Small-x Physics at the LHeC

Néstor Armesto

Departamento de Física de Partículas and IGFAE
Universidade de Santiago de Compostela
nestor.armesto@usc.es

for the LHeC Study group, http://cern.ch/lhec
Physics goals:

- Proton structure to a few $10^{-20}$ m: $Q^2$ lever arm.
- Precision QCD/EW physics.
- Higgs physics.
- High-mass frontier (lq, excited fermions, contact interactions).
- Unambiguous access, in ep and eA, to a qualitatively novel regime of matter predicted by QCD.
- Substructure/parton dynamics inside nuclei with strong implications on QGP search.
Kinematics:

- Small-x demands 1 degree acceptance. This gets worse with increasing electron energy.
- Higher luminosity would benefit high-x and $Q^2$ studies: linked to small $x$ via DGLAP evolution (see HERA final analysis).

N. Armesto - Small-x Physics at the LHeC.
N. Armesto - Small-x Physics at the LHeC.
Nuclear DIS & DY data:
- NMC (DIS)
- SLAC-E139 (DIS)
- FNAL-E665 (DIS)
- EMC (DIS)
- FNAL-E772 (DY)

Ultra-peripheral QQ:
- LHC Y (|y| < 2.5)
- LHC J/Ψ (|y| < 2.5)

p+Pb and Drell-Yan in p+A

pPb@LHC

Q^2(x, Pb^++, b=0 fm)

pPb@LHC

N. Armesto - Small-x Physics at the LHeC.
LHC vs. LHeC:

- The LHeC will explore a region overlapping with the LHC:
  → in a cleaner experimental setup;
  → on firmer theoretical grounds.

N. Armesto - Small-x Physics at the LHeC.
Contents:

1. Status and motivation.

2. Inclusive measurements at low $x$.

3. Diffractive and exclusive measurements at low $x$.

4. Summary.

2015 LHeC Workshop http://indico.cern.ch/event/356714/;
See the talks by Paul Newman, Claire Gwenlan and Max Klein.
Legacy from HERA:

- Structure functions in an extended $x$-$Q^2$ range, $xg \propto 1/x^\lambda$, $\lambda>0$.
- Large fraction of diffraction $\sigma_{\text{diff}}/\sigma_{\text{tot}} \sim 10\%$.
- But: no $eA/eD$, kinematical reach at small $x$, luminosity at high $x$ for searches (odderon,...), flavour decomposition, TMDs,...

---

N. Armesto - Small-x Physics at the LHeC: 1. Status and motivation.
Legacy from HERA:

- Structure functions in an extended $x-Q^2$ range, $x_g \propto 1/x^\lambda$, $\lambda>0$.
- Large fraction of diffraction $\sigma_{\text{diff}}/\sigma_{\text{tot}} \sim 10\%$.
- But: no $eA/eD$, kinematical reach at small $x$, luminosity at high $x$ / for searches (odderon,...), flavour decomposition, TMDs,...

N. Armesto - Small-x Physics at the LHeC: 1. Status and motivation.
Status of small-x physics:

- Three pQCD-based alternatives to describe small-x ep and eA data (differences at moderate $Q^2(>\Lambda^2_{QCD})$ and small x):
  - DGLAP evolution (fixed order perturbation theory).
  - Resummation schemes: BFKL, CCFM, ABF, CCSS.
  - Saturation (CGC, dipole models).

- **Non-linear effects** (unitarity constraints) are density effects: where? ⇒ two-pronged approach at the LHeC: ↓ x / ↑ A.
Relevance for the HI program:

Gluons from saturated nuclei $\rightarrow$ Glasma? $\rightarrow$ QGP $\rightarrow$ Reconfinement
Relevance for the Hi program:

- Nuclear wave function at small x: nuclear structure functions.
Relevance for the HI program:

- 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 $\sim$ isotropised so fast?: initial conditions for plasma formation to be studied in eA.

Gluons from saturated nuclei $\rightarrow$ Glasma? $\rightarrow$ QGP $\rightarrow$ Reconfinement
Relevance for the HI program:

- 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 $\sim$ 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.
Contents:

1. Status and motivation.

2. Inclusive measurements at low x.

3. Diffractive and exclusive measurements at low x.

4. Summary.

Proton PDFs at small x:

- Parton densities poorly known at small x and small to moderate $Q^2$: uncertainties in predictions.
- LHeC will substantially reduce the uncertainties in global fits: $F_L$ and heavy flavour decomposition most useful.
Proton PDFs at small $x$:

- Parton densities poorly known at small $x$ and small to moderate $Q^2$: uncertainties in predictions.
- LHeC will substantially reduce the uncertainties in global fits: $F_L$ and heavy flavour decomposition most useful.

$Q_0^2 = 2 \text{ GeV}^2$
Proton PDFs at small $x$:

- Parton densities poorly known at small $x$ and small to moderate $Q^2$: uncertainties in predictions.
- LHeC will substantially reduce the uncertainties in global fits: $F_L$ and heavy flavour decomposition most useful.

