From Quarks 1968 to Future DIS at CERN

Bits of History + Present

The Case for the LHeC

Updating the CDR for the European Strategy 2020

Max Klein

Introduction to the LHeC/FCCh/PERLE Workshop at Orsay, 27.6.2018
FUNDAMENTAL THEORETICAL QUESTIONS

M. Froissart, Rapporteur

Fig. 1-1. Logical map of "Fundamental" concepts.
QCD evolved from a Lagrangian with the property of asymptotic freedom to a sophisticated tool for the calculation of high energy processes. R.K. Ellis Nuovo Cimento 39C(2016)355
ELECTROMAGNETIC INTERACTIONS: LOW q^2 ELECTRODYNAMICS;
ELASTIC AND INELASTIC ELECTRON (AND MUON) SCATTERING*

W.K.H. PANOFSKY
Stanford Linear Accelerator Center
Stanford University, Stanford, California

\[ \frac{d^2\sigma}{dq^2d\nu} = \frac{E}{E'} \frac{4\pi\alpha^2}{q^4} \left[ \cos^2 \frac{\theta}{2} W_2(q^2,\nu) + 2 \sin^2 \frac{\theta}{2} W_1(q^2,\nu) \right] \]

**pagator. Therefore theoretical speculations are focused on the possibility that these data might give evidence on the behaviour of point-like, charged structures within the nucleon.**

(Presented at XIVth International Conference on High Energy Physics, August 28 to September 5, 1968, Vienna.)
The great success of the scattering program at HEPL had three consequences: Scattering experiments became more popular at existing electron synchrotrons, new synchrotrons were planned for higher energies, and discussions began at Stanford about a much larger linear accelerator - two miles long and powered by one thousand klystrons!

After more than a year of discussions and calculations, the physicists and engineers of the High Energy Physics Laboratory prepared the first proposal for a two-mile linear accelerator to be built at Stanford. E.L. Ginzton, W.K.H. Panofsky and R.B. Neal directed the design effort, and Panofsky

The new linear accelerator consisted of two miles of accelerating waveguide, mounted in a tunnel buried 25 feet underground. In the initial phase, the waveguide was powered by two hundred and forty 20-30 MW klystrons housed in a building at ground level. The accelerator was sited in the hills behind Stanford on University land, and was probably the last of the university-based high energy physics accelerators in the U.S. (Figures 10

The design parameters of the new machine - 20 GeV in energy and average currents in the neighborhood of 100 μA - presented many new problems for experiments. Two experimental areas (called End Stations in Figure 12) were developed initially - one heavily shielded area, where sec-
At over 1 GeV, the Cornell electron synchrotron was the highest energy electron machine in the world for a few years in the early 1960s. Experimenters there made a series of measurements on CH$_2$ targets, using a quadrupole spectrometer of novel design (18) (Fig. 24) and a new type of γ-ray monitor. (19) The results from Cornell started a trend toward the use of the electric and magnetic form factors (20) ($G_E$ and $G_M$), rather than one form factor for a spin 1/2 (Dirac) proton and a second for the anomalous magnetic moment of the proton.

The linear accelerator at Orsay had begun operations in 1959 and by the following year there was an active program of both nucleon and nuclear scattering. The emphasis shifted to colliding beam experiments in later years, but many scattering experiments were done in the intermediate energy stations of that accelerator with beams of up to 750 MeV.

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**Electromagnetic Properties of the Proton and Neutron**  
Published in *Phys.Rev.Lett.* 6 (1961) 286-290

...Further from R Taylor (1929-2018) Nobel Prize Lecture
Deep Inelastic Scattering $ep \rightarrow eX$ (1969)

$E_e = 1.5 \ldots 20$ GeV

$\theta = 6^\circ \ldots 26^\circ$

$Q^2 = 1 \ldots 7$ GeV$^2$

$\alpha \frac{1}{Q} \approx 10^{-16}$ m

$F_2(Q^2, \nu) \rightarrow F_2(x)$

Pointlike scattering centers inside the proton

$x = \text{momentum fraction carried by quarks}$

Friedman, Kendall, Taylor

SLAC
device unique among high energy particle accelerators. See Figure 1. An outgrowth of the smaller, 1 GeV accelerator employed by Hofstadter in his studies of the charge and magnetic moment distributions of the nucleon, it relied on advanced klystron technology devised by Stanford scientists and engineers to provide the high levels of microwave power necessary for one-pass acceleration of electrons. Proposed in 1957, approved by the Congress in 1962, its construction was initiated in 1963. It went into operation in 1967, on schedule, having cost $114M (Reference 29).

