QCD at the Electron-Ion Collider

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QCD - Old Challenges and New Opportunities

Wilhelm and Else Heraeus Physics School

Physikzentrum Bad Honnef, Sept. 24 – 30, 2017

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

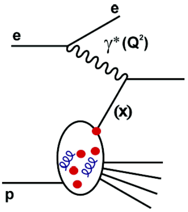
Freeman Dyson

(Theorist, mathematician; IAS, Princeton)

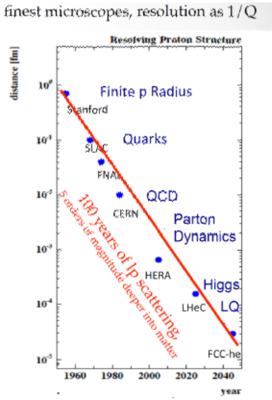
Physics areas in QCD

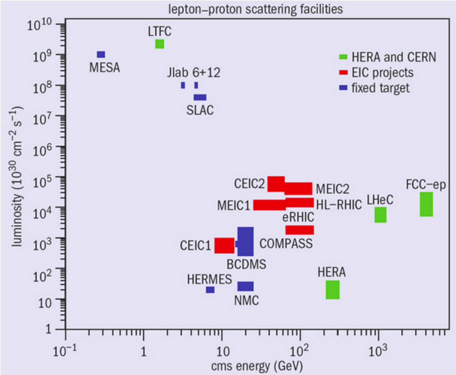
⇒⇒⇒⇒⇒⇒ QCD: richest of Standard Model Gauge Field Theories

- Deep Inelastic Scattering, DIS, and parton distribution functions (including spin)
- motion of partons in the nucleon (spin “puzzle”); nucleon “tomography”
- low-x and saturation,
- eA scattering,
- total γ-p and γ^*-p cross section,
- (exclusive) vector meson production,
- quark structure,
- compositeness (leptoquarks),
- diffraction -> pdfs,
- α_s measurement,
- jet measurements,
- heavy flavours production,
- F_L measurement,
- standard tests,
- ....



Machines: past, presence and future





EIC

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

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

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

polarization of electron and nucleon beams

LHeC FCC-ep

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

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

electron ion scattering on lead

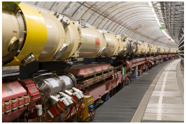
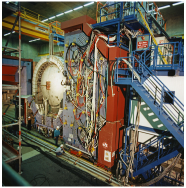
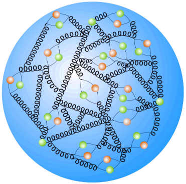
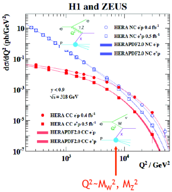
VHEeP

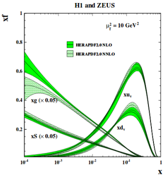
very high energy, $\sqrt{s}$ ~9 TeV
low luminosity, 10–100 pb^{-1}
electron–proton scattering

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

HadronElectronRing 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

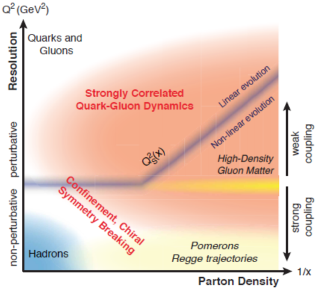
HERA's non-legacy

- 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

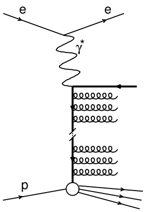
$\Rightarrow\Rightarrow\Rightarrow\Rightarrow\Rightarrow\Rightarrow$These limitations addressed by EIC (and LHeC)

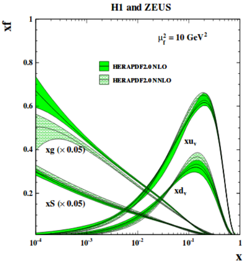
after P. Newman, DIS2016

Physics domains in (x, Q^2) plane: "Kwieciński plot"



"White paper2017", arXiv: 1708.01527v3





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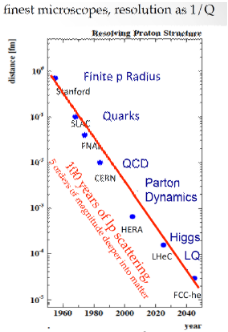
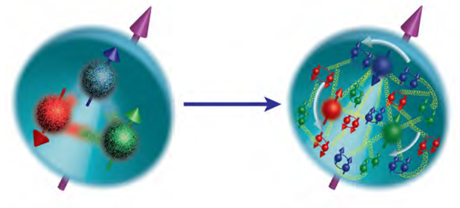
BFKL: $[\alpha_s \ln(1/x)]^n$
DGLAP: $[\alpha_s \ln(Q^2)]^n$

- At low x, energy in the γ^*p cms is large (large gluon cascades): $W^2_{\gamma^* p} = Q^2(1-x)/x$.
- Contributions from large $\alpha_s \ln(1/x)$ terms $\Rightarrow$ new evolution equations: BFKL, CCFM.
- At low x: strong increase of gluon density with decreasing x (cf. HERA data) $\Rightarrow$ gluon recombination (saturation).
- At $Q^2 \gg Q^2_{sat}$ nonlinear effects of parton evolution must be considered.

Evolution in understanding the proton structure

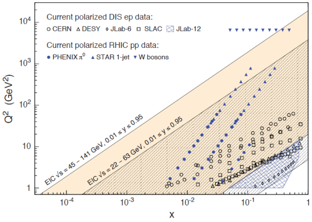


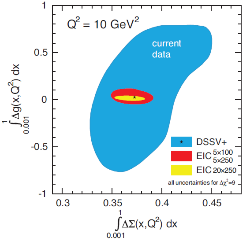
A.M. Cooper-Sarkar, Poetic7,2016



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

quark spins, gluon spins, quark&gluon orbital motion

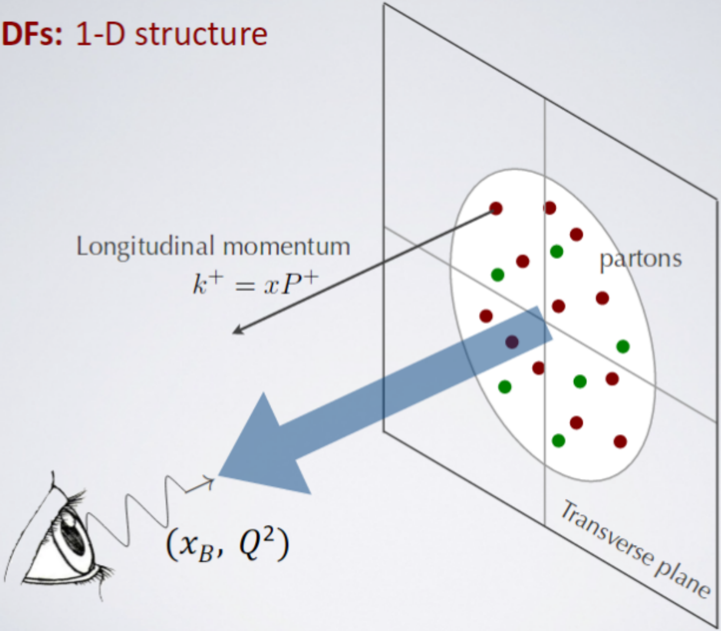




"White paper2017", arXiv: 1708.01527v3

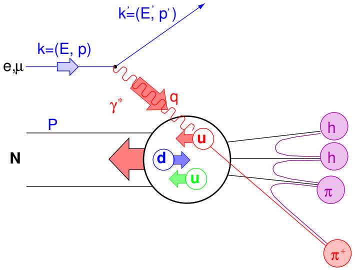
"White paper", arXiv:1212.1701

PDFs: 1-D structure



11 A. Bacchetta (Baryon 2013 Conference)

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

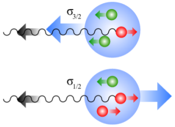


- $\dfrac{\mathrm{d}^2\sigma}{\mathrm{d}\Omega \mathrm{d}E'} = \dfrac{\alpha^2}{2Mq^4}\dfrac{E'}{E} L_{\mu\nu} W^{\mu\nu}$
- Symmetric part of $W^{\mu\nu}$ – unpolarised DIS, antisymmetric – polarised DIS
- Nominally $F_{1,2}$, $q(x, Q^2) \longrightarrow g_{1,2}$, $\Delta q(x, Q^2)$ where $q = q^+ + q^-$, $\Delta q = q^+ - q^-$, 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...

