From M. Wilfert, DIS2014

DGLAP at low x

NLO QCD analysis of g_1^p and g_1^d world data:





At LO

$$g_1(x, Q^2) \sim \exp\left[A\sqrt{\xi(Q^2)\ln(1/x)}\right], \qquad \xi(Q^2) = \int_{\mu_0^2}^{Q^2} \frac{\mathrm{d}q^2}{q^2}\frac{\alpha_s(q^2)}{2\pi}, \qquad A_s \neq A_{ns}$$

A possible singular low x behaviour of gluon and sea distributions may originate from

- parametrisation of the starting distributions at $Q_0^2 \sim 4$ GeV^2
- Evolution starting from non-singular “valence-like” parton distributions at very low scale, $\mu_0 \sim 0.35$ GeV^2

$\ln^2(1/x)$ corrections to $g_1^{ns}(x, Q^2)$

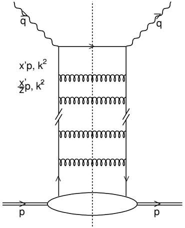
- Leading low x behaviour of g_1 (g_1^s and g_1^{ns}) generated by powers of $\alpha_s \ln^2(1/x)$; a standard DGLAP for spin dependent *pdf* generate only $\ln(1/x)$ terms.

- A way of including the above to QCD evolution: through $f(x, k_t^2)$

  where conventional parton distributions: $p(x, Q^2) = \int^{Q^2} \frac{\mathrm{d}k_t^2}{k_t^2} f(x, k_t^2)$

  This formalism permits
  an easy extrapolation to $Q^2 = 0$
  (for fixed W^2).

- $\ln^2(1/x)$ corrections to g_1^{ns}
  are generated by ladder diagrams $\Longrightarrow$



$\ln^2(1/x)$ corrections to $g_1^{ns}(x,Q^2)$... cont'd

- $\ln^2(1/x)$ corrections to g_1^{ns} are generated mathematically by equation:

$$f(x',k) = f^{(0)}(x',k) + \bar{\alpha}_s(k^2)\int_{x'}^{1}\frac{\mathrm{d}z}{z}\int_{k_0^2}^{k^2/z}\frac{\mathrm{d}k'^2}{k'^2}f(\frac{x'}{z},k'^2)$$

  and

$$g_1^{ns}(x,Q^2) = g_1^{ns(0)}(x) + \int_{k_0^2}^{W^2}\frac{\mathrm{d}k^2}{k^2}f(x' = x(1+\frac{k^2}{Q^2}),k^2)$$

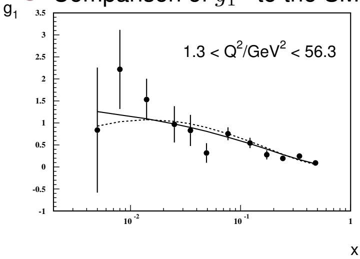
  where $\bar{\alpha}_s(k^2) = 2\alpha_s(k^2)/3\pi$ and
  $g_1^{(0)}(x)$ is a nonperturbative part, corresponding to $k^2 < k_0^2$.

- $\ln^2(1/x)$ terms originate from the z-dependent limit of the $\int \mathrm{d}k'^2/k'^2$ and x-dependent limit in $W^2(x)$.

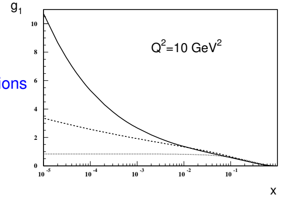
- For fixed (i.e. non-running) $\bar{\alpha}_s(k^2) \to \tilde{\alpha_s}$, small x behaviour is $g_1^{ns}(x,Q^2) \sim x^{-\lambda}$ where $\lambda = 2\sqrt{\tilde{\alpha_s}}$

$\ln^2(1/x)$ corrections to $g_1^{ns}(x, Q^2)$... cont'd

- A unified equation which incorporates the complete LO DGLAP at finite x and $\ln^2(1/x)$ effects at $x \to 0$ was formulated.
- Potentially large $\ln Q^2$ and $\ln(1/x)$ treated on equal footing.
- Assumed values $g_1^{ns(0)} = 2g_A(1-x)^3/3$, g_A = 1.257 (axial vector coupling). At $x \to 0$, $g_1^{ns(0)} \to$const, in agreement with the Regge expectation.
- The $g_1^{ns(0)}$ satisfies the Bjorken sum rule at LO: $\int_0^1 \mathrm{d}x g_1^{ns(0)}(x) = g_A/6$.
- Parameter k_0^2=1 GeV^2.
- Comparison of g_1^{ns} to the SMC data (COMPASS results ready soon)

