Spin 100-/1000+

news from the spin structure of the nucleon

Barbara Badelek
University of Warsaw

QCD and Diffraction
1000+

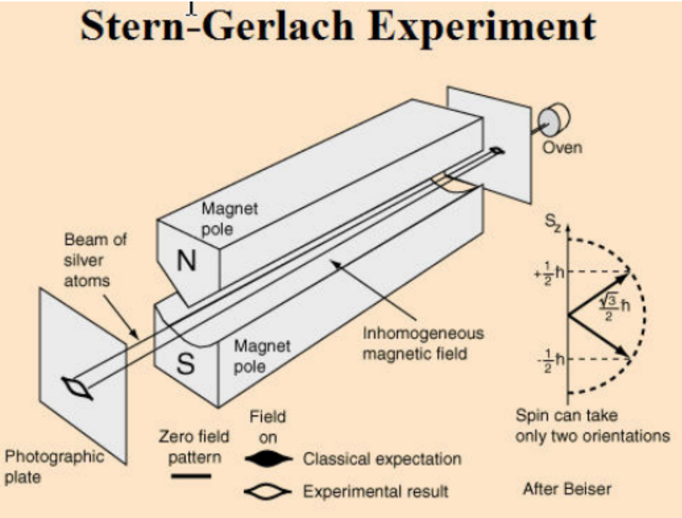
INP, Cracow, December 5 – 8, 2016

Outline

100-

Spin; Stern–Gerlach experiment (1922)

"Right experiment – wrong theory"

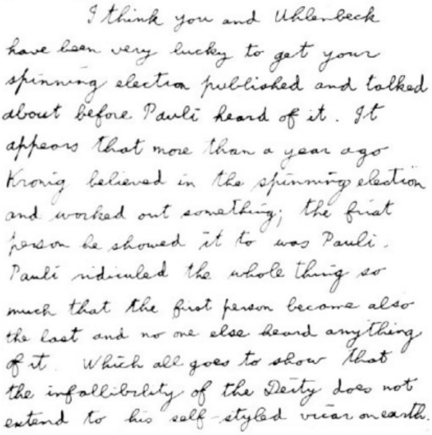


Electron spin

UPPSALA UNIVERSITET

Theory of the electron spin by Uhlenbeck & Goudsmit (1925)

George Uhlenbeck, Hendrik Kramers & Samuel Goudsmit



I think you and Uhlenbeck have been very lucky to get your spinning electron published and talked about before Pauli heard of it. It appears that more than a year ago Kronig believed in the spinning electron and worked out something; the first person he showed it to was Pauli. Pauli ridiculed the whole thing so much that the first person became also the last and no one else heard anything of it. Which all goes to show that the infallibility of the Deity does not extend to his self-styled vicar on earth.

Letter of B.L. Thomas to Sam Goudsmit (1926)

Read the story in:
http://lorentz.leidenuniv.nl/history/spin/goudsmit.html

Slide from Peter Oppeneer, UU 9

1000+

1988: European Muon Collaboration CERN ($\sim$100 members):

An Investigation of the Spin Structure of the Proton
in Deep Inelastic Muon–Proton Scattering

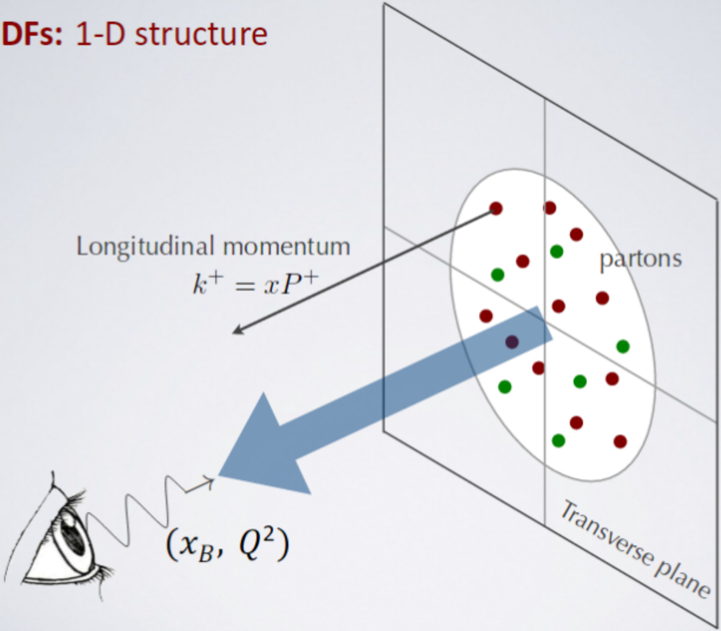
J. Ashman et al., Phys. Lett. B**206** (1988) 364

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

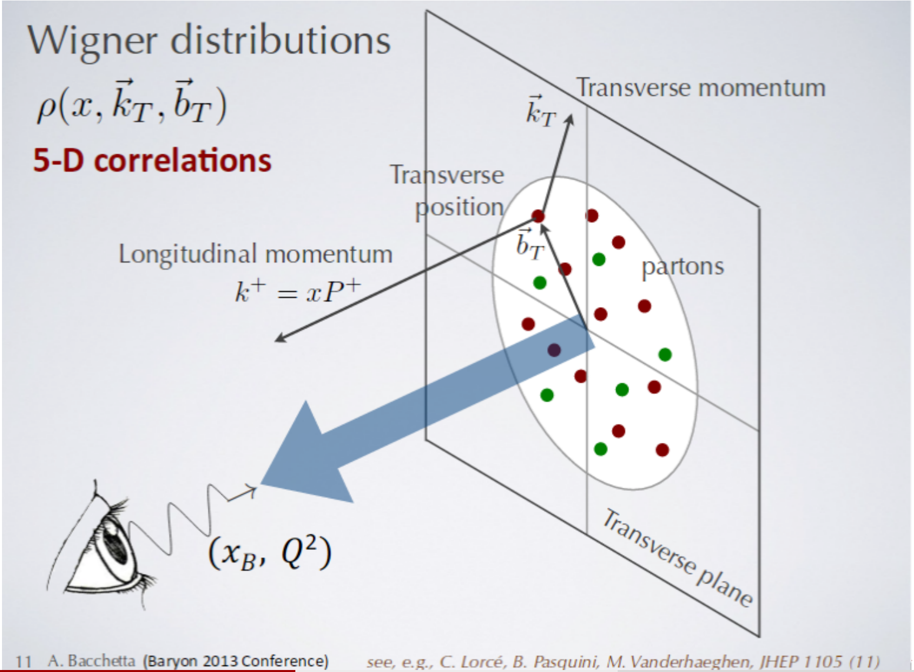
EMC measured: $\Delta\Sigma \sim 0.1!$

cited **1000+** times (exactly **1954**)

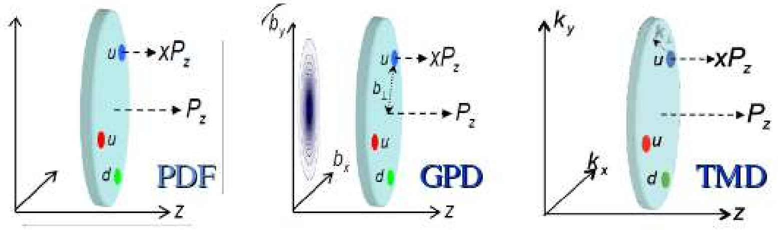
PDFs: 1-D structure



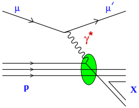
11 A. Bacchetta (Baryon 2013 Conference)


Wigner distributions
$\rho(x, \vec{k}_T, \vec{b}_T)$
5-D correlations
Transverse momentum
$\vec{k}_T$
Transverse position
$\vec{b}_T$
partons
Longitudinal momentum
$k^+ = xP^+$
(x_B, Q^2)
Transverse plane
11 A. Bacchetta (Baryon 2013 Conference)
see, e.g., C. Lorcé, B. Pasquini, M. Vanderhaeghen, JHEP 1105 (11)

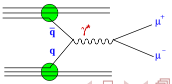
Parton distributions in the nucleon



- parton intrinsic k_{T} taken into account in TMD
- TMD related to quark angular momentum, L!
- GPD and TMD are NOT connected via the Fourier transform
- TMD may be studied in 2 ways e.g. at COMPASS:
  - semi-inclusive DIS (polarised muons on unpolarised/transversely polarised target)
  - Drell-Yan process (π beam on unpolarised/transversely polarised target)



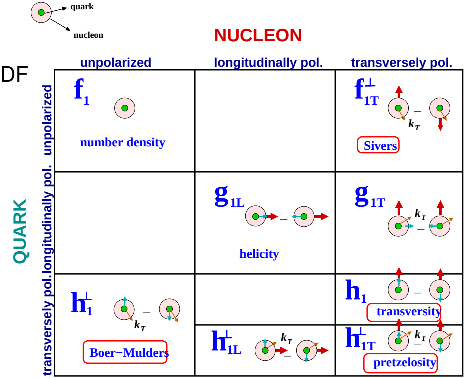
SIDIS
Obs.: final state interactions!