---

N. Armesto - Small-\(x\) Physics at the LHeC: 2
Proton PDFs at small x:

- Parton densities poorly known at small x and small to moderate \(Q^2\): uncertainties in predictions.
- LHeC will substantially reduce the uncertainties in global fits: \(F_L\) and heavy flavour decomposition most useful.

N. Armesto - Small-x Physics at the LHeC: 2
LHeC $F_2$ and $F_L$ data will have discriminatory power on models.

N. Armesto - Small-x Physics at the LHeC: 2
N. Armesto - Small-x Physics at the LHeC: 2

Effects beyond DGLAP?

- NLO DGLAP cannot simultaneously accommodate LHeC $F_2$ and $F_L$ data if saturation effects included according to current models $\Rightarrow$ two observables required: $(F_2,F_L)$, $(F_2,F_{2c})$, ...

- LHeC data will have discriminatory power on models.
Implications for UHEν's:

- ν-n/A cross section (τ energy loss) dominated by DIS structure functions / (n)PDFs at small-x and large (small) $Q^2$.
- Key ingredient for estimating fluxes.

\[ \langle \frac{dE}{dX} \rangle = a(E) + b(E)E \]
Photoproduction cross section:

- Small angle electron detector 62 m far from the interaction point: $Q^2 < 0.01 \text{ GeV}, y \sim 0.3 \Rightarrow W \sim 0.5 \sqrt{s}$.

- Substantial enlarging of the lever arm in $W$.

![Graph showing photoproduction cross section]
1. Status and motivation.

2. Inclusive measurements at low $x$.

3. Diffractive and exclusive measurements at low $x$.

4. Summary.

2015 LHeC Workshop http://indico.cern.ch/event/356714/;
See the talks by Paul Newman, Claire Gwenlan and Max Klein.
Diffraction:

- Large increase in the $M^2$, $x_P = (M^2-t+Q^2)/(W^2+Q^2)$, $\beta = x/x_P$ region studied.

- Possibility to combine LRG and LPS.

N. Armesto - Small-x Physics at the LHeC: 3. Diffractive and exclusive measurements at low $x$. 
Diffraction in ep and shadowing:

- Diffraction is linked to nuclear shadowing through basic QFT (Gribov): eD to test and set the ‘benchmark’ for new effects.
Diffraction is linked to nuclear shadowing through basic QFT (Gribov): eD to test and set the ‘benchmark’ for new effects.

N. Armesto - Small-x Physics at the LHeC: 3. Diffractive and exclusive measurements at low $x$. 
Diffractive dijets:

- Diffractive dijet and open heavy flavour production offer large possibilities for:
  - Checking factorization in hard diffraction.
  - Constraining DPDFs.
- Large yields up to large $p_T^{\text{jet}}$.
- Direct and resolved contributions: photon PDFs.

N. Armesto - Small-x Physics at the LHeC: 3. Diffractive and exclusive measurements at low $x$. 
Elastic VM production in ep:

- Elastic J/ψ production appears as a candidate to signal saturation effects at work.

Linear, sensitivity to \((xg)^2\).

Non-linear, saturation.

N. Armesto - Small-x Physics at the LHeC: 3. Diffractive and exclusive measurements at low x.
Elastic VM production in ep:

- UPCs at the LHC and beyond are a (less precise) alternative.

\[ \gamma^* + p \rightarrow J/\psi + p \]

\[ \gamma^* + p \rightarrow J/\psi + p \]

\[ \sigma (\text{nb}) \]

\[ W_{\gamma p} [\text{GeV}] \]

\[ W_{\gamma p} [\text{GeV}] \]

Linear, sensitivity to \((xg)^2\).

Non-linear, saturation.

N. Armesto - Small-x Physics at the LHeC: 3. Diffractive and exclusive measurements at low x.
Elastic VM production in eA:

- For the coherent case, predictions available.
- Challenging experimental problem.

\[ \gamma^*(Q^2) \rightarrow J/\Psi A \rightarrow \text{nosat} \]

Saturation effects

\[ \frac{1}{A^2} \frac{d\sigma}{dt} \text{ (\(\mu b/GeV^2\))} \]

N. Armesto - Small-x Physics at the LHeC: 3. Diffractive and exclusive measurements at low x.
Transverse scan: elastic VM

- t-differential measurements give a gluon transverse mapping of the hadron/nucleus.
Transverse scan: elastic VM

- The t-differential measurements give a gluon transverse mapping of the hadron/nucleus.

Unitarity limit: $N(x,r,b) = 1$

"b-Sat" dipole scattering amplitude with $r = 1\text{ GeV}^{-1}$

N. Armesto - Small-x Physics at the LHeC: 3. Diffractive and exclusive measurements at low $x$. 1402.4831
DVCS:

- Exclusive processes give information about GPDs, whose Fourier transform gives a transverse scan of the hadron: DVCS sensitive to the singlet.
- Sensitive to dynamics e.g. non-linear effects.

