Experimental results on nucleon structure
Lecture III

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National Nuclear Physics Summer School 2013

Stony Brook University, July 15 – 26, 2013

Outline

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1. Spin structure of the nucleon
   - Introduction
   - Experimental challenges
   - Observables in fixed-target and collider experiments
   - Results on helicity-dependent PDFs
   - Spin sum rules
   - Parton intrinsic k_T
   - Measurements on a transversely polarised target
   - Generalised Parton Distributions

Motto

"Polarisation data has often been the graveyard of fashionable theories. If theorists had their way, they might well ban such measurements altogether out of self-protection."

J.D.Bjorken, 1987

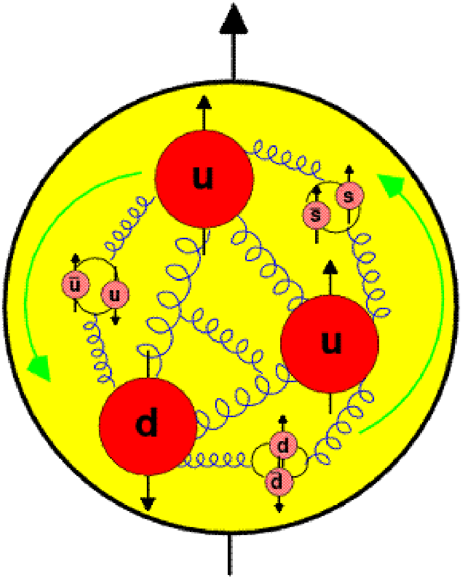
A Beautiful Spin (after X. Ji)

- 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...

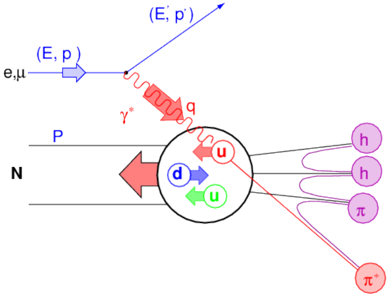
A Beautiful Spin (after X. Ji)...cont'd

- 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

Proton under a microscope



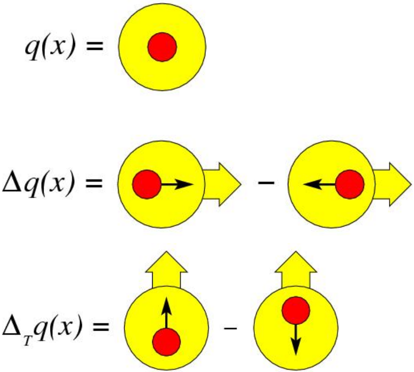
Nucleon spin structure in the electroproduction



- $$\frac{d^2\sigma}{d\Omega dE'} = \frac{\alpha^2}{2MQ^4}\frac{E'}{E}L_{\mu\nu}W^{\mu\nu}$$
- 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 $g_1(x)$
- $\ldots g_2(x)$ has no interpretation in terms of partons.

Partonic structure of the nucleon; distribution functions

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



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

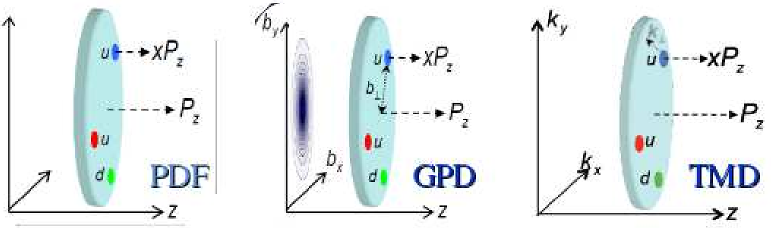
Difference in DF of quarks with spin parallel or antiparallel to the nucleon's spin;
known (polarised DIS $\rightarrow g_1(x)$).

Difference in DF of quarks with spin parallel or antiparallel to the nucleon's spin in a transversely polarised nucleon;
unknown (polarised DIS $\rightarrow h_1(x)$).

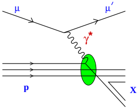
Nonrelativistically: $\Delta_T q(x) \equiv \Delta q(x)$. OBS.! $\Delta_T q(x)$ are C-odd and chiral-odd; may only be measured with another chiral-odd partner, e.g. fragmentation function.

If the k_t taken into account $\Longrightarrow$ 8 TMD distr.; e.g. $f_{1T}^{\perp}$ (accessible through "Sivers asymmetry").

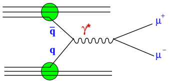
Transverse Momentum Dependent (TMD) distributions



- parton intrinsic k_{T} taken into account
- related to quark angular momentum, L!
- e.g. 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



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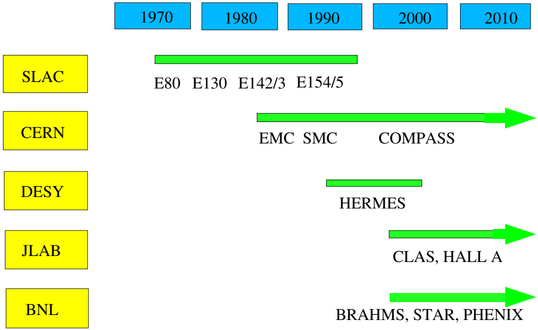
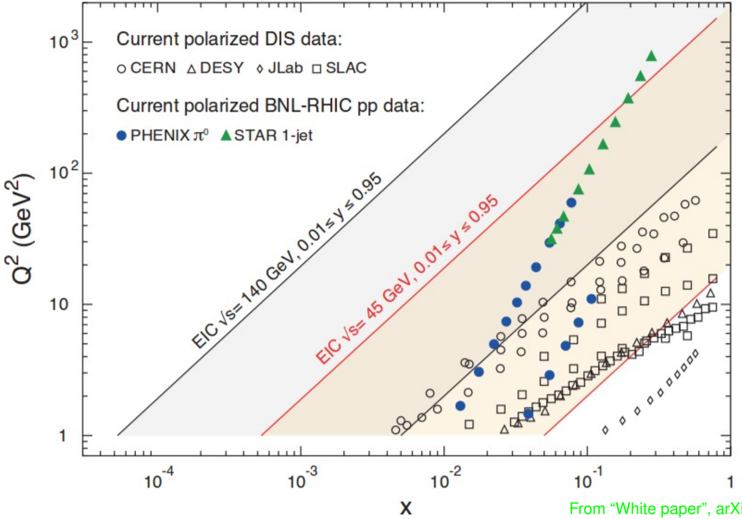
Experiments