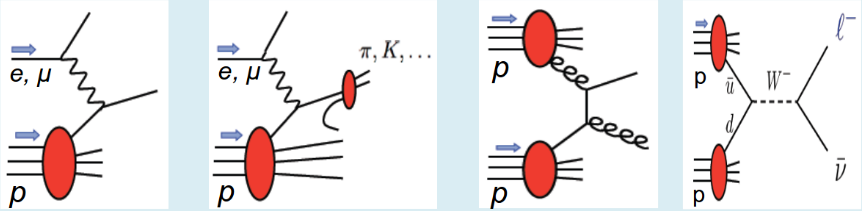
$Q^2 = -q^2$	γ^* virtuality
$x = Q^2/(2Pq)$	Bjorken variable
$y = Pq/(Pk)$	relative γ^* energy
$W = P + q$	γ^*-N cms energy

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



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

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

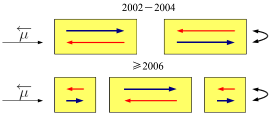
A. Bazilevsky, SPIN2016

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

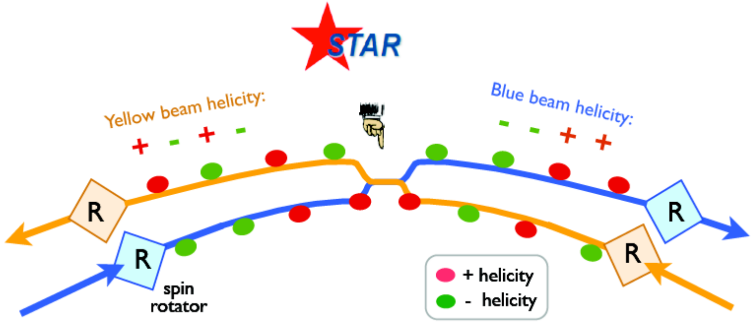
- At LO, semi–inclusive (SIDIS) asymmetry, A_1^h:

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

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

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)

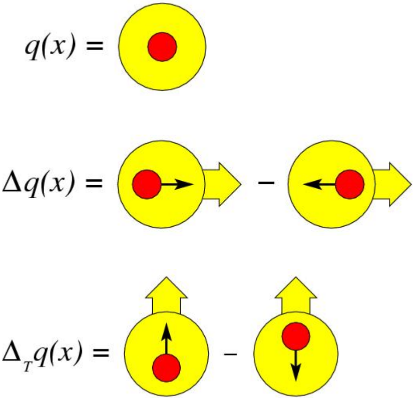
yields integrated over |eta|<1

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

Partonic structure of the nucleon; distribution functions

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



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

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 $\to$ $\mathbf{g_1(x, Q^2)}$).

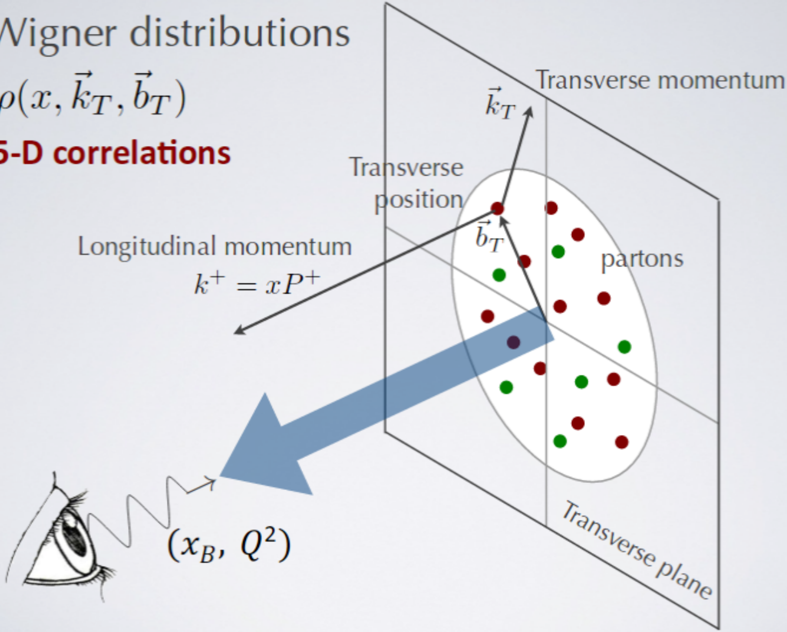
Difference in DF of quarks with spin parallel or antiparallel to the nucleon's spin in a transversely polarised nucleon;
poorly known (polarised DIS $\to$ $\mathbf{h_1(x, Q^2)}$).

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

Wigner distributions

$\rho(x, \vec{k}_T, \vec{b}_T)$

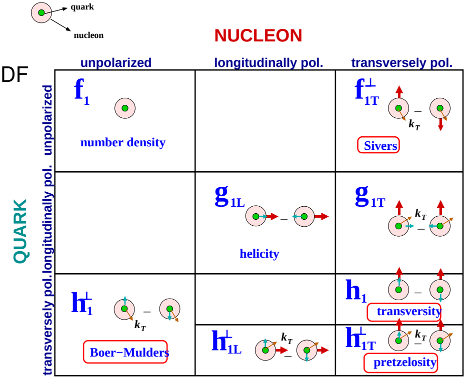
5-D correlations



11 A. Bacchetta (Baryon 2013 Conference) *see, e.g., C. Lorcé, B. Pasquini, M. Vanderhaeghen, JHEP 1105 (11)*

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$^\mathrm{target}$

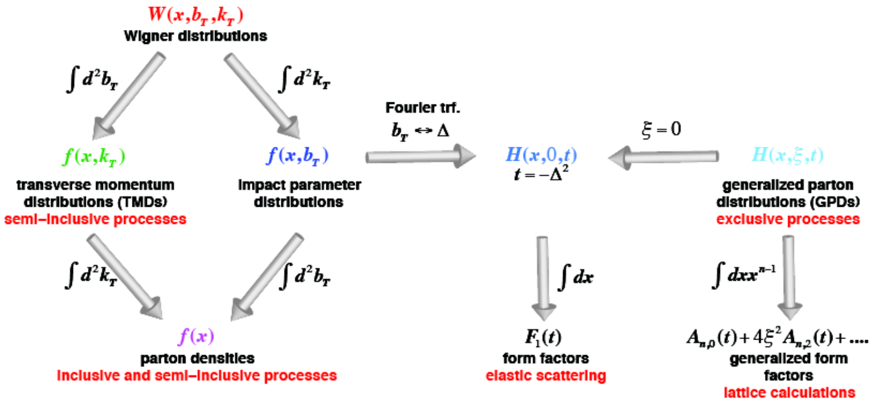


- OBS! Boer-Mulders and Sivers PDF are T-odd, i.e. process dependent

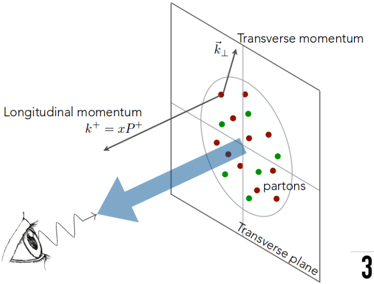
$$h_1^\perp(\mathrm{SIDIS}) = -h_1^\perp(\mathrm{DY}) \qquad f_{1T}^\perp(\mathrm{SIDIS}) = -f_{1T}^\perp(\mathrm{DY})$$

- 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!