The experimental collaboration began in 1964. After 1965, R. E. Taylor was head of SLAC Group A with J.I.Friedman and the present author sharing responsibility for the M.I.T. component. A research group from California Institute of Technology joined in the construction cycle and the elastic studies but withdrew before the inelastic work started in order to pursue other interests.
The Quark Parton Model

\[ F_2(\text{ep}) = x [e_u^2 (u+\bar{u}) + e_d^2 (d+\bar{d})] \]
\[ F_2(\text{en}) = x [e_d^2 (u+\bar{u}) + e_u^2 (d+\bar{d})] \]

\[ q = q_v + q_s \text{ (Kuti Weisskopf)} \]

If \( u_s = \bar{u} \), \( d_s = \bar{d} \)

\[ \rightarrow F_2(\text{ep}) - F_2(\text{en}) = x [e_u^2 u_v - e_d^2 d_v] \]

\( e_u = 2/3, \ e_d = -1/3 \)

Till today, \( u_v \) is better known than \( d_v \)

\[ \rightarrow F_2(\text{eN})/F_2(\nu\text{N}) = 1/2 (e_u^2 + e_d^2) \]

SLAC/GGM: 0.29 ± 0.05 (1974)

*Fig. 8: Values of \( \nu W^2 - \nu\nu W^2 \) as a function of \( x \).*

J Friedman, Nobel prize lecture
The study of the strong interactions was transformed with the advent of accelerators in the multi-GeV energy range. The famous SLAC experiments of the 1960s and 1970s were the first to show the pointlike substructure of hadrons (Bloom et al., 1969; Friedman and Kendall, 1972). The parton model (Feynman 1969; Feynman, 1972; Bjorken and Paschos, 1969) showed that elementary constituents, interacting weakly, could convincingly explain the central experimental results. In the same period, the quark model (Gell-Mann, 1964; Zweig, 1964; Kokkedee, 1969) rationalized hadron spectroscopy. Out of it grew the idea of color (Han and Naumbu, 1965; Greenberg, 1964), a new quantum number postulated in the first instance to avoid the apparent paradox that the quark model seemed to require spin-$1/2$ quarks with bosonic statistics.

The idea of extending the global color model to a gauge theory (Fritzsch et al., 1973; Gross and Wilczek, 1973b; Weinberg, 1973) was in many ways a natural one, but the motivation for doing so was incalculably strengthened by the newfound ability to quantize gauge theories in a manner that was at once unitary and renormalizable, developed, in large part to describe electroweak interactions. Concurrently, the growth of the technology of the renormalization group and the operator product expansion (Wilson, 1969; Callan, 1970; Symanzik, 1970; Christ, Hasslacher, and Mueller, 1972; Frishman, 1974) made it clear that any field theory of the strong interactions would have to have an energy-dependent coupling strength, to harmonize the low-energy nature of the strong interactions, which gives them their name, with their weakness at high energy (or short distances). The concept of asymptotic freedom (Gross and Wilczek, 1973a; Politzer, 1973), which is satisfied almost uniquely by quantum chromodynamics, brilliantly filled these demands.

