Quark Structure of the Nucleon

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Gordon Research Conferences
Photonuclear Reactions: From Quarks to Nuclei

Holderness, August 10-14, 2014

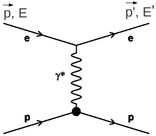
Outline

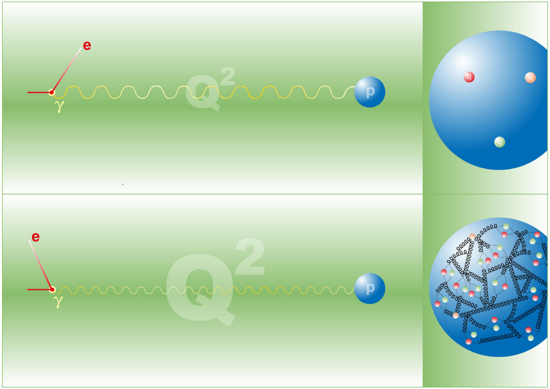
Outline

Resolution of a microscope

Given by an invariant Q^2:

$$Q^2 = -q^2 = (\vec{p} - \vec{p}\,')^2 - (E - E')^2 = -M^2_{\gamma^*} \neq 0 \;!$$

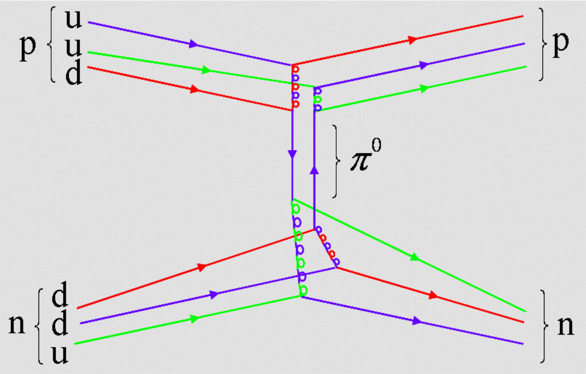




$Q^2 \lesssim$ 1 (GeV/c)^2

$Q^2 \gg$ 1 (GeV/c)^2

Residual strong interaction (in a nucleus)



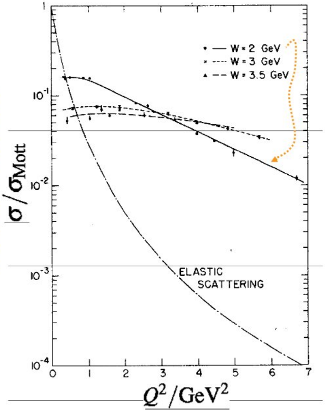
Final state quarks "dress up" into hadrons $\Longrightarrow$ fragmentation.

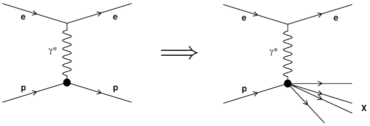
Factorization theorem: physics particles' cross section
= (calculable QCD parton cross-section) $\otimes$ (universal long-distance functions:
parton distributions and fragmentation functions)

Towards inelastic electron – nucleon scattering

- At large Q^2, elastic form factors, $G_{E,M}(Q^2) \to 0$ and inelastic scattering becomes more probable than the elastic.
- Now $Q^2 \neq 2M\nu$ (or $x \neq 1$) and a second variable, apart of Q^2 is needed to describe an inelastic scattering, e.g. $\nu = E - E'$ or $x = Q^2/2M\nu$.

M.Breidenbach et al., Phys. Rev. Lett. 23 (1969) 935

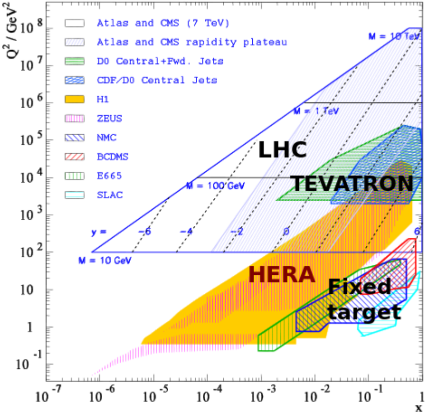


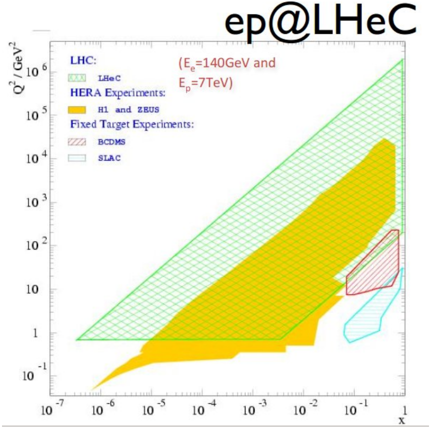


Scattering from point-like components in the proton!

From: M.A. Thomson, Michaelmas Term 2011

Acceptance of nucleon structure experiments

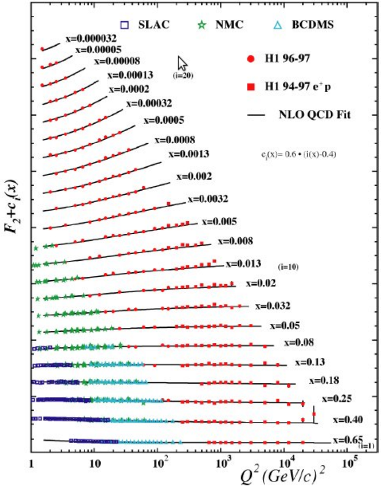




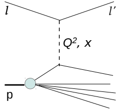
Electron beams: high statistics, high systematics (radiative processes), “cheap”
Muon beams: low statistics, low systematics, “expensive”

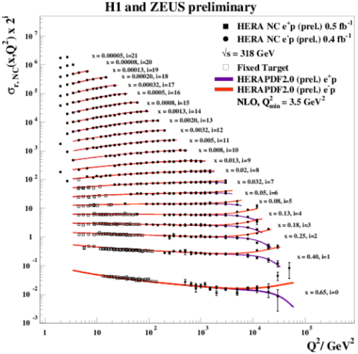
Proton beams: complicated analysis.

Structure functions



Structure function $F_2(x,Q^2)$

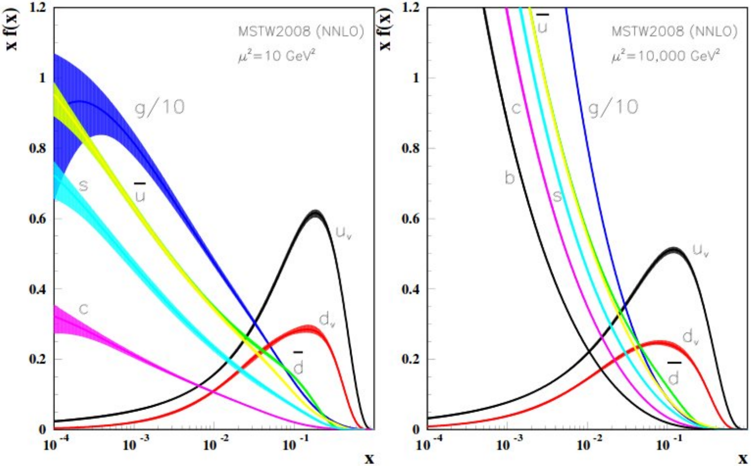




Electroweak effects visible (γ^*/Z exchange)

Outline

Parton distributions from scaling violation

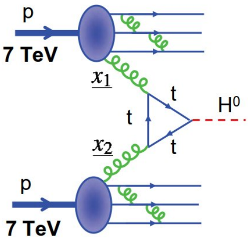


From Particle Data Tables, 2012

Universality of parton distributions

PDFs are universal!

