The Case for the LHeC

From the CDR 2012 to the time ahead 2018+



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

Max Klein Kobe 17.4.18

http://lhec.web.cern.ch

60 GeV Electron ERL added to LHC



Concurrent operation to pp, LHC/FCC become 3 beam facilities. Power limit: 100 MW 10³⁴ cm⁻² s⁻¹ luminosity and factor of 15/120 (LHC/FCCeh) extension of Q², 1/x reach 1000 times HERA luminosity. It therefore extends up to x~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**

Time for high precision, high energy, high luminosity collider experiments ee, pp and ep: 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

 \rightarrow

IAC: Two main tasks: Update CDR + Testfacility

Organisation*)

International Advisory Committee

Mandate by CERN to define "..Direction for ep/A both at LHC+FCC"

Sergio Bertolucci (CERN/Bologna) Nichola Bianchi (Frascati) Frederick Bordry (CERN) Stan Brodsky (SLAC) Hesheng Chen (IHEP Beijing) Eckhard Elsen (CERN) Stefano Forte (Milano) Andrew Hutton (Jefferson Lab) Young-Kee Kim (Chicago) Victor A Matveev (JINR Dubna) Shin-Ichi Kurokawa (Tsukuba) Leandro Nisati (Rome) Leonid Rivkin (Lausanne) Herwig Schopper (CERN) – Chair Jurgen Schukraft (CERN) Achille Stocchi (LAL Orsay) John Womersley (ESS)

We miss Guido Altarelli.

Max Klein Kobe 17.4.18

Coordination Group

Accelerator+Detector+Physics

Gianluigi Arduini Nestor Armesto Oliver Brüning – Co-Chair Andrea Gaddi Erk Jensen Walid Kaabi Max Klein – Co-Chair Peter Kostka Bruce Mellado Paul Newman Daniel Schulte Frank Zimmermann

5(12) are members of the FCC coordination team

OB+MK: co-coordinate FCCeh

*) April 2018

Working Groups

PDFs, QCD Fred Olness, Claire Gwenlan Higgs Uta Klein, Masahiro Kuze BSM Georges Azuelos, Monica D'Onofrio **Oliver Fischer** Тор Olaf Behnke, Christian Schwanenberger eA Physics Nestor Armesto Small x Paul Newman, Anna Stasto Detector Alessandro Polini Peter Kostka

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 v's..) Beyond the Standard Model

A Unique Nuclear Physics Facility

Huge increase in energy and luminosity enables unique development of particle physics

The Classic DIS Programme with the LHeC: $0 < Q^2 < 10^6$ GeV2, $1 < x < 10^{-6}$

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, N³LO...



Max Klein Kobe 17.4.18

Empowers the LHC H, **BSM + SM Physics**

Empowering pp Discoveries

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



Determination of SM Higgs Couplings, **HL-LHC** and **LHeC** \rightarrow **LHC**



LHC: ATLAS prospects PUB Note 2014-016

ttH at LHeC to 15%

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]

 α_{s} to 0.2% [0.1% with HERA] – GUT?

sin²θ_w (μ)

LHC: better than LEP with LHeC PDFs LHeC: scale dependence from 0.4 GeV (PERLE) to 1 TeV (LHeC) **NC couplings**



Beyond the Standard Model

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

H^{±±} in Vector Boson Scattering H[±] in Vector Boson Scattering H⁺ in 2HDM

Triple Gauge Couplings Top FCNC Contact Interactions Empower LHC Discoveries

D Curtin et al arXiv:1712.07135

This adds significant motivation for the construction of future e^-p colliders. Together with the invaluable proton PDF data, as well as precision measurements of EW parameters, top quark couplings and Higgs couplings, our results make clear that adding a DIS program to a pp collider is necessary to fully exploit its discovery potential for new physics.



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

LHeC as Electron Ion Collider



Precision QCD study of parton dynamics in nuclei Investigation of high density matter and QGP DGLAP to BFKL – vital for LHC and FCCpp physics 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,Q²) ?
 [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
- \rightarrow R(x,Q²) flavour dependent

 $L_{eN} = 6 \ 10^{32} \ cm^{-2} \ s^{-1}$

LHeC Detector for the HL/HE LHC



Length x Diameter: LHeC (13.3 x 9 m²) 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 Max Klein Kobe 17.4.18

Civil Engineering and Cost Optimisation





2nd full civil engineering study

Amberg + ILF consult

John Osborne et al Amsterdam FCC 12.4.

