Nucleon structure

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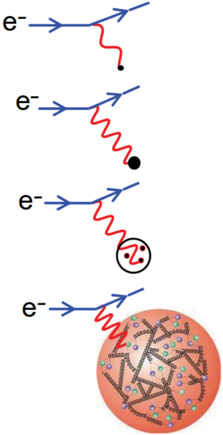
Workshop on
Frontiers and Careers in Photonuclear Physics

Paphos, 27–28 October 2019

Basics

Probing the structure of the proton

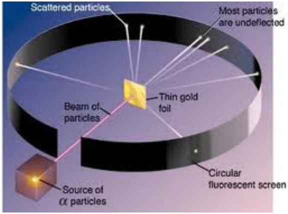
- At very low electron energies $\lambda \gg r_p$:
  the scattering is equivalent to that from a "point-like" spin-less object
- At low electron energies $\lambda \sim r_p$:
  the scattering is equivalent to that from a extended charged object
- At high electron energies $\lambda < r_p$:
  the wavelength is sufficiently short to resolve sub-structure. Scattering from constituent quarks
- At very high electron energies $\lambda \ll r_p$:
  the proton appears to be a sea of quarks and gluons.



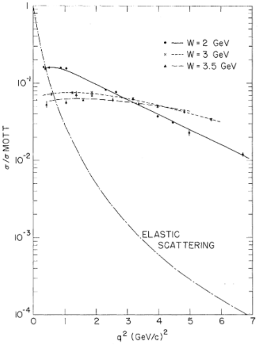
From: M.A. Thomson, Michaelmas Term 2011

A great example: studies of matter via its constituents

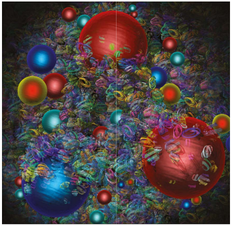
From Democritus to the present view of proton structure in terms of partons

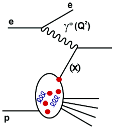


$\Longrightarrow$



$\Longrightarrow$





Deep Inelastic

ep $\rightarrow$ eX

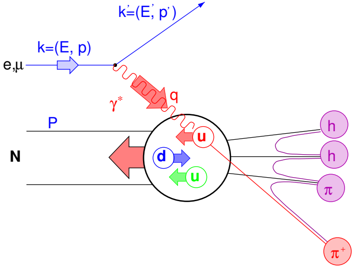
Scattering, DIS

E. Rutherford, 1910-1911

SLAC-MIT, PRL **23** (1969) 935

CERNCourier May 2019

Nucleon (spin) structure in DIS: $\vec{\mu} + \vec{\mathrm{N}} \rightarrow \mu' + \mathrm{X}$

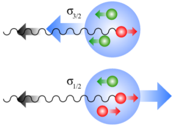


- $\dfrac{\mathrm{d}^2\sigma}{\mathrm{d}\Omega \mathrm{d}E'} = \dfrac{\alpha^2}{2Mq^4} \dfrac{E'}{E} L_{\mu\nu} W^{\mu\nu}$
- Symmetric part of $W^{\mu\nu}$ – unpolarised DIS, antisymmetric – polarised DIS
- Nominally $F_{1,2}$, $q(x,Q^2) \longrightarrow g_{1,2}$, $\Delta q(x,Q^2)$ where $q = q^+ + q^-$,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

Definitions of DIS variables...

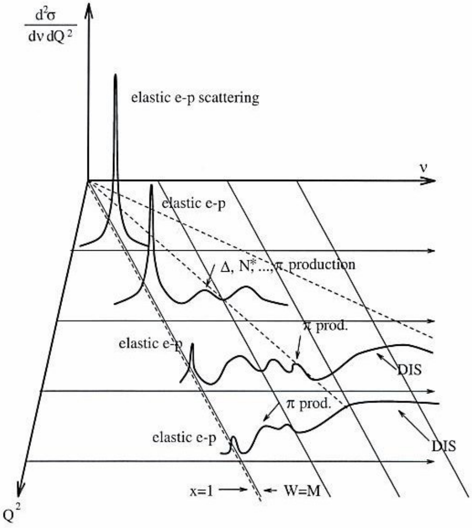
$Q^2 = -q^2$	γ^* virtuality
$x = Q^2/(2Pq)$	Bjorken variable
$y = Pq/(Pk)$	relative γ^* energy
$W = P + q$	γ^*-N cms energy

...and of the γ^*-N asymmetry (e.g. for γ^*-p):



$$A_1(x,Q^2) = \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}}$$

From elastic to (deep) inelastic electron - nucleon scattering



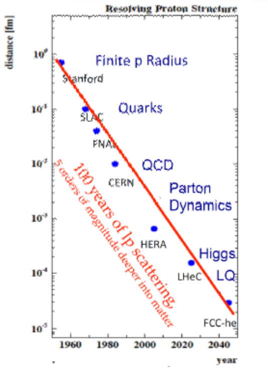
Radial, broken lines: x =const.
Parallel, continuous lines: W =const.

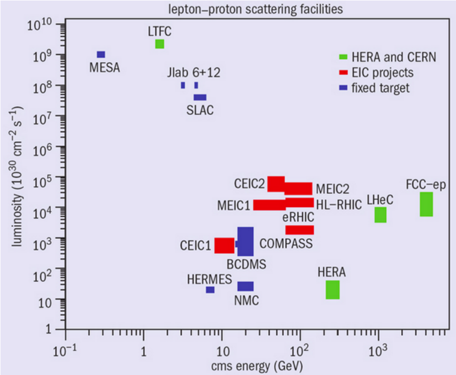
Low x – large parton (gluon) densities.
Low Q^2 – nonperturbative effects.

DIS = Deep Inelastic Scattering
(large Q^2, ν)
e + p $\rightarrow$ e′ + X

Machines: past, presence and future

finest microscopes, resolution as 1/Q





EIC

medium energy $\sqrt{s} \simeq 20 - 100\ \mathrm{GeV}$

high luminosity $10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$

wide range of nuclei from deuteron to heaviest(uranium/lead)

polarization of electron and nucleon beams

LHeC FCC-ep

high energy $\sqrt{s} \simeq 1 - 5\ \mathrm{TeV}$

high luminosity $10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$

electron ion scattering on lead

VHEeP

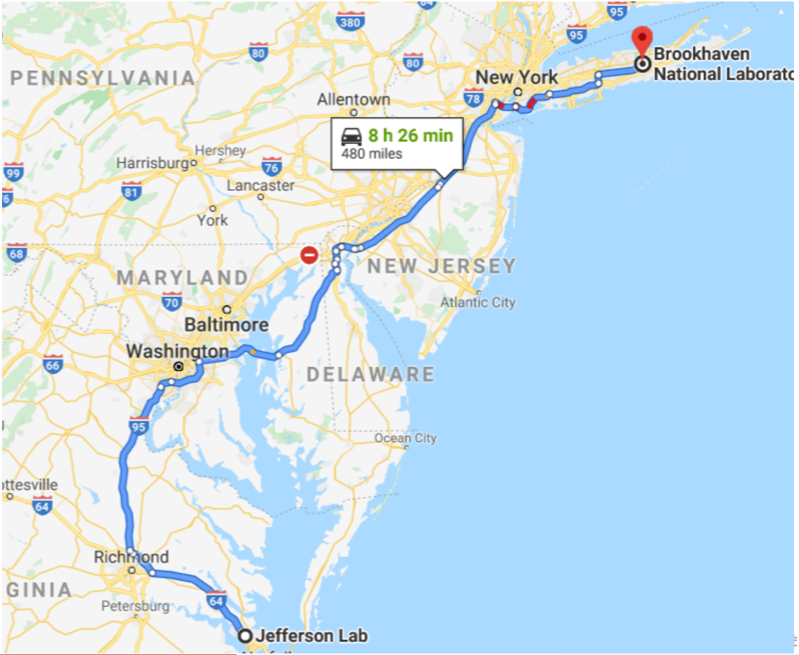
very high energy, $\sqrt{s}$ ~9 TeV
low luminosity, 10–100 pb^{-1}
electron–proton scattering

A.M. Cooper-Sarkar, Poetic7,2016; A. Stasto, Poetic7,2016; http://cerncourier.com/cws/article/cern/57304

> "New **directions** in science are **launched** by **new tools** much more often than by new concepts."
>
> *Freeman Dyson*

(Theorist, mathematician; IAS, Princeton)

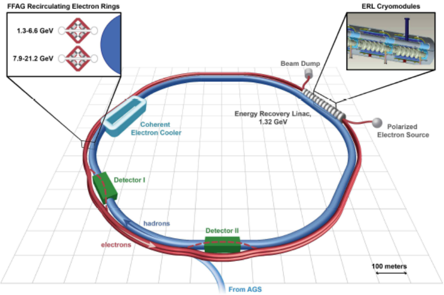
Electron Ion Collider, EIC


PENNSYLVANIA
New York
Brookhaven
National Laborato
Allentown
8 h 26 min
480 miles
Hershey
Harrisburg
Lancaster
York
NEW JERSEY
MARYLAND
Atlantic City
Baltimore
Washington
DELAWARE
Ocean City
ttesville
Richmond
GINIA
Petersburg
Jefferson Lab
380
80
95
78
76
99
81
68
70
66
64

EIC at BNL or JLab

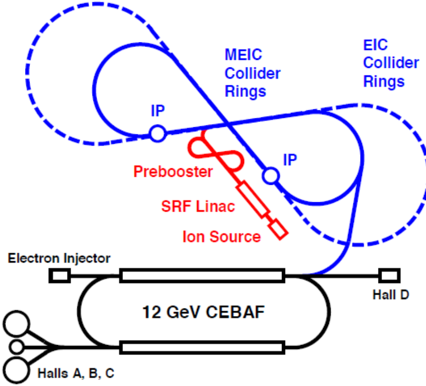
BNL (eRHIC)

Add energy recovery LINAC
(inside RHIC tunnel)



JLab (MEIC)

Add hadron rings “8” to CEBAF
(external)

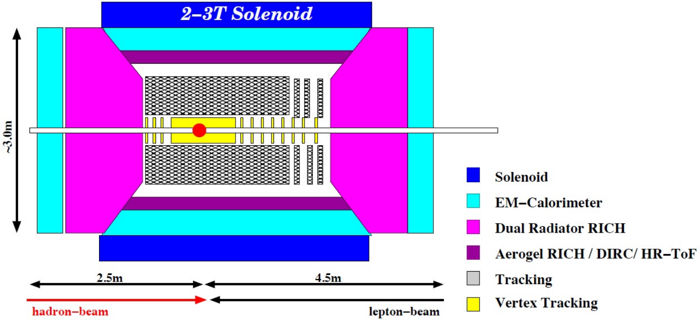


The White Paper, arXiv:1212.1701

EIC: main features

- Highly polarised ($\sim$ 70%) e, N beams
  (COMPASS: $P_\mu \sim$ 80%, $P_\mathrm{p} \sim$ 90%)
- ions from deuteron to uranium (lead ?)
- variable $\sqrt{s}$ from $\sim$ 20 GeV to $\sim$ 150 GeV
- high luminosity: $\sim 10^{33-34}$ cm^{-2} s^{-1} (cooling of hadronic beam !)
- more than one interaction region
- limits of current technology $\Longrightarrow$ R & D!
- staged realisation.