DY
Obs.: initial state interactions!

Partonic structure of the nucleon; distribution functions

- In LT and considering k_T,
  8 PDF describe the nucleon
  $\Longrightarrow$ Transverse Momentum Dependent PDF
- 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
  with different angular modulations
- SIDIS: e.g. $A_\mathrm{Sivers} \propto$ PDF $\otimes$FF
- DY: e.g. $A_\mathrm{Sivers} \propto$ PDF$^\mathrm{beam} \otimes$ PDF$^\mathrm{target}$



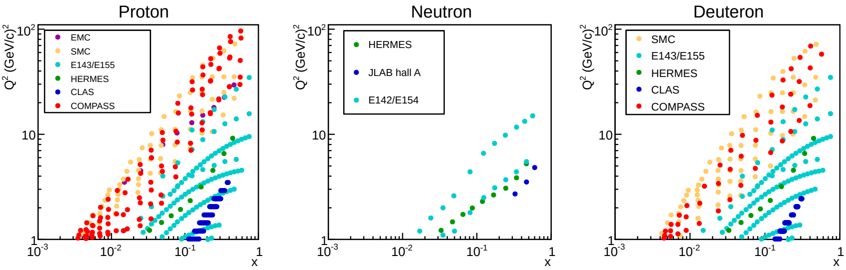
- OBS! Boer-Mulders and Sivers PDF are T-odd, i.e. process dependent

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

- OBS! transversity PDF is chiral-odd; may only be measured with another chiral-odd partner, e.g. fragmentation function.
- TMD parton distributions need TMD Fragmentation Functions!

The players @ $Q^2 > 1\ (\mathrm{GeV}/c)^2$

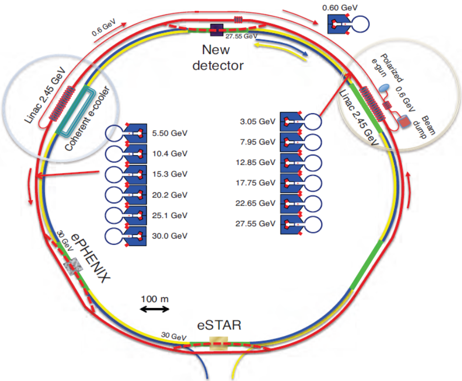
- Fixed target spin experiments:
  - JLab (Hall A, CLAS (Hall B)): polarised e of $\lesssim$ 12 GeV, polarised targets
  - CERN (COMPASS): polarised μ^+ of 160-200 GeV, polarised protons, deuterons
  - (completed) DESY (HERMES): polarised e of 27 GeV, polarised targets
- Collider spin experiments: BNL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



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

BNL

Electron beam facility needed
(inside RHIC tunnel)



JLab

ELIC + injector needed

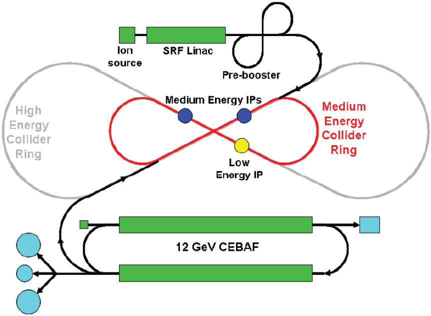


figure from The White Paper, arXiv:1212.1701

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

BNL

Electron beam facility needed
(inside RHIC tunnel)

JLab

2015 NSAC Long Range Plan:
We recommend a high-energy, high-luminosity polarized Electron Ion Collider as the highest priority for new facility construction following the completion of FRIB

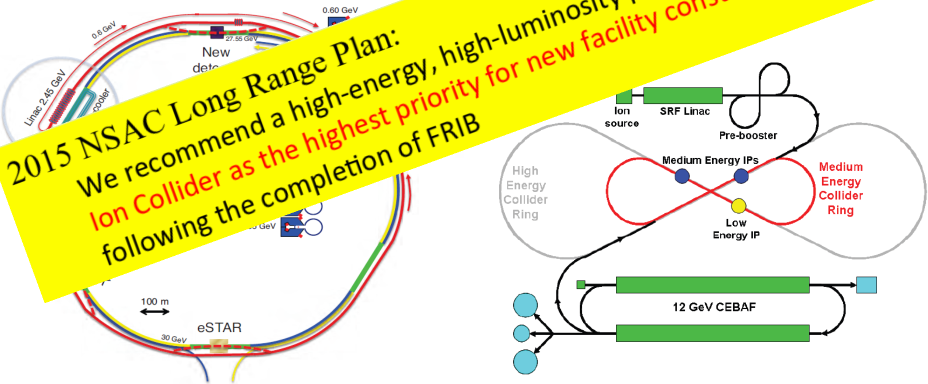


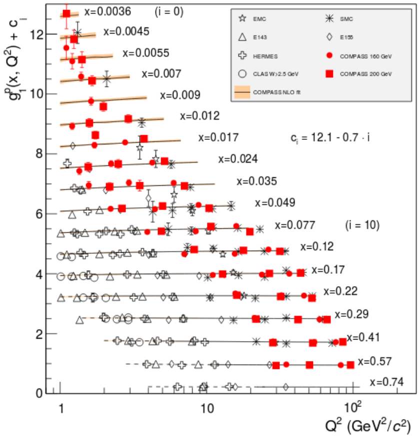
figure from The White Paper, arXiv:1212.1701

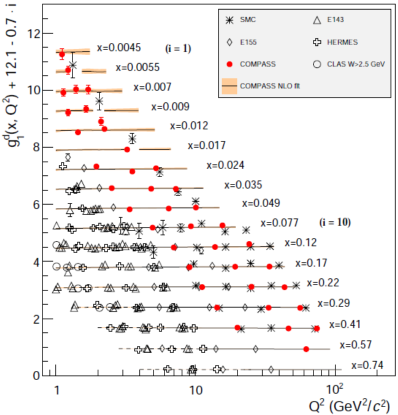
EIC: main features

- 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

$g_1^p(x,Q^2)$ and $g_1^d(x,Q^2)$, world data





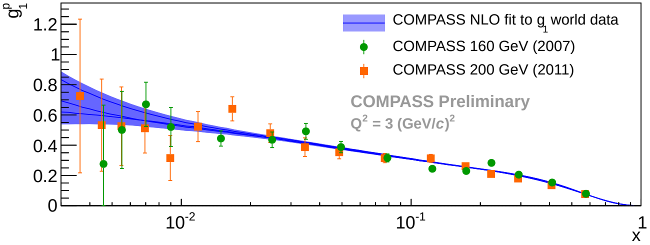
Curves: COMPASS NLO QCD fit for $W^2 > 10$ GeV^2 (dashed: extrapolation for $W^2 < 10$ GeV^2)

