Physics Opportunities at the LHeC

Emmanuelle Perez (CERN)

LHeC: A Large Hadron electron Collider at the LHC
5-140 GeV e± on 1-7 TeV p,A

Possible “upgrade” of the LHC: add-on of an electron beam to study:

Deep-inelastic scattering ep and eA at
- unprecedented energy
- with an integrated luminosity of $O(10 \text{ fb}^{-1})$

http://www.lhec.org.uk
The LHeC is not the first proposal for higher energy DIS, but it is the first with the potential for significantly higher luminosity than HERA ...

Deep Inelastic Electron-Nucleon Scattering at the LHC*

J. B. Dainton¹, M. Klein², P. Newman³, E. Perez, F. Willeke²

¹ Cockcroft Institute of Accelerator Science and Technology, Daresbury International Science Park, UK
² DESY, Hamburg and Zeuthen, Germany
³ School of Physics and Astronomy, University of Birmingham, UK
⁴ CE Sarl, LISM/LAPNIA/Spp, Gif-sur-Yvette, France

... achievable with a new electron accelerator at the LHC ...

[JINST 1 (2006) P10001]
... after further studies, discussions with CERN accelerator experts and a presentation to plenary ECFA:

Summary and Proposal as endorsed by ECFA (30.11.2007)

As an add-on to the LHC, the LHeC delivers in excess of 1 TeV to the electron-quark cms system. It accesses high parton densities ‘beyond’ what is expected to be the unitarity limit. Its physics is thus fundamental and deserves to be further worked out, also with respect to the findings at the LHC and the final results of the Tevatron and of HERA.

First considerations of a ring-ring and a linac-ring accelerator layout lead to an unprecedented combination of energy and luminosity in lepton-hadron physics, exploiting the latest developments in accelerator and detector technology.

It is thus proposed to hold two workshops (2008 and 2009), under the auspices of ECFA and CERN, with the goal of having a Conceptual Design Report on the accelerator, the experiment and the physics. A Technical Design report will then follow if appropriate.
... a working group structure agreed and convenors invited ...

First ECFA-CERN Workshop on the LHeC Divonne 1.-3.9.08

... first workshop took place in September 2008, Divonne. Eclectic mix of accelerator experts, experimentalists and theorists (~ 90 participants).
How could ep be done with LHC

...whilst allowing simultaneous ep and pp running ...

LINAC-RING

- Previously considered as 'QCD explorer' (also THERA)
- Reconsideration (Chattopadhyay, Zimmermann et al.) recently
- Main advantages: low interference with LHC, $E_e \rightarrow 140 \text{ GeV}$, LC relation

RING-RING

- First considered (as LEPxLHC) in 1984 ECFA workshop
- Recent detailed re-evaluation with new e ring (Willeke)
- Main advantage: high peak lumi obtainable.
- synchrotron limits e beam energy (70GeV)

See next talk by Max Klein!
Kinematics & Motivation (70 GeV x 7 TeV ep)

New physics, distance scales few \(10^{-20}\) m

- High mass \((M_{eq}, Q^2)\) frontier
- EW & Higgs
- \(Q^2\) lever-arm at moderate & high \(x\) \(\rightarrow\) PDFs
- Low \(x\) frontier
  - \([x\ below\ 10^{-6}\ at\ Q^2\sim 1\ GeV^2]\)
  - \(\rightarrow\) novel QCD ...

\(\sqrt{s} = 1.4\ TeV\)
New Physics at the LHeC

- Lepto-Quark Production and Decay (s and t-channel effects)
  Maximum $W < 1.4$ TeV for $E_e = 140$ GeV, $E_p = 7$ TeV

- Squarks and Gluinos

- ZZ, WZ, WW elastic and inelastic collisions

- Technicolor

- Novel Higgs Production Mechanisms

- Composite electrons

- Lepton-Flavor Violation

- QCD at High Density in ep and eA collisions

- Odderon

ECFA-CERN LHeC Workshop
Divonne, September 1, 2008

LHeC Physics Overview

J. Bartels: Theory on low $x$

Stan Brodsky, SLAC
New Physics at High Scales

In general, unlikely that a discovery at LHeC is invisible at the LHC. But:

- Following a discovery at the LHC, LHeC may provide information about the underlying theory, examples:
  - electron-quark resonances
  - new $Z'$ boson: couplings $\rightarrow$ underlying model
  - structure of a $eeqq$ contact interaction
  - study of new leptons (sleptons, excited leptons)

