New Physics with eh Scattering
work and thoughts in progress

Max Klein
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for the FCC-he/LHeC Study Group

BSM and ‘the Gluon’ in QCD
BSM with pp
Leptoquarks and Beam Energy
Recent developments

Rome, 14th of April, 2016

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Contribution to the FCC-eh Parallel Session at the Annual FCC Workshop, Rome 11-15.4.16
A Baseline for the FCC-he

Oliver Brüning¹ Max Klein¹,², Daniel Schulte¹, Frank Zimmermann¹
¹ CERN, ² University of Liverpool
March 3rd, 2016

Table 1: Baseline parameters of future electron-proton collider configurations based on the ERL electron linac.

<table>
<thead>
<tr>
<th>parameter [unit]</th>
<th>LHeC CDR</th>
<th>ep at HL-LHC</th>
<th>ep at HE-LHC</th>
<th>FCC-he</th>
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<td>$E_p$ [TeV]</td>
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<td>$E_e$ [GeV]</td>
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<tr>
<td>$\sqrt{s}$ [TeV]</td>
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<td>1.3</td>
<td>1.9</td>
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<td>bunch spacing [ns]</td>
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<td>protons per bunch [$10^{11}$]</td>
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<tr>
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<td>electron current [mA]</td>
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<td>IP beta function $\beta_p^*$ [cm]</td>
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<td>luminosity [$10^{33}$cm$^{-2}$s$^{-1}$]</td>
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<td>10.1</td>
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<td>9.2</td>
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</table>

4.3.2016 - work in progress Study value of dedicated operation $O(10^{35}$ cm$^{-2}$ s$^{-1}$), also eA
Gluons and Quarks 1989 → 2015

BCDMS

CERN-EP/89-07
January 17th, 1989

fixed target IN to ep collider →

CDHS

CERN-EP/89-103
15 August 1989

H1 and ZEUS

μ² = 10 GeV²

HERAPDF2.0 NNLO
uncertainties:
- experimental
- model
- parameterisation

arXiv:1506.06042
“Legacy” paper NC/CC
HERAPDF2.0 NNLO

High mass HL-LHC
Parton-Parton “Luminosities”

Gluon-Gluon, luminosity

$\sqrt{s} = 1.30 \times 10^4$ GeV

C.Gwenlan+M.Klein, ATLAS, Lecce 6.10.15
A remark on gluon saturation

$x_g$ is defined via theory, not directly observable: HERA has discovered rise towards low $x$

Non-linear gg interactions are expected/predicted to exist (BFKL and GLR)

The only reliable measurement of $x_g$ at HERA at $x < 0.1$ came from $dF_2/d\ln Q^2$

It shows a huge variation (in DGLAP) of $x_g(x,Q^2)$ also with $Q^2$:
In particular $x_g$ is valence like at $Q^2 \sim 1$ GeV$^2 \rightarrow \sim$ZERO at small $x$

There thus are two reasons to require $Q^2 > \sim 10$ GeV$^2$ in the search for saturation:
- The gluon density has to be large
- The strong coupling has to be small ($<<1$) for npQCD effects to not interfere

Searches for gluon saturation require energies in excess of those at HERA, not smaller

The in my view only hope to see that is to confront $F_2$ (ep) with FL (ep) data.

The direct extractions of $x_g$ in ep and eA THEN could reveal an amplification in eA..
Fluctuations of the Gluon Field - Instantons?

The Standard Model of particle physics contains certain anomalous processes induced by instantons which violate the conservation of baryon and lepton number ($B + L$) in the case of electroweak interactions and chirality in the case of strong interactions [1, 2]. In quantum chromodynamics (QCD), the theory of strong interactions, instantons are non-perturbative fluctuations of the gluon field. They can be interpreted as tunnelling transitions between topologically different vacua. Deep-inelastic scattering (DIS) offers a unique opportunity [3] to discover a class of hard processes induced by QCD instantons.