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

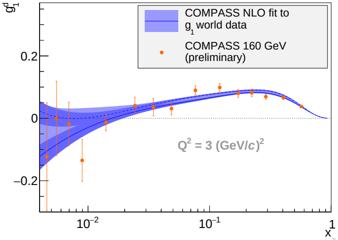
COMPASS, PLB 753 (2016) 18 COMPASS, submitted PLB

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



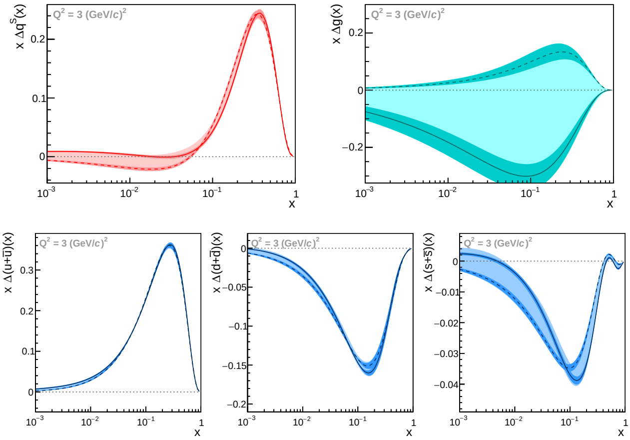
COMPASS, PLB 753 (2016) 18



COMPASS, submitted PLB

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

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

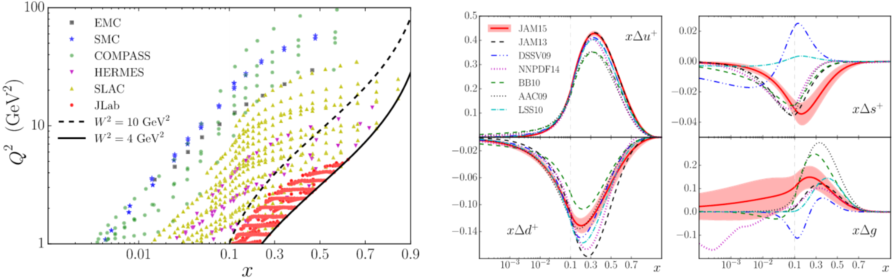


COMPASS, PLB 753 (2016) 18

JAM NLO fit to world inclusive data ($A_{\parallel}$, $A_{\perp}$)

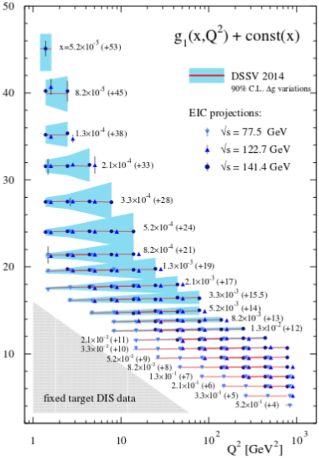
JAM: Jefferson Lab. Angular Momentum Collaboration

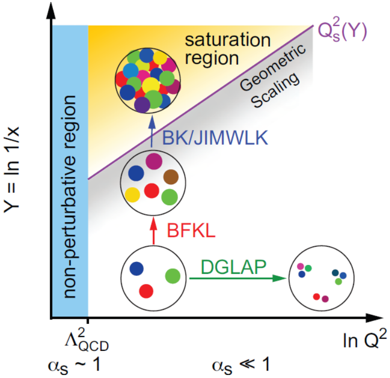
Included JLab data $W^2 > 4$ GeV^2 $\Longrightarrow$ reduced errors for valence & sea at $x > 0.1$



JAM, PRD 93 (2016) 074005

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





Errors statistical (EIC: expected, modest parameters); bands: from gluon helicity uncertainty

arXiv:1509.06489 “White paper”, arXiv:1212.1701

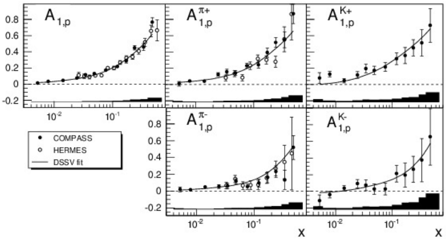
Semi-inclusive asymmetries and parton distributions

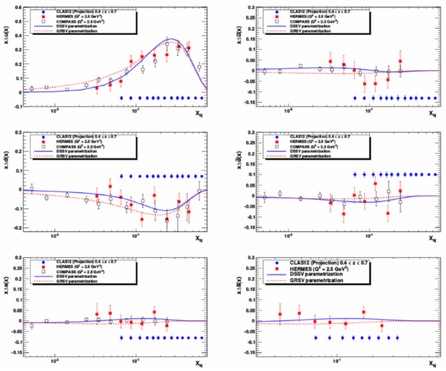
- COMPASS: measured on both proton and deuteron targets
  for identified, positive and negative pions and (for the first time) kaons

CLAS12, Update to E12-09-007

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

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

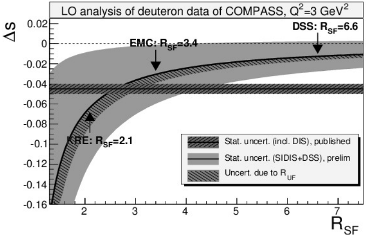


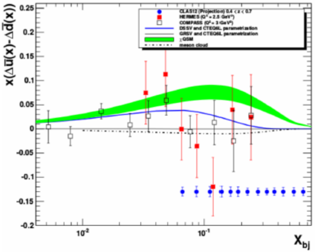


- COMPASS: LO DSS fragm. functions and LO unpolarised MRST assumed here.
- NLO parameterisation of DSSV describes the data well.

Polarisation of quark sea

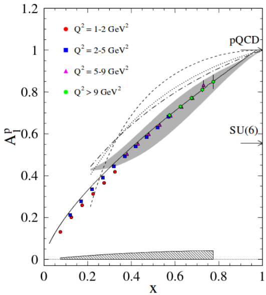
- Δs puzzle. Strange quark polarisation:
  $2\Delta S = \int_0^1 (\Delta s(x) + \Delta \bar{s}(x))dx = -0.09 \pm 0.01 \pm 0.02$ from incl. asymmetries + SU_3,
  while from semi-inclusive asymmetries it is compatible with zero
  but depends upon chosen fragmentation functions. Most critical: $R_{SF} = \frac{\int D_{\bar{s}}^{K^+}(z)dz}{\int D_u^{K^+}(z)dz}$
  $\Longrightarrow$ COMPASS extracts it from multiplicities.

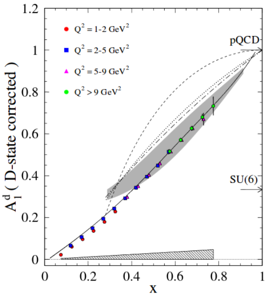




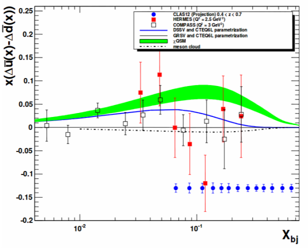
- The sea is not unsymmetric: COMPASS, Phys. Lett. B, **680** (2009) 217; ↑ CLAS12, Update to E12-09-007
  $\int_{0.004}^{0.3} \left[\Delta\bar{u}(x,Q^2) - \Delta\bar{d}(x,Q^2)\right] dx = 0.06 \pm 0.04 \pm 0.02$ @ $Q^2 = 3$ (GeV/c)^2
  Thus the data disfavour models predicting $\Delta\bar{u} - \Delta\bar{d}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

Nucleon spin structure @ high x: JLab at 12 GeV



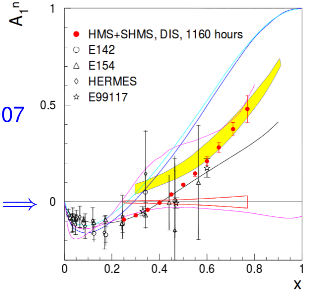


$\Longleftarrow$ Hall B (CLAS), E12-06-109
A_1^p and A_1^d



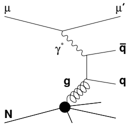
$\Longleftarrow$ Hall B (CLAS), E12-09-007
symmetry of the sea