Example of the LHC Higgs particle production in a “gluon–gluon fusion”:



$$\sigma(pp \to HX) \sim \int_0^1 \int_0^1 g(x_1)g(x_2)\sigma(gg \to H)dx_1dx_2$$

Observe: uncertainty in $g(x)$ leads to 5% uncertainty in the cross section!

How do we get PDFs? Measure $F_2(x, Q_0^2)$ for “all” values of x and assume a functional x dependence. Fit its coefficients at any Q^2 from QCD predictions of the Q^2 dependence of F_2 (“QCD evolution).

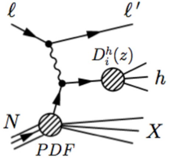
From M.A. Thomson, Michaelmas Term 2011

Outline

Other universal functions: fragmentation functions, $D_q^h(z, Q^2)$

- Studied through measurements of charged (single-) hadron multiplicities. At LO:

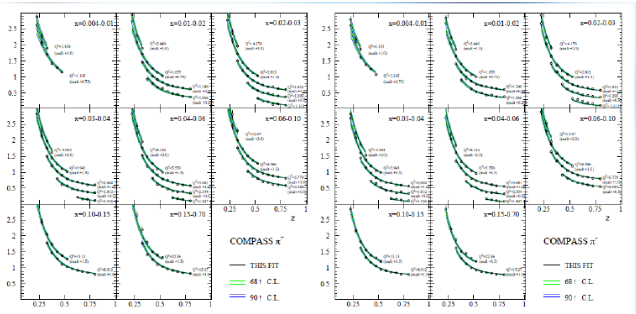
$$M^h(x,Q^2,z) = \frac{\frac{d\sigma_{\mathrm{SIDIS}}}{dx\,dz\,dQ^2}}{\frac{d\sigma_{\mathrm{DIS}}}{dx\,dQ^2}} = \frac{\Sigma_q e_q^2 \left[q(x,Q^2)D_q^h(Q^2,z) + \bar{q}(x,Q^2)D_{\bar{q}}^h(Q^2,z)\right]}{\Sigma_q e_q^2 \left[q(x,Q^2) + \bar{q}(x,Q^2)\right]}$$



$$z = \frac{E_h}{\nu}$$

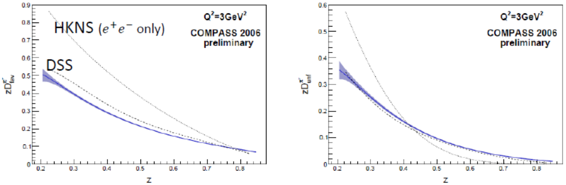
- High precision Single Inclusive e^+e^- Annihilation data do not separate q and $\bar{q}$ and only access charge sum of FF for a hadron h.
- Measurements at a fixed, large ($\sim M_Z$), scale, except BELLE (Q^2 ~10 GeV^2).
- Inclusive single hadron production by RHIC $\Longrightarrow$ improve constraints on gluon FF.
- Lepton–nucleon DIS: lower values and wide range of scales, sensitivity to parton flavour and hadron charge ($\Longrightarrow$ new data of HERMES, COMPASS).
- Global NLO analyses, e.g.: DSS, Phys. Rev. D **75** (2007) 114010.

Charged (single-) hadron multiplicities; identified pions



From R. Sassot, Workshop on FF, Bloomington 2013

Isospin, charge symmetry, ... leave 2 FF, $D^i(z, Q_0^2) = N_i z^{\alpha_i}(1-z)^{\beta_i}[1+\gamma_i(1-z)^{\delta_i}]$:



Outline

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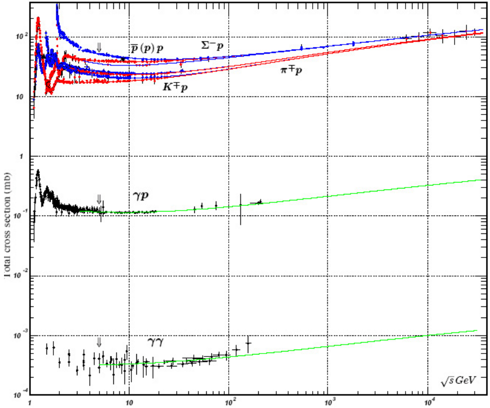
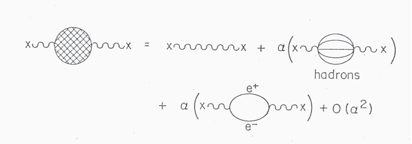
γ^* behaviour

Experimental fact: photon interactions are often similar to those of a hadron

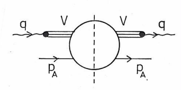


From Particle Data Tables, 2012

Contributions to the self-energy of a physical photon:



The hadron–type interaction:



V has quantum numbers of the photon!

Nucleon structure at low values of x

Hadrons in the γ fluctuation: either a pair of $q\bar{q}$ or a hadron of $J^P = 1^-$ (i.e. ρ, ω, Φ, J/Ψ,...). Observe that if ν is much larger than mass of the fluctuation, m, then the hadronic fluctuation traverses

$$d(\nu, Q^2) \sim \frac{2\nu}{Q^2 + m^2} \approx 80 \ \text{fm!!!} \ \ (\text{for } Q^2 = 0, \nu = 100\,\text{GeV}, m^2 = 0.5\,(\text{GeV}/c)^2). \quad (1)$$

But a highly virtual γ^*, $Q^2 \to \infty$, may have no time to develop a structure before the interaction:

$$d(\nu, Q^2) \sim \frac{2\nu}{Q^2 + m^2} \to \frac{\nu}{Q^2} \to 0 \quad (2)$$

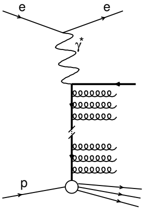
However the γ^* structure is visible! Observe that

$$\frac{2\nu}{Q^2} = \frac{1}{Mx} \quad (3)$$

and if $x \ll 1$ then $d(\nu, Q^2)$ may be very high independently of Q^2
(e.g. @ x=0.001, $d \sim$ 200 fm! proton sea quarks outside proton ???)

Nucleon structure at low values of x, ...cont’d

Low $x \equiv$ large parton densities, due to QCD processes, e.g.:

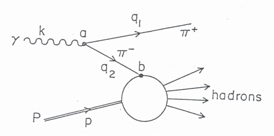


Who is probing whom?? (A. Levy)

Solution: cross section is Lorentz invariant but time developement is not. (L. Frankfurt)

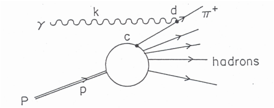
So γ^* and proton are probing each other and we are measuring the interation as a whole. A consequence: @ low x, F_2^P and F_2^γ are related!