Since QCD remains an “unsolved” theory, with no single approximation method applicable to all length scales, the justification for the use of perturbative QCD rests in large part directly on experiment.
QCD at work at the LHC

1702.05725 $Z + n$ jets ATLAS 3fb$^{-1}$ 13 TeV

1609.05331 inclusive jets, 26fb$^{-1}$ 8 TeV

LHC is the trick to attract a few 1000 physicists to work on QCD: T Sjoestrand, 2007, after we saw ATLAS
QCD has an exciting future with the LHC and next colliders, not least ep

<table>
<thead>
<tr>
<th>Developments</th>
<th>Discoveries</th>
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| AdS/CFT
Instantons
Odderon
TOTEM? CERN EP 2017-335 |
| Non-pQCD, Spin
Quark Gluon Plasma |
| QCD of Higgs boson |
| $N^k$LO, Monte Carlos...
Resummation
Saturation and BFKL |
| Photon, Pomeron, n PDFs
Non-conventional partons
(unintegrated, generalised)
Vector Mesons
The 3D view on hadrons.. |
| 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 |

C. Quigg, arXiv1308.6637
QCD with ee pp ep

Final state arises completely from short distance interaction of virtual boson with quarks: NO PDFs, but jets, $\alpha_s$
Njets +0, energy, angles. Unique association of q,g with jets

**Observation of 3-jet events at PETRA to discover the gluon**

S Ellis and D Soper, hep-ph/9306280

Successive combination jet algorithm for hadron collisions

Many initial partons but only two interact. “rest” is the underlying event of soft i.a.’s
Dynamical coupling of all components. MPIs
N jets at large pT +X, pseudorapidity + azimuth

Ledermann-Drell-Yan scattering, jets

Scattering depends on parton distributions
The “Altarelli cocktail” to save the SM (1984, Bern)

“Route royale” to the structure and dynamics of parton interactions inside the proton (nucleon)
Universal partons evolving with resolution scale x BJ fixed through electron kinematics. PDFs + $\alpha_s$
Redundant e and h final state reconstruction.

**Discovery of partons and the QPM … DGLAP**

$\sqrt{s} = 2E_e \approx [G_F V^2]^{-1/2} = 246$ GeV

$\sqrt{s} = 2E_p = 14, 27, 100$ TeV

$\sqrt{s} = 2\sqrt{E_e E_p} = 1.3, 1.8, 3.5$ TeV

ep - “option” which ought to be a real part. *Seguil tuo corso, e lascia dir el genti* (Dante, KM)
Polarised eD Scattering

SLAC-PUB-2148
July 1978

\[ A/Q^2 = (-9.5 \pm 1.6) \times 10^{-5} \text{ (GeV/c)}^{-2} \]

20 GeV polarised electrons, \( P=0.37 \), \( Q^2 \sim 2 \text{ GeV}^2 \)

C.Prescott ... W.Jentschke

\[ \rightarrow SU_L(2) \times U(1), \text{ electron r.h. singlet: GWS eweak theory} \]

Of crucial importance to this experiment was the development of an intense source of longitudinally polarized electrons. The source consisted of a gallium arsenide crystal mounted in a structure similar to a regular SLAC gun with the GaAs replacing the usual thermionic cathode.
The observed $x$-dependence of this ratio is in disagreement with existing theoretical predictions.
A MEASUREMENT OF THE SPIN ASYMMETRY AND DETERMINATION OF THE STRUCTURE FUNCTION $g_1$ IN DEEP INELASTIC MUON–PROTON SCATTERING

The 87 discovery of the spin deficit
..EMC, HERMES, COMPASS to EIC

to the conclusion that the total quark spin constitutes a rather small fraction of the spin of the nucleon.
PDFs before HERA - Gluon - $xg(x,Q^2)$

BCDMS

\[ xG(x) \]

CDHS

\[ xG(x) \]

CERN-EP/89-07
January 17th, 1989

CERN-EP/89-103
15 August 1989

9 Nov 89: R Taylor at Paris
Low $x$ + Partons - HERA

Note: HERA: QCD vacuum dominates p structure at small $x$. $xg$ vanishes/rises at low/hi $Q^2$
How to determine **low x evolution** + discover saturation?