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	$\lesssim 250+250$

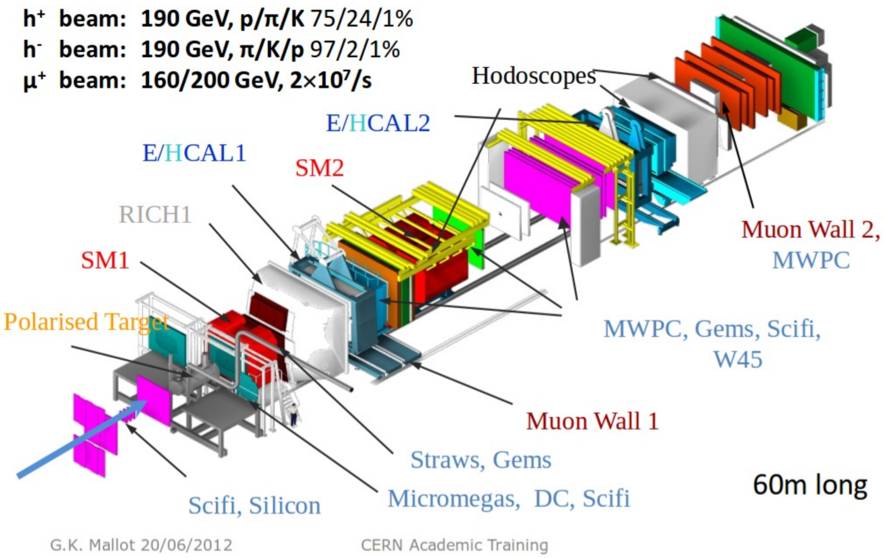
After G.Mallot, COMPASS

Acceptance of spin experiments

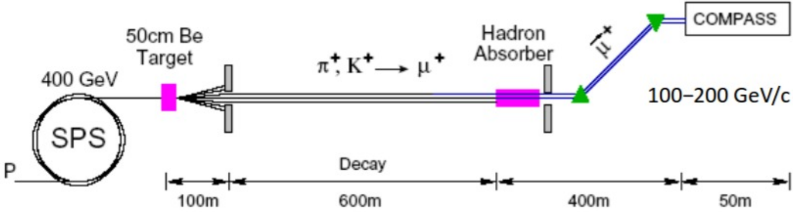


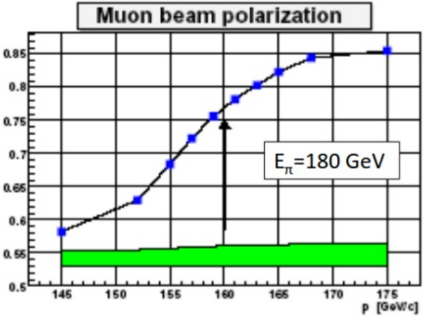
From "White paper", arXiv:1212.1701

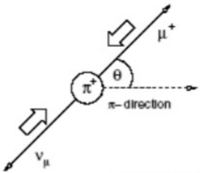
COMPASS/CERN spectrometer



High energy muon beam at CERN







Energy	160 GeV
Intensity	$2 \cdot 10^8 \mu/\mathrm{Spill}$
Polarisation	$\approx 76\,\%$

G.K. Mallot/CERN Varenna, July 2011

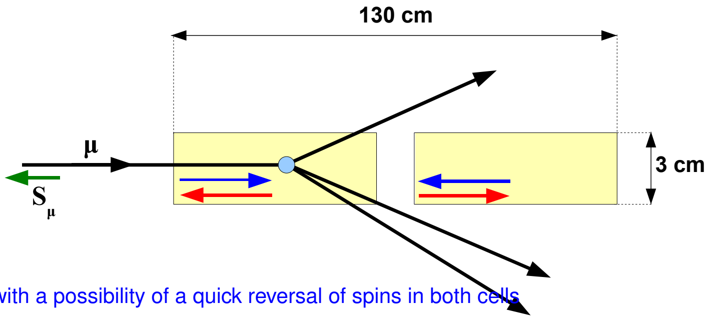
In lepton-nucleon (i.e. fixed-target) spin experiments...

- ...needed are polarised targets and beams (i.e. nucleons with aligned spins)
- of large density of those spins (dense beams and large targets)
- measurements are differential to minimise systematic errors

$$\frac{N^{\leftrightarrows} - N^{\leftleftarrows}}{N^{\leftrightarrows} + N^{\leftleftarrows}} \tag{29}$$

(upper arrow denotes lepton spin, lower one – spin of the target proton):

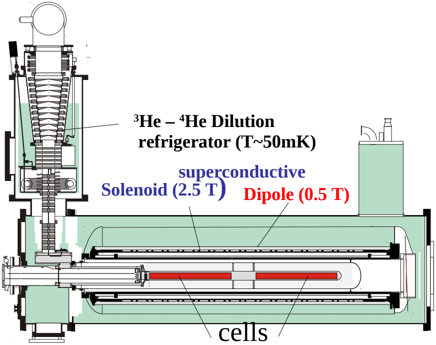
- Example of a two-cell COMPASS target:

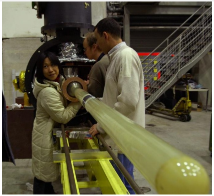


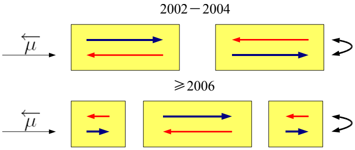
with a possibility of a quick reversal of spins in both cells

- COMPASS μ beam naturally polarised in $\sim$80% at $E =$160 GeV.

COMPASS polarised targets

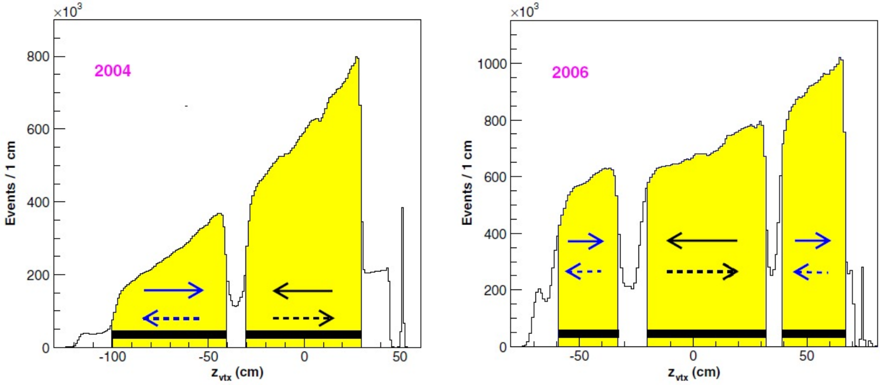






* Two (three) target cells, oppositely polarised
* Polarisation reversed every 8 h (less frequent after 2005) by field rotation
* Material: solid ^{6}LiD (NH_3)
* Polarisation: ~ 50% (~90%), by the Dynamical Nuclear Polarisation
* Dilution: f~0.4 (~0.15)
* Polar acceptance: ~70 mrad (~180 mrad after 2005)