Two ways of γ interactions (observe time ordering!)



dominant if $\nu \to \infty$ and target at rest

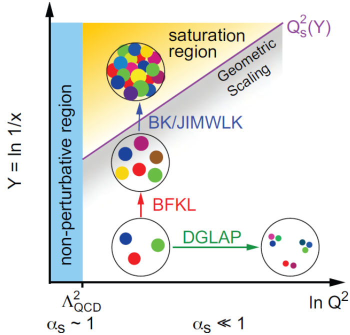
photon structure

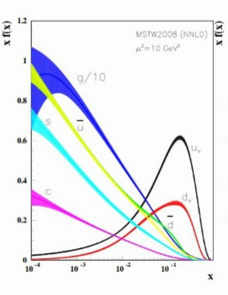


dominant in the ∞ target momentum system and finite ν

proton structure (DIS)

Physics domains: "Kwieciński plot"





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

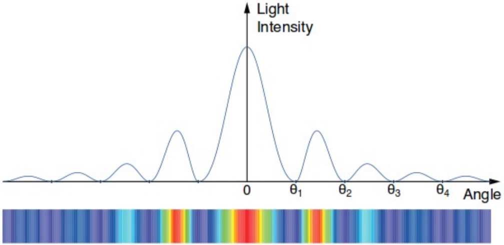
- At low x, energy in the γ^*p cms is large (large gluon cascades): $W^2_{\gamma^* p} = Q^2(1-x)/x$.
- Contributions from large $\alpha_s \ln \frac{1}{x}$ terms $\Rightarrow$ new evolution equations: BFKL, CCFM.
- At low x: strong increase of gluon density with decreasing x (cf. HERA data) $\Rightarrow$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

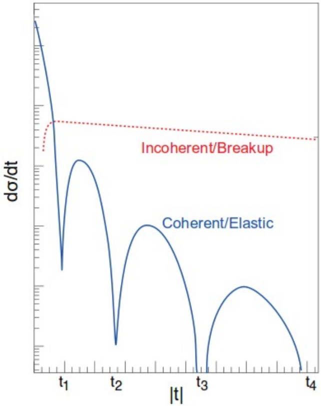
Left figure from "White paper", arXiv:1212.1701

Outline

Diffraction in optics

Diffractive pattern of light on a circular disk and diffractive cross-section in HEP;
$\vartheta_i \sim 1/(kR), \quad |t| \approx k^2\vartheta^2$ (k - wave number, R - radius)

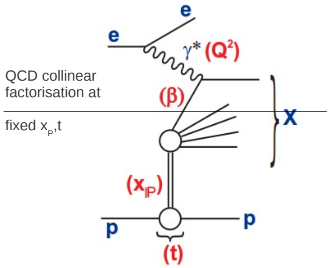




From EIC White Paper arXiv:1212.1701

Definition of diffraction in high energy physics

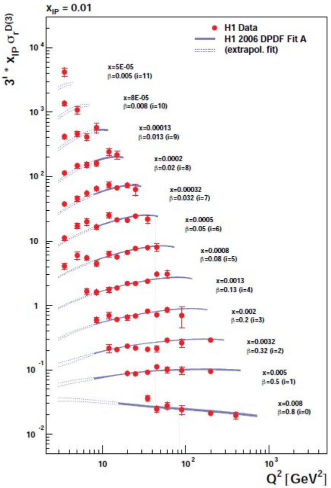
- No quantum number exchange in a process.
  Target (or both hadrons) emerges intact. "Pomeron, $\mathbb{P}$, exchange".
- Cross section not decreasing with energy.
- Secondary features: small t and large Δy (forward !) in final state hadrons.

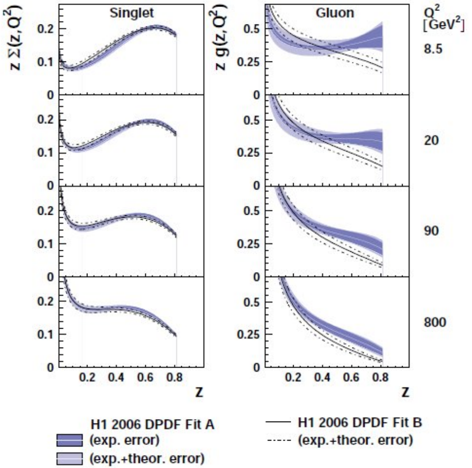


reaction described by 4 variables:
$Q^2, x, \beta = x/x_{\mathbb{P}}, t$

- Soft/hard diffraction $\Longrightarrow$ diffractive parton distributions! Universality?
  Rapidity gap survival probability for hadron–hadron.
- Diffractive PDF, $f_i^D = f_i^D(x, Q^2, x_{\mathbb{P}}, t)$.
  Within "vertex factorisation", $f_i^D(x, Q^2, x_{\mathbb{P}}, t) = f_{\mathbb{P}/p}(x_{\mathbb{P}}, t) \cdot f_i(\beta = x/x_{\mathbb{P}}, Q^2)$

Diffraction: brief experimental status

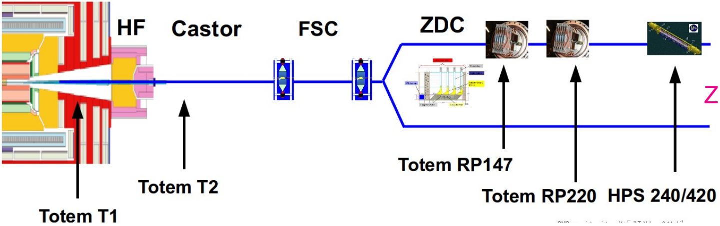




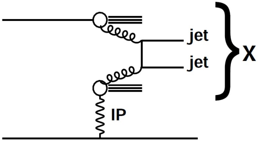
From hep-ex/0606004

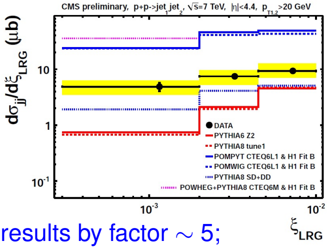
Forward physics at LHC

- LHC "forward" arrangements (not to scale):



ZDC: $|\eta| \gtrsim 8$





- Diffractive MC models overestimate the results by factor ~ 5; gap survival probability ?

After G. Brona (2012) and CMS PAS FWD-10-004

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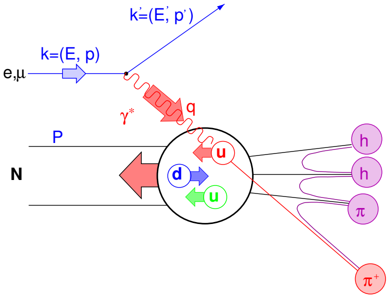
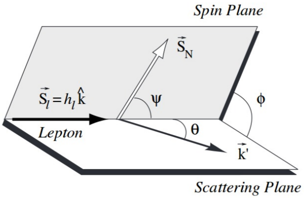
Introducing spin

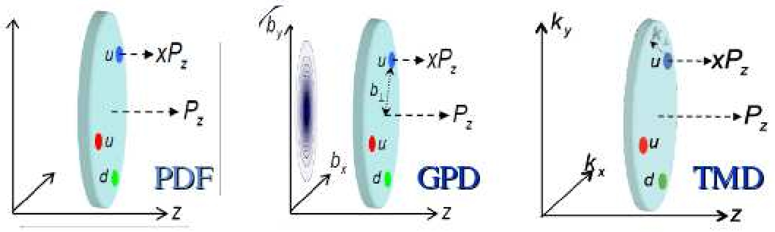




- $\frac{d^2\sigma}{d\Omega dE'} = \frac{\alpha^2}{2Mq^4}\frac{E'}{E}L_{\mu\nu}W^{\mu\nu}$
- Symmetric part of $W^{\mu\nu}$ – unpol. DIS, antisymmetric – polarised DIS
- Nominally $F_{1,2}, \quad q(x) \longrightarrow g_{1,2}, \quad \Delta q(x)$ but...
- ...anomalous gluon contribution to $g_1(x)$
- ...$g_2(x)$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

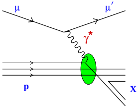
$$\sigma = \bar{\sigma} - \frac{1}{2}h_l\left(\cos\psi\Delta\sigma_{\parallel} + \sin\psi\cos\phi\Delta\sigma_{\perp}\right)$$

Transverse Momentum Dependent (TMD) distributions

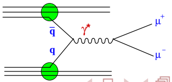


- parton intrinsic k_{T} taken into account
- related to quark angular momentum, L!
- at COMPASS studied in 2 ways:
  - semi-inclusive DIS (polarised muons on unpolarised/transversely polarised target)
  - In the future: Drell-Yan process (π beam on unpolarised/transversely polarised tgt.)

