High-Energy DIS Studies with Nucleons

Uta Klein

Speaker’s affiliations:

[Logos for University of Liverpool, ATLAS, LHeC, FCC]
ep: Resolving a non-trivial Structure...

Q=1 Gev

& solve confinement puzzle!??*

100 years of lp scattering

greater than 5 orders of magnitude
deeper into matter

Empower pp discoveries!

*Jaffe&Witten 2000: 1 out of 7 millennium prize questions
## Developments

- AdS/CFT
- Instantons
- Odderons
- TOTEM \(^{\text{\cite{CERN EP 2017-335}}}\)
- Non pQCD, Spin, Mass
- Quark Gluon Plasma
- QCD of Higgs boson
- \(N^{k\text{LO}}\) PDFs, Monte Carlos.. Resummation
- Saturation and BFKL
- Photon, Pomeron, \(n\) PDFs
- Non-conventional partons (unintegrated, generalised)
- Vector Mesons
- The 3 D view on hadrons..

## Discoveries

- Why no CP violation in QCD?
- Massless quarks?? Would solve it..
- Electric dipole moment of the neutron?
- Axions, candidates for Dark Matter
- Breaking of Factorisation \([ep-pp]\)
- Free Quarks
- Unconfined Color
- New kind of coloured matter
- Quark substructure
- New symmetry embedding QCD

QCD has an exciting future
The eh Landscape: Luminosity vs $\sqrt{s}$

China
- CEIC1 / 2 = EicC
- Chinese version of Electron-Ion Collider

U.S.
- JLEIC / JLEIC-HE = EIC@Jlab
- eRHIC / eRHIC-HL = EIC@BNL

Europe
- LHeC/FCC-ep = ep/eA collider@CERN

Includes future HL and HE extensions.

http://cerncourier.com/cws/article/cern/57304
+ Update by R Ent
The most advanced Proposals

At the high energy frontier $\sqrt{s} \sim 1.3 - 3.5$ TeV

Using polarised e&h-beams $\sqrt{s} \sim 0.01-0.14$ TeV

LHeC Conceptual Design Report
http://lhec.web.cern.ch

EIC White Paper
arXiv:1212.17010 (v2)
http://web.mit.edu/eicc/index.html
http://www.bnl.gov/cad/eRhic/
eRHIC Design Study: An EIC at BNL
arXiv:1409.1633 ; 1708.01527
Future eh Colliders: EIC and LHeC

**EIC:** $E_{\text{c.m.s.}}$ $\sim$ 20-140 GeV
- Polarised electrons with $E_e>$3 GeV
- **Polarised proton** (70%) beams and unpolarised heavy ion beams ($A\leq200$)
- High luminosity for **spin physics**.

**LHeC:** $E_{\text{c.m.s.}}$ 0.2 - 1.3 TeV
- Add 30-60 GeV **polarised** electrons to probe unpolarised LHC proton and ions

- **High-energy frontier** e-p and e-A collider **running simultaneously with** HL-LHC, expanding hugely HERA kinematics ➔ exploring QCD+EW sector (e.g. top, Higgs, BSM...)

World’s first polarised e-p collider and lower energy e-A collider → **below** HERA kinematics ($x>10^{-5}$)

$x_{\text{min}} \sim 1 \times 10^{-4}$

$x_{\text{min}} \sim 6 \times 10^{-7}$

Small x

High $Q^2$
The Structure of the Proton

Naïve Quark Model: proton = uud (valence quarks)
QCD: proton = uud + uū + dū + sū + …

The proton sea has a non-trivial structure: \( \bar{u} \neq \bar{d} \)
& gluons are abundant

- The proton is **far more** than just its up + up + down (valence) quark structure
- Gluon ≠ photon: Radiates and recombines:
**Gluons: QCD and Higgs**

- QCD is the **fundamental** theory that describes structure and interactions in nuclear matter.
- Without gluons there are no protons, no neutrons, and no atomic nuclei.
- Gluons dominate the structure of the QCD vacuum.