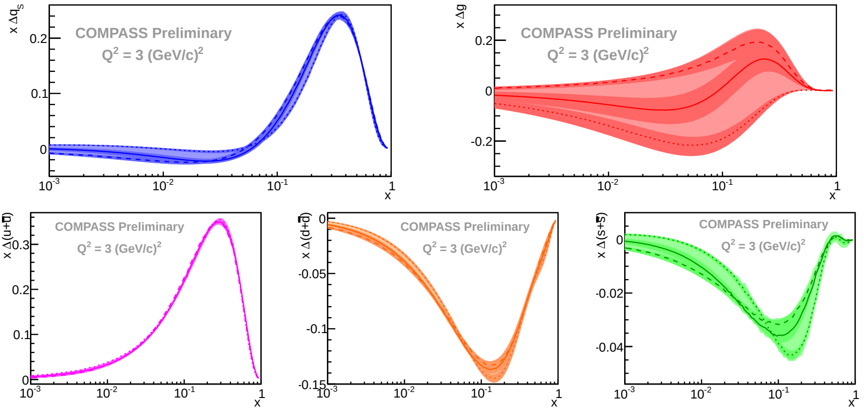


g_1^{ns} vs x
continuous – full calculations
broken – LO DGLAP



From J. Kwieciński and BB, Phys.Lett. B418 (1998) 229

COMPASS NLO fit to g_1 world data... cont'd



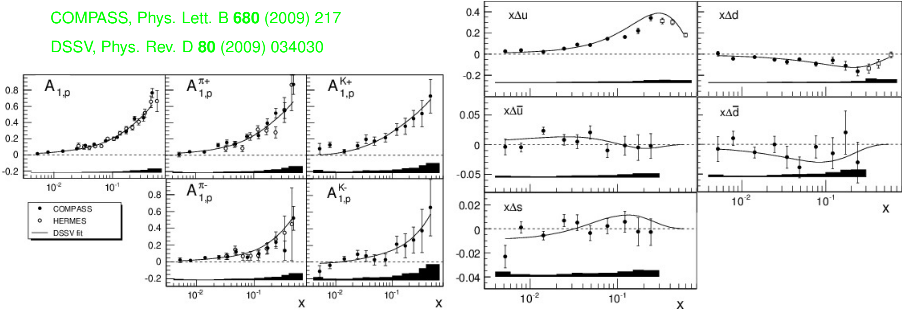
From M. Wilfert, DIS2014

Semi-inclusive asymmetries and parton distributions

- Measured on both proton and deuteron targets
- for identified, positive and negative pions and (for the first time) kaons

COMPASS, Phys. Lett. B **680** (2009) 217

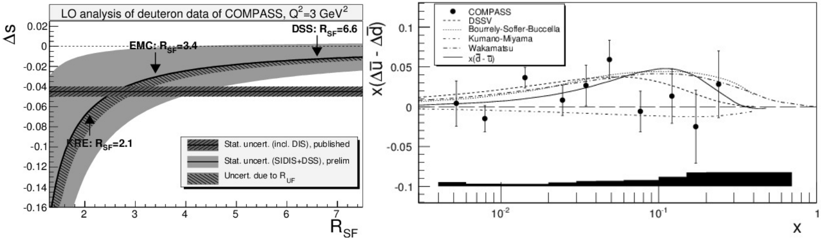
DSSV, Phys. Rev. D **80** (2009) 034030



- LO DSS fragmentation functions and LO unpolarised MRST pdf assumed here.
- NLO parameterisation of DSSV describes the data well.