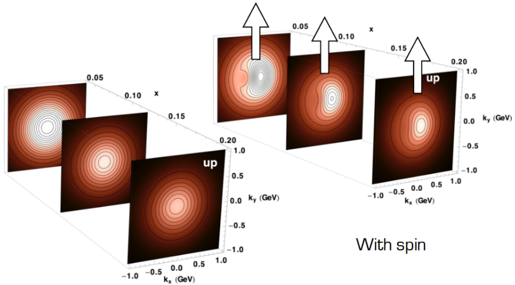
Descriptions of *pdf* ^{s} in the nucleon



From "White paper", arXiv:1212.1701



3D maps of partonic distribution

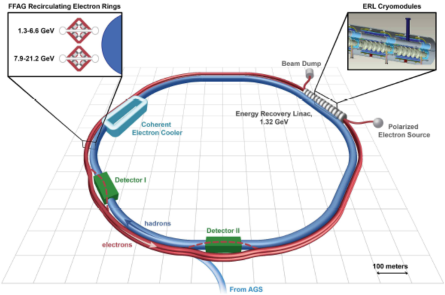


A. Bacchetta, DIS2017

EIC at BNL or JLab

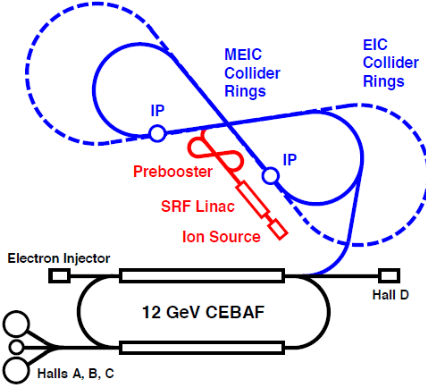
BNL (eRHIC)

Add energy recovery LINAC
(inside RHIC tunnel)



JLab (MEIC)

Add hadron rings “8” to CEBAF
(external)

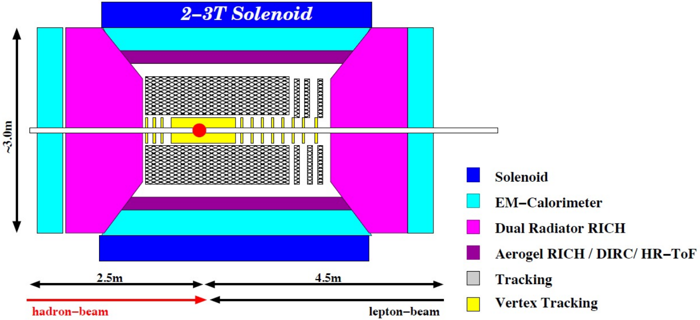


The White Paper, arXiv:1212.1701

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

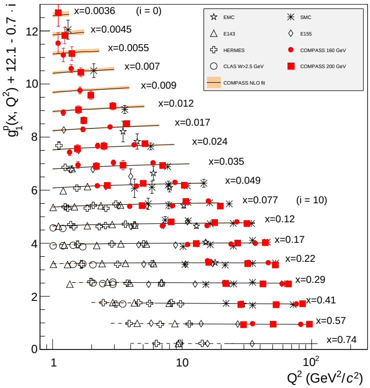


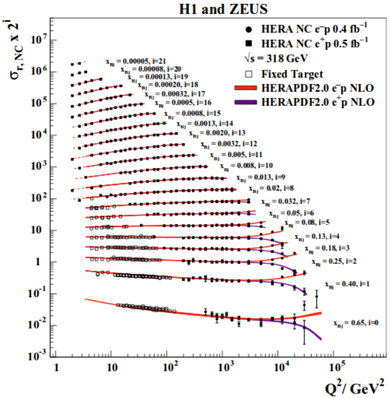
- Acceptance -5 $< \eta <$ 5 (large, comparable to CMS forward)
- PID: π, K, p, leptons
- Low material density (minimal multiple scattering and bremsstrahlung)
- Hadron beams: proton to lead

From “White paper”, arXiv:1212.1701

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

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



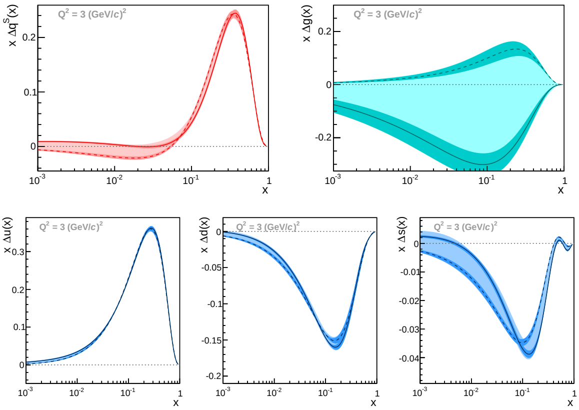


g_1 measurements little sensitive to Δg

COMPASS, PL B753 (2016) 18

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

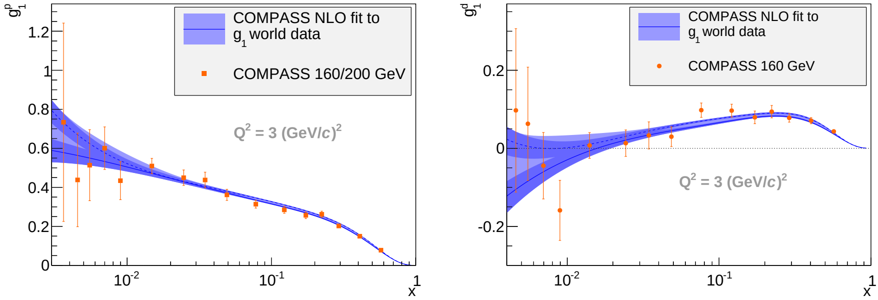
COMPASS NLO QCD fit to world data: results



- 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)

Phys. Lett. B753 (2016) 18

NLO QCD fit: results...cont'd



- g_1^{p} clearly positive at low x and raising with decreasing x
- g_1^{d} consistent with zero at low x ?

Phys. Lett. B753 (2016) 18

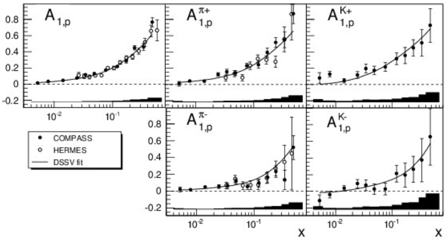
Semi-inclusive asymmetries and parton distributions

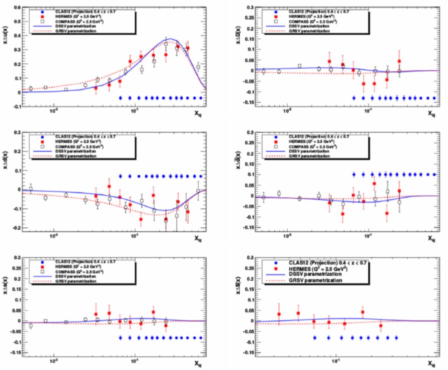
- COMPASS: measured on both proton and deuteron targets for identified, positive and negative pions and (for the first time) kaons

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.

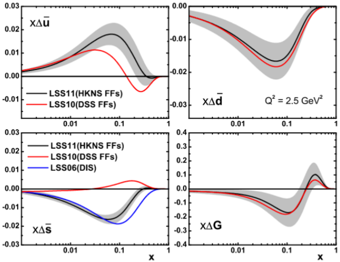
Polarisation of quark sea

- 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 SIDIS it is compatible with zero but depends upon chosen FFs.