\[
\frac{\partial F_2(x, Q^2)}{\partial \ln Q^2} = \frac{\alpha_s(Q^2)}{2\pi} \int_x^1 \frac{dz}{z} \left[ F_2\left(\frac{x}{z}\right)P_{qq}(z) + 2 \sum_{i=1}^{N_f} e_i^2 \cdot G\left(\frac{x}{z}\right)P_{qG}(z) \right]
\]

Needs cleanest DIS constraints, proton, not ion, high E: \( F_2 + F_L \)

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 \( x \sim 1/s \): Impossible at EIC

This constrains DGLAP and rules it out (or not..). cf CDR (LHeC)
The Case for the LHeC
Concurrent operation to pp, LHC/FCC become 3 beam facilities. Power limit: 100 MW $10^{34}$ cm$^{-2}$ s$^{-1}$ luminosity and factor of $15/120$ (LHC/FCCeh) extension of $Q^2$, $1/x$ reach 1000 times HERA luminosity. It therefore extends up to $x \sim 1$. Four orders of magnitude extension in deep inelastic lepton-nucleus (ion) scattering.
Towards a strategy for European Particle Physics

“Two Problems” of HEP

1980: Leon Lederman at ICHEP in Madison: “Shortage of Money and Overconfidence of Theorists” [SU(5)/SUSY ahead times..]

Today: Shortage of Money and Missing Confidence of Theory [EFT/ SUSY passed times?]

Reminiscent of the situation as experienced 50 years ago: before the SM and discovery of partons in ep at Stanford

\[
\text{Progress in particle physics needs their continuous interplay to take full advantage of their complementarity}
\]

Guido Altarelli, DIS 2009, Madrid

In 2014 CERN decided to set up a new LHeC organisation and an IAC to “assist building the international case of an ep/A collider” at CERN

IAC: Two main tasks: Update CDR + Testfacility
**Organisation*)**

**International Advisory Committee**
Mandate by CERN to define “..Direction for ep/A both at LHC+FCC”

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<tr>
<td>Sergio Bertolucci (CERN/Bologna)</td>
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<td>Nichola Bianchi (Frascati)</td>
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<td>Frederick Bordry (CERN)</td>
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<td>Stan Brodsky (SLAC)</td>
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<td>Hesheng Chen (IHEP Beijing)</td>
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<td>Eckhard Elsen (CERN)</td>
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<td>Stefano Forte (Milano)</td>
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<td>Andrew Hutton (Jefferson Lab)</td>
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<td>Young-Kee Kim (Chicago)</td>
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<td>Victor A Matveev (JINR Dubna)</td>
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<td>Leonid Rivkin (Lausanne)</td>
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<td><strong>Herwig Schopper (CERN)</strong> – Chair</td>
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<td>Jurgen Schukraft (CERN)</td>
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<td>Achille Stocchi (LAL Orsay)</td>
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<td>John Womersley (ESS)</td>
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**Working Groups**

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<td>Georges Azuelos, Monica D’Onofrio</td>
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<td>Olaf Behnke, Christian Schwanenberger</td>
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<td><strong>eA Physics</strong></td>
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<td>Paul Newman, Anna Stasto</td>
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<td><strong>Detector</strong></td>
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<td><strong>Working Groups</strong></td>
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<td>Peter Kostka</td>
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**Coordination Group**

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<td>Gianluigi Arduini</td>
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<td>Nestor Armesto</td>
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<td>Oliver Brüning – Co-Chair</td>
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<td>Andrea Gaddi</td>
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<td>Erk Jensen</td>
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<td>Walid Kaabi</td>
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<td>Max Klein – Co-Chair</td>
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<td>Peter Kostka</td>
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<td>Bruce Mellado</td>
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<td>Paul Newman</td>
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<td>Daniel Schulte</td>
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<td>Frank Zimmermann</td>
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5(12) are members of the FCC coordination team