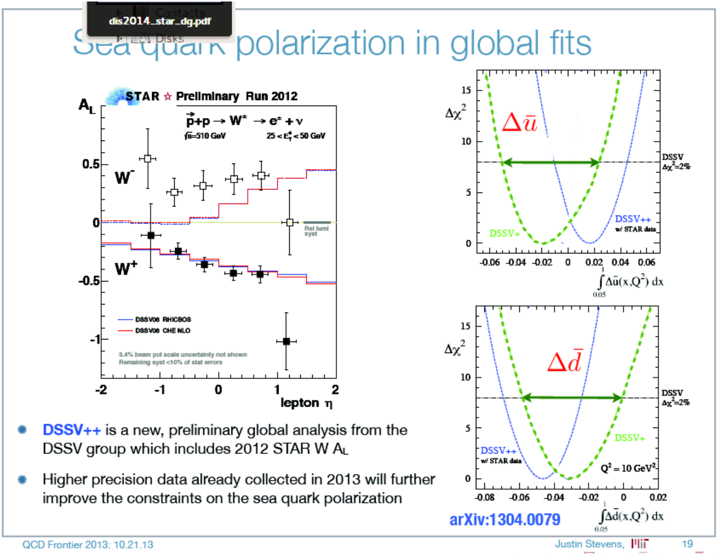
Polarisation of quark sea

- Δs puzzle. Strange quark polarisation:
  $2\Delta S = \int_0^1 (\Delta s(x) + \Delta\bar{s}(x))dx = -0.09 \pm 0.01 \pm 0.02$ from incl. asymmetries + SU$_3$,
  while from semi-inclusive asymmetries it is compatible with zero
  but depends upon chosen fragmentation functions. Most critical: $R_{SF} = \frac{\int D_{\bar{s}}^{K^+}(z)dz}{\int D_u^{K^+}(z)dz}$
  $\Longrightarrow$ plan to extract it from COMPASS data on multiplicities.

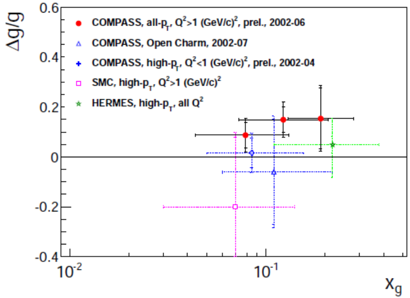


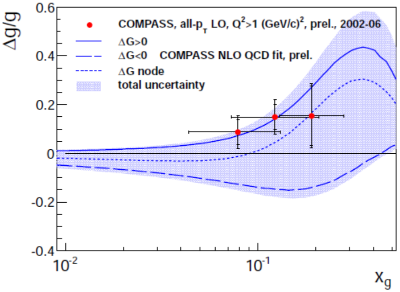
- The sea is not unsymmetric: COMPASS, Phys. Lett. B, **680** (2009) 217; ibid., **693** (2010) 227.
  $$\int_{0.004}^{0.3} \left[\Delta\bar{u}(x,Q^2) - \Delta\bar{d}(x,Q^2)\right] dx = 0.06 \pm 0.04 \pm 0.02 \ \ @ \ \ Q^2 = 3 \text{ (GeV/}c)^2$$
  Thus the data disfavour models predicting $\Delta\bar{u} - \Delta\bar{d} \gg \bar{d} - \bar{u}$

RHIC results on sea polarisation and on Δg



New results on Δg from COMPASS



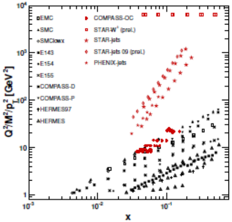


From M.Stolarski, DIS2014

Other QCD fits to world data

NNPDF fits: only DIS data (no SIDIS); recently included RHIC data
DSSV fits: DIS + SIDIS (fragmentation functions!)

Old and *new* experimental data set



- Include the experimental information from:
  → jet and W production data (collider) STAR, PHENIX
- Limited kinematic coverage at low-x
- Large Q^2 reached by collider data
- New data sets are included in `NNPDFpol1.0` (DIS-only fit) via Bayesian reweighting

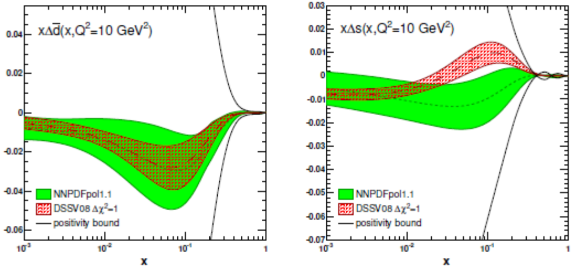
REACTION	PARTONIC SUBPROCESS	PDF PROBED	x	Q^2 [GeV^2]
$\ell^{\pm}\{p,d,n\} \to \ell^{\pm}X$	$\gamma^* q \to q$	$\Delta q + \Delta\bar{q}$ Δg	$0.003 \lesssim x \lesssim 0.8$	$1 \lesssim Q^2 \lesssim 70$
$\ell^{\pm}\{p,d\} \to \ell^{\pm}DX$	$\gamma^* g \to c\bar{c}$	Δg	$0.06 \lesssim x \lesssim 0.2$	$Q^2 \sim 10$
$\vec{p}\vec{p} \to jet(s)X$	$gg \to qg$ $qg \to qg$	Δg	$0.05 \lesssim x \lesssim 0.2$	$30 \lesssim p_T^2 \lesssim 800$
$\vec{p}p \to W^{\pm}X$	$u_L\bar{d}_R \to W^+$ $d_L\bar{u}_R \to W^-$	$\Delta u\ \Delta\bar{u}$ $\Delta d\ \Delta\bar{d}$	$0.05 \lesssim x \lesssim 0.4$	$\sim M_W^2$