  Important: SIDIS and DY measured at overlapping hase space!



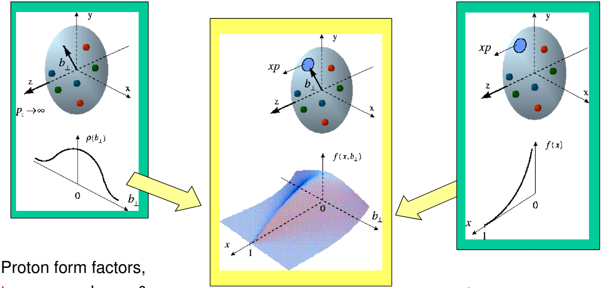
SIDIS

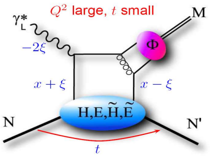


DY

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

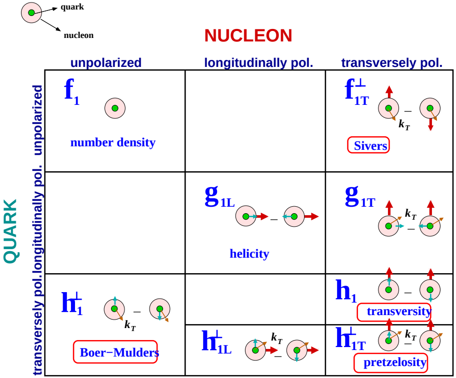
Structure functions, quark longitudinal momentum & helicity distributions

- Four GDPs $(H, E, \widetilde{H}, \widetilde{E})$ for each flavour and for gluons
- All depend on 3 variables: x, ξ, t;   DIS @ $\xi = t = 0$
- $H, \widetilde{H}$ conserve nucleon helicity; $E, \widetilde{E}$ flip nucleon helicity
- H, E refer to unpolarised distributions; $\widetilde{H}, \widetilde{E}$ refer to polarised distr.

After V.D. Volker, LANL 2007

Partonic structure of the nucleon; distribution functions

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



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

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

change of sign to provide gauge invariance!

- OBS! transversity PDF is chiral-odd (may only be measured with another chiral-odd partner, e.g. fragmentation function).
- Boer-Mulders, Sivers and transversity $(h_1^\perp, f_{1\mathrm{T}}^\perp, h_1)$ will be measured in COMPASS II

Outline

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

- Inclusive asymmetry, A_{meas}:

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

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

$$\omega_D = 0.05 \pm 0.01$$

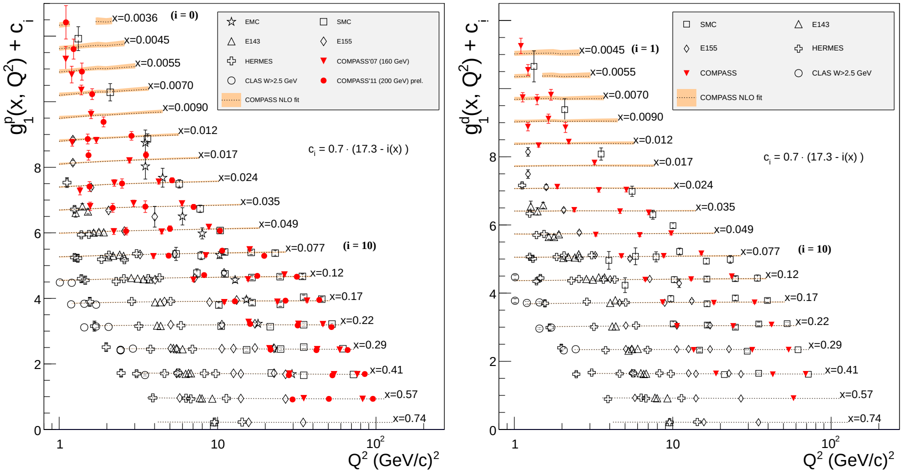
- LO SIDIS, A_1^h:

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

Outline

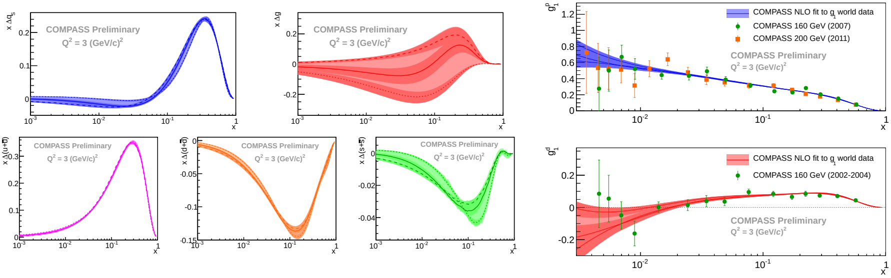
$g_1^p(x)$ and $g_1^d(x)$

NEW: COMPASS proton data 2011 (prelim.); full deuteron statistics



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

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



138/678 world data points are from COMPASS

From that:
range in $\Delta\Sigma \equiv \Delta q_s$ (due to uncertainty on Δg): 0.25-0.34 at Q^2 = 3(GeV/c)^2.

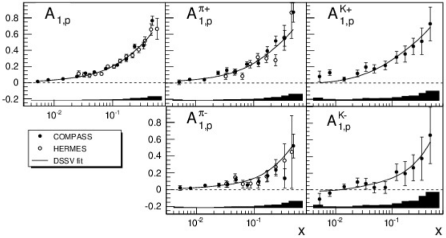
From M. Wilfert, DIS2014

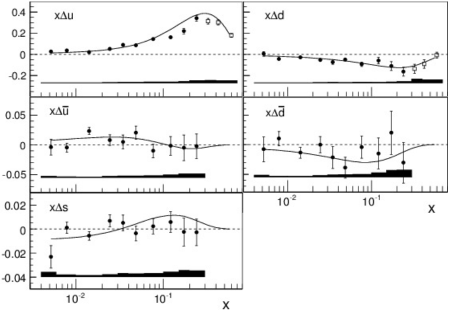
Semi-inclusive asymmetries and parton distributions

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

COMPASS, Phys. Lett. B **680** (2009) 217

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

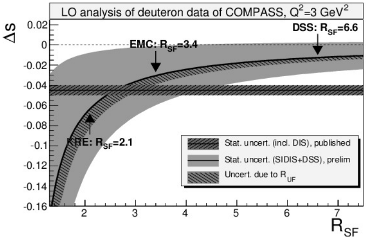


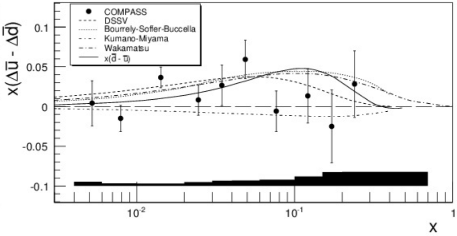


- LO DSS fragmentation functions and LO unpolarised MRST pdf assumed here.
- NLO parameterisation of DSSV describes the data well.