- A better knowledge of the proton structure may be needed
  - to better study new bosons
  - to establish unambiguously new physics effects
    (Remember excess of high ET jets at CDF in 1995)
Electron-quark resonances

- "Leptoquarks" (LQs) appear in many extensions of SM
- Scalar or Vector color triplet bosons
- Carry both $L$ and $B$, frac. em. Charge
- Also squarks in R-parity violating SUSY

$LQ\ e\ q\ \lambda\ e\ p$ $\lambda$ (unknown) coupling $l-q-LQ$

\[ LQ \text{ decays into (lq) or (vq)} : \]
- $ep$ : resonant peak, ang. distr.
- $pp$ : high $E_T$ lljj events

LHC could discover eq resonances with a mass of up to 1.5 - 2 TeV via pair production.

Quantum numbers? Might be difficult to determine in this mode.
Determination of LQ properties

- **Fermion number**

  - $F = -1$ for LQs: $\sigma(e^+)$ higher
  - $F = +1$ for LQs: $\sigma(e^-)$ higher
  - $F = 0$ for LQs: mostly $q$ in initial state

- **Scalar or Vector**

  - $q\bar{q} \rightarrow g \rightarrow LQ\bar{LQ}$: Angular distributions depend on the structure of $g$-$LQ$-$LQ$. If coupling similar to $\gamma$-$WW$, vector LQs would be produced unpolarised...

- **Chiral couplings**

  - Play with lepton beam polarisation.

E. Perez

TH Institute, Feb 09
Single LQ production at LHC

Single LQ production is better suited to study “LQ spectroscopy”.

Also possible in pp:

\[ g \rightarrow \text{LQ} \rightarrow q e^- \]

\[ \gamma \rightarrow e e \rightarrow \text{eq } \rightarrow \text{LQ } \]  
\[ \text{not considered yet. Work in progress. } \]

But with a much smaller x-section than at LHeC.

And large background from Z + 1 jet.

Not much considered yet by LHC experimental groups.

Pheno. study focusing on the extension of the discovery potential:

A.S. Belyaev et al, JHEP 0509 (2005) 005
Determination of LQ properties in single production: e.g. Fermion Number

In pp: look at signal separately when resonance is formed by \((e^+ + \text{jet})\) and \((e^- + \text{jet})\):

\[
\begin{align*}
g & \quad F=0 \quad e^+ \\
q & \quad \lambda \quad e^- \\
\end{align*}
\]

\[
\begin{align*}
g & \quad F=0 \quad e^- \\
\bar{q} & \quad \lambda \quad e^- \\
\end{align*}
\]

\[\sigma(e^+_{\text{out}}) > \sigma(e^-_{\text{out}})\]

for \(F=0\)

Sign of the asymmetry gives \(F\), but could be statistically limited at LHC. (*)

Easier in ep! Just look at the signal with incident \(e^+\) and incident \(e^-\), build the asymmetry between \(\sigma(e^+_{\text{in}})\) and \(\sigma(e^-_{\text{in}})\).

If LHC observes a LQ-like resonance, \(M < 1 - 1.5\) TeV, with indications (single prod) that \(\lambda\) not too small, LHeC would solve the possibly remaining ambiguities.

(*) First rough study done for the 2006 paper. Need to check / refine with a full analysis of signal and backgrounds.
Other examples of new physics in $eeqq$ amplitudes

- **new $Z'$ boson:** $pp$ measurements alone do not allow for a model-independent determination of all of the $Z'$ couplings ($g_{L,R}^e, g_{L,R}^u,d$)

$LHeC$ data may bring the necessary complementary information, before a LC.

T. Rizzo, PRD77 (2008) 115016

- **Contact Interactions:**

  \[
  \mathcal{L}_{CI} = \sum_{i,j=L,R} \varepsilon_{ij}^{e,q} \frac{4\pi}{\Lambda^2} (\bar{e}_i \gamma^\mu e_i) (\bar{q}_j \gamma_\mu q_j)
  \]

  At LHeC, sign of the interference can be determined by looking at the asym. between $\sigma/SM$ in $e^-$ and $e^+$. 
Supersymmetry (R-parity conserved)

Pair production via t-channel exchange of a neutralino.
Cross-section sizeable when \( \Sigma M \) below \( \sim 1 \) TeV.
Such scenarios are “reasonable”.