Emanuele R. Nocera (UNIMI) Unbiased spin-dependent PDFs April 29, 2014 8 / 24

Other QCD fits to world data... cont'd

Comparison with DSSV

$\Delta\bar{d}$ and $\Delta s = \Delta\bar{s}$

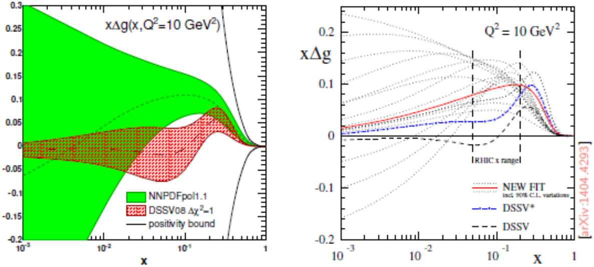


- Good agreement for the $\Delta\bar{d}$ distribution, but with large uncertainty
- Discrepancy between NNPDF and DSSV determinations of Δs (bias from the kaon fragmentation function used to include SIDIS data?)

Other QCD fits to world data... cont'd

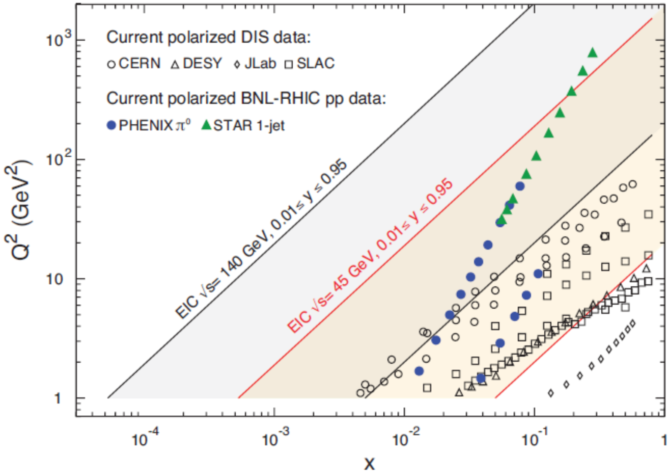
Comparison with DSSV

Δg



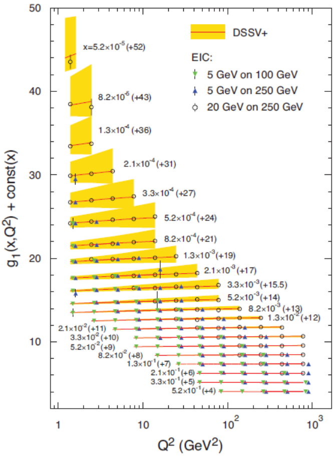
- For $x < 0.2$ the gluon has a node in DSSV08, while it is definitely positive in NNPDFpol1.1
- NNPDFpol1.1 and DSSV are in perfect agreement once recent jet data are included
- First evidence of gluon polarization in the proton in the region covered by data, $x \gtrsim 0.2$
- The uncertainty of the gluon blows up in the unmeasured small-x region

Acceptance of present spin experiments and EIC



From "White paper", arXiv:1212.1701

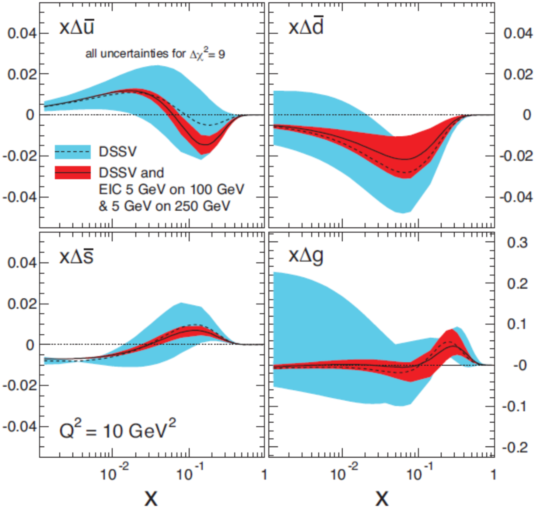
Inclusive $g_1(x, Q^2)$ at EIC (pseudo-data)



Errors statistical; bands mark current uncertainties (from DSSV+)

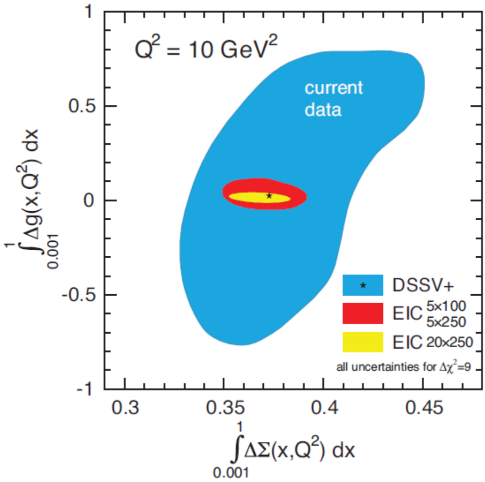
From "White paper", arXiv:1212.1701

EIC pseudo-data (inclusive and semi-inclusive)