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

  $\Longrightarrow$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 not unsymmetric:

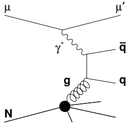
$$\int_{0.004}^{0.3} \left[\Delta\bar{u}(x,Q^2) - \Delta\bar{d}(x,Q^2)\right] dx = 0.06 \pm 0.04 \pm 0.02 \;\; @ \;\; Q^2 = 3 \text{ (GeV/}c)^2$$

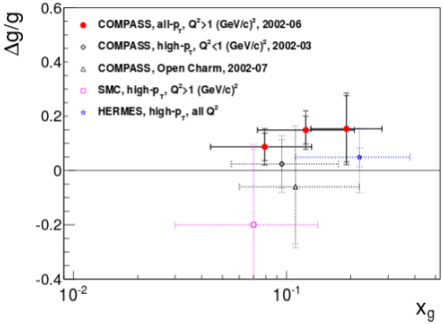
Thus the data disfavour models predicting $\Delta\bar{u} - \Delta\bar{d} \gg \bar{d} - \bar{u}$

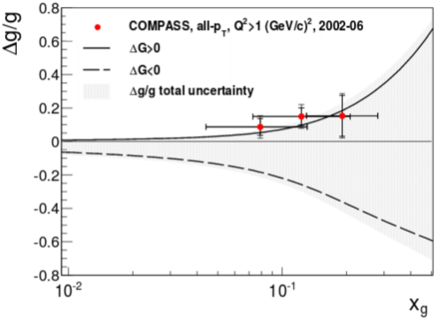
COMPASS, PL B680 (2009) 217

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)): $A_{\gamma N}^{PGF} \approx \langle a_{LL}^{PGF} \rangle \dfrac{\Delta g}{g}$







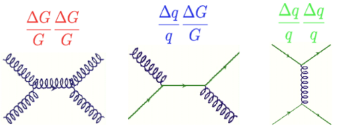
COMPASS from SIDIS on d for any $(p_T)_h$ and at LO:

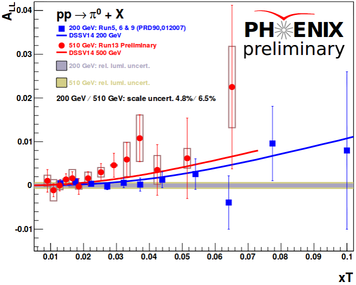
$$\Delta g/g = 0.113 \pm 0.038(\text{stat.}) \pm 0.036(\text{syst.}) \quad \text{at} \quad \langle Q^2 \rangle \approx 3\ (\text{GeV}/c)^2, \quad \langle x_g \rangle \approx 0.10$$

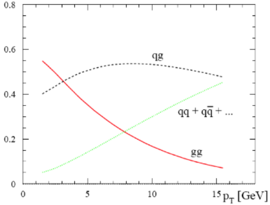
clearly positive gluon polarisation!

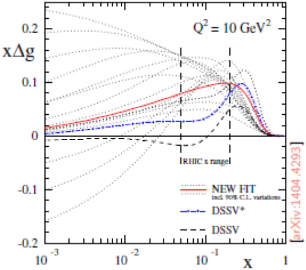
COMPASS, EPJC 77(2017) 209

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







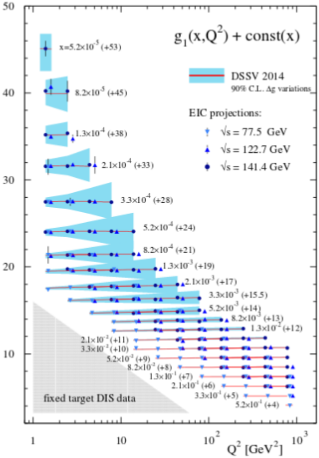


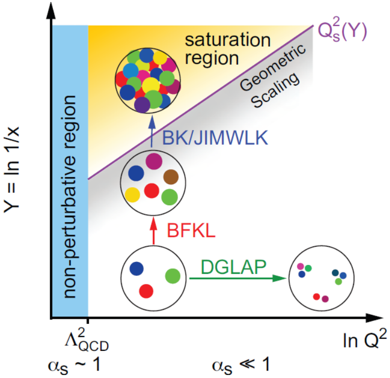
DSSV++ with 200 GeV data:

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

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

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



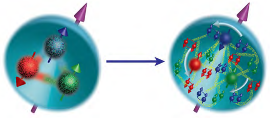


Errors statistical (EIC: expected, modest parameters); bands: from gluon helicity uncertainty

arXiv:1509.06489

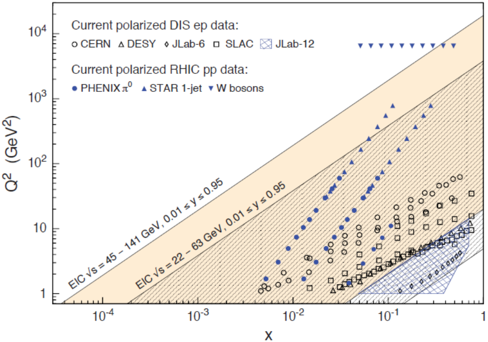
“White paper”, arXiv:1212.1701

Nucleon spin “puzzle” at EIC

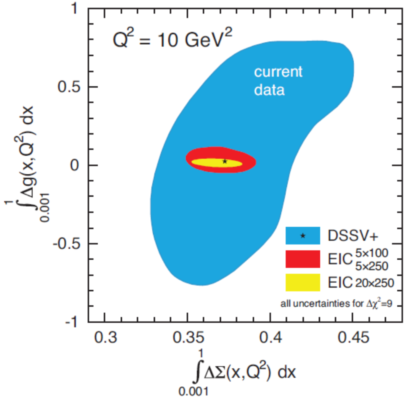


$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_z$$

quark spins — gluon spins — quark&gluon orbital motion



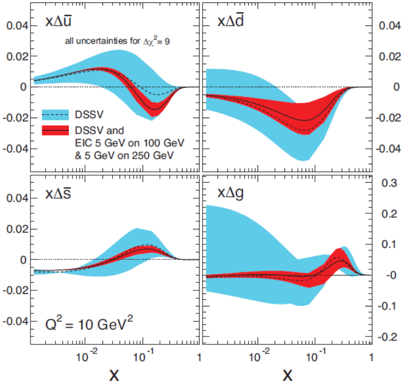
From “White paper2017”, arXiv:1708.01527v3



From “White paper”, arXiv:1212.1701

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

DIS + SIDIS

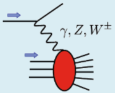


From “White paper”, arXiv:1212.1701

EW DIS

- $\Delta g(x)$ from scaling violation
- $\Delta\bar{u}, \Delta\bar{d}, \Delta s$ from SIDIS
- Flavor separation at high Q^2 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

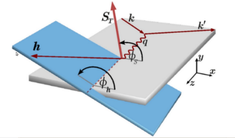
Properties of the transversity, $\Delta_T q(x)$ (or $h_1^q(x)$)

- 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 $\perp$ 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):

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



which in turn gives at LO and at collinear approach:

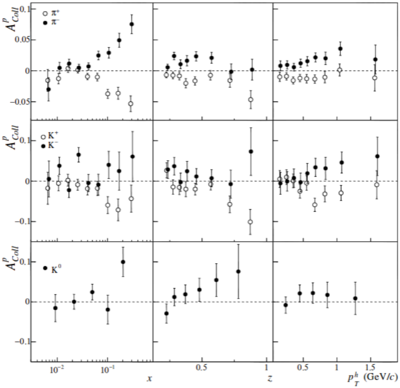
$$A_{Coll} \sim \frac{\sum_q e_q^2 \cdot \Delta_T q(x) \cdot \Delta_T^0 D_q^h(z, p_T^h)}{\sum_q e_q^2 \cdot q(x) \cdot D_q^h(z, p_T^h)}$$

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.