E.g. global SUSY fit to EW & B-physics observables
plus cosmological constraints (O. Buchmueller et al., 2008),
within two SUSY models (CMSSM & NUHM) leads to masses
of \( \sim (700, 150) \) GeV.

SUSY cross-section at LHeC:
about 15 fb for these scenarios.

Added value w.r.t. LHC to be studied:
- could extend a bit over the
  LHC slepton sensitivity
- precise mass measurements?
  → study mass reco. at LHeC,
    using variables worked out for
    LHC (MT, MT2, etc...).
- relevant information on \( \chi^0 \) sector?
  e.g. from charge / polar. asymmetries
Electron-boson resonances: excited electrons

- Single e\* production
  \[ \sigma \sim f/\Lambda \]

[Hagiwara et al. ZPC 29(1985)115]
[Boudjema et al. ZPC 57(1990)425]

LHeC prelim. analysis, looking at e\* → eγ

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

Possible determination of QNs [ cf LQs ]

Discovery potential for higher masses

LHeC sensitivity,
with L=10 fb\(^{-1}\) for Ee=70/20 GeV
with L=1 fb\(^{-1}\) for Ee=140 GeV

Precision physics at LHeC: better pdfs for LHC?

- Larger overlap than HERA with the LHC domain.
- Large luminosities would bring in constraints in domains which are currently poorly known.

To which extent do we need a better knowledge of p structure for the interpretation of LHC data?
Pdfs for LHC processes: do we know them "well enough"?

• In general not too bad.
  e.g. Higgs prod. at the LHC:
  Pdf uncertainty ~ 10%.

• However, limited knowledge at low x (g) and at large x (g & quarks)
  Relative uncertainties on partonic luminosities vs.
  $M = \sqrt{s}$ at the LHC.

\[
\mathcal{L}_{ab} = C_{ab} \int_0^1 \frac{dx}{x} f_a(x_a) f_b(x/x_a)
\]
\[
\hat{\sigma} = \sum_{a,b} \hat{\mathcal{L}}_{ab} \hat{\sigma}(ab \rightarrow M; \hat{s} = \tau s).
\]
  e.g. 40% for a 6 TeV $W'$ (within LHC reach if $g_{SM}$)
Improved determination of pdfs from LHeC

NC and CC rates allow a much improved determination of pdfs over the whole domain in x.

Flavour decomposition: e.g. from High precision c, b measurements. Systematics at 10% level

→s (& sbar) from charged current

Similarly Wb → t ?

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

CC t cross section O(5)pb
Could pdf effects “fake” new physics at the LHC?

- One possible signal of compositeness is the production of high $p_T$ jets.

Quickly a new territory with TeV jets!

- At one point there was a disagreement between theory and experiment at the Tevatron.

- Not new physics but too little high-$x$ gluon in the PDFs.
High Mass Drell-Yan at the LHC

Drell-Yan with $M_{ll} \sim \text{TeV}$ involves quarks and antiquarks with $x_{Bj} \sim 0.1$

Generic approach for new physics in DY final states: contact interactions

$$\mathcal{L}_{CI} = \sum_{i,j=1}^{L,R} \varepsilon_{ij} \frac{4\pi}{\Lambda^2} \left( \bar{e}_i \gamma^\mu e_i \right) \left( \bar{q}_j \gamma_\mu q_j \right)$$

Focus on this NP scenario

Various models, look e.g. at “VV” model (parity-conserving).

$$\varepsilon_{ij} = \pm 1 \text{ for } i,j = L,R$$
VV model, $\Lambda = 40$ TeV

DGLAP fits:
- to HERA and BCDMS ($\mu p$ and $\mu d$ data): “reference fit”
- and including in addition LHC toy-data, assuming new physics contributions to the Drell Yan.

This NP scenario looks quite different from SM, even when taking into account the stat. uncertainty of the data, and the pdf uncertainty of the SM prediction.

However, the effects of this scenario can easily be accommodated within DGLAP! [in this fit]

A fit including these LHC “data” does describe well all datasets! $\chi^2 / df = 0.93$
How does this fit compare with the “reference fit”

The plots show ratios to the “reference” fit.

In the “region of interest”, $x \sim 0.1$, the fit including the LHC NP-data mainly changes the antiquarks.

