Low x Physics at the LHeC: DIS with $E_e=70\text{GeV}$ and $E_p=7\text{TeV}$

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  - eA
  - A long list of things I missed!
The Birth of Experimental Low x Physics

- Biggest HERA discovery: strong increase of quark density ($F_2$) and gluon density ($dF_2/d\ln Q^2$) with decreasing $x$ in newly explored regime.

Low $x$, `large' $Q^2$ is high density, low coupling limit of QCD ...
**Current Status of Low x Physics**

RHIC, Tevatron and HERA have taught us a lot, ... but many questions are not fully answered...

- Are non-DGLAP parton evolution dynamics visible in the initial state parton cascade?
- How and where is the parton growth with decreasing $x$ tamed (unitarity) ... barely separated from confinement region?
- Large (~ constant?) fraction of diffraction?

Problem is that low $x$ kinematically correlated to low $Q^2$, which brings problems with partonic interpretation.
• Description of interesting low $x$ region, where $Q^2$ small and partons not appropriate degrees of freedom ...

\[ \sigma_{T,L}^{T,(L)}(x,Q^2) \sim \int dz \, d^2r \, |\psi_{\gamma^*}^{T,(L)}(z,r,Q^2)|^2 \sigma_{\text{dipole}}(x,r,z) \]

• Simple unified picture of many inclusive and exclusive processes ... strong interaction physics in (universal) dipole cross section $\sigma_{\text{dipole}}$. Process dependence in wavefunction $\Psi$ Factors

• $qq\bar{q}-g$ dipoles also needed to describe inclusive diffraction
An Example Dipole Approach to HERA Data

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

Fit inclusive HERA data with dipole models containing varying assumptions for $\sigma_{\text{dipole}}$.

- 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 $Q^2 > 1 GeV^2$, $x < 0.01$
- Only versions with saturation work for $0.045 < Q^2 < 1 GeV^2$
- Similar conclusions from final state studies
E_e = 70 GeV  
E_p = 7 TeV  
\sqrt{s} = 1.4 TeV  
(5 \times \text{HERA})

• Extension to higher Q^2 in x range covered by HERA

• Extension of low x (high W) frontier

W \leq 1.4 \text{ TeV}  
x \geq 5.10^{-7} \text{ at } Q^2 \leq 1 \text{ GeV}^2

• Unprecedented lumi = 10^{33} \text{ cm}^{-2} \text{ s}^{-1} !!!
• eA mode possible using LHC ion beam
The LHeC for Low $x$ Investigations

2 modes considered:

1) Focusing magnet To optimise lumi ... detector acceptance to $170^\circ$ ... little acceptance below $Q^2=100 \text{ GeV}^2$

2) No focusing ... acceptance to $179^\circ \rightarrow$ access to $Q^2=1$ for all $x$ $(x > 5 \times 10^{-7} !)$

Lumi $\sim 1 \text{ fb}^{-1} / \text{yr}$
Hadronic Final State Detector Considerations

- Considerably more asymmetric beam energies than HERA!
  - Hadronic final state at newly accessed lowest $x$ values goes central or backward in the detector 😊
  - At $x$ values typical of HERA (but large $Q^2$), hadronic final state is boosted more in the forward direction.

- Full Study of low $x$ / $Q^2$ and of range overlapping with HERA, with sensitivity to energy flow in outgoing proton direction requires forward acceptance for hadrons to $1^\circ$
Example $F_2$ with LHeC Data

$F_2(x, Q^2=10 \text{ GeV}^2)$

- Precise data in LHeC region ($1^\circ$ acceptance)
- Cleanly establish saturation at $Q^2$ values where partonic language applicable
- Distinguish between models of saturation

Statistical precision < 0.1%, systematics 1-3%

(Jeff Forshaw)
Example 2: Interpreting Geometric Scaling

$$\sigma_{\gamma^*p}(\tau \text{ only}), \tau = Q^2 R_0^2(x)$$

$R_0^2(x)$ is “saturation radius”

Change of behaviour near $\tau=1$ often cited as evidence for saturation

... but data below $\tau = 1$ are very low $Q^2$ - various theoretical difficulties and confinement / change to hadronic dof’s

Need to see transition in a $Q^2$ region where partonic interpretation unquestionable
Geometric Scaling at the LHeC

LHeC reaches \( \tau \approx 0.15 \) for \( Q^2 = 1 \text{ GeV}^2 \) and \( \tau \approx 0.4 \) for \( Q^2 = 2 \text{ GeV}^2 \)

Some (though limited) acceptance for \( Q^2 < Q^2_s \) with \( Q^2 \) "perturbative"

Could be enhanced with nuclei.

