The LHeC Project

A. Caldwell on behalf of J. Dainton

All slides from M. Klein, ICFA08
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.
Strong Coupling Constant

\( \alpha_s \) least known of coupling constants
Grand Unification predictions suffer from \( \delta \alpha_s \)

DIS tends to be lower than world average

LHeC: per mille accuracy indep. of BCDMS.
Challenge to experiment and to h.o. QCD

Simulation of \( \alpha_s \) measurement at LHeC

**DATA**

<table>
<thead>
<tr>
<th>Scenario</th>
<th>exp. error on ( \alpha_s )</th>
</tr>
</thead>
<tbody>
<tr>
<td>NC e(^+) only</td>
<td>0.48%</td>
</tr>
<tr>
<td>NC</td>
<td>0.41%</td>
</tr>
<tr>
<td><strong>NC &amp; CC</strong></td>
<td><strong>0.23% ((^{(1)})</strong></td>
</tr>
<tr>
<td>( \gamma_{\alpha} &gt; 5^\circ )</td>
<td>0.36% ((^{(2)})**</td>
</tr>
<tr>
<td>+ BCDMS</td>
<td>0.22%</td>
</tr>
<tr>
<td>+ BCDMS</td>
<td>0.22%</td>
</tr>
<tr>
<td>stat. * = 2</td>
<td>0.35%</td>
</tr>
</tbody>
</table>

DIS08, T.Kluge

Max Klein LHeC ICFA08
**Gluon - SM Higgs**

In SM Higgs production is gluon dominated

LHeC: huge $x,Q^2$ range for $xg$ determination

WW to Higgs fusion has sizeable $ep$ xsection

Cross section is half at 70 GeV. NLO is about 2

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In MSSM Higgs production is $b$ dominated

First measurements of $b$ at HERA can be turned to precision measurement of $b$-df.

LHeC: higher fraction of $b$, larger range, smaller beam spot, better Si detectors

CTEQ Belyayev et al. JHEP 0601:069, 2006
Single (anti) t and s Quark Production in CC

LHeC is a single top and single tbar quark ‘factory’

CC t cross section O(5)pb

s, sbar-df for the 1st time.

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Light Quark Distributions

d and u at high x: a longstanding puzzle
NC/CC: free of HT, nuclear corrections.
Essential for predictions at high x

LHeC is an electroweak machine.
e.g.: Charge asymmetry in NC measures
valence quarks down to $x \sim 10^{-3}$ at high $Q^2$

$$xF_3^{u/Z} = \frac{x}{3} (2u_v + d_v)$$
pdf’s and New Physics at the LHC

NP may be accommodated by HERA/BCDMS DGLAP fit. It cannot by the fit to also LHeC.

(recall high E_t excess at the Tevatron which disappeared when xg became modified)

Factorisation is violated in production of high p_T particles (IS and FS i.a.s).

Important, perhaps crucial, to measure pdf’s in the kinematic range of the LHC.

cf also ED limits vs pdf’s.

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LQ Quantum Numbers

Charge asymmetry much cleaner in ep than in pp. Similar for simultaneous determination of coupling and quark flavour. Polarisation for spectroscopy.
Electron-Boson Resonances: excited electrons

Single $e^*$ production x-section in $ep$ is high.

N. Trinh, E. Sauvan, Divonne

LHeC prelim. analysis, looking at $e^* \rightarrow e\gamma$

- If LHC discovers (pair prod) an $e^*$: LHeC would be sensitive to much smaller $f/\Lambda$ couplings

- Discovery potential for higher masses.
  Needs high electron beam energy
  $L$ assumed 10 (1) fb$^{-1}$ with 20/70 (140) GeV

Quark-Gluon Dynamics - Diffraction and HFS (fwd jets)

Diffraction to accompany (SUSY) Higgs fwd physics at LHC

Understand multi-jet emission (unintegr. pdf’s), tune MC’s
At HERA resolved $\gamma$ effects mimic non-kt ordered emission
Crucial measurements for QCD, and for QCD at the LHC
Quark-Gluon Dynamics (saturation, GPDs)

LHeC opens phase space to discover saturation in DIS

J. Bartels at Divonne on low x theory

High luminosity, polarisation, accuracy for GPD’s (DVCS)
Deep Inelastic Scattering off Nuclei (D,A)

LHeC extends kinematic range of partonic structure of nuclei by 3-4 orders of magnitude.

It accesses saturation effects at low x in DIS region ("beyond unitarity")

\[ \frac{g_A \pi r_A^2}{g_p \pi r_p^2} = A^{1/3} \frac{g_A}{Ag_p} \]

eRHIC with nuclei could be complementary.