Polarisation of quark sea

- Δs puzzle. Strange quark polarisation:
  $2\Delta S = \int_0^1 (\Delta s(x) + \Delta\bar{s}(x))dx = -0.09 \pm 0.01 \pm 0.02$ from incl. asymmetries + SU$_3$,
  while from semi-inclusive asymmetries it is compatible with zero
  but depends upon chosen fragmentation functions. Most critical: $R_{SF} = \frac{\int D_{\bar{s}}^{K^+}(z)dz}{\int D_u^{K^+}(z)dz}$
  $\Longrightarrow$ plan to extract it from COMPASS data on multiplicities.

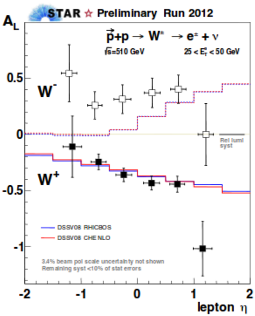


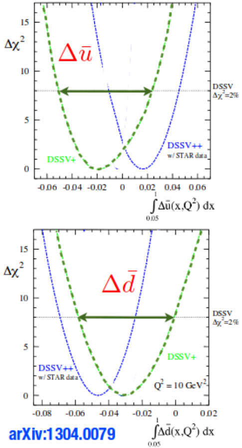


- The sea is not unsymmetric: COMPASS, Phys. Lett. B, **680** (2009) 217; ibid., **693** (2010) 227.
  $$\int_{0.004}^{0.3} \left[\Delta\bar{u}(x,Q^2) - \Delta\bar{d}(x,Q^2)\right] dx = 0.06 \pm 0.04 \pm 0.02 \quad @ \quad Q^2 = 3\ (\text{GeV}/c)^2$$
  Thus the data disfavour models predicting $\Delta\bar{u} - \Delta\bar{d} \gg \bar{d} - \bar{u}$

RHIC results on sea polarisation and on Δg

Sea quark polarization in global fits



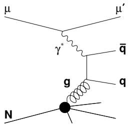


- **DSSV++** is a new, preliminary global analysis from the DSSV group which includes 2012 STAR W A_L
- Higher precision data already collected in 2013 will further improve the constraints on the sea quark polarization

From J.Stevens, DIS2014

Direct measurement of $\Delta g(x)$

Direct measurements – *via* the cross section asymmetry
for the photon–gluon fusion (PGF) with subsequent fragmentation into:

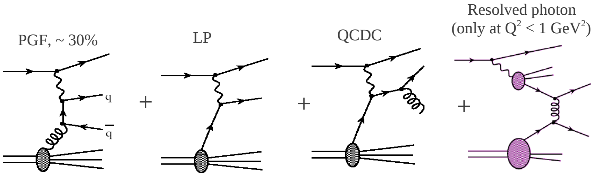


- charm mesons, q≡c, (max. @ low Q^2, perturbative scale: e.g. m_c): low statistics, few theoretical assumptions;

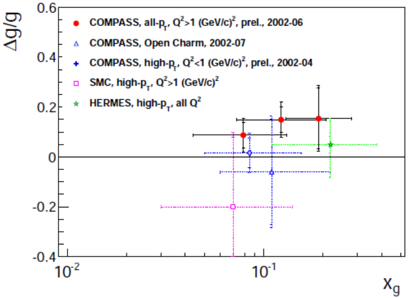
$$A_{meas} = p_B\, p_T\, f\, a_{LL}\, \frac{\sigma_{PGF}}{\sigma_{PGF}+\sigma_{BGD}}\, \frac{\Delta g}{g} + A_{BGD}$$

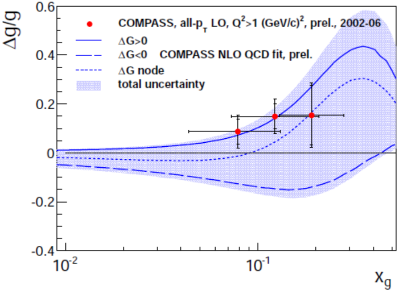
- a pair of hadrons, q≡u, d, s, separately for low- and high Q^2; high statistics, several quantities from MC. At LO, for both 2-hadron and inclusive samples:

$$A_{meas} = p_B\, p_T\, f \left[R_{PGF} \cdot a_{LL}^{PGF} \cdot \frac{\Delta g}{g} + R_{LP} \cdot D \cdot A_1^{LP} + R_{QCDC} \cdot a_{LL}^{QCDC} \cdot A_1^{LP} \right]$$



New results on Δg from COMPASS



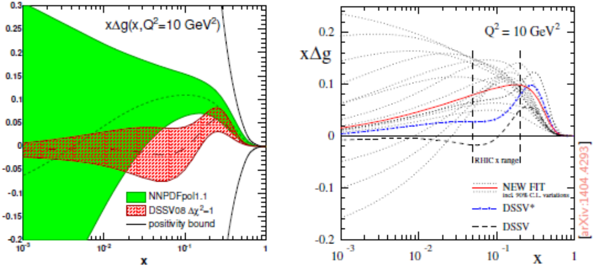


From M.Stolarski, DIS2014

Other QCD fits to world data

Comparison with DSSV

Δg



- For $x < 0.2$ the gluon has a node in DSSV08, while it is definitely positive in NNPDFpol1.1
- NNPDFpol1.1 and DSSV are in perfect agreement once recent jet data are included
- First evidence of gluon polarization in the proton in the region covered by data, $x \gtrsim 0.2$
- The uncertainty of the gluon blows up in the unmeasured small-x region

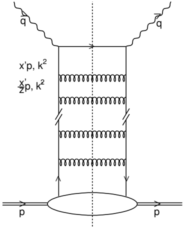
Outline

$\ln^2(1/x)$ corrections to $g_1^{ns}(x,Q^2) = g_1^p(x,Q^2) - g_1^n(x,Q^2)$

- Leading low x behaviour of g_1 (g_1^s and g_1^{ns}) generated by powers of $\alpha_s \ln^2(1/x)$; a standard DGLAP for spin dependent *pdf* generate only $\ln(1/x)$ terms.
- A way of including the above to QCD evolution: through $f(x, k_t^2)$

  where conventional parton distributions: $p(x,Q^2) = \int^{Q^2} \frac{\mathrm{d}k_t^2}{k_t^2} f(x,k_t^2)$

  This formalism permits
  an easy extrapolation to $Q^2 = 0$
  (for fixed W^2).
- $\ln^2(1/x)$ corrections to g_1^{ns}
  are generated by ladder diagrams ⟹



Outline

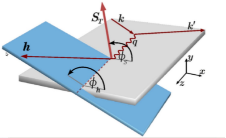
Collins and Sivers asymmetries

Properties of $\Delta_T q(x)$:

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

Transversity measured *e.g. via* the Collins asymmetry: $\perp$ polarised $q \Longrightarrow$ unpolarised h (asymmetry in the distribution of hadrons):

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



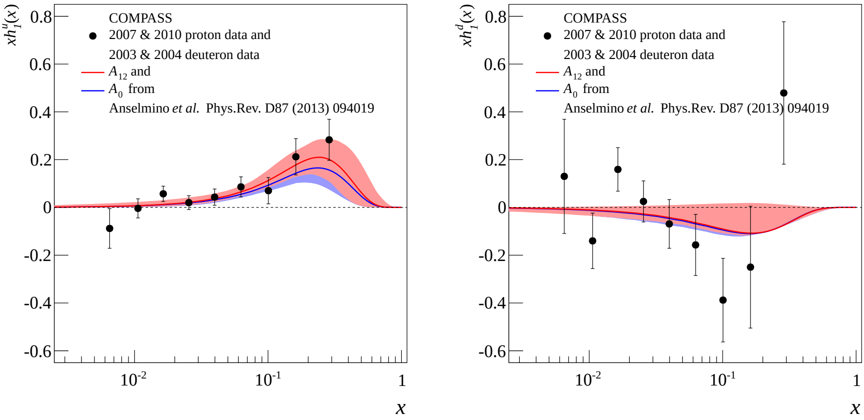
which in turn gives at LO:

