Spin-dependent DIS
presently and on planned e-p machines

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EDS Blois
The 16th conference on Elastic and Diffractive Scattering

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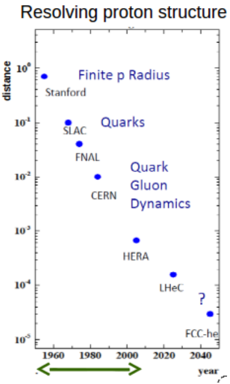
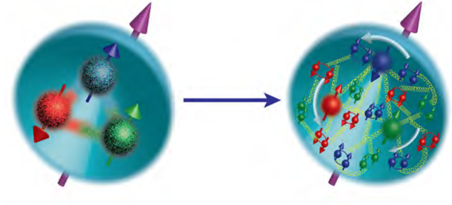
Outline

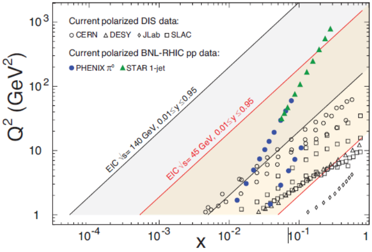
Evolution in understanding the proton structure

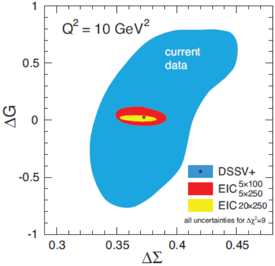




$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_z$$

(quark spins: $\Delta\Sigma$; gluon spins: ΔG; quark&gluon orbital motion: L_z)

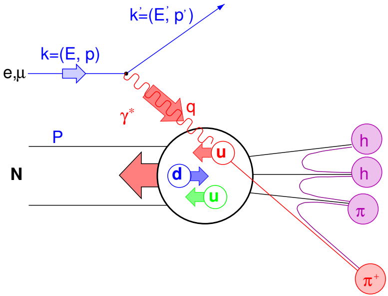




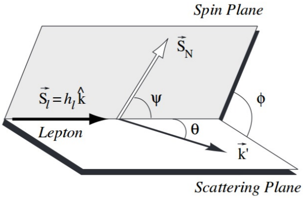
R.Ent, DIS2014

From “White paper”, arXiv:1212.1701

Nucleon spin structure in the electroproduction



- $$\frac{\mathrm{d}^2\sigma}{\mathrm{d}\Omega\mathrm{d}E'} = \frac{\alpha^2}{2Mq^4}\frac{E'}{E}L_{\mu\nu}W^{\mu\nu}$$
- 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.



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

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

- Inclusive asymmetry, A_{meas}:

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

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

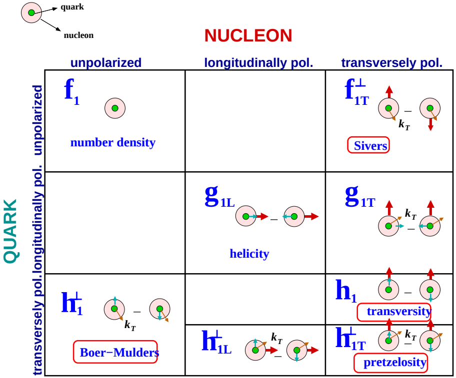
$$\omega_D = 0.05 \pm 0.01$$

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

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

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$^{\mathrm{target}}$



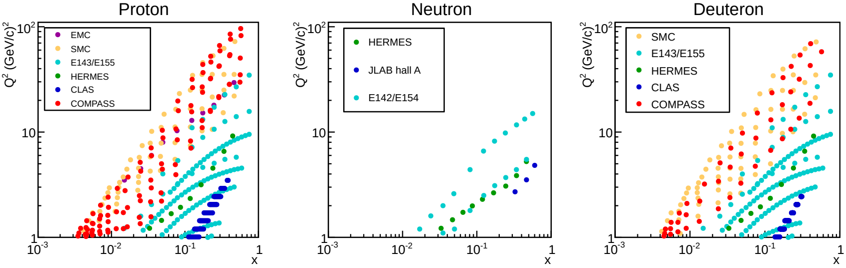
- OBS! Boer-Mulders and Sivers PDF are T-odd, i.e. process dependent

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

- 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

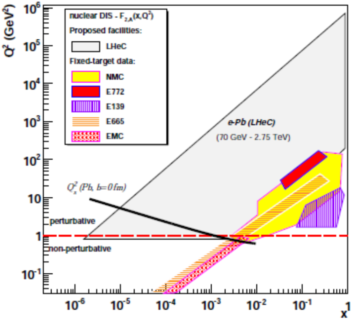
Acceptance of spin experiments @ $Q^2 > 1\ (\mathrm{GeV}/c)^2$

- Fixed target:
  - JLab (Hall A, CLAS): polarised e of $\lesssim$ 12 GeV, polarised targets
  - CERN (COMPASS): polarised μ^+ of 160-200 GeV, polarised protons (deuterons)
  - (completed) DESY (HERMES): polarised e of 27 GeV, polarised targets
- Colliders: BNL (STAR, PHENIX) polarised protons, $\sqrt{s} \lesssim$ 510 GeV



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:

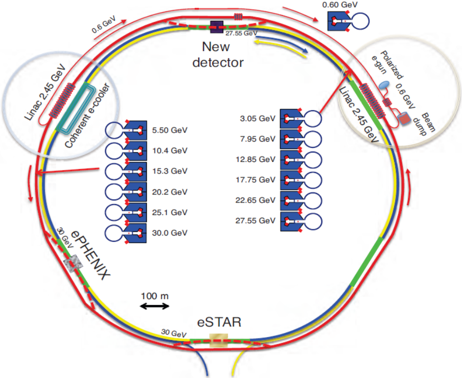


electron beam 60 GeV	Ring	Linac
e^- (e^+) per bunch N_e [10^9]	20 (20)	1 (0.1)
e^- (e^+) polarisation [%]	40 (40)	90 (0)
bunch length [mm]	6	0.6
tr. emittance at IP $\gamma\epsilon^e_{x,y}$ [mm]	0.59, 0.29	0.05
IP β function $\beta^*_{x,y}$ [m]	0.4, 0.2	0.12
beam current [mA]	100	6.6
energy recovery 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	JLab
Electron beam facility needed (inside RHIC tunnel)	ELIC + injector needed



