ENC/EIC Collider Workshop @ Milos EINN2009
(1) Projects and Physics overview
1.4 OpenQuestions - Experimental view

Dietrich von Harrach
Universität Mainz

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Qutline

- Why do we need new electron (charged lepton) scattering facilities ?
- What are the main objectives ?
- What are the challenges for machines, detectors and data analysis ?

100 years of Hadron Structure Physics

- In 1910 Rutherford could show that the atomic nucleus is an extended object

In 1955 Hofstadter showed that the proton has a charge radius of about 0.9 fm

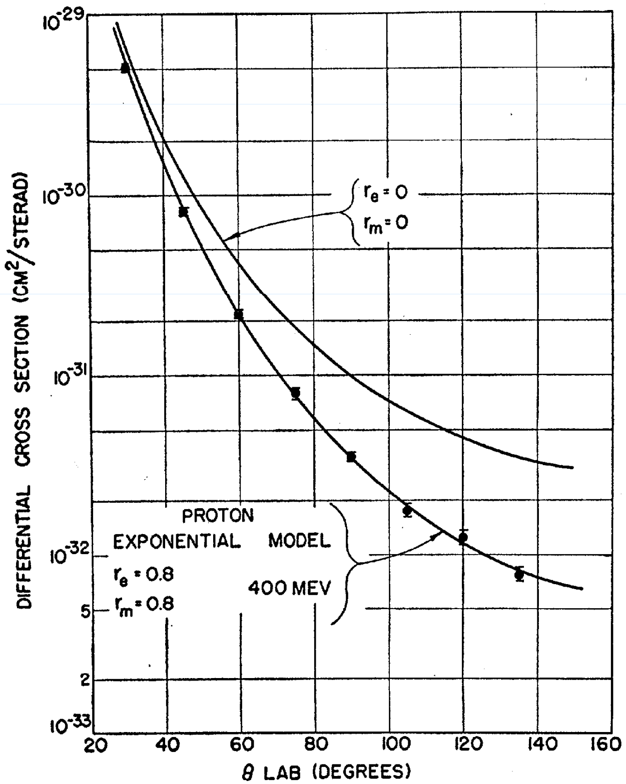
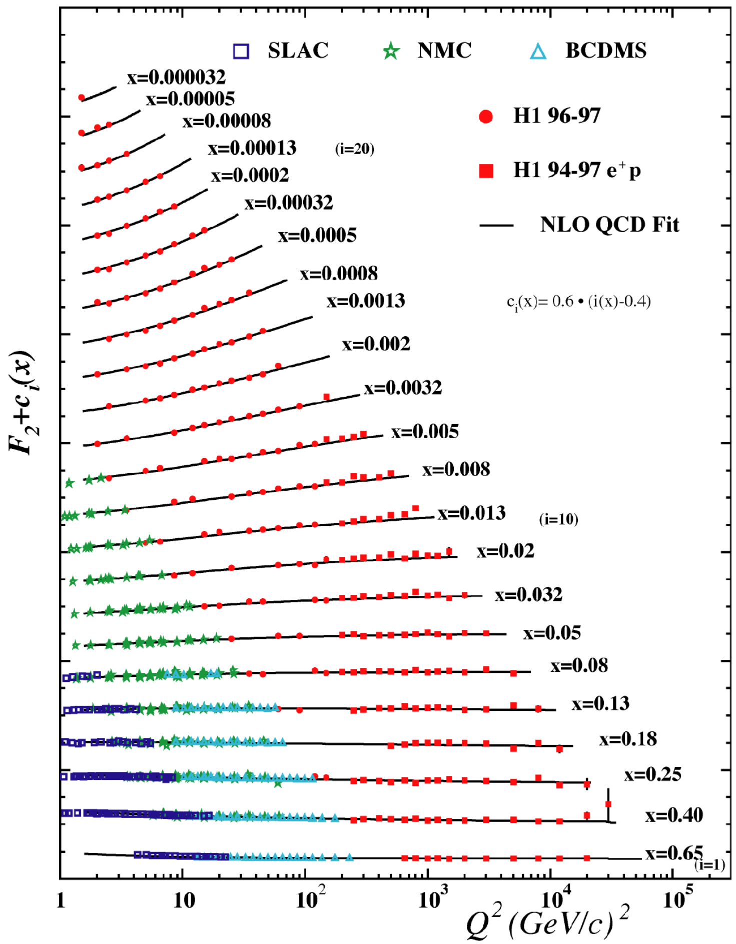
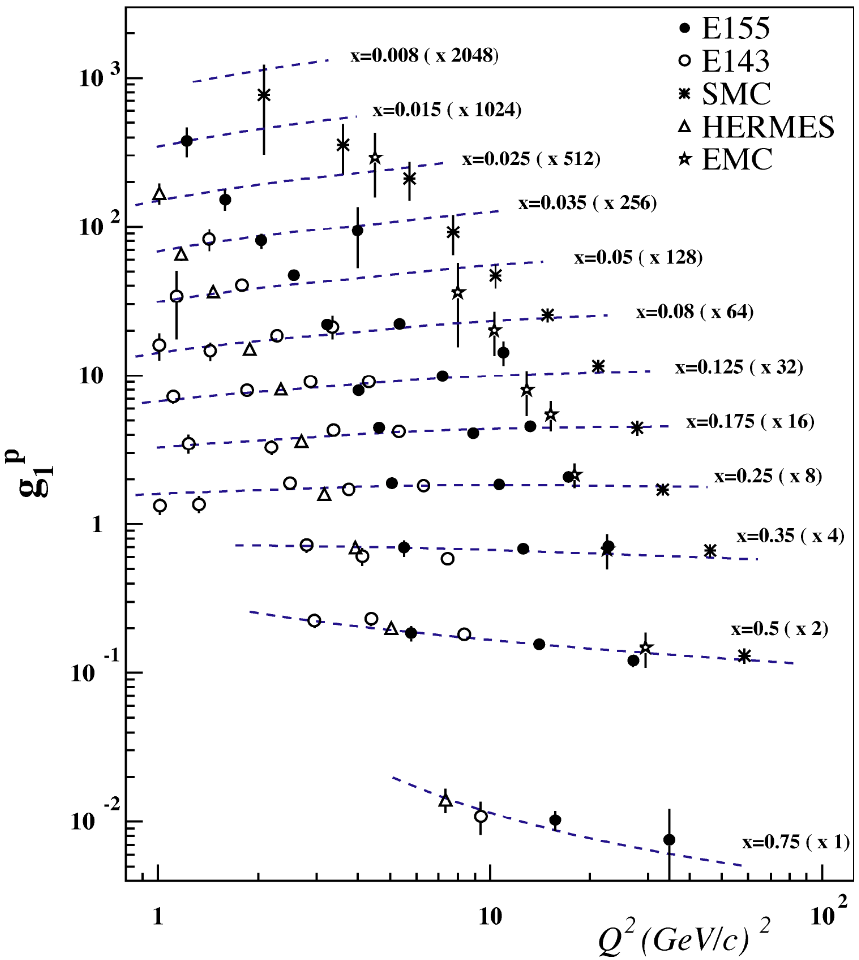