From "White paper", arXiv:1212.1701

EIC pseudo-data (inclusive and semi-inclusive)... cont'd



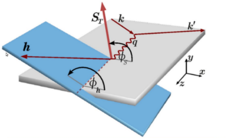
Measurements on a transversely polarised target

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)

Transversity measured *e.g. via* the Collins asymmetry: $\perp$ polarised $q \Longrightarrow$ unpolarised h (asymmetry in the distribution of hadrons):

$$N_h^{\pm}(\phi_c) = N_h^0 \left[1 \pm p_T D_{NN} A_{Coll} \sin\phi_c\right]$$
$$\phi_C = \phi_h + \phi_S$$



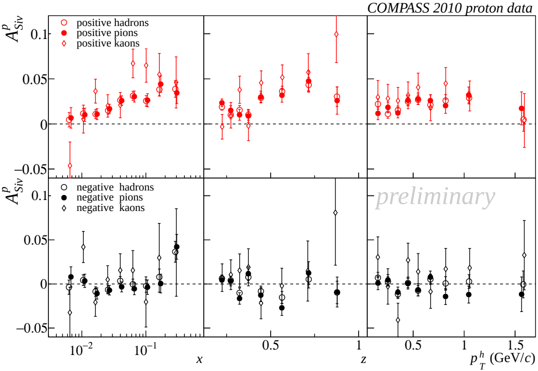
which in turn gives at LO:

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

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

Properties of the Sivers process ($\phi_S = \phi_h - \phi_S$, correlation of $\perp$ nucleon spin with k_T of unpolarised q): it is related to L_q in the proton. Fundamental !

Results for the Sivers asymmetry for protons

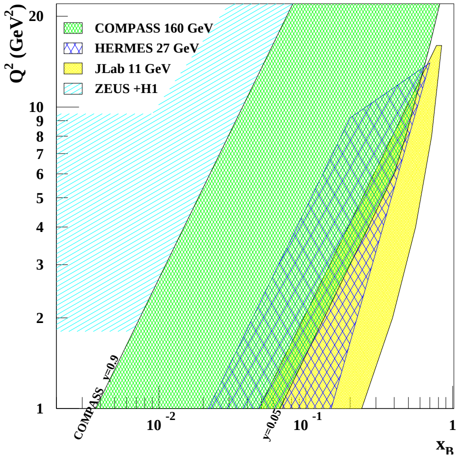


- Sivers asymmetries for proton measured for +/– unidentified and identified hadrons...
- ...are strongly dependent on Q^2 (compare with HERMES)
- COMPASS deuteron data show very small asymmetry
- Sivers functions ($f_{1T}^{\perp}$) for d and u quarks have opposite signs

COMPASS II Proposal

- CERN–SPSC–2010–014 (SPSC–P–340) of May 17, 2010
  wwwcompass.cern.ch/compass/proposal/compass-II_proposal/compass-II_proposal.pdf
- Approved in December 2010 initially 3 years data taking (Phase 1)
- Flavour separation and fragmentation in spin-averaged SIDIS (strange sector !)
- Focus on transverse structure of the nucleon
  - T-odd TMD (Sivers, Boer-Mulders distributions)
  - Drell-Yan process and TMD sign change SIDIS $\Longleftrightarrow$ DY
  - GPD, transverse size and parton orbital angular momentum
- π/K polarisabilities and tests of ChPT
  in the Compton scattering via Primakoff reaction.
- Addendum foreseen (spin-dependent GPD), Phase 2.

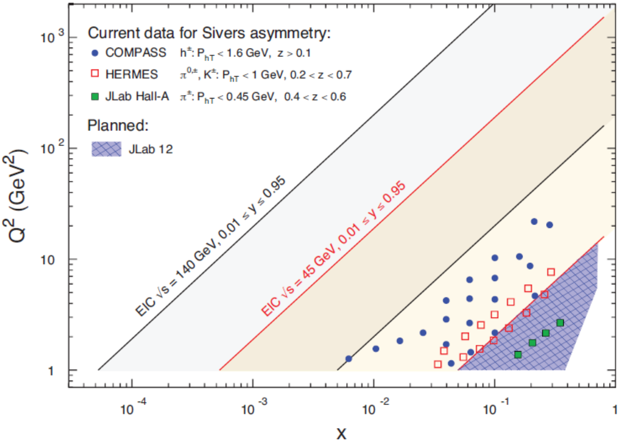
GPD at COMPASS: data taking in 2016-17



- CERN high energy muon beam
  - 100 - 190 GeV
  - 80% polarisation
  - $\mu^{+\leftarrow}$ and $\mu^{-\rightarrow}$ beams
- Kinematic range
  - between HERA and HERMES/JLab12
  - intermediate x (sea and valence)
- Separation
  - pure B-H @ low x_B
  - predominant DVCS @ high x_B
- Plans
  - DVCS
  - DVMP
- Goals
  - from unpolarised target: H (Phase 1)
  - from $\perp$ polarised target: E (Phase 2)