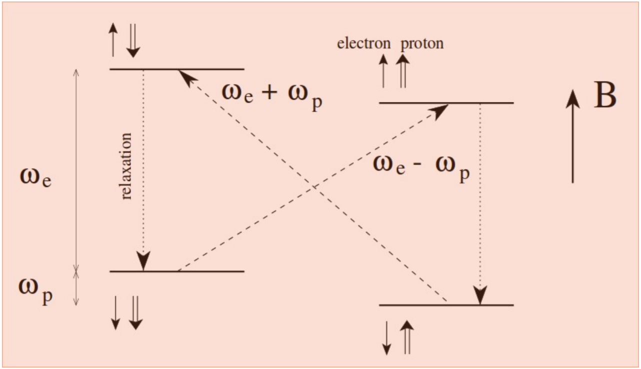
Interaction point in the COMPASS target



COMPASS, Phys.Rev., D83 (2013) 052018

Fixed targets: a dynamical nuclear polarisation

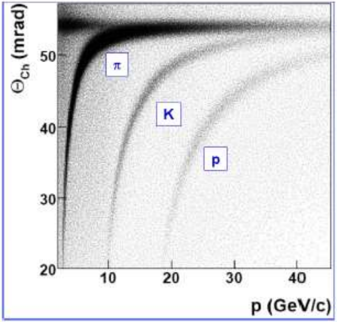
Polarisation of protons is hard: for B = 2.5 T, T = 0.5 K we get P_e = 0.998 but P_p = 0.005 !
Thus: targets polarised via Dynamical Nuclear Polarisation.

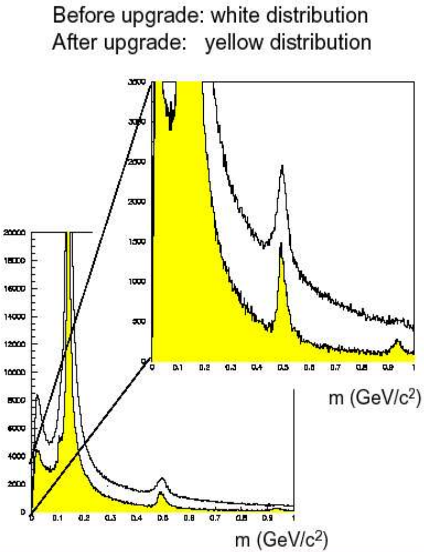


$\omega = \frac{\mu B}{\hbar}$ (μ is a proton magnetic moment), $\frac{\omega_e}{2\pi} \approx$ 70 GHz, $\frac{\omega_p}{2\pi} \approx$ 106 MHz (for B = 2.5 T)

After G. Mallot, habilitation thesis, 1996

COMPASS RICH





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Nucleon spin structure: cross section

For a longitudinally polarised proton target and longitudinally polarised lepton beam the spin-averaged, $\bar{\sigma}$ and spin-dependent $\Delta\sigma$, cross sections are (lepton mass neglected):

$$\bar{\sigma} = \frac{d^2\sigma^{\leftrightarrows}}{dxdy} + \frac{d^2\sigma^{\leftrightarrows}}{dxdy} = \frac{2\pi\alpha^2}{MEx^2y^2}\left[\left(1-y-\frac{Mxy}{2E}\right)F_2(x,Q^2) + xy^2F_1(x,Q^2)\right] \quad (30)$$

$$\Delta\sigma = \frac{d^2\sigma^{\leftrightarrows}}{dxdy} - \frac{d^2\sigma^{\leftrightarrows}}{dxdy} = \frac{4\alpha^2}{MExy}\left[\left(2-y-\frac{Mxy}{E}\right)g_1(x,Q^2) - \frac{2Mx}{E}g_2(x,Q^2)\right] \quad (31)$$

From the above, the asymmetry in γ^*-N cross sections for the absorption of a transversely polarised photon with spin polarised parallel and anti-parallel to the spin of the longitudinally polarised nucleon are:

$$A_1 \equiv \frac{\sigma_{\frac{1}{2}} - \sigma_{\frac{3}{2}}}{\sigma_{\frac{1}{2}} + \sigma_{\frac{3}{2}}} = \frac{g_1 - \frac{Q^2}{\nu^2}g_2}{F_1} \approx \frac{g_1}{F_1} \quad (32)$$

The above approximation (longitudinally polarised target!) is good since $M/E \ll 1$.

Not true for a transverse polarised target!

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

- Inclusive ($\vec{\mu}\vec{\mathrm{N}} \to \mu + \mathrm{X}$) asymmetry, A_{meas}:

$$A_{meas} = \frac{1}{f P_T P_B}\left(\frac{N^{\leftrightarrows} - N^{\leftleftarrows}}{N^{\leftrightarrows} + N^{\leftleftarrows}}\right) \approx D A_1 = D\,\frac{g_1(x,Q^2)}{F_1(x,Q^2)} = D\,\frac{\sum_q e_q^2 \Delta q(x,Q^2)}{\sum_q e_q^2 q(x,Q^2)} \quad (33)$$

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

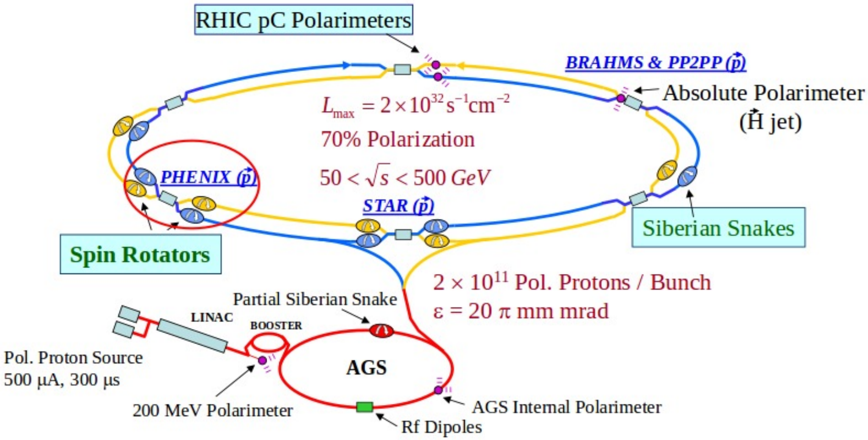
$$\omega_D = 0.05 \pm 0.01$$

- At LO, semi–inclusive ($\vec{\mu}\vec{\mathrm{N}} \to \mu + \mathrm{h} + \mathrm{X}'$) asymmetry, A_1^h:

$$A_1^h(x,z,Q^2) \approx \frac{\sum_q e_q^2 \Delta q(x,Q^2) D_q^h(z,Q^2)}{\sum_q e_q^2 q(x,Q^2) D_q^h(z,Q^2)} \qquad z = \frac{E_h}{\nu} \qquad D_q^h \neq D_{\bar{q}}^h \quad (34)$$