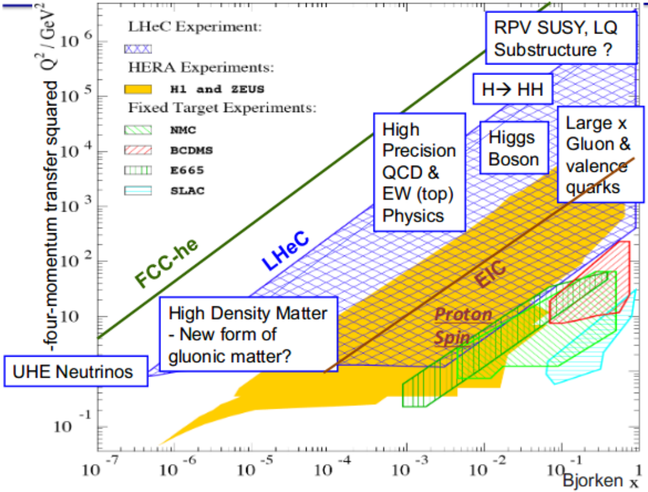
A dedicated EIC detector



- 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

New domain for ep colliders



HERA established the validity of pQCD (DGLAP) due to a very high lever arm in Q^2.

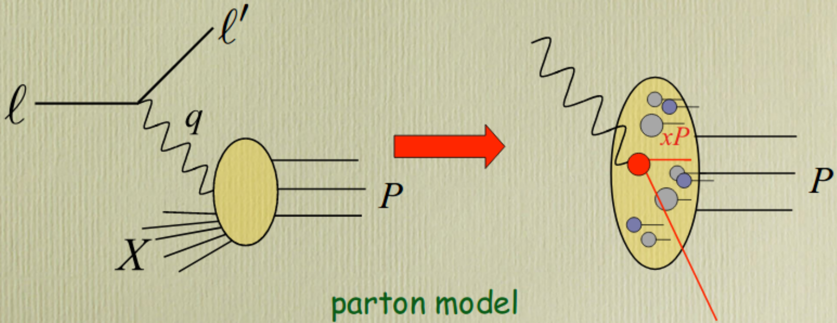
Extensions of both x and Q^2 ranges are crucial for new experiments and HEP theory developments!

Basics of QCD

$\Longrightarrow$ Parton Distribution Functions (PDFs)

R. P. Feynman, Proceedings of the 3rd Topical Conference on High Energy Collision of Hadrons, Stony Brook, N. Y. (1969), Gordon & Breach, pp 237-249, ISBN 978-0-677-13950-0

Phys. Rev. Lett. 23, 1415 – Published 15 December 1969



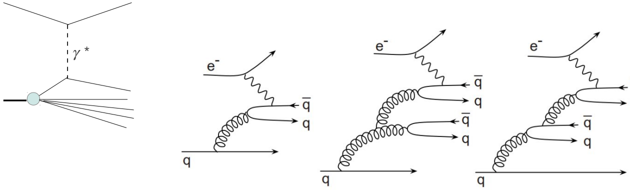
parton model

$$\frac{d\sigma^{\ell p \to \ell X}}{dx\, dQ^2} = \sum_q q(x)\, \frac{d\hat{\sigma}^{\ell q \to \ell q}}{dQ^2}$$

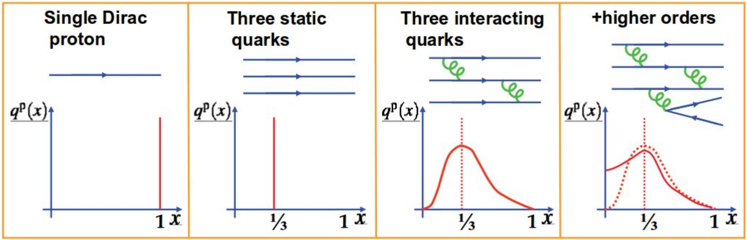
M. Anselmino, DIS2019

Strong vs electomagnetic interactions in DIS

Quark-Parton Model (QPM) becomes complicated...

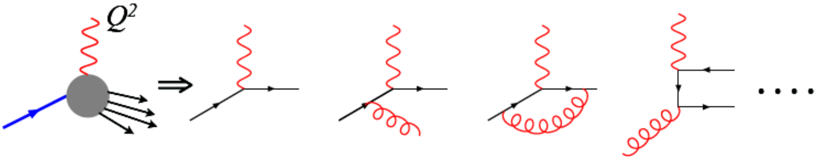


From book of Povh et al.



From M.A. Thomson, Michaelmas Term 2011

QCD interactions induce a well known Q^2 dependence



$$\mathrm{DIS-pQCD:}\quad q(x) \Rightarrow \underbrace{q(x,Q^2)}_{\text{PDFs}}$$

DGLAP evolution equations

factorization:

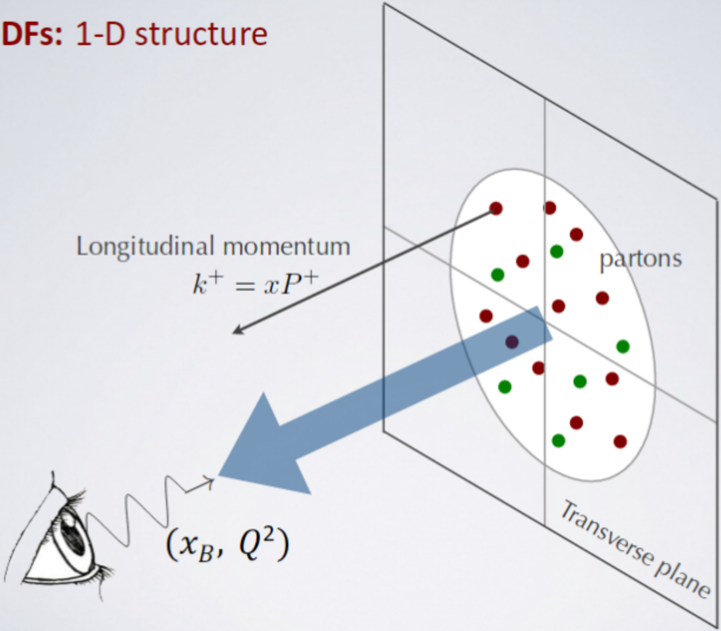
$$\frac{d\sigma}{dx\,dQ^2} = \sum_q q(x,Q^2) \otimes \frac{d\hat{\sigma}_q}{dQ^2}$$

universality: same $q(x,Q^2)$ measured in DIS can be used in other processes

M. Anselmino, Bad Honnef 2017

Here proton is 1-D

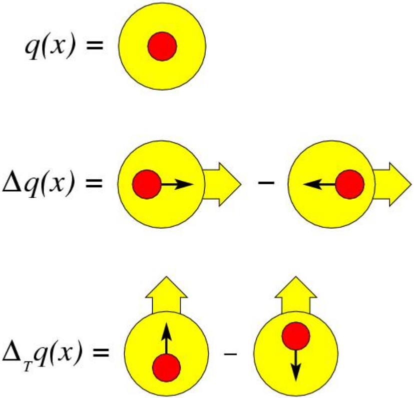
PDFs: 1-D structure



11 A. Bacchetta (Baryon 2013 Conference)

Partonic structure of the nucleon; distribution functions

Three twist-two quark distributions in QCD (momentum, helicity & transversity) after integrating over the quark intrinsic k_t



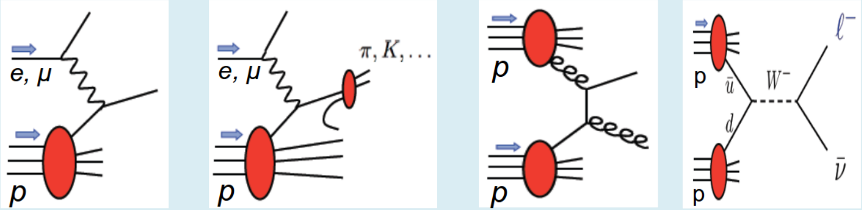
Quark momentum DF;
well known (unpolarised DIS $\rightarrow \mathbf{F_{1,2}(x, Q^2)}$).

Difference in DF of quarks with spin parallel or antiparallel to the nucleon's spin in a longitudinaly polarised nucleon;
less well known (polarised DIS $\rightarrow \mathbf{g_1(x, Q^2)}$).

Difference in DF of quarks with spin parallel or antiparallel to the nucleon's spin in a transversely polarised nucleon;
poorly known (polarised DIS $\rightarrow \mathbf{h_1(x, Q^2)}$).

Nonrelativistically: $\Delta_T q(x, Q^2) \equiv \Delta q(x, Q^2)$. OBS.! $\Delta_T q(x, Q^2)$ are C-odd and chiral-odd

Processes available for parton (helicity) distributions



DIS:

$\Delta q + \Delta \bar{q}$

Δg (From Q^2 evolution of g_1)

SIDIS:

$\Delta q, \Delta \bar{q}$

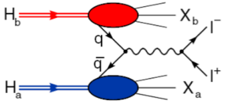
Δg

pp:

$\Delta q, \Delta \bar{q}$

Δg

A. Bazilevsky, SPIN2016



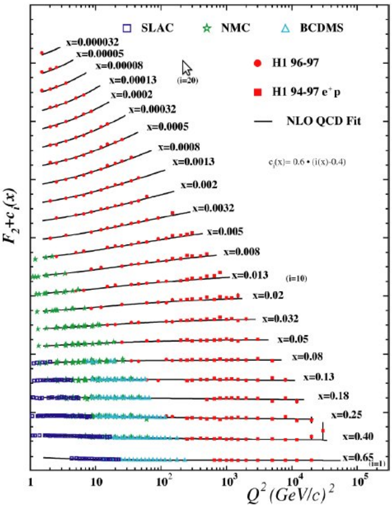
JLab
(HERMES@HERA)
COMPASS@CERN

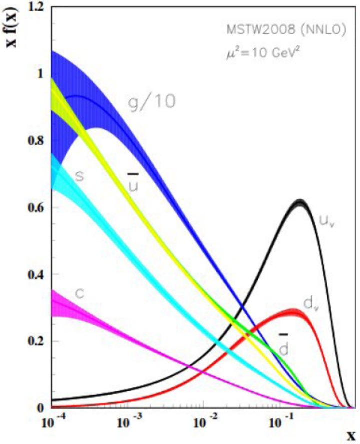
STAR@RHIC
PHENIX@RHIC

Drell-Yan process, complementary to SIDIS

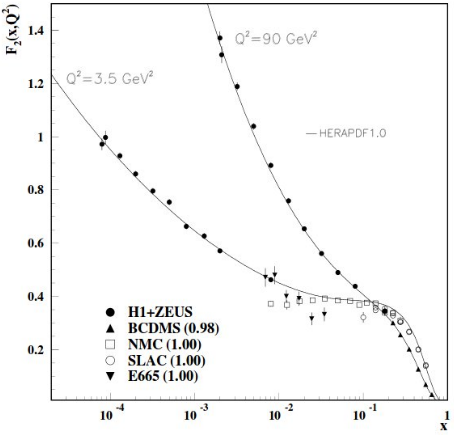
Parton distributions for the proton (universal!)