**Facts:**

- The essential features of QCD (e.g. asymptotic freedom, dynamical chiral symmetry breaking, and color confinement) are driven by gluons!
- Unique aspect of QCD is the **self interaction** of the gluons.
- **Visible mass** from massless gluons and nearly massless quarks:
  - Most of the mass of the visible universe emerges from quark-gluon interactions.
  - **The Higgs mechanism** for mass of quarks ‘only’
    ➔ but fundamental to understand it thoroughly.
EIC’s: Understanding Nucleon Mass

Relativistic motion

\[ M = E_q + E_g + \chi m_q + T_g \]

\( \chi \) Symmetry Breaking

Quantum fluctuation

Quark Energy

Gluon Energy

Quark Mass

Trace Anomaly

“... The vast majority of the nucleon’s mass is due to quantum fluctuations of quark-antiquark pairs, the gluons, and the energy associated with quarks moving around at close to the speed of light. ...”

**Preliminary Lattice QCD results:**

- Trace Anomaly: 20%
- Quark Energy: 29%
- Gluon Energy: 34%
- Quark Mass: 17%

**EIC’s expected contribution in:**

- **Trace Anomaly:**
  - J/psi and Upsilon elastic production near the threshold

- **Quark-gluon Energy:**
  - \( \propto \) quark-gluon momentum fractions

  **In nucleon with DIS and SIDIS**

  **In pions and kaons with Sullivan process**

Based on slide from T Horn, ICFA 2017
Understanding Quark-Gluon Dynamics

Low-$x$ resummation for $x \to 0$: First signs seen at HERA?

Measure change in QCD radiation pattern!? Or measure gluon saturation?

For DY, DIS, Higgs, singular behavior when $x \to 1$

$\delta(1-x) \left[ \frac{\ln^k(1-x)}{1-x} \right] \ln^k(1-x)$

Resummation:

The art of constructing for some quantity out of a subset of perturbative terms, aided by extra insight, an all-order expression

Or measure gluon saturation?

Disclaimer: I refer to high precision and unpolarised IN colliders for illustration.
Quantify the power of the rise of $xg$ and $x\Sigma$ by examining evolution of their ratio.

Large evolution at NNLO, with the ratio exceeding unity at low scales.

Ratio is $\leq 0.5$ when $\ln 1/x$ resummation is included.

$\rightarrow$ more inline with “dynamic” picture of PDFs in which the sea is generated from the gluon perturbatively like in GRV fits.

Needs new, most accurate ep data extending to smaller $x$ in perturbative region!
How to determine low x evolution + discover saturation?

Precision measurements of gluon distribution essential for quantitative studies of onset of saturation as a high density (small x in ep) and matter ($A^{1/3}$) effect.

$c.f.\ LHeC$ CDR to confirm DGLAP or rule it out

High precision $F_L$ from variation of $E_e$ independently of LHC/FCC

High precision $F_2(x,Q^2)$ from few days of nominal ep running. Needs large $Q^2$ and low $x \sim 1/s$:

Needs cleanest DIS constraints, proton, not ion, high E: $F_2+F_L$

LHeC CDR: 1206.2913 J Phys G

MK: 1802.04317
c.f. LHeC CDR to confirm DGLAP or rule it out

Precision measurements of gluon distribution essential for quantitative studies of saturation as a high density (small x in ep) and matter ($A^{1/3}$) effect.
Understanding the Gluon

Low and high $x$ partons are intertwined by momentum sum rules!

**DGLAP approach**

**Small $x < 0.01$**

**High $x > 0.1$**

**Gluon distribution at $Q^2 = 1.9$ GeV$^2$**

The gluon is uncertain by two orders of magnitude at high $x > 0.5$.

Gluon from $Q^2$ derivative of DIS cross section most accurate.

Not measured yet!
Saturation and Diffraction

Diffractive cross section: \[ \sigma_{\text{diff}} \propto [g(x, Q^2)]^2 \]

HERA legacy: 10-15\% diffractive events in ep; \( Q^2 \) dep!
If saturation (CGC) – multiple coherent gluons
\( \rightarrow \) Diffraction in eA: \(~25-30\%\) diffractive contribution
Reminder: Factorization for diffractive processes works in DIS, not in pp, pA, AA

Diffractive vector meson production:
‘Predictions’ for coherent J/ψ production

Experimental challenge: measurement of t (ZDC?) and detection of FS proton and neutron (incoherent: nucleus breaks up) in ep and eA.
Diffractive PDFs

- Low $x_{IP}$ → cleanly separate diffraction
- Low $\beta$ → Novel low $x$ effects
- High $Q^2$ → Lever-arm for gluon, flavour
- Large $M_x$ → Jets, heavy flavours, W/Z ...
- Large $E_T$ → Precision QCD with jets ...