\( Q^2 < 1 \text{ GeV}^2 \) accessible in special runs?
Linked Dipole Chain Model (~ CCFM):
Interacting dipole chains in onium-onium scattering
- Linearly (“1 pomeron”)
- Non-linearly (~ saturation) via multiple interactions & “swing” mechanism → recoupling within chains.
Effects important in saturation curve, but so is (non-scaling) finite quark mass.
Predict breaking of scaling for $\tau < 1$ if data with $Q^2 > 1$ become available (e.g. from LHeC)

Another Model: Avsar, Gustafson, Lonnblad

hep-ph/0610157,0702087
LHeC Comparison with Predictions

- '1 pom only' already disfavoured at HERA
- Subtle effects such as swing mechanism can be established cleanly at high W (low x) at LHeC
DVCS Measurement

... can be tackled as at HERA through inclusive selection of $ep \rightarrow ep\gamma$ and statistical subtraction of Bethe-Heitler background.

(Laurent Favart)
Example of DVCS at LHeC

DVCS (10 fb$^{-1}$, stat errors only)

- $Q^2 = 30$ GeV$^2$
- $b = 7$ GeV$^2$

Statistical precision 1-4%

Clearly distinguishes different models which contain saturation.

Interpretation in terms of GPDs much cleaner at larger $Q^2$ values accessed

VMs similar story

(1$^o$ acceptance)
Diffractive DIS at HERA

`Discovery' at HERA (~10% of low x events are of type ep -> eXp)

• Parton-level mechanism, relations to diffractive pp scattering, inclusive DIS, confinement still not settled.

• QCD Factorisation: Diffractive parton densities (DPDFs) universal to diffractive DIS (apply to both HERA and LHeC)

... can also be used to predict pp with additional `gap survival' factors
LHeC Diffractive Kinematics

- Tests of factorisation and evolution dynamics: DPDFs extracted at HERA predict LHeC cross section at moderate / large β, higher Q^2 using DGLAP.

- New dynamics: LHeC opens new low β region - parton saturation, BFKL etc showing up first in diffraction?

- Large Diff. Masses: Z, W, b production, studies of new 1^- states
LHeC Simulation

Statistical precision not an issue

Big extension to lower $x_{IP}$ ... cleaner separation of the diffractive exchange

Higher $Q^2$ at fixed $\beta$ & $x_{IP} \rightarrow CC$ (and $z$ in NC) allows flavour decompositions of DPDFs

Lower $\beta$ at fixed $Q^2$ & $x_{IP}$
Example $F_2^D$ with LHeC

\[ F_2^D(x_P, \beta, Q^2) \]

(10 fb^{-1})

- Diffractive structure function poorly known for $\beta \sim 0.01$ ... large extrapolation uncertainties.

- Plenty to learn from LHeC, including the proper way to saturate a qqbar-$g$ dipole

Jeff Forshaw

Large Rapidity Gap method assumed.
Statistical precision $\sim0.1\%$, systematics $\sim5\%$
Final States in Diffraction

- Factorisation tests done at HERA with gluon initiated jet / charm processes... BUT ...
- Kinematically restricted to high $\beta$ region where $F_2^D$ is least sensitive to the gluon!
- Kinematically restricted to low $p_T < M_x/2$ where scale uncertainties are large.
- $\gamma p$ surprises $\rightarrow$ understanding gap survival?... Diff H @ LHC?