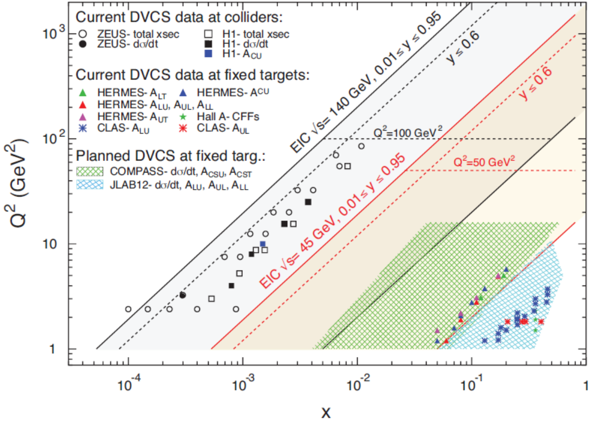
Test runs: 2008-9 and 2012; DVCS signal seen, full setup evaluated

Sivers measurements



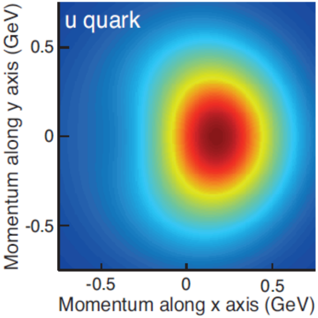
From "White paper", arXiv:1212.1701

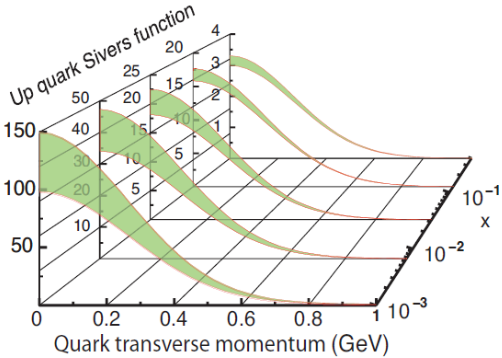
Acceptance of present and EIC DVCS



From "White paper", arXiv:1212.1701

EIC foreseen results on the Sivers function

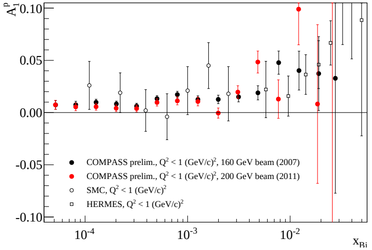


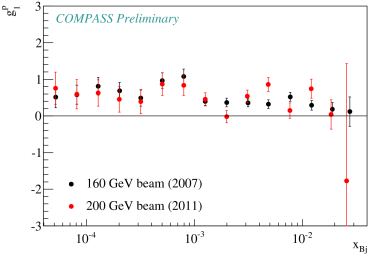


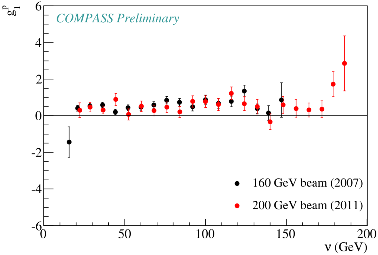
From "White paper", arXiv:1212.1701

Nonperturbative (Q^2 <1 GeV^2) region

g_1^p and g_1^d measurements: COMPASS very precise







$g_1^p(x)$, $g_1^p(\nu)$ significantly positive, $g_1^d(x) \approx 0$

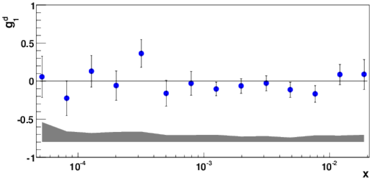


Figure above is from Phys.Lett. B647 (2007) 330

Regge model predictions for g_1

- Regge limit of DIS: $Q^2 \ll W^2 = M^2 + Q^2(1/x - 1)$ at fixed $Q^2 \implies$ low x
- For $g_1(x, Q^2)$ it gives: $g_1^i(x, Q^2) \sim \beta(Q^2) x^{-\alpha_i(0)}$, i =singlet, nonsinglet
  $(g_1^s = g_1^p + g_1^n,\ g_1^{\mathrm{ns}} = g_1^p - g_1^n)$
- Intercepts $\alpha_i(0)$ correspond to axial vector mesons:
  g_1^s: f_1 (I=0)
  g_1^{ns}: a_1 (I=1)
  where the intercepts: $\alpha_{\mathrm{s,ns}}(0) \lesssim 0$, $\alpha_s(0) \approx \alpha_{\mathrm{ns}}(0)$
- Consequence of the above: $g_1(W^2) \sim W^{2\alpha(0)}$ dependence at $Q^2 \to 0$
- At large Q^2, Regge behaviour of g_1 unstable against DGLAP
  (and against $\ln^2(1/x)$ resummation) $\implies$ more singular x dependence
- Testing Regge behaviour of g_1: through x-dependence at Q^2= const
  Not possible in SMC, not in COMPASS either
- Assuming $g_1 \sim 0$ to get $x \to 0$ extrapolation of g_1 is not correct!
  Evolve to a common Q^2 first!

Towards the nonperturbative region

- For $Q^2 \to 0$ (for fixed W^2), g_1 should be a finite function of W^2, free from kinematical singularities or zeroes at $Q^2 = 0$.
- If $g_1^{ns(0)}(x)$ has a singularity then it should be replaced by $g_1^{ns(0)}(\bar{x})$ where $\bar{x} = x(1 + k_0^2/Q^2)$. Remaining parts left unchanged.