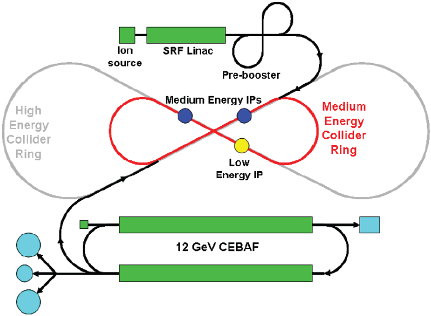
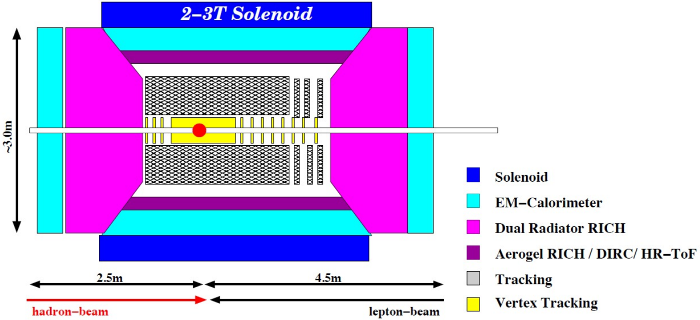


figure from The White Paper, arXiv:1212.1701

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

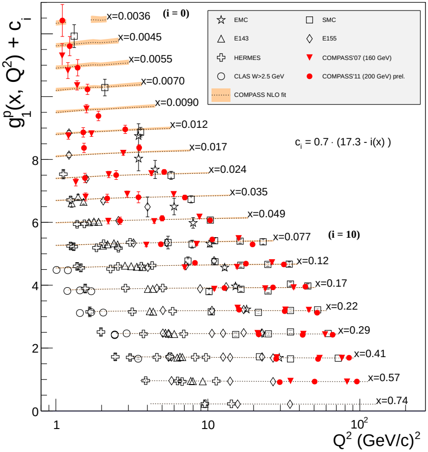
EIC: main features

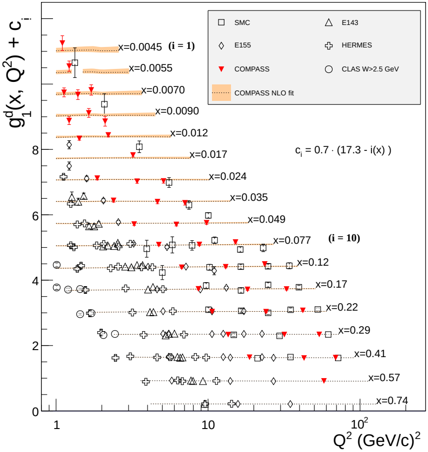
- Highly polarised ($\sim$ 70%) e, N beams
- ions from deuteron to uranium (lead ?)
- variable $\sqrt{s}$ from $\sim$ 20 GeV to $\sim$ 100 (150) GeV
- high luminosity: $\sim 10^{33-34}$ cm^{-2} s^{-1} (cooling of hadronic beam !)
- more than one interaction rregion
- limits of current technology $\Longrightarrow$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

Outline

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

COMPASS: p data 2007 @ 160 GeV + p data 2011 @ 200 GeV; full d statistics



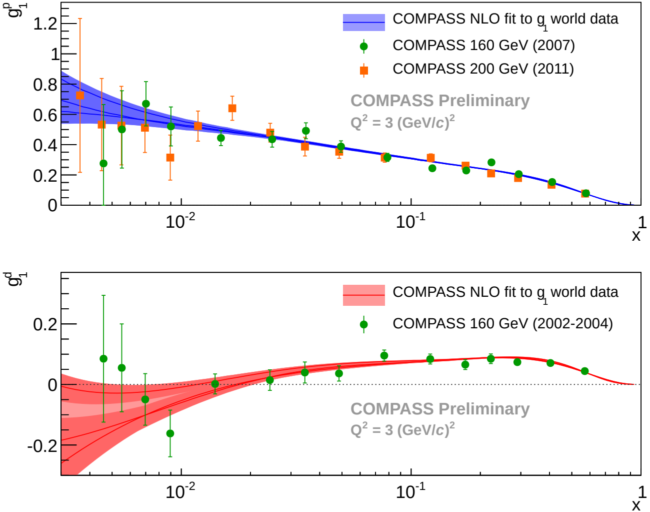


COMPASS measurements at high Q^2 important for the QCD analysis! but little sensitive to Δg

COMPASS, hep-ex/1503.08935, submitted PLB

COMPASS NLO fit to g_1 world data; Q^2 = 3 (GeV/c)^2

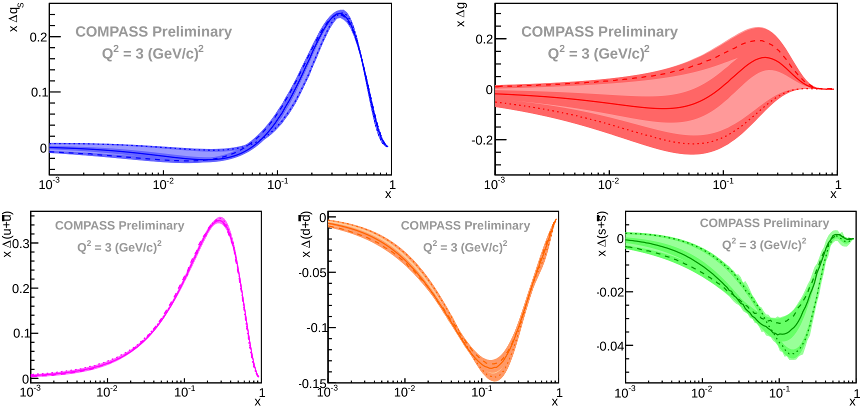
Fitted: $\Delta q_{\rm SI}, \Delta q_3, \Delta q_8, \Delta g$ at Q_0^2 = 1 (GeV/c)^2; 679 points, 28 params; $\overline{\rm MS}$ scheme



COMPASS, hep-ex/1503.08935, submitted PLB

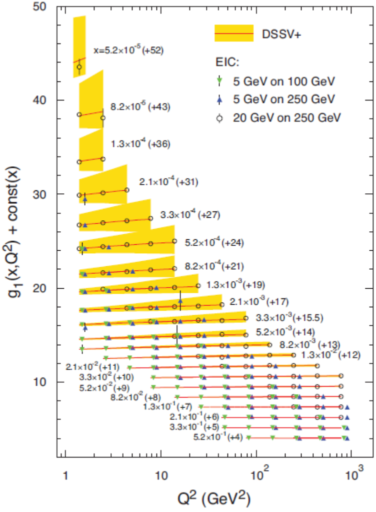
COMPASS NLO fit to g_1 world data... cont'd

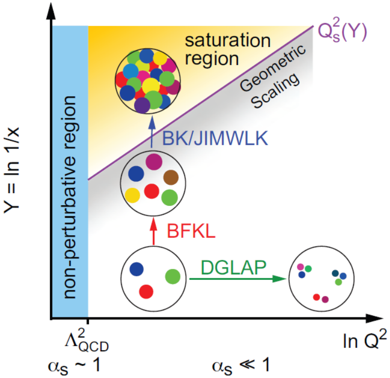
- Little sensitive to gluon polarisation
- Quark polarisation: $\Delta\Sigma = \int \Delta q_{\mathrm{SI}}(x)dx \sim 0.3$



COMPASS, hep-ex/1503.08935, submitted PLB

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





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

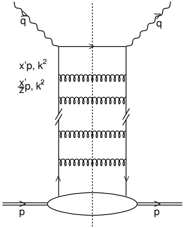
From “White paper”, arXiv:1212.1701

$\ln^2(1/x)$ 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 $\Longrightarrow$