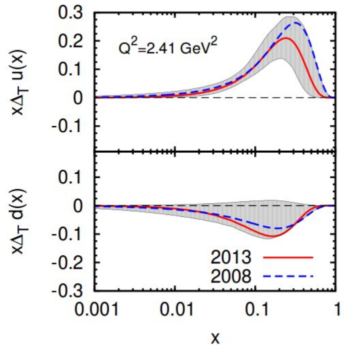
Sivers asymmetry ($\Phi_S = \phi_h - \phi_S$, correlation of $\perp$ nucleon spin with k_T of unpolarised q): if $\neq 0$ then $L_q \neq 0$ in the proton. Fundamental !

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

Results for the Collins asymmetry for protons



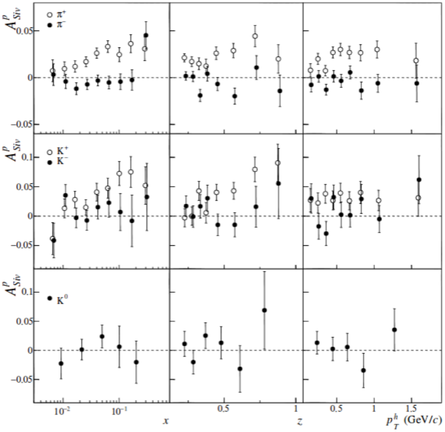
COMPASS, Phys.Lett. B744 (2015) 250

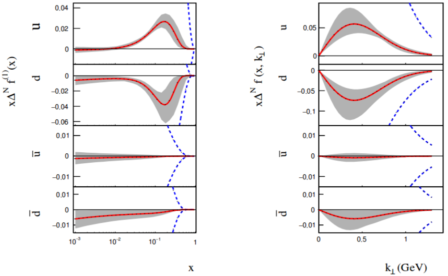


M. Anselmino et al., Phys.Rev. D87 (2013) 094019

- 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 + 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

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

Other azimuthal asymmetries

SIDIS x-section

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

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

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

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

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

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

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

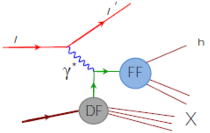
$$+S_T\lambda\left[\begin{array}{l}\cos(\phi_h-\phi_S)\left(\sqrt{(1-\varepsilon^2)}A_{LT}^{\cos(\phi_h-\phi_S)}\right)\\+\cos\phi_S\left(\sqrt{2\varepsilon(1-\varepsilon)}A_{LT}^{\cos\phi_S}\right)\\+\cos(2\phi_h-\phi_S)\left(\sqrt{2\varepsilon(1-\varepsilon)}A_{LT}^{\cos(2\phi_h-\phi_S)}\right)\end{array}\right]\Big\}$$

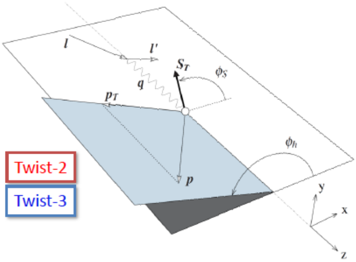
SSA ↑

DSA ↓

Twist-2

Twist-3



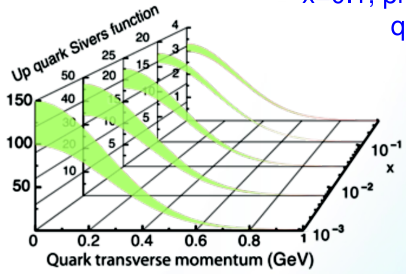


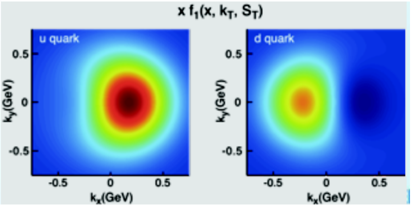
$$A_{U(L),T}^{w(\varphi_h,\varphi_s)}=\frac{F_{U(L),T}^{w(\varphi_h,\varphi_s)}}{F_{UU,T}+\varepsilon F_{UU,L}};\quad \varepsilon=\frac{1-y-\frac{1}{4}\gamma^2y^2}{1-y+\frac{1}{2}y^2+\frac{1}{4}\gamma^2y^2},\quad \gamma=\frac{2Mx}{Q}$$

22 October 2014 Bakur Parsamyan 8

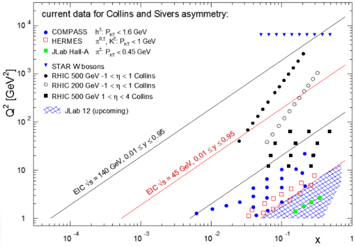
Sivers function at EIC

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





From “White paper”, arXiv:1212.1701

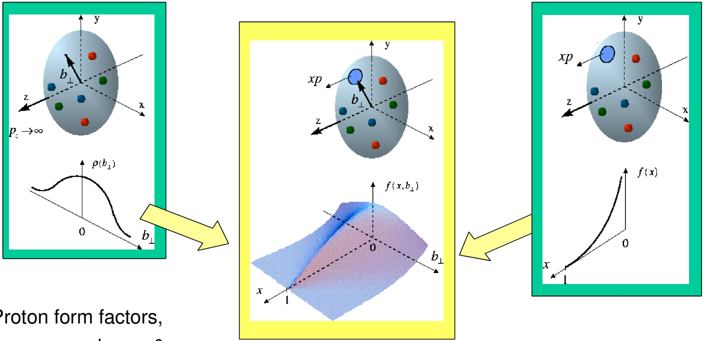


⟸ EIC acceptance for Sivers meas.

O. Eyser, SPIN2016

3D picturing of the proton *via* GPD

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



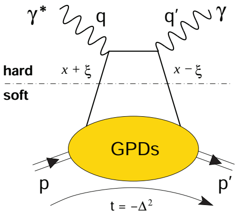
Proton form factors, transverse charge & current densities

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

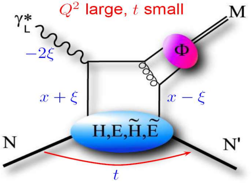


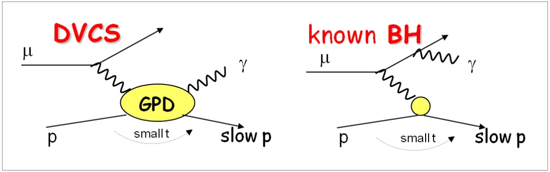
$Q^2 \to \infty$,
fixed $x_B, t \implies |t|/Q^2$ small

- 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 $x \neq x_B$!
- $H, \widetilde{H}$ conserve nucleon helicity
  $E, \widetilde{E}$ flip nucleon helicity
- H, E refer to unpolarised distributions
  $\widetilde{H}, \widetilde{E}$ refer to polarised distributions
- $H^q(x, 0, 0) = q(x), \quad \widetilde{H}^q(x, 0, 0) = \Delta q(x)$

- H, E accessed in vector meson production *via* A_{UT} asymmetries
- $\widetilde{H}, \widetilde{E}$ accessed in pseudoscalar meson production *via* A_{UT} asymmetries
- All 4 accessed in DVCS (γ production) in $A_C, A_{LU}, A_{UT}, A_{UL}$
- Integrals of $H, E, \widetilde{H}, \widetilde{E}$ over x give Dirac–, Pauli–, axial vector– and pseudoscalar vector form factors respectively.
- Important: $J_z^q = \frac{1}{2}\int dx\, x\, [H^q(x, \xi, t = 0) + E^q(x, \xi, t = 0)] = \frac{1}{2}\Delta\Sigma + L_z^q$ (X. Ji)