LHeC-A appears as natural complement and possible extension of ALICE physics programme.
Complementarity of Ap and ep

ALICE expected reach in 1 yr. pA(Ap) collisions

CMS expected reach in 1 yr. pA(Ap) collisions

Note that DY is not DIS

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Need eA collider data to determine nuclear parton distributions in the kinematic range of pA/AA collisions at the LHC

NuPECC EIC-LHeC Study group
Tullio Bressani, INFN, Torino Univ.
Jens Jørgen Gaardhøje, Niels Bohr Inst.
Günther Rosner, Glasgow Univ.
Hans Ströher, FZ Juelich

See e.g. M. Arneodo
Phys. Rept. 240 (94) 301

K. Eskola et al. JHEP 0807 (08)102

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### Saturation - Black Hole Duality

<table>
<thead>
<tr>
<th>4d Perturbative QCD</th>
<th>5d Tiny Black hole</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Dilute/dense transition</td>
<td>1. Flat/black hole transition</td>
</tr>
<tr>
<td>2. Geometric scaling</td>
<td>2. CSS</td>
</tr>
<tr>
<td>3. Critical exponent 2.44</td>
<td>3. Critical exponent 2.58</td>
</tr>
<tr>
<td>4. IR/UV competition</td>
<td>4. Gravity/kinetic competition</td>
</tr>
</tbody>
</table>

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Agustin Sabio Vera (Divonne)
Machine Considerations and Studies

high $E_{e,p,A}$, $e^\pm$ polarised, high Luminosity

**generalities**

simultaneous ep and pp

power limit set to 100MW

IR at 2 or 8

**p/A:**

SLHC - high intensity p
(LPA/50ns or ESP/25ns)

Ions: via PS2
new source for deuterons

**e Ring:**

bypasses: 1 and 5
[use also for rf]

injector: SPL, or dedicated

**e LINAC:**

limited to ~6km (Rhone)
for IP2, longer for IP8
CLIC/ILC tunnel.

Joint study with CERN, BNL, CI, Jlab, DESY, .. experts

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**e Ring** Further Considerations

**Mount** e on top of p - feasible at first sight needs further, detailed study of pathway

**Installation:** 1-2 years during LHC shutdowns.
LEP installation was ~1 year into empty tunnel.
Radiation load of LHC pp will be studied.

**Injection:**
LEP2 was $4 \times 10^{11}$ e in 4 bunches
LHeC is $1.4 \times 10^{10}$ in 2800 bunches
may inject at less than 20 GeV.

**Power for 70 (50) GeV $E_e$ fits into bypasses:**

SC system at 1.9° K (1 GHz)
r.f. coupler to cavity: 500 kW CW - R+D
9 MV/cavity.
100(28) cavities for 900(250)MV
cavity: beam line of 150 (42) m
klystrons 100 (28) at 500kW
plus 90 m racks ..
gallery of 540 (150) m length required.
Bypass point 5

- Bypass through survey gallery
  - 13m distance, 2 shafts

- 2 tunnels for ring and shielded rf

Bypass independent of IR
- ~30m distance, 1 shaft

Tunnel connection (CNGS, DESY)

Lattice study

H. Burkhardt

Combined Bypass

RF

no extra bend

LEP

S. Myers, J. Osborne
IR Design

Need low $x$ ($1^\circ$) and high $L$ ($10^\circ$?)

Separation (backscattering)

Synchrotron radiation ($100$ keV $E_{\text{crit}}$)

Crab cavities
(profit from LHC developments)

e optics and beam line

p optics

Magnet designs for IR

S shaped IR for Linac-Ring option.

...

Input/experience from
HERA, LHC, ILC, eRHIC, SUPER-B

B. Holzer, A. Kling, et al
**Ring-Ring Parameters**

\[ L = \frac{N_p \gamma}{4 \pi e_p e_n} \cdot \frac{I_e}{\sqrt{\beta_{px} \beta_{py}}} \]
\[ L = 8.310^{32} \cdot \frac{I_e}{50 mA} \cdot \frac{m}{\beta_{px} \beta_{py}} \cdot cm^{-2} s^{-1} \]

Luminosity safely \(10^{33} \text{cm}^{-2} \text{s}^{-1}\)
HERA was 1-5 \(10^{31}\)

Table values are for 14MW synrad loss (beam power) and 50 GeV on 7000 GeV. May have 50 MW and energies up to about 70 GeV.

\[ I_e = 0.35 mA \cdot \frac{P}{MW} \cdot \left( \frac{100 \text{GeV}}{E_e} \right)^4 \]

LHC upgrade: \(N_p\) increased.
Need to keep \(e\) tune shift low:
by increasing \(\beta_p\), decreasing \(\beta_e\)
but enlarging \(e\) emittance,
to keep \(e\) and \(p\) matched.