...from the measurements of $\mathrm{d}^2\sigma/\mathrm{d}x\mathrm{d}Q^2$ in inclusive ep scattering





Scaling violation



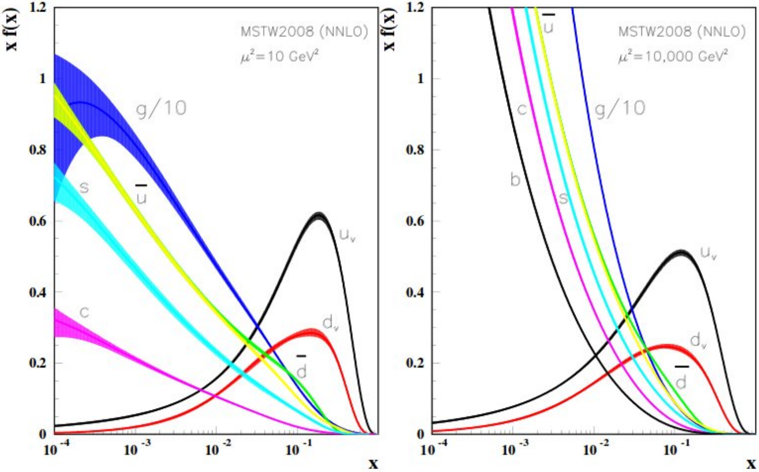
Bjorken scaling:

$Q^2 \to \infty, \nu \to \infty$
observables depend on dimensionless, finite
$x = Q^2/(2M\nu)$

From Particle Data Tables, 2012

QCD can predict the Q^2 dependence of $F_2(x, Q^2)$

Scaling violation,...cont'd



From Particle Data Tables, 2012

Dokshitzer-Gribov-Lipatov-Altarelli-Parisi evolution equation

DGLAP

$$\frac{d}{d(lnQ^2)}\, q_i(x,Q^2) = \frac{\alpha_s(Q^2)}{2\pi}\, [q_i \otimes P_{qq} + g \otimes P_{qg}]$$

$$\frac{d}{d(lnQ^2)}\, g(x,Q^2) = \frac{\alpha_s(Q^2)}{2\pi} \left[\sum_i (q_i + \bar{q}_i) \otimes P_{gq} + g \otimes P_{gg} \right]$$

$$q \otimes P = P \otimes q \equiv \int_x^1 dy\, \frac{q(y,Q^2)}{y}\, P\left(\frac{x}{y}\right)$$

$$P_{qq} = \frac{4}{3} \left[\frac{1+x^2}{(1-x)_+} + \frac{3}{2}\,\delta(1-x) \right] + \mathcal{O}(\alpha_s)$$

$$P_{qg} = \frac{1}{2}\, [x^2 + (1-x)^2] + \mathcal{O}(\alpha_s) \qquad P_{gq} = \frac{4}{3}\, \frac{1+(1-x)^2}{x} + \mathcal{O}(\alpha_s)$$

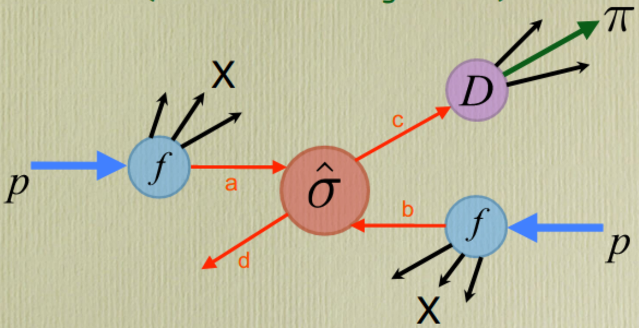
$$P_{gg} = 6 \left[\frac{x}{(1-x)_+} + \frac{1-x}{x} + x(1-x) \right] + \frac{33-2n_f}{6}\,\delta(1-x) + \mathcal{O}(\alpha_s)$$

$$\int_0^1 dx\, \frac{f(x)}{(1-x)_+} = \int_0^1 dx\, \frac{f(x)-f(1)}{(1-x)}$$

M. Anselmino, Bad Honnef2017

Cross section for $p\,p \to \pi\,X$ in pQCD

based on factorization theorem
(in collinear configuration)



$$d\sigma = \sum_{a,b,c,d=q,\bar{q},g} \underbrace{f_{a/p}(x_a) \otimes f_{b/p}(x_b)}_{\text{PDF}} \otimes d\hat{\sigma}^{ab\to cd} \otimes \underbrace{D_{\pi/c}(z)}_{\text{FF}}$$

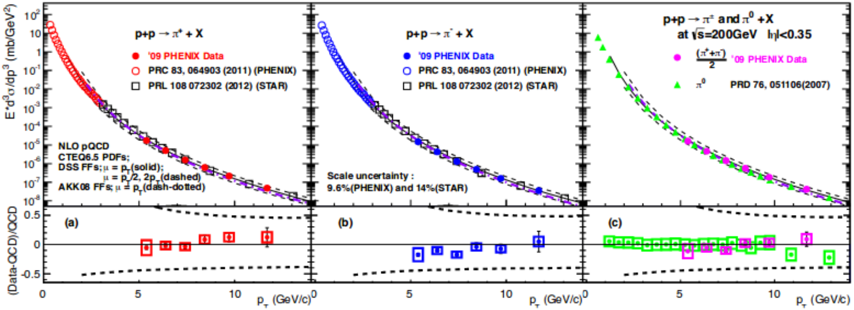
$d\hat{\sigma}^{ab\to cd}$ ↓ pQCD elementary interactions

M. Anselmino, DIS2019

mid-rapidity RHIC data, unpolarised cross sections

(arXiv:1409.1907 [hep-ex], Phys. Rev. D91 (2015) 3, 032001)

large P_T single pion production $pp \to \pi X$

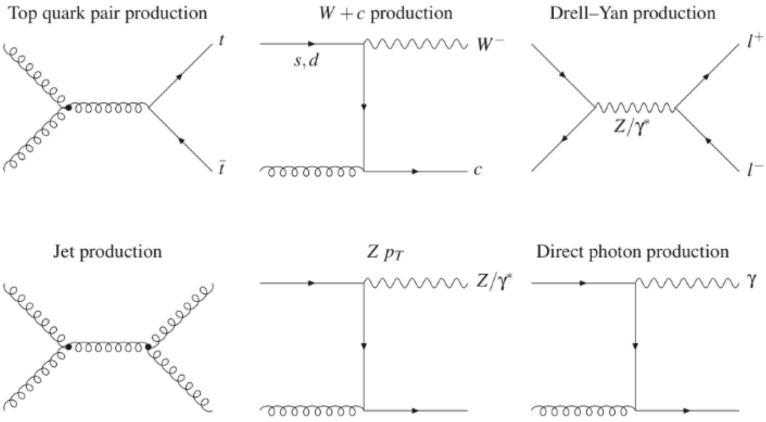


good agreement between RHIC data and collinear pQCD calculations, same for jet production at LHC

M. Anselmino, DIS2019

PDF information from p+p collisions

large-x gluon | *strangeness* | *antiquarks*



large-x gluon | *medium-x gluon* | *medium-x gluon*

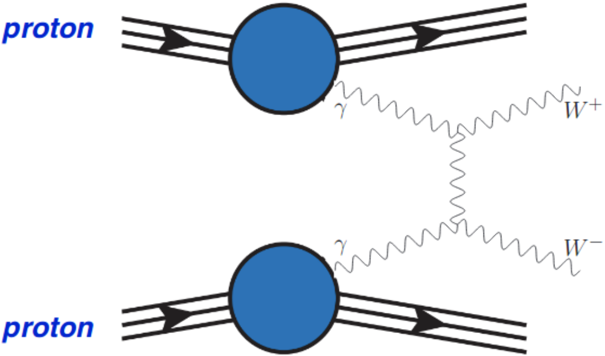
Juan Rojo 29 ***Proton Structure and PDFs*, DIS2019**

Let there be light: the photon PDF

- The proton contains not only quark and gluons as constituents: also **photons!**
- The photon PDF can be evaluated from deep-inelastic **structure functions F_2 and F_L**

LuxQED: Manohar et al 16,17

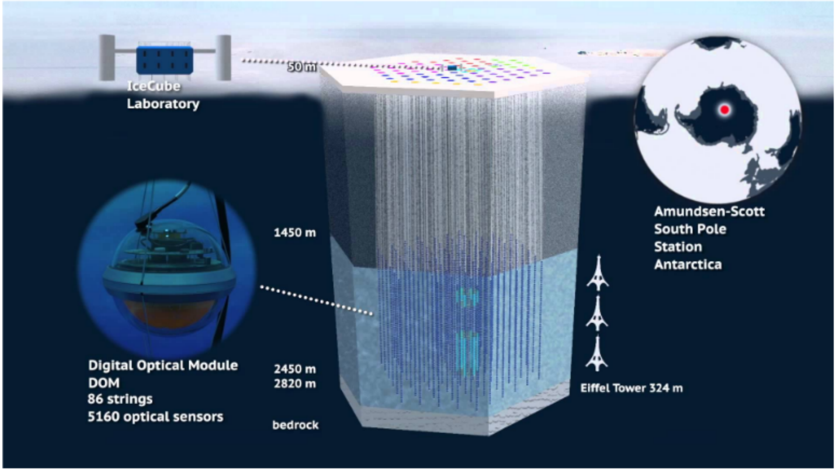
- Required for consistent implementation of **electroweak corrections** at the LHC



Juan Rojo 35 *Proton Structure and PDFs*, DIS2019

Neutrino telescopes

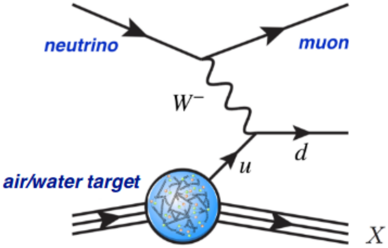
Ultra-high energy (UHE) neutrinos: novel window to the **extreme Universe!**

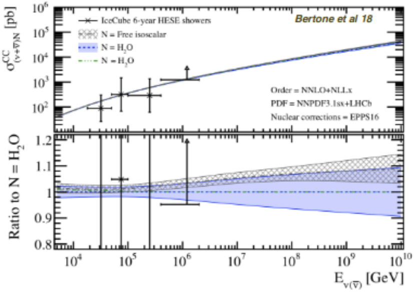


Juan Rojo 64 *Proton Structure and PDFs*, DIS2019

Neutrino telescopes as QCD microscopes

***Ultra-high energy (cosmic) neutrino** - nucleus scattering:*
*unique probe of **small-x PDFs and QCD***





JR WG1+WG7

Sensitive to **small-*x* quarks** (and gluons via evolution)
down to **x** ≃ **10^{-8}** at **Q** ≃ **M_W**

Towards including spin:

experimenting with polarised beams/targets

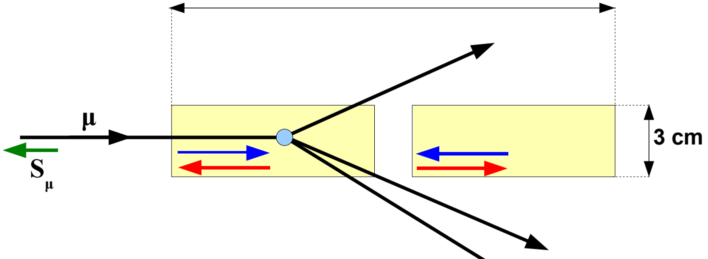
In lepton-nucleon (i.e. fixed-target) spin experiments...