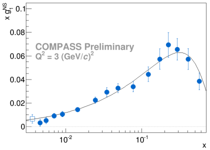
$\ln^2(1/x)$ corrections to $g_1^{ns}(x, Q^2)$... cont'd

- $\ln^2(1/x)$ 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 $\lambda = 2\sqrt{\tilde{\alpha}_s}$

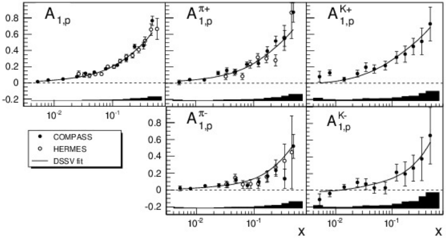
Semi-inclusive asymmetries and parton distributions

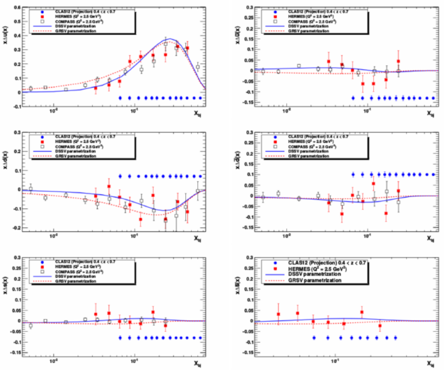
- COMPASS: measured on both proton and deuteron targets
  for identified, positive and negative pions and (for the first time) kaons

CLAS12, Update to E12-09-007

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

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





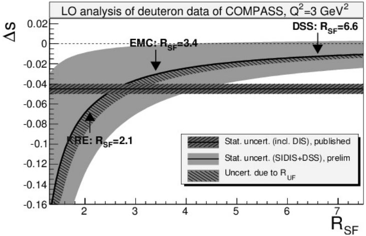
- COMPASS: LO DSS fragm. functions and LO unpolarised MRST assumed here.
- NLO parameterisation of DSSV describes the data well.

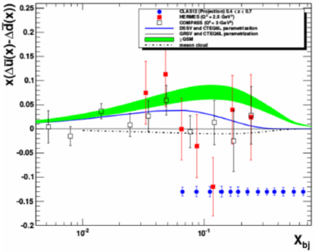
Polarisation of quark sea

- 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: $R_{SF} = \dfrac{\int D_{\bar{s}}^{K^+}(z)dz}{\int D_u^{K^+}(z)dz}$

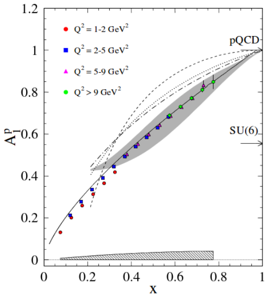
  $\Longrightarrow$ COMPASS extracts it from multiplicities.

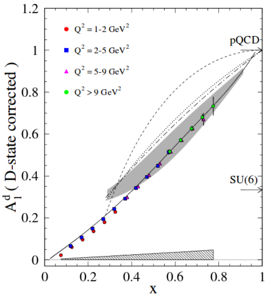




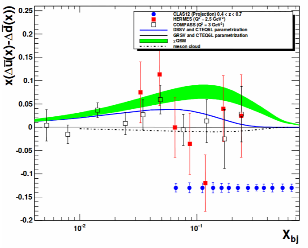
- The sea is not unsymmetric: COMPASS, Phys. Lett. B, **680** (2009) 217; ↑ CLAS12, Update to E12-09-007
  $$\int_{0.004}^{0.3} \left[\Delta\bar{u}(x,Q^2) - \Delta\bar{d}(x,Q^2)\right] dx = 0.06 \pm 0.04 \pm 0.02 \quad @ \quad Q^2 = 3\ (\mathrm{GeV}/c)^2$$
  Thus the data disfavour models predicting $\Delta\bar{u} - \Delta\bar{d} \gg \bar{d} - \bar{u}$

Nucleon spin structure @ high x: JLab at 12 GeV



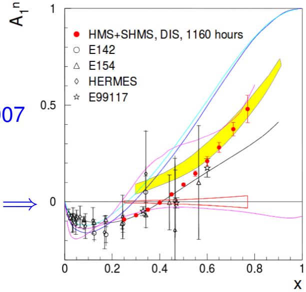


⟸ Hall B (CLAS), E12-06-109
A_1^p and A_1^d



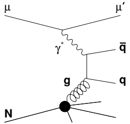
⟸ Hall B (CLAS), E12-09-007
symmetry of the sea

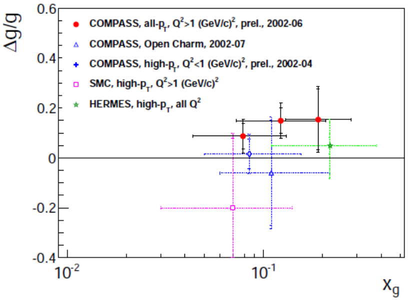
Hall C, E12-06-110, A_1^n ⟹

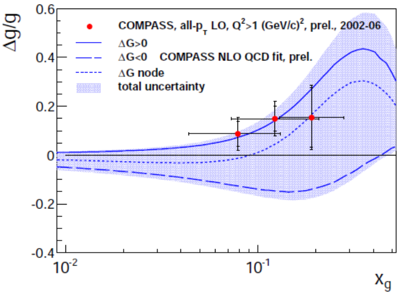


Direct measurements of $\Delta g(x)$

Direct measurements – *via* the cross section asymmetry for the photon–gluon fusion (PGF) with subsequent fragmentation into $c\bar{c}$ or $q\bar{q}$ pair.



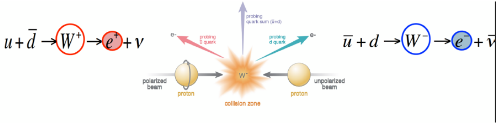




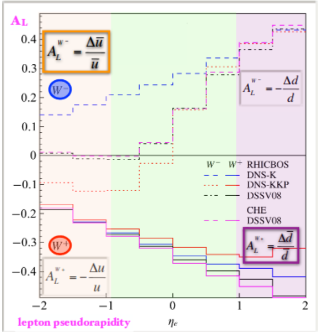
M.Stolarski, DIS2014

A_L for W$^{\pm}$ production at $\sqrt{s}$=510 GeV @ STAR

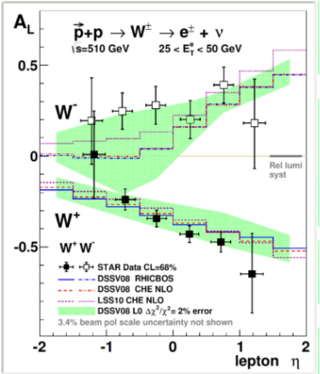
- Direct coupling to $q\bar{q}$ of interest
- Scale set by W mass
- Efficient spin separation
- Easy detection



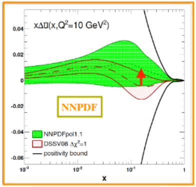
Cartoons from D.Gunarathne, DIS2015



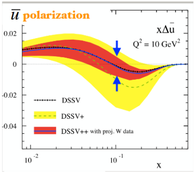
W A_L (η_e) 2012+2011



PRL 113,72301 (2014)