Powerful ERL for Experiments at Orsay



cf Walid Kaabi at Amsterdam FCC

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

Towards PERLE: 802 MHz cavity, Source, Cryomodule, Magnets

First 802 MHz cavity successfully built (Jlab)







BINP, CERN, Daresbury/Liverpool, Jlab, Orsay, + 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 http://lhec.web.cern.ch

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

FCC David D'Enterria

Large Hadron Electron Collider on one page

 $E_e = 10-60 \text{ GeV}, E_p = 1-7 \text{ TeV}: Vs = 200 - 1300 \text{ GeV}.$ Kinematics: $0 < Q^2 < s, 1 > x \ge 10^{-6}$ (DIS) Electron Polarisation P=±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 ab^{-1} for HE LHC/FCCeh e-ions 6 $10^{32} \text{ cm}^{-2} \text{ s}^{-1} O(10) \text{ fb}^{-1}$ in ePb . $O(1) \text{ fb}^{-1}$ for ep F_L measurements

Physics: QCD: develop+break? The worlds best microscope. BSM (H, top, v, 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 ~2040 for 3 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, γγ..) Very long term: FCC-eh http://lhec.web.cern.ch

Challenges: Development 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. Max Klein Kobe 17.4.18

backup

i) a huge step (in energy and luminosity) into the unknown of the space-like lepton-parton interaction which only CERN can make, a unique test bed for new physics, certainly in QCD;

- 7×Why -

ii) the continuation of a seminal tradition of particle physics in building high resolution microscopes, from Hofstadter to Wiik, for searching deeper into the substructure of matter;

iii) the next realistic option to study the Higgs boson and shed more light on its properties, by also making the LHC facility at large the first precision H factory;

iv) the necessary addendum for pp in resolving the largely unknown region of high mass (corresponding to large x_bj) where new particles or interactions may reside;

v) the real (QCD) base for physics of nuclear interactions (which is not just hydrodynamics but parton interactions, non-linear) - ways better than any low energy EIC;

vi) the next energy frontier collider which CERN could build in the twenties, boosting not only SCRF but also the arts of civil engineering, cryogenics, magnet or IR design to a new level, electrons back at CERN, prior to when the time will come for an even bigger enterprise;

vii) a convincing answer to the question as to which detector could one build next, which is becoming formulated more and more pressing, when one listens to detector builders we join in the ATLAS upgrade and elsewhere.

Luminosity for LHeC, HE-LHeC and FCC-ep

parameter [unit]	LHeC CDR	ep at HL-LHC	ep at HE-LHC	FCC-he
$E_p \; [\text{TeV}]$	7	7	12.5	50
$E_e \; [\text{GeV}]$	60	60	60	60
$\sqrt{s} [\text{TeV}]$	1.3	1.3	1.7	3.5
bunch spacing [ns]	25	25	25	25
protons per bunch $[10^{11}]$	1.7	2.2	2.5	1
$\gamma \epsilon_p \; [\mu \mathrm{m}]$	3.7	2	2.5	2.2
electrons per bunch $[10^9]$	1	2.3	3.0	3.0
electron current [mA]	6.4	15	20	20
IP beta function β_p^* [cm]	10	7	10	15
hourglass factor H_{geom}	0.9	0.9	0.9	0.9
pinch factor H_{b-b}	1.3	1.3	1.3	1.3
proton filling H_{coll}	0.8	0.8	0.8	0.8
luminosity $[10^{33} cm^{-2} s^{-1}]$	1	8	12	15

Oliver Brüning¹, John Jowett¹, Max Klein², Dario Pellegrini¹, Daniel Schulte¹, Frank Zimmermann¹

EDMS 17979910 | FCC-ACC-RPT-0012

Contains update on eA: 6 10³² in e-Pb for LHeC.

LHC Folklore: PDFs come from pp



NNPDF3.1 arXiv:1706.00428

LHC data constrain PDFs, BUT do not determine them:

- Needs complete q_i,g unfolding (miss variety) at all x, as there are sum-rules
- Needs strong coupling to per mille precision, not in pp
- Needs stronger effects (miss Q² variation) cannot come from W,Z at Q²=10⁴ GeV²
- Needs clear theory (hadronisation, one scale)
- Needs heavy flavour s,c,b,t measured and VFNS fixed
- Needs verification of BFKL at low x (only F_2 - F_L)
- Needs N³LO (as for Higgs)
- Needs external input to find QCD subtleties such as factorisation, resummation...to not go wrong
 Needs external procise input for subtle discoveries
- Needs external precise input for subtle discoveries
- Needs data which yet (W,Z) will hardly be better
- Needs agreement between the PDfs and χ^2 +1..