- ...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

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

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

- Example of a two-cell COMPASS target:

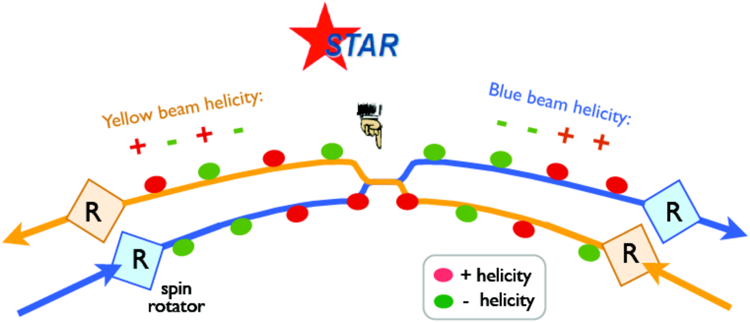


with a possibility of a quick reversal of spins in both cells

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

Helicities in the $\vec{p}\vec{p}$ collider

Helicity of beams colliding at STAR



STAR sees 4 helicity configurations
STAR runs 4 parallel measurements

RHIC measured polarization
Run 9 @ 2x250 GeV
Pol yellow 0.40
Pol blue 0.38
syst. pol (blue+yellow)=9.2%

Longitudinal asymmetries in the $\vec{p}\vec{p}$ collider

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: $A_L(P_1 - P_2)$	$(\sigma_{+-} - \sigma_{-+})\ /\ (\sigma_{-+} + \sigma_{+-})$	$\frac{A_L(P_1 - P_2)}{1 - A_{LL} P_1 P_2}$
$A_L^* \simeq A_L$	$(\sigma_{++} - \sigma_{--})\ /\ (\sigma_{++} + \sigma_{--})$	$\frac{A_L(P_1 + P_2)}{1 + A_{LL} P_1 P_2}$

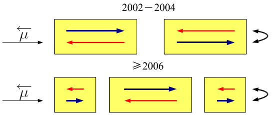
where $sum4 = \sigma_{++} + \sigma_{+-} + \sigma_{-+} + \sigma_{--}$

Method of extraction of g_1 in a $\vec{\mu}\vec{\mathrm{N}}$ fixed-target experiment

- Inclusive asymmetry, $A_{meas}(x, Q^2)$; γ^*-N asymmetry, $A_1(x, Q^2)$; $g_1(x, Q^2)$:

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

f, D: dilution and depolarisation factors; P_T, P_B: target and beam polarisations; $N^{\leftrightarrows,\leftleftarrows}$: number of $\vec{\mu}$ interactions in each target cell: (upstream, downstream) or (outer, central)



- Then $g_1(x, Q^2)$:

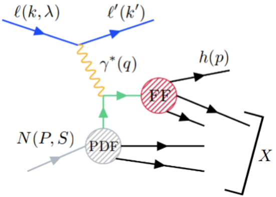
$$g_1(x, Q^2) = A_1(x, Q^2) \cdot F_1(x, Q^2) = A_1(x, Q^2) \cdot \frac{F_2(x, Q^2)}{2x(1 + R(x, Q^2))}$$

- For the deuteron target:

$$(\text{per nucleon})\; g_1^d = g_1^N\left(1 - \frac{3}{2}\omega_D\right) = \frac{g_1^p + g_1^n}{2}\left(1 - \frac{3}{2}\omega_D\right); \qquad \omega_D = 0.05 \pm 0.01$$

Method of extraction of g_1 in a $\vec{\mu}\vec{\mathrm{N}}$ fixed-target experiment,... cont'd

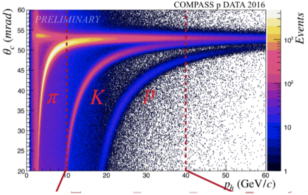
- At LO, semi–inclusive (SIDIS) asymmetry, A_1^h:



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

$$A^{\mathrm{SIDIS}} \sim \mathrm{pdf} \otimes \mathrm{FF}$$

Nonperturbative fragmentation functions $D_q^h(z,Q^2)$ need to be determined from experiment!

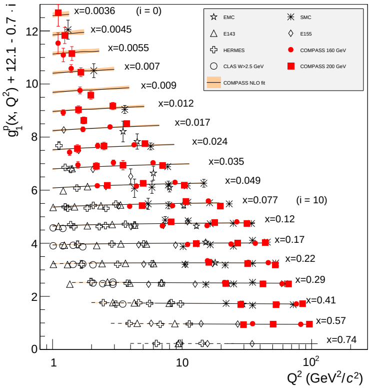


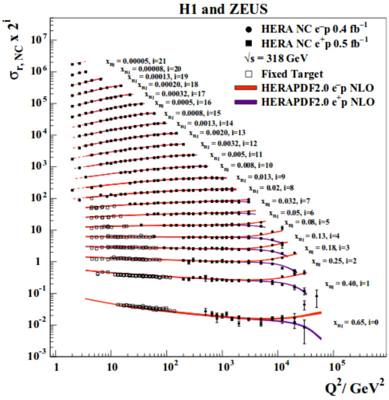
Now including spin:

helicity and transversity PDFs

Measurements of $g_1^{\mathrm{p}}(x, Q^2)$ and $F_2^{\mathrm{p}}(x, Q^2)$

COMPASS NLO QCD at $W^2 > 10$ (GeV/c^2)^2
dashed line: extrapolation to $W^2 < 10$ (GeV/c^2)^2





g_1 measurements little sensitive to Δg

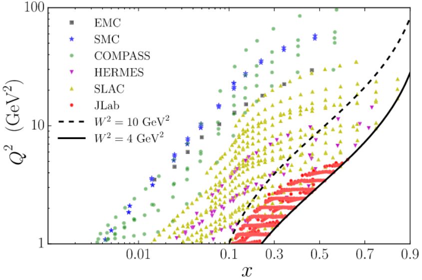
COMPASS, PL B753 (2016) 18

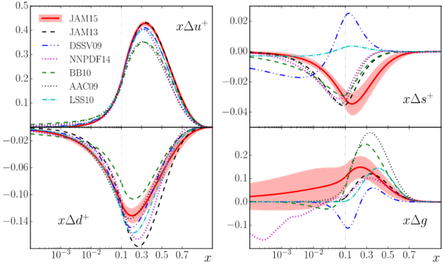
HERA, Eur.Phys.J. C75 (2015) 580

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

JAM: Jefferson Lab. Angular Momentum Collaboration

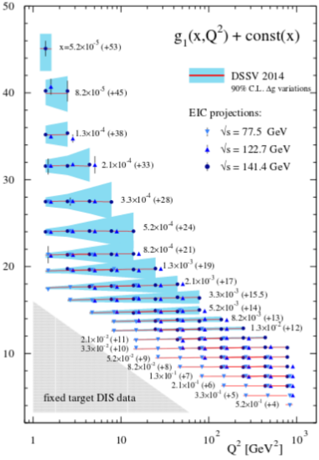
Included JLab data $W^2 > 4$ GeV^2 $\Longrightarrow$ reduced errors for valence & sea at $x > 0.1$

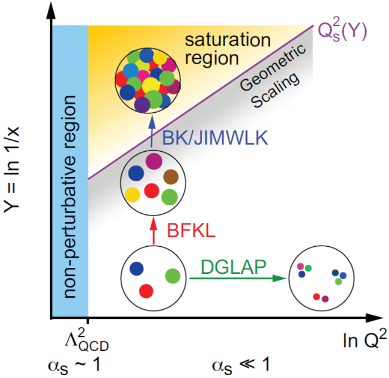




JAM, PRD 93 (2016) 074005

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

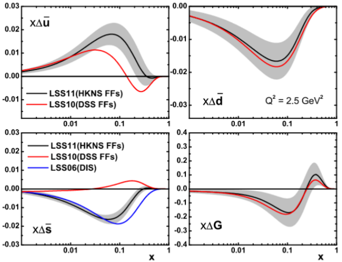
Polarisation of quark sea

- Δs puzzle. Strange quark polarisation (COMPASS):
  $$2\Delta S = \int_0^1 (\Delta s(x) + \Delta\bar{s}(x))dx = -0.09 \pm 0.01 \pm 0.02$$ from incl. asymmetries + SU_3,
  while from SIDIS it is compatible with zero but depends upon chosen FFs.

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

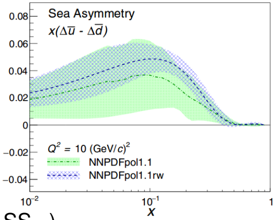
  $\Longrightarrow$COMPASS extracts it from multiplicities.

- Example of sensitivity to FFs at Q^2=2.5 (GeV/c)^2



LSS, PRD D84 (2011) 014002

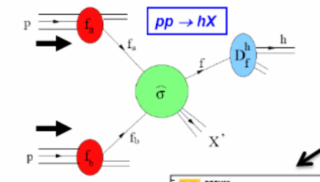
- The sea is probably unsymmetric (STAR):

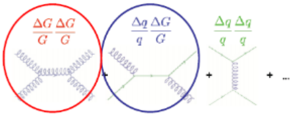


STAR, PR D99 (2019) 051102

(opposite to COMPASS...)

Measurement of the gluon polarization Δg at RHIC



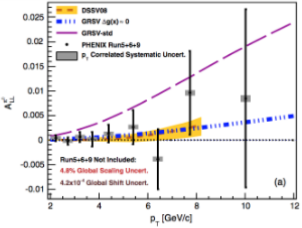


Dominates at low p_T

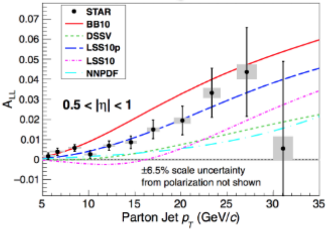
Dominates at high p_T

D. de Florian *et al*, **PRL 113 (2014) 012001**

E. Nocera et al, **NPB 887 (2014) 276**



Phys. Rev. D 90 (2014) 012007



Phys. Rev. Lett. 115 (2015) 092002

Surrow et al on sea quark spin from W production at RHIC

$\int_{0.05}^{1} dx\Delta g(x,Q^2=10\mathrm{GeV}^2) = 0.20^{+.06}_{-.07}$ DSSV++

$\int_{0.05}^{0.2} dx\Delta g(x,Q^2=10\mathrm{GeV}^2) = 0.17\pm 0.06$ NNPDFpol1.1

$\int_{0.001}^{0.8} dx\Delta g(x,Q^2 = 1\ \mathrm{GeV}^2) = 0.5\pm 0.4$ JAM15

6

H.Gao, DIS2018

The proton spin “puzzle” ($>$ 30 yers old!)

- For the proton in $\hbar$ units:

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

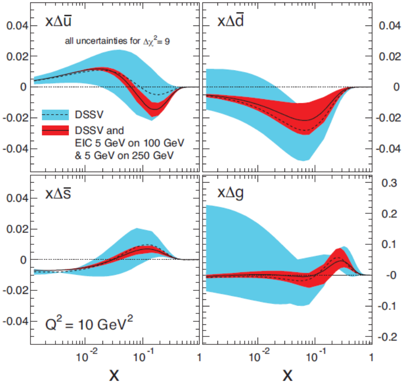
$$\Delta\Sigma \sim 0.3, \qquad \Delta G \sim \text{sizable?}, \quad \Delta L = ?$$

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, JLab.
- Electron-Ion Collider, the “imaging machine” will faciliate an accurate measurement of ΔG and an access to ΔL.