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

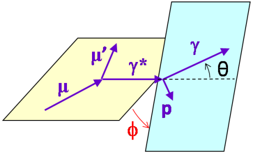




$$\mathrm{d}\sigma^{\mu p \to \mu p \gamma} = \mathrm{d}\sigma^{\mathrm{BH}} + (\mathrm{d}\sigma^{\mathrm{DVCS}}_{\mathrm{unpol}} + P_\mu \mathrm{d}\sigma^{\mathrm{DVCS}}_{\mathrm{pol}}) + e_\mu(\mathrm{Re}I + P_\mu \mathrm{Im}I)$$

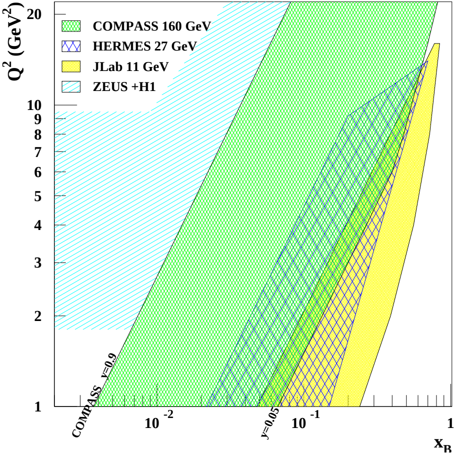
Observables (Phase 1):

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



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

GPD at COMPASS: data taking in 2016-2017

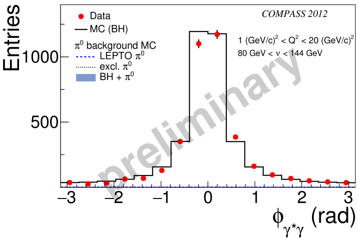


- CERN high energy muon beam
  - 100 - 190 GeV
  - 80% polarisation
  - $\mu^{+\leftarrow}$ and $\mu^{-\rightarrow}$ beams
- Kinematic range
  - between HERA and HERMES/JLab12
  - intermediate x (sea and valence)
- Separation
  - pure B-H @ low x_B
  - predominant DVCS @ high x_B
- Plans
  - DVCS
  -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

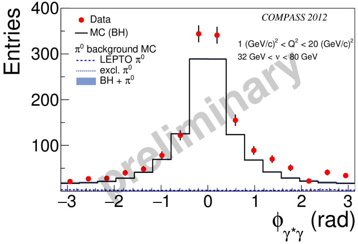
Test runs: 2008-9 and 2012; DVCS signal seen, full setup evaluated

COMPASS DVCS signal

$0.005 < x < 0.01$

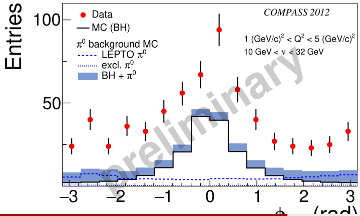


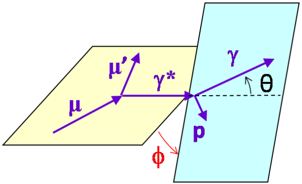
$0.001 < x < 0.03$



$x > 0.03$

$x > 0.03$

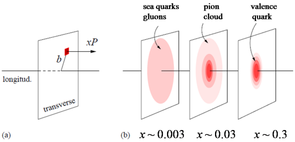




COMPASS DVCS signal,...cont'd

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

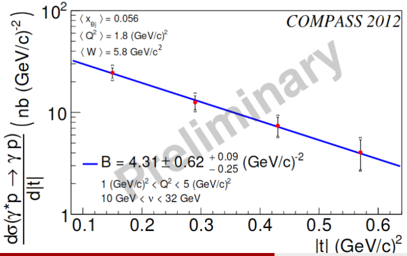
- Azimuthal dependence $A_{CS,U}$ compared to models

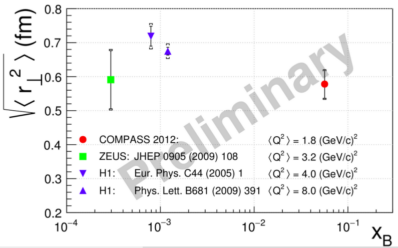


- Nucleon transverse imaging ("tomography"):

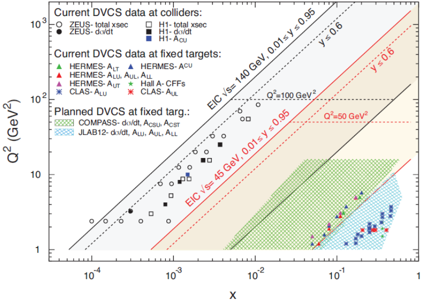
from $S_{CS,U} \Longrightarrow \frac{d\sigma^{DVCS}}{dt} \propto e^{-B(x_B)|t|}$ where at low x_B : $B(x_B) \approx \frac{1}{2}\langle r_\perp^2(x_B)\rangle$

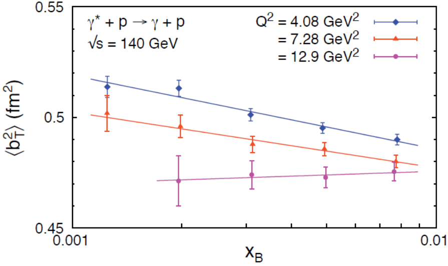
(here a simple ansatz was assumed: $B(x_B) = B_0 + 2\alpha' log\frac{x_0}{x_B}$





Acceptance of present and EIC DVCS

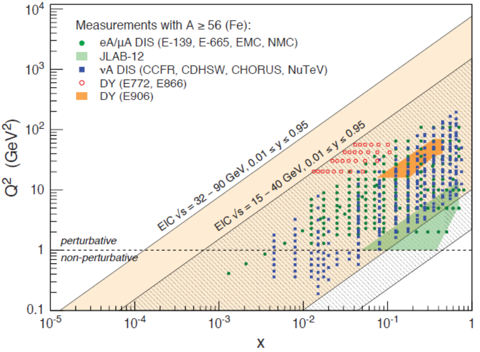




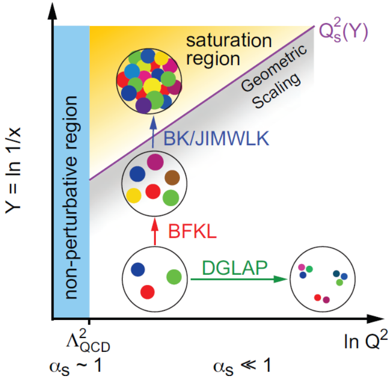
From “White paper”, arXiv:1212.1701

QCD studies through nuclei

- The EMC efect
- Extreme parton densities
- Tomography of the nucleus
- Behaviour of a colour charge in matter

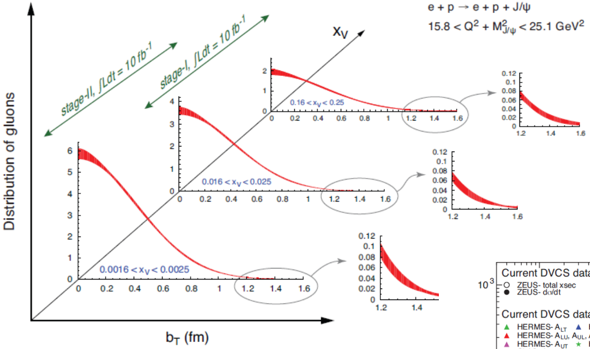


From "White paper2017", arXiv: 1708.01527v3

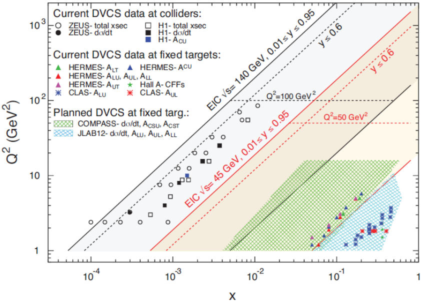


From "White paper", arXiv:1212.1701

3D picturing of nucleon (or GPDs) at EIC

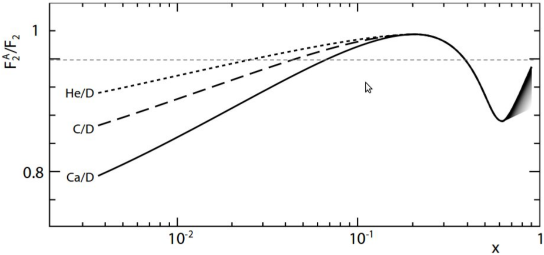


$$x_V = x\left(1 + \frac{M^2_{J/\Psi}}{Q^2}\right)$$



From “White paper”, arXiv:1212.1701

QCD through nuclei: the 'EMC effect'