Reason: currently, big uncertainty on $x \sim 0.1$ antiquarks…
What LHeC would bring in this scenario

DIS: largest contribution to the cross-section at high $x$ & $Q^2$ comes from the $u$-quark (not anti-$u$) which is already well constrained.

i.e. new physics in

\[ e^- e^- \] $u$ $u$

would be easy to disentangle from pdf effects.

Indeed: DGLAP fit including LHeC data with $\Lambda = 40$ TeV, $\varepsilon = -1$ fails:

<table>
<thead>
<tr>
<th>Dataset</th>
<th>$\chi^2$</th>
<th>$N_{\text{points}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>MB 97</td>
<td>40.3</td>
<td>45</td>
</tr>
<tr>
<td>96-97</td>
<td>75.5</td>
<td>80</td>
</tr>
<tr>
<td>NC 94-97</td>
<td>95.2</td>
<td>130</td>
</tr>
<tr>
<td>CC 94-97</td>
<td>26.6</td>
<td>25</td>
</tr>
<tr>
<td>NC 98-99</td>
<td>112.2</td>
<td>126</td>
</tr>
<tr>
<td>CC 98-99</td>
<td>18.2</td>
<td>28</td>
</tr>
<tr>
<td>HY 98-99</td>
<td>5.0</td>
<td>13</td>
</tr>
<tr>
<td>NC 99-00</td>
<td>142.7</td>
<td>147</td>
</tr>
<tr>
<td>CC 99-00</td>
<td>49.0</td>
<td>28</td>
</tr>
<tr>
<td>BCDMS p</td>
<td>145.1</td>
<td>134</td>
</tr>
<tr>
<td>BCDMS n</td>
<td>154.6</td>
<td>159</td>
</tr>
<tr>
<td>LHeC e+</td>
<td>145.1</td>
<td>134</td>
</tr>
<tr>
<td>LHeC e-</td>
<td>295.7</td>
<td>135</td>
</tr>
</tbody>
</table>

Blue & red data points = NP scenario ($\Lambda = 40$ TeV)
Black curve = SM cross-sections

\[ e^- p \text{ cross sections} \]

i.e. LHeC data would disentangle between the example NP scenario and modified pdfs.

E. Perez

TH Institute, Feb 09
Precision QCD and EW: measurement of $\alpha_S$

$\alpha_S$ 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

DATA

<table>
<thead>
<tr>
<th></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%</strong> : (1)</td>
</tr>
<tr>
<td>$\gamma_h &gt; 5^\circ$</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>

DIS00, T.Klugc

Max Klein LHeC ECFA 11/08
LHeC and a light Higgs boson?

- \( bb \) is dominant decay mode for low-mass Higgs
- Inclusive H production followed by \( H \rightarrow bb \): impossible to see at LHC, above QCD background
- \( ttH \) followed by \( H \rightarrow bb \)?

Although \( ttH \) has a \( \sigma \)-section of \( O(1 \text{ pb}) \), very difficult to see the signal taking into account syst. uncertainties...

Standard unc.: JES, jet resolution, b-tagging

**H production at LHeC**

\( \sigma \sim 0.1 \text{ pb} \)

\( m_H \) (GeV/c²) | \( S \) | \( S/B \) (%) | \( S/\sqrt{B} \) | \( S/\sqrt{(B+dB^2)} \)
---|---|---|---|---
115 | 147 | 7.0 | 3.1 | 0.20
120 | 118 | 5.3 | 2.5 | 0.16
130 | 80 | 3.6 | 1.7 | 0.11

Information on \( bbH \) at LHeC?

[ U. Klein, B. Kniehl, EP, M. Kuze ]
bbH coupling

\( H \to bb \) leads to final states similar to multijet CC DIS.
Current jet very forward (lost in beam-pipe).
Requiring both \( b \) jets (from Higgs decay) to be in the central region
\((10 < \theta < 170 \text{ deg})\) reduces the cross-section by a factor of \( \sim \) two.

Divonne: First bckgd study, CC DIS only.

Events in 10 fb\(^{-1}\), requiring :
- at least two jets with \( p_T > 20 \text{ GeV}, |\eta| < 3, \)
- \( p_T, \text{miss} > 25 \text{ GeV}, \)
- \( M_{jj} \) in a mass window around the Higgs mass, \( M_H \pm \text{width} \)

\( H \to bb \) (for light H) may be seen at LHeC with
very simple cuts.
For coupling studies: \( b \)-tagging to improve S/B.