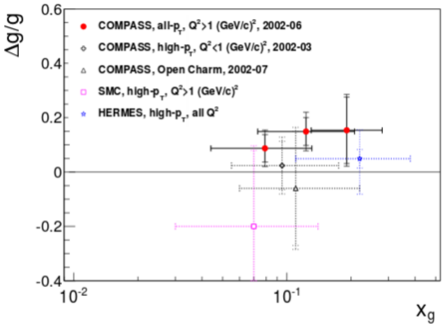
Hall C, E12-06-110, A_1^n $\Longrightarrow$

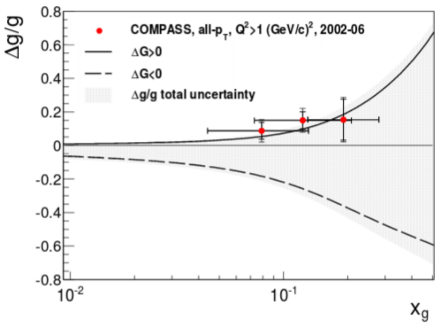


Direct measurements of $\Delta g(x)$

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.





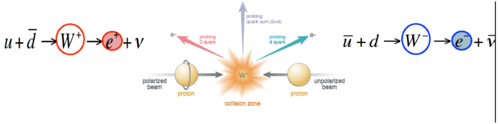


$$\Delta g/g = 0.113 \pm 0.038(\text{stat.}) \pm 0.035(\text{syst.}) \quad \text{at} \quad \langle Q^2 \rangle \approx 3\ \text{GeV}^2, \quad x_G \approx 0.10$$

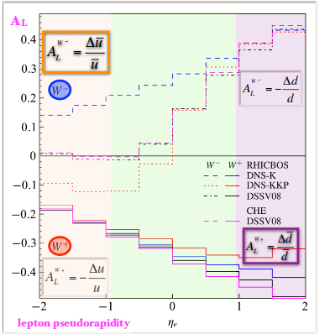
COMPASS, K. Klimaszewski, SPIN2016

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

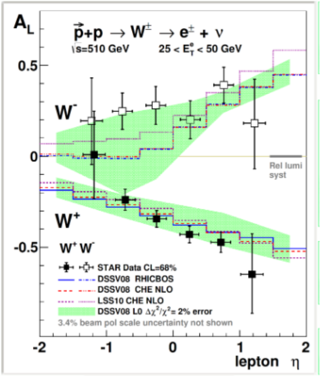
- Direct coupling to $q\bar{q}$ of interest
- Scale set by W mass
- Efficient spin separation
- Easy detection



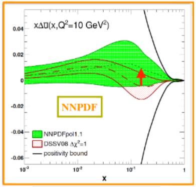
Cartoons from D.Gunarathne, DIS2015



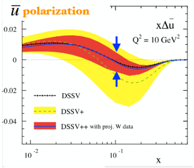
W A_L (η_e) 2012+2011



PRL 113,72301 (2014)

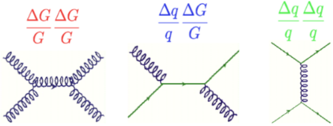


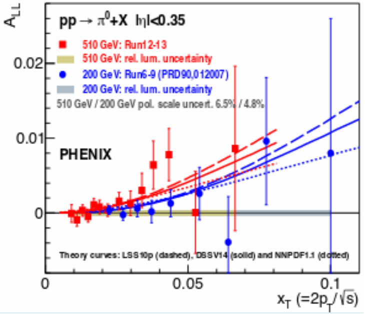
arXiv: 1403.0440

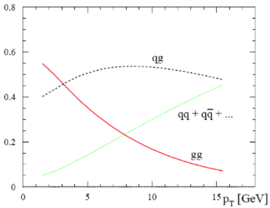


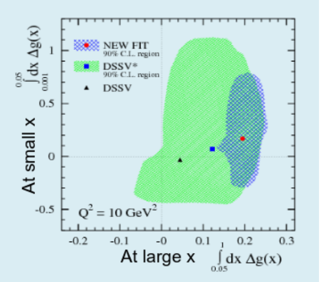
arXiv: 1304.0079

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









DSSV++ with 200 GeV data:

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

DSSV, PRL 113 (2014) 012001

Global NLO fits

Compilation by M.Stratmann (2015 Jlab Users Meeting)

overview of recent helicity PDF fits @ NLO

latest paper				uncertainties	features & focus
NNPDF 1406.5539 Ball, Forte, Guffanti, Nocera, Rodolfi, Rojo	✓	✗	✓ jets W's	100 MC replicas stat. approach	pp data w/ reweighing method
DSSV 0904.3821 1404.4293 de Florian, Sassot, MS, Vogelsang	✓	✓	✓ jets pions	Lagrange mult. (Hessian)	pp data fitted fast Mellin method
JAM 1403.3355 Jimenez-Delgado, Accardi, Avakian, Melnitchouk, Sato, ...	✓	✗	✗	Hessian	large x / JLab region pp soon
LSS 1010.0574 Leader, Sidorov, Stamenov	✓	✓	✗	Hessian	higher twist, Δs
BBS 1502.02517 1408.7057 Bourrely, Buccella, Soffer	✓	✗	✗	Hessian	statistical approach unpol/pol simult. fit
BB 1010.3113 Blumlein, Bottcher	✓	✗	✗	Hessian	α_s, higher twist
⋮		⋮			⋮
GRSV 9508347 0011215 Gluck, Reya, MS, Vogelsang	✓	✗	✗	✗	1st NLO analysis 1995

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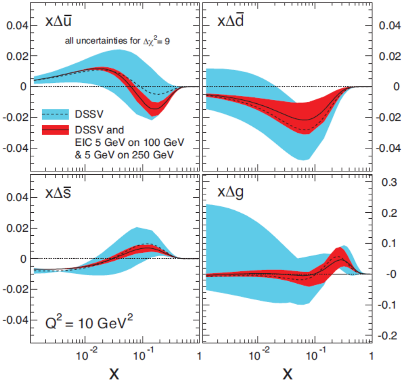
Moving towards NNLO

Higher Twist

Including more probes

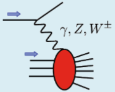
A. Bazilevsky, SPIN2016

EIC pseudo-data (inclusive and semi-inclusive)



- $\Delta g(x)$ from scaling violation
- $\Delta\bar{u}, \Delta\bar{d}, \Delta s$ from SIDIS
- Flavor separation at high Q² via CC DIS:

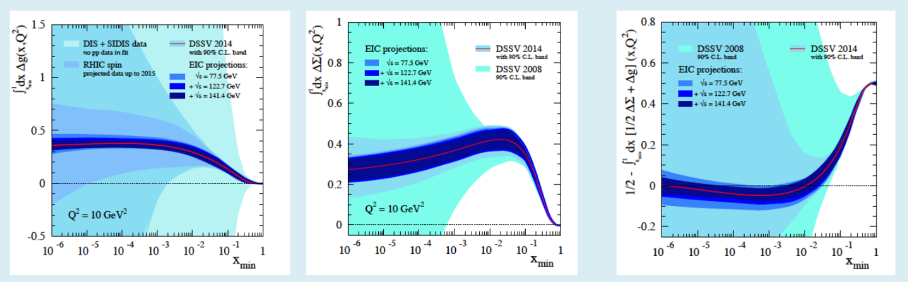
$$g_1^{W^+} = \Delta\bar{u} + \Delta d + \Delta\bar{c} + \Delta s$$
$$g_1^{W^-} = \Delta u + \Delta\bar{d} + \Delta c + \Delta\bar{s}$$
$$g_5^{W^+} = \Delta\bar{u} - \Delta d + \Delta\bar{c} - \Delta s$$
$$g_5^{W^-} = -\Delta u + \Delta\bar{d} - \Delta c + \Delta\bar{s}$$



From “White paper”, arXiv:1212.1701

E. Aschenauer, SPIN2016

Proton Spin Puzzle will be solved @ EIC ?