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

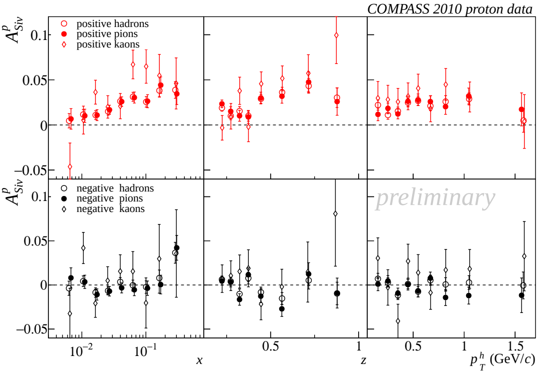
But transverse fragmentation functions $\Delta_T^0 D_q^h$ needed to extract $\Delta_T q(x)$ from the Collins assymmetry! Recently those FF measured by BELLE.

Properties of the Sivers process ($\phi_S = \phi_h - \phi_S$, correlation of $\perp$ nucleon spin with k_T of unpolarised q): it is related to L_q in the proton. Fundamental !

Transversity, $\Delta_T q \equiv h_1$, from COMPASS for p and d



Results for the Sivers asymmetry for protons



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

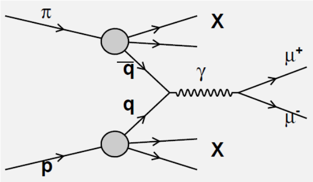
Outline

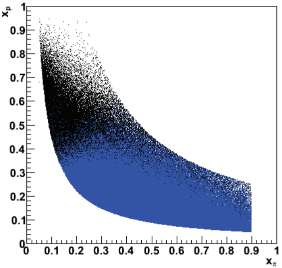
Programme until 2017

- Proposal CERN–SPSC–2010–014 (SPSC–P–340) of May 17, 2010
  wwwcompass.cern.ch/compass/proposal/compass-II_proposal/compass-II_proposal.pdf
- Approved in December 2010 initially 3 years data taking, (Phase 1
- Flavour separation and fragmentation in spin-averaged SIDIS
  (strange sector !)
- 2014–2017 focus on transverse structure of the nucleon
  - T-odd TMD (Sivers, Boer-Mulders distributions)
  - Drell-Yan process and TMD sign change SIDIS $\Longleftrightarrow$ DY
  - GPD (unpolarised), transverse size and parton orbital angular momentum
- π/K polarisabilities and tests of ChPT
  in the Compton scattering via Primakoff reaction.
- Addendum foreseen (spin-dependent GPD), Phase 2, $>$ 2017 ?.

Drell-Yan process: $\pi^- p^\uparrow \rightarrow \mu^+\mu^- X$ @ COMPASS

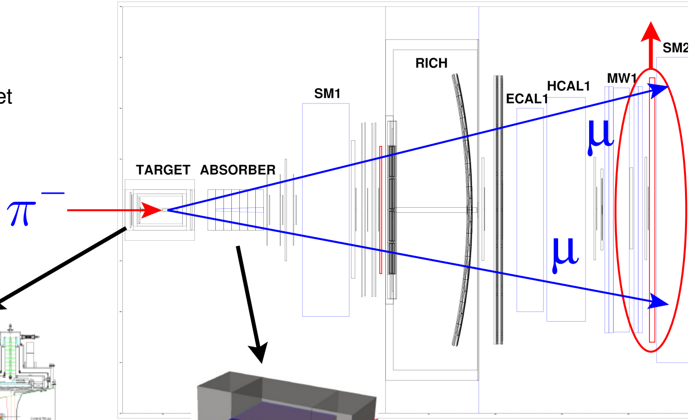
- Clean partonic process
- No fragmentation functions involved!
- Convolution of two Parton Distribution Functions
  $\sigma^{\rm DY} \propto f_{\bar{u}|\pi^-} \otimes f'_{u|{\rm p}}, \quad \sigma^{\rm DY} = \sigma^{\rm DY}(x_\pi, x_{\rm p})$
- Gives an access to azimuthal modulations of 4 PDF: transversity, pretzelosity, Boer–Mulders and Sivers.
- Ideal: $\bar{\rm p}{\rm p}$; good compromise: $\pi^-{\rm p}$
- Here dominated by annihilation of valence $\bar{u}$ from π^- and valence u from p
- COMPASS has large acceptance in the valence region of p and π (large SSA expected). Example of covered kinematics (in blue):
  π^- beam, 190 GeV/c, NH$_3$ target, $\perp$ polarised
  dimuon mass range: 4 – 9 GeV/c^2 (low bckg.)
- QCD TMD approach justified by:
  $M_{\mu\mu} \gg p_{\rm T}^{\mu\mu} \approx$ 1 GeV

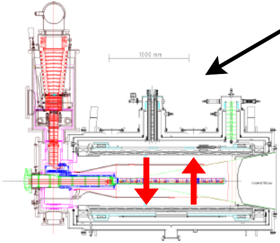


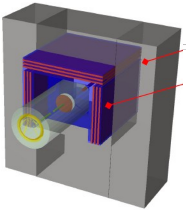


Drell–Yan @ COMPASS: data taking 2014 – 2015

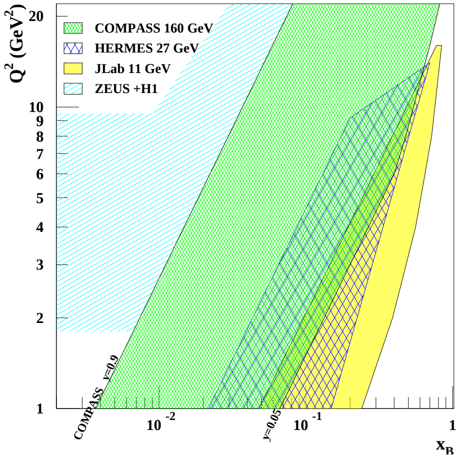
- intense π beam (up to 10^9/spill)
- hadron absorber downstream target
- di-muon trigger







GPD at COMPASS: data taking in 2016-17



- 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)

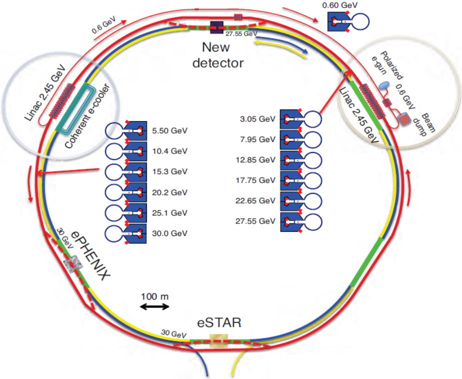
Test runs: 2008-9 and 2012; DVCS signal seen, full setup evaluated

Outline

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

BNL

Electron beam facility needed
(inside RHIC tunnel)