<table>
<thead>
<tr>
<th>( M_{H} ) (GeV)</th>
<th>width</th>
<th>( S )</th>
<th>( B )</th>
<th>( S/B )</th>
<th>( S/\sqrt{B} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 GeV</td>
<td>990</td>
<td>39000</td>
<td>0.025</td>
<td>5.0</td>
<td></td>
</tr>
<tr>
<td>20 GeV</td>
<td>990</td>
<td>78000</td>
<td>0.013</td>
<td>3.5</td>
<td></td>
</tr>
<tr>
<td>5 GeV</td>
<td>990</td>
<td>19000</td>
<td>0.05</td>
<td>7.2</td>
<td></td>
</tr>
</tbody>
</table>

Need: High \( E_e \),
high luminosity,
good acceptance,
good resolution.

LHeC may open a unique window to access the bbH coupling.
Low $x$: saturation of the gluon density

- Expect some saturation mechanism at low $x$:

Saturation, or gluon recombination, when

$$g(x, Q^2) \sim \frac{\pi}{Q^2} R_p^2$$

(naïve estimate...)

Proton rest frame

$$\gamma^p \rightarrow r_T$$

$L \sim 1/x$

$\sim 50 \text{ fm}$!

$r_T \sim 2/Q$

(size of dipole)

$\sim 1 \rightarrow .01 \text{ fm}$

At low $x$, DIS can be viewed as the high energy scattering of a $qq$ dipole with the proton. Unitarity!

$$\sigma_{\gamma^p}(W^2, Q^2) \propto \frac{4\pi^2\alpha}{Q^2} F_2(x, Q^2) \sim W^{2\delta}$$

( $W^2 = S_{\gamma p} \sim Q^2 / x$ )

• However: no “taming” of the rise of $F_2$ at low $x$ observed in HERA data.

[ though some “hints” of saturation may have been seen elsewhere in HERA data... ]
Saturation at the LHC?

Where does saturation become important?

<table>
<thead>
<tr>
<th>$x = 10^{-4}$</th>
<th>$x = 10^{-6}$</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.7</td>
<td>1.9</td>
<td>G. Soyez, 0705.3672 [hep-ph]</td>
</tr>
<tr>
<td>0.8</td>
<td>4.0</td>
<td>H. Kowalski, L. Motyka, G. Watt, hep-ph/0606272</td>
</tr>
<tr>
<td>0.8</td>
<td>2.0</td>
<td>K. Golec-Biernat, S. Sapeta, hep-ph/0607276</td>
</tr>
</tbody>
</table>

- at HERA typical $Q_s^2(x) \lesssim 1 \text{GeV}^2$

Could be seen at LHC in pp? E.g. in Drell-Yan production with $x_1 \ll x_2$

→ one very forward lepton:

e.g. for $M_{ll} \sim 10 \text{ GeV}$, $x_{\text{Bjorken}}$ down to $10^{-6}$ can be probed if coverage up to $\eta \sim 6$

(e.g. CASTOR calorimeter in CMS)

- Reduced event rates
- $M^2$ dependence different from expected

But is one observable enough to establish saturation??
Fits to HERA data extrapolated to LHeC

With 1 fb⁻¹ (1 year at 10^{33} \text{ cm}^{-2} \text{ s}^{-1}), 1° detector:
stat. precision < 0.1%, syst, 1-3%

[Forshaw, Klein, PN, Soyez]

Precise data in LHeC region,
x > \sim 10^{-6}

FS04, CGC models including saturation suppressed at low x & Q² relative to non-sat FS04-Regge

... new effects may not be easy to see and will certainly need low Q² (θ \sim 179°) region ...

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Saturation from $F_2$ measurements?

Could we see DGLAP fail at $Q^2 > \text{few GeV}^2$?

Can DGLAP be made to fit the data shown on the previous slide, which include saturation?

Fit to low $Q^2$ HERA data and to LHeC pseudo-data (FS04) with $Q^2 < 20 \text{ GeV}^2$:

$\chi^2 = 92$ for 92 data points

Only the 4 points at highest $Q^2$ and lowest $x$ are not well described by this fit.

i.e. saturation effects may not be easy to see with $F_2$ data alone...
Saturation from F2 and FL

However, this fit would NOT describe $F_L$ measurements.