NEW:
H1: DESY 16-150
March 16
O(3)pb xsection limits
Odderon

Here we will be concerned with exclusive diffractive $ep$ scattering processes in which the diffractively produced system carries positive charge parity $C = +1$. The real or virtual photon emitted by the electron carries negative $C$ parity and its transformation into a diffractive final state system of positive $C$ parity hence requires the $t$-channel exchange of an object of negative $C$ parity. Pomeron exchange thus cannot contribute to this process. It can only be mediated by the exchange of an Odderon, of a reggeon, or of a photon. The cleanest diffractive process involving Odderon exchange is the exclusive diffractive production of a single meson with positive charge parity. The mesons with the suitable quantum numbers are pseudoscalar and tensor mesons. For the case of

![Diagram](image)

Figure 1: Diagram for the process $ep \rightarrow e\pi^0 N^*$: the proton is excited into an $(I=1/2)$-isobar while a high energy single $\pi^0$ is produced by photon-odderon fusion.

Three gluon state of parity $C=-1$. A small modification to Pomeron exchange/rapidity gaps.
HERA and ABM gluons are much steeper at large $x$ than those of MMHT, CT, NNPDF

→ Can we trust factorisation, how do we test it

Gluon at large $x$ become very small and are hugely uncertain. But $M_x^2 = s x_1 x_2$ ..
<table>
<thead>
<tr>
<th>HQ scheme</th>
<th>CT14</th>
<th>MMHT15</th>
<th>NNPDF3.0</th>
<th>HERAPDF2.0</th>
<th>ABM12</th>
<th>CJ12</th>
<th>JR14</th>
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<td>LO, NLO, NLLO</td>
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<td>fixed (fitted)</td>
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<td>0.1350 0.1180 (0.120) 0.1180 (0.117)</td>
<td>0.1180 0.1180</td>
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<td>0.1180 (0.120) 0.1180 (0.117)</td>
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<td>$\overline{d}b\bar{ar}-\overline{u}bar=fit.$</td>
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<td>Monte Carlo (68% CL)</td>
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<td>Hessian $\Delta \chi^2=1$ (68% CL)</td>
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<td>$\times$</td>
<td>$\times$</td>
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</tr>
</tbody>
</table>

Gluon at High $x$?

A QCD problem by itself and a key question for searches as luminosity increases ...

Gluon distribution at $Q^2 = 1.9 \text{ GeV}^2$

Related to quark distributions, low $x$, $\alpha_s$, heavy flavour treatment, to resummation

C. Gwenlan + M. Klein, ATLAS, Lecce 6.10.15
Understanding the High $x = $ Large Mass region

Non resonant and smeared resonance searches at large masses require extra ep information at high $x$
Large Bjorken $x$

CC at HERA reached at best $x=0.5$. The luminosity was $3 \times 10^{31}$ while $>10^{33}$ is required as $xq \sim (1-x)^k$ for $x \to 1$

Fixed target DIS data suffer from TMC, HT, nuclear corrections and inconsistencies

→ There is no reliable base for predictions at large $x$

C.Gwenlan+M.Klein, ATLAS, Lecce 6.10.15
Very High Mass Dell Yan 13 TeV - $\sigma$(PDF)/$\sigma$(CT14)
Valence quarks

Related to DY, W mass etc
Recall $xq_v \sim (1-x)^3$
$d/u \rightarrow 1$ a classic question

C.Gwenlan+M.Klein, ATLAS, Lecce 6.10.15
Remarks on Precision Higgs Physics in ep

The Higgs is produced in ep predominantly via $WW \rightarrow H$ in ep$\rightarrow \nu HX$

The cross section at the LHeC is $\sim 200\text{fb}$, i.e. very similar to that of $Z^* \rightarrow ZH$ in ee

With 1ab$^{-1}$ integrated luminosity from $10^{34}$ one reaches 1% precision on $bb$ and 7% on $cc$ and corresponding numbers on other channels still to be studied. These LHeC numbers will be better at HE-LHC and FCC-eh (1%$\rightarrow 0.4\% \rightarrow 0.3\%$ for $bb$)

At the FCC-eh the cross section is almost 1pb. Therefore, statistically, FCC-ee, with 4 $10^{34}$ luminosity at ZH and FCC-eh with $10^{34}$ luminosity are about comparable, subject also to the running times: ee at ZH plans 3 years, ep with pp plans $O(10)$.