OB+MK: co-coordinate FCCeh

*) April 2018

We miss Guido Altarelli.
Physics with Energy Frontier DIS

Raison(s) d’etre of the LHeC

Cleanest High Resolution Microscope: QCD Discovery

Empowering the LHC Search Programme

Transformation of LHC into high precision Higgs facility

Discovery (top, H, heavy ν’s..) Beyond the Standard Model

A Unique Nuclear Physics Facility

- Non-linear QCD
- Precision QCD, $\alpha_s$
- PDFs ($p,\gamma,\nu$..)
- Higgs
- Top
- Hi x gluon
- $\sin^2 \Theta$
- BSM
Huge increase in energy and luminosity enables unique development of particle physics

The **Classic DIS Programme** with the LHeC: $0 < Q^2 < 10^6 \text{ GeV}^2$, $1 > x > 10^{-6}$

**Generalised Parton Distributions** [DVCS] – “proton in 3D - tomography”

**Unintegrated Parton Distributions** [Final State] – DGLAP/BFKL?

**Diffractive Parton Distributions** [Diffraction] – pomeron, confinement??

**Photon Parton Distribution** [Photoproduction Dijets,QQ; $F_{2,L}$] - fashionable..

**Neutron Parton Distributions** [Tagged en (eD) Scattering] – ignored at HERA

see the CDR 1206.2913 + updates
The LHeC collinear proton (and nuclear) PDF Programme

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

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

PDFs are NOT determined in pp but in ep
cf backup

Empowers the LHC $H$, BSM + SM Physics
$\alpha_s(\mu)$ in Deep Inelastic Scattering

$\alpha_s(M_Z^2) = 0.1150 \pm 0.0017\ (exp) \pm \frac{0.0009}{0.0005}\ (model)$

H1 inclusive (1998) NLO

hep-ph/0012053 – highest cited H1 only

$\alpha_s(M_Z^2) = 0.1157 \pm 0.0020\ (exp) \pm 0.0029\ (thy)$

H1 only jets (2017) NNLO jets!

$\alpha_s = 0.1142 \pm 0.0028\ (tot)$

H1 inclusive and jets (2017) NNLO

$\rightarrow$ It is well possible that $\alpha_s$ is smaller than hitherto assumed. Current practice to exclude ABM is questionable. Like in the lattice case, one constructs, for perhaps respectable reasons, a norm, which gives the impression of higher accuracy than a critical evaluation would lead to.

Current strong coupling precision at best 1-2%: FCC ee and eh want 1-2 per mille
Empowering pp Discoveries

External, reliable input (PDFs, factorisation..) is crucial for range extension + CI interpretation

GLUON
SUSY, RPC, RPV, LQS..

QUARKS
Exotic+ Extra boson searches at high mass

Gluino Pair Production PDF Uncertainty

ATLAS today

E. Kay & U. Klein using VRAP v0.9
Determination of SM Higgs Couplings, **HL-LHC** and **LHeC → LHC**

The addition of ep to pp (LHeC to LHC (HL,HE) and FCC-eh to FCC-pp) transforms these machines into precision Higgs facilities. **Vital complementarity with e^+e^- (JdB Amsterdam)**

Note that the HL LHC prospects are being updated (HL/HE LHC Physics workshop).
New Physics through High Precision

Masses:
- **Charm** HERA 40 MeV LHeC 3 MeV
- **W** LHC 19 → 10 MeV LHeC 15 MeV
  and prediction to ±2.8 MeV for pp
- **Top** to be studied
- **Proton**: gluon we are made of...
- **Higgs**: Cross section to 0.3%: Mass dependent. OB, MK 1305.2090
- **Neutrinos**: Heavy “sterile” Neutrinos

CKM, electroweak, alpha_s, ...

- $V_{tb}$: to 0.01
- $V_{cs}$: to 0.02 [LHC+LHeC, like ATLAS+HERA]
- $\alpha_s$ to 0.2% [0.1% with HERA] – GUT?