EIC: Very precise measurements for a different kinematic range possible
Valence Quark Distributions

Up valence distribution at $Q^2 = 1.9$ GeV$^2$

Down valence distribution at $Q^2 = 1.9$ GeV$^2$

LHC+HERA

Normalised to NNPDF 3.0
d/u at large x

Subtle measurement: \( u_v d_v \) drastically decrease for \( x \approx 1 \)

- LHeC: Combination of NC and CC DIS at very high \( Q^2 \)
- EIC’s: NC DIS in ep and eD; tagged spectator proton

Crucial test of pQCD: non-singlet quark distributions do ‘not’ evolve with \( Q^2 \)?

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d/u essentially unknown at large x

- no predictive power from current PDFs;
- conflicting theory pictures;
- data inconclusive, large nuclear uncerts.

with precision ep (n) data to v. large x:
- no nuclear corrections; relax assumptions

resolve long-standing mystery of d/u ratio at large x

\( \rightarrow \) Subtle measurement: \( u_v d_v \) drastically decrease for \( x \approx 1 \)

- LHeC: Combination of NC and CC DIS at very high \( Q^2 \)
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\( \rightarrow \) Crucial test of pQCD: non-singlet quark distributions do ‘not’ evolve with \( Q^2 \)?
Empowering Discoveries at LHC (pp)

External, accurate input is crucial for search extension + non-resonant interpretations.
Two unknowns, PDFs and new physics, require two independent sources of input.

**GLUON**

Exotic+ Extra boson searches at high mass

**QUARKS**

update of arXiv:1211.5102

**NNPDF3.0**: ‘Issues’ with negative replica
Impact of PDF: High mass Drell-Yan

- Non resonant searches for ED (interference) sensitive to tails of DY distributions thus to PDF. Predominantly q-qbar

\[ W^+ \]

Uta Klein
VRAP 0.9 for NNLO QCD

Assuming collinear factorization & momentum sum rule...

FCC-hh @100 TeV

QUESTIONs for pp/ pA / AA:
- How ‘safe’ are our factorization assumptions?
- How may we test those w/o new accurate independent inputs from DIS?
- How do we treat ‘dissident’ PDF data / fits?
- Shall we fit LHC data in global PDFs?

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Beware NP:
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“Troubles” at low and high x

FCCeh (and before, LHeC) can improve low and high \( M(\ell\ell) \) and \( M(\ell\nu) \) precision for standard candle measurements and searches for new physics

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arXiv:1711.05449
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\( \Rightarrow \) new physics may appear as radiative corrections in DY and modify cross section by 0.1-10% at 200-1000 GeV (study for HL-LHC)
.. and more Puzzles

intrinsic charm?

\[ e^+ p \text{ charm SIDIS, } \sqrt{s} = 45 \text{ GeV}, Q^2 = 9 \text{ GeV}^2 \]

\[ e^+ p \text{ charm SIDIS, } \sqrt{s} = 105 \text{ GeV}, Q^2 = 625 \text{ GeV}^2 \]

**EIC**: intrinsic charm may be probed via charm contributions to DIS reduced cross section, \( F_{L,c} \) or angular distributions
sensitivity to intrinsic vs perturbative charm; and to different shapes of intrinsic charm

**LHeC**: challenge – charm tagging in very forward direction to access large \( x \) values of interest; could be favourably done with dedicated lower proton beam energy runs (CDR study)

**LHC**: \( Z+c, \gamma+c \); most recent measurements not yet discriminating (EG. M. Stockton, WG1)
Evidence of enhanced strange-to-light sea density at $x \sim 0.01$

ATLAS 2016: 1612.0301, PRD

→ based on high precision $W$ and $Z$ data and ~ 5 years of analysis and joint HERA+ATLAS QCD fit

LHeC: Precision measurement of strange, also of charm, beauty and top → $N^3$LO

→ Complete unfolding of the flavour structure of the proton for the first time

→ Enables and requires a new kind of PDF fits and clarification of HFL scheme
\[ \alpha_s(\mu) \text{ at LHeC/FCCeh} \]