Relativistic Heavy Ion Collider

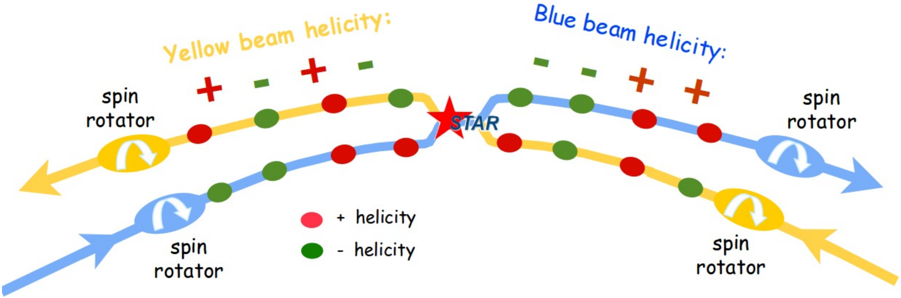
…worlds 1st $\vec{p}\,\vec{p}$ Collider



RHIC accelerates heavy ions up to 100 GeV/A and polarized protons up to 255 GeV

From M. Sarsour, DIS2013

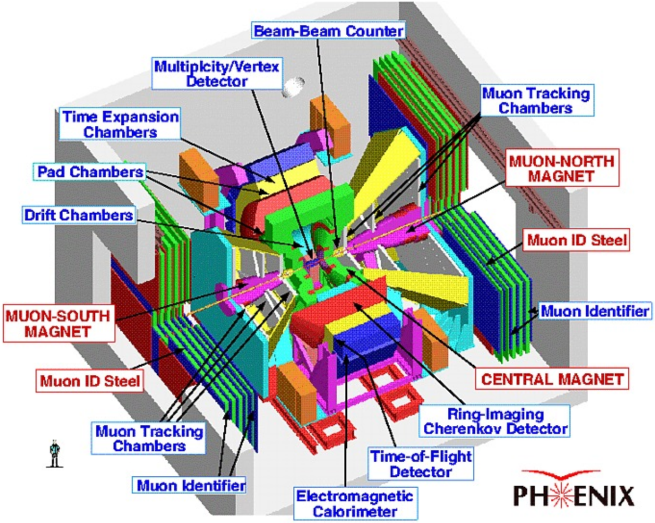
Polarised proton–proton scattering at RHIC



In 2012: centre-of-mass energy: 510 GeV, average polarisations: 55/57%

From J. Balewski, DIS2010

PHENIX/BNL spectrometer



www.phenix.bnl.gov/WWW/magnet/FIGS/Engineering/birds_view.gif

STAR

Longitudinal spin asymmetries for Ws

STAR has measured 4 independent yields for the physics process selected 3 asymmetries are independent (6 were investigated)

yields integrated over |eta|<1

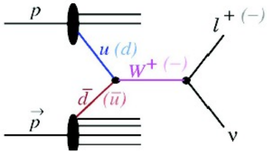
Leading physics asymmetry	cross section dependence	raw asymmetry
A_L (blue)	$(\sigma_{++}+\sigma_{+-}-\sigma_{--}-\sigma_{-+})/sum4$	$A_L P_1$
A_L (yellow)	$(\sigma_{++}+\sigma_{-+}-\sigma_{--}-\sigma_{+-})/sum4$	$A_L P_2$
A_L (average)	$(\sigma_{++}-\sigma_{--})\ /\ sum4$	$A_L \frac{P_1+P_2}{2}$
A_{LL}	$(\sigma_{++}+\sigma_{--}-\sigma_{-+}-\sigma_{+-})\ /\ sum4$	$A_{LL} P_1 P_2$
Null test $A_L(P_1-P_2)$	$(\sigma_{+-}-\sigma_{-+})\ /\ (\sigma_{-+}+\sigma_{+-})$	$\frac{A_L(P_1-P_2)}{1-A_{LL}P_1P_2}$
$A_L^* \simeq A_L$	$(\sigma_{++}-\sigma_{--})\ /\ (\sigma_{++}+\sigma_{--})$	$\frac{A_L(P_1+P_2)}{1+A_{LL}P_1P_2}$

where $sum4 = \sigma_{++}+\sigma_{+-}+\sigma_{-+}+\sigma_{--}$

From J. Balewski, DIS2010

Outline

Sea quark polarisation: RHIC/STAR



STAR measures $W^{\pm}$ through $e^{\pm}$ decays:

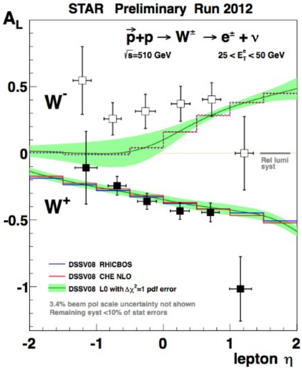
$$u + \bar{d} \quad \rightarrow \quad W^{+} \rightarrow e^{+} + \nu$$
$$\bar{u} + d \quad \rightarrow \quad W^{-} \rightarrow e + \bar{\nu}$$

Measure the parity-violating, single-spin helicity asymmetry

$$A_L = \frac{\overrightarrow{\sigma} - \overleftarrow{\sigma}}{\overrightarrow{\sigma} + \overleftarrow{\sigma}}$$

where at LO:

$$A_L^{W^+} \propto -\Delta u(x_1)\bar{d}(x_2) + \Delta\bar{d}(x_1)u(x_2)$$
$$A_L^{W^-} \propto -\Delta d(x_1)\bar{u}(x_2) + \Delta\bar{u}(x_1)d(x_2)$$



Large $\Delta\bar{u}$?

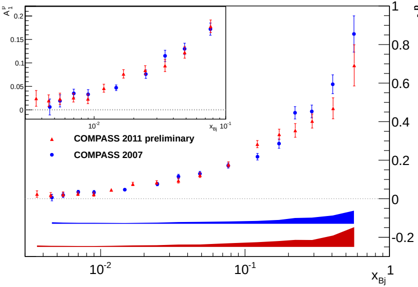
Hard scale: p_T^{lepton}, no FF uncertainties!