DVCS, $E_e=50$ GeV, $1^\circ$, $p_T^{\gamma,\text{cut}}=2$ GeV, $1\ fb^{-1}$

DVCS, $E_e=50$ GeV, $10^\circ$, $p_T^{\gamma,\text{cut}}=5$ GeV, $100\ fb^{-1}$

Note the huge $Q^2$!!!
Dihadron azimuthal decorrelation:

- Dihadron azimuthal decorrelation: currently discussed at RHIC as suggestive of saturation.
- At the LHeC it could be studied far from the kinematical limits.

\[ C(\phi_{12}) = \frac{1}{d\sigma(\gamma^* N \rightarrow h_1 h_2 + X)} \frac{d\sigma(\gamma^* N \rightarrow h_1 h_2 + X)}{dz_{h_1} dz_{h_2} d\phi_{12}} \]
Dijet azimuthal decorrelation:

- Studying **dijet azimuthal decorrelation** or forward jets ($p_T \sim Q$) would allow to understand the mechanism of radiation:
  - $k_T$-ordered: DGLAP.
  - $k_T$-disordered: BFKL.
  - Saturation?

- Further imposing a rapidity gap (diffractive jets) would be most interesting: perturbatively controllable observable.

\[
\frac{d^2\sigma}{dx d\Delta\phi} \left| \Delta\phi^* \right| \ (pb)
\]

\[
10^{-7} \leq x \leq 10^{-5}
\]

\[
10^{-4} < x < 10^{-3}
\]

N. Armesto - Small-x Physics at the LHeC: 3. Diffractive and exclusive measurements at low $x$. 

N. Armesto - Small-x Physics at the LHeC: 3. Diffractive and exclusive measurements at low $x$. 

```latex
\begin{align*}
\frac{d^2\sigma}{dx d\Delta\phi} \left| \Delta\phi^* \right| \ (pb)
\end{align*}
```
Forward jets:

- Studying dijet azimuthal decorrelation or forward jets ($p_T \sim Q$) would allow to understand the mechanism of radiation:
  - $k_T$-ordered: DGLAP.
  - $k_T$-disordered: BFKL.
  - Saturation?
- Further imposing a rapidity gap (diffractive jets) would be most interesting: perturbatively controllable observable.
Summary:

- **At an LHeC@CERN:**
  - High-precision tests of collinear factorization(s) and determination of PDFs.
  - Unprecedented access to small x in p and A.
  - Novel sensitivity to physics beyond standard pQCD.
  - Stringent tests of QCD radiation and hadronization.
  - Transverse scan of the hadron/nucleus at small x.
  - ... with implications on our understanding of QGP.

- **The LHeC will answer the question of saturation/non-linear dynamics. For that, ep AND eA essential!!!**

N. Armesto - Small-x Physics at the LHeC.
Future plans:

- Next: follow CERN mandate and go towards a TDR. This requires a further elaboration of the physics case:

  ➜ diffraction: studies on DPDFs and nDPDFs.

  ➜ GPDs: complementarity of exclusive VM production and DVCS, also in the nuclear case.

  ➜ complementarity with the LHC, both ep/pp and eA/pA.

  ➜ ...

N. Armesto - Small-x Physics at the LHeC.
Future plans:

- Next: follow CERN mandate and go towards a TDR. This requires a further elaboration of the physics case:

  - diffraction: studies on DPDFs and nDPDFs.

  - GPDs: complementarity of exclusive VM production and DVCS, also in the nuclear case.

  - complementarity with the LHC, both ep/pp and eA/pA.

  - ...

Everybody is welcome to contribute!!!

Thank you very much for your attention!!!
Backup:
Accelerator:

\[ \sqrt{s} \approx 0.8 - 1.2 \text{ TeV/nucleon} \]

**Design considerations:**
- \( L \sim 10^{33} \text{ cm}^{-2} \text{ s}^{-1}. \)
- Power < 70 MW.
- Synchronous pp/ep.
- \( E_e = 60 \text{ GeV} \) (benchmark).