PDFs are not derived from pp scattering. And yet we try, as there is nothing else.., sometimes with interesting results as on the light flavour democracy at $x \sim 0.01$ (nonsuppressed s/dbar). Can take low pileup runs, mitigate PDF influence .. – but can't do what is sometimes stated.

LHeC vs HERA: Higher Q²: CC; higher s: small x/g saturation?; high lumi: $x \rightarrow 1$; s, c,b,t...

That's it?? That may not be it..

Developments

AdS/CFT Instantons Odderons TOTEM ? CERN EP 2017-335

Non pQCD, Spin Quark Gluon Plasma

QCD of Higgs boson

N^kLO, Monte Carlos.. Resummation Saturation and BFKL

Photon, Pomeron, n PDFs Non-conventional partons (unintegrated, generalised) Vector Mesons The 3 D view on hadrons..

Díscoveríes

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 with the FCC

SM Higgs Couplings from the LHeC



LHeC: 60 GeV x 7 TeV. CLIC: 350 GeV [arXiv:1608.07538, "model dependent fit"] The principal advantage of e⁺e⁻ is the measurement of the inclusive ZH production cross section. For a joint ee/ep/pp FCC Higgs analysis see Jorge De Blas Amsterdam FCC week.

QCD of the Higgs Boson



← LHeC 1305.2090

[LHeC/FCCeh at per-mille level, mass and xsection]

True PDF errors?

PDFs to N³LO \rightarrow DIS to N³LO [10 years program]

 $\sigma \sim (\alpha_s xg)^2$

High precision pp Higgs physics requires high precision for PDFs and α_s

Figure 18: Higgs production cross-section and 68% C.L. PDF+ α_s uncertainty from the ABM12 fit and from the CT14 set computed at $\alpha_s = \alpha_s^{ABM}$, normalized by the central value obtained with the PDF4LHC combination.

 $\sigma = 48.58 \,\mathrm{pb}_{-3.27 \,\mathrm{pb} \,(-6.72\%)}^{+2.22 \,\mathrm{pb} \,(+4.56\%)} \,(\mathrm{theory}) \pm 1.56 \,\mathrm{pb} \,(3.20\%) \,(\mathrm{PDF} + \alpha_s)$

C Anastasiou et al, arXiv:1602.00695

Observations post CDR/EUSPP - 2012+ affecting ep at CERN:

LHC lifetime now extended to ~2040 to collect 3 [4] ab⁻¹. LS3 2024-2026+..

Discovery of the Higgs: L(ep): $10^{33} \rightarrow 10^{34}$ cm⁻² s⁻¹ [HERA in days] LHC brightness N_p/ ϵ about 3 times higher than "ultimately" expected

No further discovery at the LHC, so far

Detector technology developments (LHC Det. Upgrades)

Strong accelerator technology developments, notably SCRF ERL. LHeC: 720 \rightarrow 802 MHz. enhanced Q₀ > 10¹⁰

EU strategy 13: exploit LHC, study Higgs, develop SCRF+, CERN: new accelerators "with emphasis on pp and ee" Fine with the LHeC cost being a small fraction of ILC,CLIC,FCC

 → CERN in 14 set up a new LHeC organisation with a new mandate and IAC (H.Schopper et al) to prepare for the next EU strategy 2019+
 Two main tasks (IAC): Update of CDR for HL-LHeC/FCCeh + Testfacility

60 GeV Energy Recovery Linac



CDR+: Default configuration, 60 GeV, 3 passes, 802 MHz, synchronous ep+pp, L_{ep}=10³⁴



Figure 3: Determination of the gluon momentum distribution in the proton. The expected total experimental uncertainty on xg from the LHeC (dark purple bands) is compared with the most recent global PDF determinations which include the final HERA data, covering for xg a range from $x \simeq 5 \ 10^{-4}$ to $x \simeq 0.6$, and much of the LHC data from Run I. Left: xg at small x; Right at large x.

Nuclear QCD through eA at FCCeh/LHeC



eA: extends kinematic range in Q², 1/x by 3-4 orders of magnitude. Lumi 6 10³² (J.Jowett) Measure nPDFs as in ep scattering and determine then the ratio R(x,Q²)=nPDF/PDF **Shadowing? A1/3 amplification? Saturation? Colour Flow? QGP initial state, collective effects** LHeC has been co-initiated and supported by NuPECC

see: Nestor Armesto FCC week 1/2018, CDR (LHeC) M.K. DOI: 10.1051/epjconf/201611203002