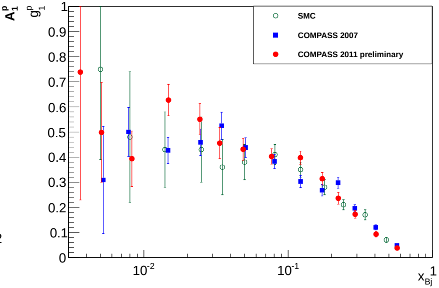
From J. Balewski, DIS2010

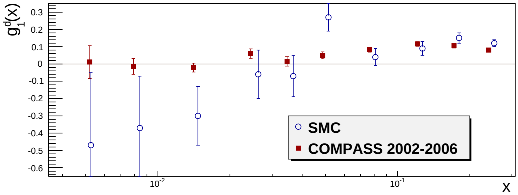
From B. Surrow, DIS2013

$g_1^p(x)$ and $g_1^d(x)$ at low x, $Q^2 > 1$ GeV^2

COMPASS inclusive data



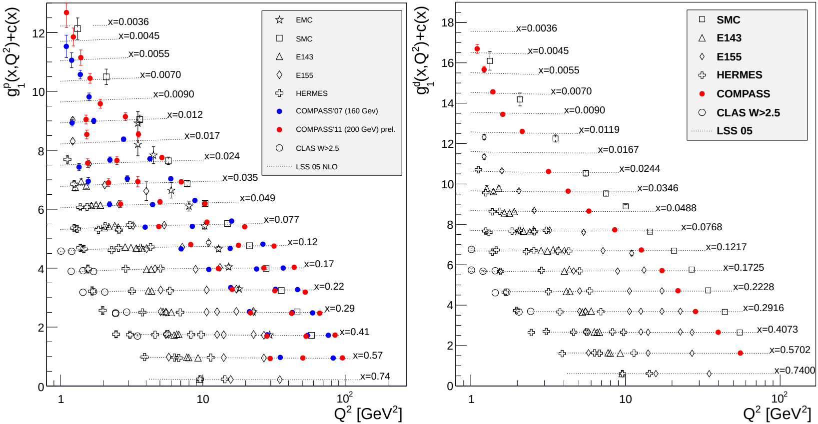




From B. Badelek, Low x 2013

$g_1^p(x,Q^2)$ and $g_1^d(x,Q^2)$ for Q^2 >1 GeV^2, W > 2.5 GeV

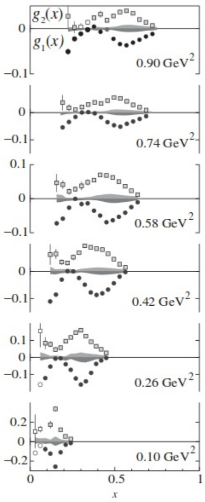
World data

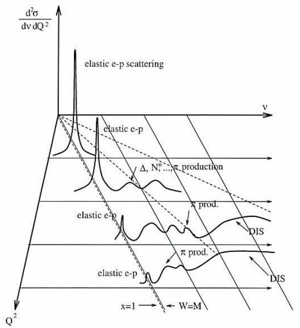


COMPASS measurements at high Q^2 important for the QCD analysis! but little sensitive to Δg

From B. Badelek, Low x 2013

Nucleon spin structure in the resonance region: JLAB results





Hall A/JLAB, E94-010, polarised ^{3}He target

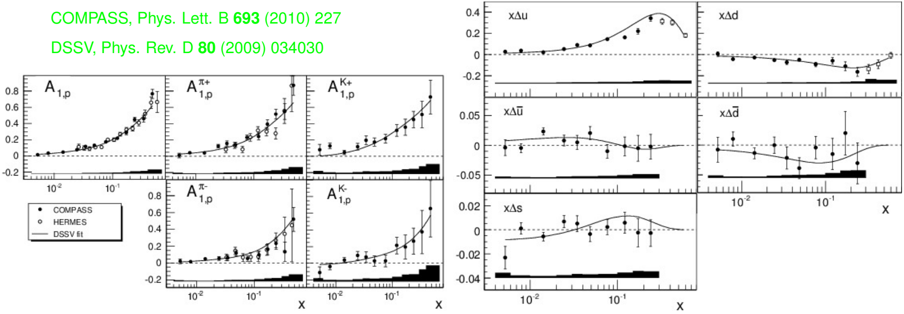
Phys.Rev.Lett., 92 (2004) 022301

Semi-inclusive asymmetries and parton distributions

- Measured on both p and d targets, for identified $\pi^{\pm}$ and $K^{\pm}$, assuming $\Delta s = \Delta \bar{s}$

COMPASS, Phys. Lett. B **693** (2010) 227

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

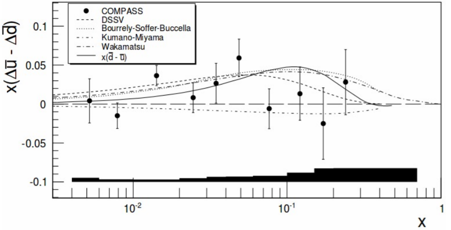


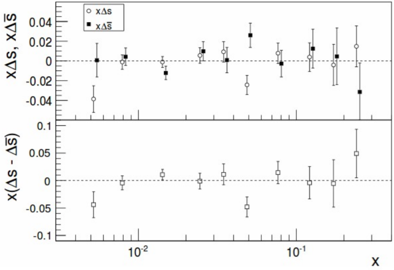
- To get helicity-dependent parton distribution functions quark fragmentation functions and unpolarised PDFs need to be assumed.

- Analysis assumes 6 unknowns and 10 equations $\Longrightarrow$ a fit.

Semi-inclusive asymmetries and sea distributions

- "Light" sea is not unsymmetric (contrary to unpolarised one, see lecture II page 67):
  $$\int_{0.004}^{0.3} \left[\Delta\bar{u}(x,Q^2) - \Delta\bar{d}(x,Q^2)\right] dx = 0.06 \pm 0.04 \pm 0.02 \;\; @ \;\; Q^2 = 3 \text{ GeV}^2$$
- and $\Delta s \approx \Delta\bar{s}$
- Δs puzzle. Strange quark polarisation:
  $$2\Delta S = \int_0^1 (\Delta s(x) + \Delta\bar{s}(x))dx = -0.09 \pm 0.01 \pm 0.02 \text{ from incl. asymmetries (+ SU}_3\text{)}$$
  while from semi-inclusive asymmetries it is compatible with zero
  but depends upon chosen fragmentation functions. MEASURE THEM!
  $\Longrightarrow$ see lecture II page 64.

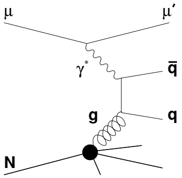




COMPASS, Phys. Lett. B, **680** (2009) 217; ibid., **693** (2010) 227.

Gluon polarisation in electroproduction

- QCD evolution of the inclusive g_1^p and g_1^d gives too large errors on Δg.
- Measurements based on special semi-inclusive channels needed!
- In $\vec{\mu}\vec{\mathrm{N}}$ a photo-gluon fusion (PGF) with subsequent fragmention into a pair of charm mesons: $\gamma^* g \to c\bar{c} \to \mathrm{D}\bar{\mathrm{D}}$.

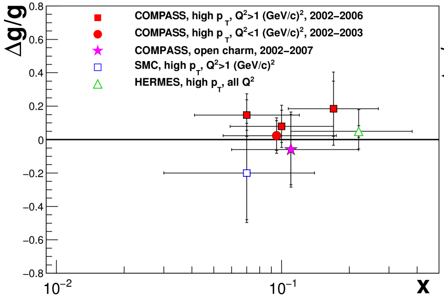


- $A_{\mathrm{meas}} = R_{\mathrm{pgf}}\, a_{\mathrm{pgf}}\, \dfrac{\Delta g}{g}$
  where R_{pgf} and a_{pgf} are taken from MC.
- Other methods:
  - high p_T hadron pairs with $Q^2 > 1$ GeV^2 or $Q^2 < 1$ GeV^2
  - single hadron production with high p_T and $Q^2 < 0.1$ GeV^2

Summary of $\langle \Delta g/g \rangle$ from electroproduction

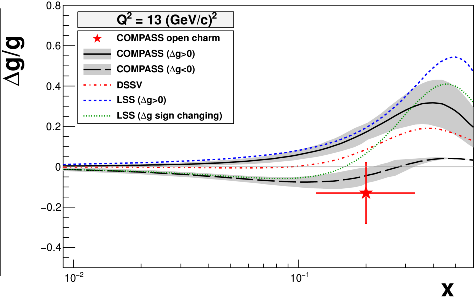
- All LO QCD data consistent and point toward small $\langle \Delta g/g \rangle$.
  Is $\Delta G = \int \Delta g(x)dx$ also small ?
- Data do not permit to determine a sign of $\Delta g/g$.