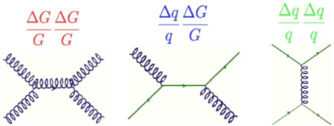


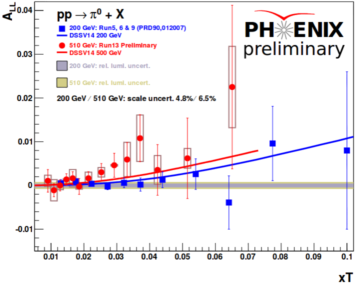
arXiv: 1403.0440

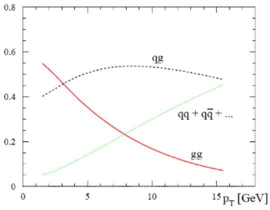


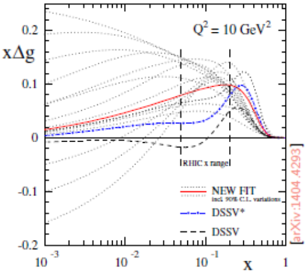
arXiv: 1304.0079

A_{LL} for π^0 production at $\sqrt{s}$=200 and 510 GeV @ PHENIX







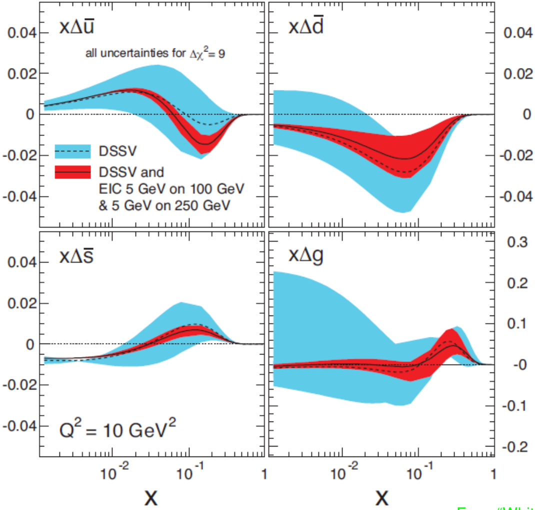


DSSV++ with 200 GeV data:

$$\int_{0.05}^{1.0} \Delta g(x)dx = 0.2^{+0.06}_{-0.07}$$

H. Guragain, DIS2015; DSSV, 113 (2014) 012001

EIC pseudo-data (inclusive and semi-inclusive)



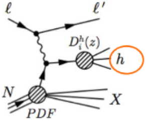
From “White paper”, arXiv:1212.1701

Outline

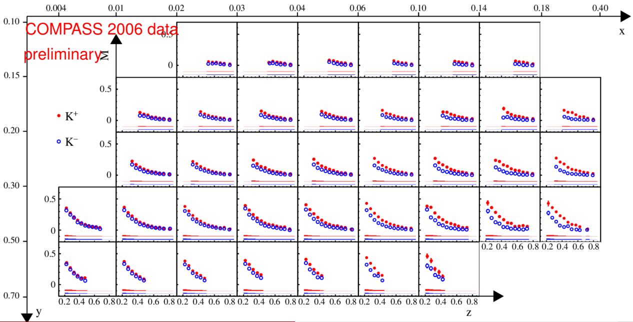
Charged hadron multiplicities; identified kaons

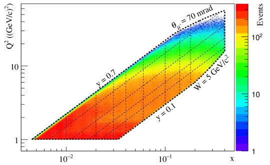
- Studied to measure fragmentation functions (FF), $D_q^h(z, Q^2)$ ($\Longrightarrow$ cf. Δs).
  At LO:

$$M^h(x,z,Q^2) = \frac{\left(\frac{d\sigma}{dx\,dz\,dQ^2}\right)_{\mathrm{SIDIS}}}{\left(\frac{d\sigma}{dx\,dQ^2}\right)_{\mathrm{DIS}}} = \frac{\Sigma_q e_q^2\left[q(x,Q^2)D_q^h(z,Q^2) + \bar{q}(x,Q^2)D_{\bar{q}}^h(z,Q^2)\right]}{\Sigma_q e_q^2\left[q(x,Q^2)+\bar{q}(x,Q^2)\right]}$$



- 2006 data; ^{6}LiD target; 317 kinematic bins.
- $Q^2 > 1$ (GeV/c)^2, 0.1 $< y <$0.7, 0.004 $< x <$0.4
  0.2 $< z <$ 0.85, 12 $< p_h <$ 40 GeV/c (coverage in W: 5 –17 GeV).



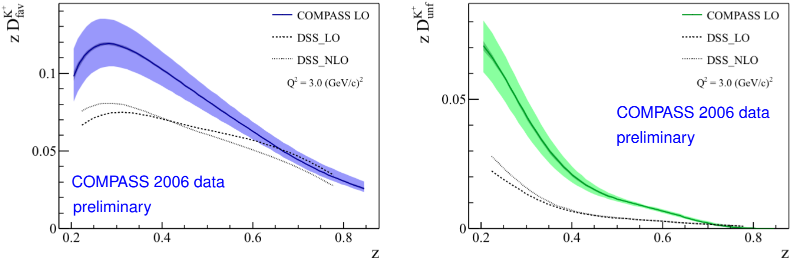


Charged hadron multiplicities; identified kaons

- Assume isospin and charge symmetry:

$$D^K_{\rm fav} = D^{K^\pm}_{\rm fav} = D^{K^+}_u = D^{K^-}_{\bar u},$$
$$D^K_{\rm unf} = D^{K^\pm}_{\rm unf} = D^{K^+}_{\bar u} = D^{K^+}_s = D^{K^-}_u = D^{K^-}_{\bar s} = D^{K^\pm}_d = D^{K^\pm}_{\bar d}$$
$$D^K_{\rm str} = D^{K^\pm}_{\rm str} = D^{K^+}_{\bar s} = D^{K^-}_s$$

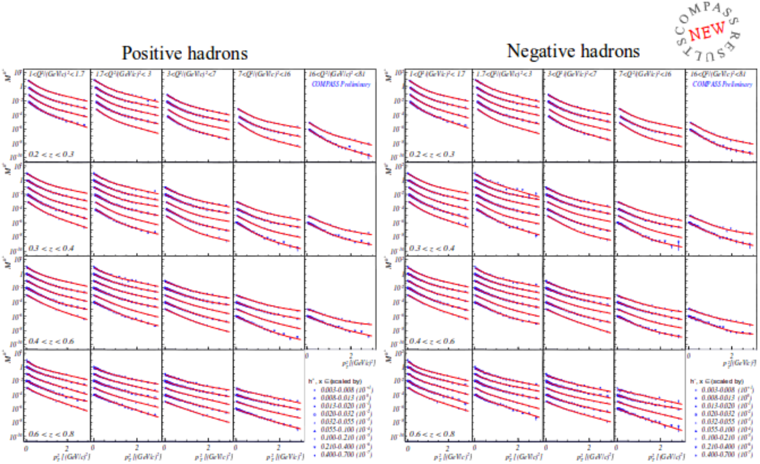
- Assume functional form of a FF $\Longrightarrow$ fit e.g. $K^\pm$ mutiplicities (DGLAP) $\Longrightarrow$ extract 2 FFs