**\( 10^{34} \text{ cm}^{-2} \text{ s}^{-1} \) Luminosity reach**

<table>
<thead>
<tr>
<th></th>
<th>PROTONS</th>
<th>ELECTRONS</th>
<th>PROTONS</th>
<th>ELECTRONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam Energy [GeV]</td>
<td>7000</td>
<td>60</td>
<td>7000</td>
<td>60</td>
</tr>
<tr>
<td>Luminosity ([10^{33} \text{ cm}^{-2} \text{ s}^{-1}])</td>
<td>16</td>
<td>16</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Normalized emittance ( \gamma \varepsilon_{x,y} \text{ [\mu m]} )</td>
<td>2.5</td>
<td>20</td>
<td>3.75</td>
<td>50</td>
</tr>
<tr>
<td>Beta Function ( \beta^*_{x,y} \text{ [m]} )</td>
<td>0.05</td>
<td>0.10</td>
<td>0.1</td>
<td>0.12</td>
</tr>
<tr>
<td>rms Beam size ( \sigma_{x,y} \text{ [\mu m]} )</td>
<td>4</td>
<td>4</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>rms Beam divergence ( \sigma^\circ_{x,y} \text{ [\mu rad]} )</td>
<td>80</td>
<td>40</td>
<td>70</td>
<td>58</td>
</tr>
<tr>
<td>Beam Current @ IP [mA]</td>
<td>1112</td>
<td>25</td>
<td>430 (860)</td>
<td>6.6</td>
</tr>
<tr>
<td>Bunch Spacing [ns]</td>
<td>25</td>
<td>25</td>
<td>25 (50)</td>
<td>25 (50)</td>
</tr>
<tr>
<td>Bunch Population ( 2.2 \times 10^{11} )</td>
<td>4 \times 10^9</td>
<td>( 1.7 \times 10^{11} )</td>
<td>( (1 \times 10^9) )</td>
<td>2 \times 10^9</td>
</tr>
<tr>
<td>Bunch charge [nC]</td>
<td>35</td>
<td>0.64</td>
<td>27</td>
<td>(0.16) 0.32</td>
</tr>
</tbody>
</table>
$\sqrt{s} \approx 0.8-1.2$ TeV/nucleon

Luminosity per nucleon

$L_{eN} = \begin{cases} 
9 \times 10^{31} \text{ cm}^{-2}\text{s}^{-1} & \text{(Nominal Pb)} \\
1.6 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1} & \text{(Ultimate Pb)} 
\end{cases}$

$eD: L_{eN} = A L_{eA} > 3 \times 10^{31}$

<table>
<thead>
<tr>
<th>$10^{34} \text{ cm}^2 \text{s}^{-1}$ Luminosity reach</th>
<th>PROTONS</th>
<th>ELECTRONS</th>
<th>PROTONS</th>
<th>ELECTRONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam Energy [GeV]</td>
<td>7000</td>
<td>60</td>
<td>7000</td>
<td>60</td>
</tr>
<tr>
<td>Luminosity [$10^{33} \text{ cm}^{-2} \text{s}^{-1}$]</td>
<td>16</td>
<td>16</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Normalized emittance $\gamma_{x,y}$ [\mu m]</td>
<td>2.5</td>
<td>20</td>
<td>3.75</td>
<td>50</td>
</tr>
<tr>
<td>Beta Function $\beta_{x,y}$ [m]</td>
<td>0.05</td>
<td>0.10</td>
<td>0.1</td>
<td>0.12</td>
</tr>
<tr>
<td>rms Beam size $\sigma_{x,y}$ [\mu m]</td>
<td>4</td>
<td>4</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>rms Beam divergence $\sigma_{x,y}$ [\mu rad]</td>
<td>80</td>
<td>40</td>
<td>70</td>
<td>58</td>
</tr>
<tr>
<td>Beam Current @ IP [mA]</td>
<td>1112</td>
<td>25</td>
<td>430 (860)</td>
<td>6.6</td>
</tr>
<tr>
<td>Bunch Spacing [ns]</td>
<td>25</td>
<td>25</td>
<td>25 (50)</td>
<td>25 (50)</td>
</tr>
<tr>
<td>Bunch Population</td>
<td>$2.2 \times 10^{11}$</td>
<td>$4 \times 10^9$</td>
<td>$1.7 \times 10^{11}$</td>
<td>$(1 \times 10^9) \times 2 \times 10^9$</td>
</tr>
<tr>
<td>Bunch charge [nC]</td>
<td>35</td>
<td>0.64</td>
<td>27</td>
<td>(0.16) 0.32</td>
</tr>
</tbody>
</table>
Accelerator:

$\sqrt{s} \approx 0.8 - 1.2$ TeV/nucleon

Luminosity per nucleon

$L_{eN} = \begin{cases} 
9 \times 10^{31} \text{ cm}^{-2}\text{s}^{-1} & \text{(Nominal Pb)} \\
1.6 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1} & \text{(Ultimate Pb)}
\end{cases}$