- Here: $R \equiv \dfrac{F_2^A}{F_2} \equiv \dfrac{(F_2^A)/A}{(F_2^d)/2}$, i.e. nuclear structure functions "per nucleon".
- For $x \lesssim$ 0.8, "the EMC effect" (a shift in the quark momentum distributions towards lower x when nuclens are bound); discovered by EMC, 1983. Observe a nuclear "shadowing" for R $<$ 1, at lowest x
- At largest $x \Longrightarrow$ scaterring on a nucleon cluster?

From M.A. Thomson, Michaelmas Term 2011

QCD through nuclei: the ‘EMC effect’,... cont’d

CERN Courier May 2013

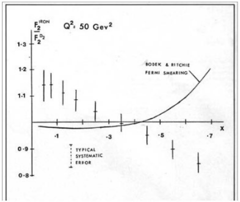
EMC effect

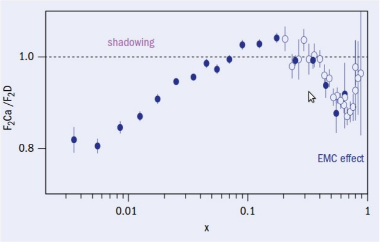
The EMC effect still puzzles after 30 years

Thirty years ago, high-energy muons at CERN revealed the first hints of an effect that puzzles experimentalists and theorists alike to this day.

Contrary to the stereotype, advances in science are not typically about shouting “Eureka!”. Instead, they are about results that make a researcher say, “That’s strange”. This is what happened 30 years ago when the European Muon collaboration (EMC) at CERN looked at the ratio of their data on per-nucleon deep-inelastic muon scattering off iron and compared it with that of the much smaller nucleus of deuterium.

The data were plotted as a function of Bjorken-x, which in deep-inelastic scattering is interpreted as the fraction of the nucleon’s



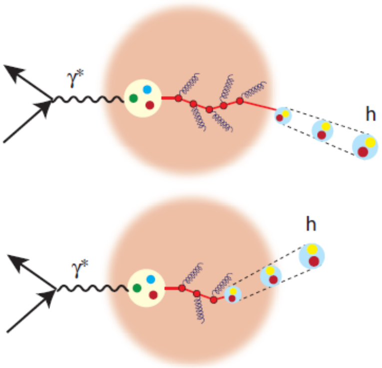


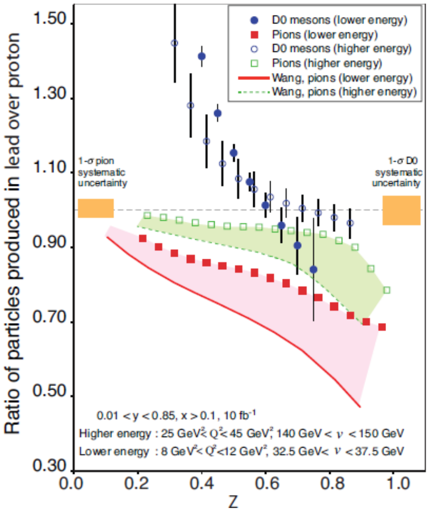
original EMC plot for $F_2^{\rm Fe}/F_2^{\rm D}$

NMC (filled symbols) and SLAC data for $F_2^{\rm Ca}/F_2^{\rm D}$

From CERN Courier, May 2013

QCD through nuclei: colour charge in matter

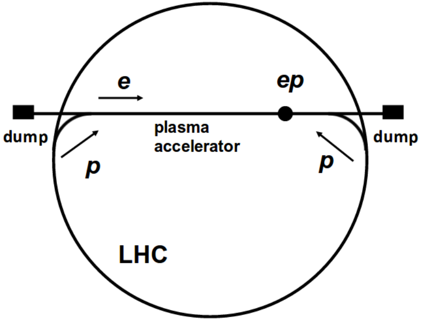




From “White paper”, arXiv:1212.1701

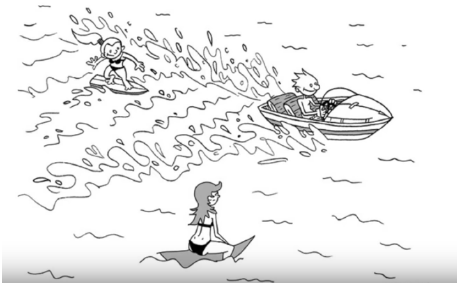
VHEeP

A very high energy electron–proton collider

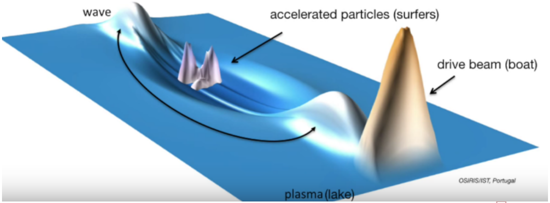


hep-ex/1606.00783v2

Principle of plasma acceleration E. Gschwendtner, TEDxCERN, 2015



Plasma Wakefield Acceleration Principle



AWAKE @ CERN

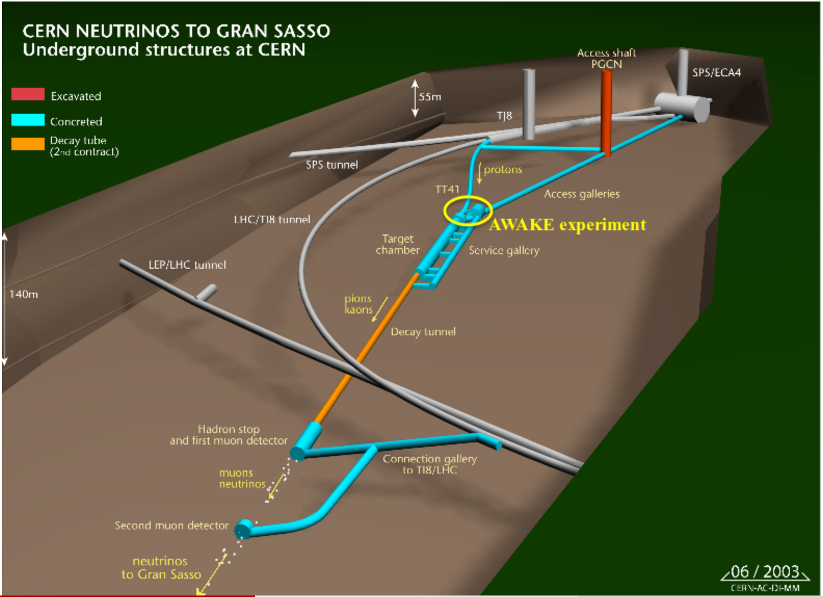
The Advanced Proton Driven Plasma Wakefield Acceleration Experiment.