Aschenauer, Stratmann,Sassot arXiv : 1509.06489

Summary of the proton spin puzzle

- For the proton in $\hbar$ units:

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

$$\Delta\Sigma \sim 0.3, \qquad \Delta G \sim \text{sizable} \qquad \Delta L = ?$$

Do we approach a solution of the proton spin puzzle?

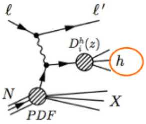
- Yes, but an independent measurement of ΔL needed;
  from the 3D (5D) analysis?
  plans at: COMPASS, BNL (USA), Jlab (USA).
- Electron-Ion Collider
  will faciliate in particular an accurate measurement of ΔG.

Outline

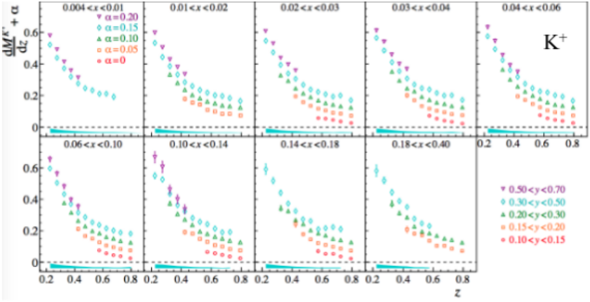
Charged hadron multiplicities; identified kaons

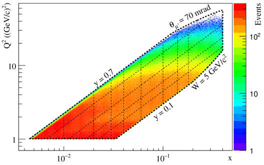
- Studied to measure fragmentation functions (FF), $D_q^h(z,Q^2)$ ($\Longrightarrow$ cf. Δs).
  At LO:

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



- 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).

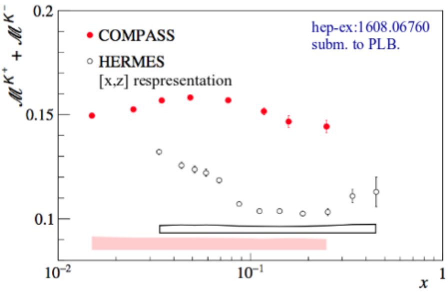




COMPASS, hep-ex:1608.06760

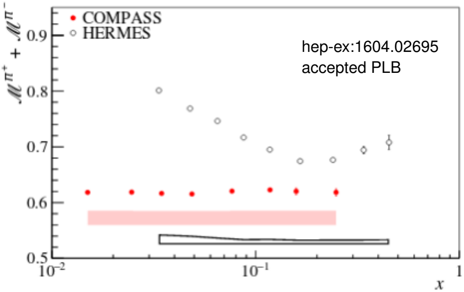
Charged hadron multiplicities; identified kaons and pions

Kaons:



HERMES, PRD 89 (2014)097101

pions:



HERMES, PRD 87 (2013) 074029

- Both π and K multiplicities on the ^{6}LiD (isoscalar) target
- strong discrepancies COMPASS/HERMES in the sum of multiplicities integrated over z, p_T, Q^2 (kinematics is similar)
- Ratio π^+/π^- is OK but K^+/K^- differ by $\sim$20% $\Longrightarrow$ under study!

Outline

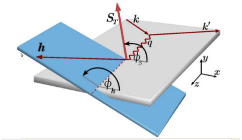
Properties of the transversity, $\Delta_T q(x)$ (or $h_1^q(x)$)

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

Examples (2 of 8) of measurements on a ⊥ polarised target

Collins asymmetry (first time by HERMES) $\Longrightarrow$ permitts to access transversity, $\perp$ polarised $q \Longleftrightarrow p_T^h$ of unpolarised h (asymmetry in the distribution of hadrons):

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



which in turn gives at LO and at collinear approach:

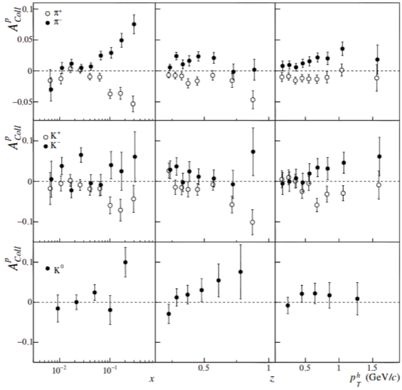
$$A_{Coll} \sim \frac{\sum_q e_q^2 \cdot \Delta_T q(x) \cdot \Delta_T^0 D_q^h(z, p_T^h)}{\sum_q e_q^2 \cdot q(x) \cdot D_q^h(z, p_T^h)}$$

But transverse fragmentation functions $\Delta_T^0 D_q^h$ (universal!) needed to extract $\Delta_T q(x)$ from the Collins asymmetry! Recently FF measured using data of Belle, BaBar and BES III.

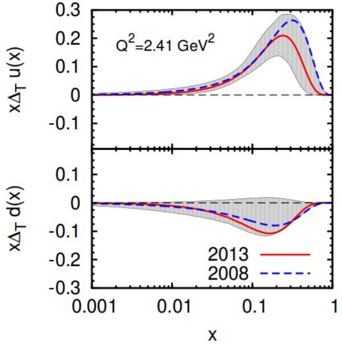
Sivers asymmetry ($\phi_S = \phi_h - \phi_S$, correlation of $\perp$ nucleon spin with k_T of unpolarised q): if $\neq 0$ then $L_q \neq 0$ in the proton. Fundamental !

$$A_{Siv} \sim \frac{\sum_q e_q^2 \cdot \Delta_0^T q(x, p_T^h/z) \cdot D_q^h(z)}{\sum_q e_q^2 \cdot q(x, p_T^h/z) \cdot D_q^h(z)}$$

Results for the Collins asymmetry for protons



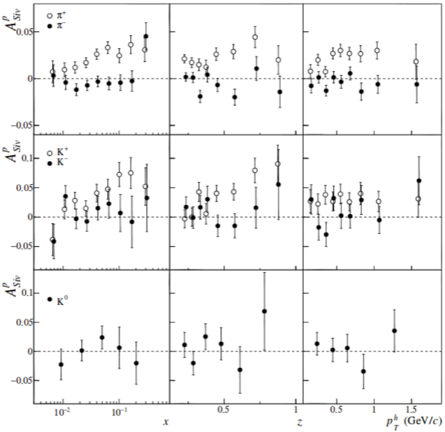
COMPASS, Phys.Lett. B744 (2015) 250



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 (2005) + 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

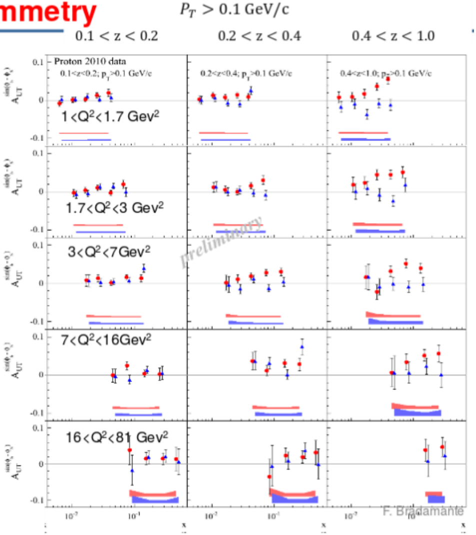
- Sivers asymmetries for proton measured for +/– identified hadrons are large for π^+, K$^+$...
- ...and even larger at smaller Q^2 (HERMES)
- COMPASS deuteron data show very small asymmetry