eD: $L_{eN} = A L_{eA} > 3 \times 10^{31}$

<table>
<thead>
<tr>
<th>$10^{34} \text{ cm}^2 \text{s}^{-1}$ Luminosity reach</th>
<th>PROTONS</th>
<th>ELECTRONS</th>
<th>PROTONS</th>
<th>ELECTRONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam Energy [GeV]</td>
<td>7000</td>
<td>60</td>
<td>7000</td>
<td>60</td>
</tr>
<tr>
<td>Luminosity [$10^{33} \text{cm}^2\text{s}^{-1}$]</td>
<td>16</td>
<td>16</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Normalized emittance $\gamma_{\varepsilon_{x,y}}$ [$\mu$m]</td>
<td>2.5</td>
<td>20</td>
<td>3.75</td>
<td>50</td>
</tr>
<tr>
<td>Beta Function $\beta^{-}_{x,y}$ [m]</td>
<td>0.05</td>
<td>0.10</td>
<td>0.1</td>
<td>0.12</td>
</tr>
<tr>
<td>rms Beam size $\sigma_{x,y}$ [$\mu$m]</td>
<td>4</td>
<td>4</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>rms Beam divergence $\sigma_{\Delta x,y}$ [$\mu$rad]</td>
<td>80</td>
<td>40</td>
<td>70</td>
<td>58</td>
</tr>
<tr>
<td>Beam Current @ IP [mA]</td>
<td>1112</td>
<td>25</td>
<td>430 (830)</td>
<td>6.6 (10.0)</td>
</tr>
<tr>
<td>Bunch Spacing [ns]</td>
<td>25</td>
<td>25</td>
<td>25 (50)</td>
<td>25 (50)</td>
</tr>
<tr>
<td>Bunch Population</td>
<td>$2.2 \times 10^{11}$</td>
<td>$4 \times 10^{9}$</td>
<td>$1.7 \times 10^{11}$</td>
<td>$(1 \times 10^{9}) 2 \times 10^{9}$</td>
</tr>
<tr>
<td>Bunch charge [nC]</td>
<td>35</td>
<td>0.64</td>
<td>27</td>
<td>(0.16) 0.32</td>
</tr>
</tbody>
</table>
\[ \sqrt{s} = 0.8 - 1.2 \text{ TeV} \]

**Luminosity**

\[ L_{eN} = \begin{cases} 9 \times 10^{31} \text{ cm}^{-2} \text{s}^{-1} \\ 1.6 \times 10^{32} \text{ cm}^{-2} \text{s}^{-1} \end{cases} \]

\[ eD = L_{eN} \times A_{eA} \]

**Accelerator:**

- With HL-LHC parameters, luminosities around \(10^{34} \text{ cm}^{-2} \text{s}^{-1}\) are within reach: 1 ab\(^{-1}\) in 10 years!!!

\[ \sqrt{s} = 0.8 - 1.2 \text{ TeV} \]

\[ L_{eN} = \begin{cases} 9 \times 10^{31} \text{ cm}^{-2} \text{s}^{-1} \\ 1.6 \times 10^{32} \text{ cm}^{-2} \text{s}^{-1} \end{cases} \]

**Lepton–Proton Scattering Facilities**

- \( L_{eN} = \text{AL} \times eA \)

**Electrons**

- \( \sqrt{s} = 0.8 - 1.2 \text{ TeV} \)
- \( L_{eN} = 9 \times 10^{31} \text{ cm}^{-2} \text{s}^{-1} \)
- \( eD = L_{eN} \times A_{eA} \)
- \( \sqrt{s} = 0.8 - 1.2 \text{ TeV} \)
- \( L_{eN} = 1.6 \times 10^{32} \text{ cm}^{-2} \text{s}^{-1} \)
- \( eD = L_{eN} \times A_{eA} \)

**Luminosity per nucleon**

\[ N. \text{ Armesto - Small-x Physics at the LHeC.} \]

\[ L_{eN} = \begin{cases} 9 \times 10^{31} \text{ cm}^{-2} \text{s}^{-1} \\ 1.6 \times 10^{32} \text{ cm}^{-2} \text{s}^{-1} \end{cases} \]

\[ eD = L_{eN} \times A_{eA} \]

**With HL-LHC parameters, luminosities around \(10^{34} \text{ cm}^{-2} \text{s}^{-1}\) are within reach: 1 ab\(^{-1}\) in 10 years!!!**

\[ N. \text{ Armesto - Small-x Physics at the LHeC.} \]
Detector:
Detector:

- Other detector options: low acceptance (8°-172°), solenoid outside, also considered.
- Plus luminosity detector, electron tagging, polarimeter, ZDC and leading proton detector.
Kinematics:

- Small-x demands 1 degree acceptance.
- Higher luminosity would benefit high-x and $Q^2$ studies.

N. Armesto - Small-x Physics at the LHeC.
Kinematics:

- Small-x demands 1 degree acceptance.
- Higher luminosity would benefit high-x and $Q^2$ studies.

N. Armesto - Small-x Physics at the LHeC.
QCD radiation of partons when $x$ decreases leads to a large number of partons (gluons), provided each parton evolves independently (linearly, $\Delta[xg] \propto xg$).

This independent evolution breaks at high densities (small $x$ or high mass number $A$): non-linear effects ($gg \to g, \Delta[xg] \propto xg - k(xg)^2$).
Small $x$ and saturation:

• **QCD** radiation of partons when $x$ decreases leads to a large number of partons (gluons), provided each parton evolves independently (linearly, $\Delta[xg] \propto xg$).