LO



COMPASS, Phys. Lett. B **718** (2013) 922;

NLO

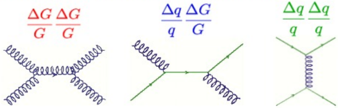


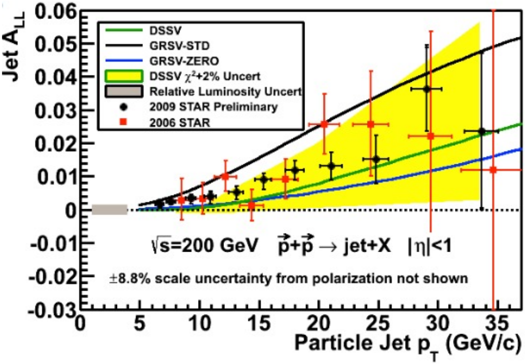
COMPASS, Phys.Rev. D **87** (2013) 052018

Gluon polarisation: jets at RHIC/STAR

$$A_{LL} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}} \propto \frac{\Delta f_a \Delta f_b}{f_a f_b} \hat{a}_{LL}$$

Δf: polarized parton distribution functions



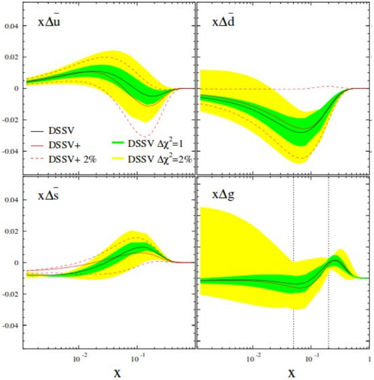


Observe that p_T^2 is taken as Q^2 in the acceptance (and similar) plot for RHIC; a corresponding x is representative for a measurement at this scale.

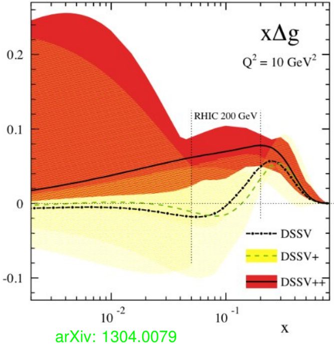
From C. Gagliardi, DIS2013

Status of helicity-dependent PDFs

- Global fits (DSSV/DSSV+/DSSV++) include: spin-dependent DIS data, SIDIS data with identified π and K, and proton-proton data $\Longrightarrow$ extracting PDFs at NLO. L_q and L_g decouple from this procedure $\Longrightarrow$ TMDs and GPDs ?.
  - Limited (x, Q^2) range $\Longrightarrow$ hard to get Δg from DIS
  - Separation of $q(x)$ and $\bar{q}(x)$ exclusively from SIDIS $\Longrightarrow$ FF needed! $\Longrightarrow$ COMPASS data crucial ($x_{\mathrm{min}} \approx 5 \cdot 10^{-3}$).

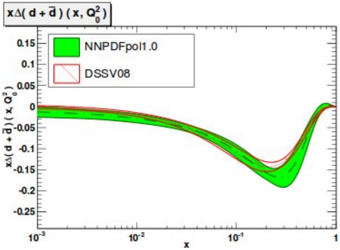


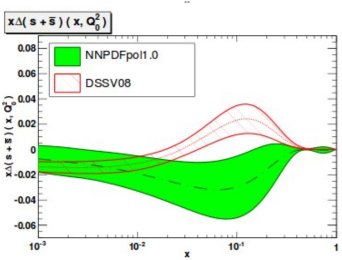
arXiv:1108.1713



arXiv: 1304.0079

Status of helicity-dependent PDFs,...cont'd





NNPDF, R.D. Ball et al., arXiv: 1303.7236

DSSV: DIS + SIDIS data;   NNPDF: only DIS

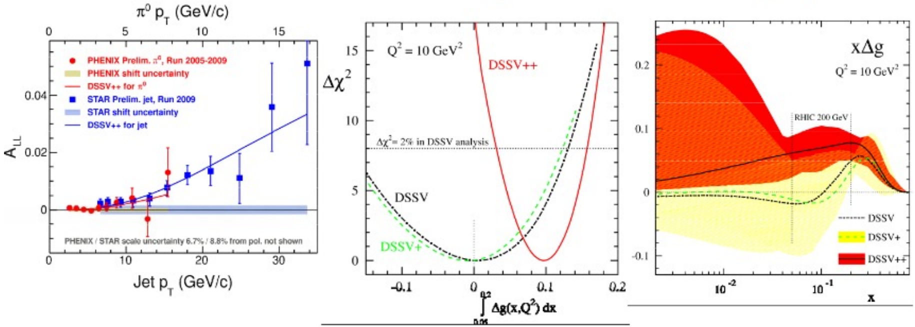
- $\Delta s(x)$ conundrum: negative from DIS but zero (slightly positive ?) from all data
  $\Longrightarrow$ strong dependence on FF? Measurements coming from COMPASS, B–factories, LHC
  '3F-D' rule: $\int_0^1 dx[\Delta s(x) + \Delta\bar{s}(x)] \approx$ –0.1 Validity ???
  Lattice QCD: –0.020$\pm$ 0.010$\pm$ 0.001.

- The PDF status not likely to change befor the advent of EIC!

Impact of new Δq and Δg data

New global analysis with 2009 RHIC data

Special thanks to the DSSV group!