The Advanced Proton Driven Plasma Wakefield Acceleration Experiment (AWAKE) aims at studying plasma wakefield generation and electron acceleration driven by proton bunches. It is a proof-of-principle R&D experiment at CERN and the world´s first proton driven plasma wakefield acceleration experiment. The AWAKE experiment will be installed in the former CNGS facility and uses the 400 GeV/c proton beam bunches from the SPS. The first experiments will focus on the self-modulation instability of the long
(rms ~12 cm) proton bunch in the plasma. These experiments are planned for the end of 2016. Later, in 2017/2018, low energy (~15 MeV) electrons will be externally injected into the sample wakefields and be accelerated beyond 1 GeV.

AWAKE is a proof-of-concept acceleration experiment with the aim to inform a design for high energy frontier particle accelerators and is currently being built at CERN. The AWAKE experiment is the world´s first proton driven plasma wakefield acceleration experiment, which will use a high-energy proton bunch to drive a plasma wakefield for electron beam acceleration. A 400 GeV/c proton beam will be extracted from the CERN Super Proton Synchrotron, SPS, and utilized as a drive beam for wakefields in a 10 m long plasma cell to accelerate electrons with amplitudes up to the GV/m

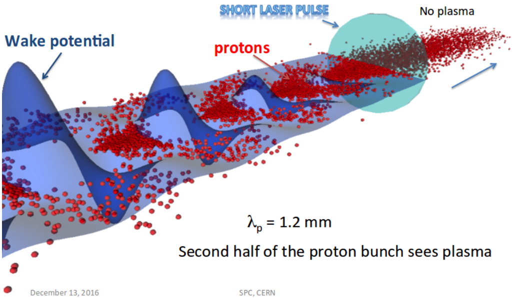
AWAKE @ CERN... cont'd

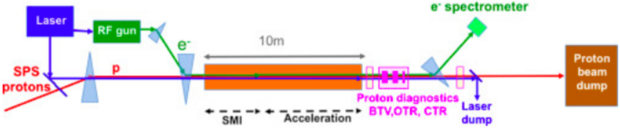
A. Caldwell, SPC CERN, 13.XII.2016



AWAKE @ CERN... cont'd

A. Caldwell, SPC CERN, 13.XII.2016





Drivers:
PW lasers today, ~40 J/Pulse

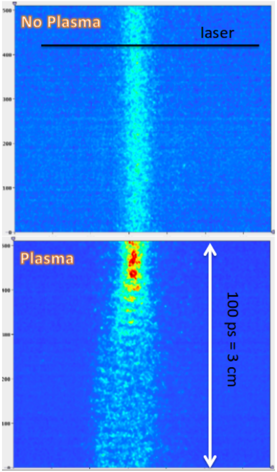
FACET, 30J/bunch

SPS 20kJ/bunch
LHC 300 kJ/bunch

Witness:
10^{10} particles @ 1 TeV ≈ few kJ

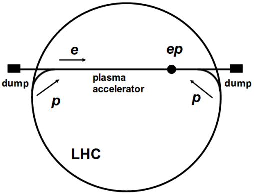
- Accelerating power up to 1 GV/m ($\sim$ 1000$\times$ more than present)

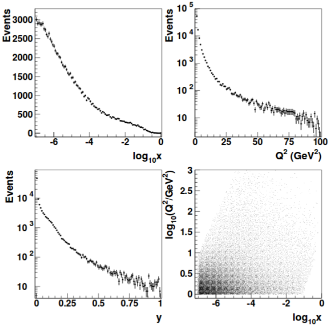
Phase I $\Longrightarrow$ SUCCESS! (Dec. 2016)



VHEeP kinematics and basic parameters

- ep cms energy: 3 TeV (e) + 7 TeV (p, LHC) $\Longrightarrow \sqrt{s} \sim 9$ TeV
  (6$\times$ higher than proposed for LHeC; 30$\times$ higher than HERA)
- luminosity: $\sim 10 - 100$ pb^{-1} over lifetime (1000 – 100 $\times$ less than HERA)
  lower OK for low x physics; higher needed for BSM (typically @ high Q^2)
- plasma accelerator must be $\lesssim$ 4 km long
- ARIADNE MC for $Q^2 > 1$ GeV^2, $W^2 > 5$ GeV^2, $x > 10^{-7}$, 0.01 pb^{-1}

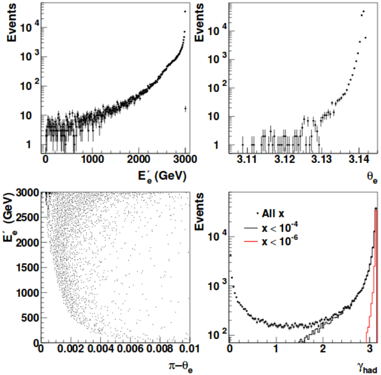




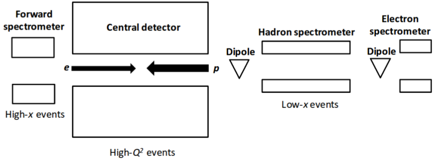
x_{min} : $1000\times$ less than @ HERA!

hep-ex/1606.00783v2

VHEeP kinematics and basic detector design



Same simulation parameters and conditions as before



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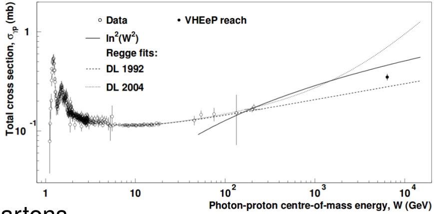
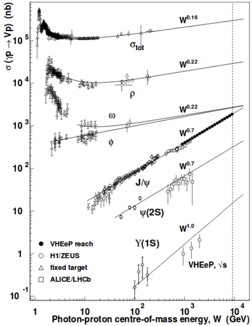
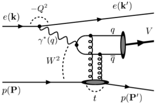
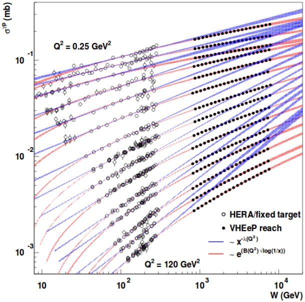
- **Total $\gamma - p$ cross section:**
  resolving models,
  constrain cosmic-ray simulations



- **Vector meson production:**
  particularly sensitive to saturation of partons





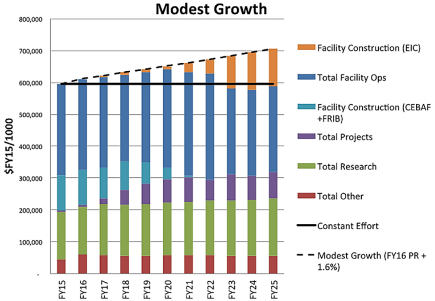


hep-ex/1606.00783v2

Status of EIC and VHEeP

EIC: The White Paper (arXiv:1212.1701), EIC Users Group http://www.eicug.org; construction recommendation NSAC LRP2

- 2018: acceptation by DOE
- 2020: site selection
- 2023/24: start construction
- 2030: physics operation



igure 10.4: DOE budget in FY 2015 dollars for the Modest Growth scenario.

VHEeP: e.g. arXiv:1606.00783v2, first meeting of physics community in VI. 2017. proton-driven wakefield acceleration achieved XII.2016! Exp. AWAKE @ CERN

Take-away menu

New e–p machine(s) planned to develop QCD, e.g. (in increasing $\sqrt{s}$ order):

☺

- **EIC:** Electron–Ion Collider, BNL or JLab
  (alternatives: eRHIC/MEIC)
  Polarised beams, high lumi, heavy ions, as good as approved, operational 2028
  "Imaging" device!

- **LHeC:** Large Hadron–electron Collider, CERN
  (also: FCC-ep: Future Circular Collider-ep)
  Unpolarised beams, high luminosity, some ions

?

- **VHEeP:** Very High Energy electron–Proton (collider), CERN
  VERY attractive technology, unprecedented kinematic reach, unpolarised beams, low luminosity