LHeC profits from LHC upgrade
but not proportional to \(N_p\)

<table>
<thead>
<tr>
<th>Standard Parameter</th>
<th>Protons</th>
<th>Elektrons</th>
</tr>
</thead>
<tbody>
<tr>
<td>(nb=2808)</td>
<td>(N_p=1.15 \times 10^{11})</td>
<td>(N_e=1.4 \times 10^{10})</td>
</tr>
<tr>
<td>(I_p=582\ mA)</td>
<td>(I_e=71\ mA)</td>
<td></td>
</tr>
<tr>
<td>Optics</td>
<td>(\beta_{xp}=180\ cm)</td>
<td>(\beta_{xe}=12.7\ cm)</td>
</tr>
<tr>
<td>(\beta_{yp}=50\ cm)</td>
<td>(\beta_{ye}=7.1\ cm)</td>
<td></td>
</tr>
<tr>
<td>(\varepsilon_{xp}=0.5\ nm\ rad)</td>
<td>(\varepsilon_{xe}=7.6\ nm\ rad)</td>
<td></td>
</tr>
<tr>
<td>(\varepsilon_{yp}=0.5\ nm\ rad)</td>
<td>(\varepsilon_{ye}=3.8\ nm\ rad)</td>
<td></td>
</tr>
<tr>
<td>Beamsize</td>
<td>(\sigma_{x}=30\ \mu m)</td>
<td>(\sigma_{y}=15.8\ \mu m)</td>
</tr>
<tr>
<td>(\Delta \nu_x=0.00055)</td>
<td>(\Delta \nu_x=0.0484)</td>
<td></td>
</tr>
<tr>
<td>(\Delta \nu_y=0.00029)</td>
<td>(\Delta \nu_y=0.0510)</td>
<td></td>
</tr>
<tr>
<td>Luminosity</td>
<td>(L=8.2 \times 10^{32})</td>
<td></td>
</tr>
</tbody>
</table>

**Upgrade [LPA]**

| \(nb=1404\) | \(N_p=5 \times 10^{11}\) | \(N_e=1.4 \times 10^{10}\) |
| \(I_p=1265\ mA\) | \(I_e=71\ mA\) |
| Optics | \(\beta_{xp}=400\ cm\) | \(\beta_{xe}=8\ cm\) |
| \(\beta_{yp}=150\ cm\) | \(\beta_{ye}=5\ cm\) |
| \(\varepsilon_{xp}=0.5\ nm\ rad\) | \(\varepsilon_{xe}=25\ nm\ rad\) |
| \(\varepsilon_{yp}=0.5\ nm\ rad\) | \(\varepsilon_{ye}=15\ nm\ rad\) |
| Beamsize | \(\sigma_{x}=44\ \mu m\) | \(\sigma_{y}=27\ \mu m\) |
| \(\Delta \nu_x=0.0011\) | \(\Delta \nu_x=0.057\) |
| \(\Delta \nu_y=0.00069\) | \(\Delta \nu_y=0.058\) |
| Luminosität | \(L=1.44 \times 10^{33}\) |

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SPL as e injector/linac to Point 2 via TI2 tunnel
here with new re-circulating loop (r \sim 20\text{m}, l \sim 400\text{ m}),
use of service tunnel or dogbone to be studied ... 20\text{ GeV}
Luminosity: Linac-Ring

\[ L = \frac{N_p \gamma}{4\pi e \epsilon_{pn} \beta^*} \cdot \frac{P}{E_e} = 5 \cdot 10^{32} \cdot \frac{P / MW}{E_e / GeV} \text{cm}^{-2} s^{-1} \]


SLHC - LPA

\[ \epsilon_{pn} = 3.8 \mu m \]

\[ N_p = 5 \cdot 10^{11} \]

\[ \beta^* = 0.10 m \]

LINAC is not physics limited in energy, but with its cost/length + power

\( > 10^{32} \) are in reach at large \( E_e \).

LINAC - no periodic loss+refill, ~twice as efficient as ring...

8,4,3fb\(^{-1}\) /year at (50)100[150] GeV

Note: positron source challenge:

LHeC \( 10^{32} \) needs few times \( 10^{14} / \text{sec} \)
<table>
<thead>
<tr>
<th></th>
<th>e- energy [GeV]</th>
<th>Pulsed</th>
<th>CW</th>
</tr>
</thead>
<tbody>
<tr>
<td>comment</td>
<td>SPL* (20)+TI2</td>
<td>LINAC</td>
<td>LINAC</td>
</tr>
<tr>
<td>#passes</td>
<td>4+1</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>wall plug power RF+Cryo [MW]</td>
<td>100 (1 cr.)</td>
<td>100 (3 cr.)</td>
<td>100 (35 cr.)</td>
</tr>
<tr>
<td>bunch population [10⁹]</td>
<td>10</td>
<td>3.0</td>
<td>0.1</td>
</tr>
<tr>
<td>duty factor [%]</td>
<td>5</td>
<td>5</td>
<td>100</td>
</tr>
<tr>
<td>average e- current [mA]</td>
<td>1.6</td>
<td>0.5</td>
<td>0.3</td>
</tr>
<tr>
<td>emittance γε [µm]</td>
<td>50</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>RF gradient [MV/m]</td>
<td>25</td>
<td>25</td>
<td>13.9</td>
</tr>
<tr>
<td>total linac length β=1 [m]</td>
<td>350+333</td>
<td>3300</td>
<td>6000</td>
</tr>
<tr>
<td>minimum return arc radius [m]</td>
<td>240 (final bends)</td>
<td>1100</td>
<td>1100</td>
</tr>
<tr>
<td>beam power at IP [MW]</td>
<td>24</td>
<td>48</td>
<td>30</td>
</tr>
<tr>
<td>e- IP beta function [m]</td>
<td>0.06</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>ep hourglass reduction factor</td>
<td>0.62</td>
<td>0.86</td>
<td>0.86</td>
</tr>
<tr>
<td>disruption parameter D</td>
<td>56</td>
<td>17</td>
<td>17</td>
</tr>
<tr>
<td>luminosity [10³² cm⁻² s⁻¹]</td>
<td>2.5</td>
<td>2.2</td>
<td>1.3</td>
</tr>
</tbody>
</table>

proton parameters: LPA upgrade SLHC: \( N_b=5\times10^{11} \), 50 ns spacing, \( \gamma_{\varepsilon}=3.75 \mu m \), \( \beta^{*}=0.1 \text{ m} \), \( \sigma_z=11.8 \text{ cm} \)

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F. Zimmermann, S. Chattopadhyay
100 GeV e LINAC with recirculator.

ILC/CLIC tunnel much deeper

CLIC cavities don’t fit to LHC

CW LINAC longer: energy recovery

ERL is probably THE R+D project of the LHeC if the LINAC is chosen.

[Tigner 1965, Jlab, Cornell, …]
Detector Design Considerations

Large fwd acceptance and high luminosity

Forward tagging of p, n, d
Backward tagging of e, γ
Tagging of c and b in max. angular range
High resolution final state (Higgs to bbar)

High precision tracking and calorimetry

<table>
<thead>
<tr>
<th>Largest possible acceptance</th>
<th>LHeC</th>
<th>HERA</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-179°</td>
<td>7-177°</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>High resolution tracking</th>
<th>LHeC</th>
<th>HERA</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1 mrad</td>
<td>0.2-1 mrad</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Precision electromagnetic calorimetry</th>
<th>LHeC</th>
<th>HERA</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1%</td>
<td>0.2-0.5%</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Precision hadronic calorimetry</th>
<th>LHeC</th>
<th>HERA</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5%</td>
<td>1%</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>High precision luminosity measurement</th>
<th>LHeC</th>
<th>HERA</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5%</td>
<td>1%</td>
<td></td>
</tr>
</tbody>
</table>
L1 Detector: version for low x Physics

**Muon chambers**
(fwd,bwd,central)

**Coil** (r=3m l=8.5m, 2T)
[Return Fe not drawn]

**Central Detector**

**Hadronic Calo** (Fe/LAr)
**El.magn. Calo** (Pb,Sc)
**GOSSIP** (fwd+central)
[Gas on Slimmed Si Pixels]
[0.6m radius for 0.05% * pt in 2T field]
**Pixels**
**Elliptic beam pipe** (~3cm)

**Fwd Spectrometer**
(down to 1°)

**Tracker**
**Calice** (W/Si)
**FwdHadrCalo**

**Bwd Spectrometer**
(down to 179°)

**Tracker**
**Spacal** (elm, hadr)

To be extended further in fwd direction. Tag p,n,d. Also e,γ (bwd)
L1 Detector: version for hiQ^2 Physics

Muon chambers (fwd,bwd,central)

**Coil** (r=3m l=8.5m, 2T)

Central Detector

Hadronic Calo (Fe/LAr)
El.magn. Calo (Pb,Sc)
GOSSIP (fwd+central)

Pixels
Elliptic pipe (~3cm)

**Fwd Calorimeter**
(down to 10°)

**Lepton low β magnets**
FwdHadrCalo

**Bwd Spectrometer**
(down to 170°)

**Lepton low β magnets**
Spacal (elm, hadr)

Max Klein LHeC ICFA08
ECFA + CERN in 11/07 set the task to work out a CDR within 2 years on the physics, machine and detector for a TeV energy ep collider based on the LHC DIS workshops since 05, EPAC08. ECFA-CERN: Divonne - 9/08.
First ECFA-CERN Workshop on the LHeC Divonne 1.-3.9.08

Opening: J.Ellis, Kh.Meier, G.Rosner, J.Engelen, G.Altarelli

Max Klein LHeC SAC-CI 11/08