- **DSSV++** is a new, preliminary global analysis from the DSSV group that includes preliminary 2009 A_{LL} measurements from PHENIX and STAR

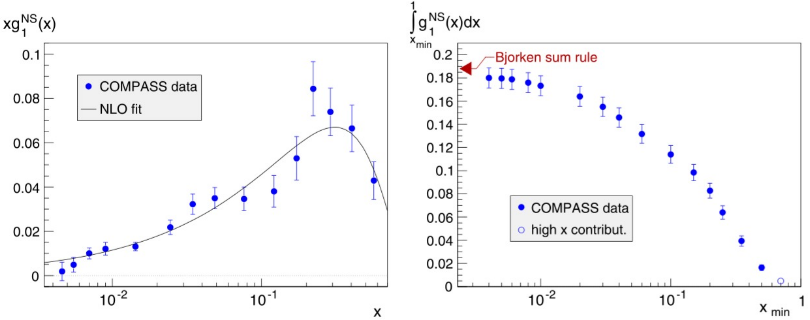
$$\int_{0.05}^{0.2} \Delta g(x, Q^2 = 10\,\mathrm{GeV}^2)\,dx = 0.10^{+0.06}_{-0.07}$$

From C. Gagliardi, DIS2013

Outline

Bjorken sum rule

- From the p and d data: $g_1^{NS} = g_1^p - g_1^n$; its first moment,
  $\Gamma_1^{NS}(Q^2) = \int_0^1 (g_1^p - g_1^n)dx = \frac{1}{6}\left|\frac{g_A}{g_V}\right| C^{NS}(Q^2)$ (fundamental Bjorken sum rule)
- From QCD NLO fit to g_1^{NS} (COMPASS data only): $\frac{g_A}{g_V} = 1.28 \pm 0.07 \pm 0.10$
  ($g_A/g_V = \Delta u - \Delta d = 1.260 \pm 0.003$ from the β decay of the neutron).
  Test and confirmation of the Bjorken sum rule.



COMPASS, Phys. Lett. B690 (2010) 466

Nucleon spin sum rule (nucleon spin 'puzzle')

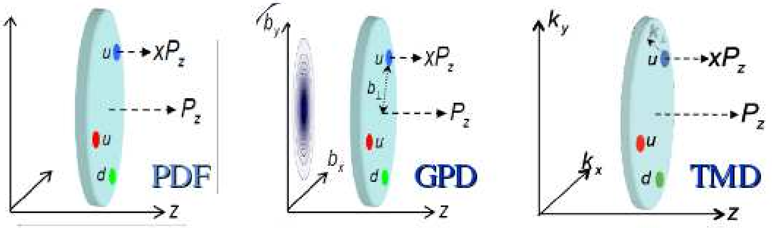
- Spin projection in units $\hbar$ is (debate: how to perform a gauge-invariant decomposition):

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

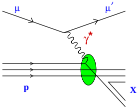
- here: $\Delta\Sigma$ – a contribution from all quarks, $\Delta\Sigma = \Delta u + \Delta d + \Delta s + \ldots$,
ΔG – contribution from gluons, ΔL – contribution from the quark and gluon orbital mom.
Each quantity is the 'first moment', e.g. $\Delta u = \int_0^1 \Delta u(x)dx$
Naively: $\Delta\Sigma$ =1, ΔG = 0, others = 0. Relativistically $\Delta\Sigma \sim 0.6$
- European Muon Collaboration at CERN (1987): $\Delta\Sigma$ =0.12 ± 0.09 ±0.14
- Since then a large experimental effort: SLAC, SMC (CERN), HERMES (DESY), JLAB, COMPASS (CERN), STAR, PHENIX (BNL). Now $\Delta\Sigma \sim$ 0.3
- Measurements of ΔG (COMPASS, HERMES, STAR, PHENIX),
only in a narrow interval around $x \sim 0.1$ but it seems that it is small!
- ΔL is completely unknown $\Longrightarrow$ MEASURE !

Outline

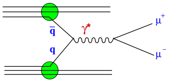
Transverse Momentum Dependent (TMD) distributions



- parton intrinsic k_T taken into account
- related to quark angular momentum, L!
- e.g. 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.)



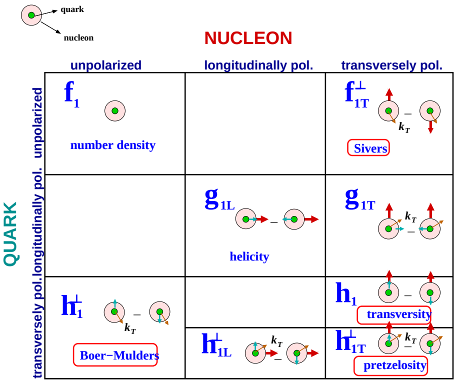
SIDIS



DY

TMD distributions...cont'd

- In LT and considering k_T, 8 PDF describe the nucleon
- QCD-TMD approach valid $k_T \ll \sqrt{Q^2}$
- 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. $A_{\text{Sivers}} \propto$ PDF $\otimes$FF
- DY: e.g. $A_{\text{Sivers}} \propto \text{PDF}^{\text{beam}} \otimes \text{PDF}^{\text{target}}$



- OBS! Boer-Mulders and Sivers PDF are T-odd, i.e. process dependent

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

- OBS! transversity PDF is chiral-odd, see page 8.
- Boer-Mulders, Sivers and transversity $(h_1^{\perp}, f_{1T}^{\perp}, h_1)$ will be measured in COMPASS II

Outline

1. Spin structure of the nucleon
   - Introduction
   - Experimental challenges
   - Observables in fixed-target and collider experiments
   - Results on helicity-dependent PDFs
   - Spin sum rules
   - Parton intrinsic k_{T}
   - **Measurements on a transversely polarised target**
   - Generalised Parton Distributions

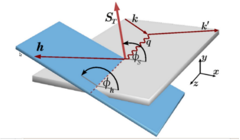
Measurements on a transversely polarised target

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):

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



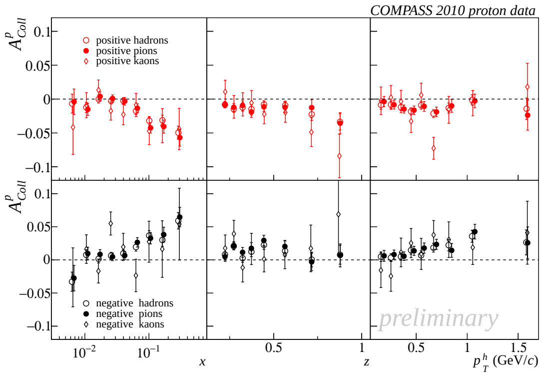
which in turn gives at LO:

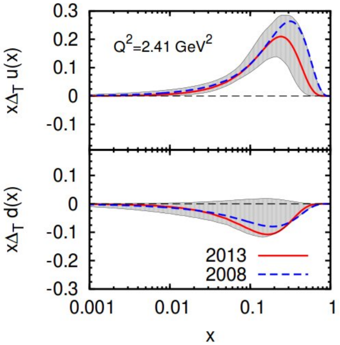
$$A_{Coll} \sim \frac{\sum_q e_q^2 \cdot \Delta_T q \cdot \Delta_T^0 D_q^h}{\sum_q e_q^2 \cdot q \cdot D_q^h}$$

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 Collins asymmetry for protons