Parton separation at EIC pseudo-data (inclusive and semi-inclusive)

DIS + SIDIS

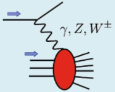


From “White paper”, arXiv:1212.1701

EW DIS

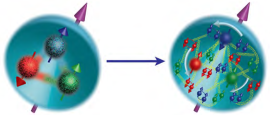
- $\Delta g(x)$ from scaling violation
- $\Delta\bar{u}$, $\Delta\bar{d}$, Δs from SIDIS
- Flavor separation at high Q² via CC DIS:

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

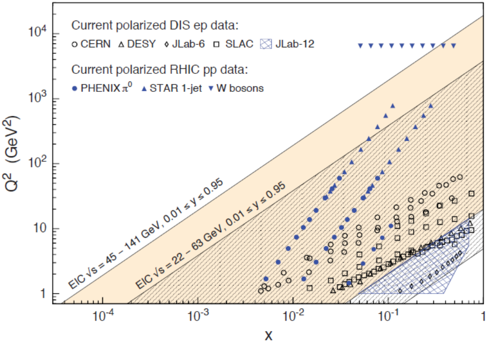


E. Aschenauer, SPIN2016

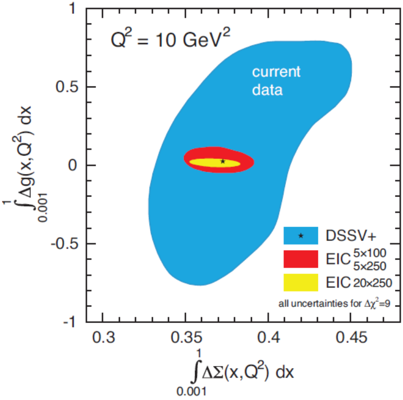
Nucleon spin "puzzle" at EIC



$$\frac{1}{2} = \frac{1}{2}\underbrace{\Delta\Sigma}_{\text{quark spins}} + \underbrace{\Delta G}_{\text{gluon spins}} + \underbrace{L_z}_{\text{quark\&gluon orbital motion}}$$



From "White paper2017", arXiv:1708.01527v3

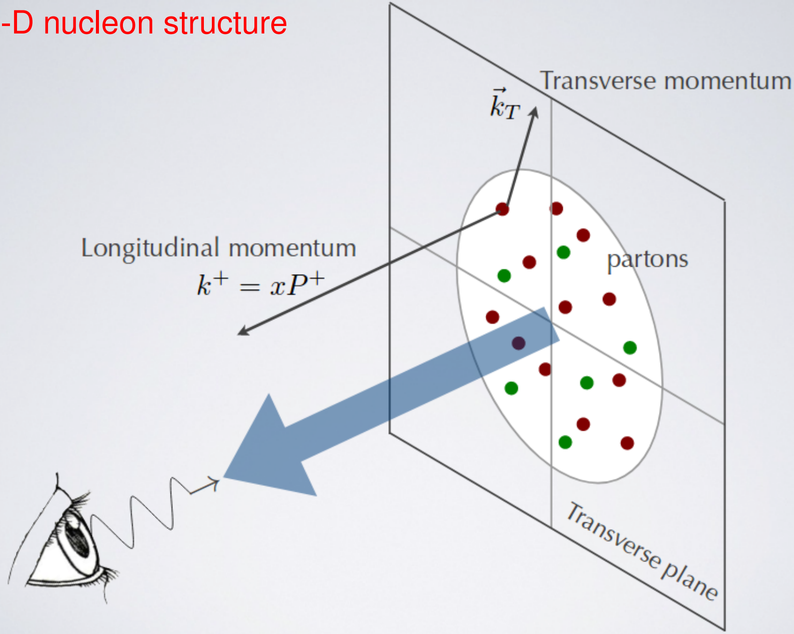


From "White paper", arXiv:1212.1701

There are more dimensions to explore, e.g. 3-D!

chiefly due to failures of the 1-D picture

3-D nucleon structure

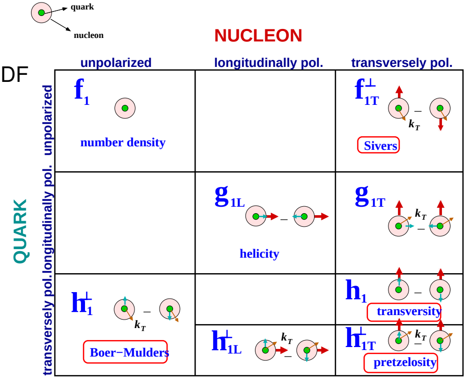


11 A. Bacchetta

With 3D projections, we will be entering a new age.
Something which was never technically possible before
James Cameron

Partonic structure of the nucleon; distribution functions

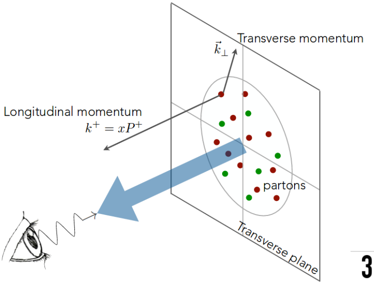
- In LT and considering k_{T},
  8 PDF describe the nucleon
  $\Longrightarrow$ Transverse Momentum Dependent PDF
- QCD-TMD approach valid $k_{\mathrm{T}} \ll \sqrt{Q^2}$
- After integrating over k_{T}
  only 3 survive: f_1, g_1, h_1
- TMD accessed in SIDIS and DY
  by measuring azimuthal asymmetries
  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$^{\mathrm{target}}$



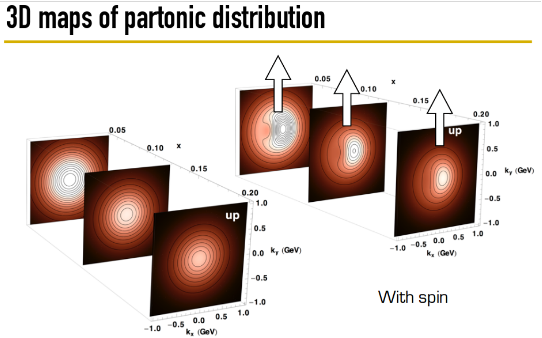
- OBS! Boer-Mulders and Sivers PDF are T-odd, i.e. process dependent

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

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



What does Sivers effect do?

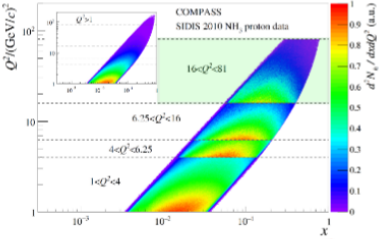


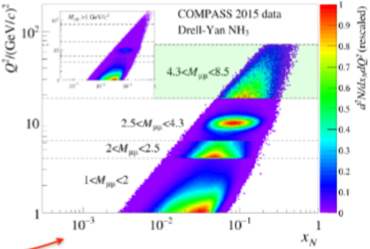
A. Bacchetta, DIS2017

COMPASS SIDIS-DY bridge (from R. Longo, Low-x 2018)

$$\frac{d\sigma^{LO}}{dx\,dy\,dz\,dp_T^2\,d\varphi_h\,d\psi} \propto \left\{ \begin{array}{l} 1+\cos(2\phi_h)\varepsilon A_{UU}^{\cos(2\phi_h)} \\ + S_T \left[\begin{array}{l} \sin(\phi_h-\phi_S)A_{UT}^{\sin(\phi_h-\phi_s)} \\ +\sin(\phi_h+\phi_S)\varepsilon A_{UT}^{\sin(\phi_h+\phi_s)} \\ +\sin(3\phi_h-\phi_S)\varepsilon A_{UT}^{\sin(3\phi_h-\phi_s)} \end{array} \right] \end{array} \right\}$$

$$\frac{d\sigma^{LO}}{d\Omega\, d^4q} \propto \left\{ \begin{array}{l} 1+D_{[\sin^2\theta]}\cos(2\varphi_{CS})A_U^{\cos 2\varphi_{CS}} \\ + S_T \left[\begin{array}{l} \sin\varphi_S A_T^{\sin\varphi_S} \\ + D_{[\sin^2\theta]} \begin{pmatrix} \sin(2\varphi_{CS}+\varphi_S)A_T^{\sin(2\varphi_{CS}+\varphi_S)} \\ \sin(2\varphi_{CS}-\varphi_S)A_T^{\sin(2\varphi_{CS}-\varphi_S)} \end{pmatrix} \end{array} \right] \end{array} \right\}$$





comparable x:Q² kinematic coverage

minimization of possible Q² evolution effects

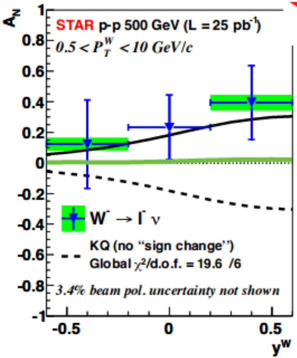
Unique experimental environment to test TMD universality and Sivers and Boer-Mulders sign change

29/08/2018 Riccardo Longo 9

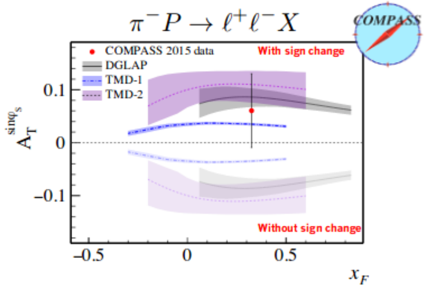
SIVERS FUNCTION SIGN CHANGE

Sivers function SIDIS = – Sivers function Drell-Yan

Collins, PLB 536 (02)



STAR Collab. arXiv:1511.06003

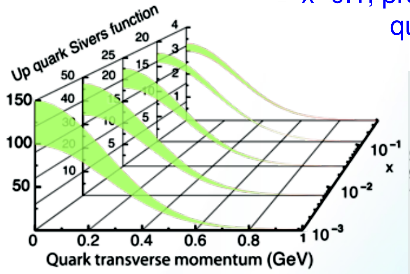


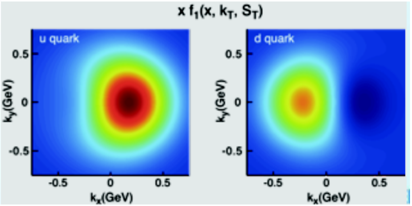
prediction with TMD evolution equations

A. Bacchetta, DIS2019

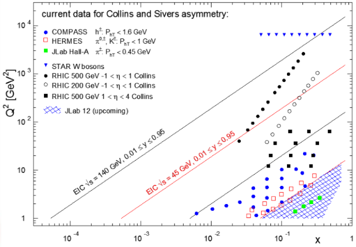
Sivers function at EIC

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





From “White paper”, arXiv:1212.1701

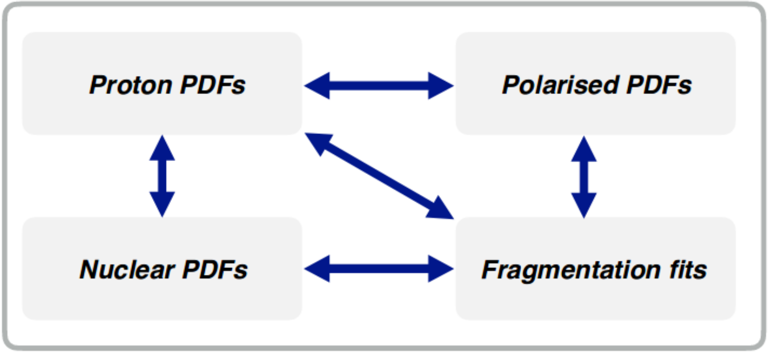


⟸ EIC acceptance for Sivers meas.