- Then g_1^{ns} can be extrapolated to the low Q^2 for fixed $2M\nu = Q^2/x$ including $Q^2 = 0$. Observe! That is just the partonic contribution to the low Q^2 region; it may not be the only one there.
- Data on $g_1(x, Q^2)$ extend to low $Q^2 \sim 0.0001$ GeV^2
- Nonperturbative mechanisms dominate the particle dynamics there; transition from "soft" to "hard" physics may be studied
- Partonic contribution to g_1 has to be suitably extrapolated to low Q^2 and complemented by a nonperturbative component
- Low Q^2, spin-independent electroproduction well described by the GVMD $\Longrightarrow$ GVMD should be used to describe the g_1

Nonperturbative effects in g_1

BB, Kiryluk and Kwiecinski, Phys. Rev. D61 (2000) 014009

Method I

$$g_1(x,Q^2) = g_1^{VMD}(x,Q^2) + g_1^{part}(x,Q^2)$$

g_1^{part} at low x is controlled by the $\ln^2(1/x)$ terms Kwiecinski, Ziaja, Phys. Rev. D60 (1999) 054004.

$$g_1^{VMD}(x,Q^2) = \frac{M\nu}{4\pi} \sum_{V=\rho,\omega,\phi} \frac{M_V^4 \Delta\sigma_V(W^2)}{\gamma_V^2 (Q^2+M_V^2)^2}$$

The unknown $\Delta\sigma_V(W^2)$ are combinations of the total cross sections for the scattering of polarised vector mesons and nucleons. At high W^2: $\Delta\sigma_V = (\sigma_{1/2} - \sigma_{3/2})/2$

$$\frac{M\nu}{4\pi} \sum_{V=\rho,\omega} \frac{M_V^4 \Delta\sigma_V}{\gamma_V^2 (Q^2+M_V^2)^2} =$$

$$C \left[\frac{4}{9} \left(\Delta u_{val}^0(x) + 2\Delta\bar{u}^0(x) \right) + \frac{1}{9} \left(\Delta d_{val}^0(x) + 2\Delta\bar{d}^0(x) \right) \right] \frac{M_\rho^4}{(Q^2+M_\rho^2)^2},$$

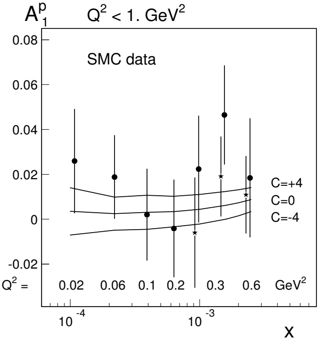
$$\frac{M\nu}{4\pi} \frac{M_\phi^4 \Delta\sigma_{\phi p}}{\gamma_\phi^2 (Q^2+M_\phi^2)^2} = C \frac{2}{9} \Delta\bar{s}^0(x) \frac{M_\phi^4}{(Q^2+M_\phi^2)^2},$$

Nonperturbative effects in g_1... cont'd

Each $\Delta p_j^0(x) \to x^0$ for $x \to 0$. Thus $\Delta\sigma_V \to 1/W^2$ at large W^2, i.e. zero intercept of the appropriate Regge trajectories.

