High $Q^2$ physics at the LHeC and FCC-he (electroweak, top and BSM)

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for the LHeC and FCC-he study groups

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with thanks to G. Azuelos, O. Cakir, M. Klein, M. Kumar, C. Schwanenberger
LHeC and FCC-he

energy recovery LINAC

e$^-$ beam: 60 GeV
Lint $\rightarrow 1\ ab^{-1}$

see talk by M. Klein

operating synchronously:

• with HL-LHC:
p beam: 7 TeV, $\sqrt{s} = 1.3$ TeV

• and/or later with FCC-hh:
p beam: 50 TeV, $\sqrt{s}=3.5$ TeV

C. Gwenlan, High $Q^2$ Physics at the LHeC
eh physics at the high energy frontier

- parton distribution functions (A. M. Cooper-Sarkar)
- Higgs (C. Zhang)
- physics at high pt (this talk)
  - LHeC increases LHC precision (from much improved PDFs, $\alpha_s$)
  - precision electroweak
  - electron-quark specific interactions (EG. leptoquarks, compositeness)
  - precision top quark studies
  - also, eA option (N. Armesto), low $x$ (A. Stasto), …

LHeC (FCC-he) complementary to, synchronous with, HL-LHC (FCC) potential to improve sensitivity of LHC, to characterise or possibly discover new phenomena
outline

precision electroweak physics

BSM

top quark physics
precision electroweak physics

BSM

top quark physics
Deep Inelastic Scattering (DIS)

Neutral Current (NC)

\[ Q^2 = -(k-k')^2 \]

Charged Current (CC)

\[ Q^2 = -(k-k')^2 \]

\[ P_q = xP \]

LHeC is a unique facility for testing electroweak theory
(two) e beam charges, two e polarisation states, NC+CC, p or isoscalar targets
scale dependence of $\sin^2\theta_W$

$$A^{-} = \frac{\sigma_{NC}^{-}(P_R) - \sigma_{NC}^{-}(P_L)}{\sigma_{NC}^{-}(P_R) + \sigma_{NC}^{-}(P_L)} \quad R^{-} = \frac{\sigma_{NC}^{-}}{\sigma_{CC}^{-}}$$

extract $\sin^2\theta_W$ with $\alpha$, $M_Z$ fixed

probe large range of scale dependence

C. Schwanenberger, ICHEP16
NC vector and axial vector couplings


significant improvements expected from higher luminosity and FCC-hh

very high precision measurement sensitive to new physics: Z', leptoquarks, R-parity violating SUSY, …

e-beam: 50 GeV
1 fb⁻¹ of each of e⁻p and e⁺p polarisation: 40%

C. Gwenlan, High Q² Physics at the LHeC
precision electroweak physics

**BSM**

LHC (FCC) is/ will be main discovery machine; **LHeC (FCC-he)** has potential for improving or possibly discovering new physics

**B** and **L** quantum numbers in initial state, and very **clean environment** – favourable for specific BSM models; now strong constraints from LHC, and LHeC discovery window remains open only for certain scenarios; FCC-he energy offers more potential; improved PDFs and $\alpha_s$ from **LHeC** transforms LHC into high precision machine

**top quark physics**
leptoquarks (LQs)

ep collider: both baryon and lepton quantum numbers in initial state
LHeC (FCC-he) ideal to study properties of new particles coupling to eq pairs

LQs:

• 1st generation leptoquark bosons
  (E6 GUTs, extended technicolor, Pati-Salam model, lepton-quark compositeness models)
• or, squarks in R-parity violating SUSY (see later)

can be scalar or vector, with fermion number 0 or 2
Buchmüller classification

LHC: mostly pair production (through gg or qq)
if \( \lambda \) not too large (\( \lambda < e = \sqrt{4\pi\alpha} = 0.3 \)), cross section insensitive to \( \lambda \)
determination of QNs impossible, or ambiguous / model dependent

ep: single resonant LQ production (sensitive to \( \lambda \); suited for determination of QNs)
LQ bounds

1\textsuperscript{st} generation LQs, $\beta = \text{BR}(\text{LQ}\rightarrow \text{eq}) = 1$

ATLAS+CMS: $M_{\text{LQ}} \lesssim 1.1 \text{ TeV}$

can expect up to 1.5 TeV from LHC (pair production) with 300 fb\textsuperscript{-1} at $\sqrt{s} = 14$ TeV

ep scenarios:
also sensitive to $\lambda \ll e = \sqrt{4\pi\alpha} = 0.3$

(preliminary study, G. Azuelos)
LQ properties

- **single LQ production** more powerful for determination of QNs
- **LHeC (FCC-he)**: much higher cross section for **single production** than LHC
- if LQs observed at LHC, **future ep collider** could measure **fermion number**, spin, flavour structure, chiral structure, coupling

EG. Fermion Number (e⁻p and e⁺p)

\[
A = \frac{\sigma_{e^-} - \sigma_{e^+}}{\sigma_{e^-} + \sigma_{e^+}} \begin{cases} > 0 & \text{for } F=2 \\ < 0 & \text{for } F=0 \end{cases}
\]

- *asymmetry, A*, since u, d \(\gg\) ubar, dbar at high x
- asymmetry also sensitive to quark flavour

much of this mass range now excluded but can be extended to **FCC**
new physics in high $Q^2$ inclusive DIS

- new physics at higher scales $\Lambda \gg \sqrt{s}$, may become observable as deviations from SM predictions
- seen as an effective 4-fermion contact interaction (CI)

observed as a modification of the $Q^2$ dependence – all information contained in $d\sigma/dQ^2$