- Results much above the DSS world fit and in tension with HERMES
- At this stage of analysis, results for $zD^K_{\rm str}$ not stable
- Analysis almost concluded with $\pi^\pm$ multiplicites/FFs; continues with proton data
- 2016-2017 proton data will be taken parallely to GPD programme

Charged hadron multiplicities; p_T dependence

p_T^2 – dependent multiplicities vs. (x, Q^2, z, p_T^2) for $h^\pm$



Very good description of shape of experimental data fitting with $a.e^{-\alpha pt2} + b.e^{-\beta pt2}$

N. MAKKE - SPIN 2014, BEIJING, CHINA 34

Outline

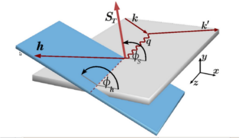
Measurements on a transversely polarised target

Properties of transversity $\Delta_T q(x)$:

- is chiral–odd $\Longrightarrow$ hadron(s) in final state needed to be observed
- simple QCD evolution since no gluons involved
- 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 (spin asymmetry in the azimuthal 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:

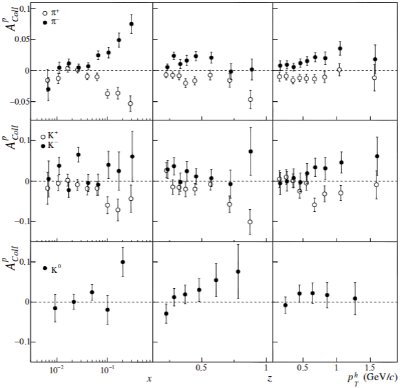
$$A_{Coll} \sim \frac{\sum_q e_q^2 \cdot \Delta_T q \cdot \Delta_T^0 D_q^h}{\sum_q e_q^2 \cdot q \cdot D_q^h}$$

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

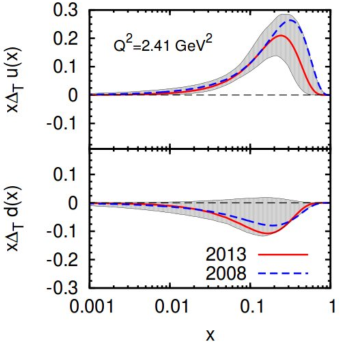
Sivers process ($\phi_S = \phi_h - \phi_S$, correlation of $\perp$ nucleon spin with k_T of unpolarised q):

related to L_q in the proton. Fundamental !

Results for the Collins asymmetry for protons



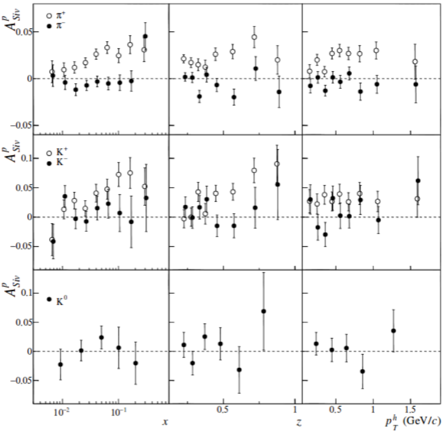
COMPASS, Phys.Lett. B744 (2015) 250



M. Anselmino et al., Phys.Rev. D87 (2013) 094019

- Collins asymmetries for proton measured for +/– unidentified and identified hadrons...
- ...are large at $x \gtrsim$ 0.03 and consistent with HERMES (in spite of different Q^2!)
- but negligible for the deuteron
- COMPASS data on p,d + HERMES data on p + BELLE on e^+e^-: $\Longrightarrow \Delta_T u,\ \Delta_T d$
- Transversity also obtained from 2-hadron asymmetries (and "Interference Fragmentation Function")

Results for the Sivers asymmetry for protons



COMPASS, Phys.Lett. B744 (2015) 250

- Sivers asymmetries for proton measured for +/– identified hadrons are large for π^+, K$^+$...
- ...and even larger at smaller Q^2 (HERMES)
- COMPASS deuteron data show very small asymmetry

Other azimuthal asymmetries

SIDIS x-section

A.Kotzinian, Nucl. Phys. B441, 234 (1995).
Bacchetta, Diehl, Goeke, Metz, Mulders and Schlegel JHEP0702:093 (2007).

$$\frac{d\sigma}{dx\,dy\,dz\,dP_{hT}^2\,d\varphi_h\,d\psi} = \left[\frac{\alpha}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\right]\left(F_{UU,T}+\varepsilon F_{UU,L}\right)\times$$

$$\Big\{1+\cos\phi_h\left(\sqrt{2\varepsilon(1+\varepsilon)}A_{UU}^{\cos\phi_h}\right)+\cos 2\phi_h\left(\varepsilon A_{UU}^{\cos 2\phi_h}\right)$$

$$+\lambda\sin\phi_h\left(\sqrt{2\varepsilon(1-\varepsilon)}A_{LU}^{\sin\phi_h}\right)$$

$$+S_L\left[\sin\phi_h\left(\sqrt{2\varepsilon(1+\varepsilon)}A_{UL}^{\sin\phi_h}\right)+\sin 2\phi_h\left(\varepsilon A_{UL}^{\sin 2\phi_h}\right)\right]$$

$$+S_L\lambda\left[\sqrt{1-\varepsilon^2}A_{LL}+\cos\phi_h\left(\sqrt{2\varepsilon(1-\varepsilon)}A_{LL}^{\cos\phi_h}\right)\right]$$

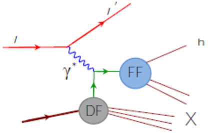
$$+S_T\left[\begin{array}{l}\sin(\phi_h-\phi_S)\left(A_{UT}^{\sin(\phi_h-\phi_S)}\right)\\+\sin(\phi_h+\phi_S)\left(\varepsilon A_{UT}^{\sin(\phi_h+\phi_S)}\right)\\+\sin(3\phi_h-\phi_S)\left(\varepsilon A_{UT}^{\sin(3\phi_h-\phi_S)}\right)\\+\sin\phi_S\left(\sqrt{2\varepsilon(1+\varepsilon)}A_{UT}^{\sin\phi_S}\right)\\+\sin(2\phi_h-\phi_S)\left(\sqrt{2\varepsilon(1+\varepsilon)}A_{UT}^{\sin(2\phi_h-\phi_S)}\right)\end{array}\right]$$