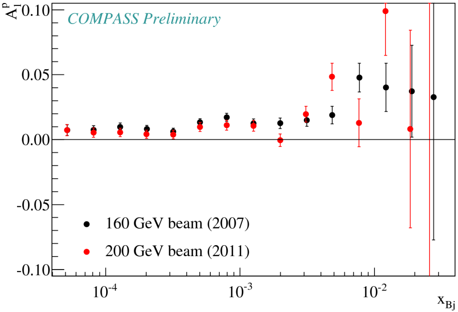
Results for the proton spin asymmetry, $A_1 = g_1/F_1$ and for different C:

C ??



SMC data

$C > 0$?



COMPASS preliminary data

Nonperturbative effects in g_1

BB, Kwiecinski and Ziaja, Eur. Phys. J. C26 (2002) 45

Method II (GVMD)

For fixed $W^2 \gg Q^2$, i.e. small $x = Q^2/(Q^2 + W^2 - M^2)$ assume:

$$g_1(x, Q^2) = g_1^L(x, Q^2) + g_1^H(x, Q^2) = \frac{M\nu}{4\pi} \sum_V \frac{M_V^4 \Delta\sigma_V(W^2)}{\gamma_V^2 (Q^2 + M_V^2)^2} + g_1^H(x, Q^2)$$

g_1^L: light vector mesons, $M_V < Q_0$, $Q_0^2 \sim 1$ GeV^2. Unknown $\Delta\sigma_V$: from combinations of nonperturbative parton distributions, evaluated at fixed Q_0^2, similar to method I.

g_1^H: heavy vector mesons, $M_V > Q_0$

$$g_1^H(x, Q^2) = M\nu \int_{Q_0^2}^{\infty} \mathrm{d}Q'^2 \frac{\Phi(Q'^2, W^2)}{(Q^2 + Q'^2)^2} \qquad x = \frac{Q^2}{(Q^2 + W^2 - M^2)}$$

Here:

$$\Phi(Q^2, W^2) = -\frac{1}{\pi} \Im \int^{-Q^2} \frac{\mathrm{d}Q'^2}{Q'^2} g_1^{AS}\left(x' = \frac{Q'^2}{(Q^2 + W^2 - M^2)}, Q'^2\right)$$

By construction:

$$\lim_{Q^2 \to \infty} g_1^H(x, Q^2) = g_1^{AS}(x, Q^2)$$

Nonperturbative effects in g_1... cont'd

Representation of Φ can also be treated as an extrapolation of the QCD improved parton model structure function, $g_1^{AS}(x, Q^2)$, to arbitrary values of Q^2: $g_1^H(x, Q^2) = g_1^{AS}(\bar{x}, Q^2 + Q_0^2)$. Here $\bar{x} = (Q^2 + Q_0^2)/(Q^2 + Q_0^2 + W^2 - M^2)$.

$$
\begin{aligned}
g_1(x, Q^2) \quad &= \quad C \left[\frac{4}{9} (\Delta u_{val}^0(x) + 2\Delta \bar{u}^0(x)) + \frac{1}{9} (\Delta d_{val}^0(x) + 2\Delta \bar{d}^0(x)) \right] \frac{M_\rho^4}{(Q^2 + M_\rho^2)^2} \\
&+ \quad C \left[\frac{1}{9} (2\Delta \bar{s}^0(x)) \right] \frac{M_\phi^4}{(Q^2 + M_\phi^2)^2} + g_1^{AS}(\bar{x}, Q^2 + Q_0^2).
\end{aligned}
$$

Here Q_0^2 = 1.2 GeV^2 and the only free parameter C is fixed in the $Q^2 = 0$ limit via the DHGHY sum rule:

$$
I(0) = I_{res}(0) + M \int_{\nu_t(0)}^{\infty} \frac{\mathrm{d}\nu}{\nu^2} g_1(x(\nu), 0) = -\frac{\kappa_{p(n)}^2}{4}, \qquad \kappa_{p(n)} = 1.79\ (-1.91)
$$

First moment of g_1, Γ_1 is related to DHGHY moment, $I(Q^2)$: $\lim_{Q^2 \to 0} \Gamma_1 \to \frac{Q^2}{2M^2} I(Q^2)$

and I_{res} = contribution from resonances, measured! Coefficient $C \sim -0.3$

Outlook

- A wealth of data on polarised (SI)DIS collected by fixed target experiments and by RHIC
- COMPASS II running starts fall 2014
- Great hopes for EIC (BNL or JLab)
  $\Longrightarrow$ higher energy and low(er) x
- Long Range Planning in Nuclear Physics just started; final report will be submitted to DOE fall of 2015?
- Do not underestimate the fixed target results. Remember NMC vs HERA!