Multidimensional analyses: Sivers asymmetry $(x, Q^2; z, p_T)$

the Sivers asymmetry

multiD $(x, Q^2; z, P_T)$ results

an example

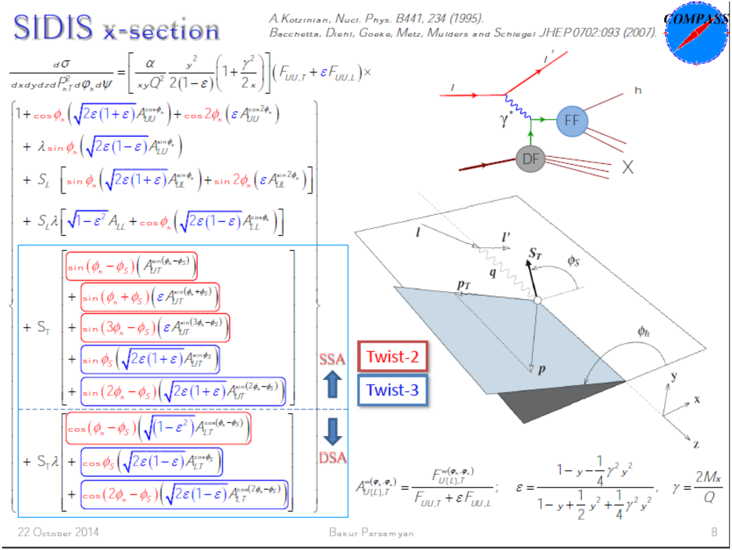


COMPASS

SPIN2014

SPIN2016

Other azimuthal asymmetries



Other azimuthal asymmetries...cont'd

SIDIS x-section

A.Kotzinian, Nucl. Phys. B441, 234 (1995).
Bacchetta, Diehl, Goeke, Metz, Mulders and Schlegel JHEP 0702:093 (2007).

COMPASS

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

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

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

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

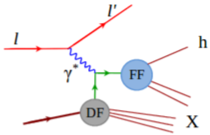
$$+S_L\lambda\left[\sqrt{1-\varepsilon^2}A_{LL}+\cos\phi_h\left(\sqrt{2\varepsilon(1-\varepsilon)}A_{LL}^{\cos\phi_h}\right)\right]$$

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

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

SSA ↑

↓ DSA



$A_{UT}^{\sin(\phi_h-\phi_s)} \propto f_{1T}^{\perp q}\otimes D_{1q}^{h}$

$A_{UT}^{\sin(\phi_h+\phi_s)} \propto h_{1}^{q}\otimes H_{1q}^{\perp h}$

$A_{UT}^{\sin(3\phi_h-\phi_s)} \propto h_{1T}^{\perp q}\otimes H_{1q}^{\perp h}$

$A_{UT}^{\sin(\phi_s)} \propto Q^{-1}\left(h_{1}^{q}\otimes H_{1q}^{\perp h} + f_{1T}^{\perp q}\otimes D_{1q}^{h}+\ldots\right)$

$A_{UT}^{\sin(2\phi_h-\phi_s)} \propto Q^{-1}\left(h_{1T}^{\perp q}\otimes H_{1q}^{\perp h} + f_{1T}^{\perp q}\otimes D_{1q}^{h}+\ldots\right)$

$A_{LT}^{\cos(\phi_h-\phi_s)} \propto g_{1T}^{q}\otimes D_{1q}^{h}$

$A_{LT}^{\cos(\phi_s)} \propto Q^{-1}\left(g_{1T}^{q}\otimes D_{1q}^{h}+\ldots\right)$

$A_{LT}^{\cos(2\phi_h-\phi_s)} \propto Q^{-1}\left(g_{1T}^{q}\otimes D_{1q}^{h}+\ldots\right)$

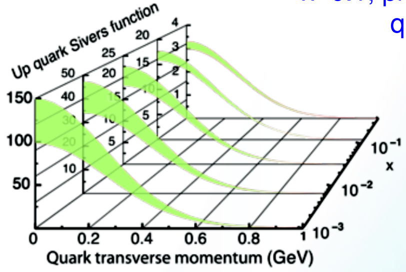
Twist-2

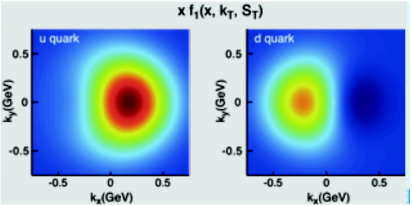
Twist-3

26 May 2015 Bakur Parsamyan 11

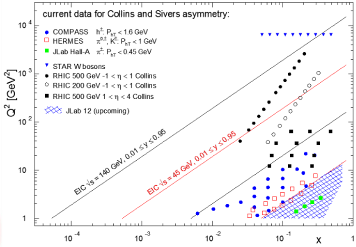
Sivers function at EIC

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





From “White paper”, arXiv:1212.1701



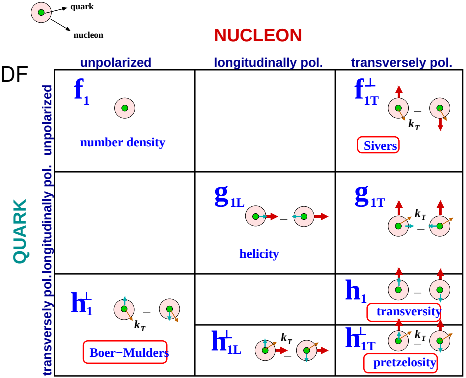
⟸ EIC acceptance for Sivers meas.

O. Eyser, SPIN2016

Outline

Partonic structure of the nucleon; distribution functions

- In LT and considering k_T,
  8 PDF describe the nucleon
  $\Longrightarrow$ Transverse Momentum Dependent PDF
- 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
  with different angular modulations
- 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

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

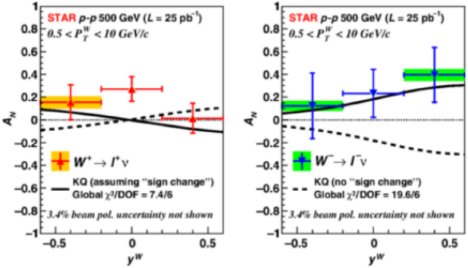
- OBS! transversity PDF is chiral-odd; may only be measured with another chiral-odd partner, e.g. fragmentation function.
- TMD parton distributions need TMD Fragmentation Functions!

Sivers sign change?

The STAR experiment at RHIC recently reported the measurement of A_N in $p^{\uparrow} + p \rightarrow W^{\pm}/Z^0$ at $\sqrt{s} = 500GeV$. One of the beams is polarized ($\langle P \rangle = 53\%$)

STAR, Phys.Rev.Lett. **116**, 132301 (2016)

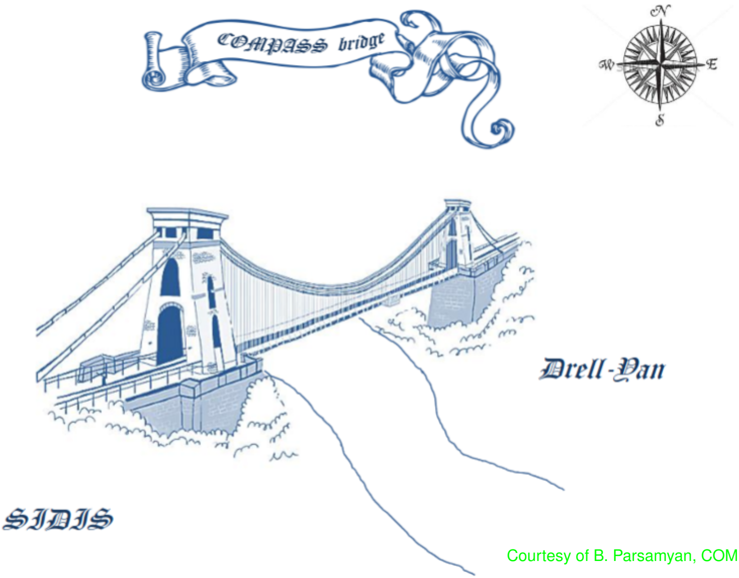
A_N compared to models where Sivers TMD is obtained from SIDIS data