<table>
<thead>
<tr>
<th>case</th>
<th>cut ([Q^2 \text{ (GeV}^2)])</th>
<th>uncertainty</th>
<th>relative precision (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HERA only</td>
<td>(Q^2 &gt; 3.5)</td>
<td>0.00224</td>
<td>1.94</td>
</tr>
<tr>
<td>HERA+jets</td>
<td>(Q^2 &gt; 3.5)</td>
<td>0.00099</td>
<td>0.82</td>
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<tr>
<td>LHeC only</td>
<td>(Q^2 &gt; 3.5)</td>
<td>0.00020</td>
<td>0.17</td>
</tr>
<tr>
<td>LHeC+HERA</td>
<td>(Q^2 &gt; 3.5)</td>
<td>0.00013</td>
<td>0.11</td>
</tr>
<tr>
<td>LHeC+HERA</td>
<td>(Q^2 &gt; 7.0)</td>
<td>0.00024</td>
<td>0.20</td>
</tr>
<tr>
<td>LHeC+HERA</td>
<td>(Q^2 &gt; 10)</td>
<td>0.00030</td>
<td>0.26</td>
</tr>
</tbody>
</table>

Table 3: Results of NLO QCD fits to HERA data (top, without and with jets) to the simulated LHeC data alone and to their combination, for details of the fit see [5]. The resulting uncertainty includes all the statistical and experimental systematic error sources taking their correlations into account. The LHeC result does not include jet data.

- LHeC/FCCeh lead to 0.1\% uncertainty (stat+syst), free of previous DIS deficiencies (HT,nc)
- Joint determination with parton distributions (maybe simplified as H1 published in 2001)
- Needs clarity about low \(x\) behaviour as this uses DGLAP.
- Requires to control heavy flavour (theory) at new level (measure s, c, b, t also)
- Very high precision of NC (\(y\) and Z) and CC and extension to \(x\) near 1 will drastically reduce the PDF parameterisation uncertainties
- Scale uncertainties require that N^3LO formalism be applied (the bizarre 1/2 .. 2 rule.??)
- The attempt to measure the strong coupling in DIS to permille accuracy requires nothing less than a renaissance of experimental and theoretical DIS (ep) physics

and do not forget strong coupling measurements from polarised DIS!
The Proton Spin

- The sum rule: \( S(\mu) = \sum_f \langle P, S | \hat{J}^z_f(\mu) | P, S \rangle = \frac{1}{2} \equiv J_q(\mu) + J_g(\mu) \)
  - Infinite possibilities of decompositions – connection to observables?
  - Intrinsic properties + dynamical motion and interactions

- An incomplete story: ... after more than 20 years of efforts ... see Spin WG Summary!

- Jaffe-Manohar, 90 Ji, 96, ...

\[ \frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta G + (L_q + L_g) \]

Proton Spin

- Quark helicity
  - Best known
  - \( \frac{1}{2} \int dx (\Delta u + \Delta \bar{u} + \Delta d + \Delta \bar{d} + \Delta s + \Delta \bar{s}) \approx 30\% \)

- Gluon helicity
  - Start to know
  - \( \Delta G = \int dx \Delta g(x) \)
  - \( \approx 40\% \) (with RHIC data)

- Orbital Angular Momentum of quarks and gluons
  - Little known

How to explore the polarised gluon and sea quark contribution fully?
How to quantify the role of orbital motion?
Spin at EIC: $\Delta \Sigma$ & $\Delta g$

EIC projected data:
- eRHIC + JLEIC
  - $\sqrt{s} = 44.7$ GeV
  - $\sqrt{s} = 63.2$ GeV
- eRHIC only
  - $\sqrt{s} = 141.4$ GeV

Theory

Uncertainty

pQCD scaling violations

EIC prospects:
- extremely challenging measurement
- spin asymmetries very small for $x \to 0$
- needs excellent control of detector stability, polarisation measurements and measurements of $F_2$ and $F_L$
Proton Spin @ EIC

Requires longitudinally polarised hadron and electron beams ➔ unique for EIC!

✝ Precision measurement of $\Delta G$ and $\Delta \Sigma$ via extension to smaller $x$ regime

✝ Orbital angular momentum?