FIG. 26. Typical angular distribution for elastic scattering of 400-Mev electrons against protons. The solid line is a theoretical curve for a proton of finite extent. The model providing the theoretical curve is an exponential with rms radii $=0.80\times10^{-13}$ cm.

- In 1965 SLAC experiments exhibited approximate scaling. Parton distributions of the proton are derived

- In 1970-2000 Analysis of DIS scaling underpinned PQCD with NNN...LO





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- In 1985 came the spin crisis and it is not over yet !

Lessons from the spin crisis

- Hadrons are composite systems of strongly interacting quarks and gluons i.e. QCD is in its strong coupling regime

- Structure functions (as form factors or GPDs) cannot be guessed on the basis of symmetry arguments or PQCD mechanisms
  (GLS and Bjorken sumrules are exceptions)

  - They are genuinely of non-perturbative origin and reflect process like chiral symmetry breaking and quark-quark or quark-gluon correlations mediated by the QCD vacuum or Instantons
  - Spin, $k_\perp$ and orbital angular momentum effects are particularly sensitive on the strong QCD dynamics
  - Low moments of (generalized) structure functions are now becoming calculable in LQCD and we can hope to learn how a proton works inside

- The notion of GPDs and the idea of transverse imaging of hadrons emerged which naturally embraces orbital angular momentum and transverse momentum of partons

The challenge is:

- understand the structure of hadrons and their excited states from first principles
  - compare selected observables with LQCD predictions
  - extract from LQCD the driving mechanisms
- find an effective effective description - more effective than LQCD
  (nobody will design drugs using the QED Lagrangian)
- predict hadonic properties and processes with good and controlled precision.

Practical Use

Whatever super-super collider (including the cosmic ones) you use:

If hadrons are not in the initial state they inevitably occur in the final state

Examples:

- it has recently been argued that the u_V/d_v ratio is needed with $\approx$1% precision to determine $M_{W^\pm}$to better than 10 MeV at LHC

- CKM precision and CP-violation experiments and other BSM (beyond standard model) searches (e.g. g-2) need precise hadronic corrections

Advantages of Charged Lepton - Nuleon Scattering

Quarks are fermions with

charge, flavour, mass, colour

Gluons are massless spin-1 Bosons with

colour

- the ideal probe would be CC neutrino and anti-neutrino interactions (we are waiting for the experiments with intense monoenergetic pencil like neutrino beams on hydrogene and deuterium targets)

- more realistic: interaction of **polarized** charged lepton beams $e^{\pm}, \mu^{\pm}$ with **polarized** p and d $(^3He, ...^{238}U)$
  - dominated by γ^* exchange at $Q^2 \ll M^2_{Z^0,W^\pm}$ coupling to quark charges only
  - NC Parity violating asymmetries $\gamma^* Z^0$: EW-coupling constants and flavour separation
  - doubly polarized: projecting helicities

Alternative approaches to hadron structure

- Meson and Baryon Resonances (exotic states, strange, charmed and beautyful mesons and Baryons)