$\sin^2\theta_W (\mu)$
- LHC: better than LEP with LHeC PDFs
- LHeC: scale dependence from 0.4 GeV (PERLE) to 1 TeV (LHeC)

**NC couplings**

Antusch, Cazzato, Fischer – work still in progress

Britzger, MK, Spiessberger, Zhang – work still in progress
Beyond the Standard Model

Higgs into Dark Matter
Higgs into Neutralinos (RPV SUSY)
Higgs into Scalars → 4b

H\(^{\pm\pm}\) in Vector Boson Scattering
H\(^{\pm}\) in Vector Boson Scattering
H\(^{+}\) in 2HDM

Triple Gauge Couplings
Top FCNC
Contact Interactions
Empower LHC Discoveries

Higgsinos: mass degenerate
Wino/bino compressed
Prompt decays or long lifetimes

→ SUSY ewk sector most challenging for pp colliders

cf U Klein + M Donofrio at Amsterdam FCC
Thanks to Hao Sun

50 journal papers on NP with LHeC in recent years
pQCD Theory

Substantial and remarkable theoretical progress in pQCD calculations to $N^k$LO, e.g.

**N$^3$LO Corrections to Jet Production in Deep Inelastic Scattering using the Projection-to-Born Method**


**QCD calculations for the LHC: status and prospects**

G Heinrich

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<th>method</th>
<th>analytic integr. of subtraction terms</th>
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<td>$q_T$-subtraction [2]</td>
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<td>slicing; colourless final states</td>
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<td>subtraction</td>
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1803.09973, 2 weeks ago

1710.04998
**LHeC as Electron Ion Collider**

Extension of kinematic range in IA by 4-5 orders of magnitude will change QCD view on nuclear structure and parton dynamics

May lead to genuine surprises...

- No saturation of $xg (x,Q^2)$?
  
  [discover saturation in ep
  THEN analyse $eA$ –separate nonlinear $g$ from nuclear effects]

- Small fraction of diffraction?

- Broken isospin invariance?

- Flavour dependent shadowing?

- Safe: nuclear PDFs like at HERA
  \[ R(x,Q^2) \] flavour dependent

\[ L_{eN} = 6 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1} \]

**Precision QCD study of parton dynamics in nuclei**

Investigation of high density matter and QGP

DGLAP to BFKL – vital for LHC and FCCpp physics
LHeC Detector for the HL/HE LHC

Length x Diameter: LHeC (13.3 x 9 m^2)  HE-LHC (15.6 x 10.4)  FCCeh (19 x 12)  ATLAS (45 x 25)  CMS (21 x 15): [LHeC < CMS, FCC-eh ~ CMS size]

If CERN decides that the HE LHC comes, the LHeC detector should anticipate that
Powerful ERL for Experiments at Orsay

- 2 Linacs (Four 5-Cell 801.58 MHz SC cavities)
- 3 turns (160 MeV/turn)
- Max. beam energy 500 MeV at 20mA → 10 MW

New SCRF, High Intensity (100 x ELI) ERL Development Facility with unique low E Physics

Max Klein Kobe 17.4.18
Towards PERLE: 802 MHz cavity, Source, Cryomodule, Magnets

First 802 MHz cavity successfully built (Jlab)

BINP, CERN, Daresbury/Liverpool, Jlab, Orsay, + Max Klein Kobe 17.4.18

CDR 1705.08783 [J.Phys G] → TDR in 2019
Recent Presentations on LHeC and FCCeh

FCC Week Amsterdam 9-13.4.18

Theory
Jo Rudermann, Jorge de Blas

Overviews
Bruce Mellado, Uta Klein

QCD Max Klein
Top Christian Schwanenberger and Orhan Cakir
Higgs Uta Klein
BSM Monica D’Onofrio
Detector Peter Kostka

Machine Oliver Bruening
Civil Engineering John Osborne
Cavity Frank Marhauser
IR Roman Martin
PERLE Walid Kaabi

DIS Workshop Kobe 16.4.-18.4.