JLab

ELIC + injector needed

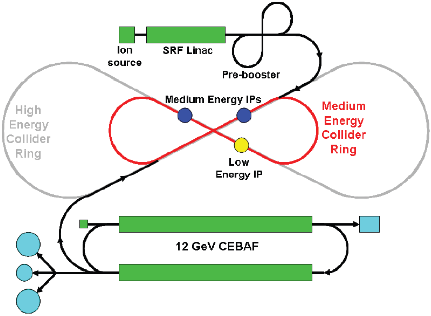
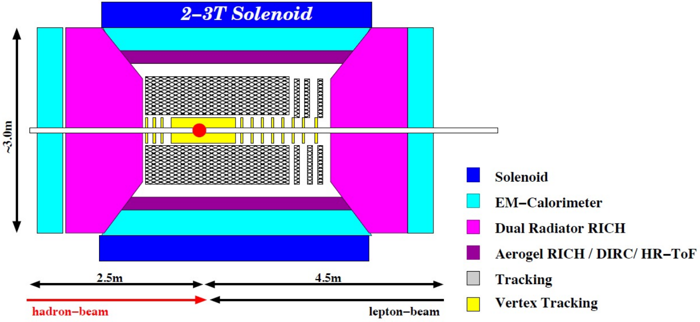


figure from The White Paper, arXiv:1212.1701

A dedicated EIC detector



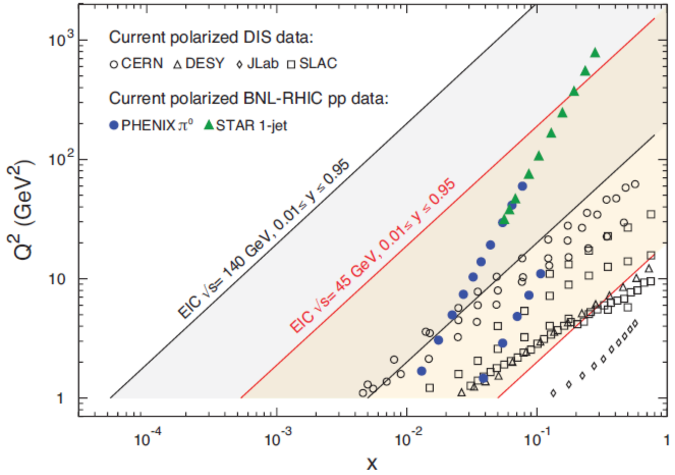
- Acceptance -5 $< \eta <$ 5 (large, comparable to CMS forward)
- PID: π, K, p, leptons
- Low material density (minimal multiple scattering and bremsstrahlung)
- Hadron beams: proton to lead

From "White paper", arXiv:1212.1701

EIC: main features

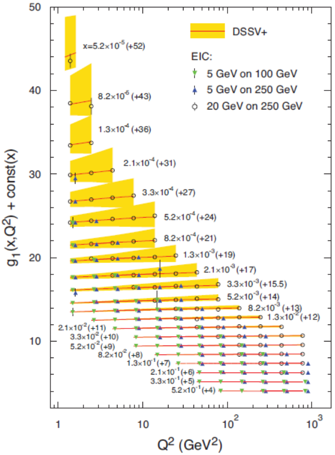
- Highly polarised ($\sim$ 70%) e, N beams
- ions from deuteron to uranium (lead ?)
- variable $\sqrt{s}$ from $\sim$ 20 GeV to $\sim$ 100 (150) GeV
- high luminosity: $\sim 10^{33-34}$ cm^{-2} s^{-1} (cooling of hadronic beam !)
- more than one interaction region
- limits of current technology $\Longrightarrow$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

Acceptance of present spin experiments and EIC



From "White paper", arXiv:1212.1701

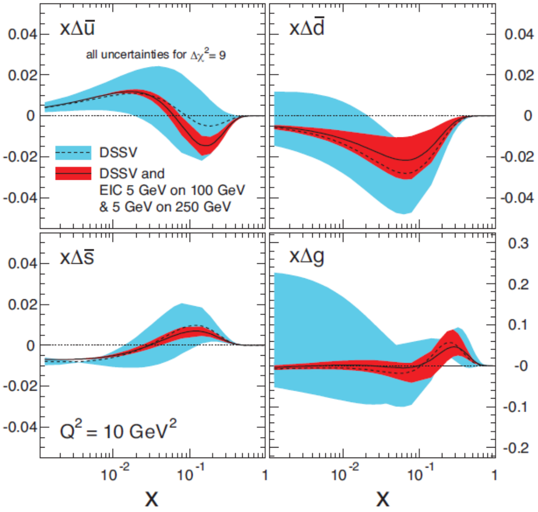
Inclusive $g_1(x, Q^2)$ at EIC (pseudo-data)

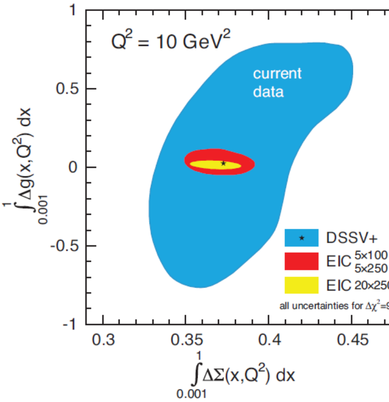


Errors statistical; bands mark current uncertainties (from DSSV+)

From "White paper", arXiv:1212.1701

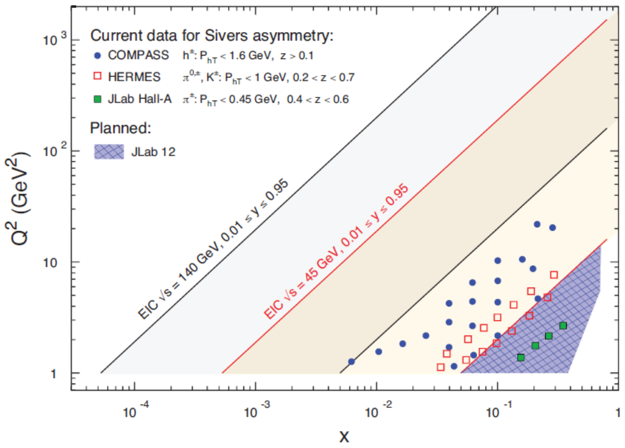
EIC pseudo-data (inclusive and semi-inclusive)





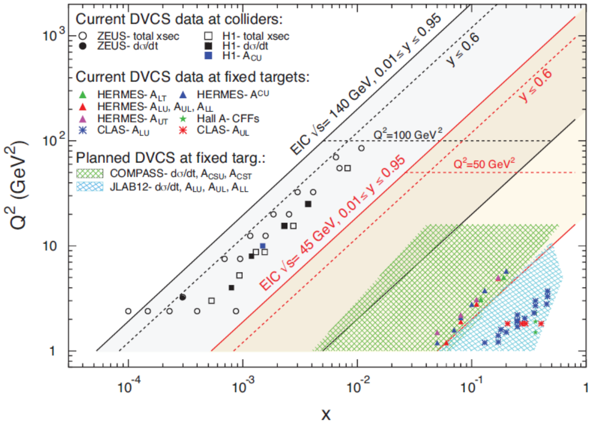
From "White paper", arXiv:1212.1701

Sivers measurements



From "White paper", arXiv:1212.1701

Acceptance of present and EIC DVCS



From "White paper", arXiv:1212.1701

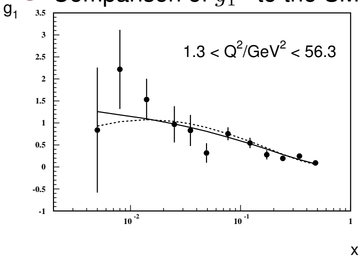
Outlook: parton structure of the nucleon

- A wealth of data on polarised (SI)DIS collected by fixed target experiments and by RHIC
- COMPASS II running starts fall 2014 (DY)
- Great hopes for EIC (BNL or JLab)
  $\Longrightarrow$ higher energy and low(er) x
- Long Range Planning in Nuclear Physics just started; final report will be submitted to DOE fall of 2015?
- Do not underestimate the fixed target results. Remember NMC vs HERA!