These could be obtained by varying the proton beam energy as recently done at HERA.

Example for 1 year:

<table>
<thead>
<tr>
<th>$E_p$ (TeV)</th>
<th>Lumi (fb$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>0.8</td>
</tr>
<tr>
<td>2</td>
<td>0.2</td>
</tr>
<tr>
<td>1</td>
<td>0.05</td>
</tr>
</tbody>
</table>

... precision typically 5%

Similar conclusions within the NNPDF approach

[ J. Rojo, Divonne ]

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Saturation: conclusions

Saturation effects at LHeC (FS04-sat, CGC-sat) cannot be absorbed into a DGLAP analysis when $F_2$ and $F_L$ are both fitted.

Saturation maybe much more difficult to establish unambiguously from $F_2$ data alone.
→ important to have measurements at various $\sqrt{s}$
→ may be also difficult to establish if we have only LHC Drell-Yan data!

Other observables at LHeC could also provide a handle: heavy quark structure functions, DVCS, exclusive vector meson production, diffractive DIS.

e.g. DVCS at LHeC, together with $F_2$ & $F_L$, could help disentangle between different model which contain saturation.

Statistical precision with 1fb-1 ~ 2-11%

[ Favart, Forshaw, Newman ]
[Studies with $1^\circ$ acceptance, $1\text{ fb}^{-1}$]

- 5-10% data, depending on detector
- (D)PDFs / fac'n in much bigger range
- Enhanced parton satn sensitivity?
- $M_x \to 100\text{ GeV}$ with $x_{IP} = 0.01 \ldots$
  $\to X$ including $W, Z, b \ldots$
- Exclusive production of any $1^-$ state
With AA at LHC, LHeC is also an eA collider

- Very limited $x$ and $Q^2$ range so far (unknown for $x \sim 10^{-2}$, gluon very poorly constrained)

- LHeC extends kinematic range by 3-4 orders of magnitude

  opportunity to extract and understand nuclear parton densities in detail ...

$\rightarrow A^{1/3}$ enhanced gluon density $\rightarrow$ additional sat^n sensitivity

$\rightarrow$ initial state in AA quark-gluon plasma studies @ LHC / RHIC

$\rightarrow$ relations between diffraction and shadowing meas. of both eA and ep at high densities to test the Gribov-Glauber relationship of nuclear shadowing to diff.

$\rightarrow$ Neutron structure & singlet PDF evolution from deuterons

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

Nuclear $xg(x)$ is unknown for $x$ below $\sim 10^{-3}$!

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

Max Klein LHeC ICFA08

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

• LHC is a totally new world of energy and luminosity! LHeC proposal aims to exploit this for TeV lepton-hadron scattering.

• ep data complementing pp maybe needed for the full interpretation of discoveries at the LHC.

• LHeC would lead to much better determined pdfs (p and A) in the whole domain needed for LHC.

• Would study novel QCD phenomena at low x.

• First ECFA/CERN workshop successfully gathered accelerator, theory & experimental colleagues.

• Conceptual Design Report by early 2010
Backups
DIS at highest $Q^2$ : towards quark substructure?

LHeC promises to reach $10^{-19}$ m, i.e.
1/100000 (1000) of proton (quark) radius

Assign a finite size $< r >$ to the EW charge distributions:

$$
\frac{d\sigma}{dQ^2} = \text{SM}_\text{value} \times f(Q^2)
$$

$$
f(Q^2) = 1 - \frac{< r^2 >}{Q^2}
$$

Global fit of PDFs and $< r >$ using $d\sigma/dxdQ^2$ from LHeC simulation, 10 fb$^{-1}$ per charge, $Q^2$ up to 500000 GeV$^2$:

$< r_q > < 8 \times 10^{-20}$ m

One order of mag. better than current bounds.