- DY like processes pp,$p\bar{p}$,πp..... $\rightarrow \gamma^*(W^*, Z) + X$

- e^+e^-

Specific advantages (flavour, spin selective) DIS:fD DY:ff e^+e^-:DD

but more complex initial and final state interactions and backgrounds

no equivalent to OPE and factorisation properties proven for DIS

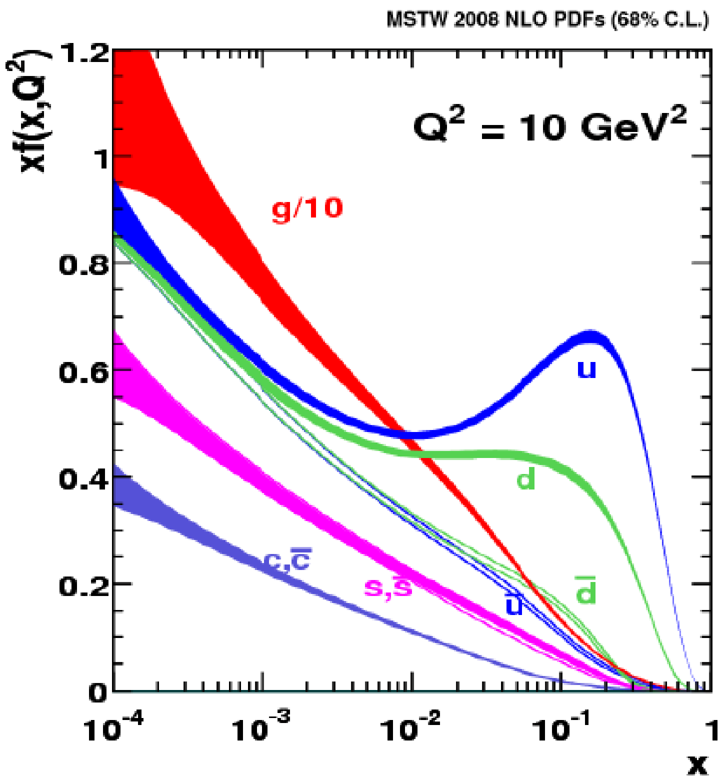
Parton distributions of the proton

- play a central role in all applications involving hard sacttering
- Moments and Sumrules are objects to compare with theory

At low scales $1 < Q^2 < 10\, GeV^2$ light quarks and gluons dominate

there are 20 Twist-2 structure functions at a given scale

7 unpolarized parton distributions:
6 quark distr.
$u(x)$, $\bar{u}(x)$, $d(x)$, $\bar{d}(x)$, $s(x)$, $\bar{s}(x)$
and the Gluonistribution
$g(x)$



- there are 13 polarized parton distributions $\Delta q(x), \Delta\bar{q}(x), \delta q(x), \delta\bar{q}(x)$ (for $u, d.s$) and $\Delta g(x)$

- for the free neutron the deuteron and all other nuclear species there are different sets of 20 each
  (this brings you to isospin arguments and nuclear dependencies)

None of them can be measured directly with DIS on a polarized proton target

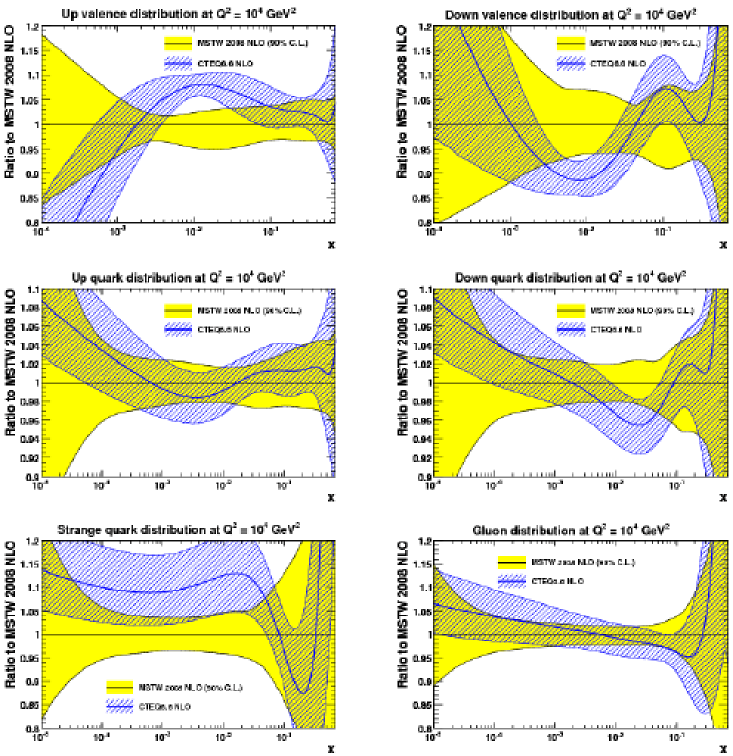
Different targets and different processes are needed.

Extraction of pdfs is the business of CTEQ and MSTW (MRS,MRST)

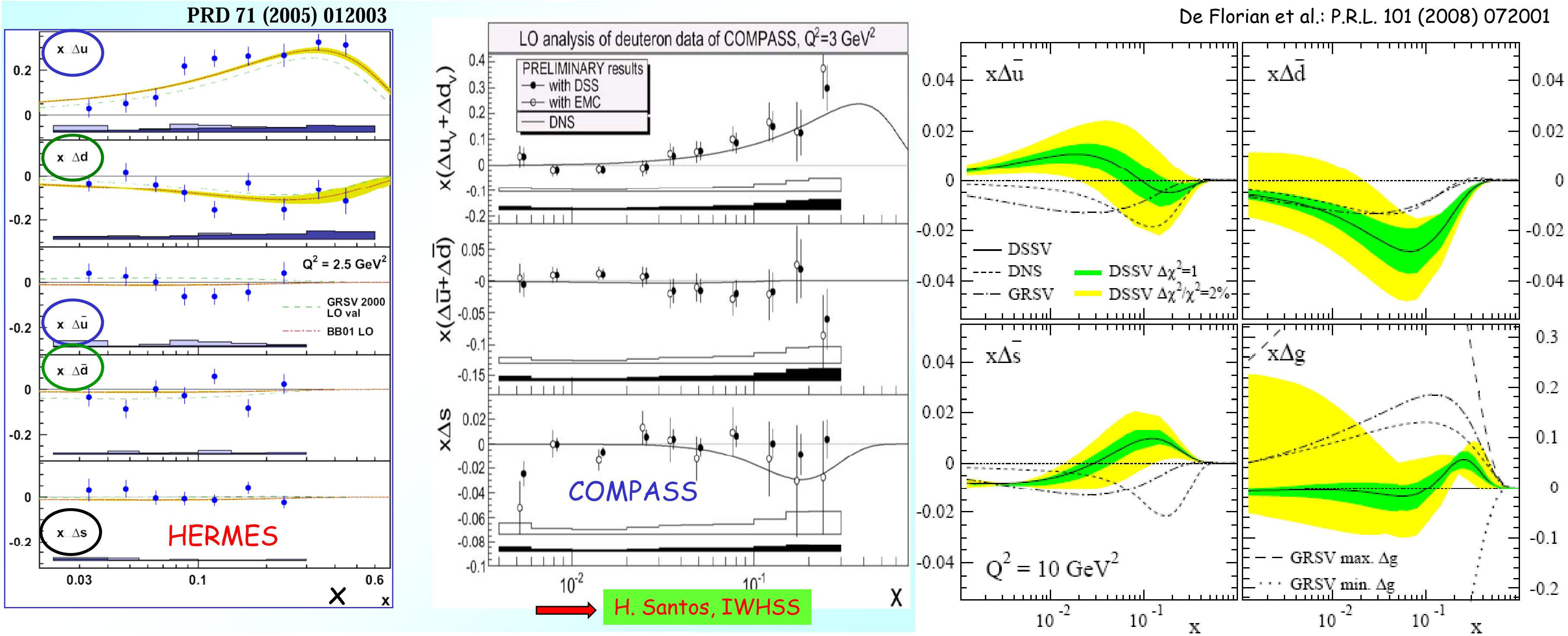
What is needed in PDFs ?