• This independent evolution breaks at high densities (small $x$ or high mass number $A$): non-linear effects ($gg \rightarrow g, \Delta[xg] \propto xg - k(xg)^2$).
Our aims: understanding

- The implications of unitarity in a QFT.
- The behaviour of QCD at large energies.
- The hadron wave function at small $x$.
- The initial conditions for the creation of a dense medium in heavy-ion collisions.

Origin in the early 80’s: GLR, Mueller et al, McLerran-Venugopalan.
The ‘QCD phase’ diagram:

- Understanding the implications of unitarity in QFT.
- The behavior of QCD at large energies.
- The hadron wave function at small $x$.
- The initial conditions for the creation of a dense medium in heavy-ion collisions.

Origin in the early 80's: GLR, Mueller et al, McLerran-Venugopalan.
The 'QCD phase' diagram:

Questions:

- **Theory**: can the dense regime be described using pQCD techniques? Or non-perturbative - Regge, AdS/QCD,...? Which factorisation is at work?
- **Experiment**: where do present/future experimental data lie?
### LHeC scenarios:

| config. | E(e) | E(N) | N | |L(e^+)| |L(e^-)| |Pol| | L/10^{32} P/MW years | type |
|---------|------|------|---|----------|----------|----------|----------|----|-------------------|------|
| A       | 20   | 7    | p | 1        | 1        | -        | 1        | 10 | 1                | SPL  |
| B       | 50   | 7    | p | 50       | 50       | 0.4      | 25       | 30 | 2                | RR hiQ^2 |
| C (circled) | 50 | 7    | p | 1        | 1        | 0.4      | 1        | 30 | 1                | RR lo x |
| D       | 100  | 7    | p | 5        | 10       | 0.9      | 2.5      | 40 | 2                | LR   |
| E       | 150  | 7    | p | 3        | 6        | 0.9      | 1.8      | 40 | 2                | LR   |
| F       | 50   | 3.5  | D | 1        | 1        | --       | 0.5      | 30 | 1                | eD   |
| G (circled) | 50 | 2.7  | Pb | 10^{-4} | 10^{-4} | 0.4      | 10^{-3}  | 30 | 1                | ePb  |
| H       | 50   | 1    | p | --       | 1        | --       | 25       | 30 | 1                | lowEp |
| I (circled) | 50 | 3.5  | Ca | 5 \cdot 10^{-4} | ? | 5 \cdot 10^{-3} | ? | ? | eCa |

- **For F_2**: $10, 25, 50 + 2750 (7000)$; $Q^2 \leq s_x$; Lumi=$5, 10, 100$ pb$^{-1}$ respectively; charm and beauty: same efficiencies in ep and eA.

*N. Armesto - Small-x Physics at the LHeC: 2.*
Note: $F_L$ in eA

$$\sigma_r^{NC} = \frac{Q^4 x d^2 \sigma^{NC}}{2 \pi \alpha^2 Y_+ d x d Q^2} = F_2 \left[ 1 - \frac{y^2 F_L}{Y_+ F_2} \right], \quad Y_+ = 1 + (1 - y)^2$$

- $F_L$ traces the nuclear effects on the glue (Cazarotto et al ’08).
- Uncertainties in the extraction of $F_2$ due to the unknown nuclear effects on $F_L$ of order 5% (larger than expected stat.+syst.) ⇒ measure $F_L$ or use the reduced cross section (but then ratios at two energies...).

NA, Paukkunen, Salgado, Tywoniuk, ’10

N. Armesto - Small-x Physics at the LHeC: 2.
Dipole models show differences with linear-based extrapolations (HERA-based dpdf’s) and among each other: possibility to check saturation and its realization.
Diffractive DIS on nuclear targets:

- Challenging experimental problem, requires Monte Carlo simulation with detailed understanding of the nuclear break-up.

- For the coherent case, predictions available.
Odderon:
- **Odderon** (C-odd exchange contributing to particle-antiparticle difference in cross section) searched in $\gamma^{(*)} p \rightarrow Cp$, where $C = \pi^0, \eta, \eta', \eta_c \ldots$ or through O-P interferences.

- Sizable charge asymmetry, yields and reconstruction pending.

\[ A(Q^2, t, m_{2\pi}^2) = \frac{\int \cos \theta \ d\sigma(W^2, Q^2, t, m_{2\pi}^2, \theta)}{\int d\sigma(W^2, Q^2, t, m_{2\pi}^2, \theta)} = \frac{\int_{-1}^{1} \cos \theta \ d\theta}{\int_{-1}^{1} d\theta} \frac{\text{Re} \left[ M_P^\ast (M_O^\ast) \right]}{\left[ |M_P^\ast|^2 + |M_O^\ast|^2 \right]} \]

\[ Q^2 = 3 \text{ GeV}^2 \]
\[ t = -0.8 \text{ GeV}^2 \]
\[ \alpha_{\text{soft}} = 0.3 \ldots 0.7 \]
\[ \Lambda_{\text{QCD}} = 0.2 \ldots 0.35 \text{ GeV} \]
\[ \Gamma_b = 0.05 \text{ GeV} \]
Transversity GPDs:

- Chiral-odd transversity GPDs are largely unknown.