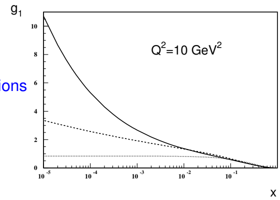
BACKUP

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

- A unified equation which incorporates the complete LO DGLAP at finite x and $\ln^2(1/x)$ effects at $x \to 0$ was formulated.
- Potentially large $\ln Q^2$ and $\ln(1/x)$ treated on equal footing.
- Assumed values $g_1^{ns(0)} = 2g_A(1-x)^3/3$, g_A = 1.257 (axial vector coupling). At $x \to 0$, $g_1^{ns(0)}$ →const, in agreement with the Regge expectation.
- The $g_1^{ns(0)}$ satisfies the Bjorken sum rule at LO: $\int_0^1 \mathrm{d}x g_1^{ns(0)}(x) = g_A/6$.
- Parameter k_0^2=1 GeV^2.
- Comparison of g_1^{ns} to the SMC data (COMPASS results ready soon)



g_1^{ns} vs x
continuous – full calculations
broken – LO DGLAP



From J. Kwieciński and BB, Phys.Lett. B418 (1998) 229

Inelastic electron – nucleon scattering

Elastic electron–nucleon cross section may be written as

$$\frac{d\sigma}{dQ^2} = \frac{4\pi\alpha^2}{Q^4}\left[\left(1 - y - \frac{M^2y^2}{Q^2}\right) f_2(Q^2) + \frac{1}{2}y^2 f_1(Q^2)\right]$$

where $f_{1,2}(Q^2)$ are combinations of $G_{E,M}(Q^2)$.
This may be compared with an inelastic cross-section:

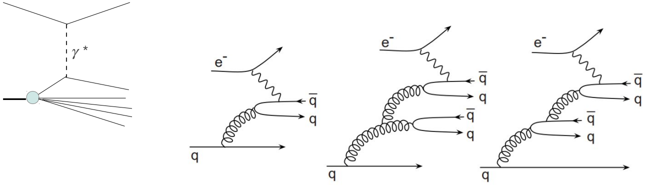
$$\frac{d^2\sigma}{dQ^2dx} = \frac{4\pi\alpha^2}{Q^4}\left[\left(1 - y - \frac{M^2y^2}{Q^2}\right) \frac{F_2(x,Q^2)}{x} + y^2 F_1(x,Q^2)\right]$$

where $y = \nu/E$, $x \neq 1$ and a second variable (like $x, \nu, ...$) appears.

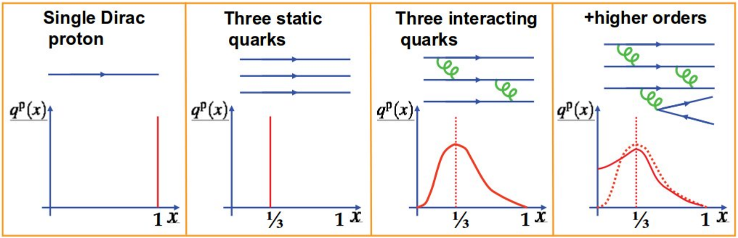
- Q^2 dependence of $F_{1,2}(x,Q^2)$ is very weak
- Quark Parton Model: $F_2(x) = x\sum_{i=1}^{6} e_i^2 q_i(x), \quad 2xF_1(x) = F_2(x)$

Towards QCD

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

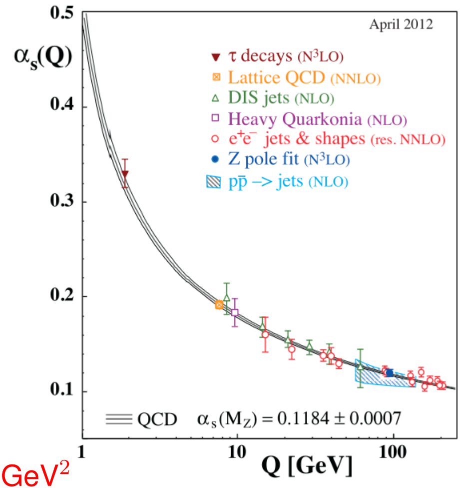


From the book of Povh et al.



From M.A. Thomson, Michaelmas Term 2011

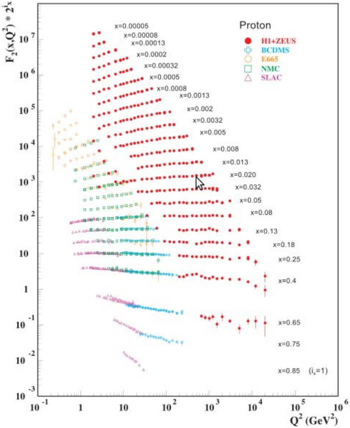
Strong coupling "constant"



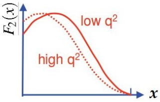
$Q^2 \lesssim$ 1 GeV^2
Confinement

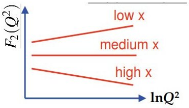
$Q^2 \to \infty$
"Asymptotic freedom"!!

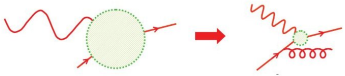
Towards QCD: scaling violation



low Q^2 $\Longrightarrow$ high Q^2







QCD evolution equation (at lowest order):

$$\frac{dq(x,t)}{dt} = \frac{\alpha_s(Q^2)}{2\pi} \int_x^1 dy \frac{q(y,t)}{y} \cdot P\left(\frac{x}{y}\right)$$

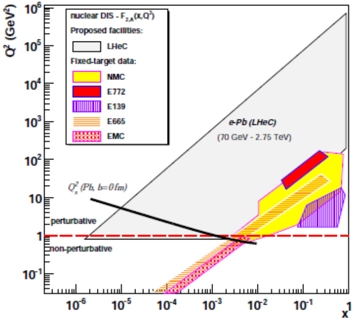
$$t = \ln \frac{Q^2}{\Lambda^2}$$

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

From Particle Data Tables, 2012 and from M.A. Thomson, Michaelmas Term 2011

A Large Hadron Electron Collider (LHeC) at CERN

- Symposium on the European Strategy for Partice Physics, Cracow, 2012 arXiv:12111.483
- Two options: ring–ring (RR) and linac–ring (LR). Basic beam design:



electron beam 60 GeV	Ring	Linac
e^- (e^+) per bunch N_e [10^9]	20 (20)	1 (0.1)
e^- (e^+) polarisation [%]	40 (40)	90 (0)
bunch length [mm]	6	0.6
tr. emittance at IP $\gamma\epsilon^e_{x,y}$ [mm]	0.59, 0.29	0.05
IP β function $\beta^*_{x,y}$ [m]	0.4, 0.2	0.12
beam current [mA]	100	6.6
energy recovery efficiency [%]	–	94
proton beam 7 TeV		
protons per bunch N_p [10^{11}]	1.7	1.7
transverse emittance $\gamma\epsilon^p_{x,y}$ [μm]	3.75	3.75
collider		
Lum e^-p (e^+p) [10^{32}cm^{-2}s^{-1}]	9 (9)	10 (1)
bunch spacing [ns]	25	25
rms beam spot size $\sigma_{x,y}$ [μm]	45, 22	7
crossing angle θ [mrad]	1	0
$L_{eN} = A\ L_{eA}$ [10^{32}cm^{-2}s^{-1}]	0.45	1

- The “Strategy” has not recommended a continuation of R&D for LHeC!