flavour separation u,d,s for **polarized** and unpolarized PDFs

- Present precision of unpolarized $q(x)$, $\bar{q}(x)$, $g(x)$
  unpolarized PDFs at $Q^2 = 10\,GeV^2$ $10^{-3} < x < 10^{-1}$ to 3-5% (u,d,g) 10-15% s

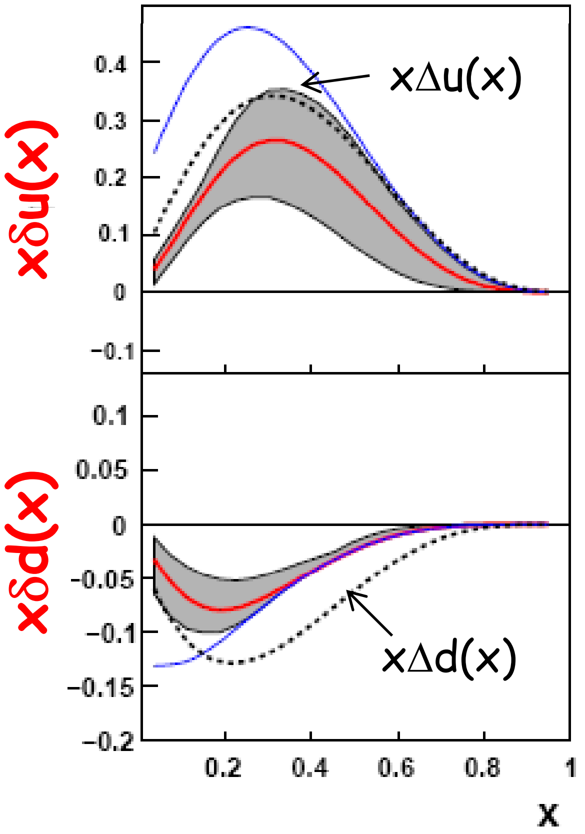


- longitudinally polarized PDFS Δq



- first attempts to extract transversly polarized PDFS δq

M. Anselmino et al., arXiv-0812.4366



unpolarized d and s has to be improved at all x

all polarized need to be improved in particular $\Delta s(x)(\Delta\bar{s}(x)$ and $\Delta g(x)$

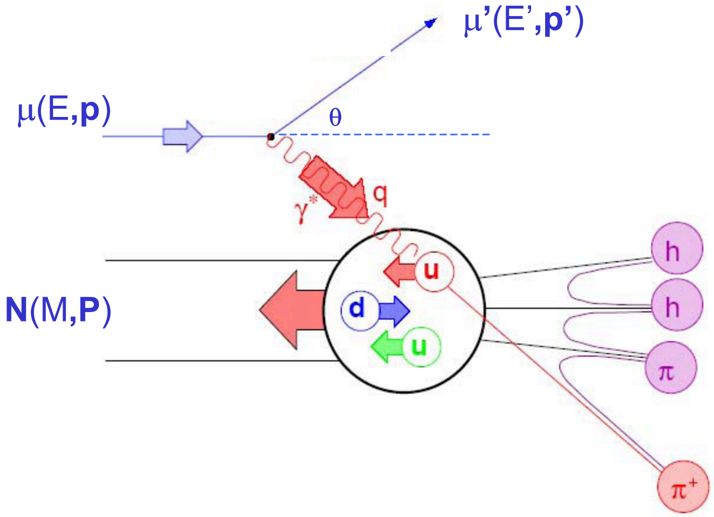
transverse PDFs is an open field and needs dedicated efforts eg to compare $\delta q(x) \Leftrightarrow \Delta q(x)$

Possibilities for Flavour Separation in DIS

NC charged lepton scattering:

- Comparison of different (polarized) targets p, d e.g. F_2^d/F_2^p
  - nuclear effects, systematics
- Spectator tagging in $e + d$
  - neutron tagging
  - only possible in colliders
- PV-DIS on p
  - $A^{PV} \approx \frac{Q^2}{M_{Z^0}} = 10^{-4} - 10^{-3}$ at $Q^2 = 1 - 10\,GeV^2$
- Semiinclusive deep inelastic scattering (SIDIS)
  - factorisation, fragmentation functions, corrections, systematics

Flavour separation with SIDIS



Flavour separation $q(x)$ in doubly polarized electron scattering (below $M^2_{z^0}$) needs semi-inclusive DIS (SIDIS)

$\Delta g(x)$ needs a tagging of photon gluon fusion events in the hadronic final state $(p_\perp, c, \bar{c})$