- They can be accessed through double exclusive production:

\[ ep(p_2) \rightarrow e' \gamma_{L/T}^{(*)}(q) \ p(p_2) \rightarrow e' \rho_{L/T}(q) \ \rho_T(p_\rho) \ N'(p_2') \]
Radiation and hadronization:

- **LHeC:** dynamics of QCD radiation and hadronization.
- Most relevant for particle production off nuclei and for QGP analysis in HIC.
- **Low energy:** hadronization inside $\rightarrow$ formation time, (pre-)hadronic absorption,...

- **High energy:** partonic evolution altered in the nuclear medium.

\[ R_A^h(z, \nu) = \frac{1}{N_A^e} \frac{dN_A^h(z, \nu)}{d\nu \, dz} \bigg/ \frac{1}{N_D^e} \frac{dN_D^h(z, \nu)}{d\nu \, dz} \]

- $z=p_{\text{hadr}}/p_{\text{parton}}$
- $\nu=E_{\text{hadron rest frame}}$
- $q_{\text{struck parton}}$

N. Armesto - Small-x Physics at the LHeC: 3. Diffractive and exclusive measurements at low $x$. 
Radiation and hadronization:

- **LHeC**: dynamics of QCD radiation and hadronization.
- Most relevant for particle production off nuclei and for QGP analysis in HIC.
- **Low energy**: hadronization inside $\rightarrow$ formation time, (pre-)hadronic absorption,...

- **High energy**: partonic evolution altered in the nuclear medium.

$$R_A^h(z, \nu) = \frac{1}{N_A^e} \frac{dN_A^h(z, \nu)}{d\nu \, dz} \bigg/ \frac{1}{N_D^e} \frac{dN_D^h(z, \nu)}{d\nu \, dz}$$
Radiation and hadronization:

- Large (NLO) yields at small-$x$ (H1 cuts, 3 times higher if relaxed).
- Nuclear effects in hadronization at small $\nu$ (LO plus QW, Arleo '03).

\[ R_A^h(z, \nu) = \frac{1}{N_A^e} \frac{dN_A^h(z, \nu)}{d\nu dz} / \frac{1}{N_D^e} \frac{dN_D^h(z, \nu)}{d\nu dz} \]

Data from HERMES, Nucl. Phys. B 780 (2007) 1

N. Armesto - Small-$x$ Physics at the LHeC: 3. Diffractive and exclusive measurements at low $x$. 
Radiation and hadronization:

- Large (NLO) yields at small-\(x\) (H1 cuts, 3 times higher if relaxed).
- Nuclear effects in hadronization at small \(\nu\) (LO plus QW, Arleo ’03).

\[
\begin{align*}
\frac{d\sigma}{dx} &\leq 8 \text{ GeV}^2 \\
\frac{d\sigma}{dx} &\leq 20 \text{ GeV}^2 \\
\frac{d\sigma}{dx} &\leq 70 \text{ GeV}^2 \\
p_T &\geq 3.5 \text{ GeV} 
\end{align*}
\]
Radiation and hadronization:

- Large (NLO) yields at small-\(x\) (H1 cuts, 3 times higher if relaxed).
- Nuclear effects in hadronization at small \(\nu\) (LO plus QW, Arleo ’03).

N. Armesto - Small-\(x\) Physics at the LHeC: 3. Diffractive and exclusive measurements at low \(x\).
Jets:

- Jets: large $E_T$ even in eA.
- Useful for studies of parton dynamics in nuclei (hard probes), and for photon structure.
- Background subtraction, detailed reconstruction pending.

N. Armesto - Small-x Physics at the LHeC: 3. Diffractive and exclusive measurements at low $x$. 

\[
\frac{d\sigma}{dQ^2} [\text{pb/GeV}^2]
\]

\[
E_{\text{T,jet}} [\text{GeV}]
\]

\[
\frac{d\sigma}{dE_{\text{T,Breit}}} [\text{pb/GeV}]
\]
Future plans:

• Next: follow CERN mandate and go towards a TDR. This requires a further elaboration of the physics case:

  ➜ diffraction: studies on DPDFs and nDPDFs.

  ➜ GPDs: complementarity of exclusive VM production and DVCS, also in the nuclear case.

  ➜ complementarity with the LHC, both ep/pp and eA/pA.

  ➜ ...

Any collaboration is more than welcome!!!
Future plans:

- Next: follow CERN mandate and go towards a TDR. This requires a further elaboration of the physics case:
  - diffraction: studies on DPDFs and nDPDFs.
  - GPDs: complementarity of exclusive VM production and DVCS, also in the nuclear case.
  - complementarity with the LHC, both ep/pp and eA/pA.
  - ...