➔ (Spatial distance from origin) $\times$ (Transverse Momentum)
Explore Spin & Quantum Correlations

EIC: transversely polarised hadron beam

Quantum correlation between hadron spin and parton motion:

Sivers effect – Sivers function

Hadron spin influences density of unpol. partons in transverse-momentum plane

Observed particle

Quantum correlation between parton spin and hadronization:

Transversity

Collins effect – Collins function

Parton’s transverse spin influence its hadronization

JLab12 GeV upgrade and COMPASS for valence, EIC covers sea-quarks and gluon!

connection of observables to L remains a theoretical challenge
Spatial Imaging of Partons &

**Ji Sum Rule**

$$\lim_{t \to 0} \int x dx [H_f(x, \xi, t) + E_f(x, \xi, t)] = 2 \int H_f$$

**Exclusive processes - DVCS:**

$$\frac{d\sigma}{dx_B dQ^2 dt}$$

$$t = (p' - p)^2$$

$$\xi = (P' - P) \cdot n / 2$$

**GPDs**

$$H_q(x, \xi, t, Q), E_q(x, \xi, t, Q), \ldots$$

**F.T. of t-dep**

Spatial distributions of valence quarks and sea-quarks at large and medium x values

**Exclusive vector meson production:**

$$\frac{d\sigma}{dx_B dQ^2 dt}$$

$$\rightarrow$$ Fourier transform of the t-dependence

$$\rightarrow$$ Spatial imaging of glue density

$$\rightarrow$$ Resolution ~ $1/Q$ or $1/M_Q$

→ Collect as much flavour-separated data as possible on TMDs and GPDs

→ Huge experimental task!
3-dimensional exploration of nucleon has just started: collect as much data as possible on TMDs and GPDs and try to reconstruct the complete phase-space distribution

ideal machine:
high luminosity
x-range including the valence region
$Q^2$ high enough to neglect higher-twist corrections
$P_T$ high enough to see transition from TMDs to pQCD
precise $P_T$-$Q^2$ bins
measure jet asymmetries....

plenty of challenging theoretical issues....

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**Status of Ji Sum Rule**

C Hyde, DIS2018

- $H_f(x,0,t)$ essentially known from fits to $F_{1f}(-t) \otimes q_f(x)$
  - Measure $H_f(x,x,t)$ → Determines DD Profile function
  - $JLab$ 12 → higher $x$, $Q^2$ range

- $E_f(x,0,t)$ constrained from $F_{2f}(-t)$ and assumption $e_f(x)$ does not change sign.
  - Test this assumption
    - $x \approx 0.1$ COMPASS 2020
    - $x \approx 0.4$ Jlab12
    - Lattice QCD

- My prediction: In 10 years, we will be confident in value of $J_{u,d}$
Proton spin “puzzle”

- Nucleon Spin and Momentum Decomposition Using Lattice QCD Simulations
  - ETMC: C. Alexandrou et al [PRL 119 (2017) 142002]
  - using Ji’s gauge invariant decomposition

\[ J_N = \sum_{q=u,d,s,c,...} \left( \frac{1}{2} \Delta \Sigma_q + L_q \right) + J_g \]

- on-physical point simulation
- only one lattice spacing
- total J consistent with 1/2
  claiming
  “resolving a long standing puzzle”
- systematic errors not fully investigated
  - twisted mass \(\rightarrow\) isospin violation should be investigated
  - adding another lattice spacing will help!

<table>
<thead>
<tr>
<th>(\frac{1}{2} \Delta \Sigma)</th>
<th>(J)</th>
<th>(L)</th>
<th>(\langle x \rangle)</th>
</tr>
</thead>
<tbody>
<tr>
<td>u 0.415(13)(2)</td>
<td>0.308(30)(24)</td>
<td>-0.107(32)(24)</td>
<td>0.453(57)(48)</td>
</tr>
<tr>
<td>d -0.193(8)(3)</td>
<td>0.054(29)(24)</td>
<td>0.247(30)(24)</td>
<td>0.259(57)(47)</td>
</tr>
<tr>
<td>s -0.021(5)(1)</td>
<td>0.046(21)(0)</td>
<td>0.067(21)(1)</td>
<td>0.092(41)(0)</td>
</tr>
<tr>
<td>g -</td>
<td>0.133(11)(14)</td>
<td>-</td>
<td>0.267(22)(27)</td>
</tr>
<tr>
<td>tot. 0.201(17)(5)</td>
<td>0.541(62)(49)</td>
<td>0.207(64)(45)</td>
<td>1.07(12)(10)</td>
</tr>
</tbody>
</table>

Lattice calculations have been impressively improving over the past decade
Lattice calculations ‘deserve’ to be challenged by precise and accurate measurements for fundamental QCD properties like proton spin&mass and the strong coupling as they could be enabled by EIC and LHeC.
Deep Inelastic lepton-Nucleon Scattering is a fantastic and unique tool to study nucleon structure and unravel QCD (mass, spin, 3D nucleon structure, nucleon’s flavour structure, $N^3LO, \alpha_s$) and search for BSM and Higgs physics (not discussed here) with high precision data and on firm theoretical grounds.

