• A Lepton-hadron collider for the 2020s / 2030s, based on the high lumi LHC
• Adding ep and eA collisions to the LHC pp, AA, pA programme
- Lepton-hadron scattering at the TeV centre of mass scale (60 GeV electrons x LHC protons & ions)

- High luminosity: $10^{33} - 10^{34}$ cm$^{-2}$ s$^{-1}$

- Runs simultaneous with ATLAS / CMS in post-LS3 HL-LHC period
Baseline Design (Electron “Linac”)

Design constraint: power consumption < 100 MW \( \rightarrow E_e = 60 \text{ GeV} \)

- Two 10 GeV linacs,
- 3 returns, 20 MV/m
- Energy recovery in same structures
  [CERN plans energy recovery prototype]

- ep Lumi \( 10^{33} - 10^{34} \text{ cm}^{-2} \text{ s}^{-1} \)
  \( \rightarrow 10 - 100 \text{ fb}^{-1} \text{ per year} \)
  \( \rightarrow 100 \text{ fb}^{-1} - 1 \text{ ab}^{-1} \text{ total} \)
- eD and eA collisions have always been integral to programme
- e-nucleon Lumi estimates \( \sim 10^{31} \ (10^{32}) \text{ cm}^{-2} \text{ s}^{-1} \) for eD (ePb)

# Alternative designs based on electron ring and on higher energy, lower luminosity, linac also exist
Physics Overview

Wide ranging and varied physics goals require precision throughout accessible region.

Newly accessed low x region is special.

High density, small coupling partonic regime of non-linear evolution dynamics, dominated by gluons → confinement and hadronic mass generation.
LHeC: Accessing saturation region at large $Q^2$

LHeC delivers a 2-pronged approach:

Enhance target `blackness' by:
1) Probing lower $x$ at fixed $Q^2$ in ep
   [evolution of a single source]
2) Increasing target matter in eA
   [overlapping many sources at fixed kinematics …
Density ~ $A^{1/3}$ ~ 6 for Pb … worth 2 orders of magnitude in $x$]

... Reaches saturated region in both ep & eA inclusive data according to models
Access to $Q^2 = 1$ GeV$^2$ in $ep$ mode for all $x > 5 \times 10^{-7}$ requires scattered electron acceptance to $179^\circ$.

Small angle forward acceptance similarly important for hadronic final state studies - e.g. forward (Mueller-Navalet) jets.
• Forward / backward asymmetry reflecting beam energies
• $1^\circ$ electron hits two tracker planes
• Present size 14m x 9m (c.f. CMS 21m x 15m, ATLAS 45m x 25m)
Low $x$ PDF Constraints

Full simulation of inclusive NC and CC DIS data, including systematics $\rightarrow$ NLO DGLAP fit using HERA technology...

Current gluon knowledge at $x<10^{-4}$ very limited, even with LHC

LHeC offers strong constraints to $x=10^{-6}$, including full flavour decomposition
- $\eta_{\text{max}}$ cut around 3 selects events with $x_{\text{IP}} < \sim 10^{-3}$

- `FP420’-style proton spectrometer approaching beam to $12\sigma$ ($\sim 250$ $\mu$m), gives complementary acceptance around $x_{\text{IP}} \sim 10^{-2}$

- Leading neutron (ZDC) calorimeter foreseen around 100m from IP
1) [Low-Nussinov] interpretation as 2 gluon exchange enhances sensitivity to low x gluon

2) Additional variable t gives access to impact parameter (b) dependent amplitudes

→ Large t (small b) probes densest packed part of proton?
Test Case: Elastic $J/\Psi$ Photoproduction

- `Cleanly’ interpreted as hard 2g exchange coupling to qqbar dipole (see HERA/LHC UPC data via MNRT etc)

- c and c-bar share energy equally, simplifying VM wavefunction

- Clean experimental signature (just 2 leptons)

... LHeC reach extends to: $x_g \sim (Q^2 + M_V^2) / (Q^2 + W^2) \sim 5 \times 10^{-6}$

$$Q^2 = (Q^2 + M_V^2) / 4 \sim 3 \text{ GeV}^2$$

- Simulations (DIFFVM) of elastic $J/\Psi \rightarrow \mu\mu$ photoproduction → scattered electron untagged, 1° acceptance for muons (similar method to H1 and ZEUS)
• At fixed $\sqrt{s}$, decay muon direction is determined by $W = \sqrt{s_{\gamma p}}$

• To access highest $W$, acceptance in outgoing electron beam direction crucial
Comparison with Dipole model Predictions

e.g. “b-Sat” Dipole model
- “eikonalised”: with impact-parameter dependent saturation
- “1 Pomeron”: non-saturating

• Significant non-linear effects expected in LHeC kinematic range.