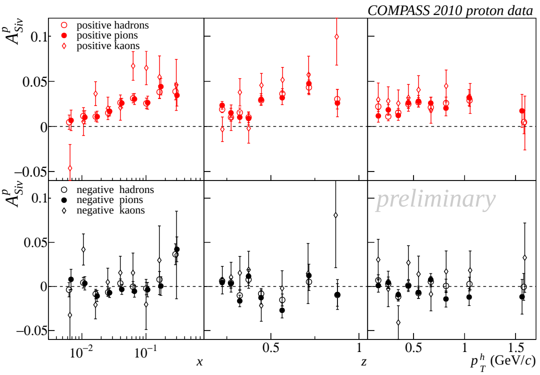




M. Anselmino et al., 1303.3822

- Collins asymmetries for proton measured for +/– unidentified and identified hadrons...
- ...are large at $x \gtrsim$ 0.1 and consistent with HERMES (in spite of different Q^2!)
- but negligible for the deuteron
- These data + HERMES + BELLE: $\Longrightarrow \Delta_T u + \Delta_T d \sim 0$
- Transversity also obtained from 2-hadron asymmetries (and “Interference Fragmentation Function”)

Results for the Sivers asymmetry for protons

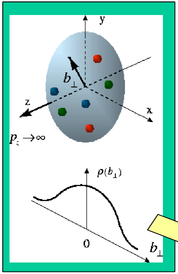


- Sivers asymmetries for proton measured for +/– unidentified and identified hadrons...
- ...are larger at larger Q^2 (HERMES)
- COMPASS deuteron data show very small asymmetry
- Sivers functions ($f_{1T}^{\perp}$) for d and u quarks have opposite signs

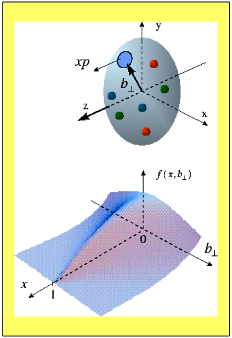
Outline

3D picturing of the proton *via* GPD

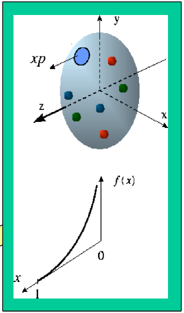
D. Mueller, X. Ji, A. Radyushkin, A. Belitsky, …
M. Burkardt, … Interpretation in impact parameter space



Proton form factors, transverse charge & current densities



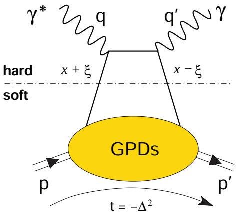
Correlated quark momentum and helicity distributions in transverse space - GPDs



Structure functions, quark longitudinal momentum & helicity distributions

Slide from V.D. Volker, LANL 2007

Access GPD through the DVCS/DVMP mechanism

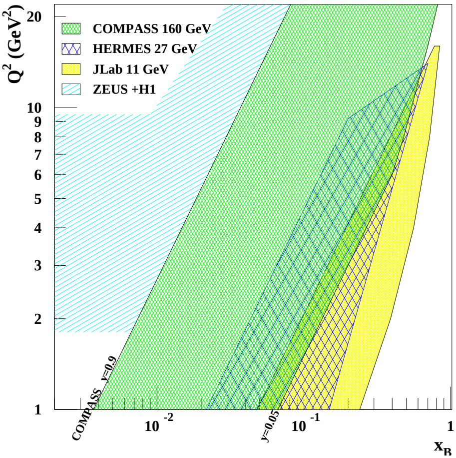


$Q^2 \to \infty$,
fixed $x_B, t \implies |t|/Q^2$ small

- 4 GDPs $(H, E, \widetilde{H}, \widetilde{E})$ for each flavour and for gluons
- Factorisation proven for σ_L only
- All depend on 4 variables: x, ξ, t, Q^2; DIS @ $\xi = t = 0$; Later Q^2 dependence omitted. Careful! Here $x \neq x_B$!
- $H, \widetilde{H}$ conserve nucleon helicity
  $E, \widetilde{E}$ flip nucleon helicity
- H, E refer to unpolarised distributions
  $\widetilde{H}, \widetilde{E}$ refer to polarised distributions
- $H^q(x,0,0) = q(x), \quad \widetilde{H}^q(x,0,0) = \Delta q(x)$

- 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 respectively.
- Important: $J_z^q = \frac{1}{2} \int dx\, x \left[H^q(x,\xi,t=0) + E^q(x,\xi,t=0)\right] = \frac{1}{2}\Delta\Sigma + L_z^q$ (X. Ji)

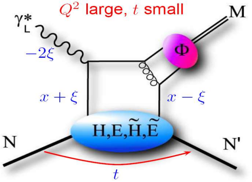
Why GPD at COMPASS ?

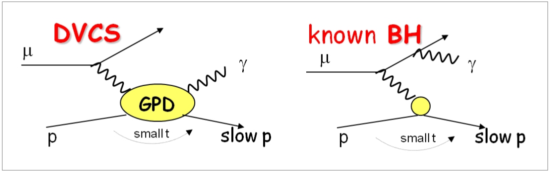


- CERN high energy muon beam
  - 100 - 190 GeV
  - 80% polarisation
  - $\mu^{+\leftarrow}$ and $\mu^{-\rightarrow}$ beams
- Kinematic range
  - between HERA and HERMES/JLab12
  - intermediate x (sea and valence)
- Separation
  - pure B-H @ low x_{B}
  - predominant DVCS @ high x_{B}
- Plans
  - DVCS
  - 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

DVCS/DVMP: $\mu p \to \mu p \gamma(M)$; what do we measure?

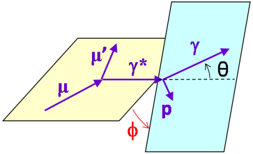




$$d\sigma^{\mu p \to \mu p \gamma} = d\sigma^{BH} + (d\sigma^{DVCS}_{unpol} + P_\mu d\sigma^{DVCS}_{pol}) + e_\mu(\mathrm{Re}I + P_\mu \mathrm{Im}I)$$

Observables (Phase 1):

- $S_{CS,U} \equiv \mu^{+\leftarrow} + \mu^{-\rightarrow} = 2\left(d\sigma^{BH} + d\sigma^{DVCS}_{unpol} + e_\mu P_\mu \mathrm{Im}I\right)$
- $D_{CS,U} \equiv \mu^{+\leftarrow} - \mu^{-\rightarrow} = 2\left(P_\mu d\sigma^{DVCS}_{pol} + e_\mu \mathrm{Re}I\right)$
- $A_{CS,U} \equiv \dfrac{\mu^{+\leftarrow} - \mu^{-\rightarrow}}{\mu^{+\leftarrow} + \mu^{-\rightarrow}} = \dfrac{D_{CS,U}}{S_{CS,U}}$
- Each term ϕ-modulated
  If ϕ-dependence integrated over $\Longrightarrow$ twist-2 DVCS contribution;
  if ϕ-dependence analysed: $\Longrightarrow$ Im $(F_1 H)$ and Re $(F_1 H)$



Analogously for transversely polarised target (Phase 2): $S_{CS,T}, D_{CS,T}, A_{CS,T} \Longrightarrow E$