Machine+PERLE Gianluigi Arduini

PDFs Claire Gwenlan
Low x+Diffraction Paul Newman
Nuclear PDFs Nestor Armesto
Higgs Uta Klein
Top Hao Sun
Electroweak Max Klein
New and BSM Jose Zurita

Project Max Klein
Structure of the Proton Uta Klein

PERLE Walid Kaabi

Max Klein Kobe 17.4.18
15/15.11. ECFA Symposium at CERN about Future Colliders

December 2018: Submission of a 10 page LHeC (HL/HE LHC) Document
‘eh’ also part of the separate FCC submission
[Book1 on Physics, Book2 on FCChh +eh, …]

February 2019: Update of the CDR to appear [Main Topic of this Workshop]

May 13, 2019: Symposium in Spain

January 2020: Council + Secretariat Meeting in Bad Honnef (D)

Large Hadron Electron Collider on one page

\( E_e = 10-60 \text{ GeV}, \ E_p = 1-7 \text{ TeV}: \ \sqrt{s} = 200 - 1300 \text{ GeV}. \) **Kinematics:** \( 0 < Q^2 < s, \ 1 > x \geq 10^{-6} \) (DIS) Electron Polarisation \( P = \pm 80\%. \) Positrons: significantly lower intensity, unpolarised

**Luminosity:** \( O(10^{34}) \text{ cm}^{-2} \text{ s}^{-1}. \) integrated \( O(1) \text{ ab}^{-1} \) for HL LHC and 2 \text{ ab}^{-1} for HE LHC/FCCeh
e-ions \( 6 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1} \) \( O(10) \text{ fb}^{-1} \) in ePb. \( O(1) \text{ fb}^{-1} \) for ep \( F_L \) measurements

**Physics:** QCD: develop+break? The world's best microscope. BSM (H, top, \( \nu \), SUSY..) Transformations: Searches at LHC, LHC as Higgs Precision Facility, QCD of Nuclear Dynamics

The LHeC has a deep, unique QCD, H and BSM precision and discovery physics programme.

**Time:** Determined by the Large Hadron Collider (HL LHC needs till \( \sim 2040 \) for 3 \text{ ab}^{-1})

LHeC: Detector Installation in 2 years, earliest in LS4 (2030/31).

HE LHC: re-use ERL. In between HL-HE, 10 years time of ERL Physics (laser, \( \gamma \gamma \).)

Very long term: FCC-eh

**Challenges:** Demonstration of ERL Technology (high electron current, multi-turn)

Design 3-beam IR for concurrent ep+pp operation, New Detector with Taggers - in 10 years.

**The LHeC is a great opportunity to sustain deep inelastic physics within future HEP.**

The cost of an ep Higgs event is \( O(1/10) \) of that at any of the 4 e^+e^- machines under consideration

It can be done: the Linac is shorter than 2 miles and the time we have longer than HERA had.

**CERN and world HEP:** Vital to make the High Luminosity LHC programme a success.
A Higgs Facility Resolving the Substructure of Matter

Update on the 2012 LHeC Report on the Physics and Design Concepts for Machine and Detector

LHeC Collaboration

Submitted to J.Phys. G
1 Modern Particle Physics and the Large Hadron Collider

2 Higgs, Discovery and Precision Physics

2.1 Electron-Hadron Scattering at the HL and HE LHC
2.1.1 Kinematics and Reconstruction of Final States
2.1.2 Opportunities through Energy Frontier ep and eA Interactions
2.1.3 Luminosity and Operation of an eh Collider at the LHC

2.2 Higgs Physics
2.2.1 High Precision Higgs Coupling Measurements
2.2.2 HtH Coupling Measurement
2.2.3 Combined ep and pp Analysis - the Potential for Precision Higgs Physics at the LHC
2.2.4 Discovery of the H-HH Selfcoupling
2.2.5 Exotic Higgs Decays and Dark Matter
2.2.6 Extension of the SM Higgs Sector

2.3 Challenging the Standard Model through High Precision and Energy
2.3.1 Resolving the Parton Substructure of the Proton
2.3.2 Electroweak, W Boson and Top Quark Physics
2.3.3 Non-Conventional Proton Structure Resolution

2.4 Searches for Physics Beyond the Standard Model
2.4.1 Heavy Neutrinos
2.4.2 Flavour Changing Neutral Currents
2.4.3 Substructure
2.4.4 Leptoquarks