Luminosity and excellent detectors are KEY for a new level of PRECISION in DIS.

The quest of new generation DIS machines is now imminent: for a full exploitation of our highest energy machine(s) and for unraveling the secrets of nuclear and particle physics: by employing fully the complementarity of ee, ep and pp – in the tradition of Tevatron, HERA & LEP side by side with a wealth of Fixed Target experiments.

The future of DIS experiments is bright with wealth of new proposed machines for various energy ranges to tackle ‘old’ and ‘new’ problems -

to explore the ‘unknown knowns and unknown unknowns’
Thank You!

Special thanks to my ‘old’ and ‘new’ colleagues in the LHeC/FCC-study group, and the EIC colleagues R Ent, B Surrow, R Yoshida, E Aschenauer, J Furletova.

A very warm Thank You to the spirit of this DIS conference, guided by the endless efforts of Y Yamazaki.

And sorry, if I missed to mention someone’s name here. All mistakes are mine.
In the absence of any explicit new states, or overwhelming theory prejudice, the goal is to systematically study the SM EFT for hints of NP, using all possible future facilities to maximize physics conclusions.

What is the SM EFT? A linear realization of gauge symmetry and the new state is a 0+ scalar:

59 operators or 2499 parameters experimentally to constraint!

where nearly 50% of the parameters (1053) are sensitive to lepton-quark interactions – not just about lepto-quarks

ep potential for general BSM searches ‘that look like hadronic noise’ in pp
Kinematic Plane for Spin

Current polarized DIS ep data:
- CERN
- DESY
- JLab-6
- SLAC
- JLab-12

Current polarized RHIC pp data:
- PHENIX $\pi^0$
- STAR 1-jet
- W bosons

$Q^2 \text{ (GeV}^2\) vs. x$ for EIC $\sqrt{s} = 45 - 141 \text{ GeV}, 0.01 \leq y \leq 0.95$
$EIC \sqrt{s} = 22 - 63 \text{ GeV}, 0.01 \leq y \leq 0.95$
Collider → allows a *precision measurement* of the spectator nucleon.

First precision measurement of polarized (and unpolarized) neutron is possible at EIC

Extrapolation from bound to free neutron under control

F₂ⁿ can be extracted at % level accuracy

Investigate nuclear effects at the level of partons with Tensor Polarization Observables

Polarized Deutron Structure Function b₁

Are quarks sensitive to the shape of the nucleus?

Double helicity-flip distribution Δ(x,Q²)

→ Gluon Transversity

- Non-nucleonic gluon component!
- Lattice results ≠ 0!
EIC Science: Imaging quarks and gluons in nucleons

3D Sea Quark distributions unpolarized and polarized

3D Gluon distributions

Polarized Quark 3D Momentum distributions

Slide from R Ent
World Data on $F_2^p$  

$F_2^p$ has similar data to $g_1^p$. 

An EIC makes it possible! 

Note: need to update plots for COMPASS data.

Similar for $F_2^n$, $g_2^p$, $g_2^n$ (and $b_1^d$).

$F_{UT} \sin(\phi h + \phi s)(x, Q^2) + C(x) \propto h_1$

Based on slide from R Ent.
Transverse Momentum Distributions

- **TMDs - rich quantum correlations:**
  - Similar for gluons

<table>
<thead>
<tr>
<th>Nucleon Polarization</th>
<th>Quark Polarization</th>
<th>Transversely Polarized (T)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Un-Polarized (U)</td>
<td>$f_1 = \uparrow \downarrow$</td>
<td>$h_1^\perp = \uparrow \downarrow$ Boer-Mulders</td>
</tr>
<tr>
<td>Longitudinally Polarized (L)</td>
<td>$g_{1L} = \uparrow \downarrow$ Helicity</td>
<td>$h_{1L}^\perp = \uparrow \downarrow$</td>
</tr>
<tr>
<td>Transversely Polarized (T)</td>
<td>$f_{1T}^\perp = \uparrow \downarrow$ Sivers</td>
<td>$g_{1T}^\perp = \uparrow \downarrow$</td>
</tr>
<tr>
<td></td>
<td>$h_1^\perp = \uparrow \downarrow$ Transversity</td>
<td>$h_{1T}^\perp = \uparrow \downarrow$</td>
</tr>
</tbody>
</table>