Any collaboration is more than welcome!!!
Future plans:

- New TDR: follow CERN mandate and go towards a TDR. This requires a further elaboration of the physics case:
  - diffraction: studies on DPDFs and nDPDFs.
  - GPDs: complementarity of exclusive VM production and DVCS, also in the nuclear case.
  - complementarity with the LHC, both ep/pp and eA/pA.
- Any collaboration is more than welcome!!!

Thanks for your attention!
Commitees and authors:

Scientific Advisory Committee
Guido Altarelli (Roma)
Sergio Bertolucci (CERN)
Stan Brodsky (SLAC)
Allen Caldwell (MPI Munich) - Chair
Swapan Chattopadhyay (Cockcroft Institute)
John Dainton (Liverpool)
John Ellis (CERN)
Jos Engelen (NWO)
Joel Feltesse (Saclay)
Roland Garoby (CERN)
Rolf Hauer (CERN)
Roland Horisberger (PSI)
Young-Kee Kim (Fermilab)
Aharon Levy (Tel Aviv)
Lev Lipatov (St. Petersburg)
Karlheinz Meier (Heidelberg)
Richard Milner (MIT)
Joachim Minich (DESY)
Steve Myers (CERN)
Guenther Roener (Glasgow)
Alexander N. Skrinsky (INP Novosibirsk)
Anthony Thomas (JLab)
Steve Vigdor (Brookhaven)
Ferdinand Willeke (Brookhaven)
Frank Wilczek (MIT)

Working Group Convenors

Accelerator Design
Oliver Bruening (CERN)
John Dainton (Liverpool)

Interaction Region and Fwd/Bwd
Bernhard Holzer (CERN)
Uwe Schneekloth (DESY)
Pierre van Mechelen (Antwerpen)

Detector Design
Peter Kostka (DESY)
Alessandro Polini (Bologna)
Rainer Wallny (Zurich)

New Physics at Large Scales
Georges Azuelos (Montreal)
Emmanuel Perez (CERN)
Georg Weiglein (Hamburg)

Precision QCD and Electroweak
Olaf Behnke (DESY)
Paolo Gambino (Torino)
Thomas Gehrmann (Zurich)
Claire Gwenlan (Oxford)

Physics at High Parton Densities
Néstor Armesto (Santiago de Compostela)
Brian A. Cole (Columbia)
Paul R. Newman (Birmingham)
Anna M. Stasto (PennState)

Referees of the Draft Report

Ring Ring Design
Kurt Hueber (CERN)
Alexander N. Skrinsky (INP Novosibirsk)
Ferdinand Willeke (BNL)

Linac Ring Design
Reinhard Brinkmann (DESY)
Andy Wolski (Cockcroft)
Kaoru Yokoya (KEK)

Energy Recovery
Georg Hoffstaetter (Cornell)
Ilan Ben Zvi (BNL)

Magnets
Neil Marks (Cockcroft)
Martin Wilson (CERN)

Interaction Region
Daniel Pitzl (DESY)
Mike Sullivan (SLAC)

Detector Design
Philippe Bloch (CERN)
Roland Horisberger (PSI)

Installation and Infrastructure
Sylvain Weisz (CERN)

New Physics at Large Scales
Cristinel Diaconu (IN2P3 Marseille)
Gian Giudice (CERN)
Michelangelo Mangano (CERN)

Precision QCD and Electroweak
Guido Altarelli (Roma)
Vladimir Chekelian (MPI Munich)
Alan Martin (Durham)

Physics at High Parton Densities
Alfred Mueller (Columbia)
Raju Venugopalan (BNL)
Michele Arneodo (INFN Torino)
Commitees and authors:

Commitees and authors:

The LHeC Study Group
http://cern.ch/lhec

2007: Invitation by SPC to ECFA and by (r)ECFA to work out a design concept

2008: First CERN-ECFA Workshop in Divonne (1.-3.9.08)

2009: 2\textsuperscript{nd} CERN-ECFA-NuPECC Workshop at Divonne (1.-3.9.09)

2010: Report to CERN SPC (June)
   3\textsuperscript{rd} CERN-ECFA-NuPECC Workshop at Chavannes-de-Bogis (12.-13.11.10)
   NuPECC puts LHeC to its Longe Range Plan for Nuclear Physics (12/10)

2011: Draft CDR (530 pages on Physics, Detector and Accelerator) (5.8.11)
   being refereed and updated

2012: Publication of CDR – European Strategy
   New workshop June 14-15 2012

Goal: TDR by 2015
Perspective: Operation after LS3 (synchronous with pp/pA/AA)
Tentative timeline:

New rough draft 10 year plan

Not yet approved!

July 26, 2011

S. Myers, HEP2011, Grenoble
Tentative timeline:

→ LHC death by radiation damage estimated by 2030-2035.

→ LHeC should work for ~10 years.

→ No disturbance to LHC operation: built on surface, installation during LSN, N>3.
Tentative timeline:

New rough draft 10 year plan

Not yet approved!