Charm in DIS

Jets in DIS

Jets in $\gamma p$

H1 preliminary data (corr. err.)
H1 2006 DPDF fit B (scale err.)
H1 Data
H1 2006 Fit B DPDF
correlated uncertainty
NLOX($1 + \delta_{\text{had}}$)
NLO
H1 Data
H1 D$^-$ Data
ZEUS D$^-$
H1 2006 DPDF fit A
H1 2006 DPDF fit B

$Q^2 = 35$ GeV$^2$

$X_{IP} = 0.004$
Final States in Diffraction at the LHeC

• At LHeC, diffractive masses $M_x$ up to hundreds of GeV can be produced with low $x_{IP}$

• Low $\beta$, low $x_{IP}$ region for jets and charm accessible

• Final state jets etc at higher $p_t$ ... much more precise factorisation tests and DPDF studies (scale uncty)

• New diffractive channels ... beauty, $W / Z$ bosons

• Unfold quantum numbers / precisely measure exclusively produced new / exotic 1- states
Diffractive Detector Considerations

- Accessing $x_{IP} = 0.01$ with rapidity gap method requires $\eta_{\text{max}}$ cut around 5 ...forward instrumentation essential!

- Roman pots, FNC should clearly be an integral part

- Not new at LHC: Roman pots already integrated into CDF, Atlas via Totem, FP420, FP220)

\[ \eta_{\text{max}} \text{ and LRG selection ...} \]
Long HERA program to understand parton cascade emissions by direct observation of jet pattern in the forward direction. ... DGLAP v BFKL v CCFM v resolved γ* ...

Conclusions limited by kinematic restriction to high $x (\approx 2.10^{-3})$ and detector acceptance.

At LHeC ... more emissions due to longer ladder & more instrumentation → measure at lower $x$ where predictions really diverge.
Beauty as a Low $x$ Observable!!!

$F_2^b(x,Q^2=30 \text{ GeV}^2)$

(10° acceptance)

$F_2^c$ and $F_2^s$ also measurable (see Max Klein's talk).

Statistical errors $\sim 1\%$, systematics $\sim 5\%$
With AA at LHC, LHeC is also an eA Collider

- Rich physics of nuclear parton densities.

- Limited x and $Q^2$ range so far (unknown For $x \sim 10^{-2}$ and $Q^2 > 1 \text{ GeV}^2$)

- LHeC extends by orders of magnitude towards lower x.

- With wide range of $x$, $Q^2$, $A$, opportunity to extract and understand nuclear parton densities in detail

- Symbiosis with ALICE, RHIC, EIC … disentangling Quark Gluon Plasma from shadowing or parton saturation effects
Simple Model of Gluon Saturation

- Saturation point when $xg(x) \sim \frac{Q^2}{\alpha_s(Q^2)}$
- Nuclear enhancement of gluon density $a A^{1/3}$
- Compare extrapolated (NLO) gluon density from HERA

Saturation point reached in ep at LHeC for $Q^2 \lesssim 5 \text{ GeV}^2$
Reached in eA for much higher $Q^2$
Uncovered Topics

This talk contained an (embarrassingly) limited number of studies, which only scratches the surface of the low $x$ physics potential of the LHeC.

Some obvious omissions:
- Lots of $eA$ physics!
- All sorts of low $x$ jet measurements
- All sorts of low $x$ charm measurements
- $F_L$
- Prompt photons
- Photoproduction and photon structure
- Leading neutrons and other semi-inclusives
- Exclusive vector meson production

... studies of these and many other topics are very welcome, to evaluate the physics case for such a facility!
Summary

To further pursue low x physics with unpolarised targets, the natural next step is an extension to lower x (i.e. higher energy)

For its relative theoretical cleanliness, ep should be a large feature of this.

For its enhanced sensitivity to high parton densities, eA should also be a large part of the programme.

All of this is possible in the framework of the LHC - a totally new world of energy and luminosity!... Why not exploit it for lepton-hadron scattering?

First conceptual design exists ... no show-stopper so far ... some encouraging first physics studies shown here.

Much more to be done to fully evaluate physics potential and determine optimum running scenarios!