Transversity ($h_1$or δq) via the COLLINS effect requires SIDIS

with a **factorisation** ansatz

$$d\sigma^h \propto \sum_i e_i^2 \cdot q_i(x, Q^2) \times D^h_{q_i}(z, Q^2)$$

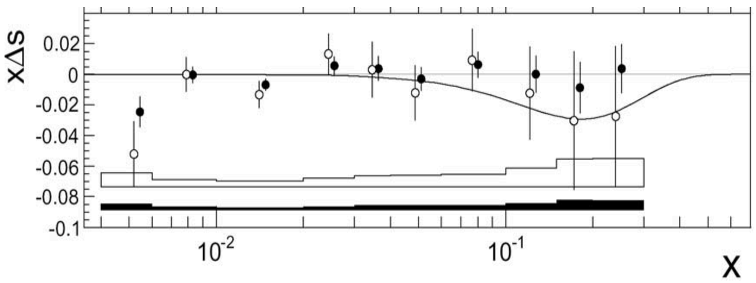
Flavour separation would correspond 6x6 matrix inversion $(\sigma_{p,d}, \sigma^{\pi^\pm}_{p,d}, \sigma^{K^\pm}_{p,d})$

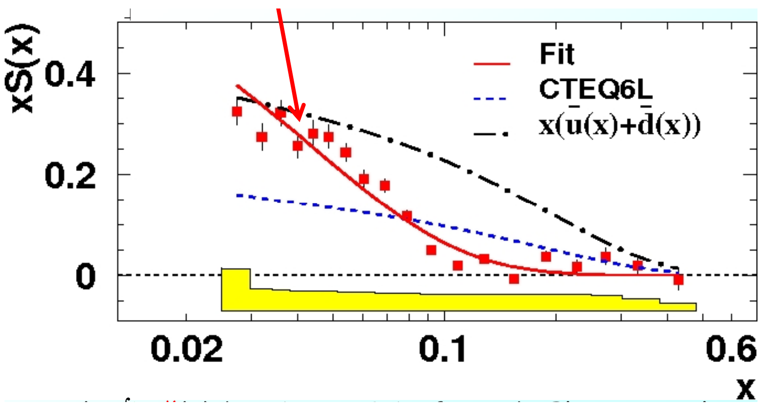
- If the factorisation ansatz is valid
- if fragmentation functions $D_q^h(z, Q^2)$ are target and spin independent for spin-0 mesonsπ, K

Alternatively fragmentation models (e.g. based on Lund MC) could be used

A particular problem seems to be the derivation of $\Delta s(x)$

There unresolved contradictions of DIS vs SIDIS analysis





Can SIDIS become a precision tool ?

flavour separation, transversity, Δg, quark $p_\perp$effects (Sivers, Boer-Mulders etc.)

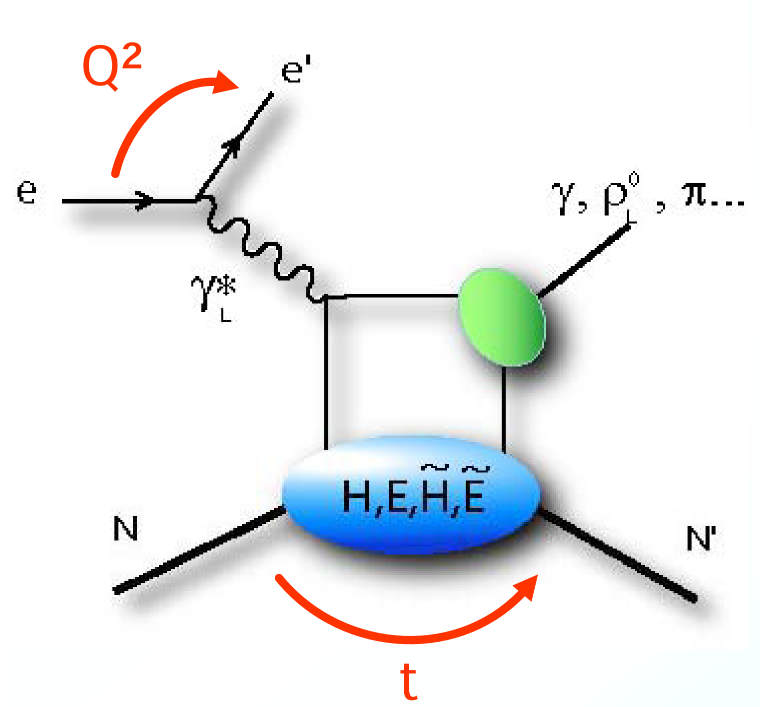
depend on the **analysis of the hadronic final state**

-complete coverage and identification of the hadronic final state $(-1 < x_f < 1)$ with all neutrals and secondary vertices

- large Q^2 lever arm e.g. $2 < Q^2 < 20\, GeV^2$
- high statistics for multi differential distributions $(x, Q^2, z, p_\perp)$and h_1, h_2 correlations

- factorisation breaking in detail (measure and understand differential hadron distributions $\sigma^h(x, Q^2, z, , p_t)$)
- leading to subleading correlations and other correlations $(p_\perp, flavour$ copmensation, retention)
- role of intermediate resonances and sequential processes
  here contact has to be made with exclusive processes
- target remnants (fracture functions)
- spin dependence of fragmentation