At LHC: quark substructure may be seen as a deviation in the dijet spectrum. Such effects could also be due to e.g. a very heavy resonance.
Could we establish quark substructure with pp data only?
Parton Saturation after HERA?

e.g. Forshaw, Sandapen, Shaw
hep-ph/0411337,0608161
... used for illustrations here

Fit inclusive HERA data using dipole models with and without parton saturation effects

- **FS04 Regge (~FKS):** 2 pomeron model, **no saturation**
- **FS04 Satn:** Simple implementation of saturation
- **CGC:** Colour Glass Condensate version of saturation

- All three models can describe data with \( Q^2 > 1 \text{GeV}^2, x < 0.01 \)
- Only versions with saturation work for \( 0.045 < Q^2 < 1 \text{ GeV}^2 \)

... any saturation at HERA not easily interpreted partonically...
ep : golden machine to study LQ properties

F = 0 or 2 ? Compare rates in e⁻p and e⁺p
Spin ? Angular distributions
Chiral couplings ? Play with polarisation of lepton beam
Couples to ν ? Easy to see since good S/B in νj channel

Classification in the table below relies on minimal assumptions.
ep observables would allow to disentangle most of the possibilities (having a polarised p beam would complete the picture).

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<th>( S_{0,L} )</th>
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<th>( S_{0,R} )</th>
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<td>F = 2</td>
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<td>F = 0</td>
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If LHC observes a LQ-like resonance, M below 1 - 1.5 TeV, LHeC could solve the possibly remaining ambiguities (if \( \lambda \) is not too small)
Hints for saturation in the HERA data?

- Saturation may be thought as something like a phase transition: from free to strongly interacting partons from a low to a high density system.
- Some of the QCD based nonlinear equations proposed for saturation accept naturally solutions with geometric scaling behavior.

"geometric scaling"

\[ \tau \sim Q^2 x^\lambda \]

And also described well in dipole models with a saturating dipole-proton cross-section.

TH Institute, Feb 09
Example: saturation in dipole models

At low $x$, $\gamma^* \to qq$ and the long-lived dipole scatters from the proton

$\sigma = \sigma_0 \left(1 - \exp(-1/\tau)\right)$
Involves only
$\tau = Q^2 R_0^2(x)$
$\tau = Q^2 / Q_0^2 \left(x/x_0\right)^{1/2}$

And INDEED, for $x<0.01$, $\sigma(\gamma^* p)$ depends only on $\tau$, not on $x$, $Q^2$ separately

Transition between $\sigma(\gamma^* p) \sim \sigma_0$ ($\tau$ small) to $\sigma(\gamma^* p) \sim \sigma_0 / \tau$ ($\tau$ large)
observed indeed for $\tau \sim 1$.

Not a proof of saturation... but indicative...

Another “hint” for saturation comes from diffractive data.

E. Perez
\( \sigma_{\text{diff}} \) and \( \sigma_{\text{tot}} \) have the same energy dependence in the full \( Q^2 \) range!

High \( Q^2 : \sigma_{\text{tot}} \sim (W^2)\delta \) with \( \delta \sim 0.4 \)

- not explained in Regge phenomenology: \( \sigma_{\text{diff}} \sim (W^2)\delta \) with \( \delta \sim 0.08 \)

- not explained in QCD:
  \[ \sigma_{\text{diff}} \sim (xg(x))^2 \sim x^{-2\lambda} \]
  while \( \sigma_{\text{tot}} \sim xg(x) \)
  \( (W^2 \sim 1/x) \)

- Naturally explained in dipole models with saturation

\[ \sigma_{\text{diff}} \]

\[ \gamma^* \to p \]

\[ x \]

E. Perez

\[ 2 \]

\[ M_\Lambda < 3 \text{ GeV} \]

\[ 3 < M_\Lambda < 7.5 \text{ GeV} \]

\[ 7.5 < M_\Lambda < 15 \text{ GeV} \]

\[ W^2 \sim 1/x \]

E.g. with a dipole cross-section similar to that shown on two slides ago.

E.g. Golec-Biernat, Wustoff, PRD 60 (1999) 114023
Conclusions

For “new physics” phenomena “coupling” directly electrons and quarks (e.g. leptoquarks, eeqq contact interactions): LHeC has a sensitivity similar to that of LHC.

The further study, in ep, of such phenomena could bring important insights: leptoquark quantum numbers, structure of the “eeqq” new interaction, SUSY, Higgs coupling,... These studies may be difficult, if possible at all, in pp.

LHC sensitivity to new (directly produced) particles not much limited by our pdf knowledge. “Contact-interactions” deviations may be more demanding.

However, the interpretation of discoveries at LHC may require a better knowledge of the high x pdfs: e.g. determination of the couplings of a $W'$ or $Z'$ if “at the edge”.

Complementarity of Ap and ep

Note that DY is not DIS