Both ee and ep thus provide high precision measurements on Higgs, much complementary wrt each other AND to pp: for example
- ee uses mostly $Z \rightarrow ZH$, eh uses mostly $WW \rightarrow H$
- ee provides measurement of the Higgs boson width (to be studied in $ZZ \rightarrow H$ at ep)
- ep provides $N^3LO$ PDFs as are crucial for understanding the $gg \rightarrow H$ production it also provides prediction of Higgs mass with 100 MeV error (cf top mass and cross section physics)

Specifically: LHeC and HL-LHC are an exciting couple for precision Higgs physics at LHC
• **GLUON FUSION AND $W$ FUSION $\Rightarrow$ PDF+$\alpha_s$ UNCERTAINTY REMOVED** (hatched bands)

• **$H\bar{b}b$ MEASURED TO PERCENTAGE PRECISION**;

• **$\tau\tau$ AND $\bar{c}c$ ALSO MEASURABLE**
Invisible Higgs@LHeC
relating the Higgs and the ‘dark’ sector

\[ \text{Br}(h \rightarrow E_T) \]

HL-LHC @ 3 ab\(^{-1}\) [arXiv:1411.7699]

< 3.5% @90% C.L., MVA based

For LHeC, assume 1 ab\(^{-1}\), P = 0.9, cut based

\[ C_{\text{MET}}^2 = \kappa_Z^2 \times \text{Br}(h \rightarrow E_T) \]

potential much enhanced for FCC-eh @ 3.5 TeV and HE-LHC-eh

Colours: expected statistical significance

Uta Klein, FCC-eh

Y.-L. Tang et al., arXiv: 1508.01095 → Talk by C. Zhang

FCNC Top and Higgs couplings:
H. Sun [arXiv:1602.04670]
New study for HE-LHC
14 TeV \( p \times 150 \text{ GeV} e \)

\[ \text{BR}(t \rightarrow qh) < 0.23\% \]
@ 95% C.L. and 100 fb\(^{-1}\)
Top quark electroweak interactions

Precise measurement of couplings between SM bosons and fermions sensitive test of new physics (search for deviations): top quark expected to be most sensitive to BSM physics, due to large mass.

- High precision measurements of $V_{tb}$ and search for anomalous $W_{tb}$ couplings.
- Direct measurement of top quark charge and search for anomalous $tt\gamma$ couplings (e.g. EDM, MDM).
- Measurement of top isospin and search for anomalous $tt\bar{b}Z$ couplings (e.g. EDM, MDM).
- Sensitive search for FCNC couplings will constrain BSM models that predict FCNC (e.g. SUSY, little Higgs, technicolour).
\[ V_{tb} \]

**Initial \( ep \) Top Results**

**LHeC, 100 \( fb^{-1} \)**

1.000 ± 0.005 (expected)

\[ V_{tb} \]: High precision: 1306.1688

LHeC: 10x lumi, FCC-ep to be added

LHC and FCC possibilities to be considered

**Anomalous Wtb Coupling**

<table>
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<tr>
<th>property</th>
<th>precision</th>
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<tr>
<td>( f_V^L )</td>
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<tr>
<td>( f_V^R, f_T^L, f_T^R )</td>
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**Top PDF** (CDR LHeC and 1503.01590)

**Mass of top?** To study

Note Mass of Charm (b) to 3 (~10) MeV
Remarks on Lepto-Quarks

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<tr>
<th>Model</th>
<th>Fermion number F</th>
<th>Charge Q</th>
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<td>$+1/3$</td>
<td>$0$</td>
<td>$\nu \bar{d}$</td>
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</table>

LQs are produced in s channel eq fusion

DIS is ideal for LQ spectroscopy

The huge energy in pp implies that LQs are more likely discovered in pp:

LHC limits are near $\sqrt{s}$ of LHeC

FCC-ep when operating in parallel with FCC-pp has strong discovery potential up to its maximum energy of 3.5 TeV