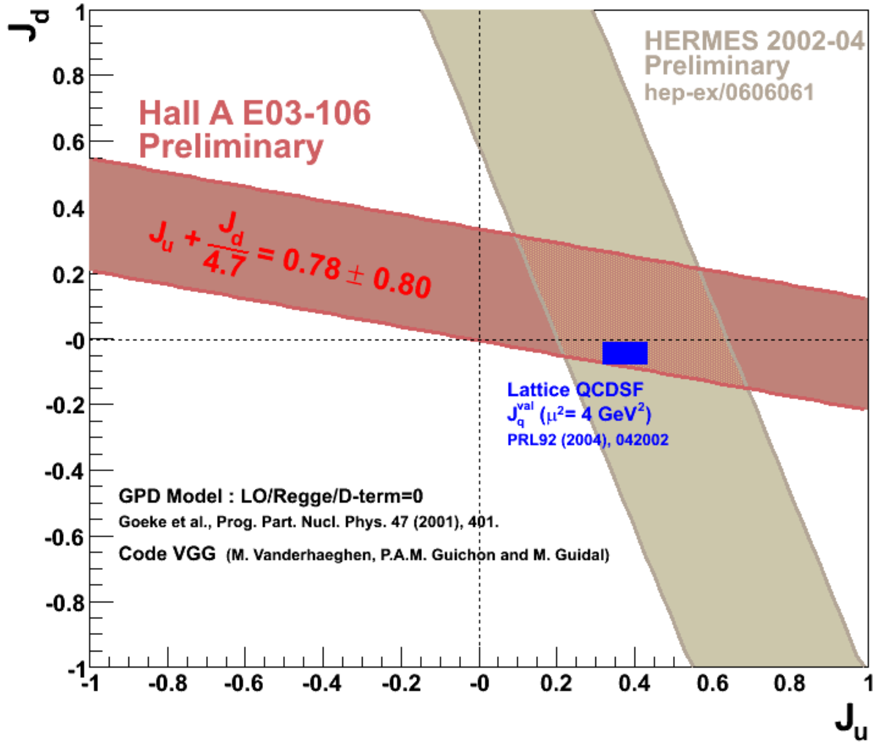
Exclusive Processes



-The concept of GPDs and their accessibility in hard exclusive lepton scattering has been developed in recent 10 years
(the spin crises and the angular momentum debate has triggered that !)

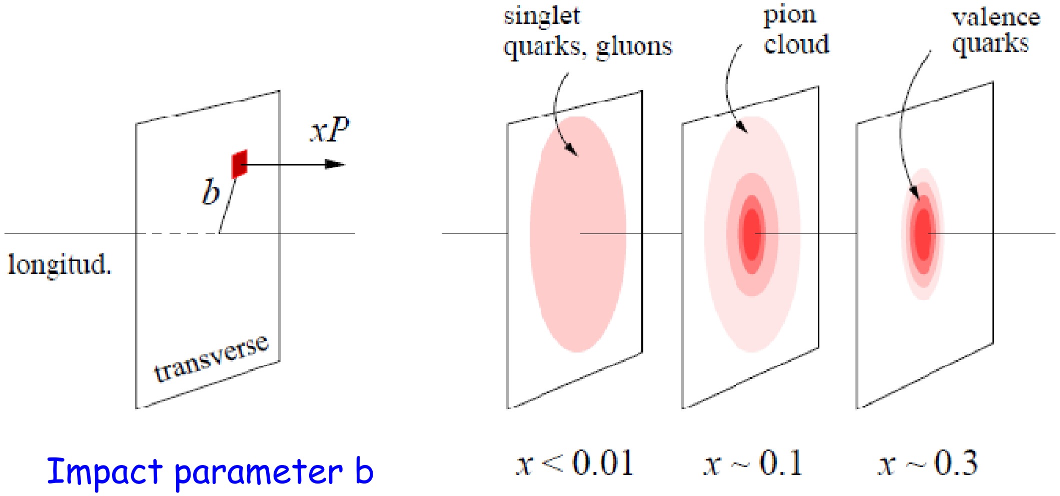
$$J_q = 1/2\Delta\Sigma + L_q = \lim_{t \to 0} \int_{-1}^{1} dx \times [H(x,\zeta,t) + E(x,\zeta,t)]$$

-First experiments at HERMES, HERA and JLAB have shown the experimental feasibility qualitative agreement for DVCS