- **Naturally, two scales and two planes:**
  - **Two scales:**
    - high $Q$ - localized probe
    - Low $p_T$ - sensitive to confining scale
  - **Two planes:**
    - angular modulation to separate TMDs

Hard to separate TMDs in hadronic collisions
At high $Q^2 \sim m_t^2$ top demands a fraction of proton’s momentum – need to understand what a “top PDF” is. Scheme dependence

.. a totally new challenge ...

\[
\tau_t = \left(1 + \frac{4m_t^2}{Q^2}\right)^{1+\lambda} \frac{Q^2}{Q_0^2} \left(\frac{x_B}{x_0}\right)^\lambda
\]
The LHeC PDF Programme

Resolve parton structure of the proton completely: $u, d, s, ?, u, d, s, c, b, t$ and $xg$

Unprecedented range, sub% precision, free of parameterisation assumptions, Resolve p structure, solve non linear and saturation issues, test QCD, $N^3LO$...

Strong Coupling in inclusive DIS at LHeC to 0.1%

Lattice??
Jets??
BCDMS??
GUTs?
Higgs in pp

Solve the PDF issues for pp and test QCD with permille measurement of strong coupling
Plenty of charm, beauty and top...to explore in detail and with high precision heavy flavour schemes

$E_p = 7$ TeV

Plot by O Behnke

No top at HERA

$E_e = 60$ GeV well above top threshold

LHeC CDR arXiv:1206.2913
Charm $F_2^{cc}$ and Mass

Heavy Flavour with LHeC
Beam spot (in xy): 7μm
Impact parameter: better than 10μm
Modern Silicon detectors, no pile-up
Higher E, L, Acceptance, $\varepsilon$, than at HERA
→ Huge improvements predicted

<table>
<thead>
<tr>
<th></th>
<th>HERA</th>
<th>LHeC</th>
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<tr>
<td>$m_c(m_c)/GeV$</td>
<td>1.26</td>
<td>?</td>
</tr>
<tr>
<td>$\delta(\exp)$</td>
<td>0.05</td>
<td>0.003</td>
</tr>
<tr>
<td>$\delta(\mod)$</td>
<td>0.03</td>
<td>~0.002</td>
</tr>
<tr>
<td>$\delta(\par)$</td>
<td>0.02</td>
<td>~0.002</td>
</tr>
<tr>
<td>$\delta(\alpha_s)$</td>
<td>0.02</td>
<td>0.001</td>
</tr>
</tbody>
</table>

LHeC determines strong coupling to 0.1%
High precision PDF data will reduce the model and parameterization uncertainties.

Determination of charm mass to 3 MeV: crucial for $M_W$ in pp or $H \rightarrow cc$ in ep

cf also NNPDF3.1 (arXiv:1706.00428) and refs

HERA 0.0005 - 0.05 for 2.5-2000 GeV²
LHeC 0.00001 - 0.2 for 1-200000 GeV²
$\varepsilon(c)$ assumed 10%, 1% light background, ~3% $\delta$(syst)
Bottom $F_{2}^{bb}$ and Mass

Bottom density not well known

Scheme dependence affects LHC interpretations

In MSSM: Higgs from $bb \rightarrow H$ not $gg$

(we only miss the MSSM..)

$m_{b}(m_{b})$ with LHeC to 10 MeV

Huge improvement vs HERA for the same reasons as for charm
Using LHeC input: experimental uncertainty of predicted LHC Higgs cross section due to PDFs and $\alpha_s$ is strongly reduced to <0.5%.

Theoretically clean path to determine $N^3$LO PDFs using ep DIS.

All those ‘benefits’ for pp within the first few years, using ~100 fb$^{-1}$ ep data.

NNLO pp–Higgs Cross Sections at 14 TeV.