→ The choice of $E_e$ is much dictated by new physics (also Higgs and top and low x)
LQ production at LHC and LHeC

- Leptoquarks (LQs) appear in several extensions to SM: production $\sigma \sim \lambda^2 q(x)$
- Can be scalar or vector, with fermion number 0 ($e^-\bar{q}$bar) or 2 ($e^-q$)
- At LHC, mostly pair production (from $gg$ or $qq$)
  - If $\lambda$ not too strong (0.3 or lower), cross section independent on $\lambda$
  - Exclude up to 900 GeV for 1° generation
  - Expect to exclude up to 1.2 (1.5) TeV at 14 TeV 300 fb$^{-1}$ for scalar (vector)-LQ

At the LHeC: both baryon and lepton quantum numbers - ideally suited to search for and study properties of new particles coupling to both leptons and quarks

- Single, resonant production; sensitive to $\lambda$
Cost strongly rising with tunnel circumference. Presently stick to LHeC default.

Maximise independence of ring installation, design for synchronous ep and pp OP.
Reach for $\Delta$ (CI eeqq):

Search for + verification of Contact Interactions into $O(100)$ TeV. eq Fusion: Leptoquarks $M < \sqrt{s}$
Right Handed Currents and Heavy Neutrinos

\[
\begin{pmatrix}
\nu_L \\
N_R
\end{pmatrix} = \begin{pmatrix}
U_{3\times3} & V_{3\times n} \\
X_{n\times 3} & K_{R\dagger}^{-1}_{n\times n}
\end{pmatrix}
\begin{pmatrix}
\nu \\
N
\end{pmatrix}
\]
The FCCs provide great prospects for discovering the origin of neutrino masses.

Future electron-proton colliders provide significant gain in mass reach and fairly “stable” production cross sections.
Kinematic Range of Acceptance of a 750 GeV Particle coupling to $yy$ (and $ZZ$?)

$LHeC - hadronic final state kinematics$

- $W^2 = Q^2 \left( \frac{1-x}{x} + M_p^2 \right)$
- $Q^2 \leq W^2 \frac{x}{1-x}$
- $x < 0.01$: $Q^2 \approx W^2 x$
- $W^2 \approx 5y$
- $y > (750)^2 / \gamma_{\text{GeV}}^2$
  - $\gamma_{\text{GeV}} = 0.33 \text{ LHeC}$
  - $0.047 \text{ FCC }$
Acceptance of a 750 GeV Ghost S

\[ \sigma(\gamma\gamma \rightarrow S) = ? \]

For \( x < 10^{-3} \) no (average) energy deposition exceeding the electron beam energy

\( E_e = 50000 \text{ GeV} \)
\( E_e = 60 \text{ GeV} \)

\( \Upsilon > 0.047 \) (\( = 0.33 \text{ LHeC} \))
\( \theta = 179^\circ \)

\( \text{very low } x \) requires not the maximum of \( E_e \)

\( \text{FCC-he } 60 \text{ GeV} \)
\( \text{LHeC} \)
The 750 GeV Ghost in ep

Initial simulations of the 750 GeV signal and backgrounds (G.Azuelos)

Couplings, Cross Section, Confirmation – three big unknowns ...
Some Remarks

The ep configuration has much to offer by itself and in complementarity to ee and pp. For the FCC-eh, more studies are under way and need to be pursued.

The LHeC Study has been the base for FCC-eh also, and time and energy order need to be imposed by us in order to have clearer what can be gained where. This will also need to include the HE-LHC configuration which looks good to eh.

Basically: high x may be done by LHeC, but low x and high masses (equivalent) require FCC-ep

Areas of further study: top, Higgs, BSM

Areas of renewed study: low x, PDFs

Areas of new directions: Heavy neutrinos, BSM Higgs, 750 (if)

Much effort has been put in the detector software and design which needs to be coupled closer to the physics analyses.

Lots to be done for CDR on LHeC (1034) and FCC, while eh physics remains fascinating to some of us and useful to everybody.

If you want to join, please do so