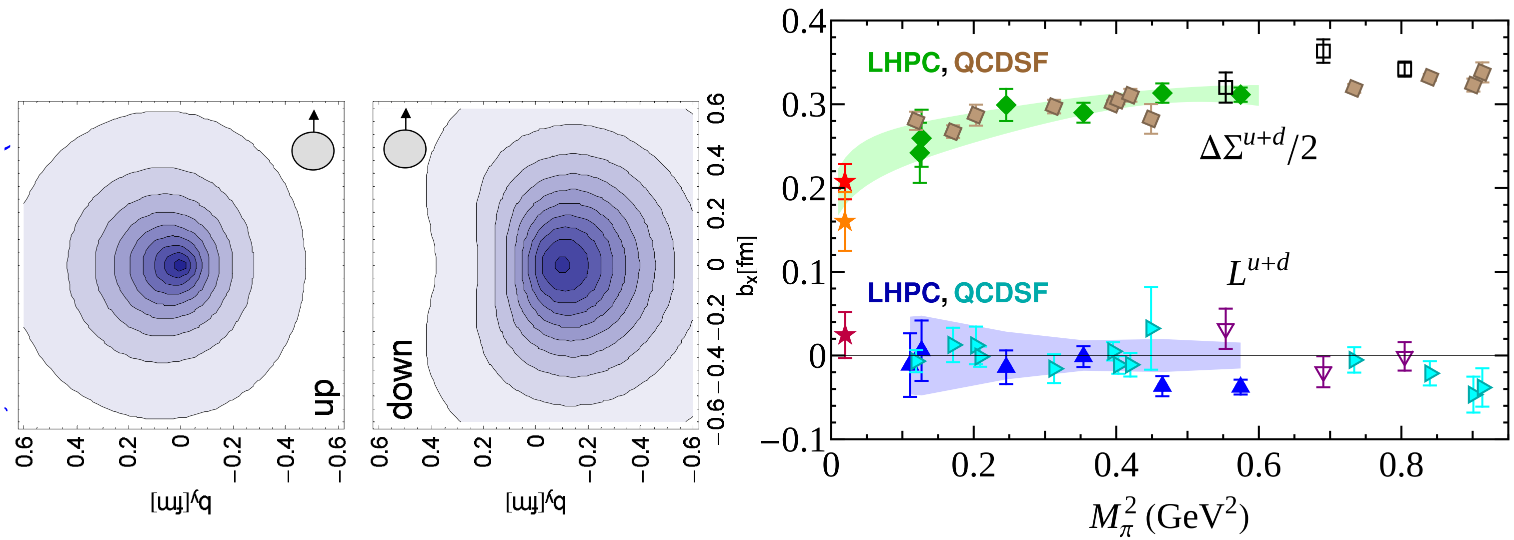


-New experiments are planned at JLAB-12 GeV and COMPASS-160 GeV

-The concept of a transverse imaging the momentum distribution of (polarized) quarks in a polarized nucleon has emerged
unifying the idea of form factors and structure functions



-Lattice QCD is delivering images to compare with



my personal view:

-Comparing moments of (generalized) structure functions with LQCD calculations will be the key for a mastering hadron structure physics from first principles (from art to science)

-And if we are lucky hadron **spectroscopy** could make a similar transition exploiting processes like

$e + p \rightarrow e' + \gamma + N*$ or $e + p \rightarrow e' + M + B$

Priority 1: The Exclusive Program

- Validation of the concept of GPDs and their extraction: scale dependence, factorisation properties

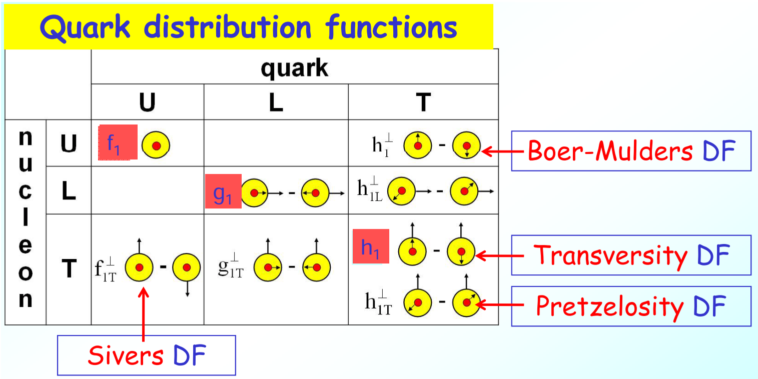
- Precision determination of the four GPDs and their flavour components

Guidal has made a list of processes and their relevance to extract H , $\tilde{H}$, E, $\tilde{E}$:

DVCS

of longitudinally **polarized electrons and positrons** on longitudinally or transversely **polarized deuteron and protons**

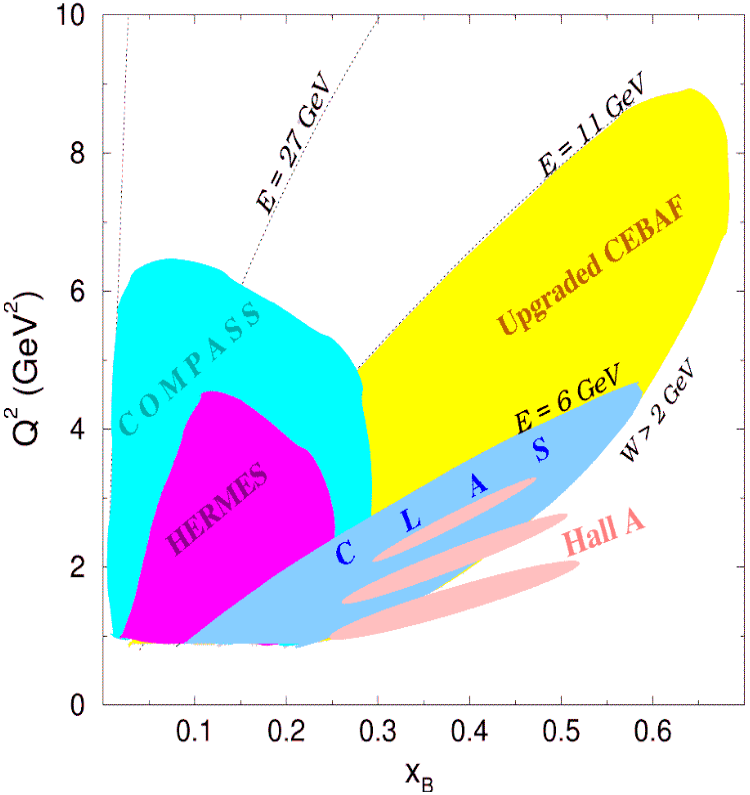
Priority 2: The Transversity an $k_\perp$ Program



- see parallel workshop
- study of azimuthal hadron distributions with transversly polarized protons and deuterons
- First evidence of Collins and Sivers asymmetries on proton and deuterium from HERMES and COMPASS
- high statistics multidimensional analysis $(x, Q^2, p_\perp, z, ..)$ needed, leading to subleading correlations ...

Colliders and Fixed Target

Kinematical range of polarized facilities compared: What are the minimum requirements in s and $\mathcal{L}$?