O. Eyser, SPIN2016

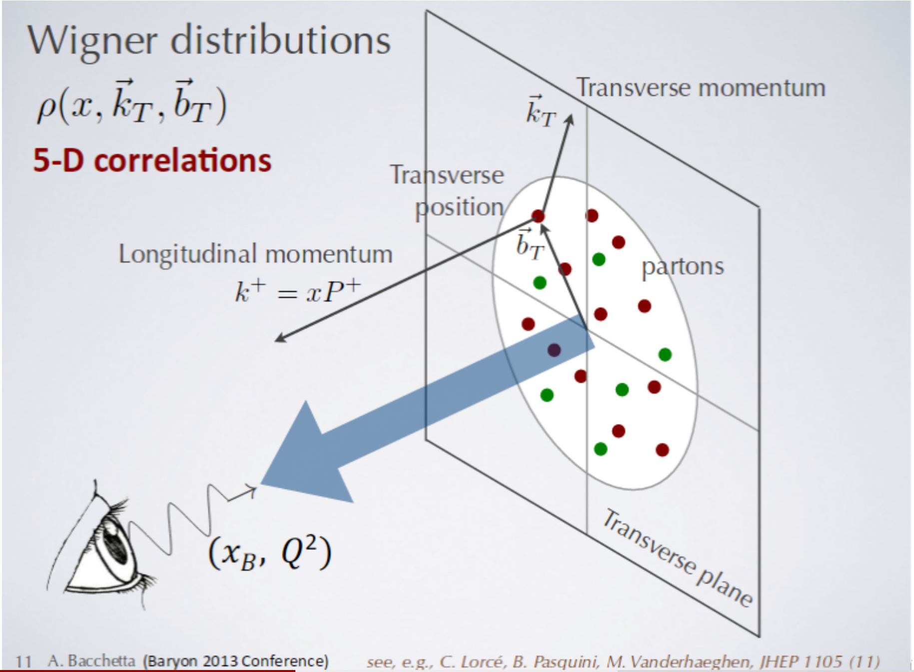
Universal QCD fits

Pushing the **precision frontier** of **QCD fits** requires accounting for **cross-talk** between different **non-perturbative QCD** quantities

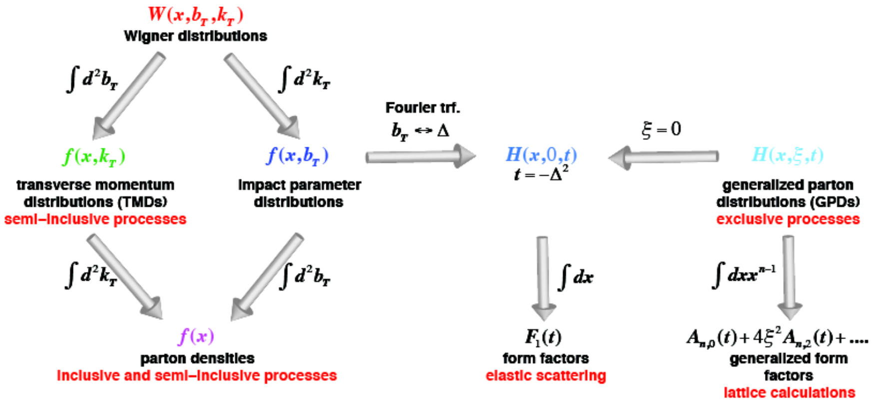


*Towards **universal/integrated global analyses** of non-perturbative QCD*

...Proton even 5-D!


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

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



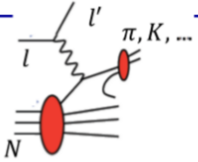
From “White paper”, arXiv:1212.1701

Take-away menu: proton structure very rich!

- 1-D proton structure accurate and well controlled.
- Experimental results suggest a necessity to go beyond the collinear parton picture of the nucleon.
- New promising concepts:
  1. Transverse Momentum Dependent distributions, TMD
  2. Generalised Parton Distributions, GPD (not discussed).
- Data from: SIDIS, pp, Drell-Yan, e^+e^- (not discussed)
  $\Longrightarrow$ formulation of the 3-D imaging of the nucleon well advanced.
- Expected: new data from COMPASS, RHIC, JLab at 12 GeV and the forthcoming Electron Ion Collider!
- Topical issue of EPJA dedicated to the 3-D nucleon structure: EPJ A52 (2016) no.6 (15 articles)!

SPARES

Semi-Inclusive Deep Inelastic Scattering



$$
\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} =
$$

$$
\frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Bigg\{F_{UU,T}+\varepsilon F_{UU,L}+\sqrt{2\varepsilon(1+\varepsilon)}\cos\phi_h\,F_{UU}^{\cos\phi_h}
$$

$$
+\varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h}+\lambda_e\sqrt{2\varepsilon(1-\varepsilon)}\sin\phi_h\,F_{LU}^{\sin\phi_h}
$$

$$
+S_\parallel\left[\sqrt{2\varepsilon(1+\varepsilon)}\sin\phi_h\,F_{UL}^{\sin\phi_h}+\varepsilon\sin(2\phi_h)\,F_{UL}^{\sin 2\phi_h}\right]+S_\parallel\lambda_e\left[\sqrt{1-\varepsilon^2}\,F_{LL}+\sqrt{2\varepsilon(1-\varepsilon)}\cos\phi_h\,F_{LL}^{\cos\phi_h}\right]
$$

$$
+|\boldsymbol{S}_\perp|\Bigg[\sin(\phi_h-\phi_S)\left(F_{UT,T}^{\sin(\phi_h-\phi_S)}+\varepsilon\,F_{UT,L}^{\sin(\phi_h-\phi_S)}\right)
$$

$$
+\varepsilon\,\sin(\phi_h+\phi_S)\,F_{UT}^{\sin(\phi_h+\phi_S)}+\varepsilon\,\sin(3\phi_h-\phi_S)\,F_{UT}^{\sin(3\phi_h-\phi_S)}
$$

$$
+\sqrt{2\varepsilon(1+\varepsilon)}\sin\phi_S\,F_{UT}^{\sin\phi_S}+\sqrt{2\varepsilon(1+\varepsilon)}\sin(2\phi_h-\phi_S)\,F_{UT}^{\sin(2\phi_h-\phi_S)}\Bigg]
$$

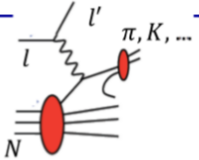
$$
+|\boldsymbol{S}_\perp|\lambda_e\Bigg[\sqrt{1-\varepsilon^2}\cos(\phi_h-\phi_S)\,F_{LT}^{\cos(\phi_h-\phi_S)}+\sqrt{2\varepsilon(1-\varepsilon)}\cos\phi_S\,F_{LT}^{\cos\phi_S}
$$

$$
+\sqrt{2\varepsilon(1-\varepsilon)}\cos(2\phi_h-\phi_S)\,F_{LT}^{\cos(2\phi_h-\phi_S)}\Bigg]\Bigg\},
$$

IWHSS19, Aveiro, 24 June 2019

F. Bradamante

Semi-Inclusive Deep Inelastic Scattering



$$\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} =$$

$$\frac{\alpha^2}{xyQ^2}\,\frac{y^2}{2\,(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Big\{F_{UU,T}+\varepsilon F_{UU,L}+\sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\,F_{UU}^{\cos\phi_h}$$

$h_1^\perp \otimes H_1^\perp$ ← $F_{UU}^{\cos 2\phi_h}$

$$+\,\varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h}+\lambda_e\,\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{LU}^{\sin\phi_h}$$

$h_{1L}^\perp \otimes H_1^\perp$ ← $F_{UL}^{\sin 2\phi_h}$

$$+\,S_\parallel\left[\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_h\,F_{UL}^{\sin\phi_h}+\varepsilon\sin(2\phi_h)\,F_{UL}^{\sin 2\phi_h}\right]+S_\parallel\lambda_e\left[\sqrt{1-\varepsilon^2}\,F_{LL}+\sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_h\,F_{LL}^{\cos\phi_h}\right]$$

$f_{1T}^\perp \otimes D_1$ ← $F_{UT,T}^{\sin(\phi_h-\phi_S)}$

$$+\,|\boldsymbol{S}_\perp|\Big[\sin(\phi_h-\phi_S)\left(F_{UT,T}^{\sin(\phi_h-\phi_S)}+\varepsilon\,F_{UT,L}^{\sin(\phi_h-\phi_S)}\right)$$

$h_1 \otimes H_1^\perp$ ← $F_{UT}^{\sin(\phi_h+\phi_S)}$; $h_{1T}^\perp \otimes H_1^\perp$ ← $F_{UT}^{\sin(3\phi_h-\phi_S)}$

$$+\,\varepsilon\,\sin(\phi_h+\phi_S)\,F_{UT}^{\sin(\phi_h+\phi_S)}+\varepsilon\,\sin(3\phi_h-\phi_S)\,F_{UT}^{\sin(3\phi_h-\phi_S)}$$

$$+\,\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_S\,F_{UT}^{\sin\phi_S}+\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin(2\phi_h-\phi_S)\,F_{UT}^{\sin(2\phi_h-\phi_S)}\Big]$$

$$+\,|\boldsymbol{S}_\perp|\lambda_e\Big[\sqrt{1-\varepsilon^2}\,\cos(\phi_h-\phi_S)\,F_{LT}^{\cos(\phi_h-\phi_S)}+\sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_S\,F_{LT}^{\cos\phi_S}$$

$$+\,\sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos(2\phi_h-\phi_S)\,F_{LT}^{\cos(2\phi_h-\phi_S)}\Big]\Big\},$$

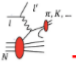
$F_{LT}^{\cos(\phi_h-\phi_S)}$ → $g_{1T} \otimes D_1$

14 independent azimuthal modulations

amplitudes of the modulations
→ TMD PDFs

IWHSS19, Aveiro, 24 June 2019 F. Bradamante

Semi-Inclusive Deep Inelastic Scattering



MAJOR RESULT:
in the past 15 years 2 of these new PDF's have been measured and shown to be different from zero
by COMPASS and HERMES

the transversity PDF — Collins asymmetry $\sim h_1 \otimes H_1^{\perp}$
amplitude of the sine modulation in $\phi_h + \phi_s - \pi$

the Sivers PDF — Sivers asymmetry $\sim f_{1T}^{\perp} \otimes D_1$
amplitude of the sine modulation in $\phi_h - \phi_s$

A STEP TOWARDS
THE 3-D STRUCTURE OF THE NUCLEON

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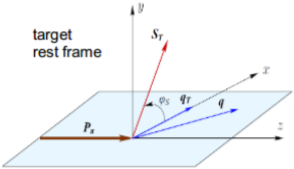
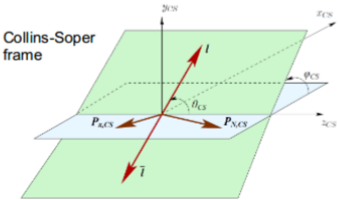
Drell-Yan cross-section



general expression

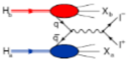
$$
\begin{aligned}
\frac{d\sigma}{dq^4 d\Omega} \propto \hat{\sigma}_U \Big\{ & 1 + \cos^2\theta_{CS}\, A_U^1 + \sin 2\theta_{CS}\, A_U^{\cos\varphi_{CS}} \cos\varphi_{CS} + \sin^2\theta_{CS}\, A_U^{\cos 2\varphi_{CS}} \cos 2\varphi_{CS} \\
& + S_T \Big[\Big(A_T^{\sin\varphi_S} + \cos^2\theta_{CS}\, \tilde{A}_T^{\sin\varphi_S} \Big) \sin\varphi_S \\
& + \sin 2\theta_{CS} \Big(A_T^{\sin(\varphi_{CS}+\varphi_S)} \sin(\varphi_{CS}+\varphi_S) + A_T^{\sin(\varphi_{CS}-\varphi_S)} \sin(\varphi_{CS}-\varphi_S) \Big) \\
& + \sin^2\theta_{CS} \Big(A_T^{\sin(2\varphi_{CS}+\varphi_S)} \sin(2\varphi_{CS}+\varphi_S) + A_T^{\sin(2\varphi_{CS}-\varphi_S)} \sin(2\varphi_{CS}-\varphi_S) \Big) \Big] + \cdots \Big\}
\end{aligned}
$$

$\lambda = A_U^1, \mu = A_U^{\cos\varphi_{CS}}, \nu = 2\, A_U^{\cos 2\varphi_{CS}}$