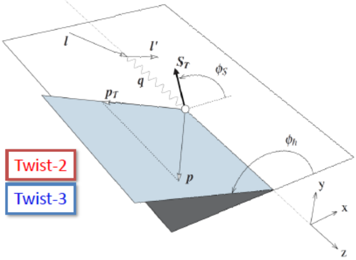
$$+S_T\lambda\left[\begin{array}{l}\cos(\phi_h-\phi_S)\left(\sqrt{1-\varepsilon^2}A_{LT}^{\cos(\phi_h-\phi_S)}\right)\\+\cos\phi_S\left(\sqrt{2\varepsilon(1-\varepsilon)}A_{LT}^{\cos\phi_S}\right)\\+\cos(2\phi_h-\phi_S)\left(\sqrt{2\varepsilon(1-\varepsilon)}A_{LT}^{\cos(2\phi_h-\phi_S)}\right)\end{array}\right]\Big\}$$

SSA ↑ ↓ DSA

Twist-2

Twist-3



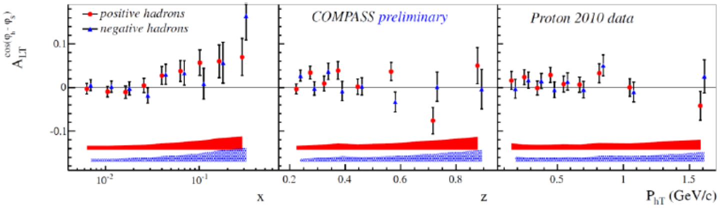


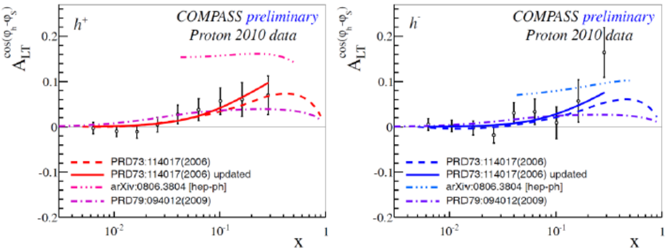
$$A_{U(L),T}^{w(\varphi_h,\varphi_s)}=\frac{F_{U(L),T}^{w(\varphi_h,\varphi_s)}}{F_{UU,T}+\varepsilon F_{UU,L}};\quad \varepsilon=\frac{1-y-\frac{1}{4}\gamma^2y^2}{1-y+\frac{1}{2}y^2+\frac{1}{4}\gamma^2y^2},\quad \gamma=\frac{2Mx}{Q}$$

22 October 2014 Bakur Parsamyan 8

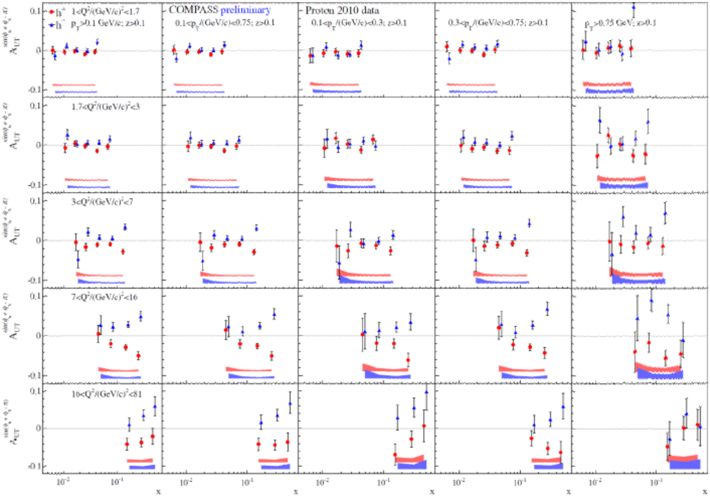
Example of TSA: $A_{LT}^{\cos(\phi_h-\phi_s)}$ sensitive to g_{1T}

- g_{1T}: the only T-even, chiral-even, off-diagonal, twist-2 TMD





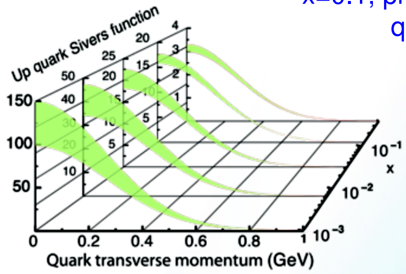
Multidimensional analyses: Collins asym. 3D (Q^2, p_T, x), $z > 0.1$

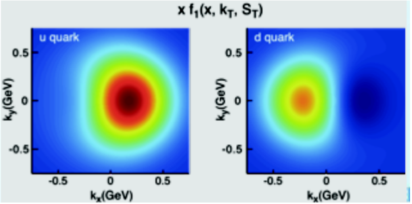


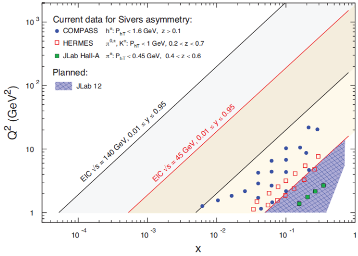
$\Longleftarrow$ DY!

EIC: up and down quark Sivers function

x=0.1, proton ⊥ polarised along y, moving along z
quark “flow” in a nucleon





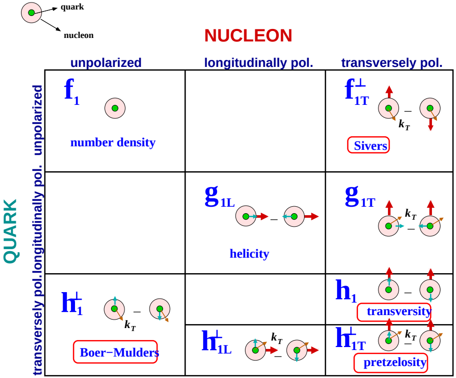


⟸ EIC acceptance for Sivers meas.

From “White paper”, arXiv:1212.1701

Outline

Partonic structure of the nucleon; distribution functions

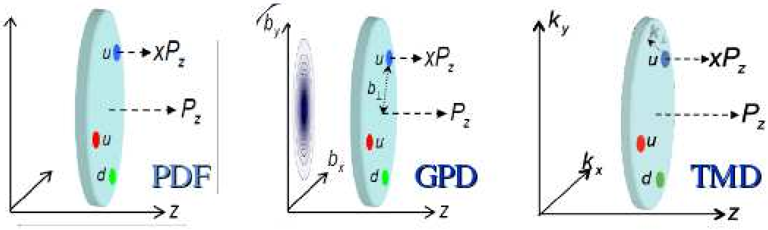


- In LT and considering k_{T}, 8 PDF describe the nucleon
- QCD-TMD approach valid $k_{\mathrm{T}} \ll \sqrt{Q^2}$
- After integrating over k_{T} only 3 survive: f_1, g_1, h_1
- TMD accessed in SIDIS and DY by measuring azimuthal asymmetries
- SIDIS: e.g. $A_{\mathrm{Sivers}} \propto$ PDF $\otimes$FF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

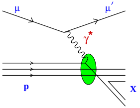
$$h_1^{\perp}(\mathrm{SIDIS}) = -h_1^{\perp}(\mathrm{DY}) \qquad f_{1\mathrm{T}}^{\perp}(\mathrm{SIDIS}) = -f_{1\mathrm{T}}^{\perp}(\mathrm{DY})$$

- 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

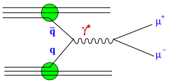
Transverse Momentum Dependent (TMD) distributions



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



SIDIS
Obs.: final state interactions!