- HERA (the worlds one and only ep collider) has contributed significantly to the $F_2^p(x, Q^2)$ and $g(x, Q^2)$
  - HERA used protons against polarized **positrons** and **electrons** at a single energy (upgraded once)

- no polarized protons or deuterons
- no deuteron or ion beams

- Fixed targed Experiments are limited in cm Energy $s^* = 2E_\ell m_p$
  - $Q^2 = x \cdot y \cdot s^*$
  - CEBAF (now) $s^* = 12\,GeV^2$
  - CEBAF (planned $s^* = 22\,GeV^2$
  - HERMES $s^* = 56\,GeV^2$
  - COMPASS $s^* = 180 - 400\,GeV^2$

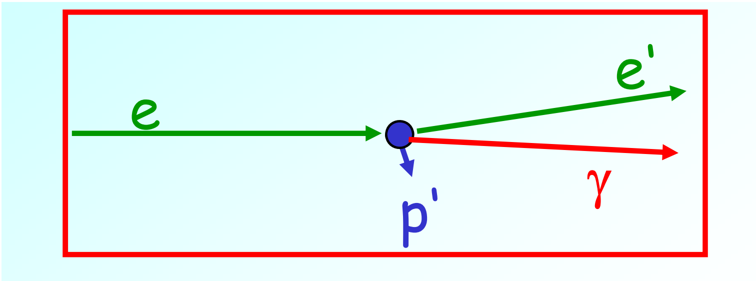
Projects

- Collider projects
  - $s^* = 4E_eE_N$
  - ENC@FAIR:
  - $s^* = 200\, GeV^2$ for protons, $x_{min} = 5 \cdot 10^{-3}$
  - $s^* = 100\, GeV^2$ for nucleons (e.g. Deuteron, $^4He^{++}$), $x_{min} = 10^{-2}$
  - eRHIC 10+250 $s^* = 10000\, GeV^2$, $x_{min} = 10^{-4}$ compare to HERA $s^* = 10^5$, $x_{min} = 10^{-5}$
  - ELIC
  - LHeC

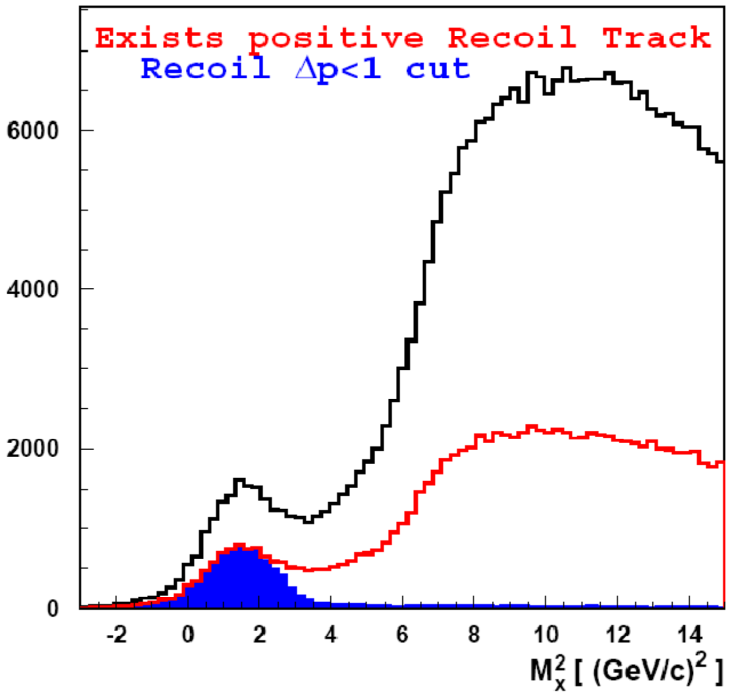
What are the essential experiments and their kinematical ranges?

- Example: Measurement of $E(x, \xi, Q^2, t)$ in DVCS

  - transversely polarized proton target
  - coverage $0.1 < x < 1$ with $2 < Q^2 < 20\,GeV^2$, $|t| > |t_{min}|$
  - Missing mass analysis: full reconstruction of final 3 particle final state (e', p', γ with full supression of background
    - With HERMES, COMPASS : Recoil Detector
    - With Collider option : fast proton (+ spectator) at hadron beam rapidity



DVCS event candidates



- **Fixed Target alternative** at 50 GeV aka ELFE (10% duty cycle)
  - Solid state target NH_3 reduction factor in luminosity $f^2 = 1/32$, HD ice $f^2 \approx 1/14$
  - beam current limit $I_{max} \approx 5nA$ on $5g/cm^2$: $0.1 * 5 * 10^{-9} * 0.6 * 10^{19} * 6 * 5 * 10^{23} = 9.0 * 10^{33}$
    with reduction factors for Dilution and Polarisation (NH3) we get $\mathcal{L}_{eff} = 0.12 * 10^{33}$
  - further losses due to t_{min} in recoil detection and acceptance cuts only be roughly estimated
  - systematics of polarisation reversal, multiple scattering in 10% X_0 target limiting δM

- Collider option
  - pure polarized targets (no dilution), no atomic electrons
  - "recoil" detected in a range $\Theta < 5^{\circ}$, possibility of tagging
  - wide acceptance with the standard target solenoid, charm with displaced secondary vertices
  - **Luminosities** $\mathcal{L} > 10^{33}$ hard to obtain (the so called "Knackpunkt")

Conclusions

- Hadron structure physics is adressing fundamental problems
  - Can we understand the emergence of hadrons and their properties from first principles i.e. on the basis of the QCD and the Standard Model
  - Can we predict hadronic processes with good and controlled precision

- Scattering of polarized charged leptons on hadrons is a key process
  - to understand shape and momentum distribution of charged partons
  - now we can combine these into an image, correlating both aspects like in tomography
  - Theory is at hand: Lattice QCD, PQCD and effective field theory can cover all scales

- CEBAF 6 /12 GeV and COMPASS are the only places to do experiments now
  - beam and target polarisation, high effective luminosity $\mathcal{L}^{eff} = \mathcal{L} \cdot f^2 \cdot P_e^2 \cdot P_t^2$ is needed
  - for parton distributions and GPDs $s \gtrsim 50 - 100\, GeV$ might be sufficient
  - a new fixed target option at 25-50 GeV or a collider would be equally welcome at $\mathcal{L}^{eff} \gtrsim 10^{32} cm^{-2} s^{-1}$