- KQ: Z-B. Kang and J-W. Qiu, Phys.Rev.Lett. **103**, 172001 (2009)
- KQ model does not include TMD evolution effect. It does not take into account the very large difference between k_T at SIDIS and at DY.
- Data comparison with KQ model shows **preference for a sign change of Sivers TMD from DY wrt SIDIS**

★ Devika Gunarathne talk, tuesday morning

The COMPASS bridge



Courtesy of B. Parsamyan, COMPASS

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

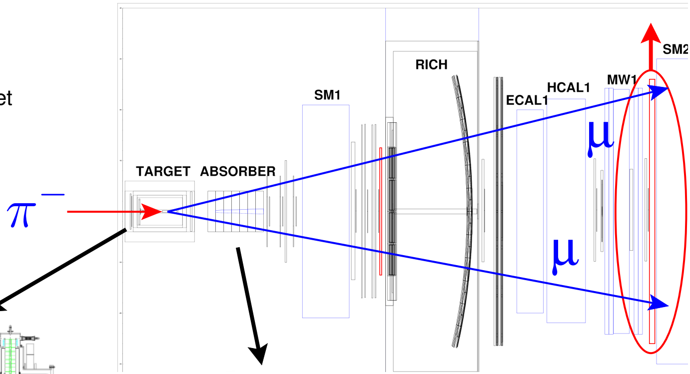
Color code:

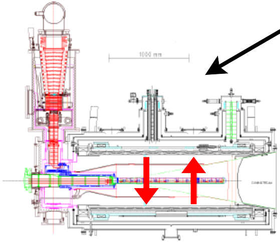
LO asymmetries: twist 2 TMDs $\otimes$ FFs

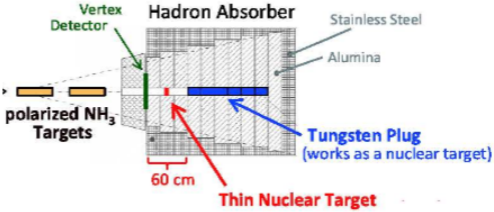
HT asymmetries

Drell–Yan @ COMPASS: experimental requirements

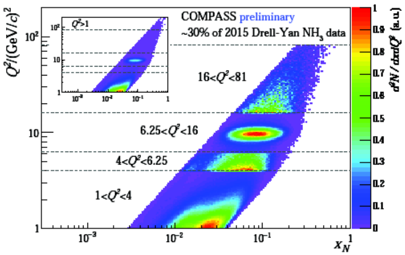
- intense π beam (up to 10^9/spill)
- hadron absorber downstream target
- di-muon trigger

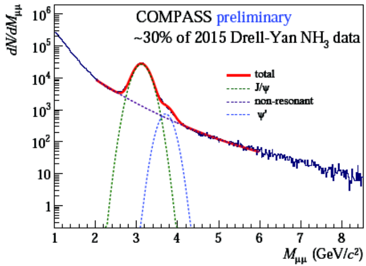


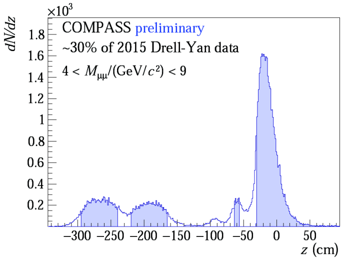


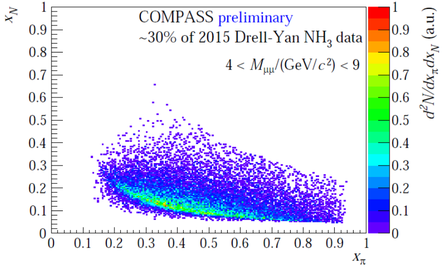


Drell–Yan @ COMPASS: preliminary results from 30% 2015 data









TSAs from (un)polarized DY – the future

After the check of sign of Sivers TMD in Drell-Yan wrt SIDIS, a new phase will come for studying in detail dependencies and TMD evolution. It will require input from both type of processes.

Several (un)polarized Drell-Yan experiments are being planned:

Experiment	type	$\sqrt{s}(GeV)$	when
STAR (RHIC)	collider; $p^{\uparrow}p$	510	2017
COMPASS (CERN)	fixed target; $\pi^{-}\ p^{\uparrow}$, $K^{-}p^{\uparrow}$	18.9	2018
E1039 (FNAL)	fixed target; $pp\uparrow$	15	2018-2019
J-PARC (KEK))	fixed target; $\pi^{-}p$	3-5.5	>2018
NICA (JINR)	collider; $p^{\uparrow}p^{\uparrow}$, $p^{\uparrow}d^{\uparrow}$	10-26	>2018
E1027 (FNAL)	fixed target; $p^{\uparrow}p$	15	>2020
PANDA (FAIR)	fixed target; $\bar{p}p$	5.5	>2022
J-PARC (KEK)	fixed target; K^{-}p, $\bar{p}p$	2.2-4.5	>2022
AFTER (CERN)	fixed target; $pp^{\uparrow}$	115	2025
COMPASS+ (CERN)	fixed target; $K^{-}p^{\uparrow}$, $\bar{p}p^{\uparrow}$	≈ 20	2025

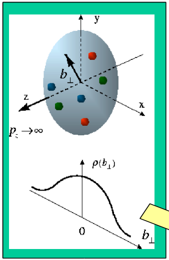
* List possibly not complete

SPIN 2016 C. Quintans, "Nucleon Spin Structure from Experiments using Drell-Yan Process" Page 32

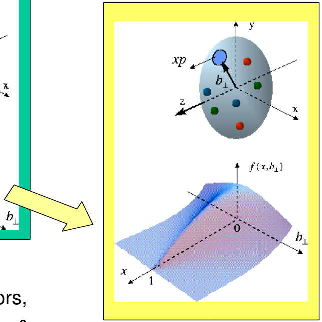
Outline

3D picturing of the proton *via* GPD

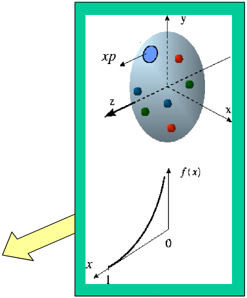
D. Mueller, X. Ji, A. Radyushkin, A. Belitsky, …
M. Burkardt, … Interpretation in impact parameter space



Proton form factors, transverse charge & current densities



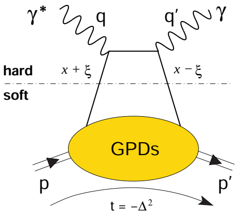
Correlated quark momentum and helicity distributions in transverse space - GPDs



Structure functions, quark longitudinal momentum & helicity distributions

After V.D. Volker, LANL 2007

Access GPD through the DVCS/DVMP mechanism

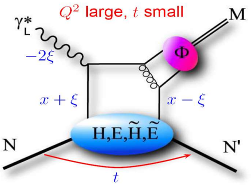


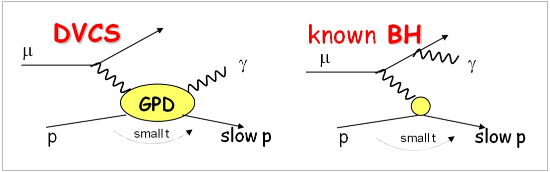
$Q^2 \to \infty$,
fixed $x_{\mathrm{B}}, t \implies |t|/Q^2$ small

- 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

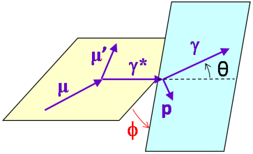




$$d\sigma^{\mu p \to \mu p \gamma} = d\sigma^{BH} + (d\sigma^{DVCS}_{unpol} + P_\mu d\sigma^{DVCS}_{pol}) + e_\mu (\mathrm{Re} I + P_\mu \mathrm{Im} I)$$