IWHSS19, Aveiro, 24 June 2019

Drell-Yan cross-section



general expression $\pi^- p \to l^+ l^- X$

Boer-Mulders of the π · **Boer-Mulders** of the p: $h_1^\perp \otimes h_1^\perp$ ↑

$$\frac{d\sigma}{dq^4 d\Omega} \propto \hat{\sigma}_U \Big\{ 1 + \cos^2\theta_{CS} A_U^1 + \sin 2\theta_{CS}\, A_U^{\cos\varphi_{CS}} \cos\varphi_{CS} + \sin^2\theta_{CS}\, A_U^{\cos 2\varphi_{CS}} \cos 2\varphi_{CS}$$
$$+ S_T \Big[\Big(A_T^{\sin\varphi_S} + \cos^2\theta_{CS} \tilde{A}_T^{\sin\varphi_S} \Big) \sin\varphi_S$$
$$+ \sin 2\theta_{CS} \Big(A_T^{\sin(\varphi_{CS}+\varphi_S)} \sin(\varphi_{CS}+\varphi_S) + A_T^{\sin(\varphi_{CS}-\varphi_S)} \sin(\varphi_{CS}-\varphi_S) \Big)$$
$$+ \sin^2\theta_{CS} \Big(A_T^{\sin(2\varphi_{CS}+\varphi_S)} \sin(2\varphi_{CS}+\varphi_S) + A_T^{\sin(2\varphi_{CS}-\varphi_S)} \sin(2\varphi_{CS}-\varphi_S) \Big) \Big] + \cdots \Big\}$$

$A_T^{\sin\varphi_S}$ → $f_1 \otimes f_{1T}^\perp$ — of the π · **Sivers** of the p

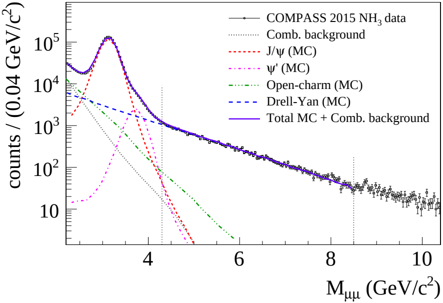
$A_T^{\sin(2\varphi_{CS}+\varphi_S)}$ → $h_1^\perp \otimes h_{1T}^\perp$ — **Boer-Mulders** of the π · **pretzelosity** of the p

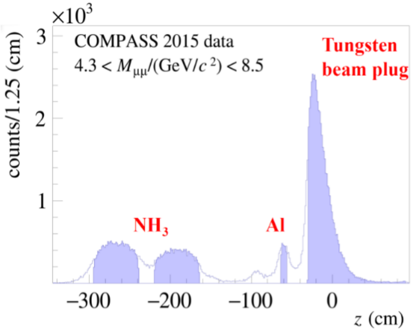
$A_T^{\sin(2\varphi_{CS}-\varphi_S)}$ → $h_1^\perp \otimes h_1$ — **Boer-Mulders** of the π · **transversity** of the p

IWHSS19, Aveiro, 24 June 2019 F. Bradamante

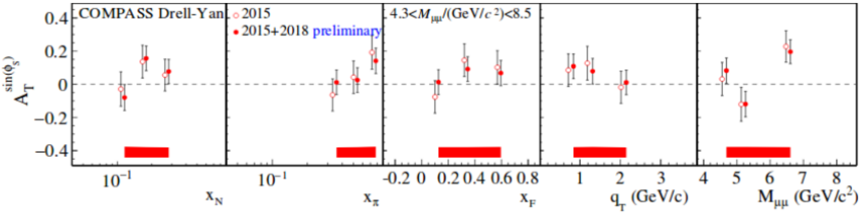
Drell-Yan process at COMPASS

- $\pi^- + p \to \mu^+\mu^- + X$, beam: 190 GeV/$c$, target: $\perp$ polarised proton (NH_3)



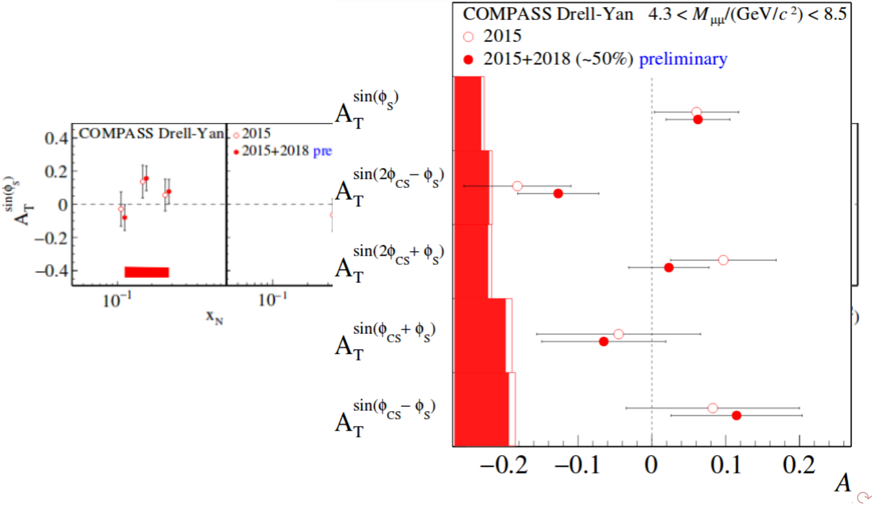


- Sivers asymmetry in bins of $x_N, x_\pi, x_F, q_T, M_{\mu\mu}$



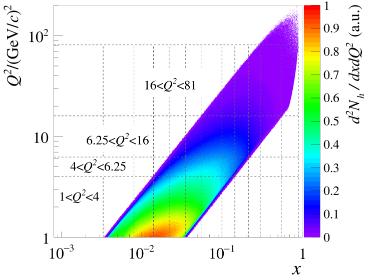
Drell-Yan process at COMPASS,...cont’d

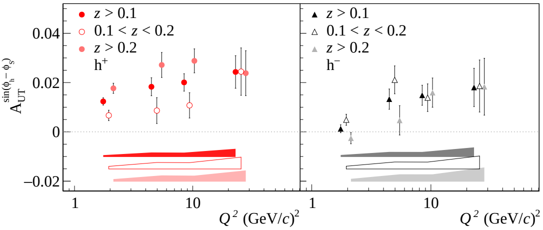
- ...and other (integrated, transverse spin) asymmetries



Sivers asymmetry results from SIDIS at the DY $Q = M_{\mu\mu}$ scale bins

(all other Transverse Spin Asymmetries measured as well)

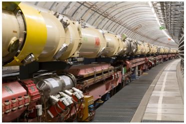


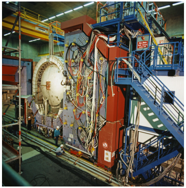


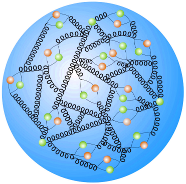
COMPASS, Phys. Lett. B770 (2017) 138

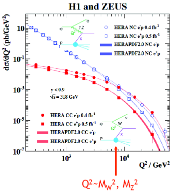
HadronEelectronRing Accelerator (1990–2007) legacy 300 authors, 70 institutions

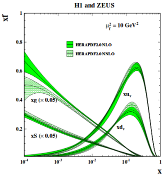
- A collider of protons and electrons (positrons); $\sqrt{s} \sim$ 300 GeV; $\sim$0.5 fb $^{-1}$/exp.
- 6.3-kilometre superconducting p ring; separate (normalcond.) for e^{+}/e^{-}; 2 intersection points, detectors: ZEUS and H1
- Most precise picture of inner proton dynamics (without spin) $\Longrightarrow$ QCD (-> NNLO)
- Unification of electromagnetic and weak forces at high energies
- Joint ZEUS+H1 set of DIS data: HERAPDF2.0 (LO, NLO, NNLO)
- Tension between the data and QCD at $Q^2 \lesssim 15$ GeV^2
- No deviations from SM $> 2.5\sigma$; compositeness: $R_q < 0.43 \cdot 10^{-18}$m











Eur.Phys.J. C75(2015) 580

HERA's non-legacy

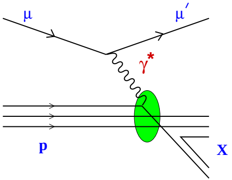
- Insufficient luminosity for high x precision or searches
- Lack of Q^2 lever-arm restricts precision on low x for gluons
- Limited quark flavour info (no deuterons to separate u and d)
- Protons not polarised except HERMES
  (no spin, transverse structure...)
- No nuclear targets

$\Rightarrow\Rightarrow\Rightarrow\Rightarrow\Rightarrow\Rightarrow$These limitations addressed by EIC (and LHeC)

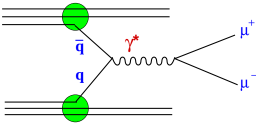
after P. Newman, DIS2016

3-D nucleon;   one attempt

- Transverse Momentum Dependent distributions:
  parton intrinsic k_{T} taken into account
- TMD related to quark angular momentum, L!
- 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)

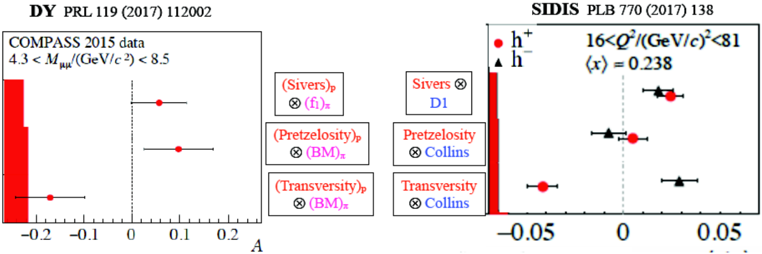


SIDIS
Obs.: final state interactions!



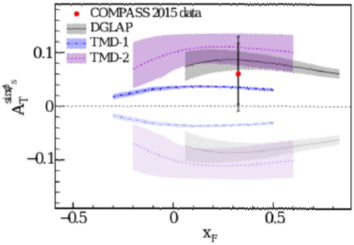
DY
Obs.: initial state interactions!

COMPASS spin-dependent asymmetries in DY–SIDIS



In 2018

statistics ≈ 1.5 × 2015!



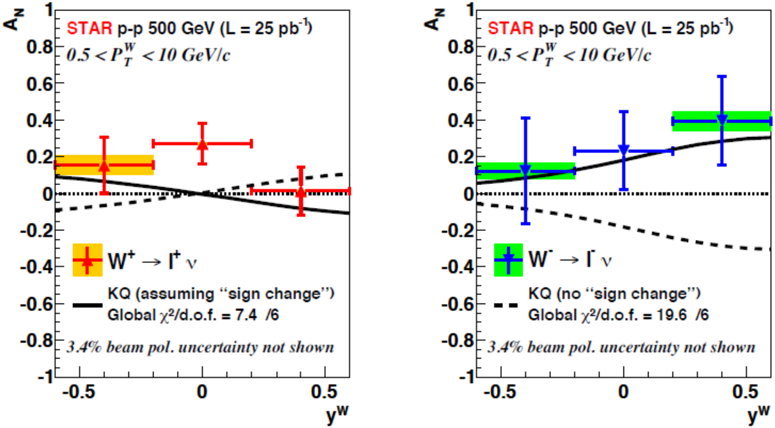
← sign change hypothesis

← NO sign change

PRL 119 (2017) 112002

First results from RHIC, $p^{\uparrow}p \rightarrow W^{\pm}X$

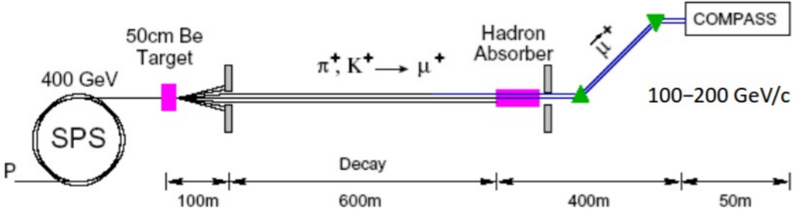
STAR Collaboration, PRL 116 (2016) 132301

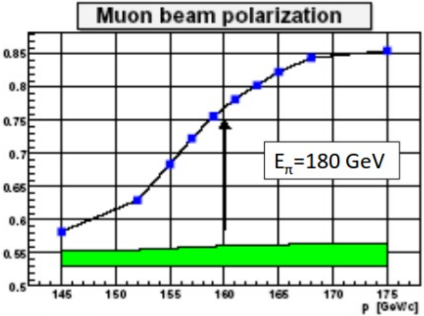


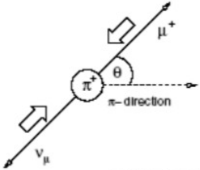
some hints at sign change of Sivers function.....