With detailed exploration of ep and eA, including t dependences, this becomes a powerful probe!...
t Dependence of Elastic J/ψ Photoproduction

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

- J/ψ photoproduction double differentially in W and t ...
- Precise t measurement from decay μ tracks over wide W range extends to |t| \( \sim 2 \text{ GeV}^2 \) and enhances sensitivity to saturation effects
- Measurements also possible in multiple Q² bins
Exclusive Diffraction in eA

Experimentally clear signatures and theoretically cleanly calculable saturation effects in coherent diffraction case (eA → eVA)

Experimental separation of incoherent diffraction based mainly on ZDC
Deeply Virtual Compton Scattering

- No vector meson wavefunction

Complications

- Cross sections suppressed by photon coupling
  - limited precision at HERA
  - would benefit most from high luminosity of LHeC

Simulations based on FFS model in MILOU generator

- Double differential distributions in \((x, Q^2)\) with
  - 1° and 10° cuts for scattered electron

- Kinematic range determined largely by cut on \(p_T^{\gamma}\)
  (relies on ECAL performance / linearity at low energies)
DVCS with low luminosity & high acceptance

1 fb$^{-1}$, $E_e = 50$ GeV, 1$^\circ$ acceptance, $p_T^\gamma > 2$ GeV

• Precise double differential data in low $Q^2$ region
• Statistical precision deteriorates for $Q^2 \sim 25$ GeV$^2$
• W acceptance to $\sim 1$ TeV (five times HERA)
DVCS with high luminosity and low acceptance

100 fb$^{-1}$, $E_e = 50$ GeV, $10^\circ$ acceptance, $p_T^\gamma > 5$ GeV

• High lumi gives precision data to $Q^2$ of several hundred GeV$^2$
  → Completely unprecedented region for DVCS / GPDs
For DPDFs ...

- Low $x_{IP}$ → cleanly separate diffraction
- Low $\beta$ → Novel low $x$ DPDF effects / non-linear dynamics?
- High $Q^2$ → Lever-arm for gluon, Flavour separation via EW
New Region of Large Diffractive Masses

Large $x_{\text{IP}}$ region highly correlated with large $M_X$

- 'Proper' QCD (e.g. large $E_T$) with jets and charm accessible
- New diffractive channels ... beauty, $W / Z$ bosons
- Unfold quantum numbers / precisely measure new 1$^-$ states
Nuclear shadowing can be described (Gribov-Glauber) as multiple interactions, starting from ep DPDFs.

... starting point for extending precision LHeC studies into eA collisions.
First studies with current electron design, \((E_e = 60\ \text{GeV})\) enhanced with crab cavities, and \(E_p = 50\ \text{TeV}\). Detector, scaled by up to \(\ln(50/7) \sim 2\)

\[\sqrt{s_{ep}} = 3.5\ \text{TeV},\ Lumi = \text{few}.10^{34}\ \text{cm}^{-2}\text{s}^{-1}\]
Sensitive to gluon density down to $x \sim 10^{-7}$ for $Q^2 > 1 \text{ GeV}^2$

e.g. exclusive $J/\Psi$ photoproduction to $W \sim 3 \text{ TeV}$

→ No detailed studies done so far
Status and Plans

• CDR 2012 (630 pages, summarising 5 year workshop. 200 authors from 69 institutes)

• Renewed interest following
  1) Possibility of $10^{34}$ cm$^{-2}$ s$^{-1}$ luminosity
  2) Higgs discovery $\rightarrow$ closer look at what limits HL-LHC sensitivity and precision,
  3) Associated technical developments (High gradient cavities, Energy recovery linacs)

• New International Advisory Committee and Coordination Group set up by CERN, with mandate to further develop LHeC, also in context of FCC.