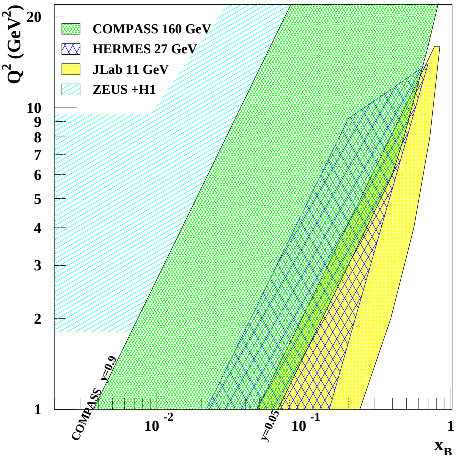
Observables (Phase 1):

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



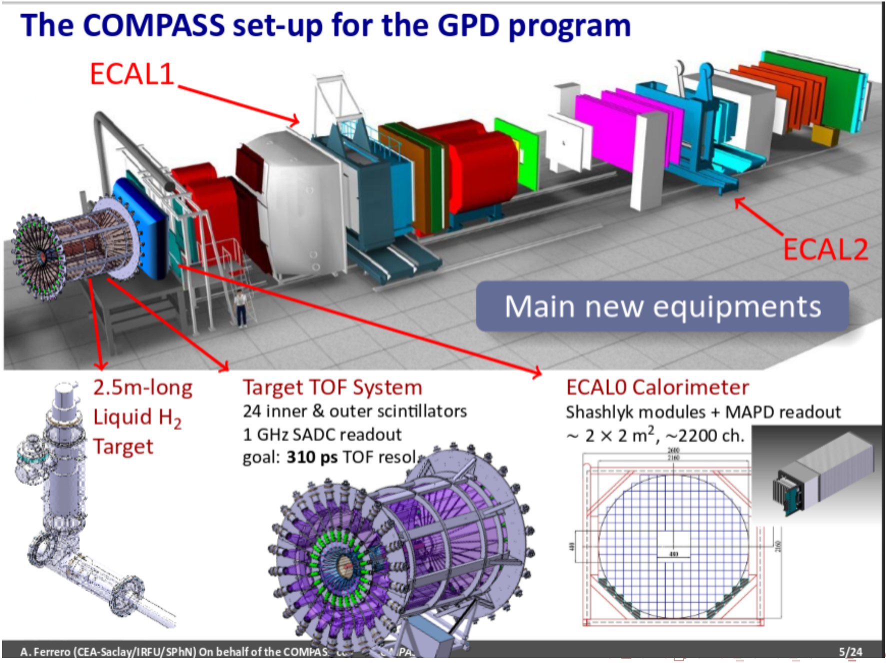
Analogously for transversely polarised target (Phase 2): $S_{CS,T}, D_{CS,T}, A_{CS,T} \Longrightarrow E$

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 $x_{\rm B}$
  - predominant DVCS @ high $x_{\rm B}$
- Plans
  - DVCS
  - DVMP
- Goals
  - from unpolarised target: H (Phase 1)
  - from $\perp$ polarised target: E (Phase 2)

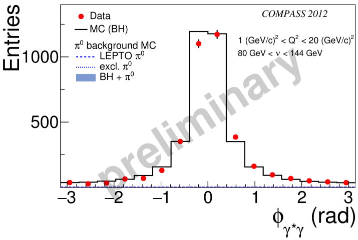
Test runs: 2008-9 and 2012; DVCS signal seen, full setup evaluated



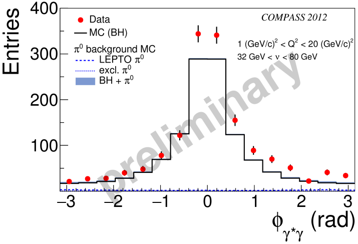
The COMPASS set-up for the GPD program
ECAL1
ECAL2
Main new equipments
2.5m-long
Liquid H2
Target
Target TOF System
24 inner & outer scintillators
1 GHz SADC readout
goal: 310 ps TOF resol.
ECAL0 Calorimeter
Shashlyk modules + MAPD readout
~ 2 × 2 m2, ~2200 ch.
A. Ferrero (CEA-Saclay/IRFU/SPhN) On behalf of the COMPASS
5/24

DVCS signal

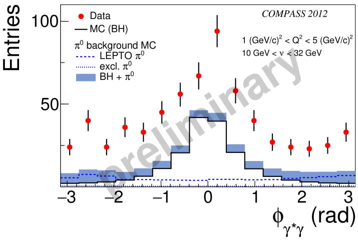
$0.005 < x < 0.01$

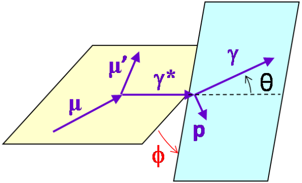


$0.001 < x < 0.03$



$x > 0.03$

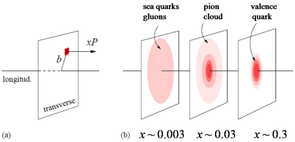




Plans for 2016–2017 run

- $S_{\mathrm{CS,U}}, D_{\mathrm{CS,U}}, A_{\mathrm{CS,U}}$ measured in 6 $x_{\mathrm{B}} \times$ 4 Q^2 bins as function of ϕ
  $\Longrightarrow$ determination of H with flavour separation
  (from VM production)

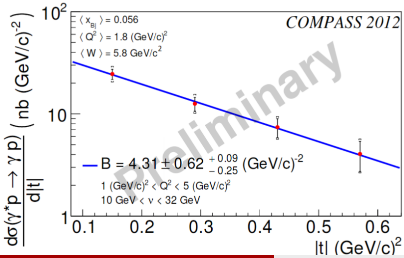
- Azimuthal dependence $A_{\mathrm{CS,U}}$ compared to models

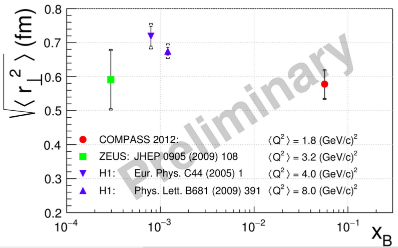


- Nucleon transverse imaging ("tomography"):

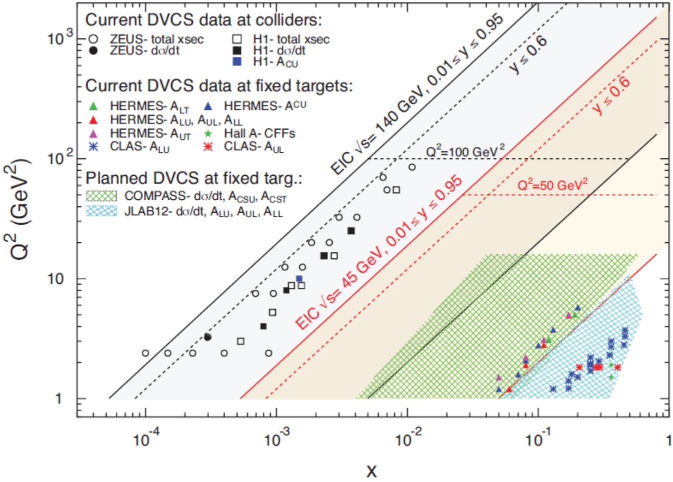
from $S_{CS,U} \Longrightarrow \frac{d\sigma^{\mathrm{DVCS}}}{dt} \propto e^{-B(x_{\mathrm{B}})|t|}$ where at low x_{B} : $B(x_{\mathrm{B}}) \approx \frac{1}{2}\langle r_{\perp}^2(x_{\mathrm{B}})\rangle$

(here a simple ansatz was assumed: $B(x_{\mathrm{B}}) = B_0 + 2\alpha' log \frac{x_0}{x_{\mathrm{B}}}$





Acceptance of present and EIC DVCS

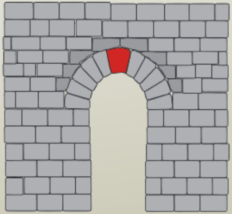


From "White paper", arXiv:1212.1701

Instead of a summary

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.



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.