M. Anselmino, Bad Honnef 2017

High energy polarised muon beam at CERN



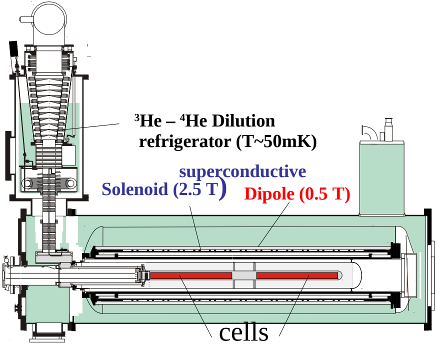


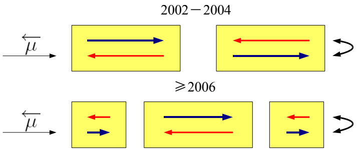


Energy	160 GeV
Intensity	$2 \cdot 10^8 \mu/\text{Spill}$
Polarisation	$\approx 76\,\%$

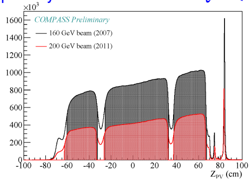
G.K. Mallot/CERN Varenna, July 2011

COMPASS polarised targets: NH_3 and ^{6}LiD



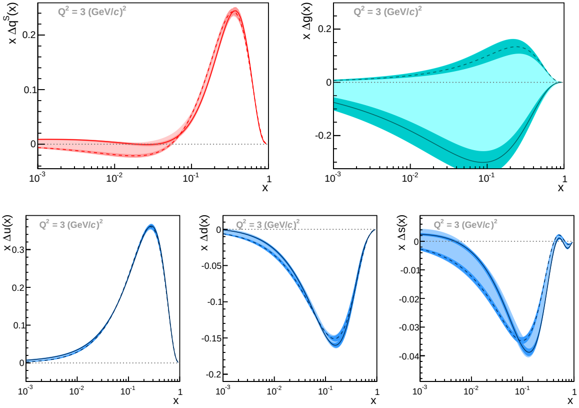


NH_3, primary vertex resolution at Q^2 <1 (GeV/c)^2



- * 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)

NLO QCD fit: results for g_1^p, g_1^d, $g_1^{^3He}$ inclusive data, $W^2 > 10$ (GeV/c^2)^2



PLB 753 (2016) 18

- Statistical uncertainties (dark bands) $\ll$ systematic (light bands)
- Gluon polarisation poorly constraint $\Longrightarrow$ “direct” methods
- Quark spin contribution to the nucleon spin: 0.26 $< \Delta\Sigma <$0.36 (due to poor Δg)

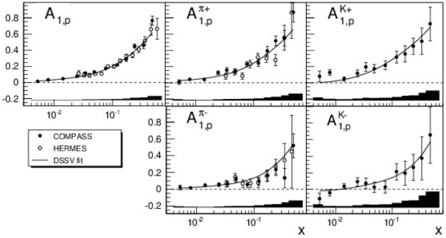
Semi-inclusive asymmetries and parton distributions

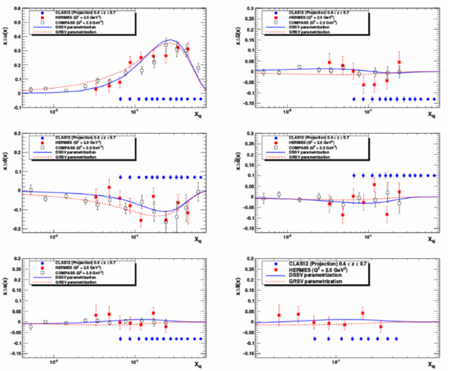
- COMPASS: measured on both proton and deuteron targets
  for identified, positive and negative pions and (for the first time) kaons

CLAS12, Update to E12-09-007

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

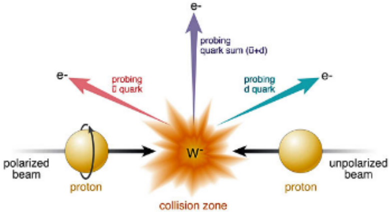
DSSV, Phys. Rev. D **80** (2009) 034030





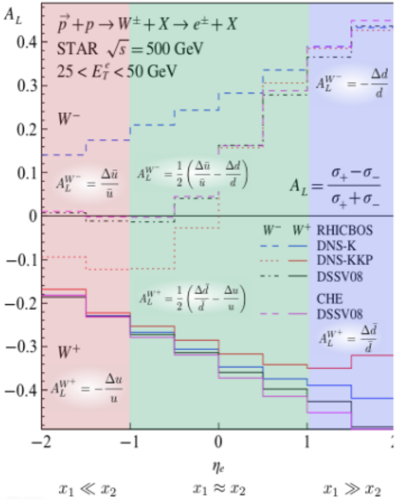
- COMPASS: LO DSS fragm. functions and LO unpolarised MRST assumed here.
- NLO parameterisation of DSSV describes the data well.

Single Spin Asymmetry of W



$$A_L^{e^-} \approx \frac{\int_{\otimes(x_1,x_2)} \left[\Delta\bar{u}(x_1)d(x_2)(1-\cos\theta)^2 - \Delta d(x_1)\bar{u}(x_2)(1+\cos\theta)^2\right]}{\int_{\otimes(x_1,x_2)} \left[\bar{u}(x_1)d(x_2)(1-\cos\theta)^2 + d(x_1)\bar{u}(x_2)(1+\cos\theta)^2\right]}$$

$$A_L^{e^+} \approx \frac{\int_{\otimes(x_1,x_2)} \left[\Delta\bar{d}(x_1)u(x_2)(1+\cos\theta)^2 - \Delta u(x_1)\bar{d}(x_2)(1-\cos\theta)^2\right]}{\int_{\otimes(x_1,x_2)} \left[\bar{d}(x_1)u(x_2)(1+\cos\theta)^2 + u(x_1)\bar{d}(x_2)(1-\cos\theta)^2\right]}$$

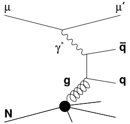


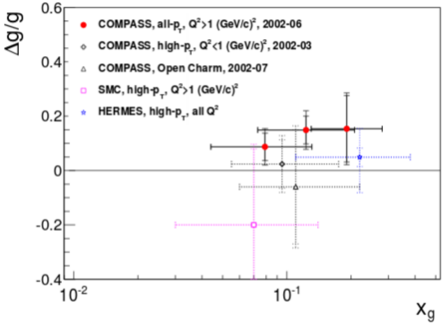
A. Kraishan DIS2019

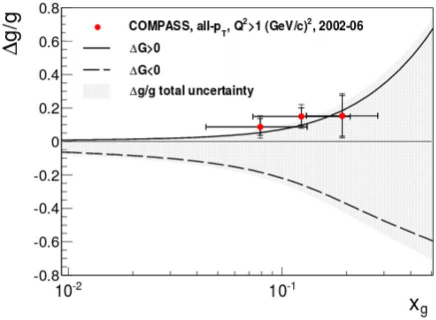
Amani Kraishan 5

Direct measurements of $\Delta g(x)$

Direct measurements – *via* the cross section asymmetry for the photon–gluon fusion (PGF) with subsequent fragmentation into $c\bar{c}$ (LO, NLO) or $q\bar{q}$ (high p_{T} hadron pair (LO)): $A^{\mathrm{PGF}}_{\gamma\mathrm{N}} \approx \langle a^{\mathrm{PGF}}_{\mathrm{LL}} \rangle \dfrac{\Delta g}{g}$







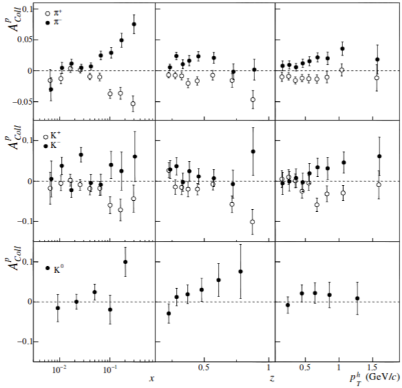
COMPASS from SIDIS on d for any $(p_{\mathrm{T}})_{\mathrm{h}}$ and at LO:

$$\Delta g/g = 0.113 \pm 0.038(\mathrm{stat.}) \pm 0.036(\mathrm{syst.}) \quad \text{at} \quad \langle Q^2 \rangle \approx 3\ (\mathrm{GeV}/c)^2, \quad \langle x_g \rangle \approx 0.10$$

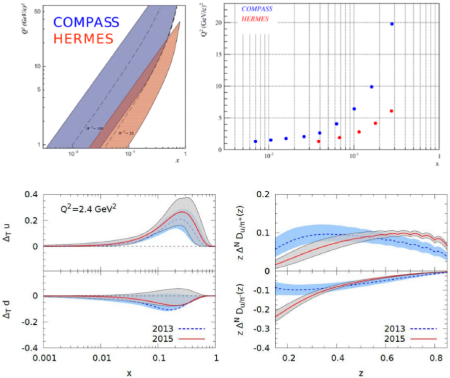
clearly positive gluon polarisation!

COMPASS, EPJC 77(2017) 209

Results for the Collins asymmetry for protons (SIDIS)

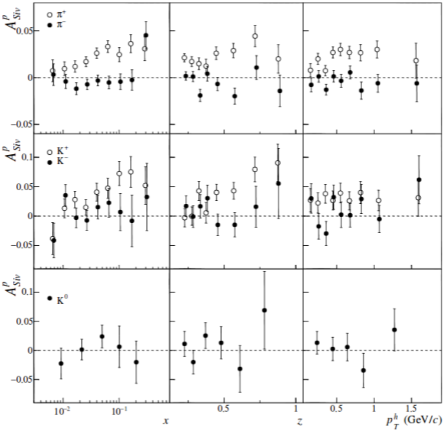


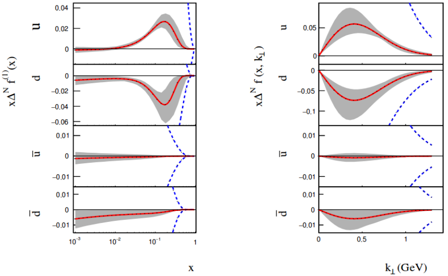
COMPASS, Phys.Lett. B744 (2015) 250



M. Anselmino et al., Phys.Rev. D92 (2015) 114023

- 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”)





COMPASS, Phys.Lett. B744 (2015) 250

M.Anselmino et al.,JHEP 1704(2017)046

- 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