DY
Obs.: initial state interactions!

Nucleon TMD PDFs accessed via SIDIS and Drell-Yan asymmetries

SIDIS $\ell^{\rightarrow} N^{\uparrow}$	Nucelon TMD PDF	Drell-Yan $\pi N^{\uparrow}$ (LO)
$A_{UU}^{\cos 2\phi_h}$, $A_{UU}^{\cos\phi_h}$	$h_1^{\perp q}$ - "Boer-Mulders"	$A_U^{\cos 2\varphi_{CS}}$
$A_{UT}^{\sin(\phi_h-\phi_s)}$, $A_{UT}^{\sin\phi_s}$, $A_{UT}^{\sin(2\phi_h-\phi_s)}$	$f_{1T}^{\perp q}$ - "Sivers"	$A_T^{\sin\varphi_S}$
$A_{UT}^{\sin(\phi_h+\phi_s-\pi)}$, $A_{UT}^{\sin\phi_s}$	h_1^q - "Transversity"	$A_T^{\sin(2\varphi_{CS}-\varphi_S)}$
$A_{UT}^{\sin(3\phi_h-\phi_s)}$, $A_{UT}^{\sin(2\phi_h-\phi_s)}$	$h_{1T}^{\perp q}$ - "Pretzelosity"	$A_T^{\sin(2\varphi_{CS}+\varphi_S)}$
$A_{LT}^{\cos(\phi_h-\phi_s)}$, $A_{LT}^{\cos\phi_s}$, $A_{LT}^{\cos(2\phi_h-\phi_s)}$	g_{1T}^q - "Worm-Gear" (T)	Double-polarized DY

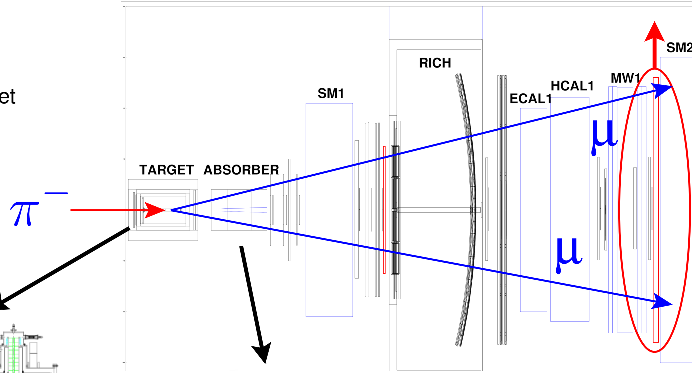
Color code:

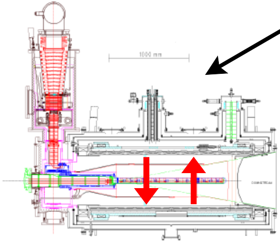
LO asymmetries: twist 2 TMDs $\otimes$ FFs

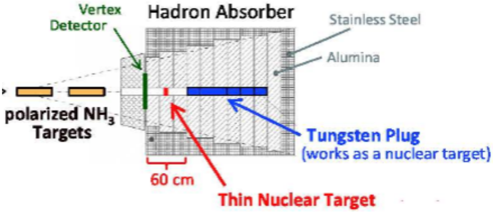
HT asymmetries

Drell–Yan @ COMPASS: experimental requirements

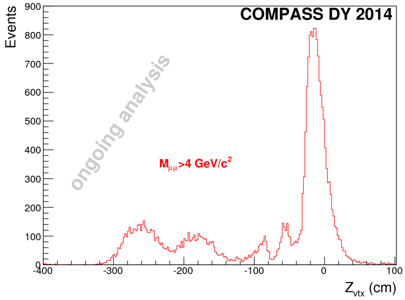
- intense π beam (up to 10^9/spill)
- hadron absorber downstream target
- di-muon trigger

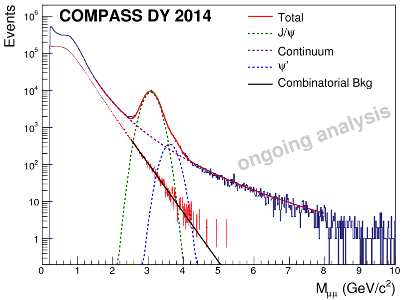


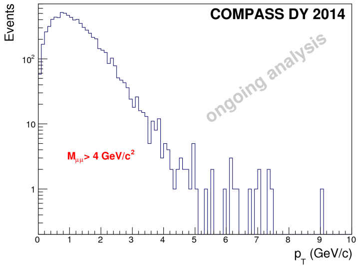


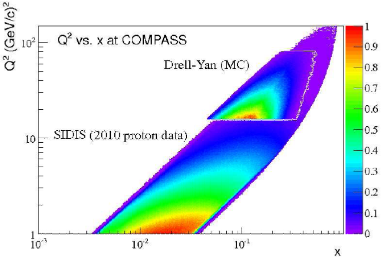


Drell–Yan @ COMPASS: results from 2014 pilot run







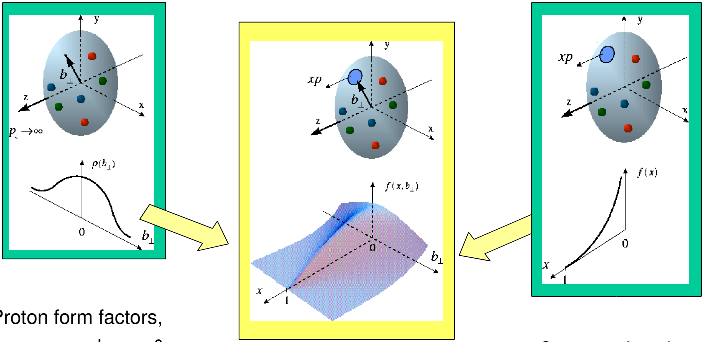


DY & SIDIS have overlapping acceptance!

Outline

3D picturing of the proton *via* GPD

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



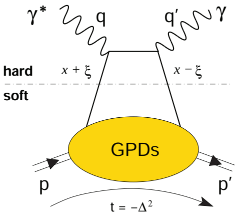
Proton form factors, transverse charge & current densities

Correlated quark momentum and helicity distributions in transverse space - GPDs

Structure functions, quark longitudinal momentum & helicity distributions

After V.D. Volker, LANL 2007

Access GPD through the DVCS/DVMP mechanism

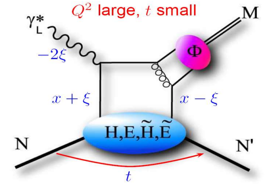


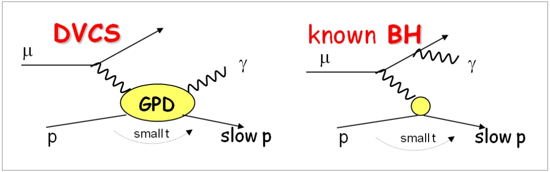
$Q^2 \to \infty$,
fixed $x_{\mathrm{B}}, t \implies |t|/Q^2$ small