2.5 Discovery through Precision QCD
2.5.1 High Mass and Bjorken x Searches at the LHC
2.5.2 Strong Coupling and Grand Unification
2.5.3 New QCD Dynamics at small x
2.5.4 A New Era of Nuclear Particle Physics with eA

3 Experimentation at the LHc

3.1 Detector Design Considerations for HL and HE LHC
3.2 Detector Overview
3.2.1 Magnets
3.2.2 Interaction Region, Beam Pipe and Radiation
3.2.3 Inner Tracking
3.2.4 Calorimetry
3.2.5 Muon Detector
3.2.6 Central Detector Performance

3.3 Forward and Backward Detectors
3.3.1 Proton and Neutron Forward Taggers
3.3.2 Electron and Photon Backward Detectors

3.4 Detector Installation and Infrastructure
The SM looks complete, some people believe in the new dark aether, need precision+diversity.
Time comes to unite pp with ep and ee at TeV scale

A currently best bet is HL/HE LHC, ep with both, and CepC: a realistic program for exploring the SM deeper and leading beyond, for the next 40 years ahead.
It needs

Welcome on behalf of the Coordination Group.
backup
\[ L = \frac{1}{4g^2} G_{\mu\nu}^a G^{a\mu\nu} + \sum_j \bar{q}_j \left( i\gamma^\mu D_\mu + m_j \right) q_j \]

where \[ G_{\mu\nu}^a = \partial_\mu A_\nu^a - \partial_\nu A_\mu^a + i f^{abc} A_\mu^b A_\nu^c \]

and \[ D_\mu = \partial_\mu + i t^a A_\mu^a \]

That's it!
\[
\frac{d\sigma}{dQ^2} = \sum_q S d x_q S d x_{\bar{q}} q(x_q) \frac{d\sigma_{q\bar{q}}}{dQ^2} \bar{q}(x_{\bar{q}})
\]

\[
\frac{d\tilde{\sigma}}{dQ^2} = \frac{4\pi\alpha^2}{3 N_c Q^2 S} e_q^2 \delta \left( \frac{Q^2}{S} - x_q x_{\bar{q}} \right)
\]

Rapidity variable of $q^*$: $x = \frac{M}{\sqrt{S}} e^{\pm y}$

For vector boson or Higgs production:

$M^2$ and $\frac{M}{\sqrt{S}} e^{\pm y}$ are equivalent to $Q^2 x$ in DIS

Factorisation in pp scattering:

\[
\sigma = \sum_{p, p'} f_p(\mu^2) \otimes f_{p'}(\mu^2) \otimes \tilde{\sigma}_{pp}(\mu)
\]

Need to know the parton distribution functions (pdf's):

- From DIS: HERA
- Measure $\sigma$, pdf's, calculate $\tilde{\sigma} \to \ell^+ \ell^-$

W, Z production
Jets
Directed photons
Jets from Quantum Chromodynamics

Jets in $e^+e^-$ at $>5$ GeV at SPEAR at Stanford


Rise of Gluon (and Quark) densities towards low x discovered at HERA. This may lead to saturation – non-linear interactions and BFKL $\ln(1/x)$ effects. Not discovered at HERA, to much surprise, despite recent ‘speculations’ .. Change of parton distributions + evolution $\rightarrow$ to be clarified for FCC + (HE) LHC
\(\alpha_s(\mu)\) at LHeC/FCCeh

- 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 \(N^3\)LO 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

### 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.

<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>
</tr>
<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>

CDR 2012
The Case for the LHeC

From the CDR 2012 to the time ahead 2018+

Max Klein

Particle Physics

Physics Case

Preparations

Max Klein

http://lhec.web.cern.ch

Contribution to a Panel on Future DIS, 17.4.2018, Kobe, for the LHeC/FCCeh Study Group

Max Klein Kobe 17.4.18
The basic experimental set ups:
- no initial hadron (....LEP, ILC, CLIC)
- 1 hadron (....HERA, .... LHeC)
- 2 hadrons (....SppS, Tevatron, LHC)

Progress in particle physics needs their continuous interplay to take full advantage of their complementarity