• Low x / eA group (N Armesto, P Newman, A Stasto)
  $\rightarrow$ Please contact us ...
Summary

• Low x physics is Strong Interaction energy frontier: discovery!
  - Dense partonic systems → correlations / interactions
  - Onset of non-linear dynamics → Gribov black-disk limit → Confinement, Hadronic mass generation ...

• Diffraction plays a pivotal role:
  - Enhances / complements inclusive data in saturation search
  - Parton correlations, impact parameter dependence

• Lots still to be studied to fully make case for LHeC and FCC-he
  - Better modelling of simulated LHeC measurements
  - Propagation to underlying physics (GPDs, DPDFs)
  - Poorly covered LHeC topics, FCC studies barely began

• More, at LHeC web http://lhec.web.cern.ch and ...
  - Klein & Schopper, CERN Courier, June 2014
  - Bruening & Klein, Mod Phys Lett A28 (2013) 1130011
Back-ups
Diffractive DIS, Dipole Models & Saturation

Inclusive Cross Section

$$\sigma_{T,L}(x, Q^2) = \int d^2r \int_0^1 d\alpha |\Psi_{T,L}(\alpha, r)|^2 \hat{\sigma}(x, r^2)$$

Diffractive DIS

$$\left. \frac{d\sigma^{D}_{T,L}}{dt} \right|_{t=0} = \frac{1}{16\pi} \int d^2r \int_0^1 d\alpha |\Psi_{T,L}(\alpha, r)|^2 \hat{\sigma}^2(x, r^2)$$

Extra factor of dipole cross section weights DDIS cross section towards larger dipole sizes $\rightarrow$ enhanced sensitivity to saturation effects.
Signals in $t$ Dependences: e.g. $J/\psi$ Photoproduction

t dependences measure Fourier transform of impact parameter distribution. → Unusual features can arise from deviations from Gaussian matter distribution e.g. Characteristic dips in model by Rezaeian et al, (just) within LHeC sensitive $t$ range.
• With $\theta_n < 1$ mrad, similar $x_L$ and $p_t$ ranges to HERA (a bit more $p_t$ lever-arm for $\pi$ flux).

• Extensions to lower $\beta$ and higher $Q^2$ as in leading proton case. $\Rightarrow F_2^\pi$
  
  At $\beta < 5 \times 10^{-5}$ (cf HERA reaches $\beta \sim 10^{-3}$)

Also relevant to absorptive corrections, cosmic ray physics ...
Establishing Saturation in Inclusive Data

(Lack of) quality of NNPDF fit to $F_2$ and $F_L$ pseudodata with saturation effects included ...

- Unambiguous observation of saturation will be based on tension between different observables e.g. $F_2 \nu F_L$ in $ep$ or $F_2$ in $ep \nu eA$
Conceptual Design Report
(July 2012)

[arXiv:1206.2913]

Substantial low x chapter
(81 pages, 34 authors)

See also talks by Nestor and Hannu
Filling up the Proton

Lines of constant ‘blackness’ ~diagonal in kinemaic plane …
Scattering cross section appears constant along them
(`Geometric Scaling’)

Limited previous evidence in ep and eA restricted to small $Q^2 <\sim 1\text{ GeV}^2$.

→ Partonic interpretation precluded

Usual to implement via `dipole models’, with saturation built into dipole-proton x-section.
Signatures and Selection Methods at HERA

1) Measure scattered Proton in Roman Pots
- Allows \( t \) measurement, but limited by stats, p- tagging systs

2) Select Large Rapidity Gaps
- Limited by control over proton dissociation contribution

- Methods have very different systematics \( \rightarrow \) complementary
- What is possible at LHeC?...
With `FP420’-style proton spectrometer approaching beam to $12\sigma$ ($\sim 250$ µm), can tag and measure elastically scattered protons with high acceptance over a wide $x_{IP}$, $t$ range.

Complementary acceptance to Large Rapidity Gap method.

Together cover full range of interest with some redundancy.

Good acceptance for $0.002 < \xi < 0.013$. 

~100% acceptance
Leading Neutrons

- Crucial in eA, to determine whether nucleus remains intact e.g. to distinguish coherent from incoherent diffraction

- Crucial in ed, to distinguish scattering from p or n

- Forward $\gamma$ and n cross sections relevant to cosmic ray physics

- Has previously been used in ep to study $\pi$ structure function

Possible space at $z \sim 100m$ (also possibly for proton calorimeter)
In the absence of a detailed simulation set-up, simulated `pseudo-data' produced with reasonable assumptions on systematics (typically 2x better than H1 and ZEUS at HERA).