- 4 GDPs ($H, E, \widetilde{H}, \widetilde{E}$) for each flavour and for gluons plus 4 chiral odd ones ($H_T, E_T, \widetilde{H}_T, \widetilde{E}_T$)
- DVMP: 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 $x \neq x_{\mathrm{B}}$!
- $H, \widetilde{H}$ 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: $J_z^q = \frac{1}{2}\int dx\, x\,[H^q(x,\xi,t=0) + E^q(x,\xi,t=0)] = \frac{1}{2}\Delta\Sigma + L_z^q$ (X. Ji)

DVCS/DVMP: $\mu p \to \mu p \gamma(M)$; observables

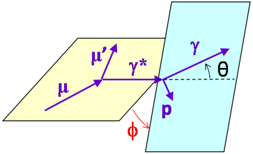




$$\mathrm{d}\sigma^{\mu p\to\mu p\gamma} = \mathrm{d}\sigma^{\mathrm{BH}} + (\mathrm{d}\sigma^{\mathrm{DVCS}}_{\mathrm{unpol}} + P_\mu \mathrm{d}\sigma^{\mathrm{DVCS}}_{\mathrm{pol}}) + e_\mu(\mathrm{Re}I + P_\mu \mathrm{Im}I)$$

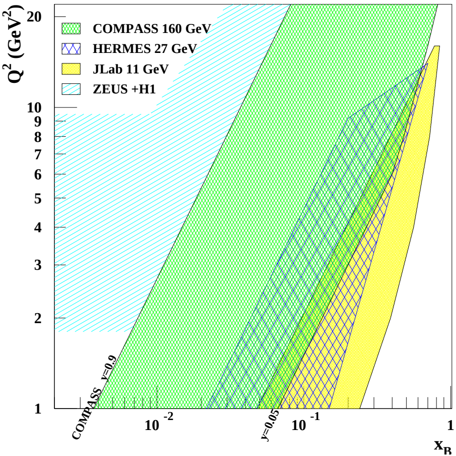
Observables (Phase 1):

- $S_{\mathrm{CS,U}} \equiv \mu^{+\leftarrow} + \mu^{-\rightarrow} = 2\left(\mathrm{d}\sigma^{\mathrm{BH}} + \mathrm{d}\sigma^{\mathrm{DVCS}}_{\mathrm{unpol}} + e_\mu P_\mu \mathrm{Im}I\right)$
- $D_{\mathrm{CS,U}} \equiv \mu^{+\leftarrow} - \mu^{-\rightarrow} = 2\left(P_\mu \mathrm{d}\sigma^{\mathrm{DVCS}}_{\mathrm{pol}} + e_\mu \mathrm{Re}I\right)$
- $A_{\mathrm{CS,U}} \equiv \dfrac{\mu^{+\leftarrow} - \mu^{-\rightarrow}}{\mu^{+\leftarrow} + \mu^{-\rightarrow}} = \dfrac{D_{\mathrm{CS,U}}}{S_{\mathrm{CS,U}}}$
- 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 $(F_1 H)$; H dominance @ COMPASS kin.



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

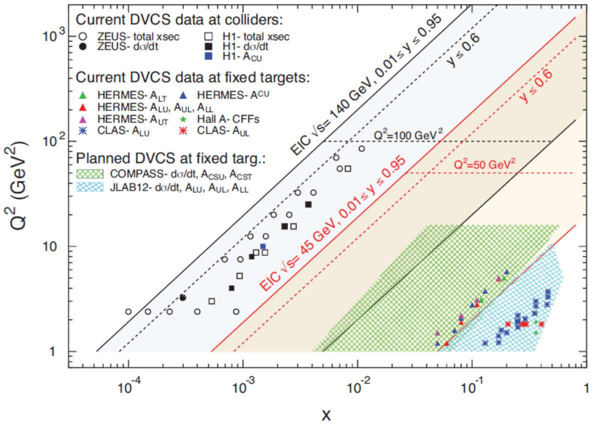
GPD at COMPASS: data taking in 2016-2017



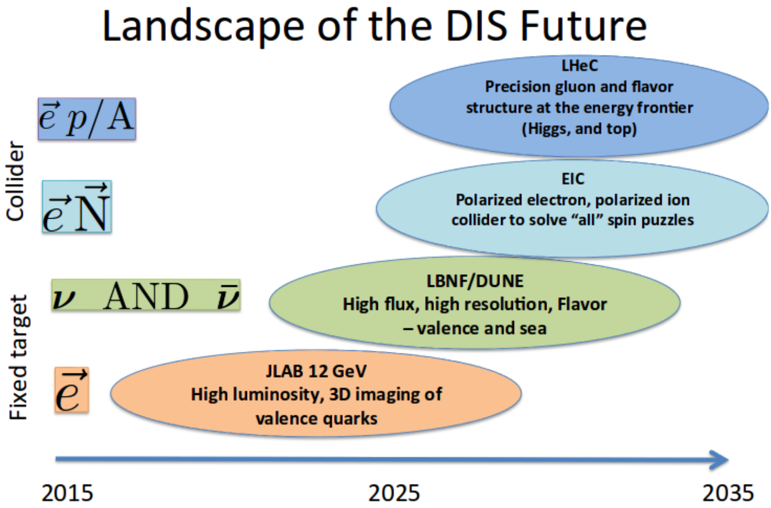
- CERN high energy muon beam
  - 100 - 190 GeV
  - 80% polarisation
  - $\mu^{+\leftarrow}$ and $\mu^{-\rightarrow}$ beams
- Kinematic range
  - between HERA and HERMES/JLab12
  - intermediate x (sea and valence)
- Separation
  - pure B-H @ low x_{B}
  - predominant DVCS @ high x_{B}
- Plans
  - DVCS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

Acceptance of present and EIC DVCS



From "White paper", arXiv:1212.1701


Landscape of the DIS Future
Collider
Fixed target
$\vec{e}\,p/A$
$\vec{e}\vec{N}$
ν AND $\bar{\nu}$
$\vec{e}$
LHeC
Precision gluon and flavor structure at the energy frontier (Higgs, and top)
EIC
Polarized electron, polarized ion collider to solve "all" spin puzzles
LBNF/DUNE
High flux, high resolution, Flavor – valence and sea
JLAB 12 GeV
High luminosity, 3D imaging of valence quarks
2015
2025
2035

Instead of a summary

P. Mulders, DIS2015

Spin Physics and Transverse Structure

Piet Mulders (Nikhef Theory Group/VU University Amsterdam)

Spin is a welcome complication in the study of partonic structure that has led to new insights, even if experimentally not all dust has settled, in particular on quark flavor dependence and gluon spin. At the same time it opened new questions on angular momentum and effects of transverse structure, in particular the role of the transverse momenta of partons. This provides again many theoretical and experimental challenges and hurdles. But it may also provide new tools in high-energy scattering experiments linking polarization and final state angular dependence.

D. Soper, DIS2015

- Thus the DIS experiments on which the parton distribution functions are largely based are like a keystone in the arch that supports the edifice of particle physics.