Precision from LHeC can add a very significant constraint on the Higgs mass and challenge Lattice QCD calculations for $\alpha_s$.
Synergy: eA and AA

The LHeC-eA will explore a region overlapping (EIC-eA partially) with the LHC-AA
→ in a cleaner experimental setup;
→ on firmer theoretical grounds.

- Nuclear wave function at small x: nuclear structure functions.
- Particle production at the very beginning: which factorisation in eA?
  - How does the system behave as ~ isotropised so fast?: initial conditions for plasma formation to be studied in eA.
- Probing the medium through energetic particles (jet quenching etc.): modification of QCD radiation and hadronization in the nuclear medium.

eA: measure in semi-inclusive DIS modification of fragmentation/hadronisation in dense nuclear medium.

Gluons from saturated nuclei → Glasma? → QGP → Reconfinement

hadrons π, K, D and B etc.
US-based EIC’s

Brookhaven Lab
Long Island, NY

Jefferson Lab
Newport News, VA
LHeC and FCC-he: Sites at CERN


High-Luminosity LHC anticipated to run until ~2040

➔ Potential for 10 years LHeC (2030-2040) with ~1000 fb⁻¹
➔ joint ep and pp data taking!

Update 2017: Interaction point L
Resolving Partonic Structure
accurate and free of symmetry assumptions

• One can see that for HERA data, if we relax the low x constraint on u and d, the “PDF errors” are increased tremendously!
→ when adding the LHeC simulated data, we observe that uncertainties are visibly improved even without this assumption.
• Further important cross check comes from the deuteron measurements, with tagged spectator and controlling shadowing (small x partons) with diffraction...
• All parton distribution functions of the proton at N^3LO!
The ep Physics at the Energy Frontier

-4-momentum transfer squared $Q^2 / \text{GeV}^2$

LHeC Experiment:
- HERA Experiments:
  - H1 and ZEUS
Fixed Target Experiments:
  - NMC
  - BCDMS
  - E665
  - SLAC

-4-momentum transfer squared $Q^2 = M^2$

UHE Neutrinos

High Density Matter - New form of gluonic matter?

High Precision QCD & EW (top) Physics

RPV SUSY, LQ Substructure?

Higgs Boson

Large x Gluon & valence quarks

Proton Spin

Relation to pp: $x_{1,2} = (M/\sqrt{s}) \exp(\pm y)$ & $Q^2 = M^2$

HERA established the validity of pQCD down to $x > 10^{-4}$ (DGLAP) due to a very high lever arm in $Q^2$.

Extensions of both $x$ and $Q^2$ ranges are crucial for new experiments and HEP theory developments!
This physics program requires very high luminosity.
- Multi-dimensional measurements
- Exclusive processes.
- Many configurations. (typ. 10(fb^-1) per meas.)

**EIC Science Program**

- Tomography (p/A)
- Transverse Momentum Distribution and Spatial Imaging
- Spin and Flavor Structure of the Nucleons and Nuclei
- Internal Landscape of Nuclei
- QCD at Extreme Parton Densities - Saturation
Unified view of nucleon structure

- Wigner distributions:
  - EIC – 3D imaging of sea and gluons:
    - TMDs – confined motion in a nucleon (semi-inclusive DIS)
    - GPDs – Spatial imaging of quarks and gluons (exclusive DIS)

- TMDs – confined motion in a nucleon (semi-inclusive DIS)
- GPDs – Spatial imaging of quarks and gluons (exclusive DIS)
On the Synergies of $ee$, $ep$ and $pp$

The basic experimental set ups for accelerator particle physics:

- no initial hadron (....LEP, ILC, CLIC)
- 1 hadron (....HERA, LHeC)
- 2 hadrons (Tevatron, LHC, FCC)

The pdf are defined in DIS
The theory of inclusive DIS is crystal clear
Thru the factorization “theorem” the pdf’s and $\alpha_s$ determine the hadron collider rates
On the Synergies of $ee$, $ep$ and $pp$

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The pdf are defined in DIS
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We often hear the statement that all the relevant info on pdf’s can directly be obtained from the LHC without need of the LHeC

Not really true. Certainly not at the same level of precision
One example:

The factorization “theorem” is essential.
Not fully proved theoretically (beware of non pert. effects)
[nearly complete arguments only for Drell-Yan & similar]
Should finally be experimentally tested with precision