<table>
<thead>
<tr>
<th></th>
<th>LHeC</th>
<th>HERA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lumi [cm(^{-2})s(^{-1})]</td>
<td>(10^{33})</td>
<td>(1-5\times10^{31})</td>
</tr>
<tr>
<td>Acceptance [(^\circ)]</td>
<td>1-179</td>
<td>7-177</td>
</tr>
<tr>
<td>Tracking to</td>
<td>0.1 mrad</td>
<td>0.2-1 mrad</td>
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<td>EM calorimetry to</td>
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<td>0.2-0.5%</td>
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<tr>
<td>Hadronic calorimetry</td>
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<td>1-2%</td>
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<tr>
<td>Luminosity</td>
<td>0.5%</td>
<td>1%</td>
</tr>
<tr>
<td>10^{33} cm^{-2} s^{-1} Luminosity reach</td>
<td>PROTONS</td>
<td>ELECTRONS</td>
</tr>
<tr>
<td>----------------------------------------</td>
<td>---------</td>
<td>-----------</td>
</tr>
<tr>
<td>Beam Energy [GeV]</td>
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<td>Luminosity [10^{33} cm^{-2}s^{-1}]</td>
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<tr>
<td>Normalized emittance γε_{x,y} [μm]</td>
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<tr>
<td>Beta Function β^{*}_{x,y} [m]</td>
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<td>rms Beam size σ^{*}_{x,y} [μm]</td>
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<tr>
<td>rms Beam divergence σ^{*'}_{x,y} [μrad]</td>
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<tr>
<td>Beam Current [mA]</td>
<td>430 (860)</td>
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<td>Bunch Spacing [ns]</td>
<td>25 (50)</td>
<td>25 (50)</td>
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<tr>
<td>Bunch Population</td>
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<td>(1×10^{9}) 2×10^{9}</td>
</tr>
<tr>
<td>Bunch charge [nC]</td>
<td>27</td>
<td>(0.16) 0.32</td>
</tr>
</tbody>
</table>

“Ultimate” proton beam parameters

100 times HERA Luminosity and 4 times cms Energy
### Advanced Luminosity Parameters* - LHeC

<table>
<thead>
<tr>
<th></th>
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<th>ELECTRONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>10^{34} cm^{-2} s^{-1} Luminosity reach</td>
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<td></td>
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<tr>
<td>Beam Energy [GeV]</td>
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<td>Luminosity [10^{33}cm^{-2}s^{-1}]</td>
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<td>Normalized emittance γε_{x,y} [μm]</td>
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<td>Beta Function β_{x,y} [m]</td>
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<td>rms Beam size σ_{x,y} [μm]</td>
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<tr>
<td>rms Beam divergence σ'_{x,y} [μrad]</td>
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<td>Beam Current [mA]</td>
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<tr>
<td>Bunch Spacing [ns]</td>
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<tr>
<td>Bunch Population</td>
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<td>4*10^{9}</td>
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<tr>
<td>Bunch charge [nC]</td>
<td>35</td>
<td>0.64</td>
</tr>
</tbody>
</table>

* HL-LHC proton beam parameters

*) under study now
Max Klein, Susdal, 8/2014

1000 times HERA Luminosity and 4 times cms Energy
LHeC Sensitivity to Different Saturation Models

With 1 fb\(^{-1}\) (1 month at \(10^{33}\) cm\(^{-2}\) s\(^{-1}\)), \(F_2\) stat. < 0.1%, syst, 1-3% \(F_L\) measurement to 8% with 1 year of varying \(E_e\) or \(E_p\)

\(F_2\) and \(F_L\) pseudodata at \(Q^2 = 10\) GeV\(^2\)

- LHeC can distinguish between different QCD-based models for the onset of non-linear dynamics
  ... but can sat\(^n\) effects hide in standard fit parameterisations?
• $\text{Sat}^n$ effects smaller than $J/\Psi$ (smaller dipole sizes, higher $x$).
• Cross sections also much smaller than for $J/\Psi$.

• Huge increase over HERA range $\rightarrow$ anomalously large HERA cross sections can be tested.

[b-sat curves scaled to match best fit to HERA data]