- may be applied very generally to new phenomena:

\[ \Lambda \]

\[
\begin{align*}
\text{LQ, mass } &\gg \sqrt{s} \\
\text{Planck scale (M}_s\text{) of extra-dimensional models} \\
\text{compositeness scale} \\
\text{...}
\end{align*}
\]

\[
\mathcal{L} = \frac{4\pi e}{\Lambda^2} j_{\mu}^{(e)} j_{\mu}^{(q)}; \quad q = u, d; \quad \varepsilon = \pm 1 \\
j_{\mu}^{(f=\varepsilon,q)} = \eta_L \bar{f}_L \gamma_\mu f_L + \eta_R \bar{f}_R \gamma_\mu f_R + \text{h.c.} \\
\Rightarrow \text{all combinations of couplings } \eta_{ab} = 4\pi \varepsilon \frac{\eta_a^{(e)} \eta_b^{(q)}}{\Lambda_{ab}^2}
\]
scale of Cl at future colliders

present LHC constraints on scale of $qqll$ contact interactions: 15–26 TeV, depending on model (expect up to 40 TeV at LHC at $\sqrt{s}=14$ TeV)

also advantages over, and complementarities with, pp and $e^+e^-$ in characterising nature of new physics
supersymmetry

- **improved sensitivity for HL-LHC**

  SUSY searches near HL–LHC kinematic boundary may be ultimately limited by PDF uncerts., especially high x gluon

  **LHeC** reduces PDF uncertainties considerably

  - plot by C. Borschensky and M. Kramer; update to LHeC note arXiv:1211.5102

- **R-parity violating supersymmetry**

  "stops"

  W. Hong-Tang et al. 1107.4461

  with high luminosity, **RPV SUSY** can be probed to unprecedented levels

  R parity violating supersymmetry, where RPV interactions can be measured and kinematic distributions can be obtained by convoluting parton-level diagrams in FIG. 1.

  \[ \hat{t} \rightarrow \mu \hat{b} \]

  **LHeC**

  Gluino Pair Production PDF Uncertainty

  \[ \sigma(p_T, M_{\tilde{g}}) \]

  NLO QCD

  M[squark]=M[gluino]=\mu R=\mu F

  LHC (14 TeV)

  CT14

  MMHT14

  NNPDF30

  HERA20

  ABM11

  LHeC
BSM in vector boson scattering

**FCC-he:** explore vector boson scattering at high mass

(anomalous TGC, QGC couplings?)

*LHeC* studies show sensitivity comparable to LHC; enhanced sensitivity with polarised e beam

I.T.Cakir et al., arXiv:1406.7696

**is unitarity restored only by Higgs?** are there new resonances? (EG. composite Higgs)

expect below $\propto 2-3$ TeV

eq \rightarrow (eq)VV, (vq)VV

search for deviations from SM

**LHC:** hadronic modes challenging

large QCD backgrounds not present in ep, pileup, difficult if no lepton triggers used, …
precision electroweak physics

BSM

top quark physics

precise measurements of couplings between SM bosons and fermions are sensitive test of new physics (search for deviations); top quark expected to be most sensitive to BSM physics, due to large mass

ep future collider offers excellent prospects for top physics
measurement of $|V_{tb}|$


**$V_{td}$**

$$
\begin{pmatrix}
V_{ud} & V_{us} & V_{ub} \\
V_{cd} & V_{cs} & V_{cb} \\
V_{td} & V_{ts} & V_{tb}
\end{pmatrix}
$$

- **LHeC**, $100 \text{ fb}^{-1}$
  - $1.000 \pm 0.005$ (expected)

- **LHC+Tevatron average**: $|V_{tb}| = 1.009 \pm 0.031$
  (PDG 2016)

**LHeC**: very high precision measurement

- **e beam**: 60 GeV
- $L_{\text{int}} = 100 \text{ fb}^{-1}$ and simple cuts:
  - **HAD**: $N_t = 22000$, S/B=1.2
  - **LEP**: $N_t = 11000$, S/B=11
anomalous Wtb couplings

\[ \mathcal{L}_{Wtb} = \frac{g}{\sqrt{2}} \left[ W_\mu \bar{t} \gamma^\mu (V_{tb} f_1^L P_L + f_1^R P_R) b \right. \\
\left. - \frac{1}{2 m_W} W_{\mu \nu} \bar{t} \sigma^{\mu \nu} (f_2^L P_L + f_2^R P_R) b \right] + h.c. \]

\[ = 1 \text{ in SM} \]
anomalous Wtb couplings

\[ \mathcal{L}_{Wtb} = \frac{g}{\sqrt{2}} \left[ W_\mu \bar{t} \gamma^\mu (V_{tb} f_1^L P_L + f_1^R P_R) b - \frac{1}{2m_W} W_{\mu\nu} \bar{t} \sigma^{\mu\nu} (f_2^L P_L + f_2^R P_R) b \right] + h.c. \]

=1 in SM

LH and RH tensor

RH vector

J.A. Aguilar-Saavedra, NP B812 (2009) 181
anomalous Wtb couplings

J.A. Aguilar-Saavedra, NP B812 (2009) 181

\[ \mathcal{L}_{Wtb} = \frac{g}{\sqrt{2}} \left[ W_\mu \bar{t}\gamma^\mu (V_{tb} f_1^L P_L + f_1^R P_R) b - \frac{1}{2m_W} W_{\mu\nu} \bar{t} \sigma^{\mu\nu} \left( f_2^L P_L + f_2^R P_R \right) b \right] + h.c. \]

LHC and RH tensor

LHeC: 95% CL, hadronic mode

(100 fb\(^{-1}\), systs. 1,5,10%) similar sensitivity with leptonic mode from asymmetry of kinematic variable distributions

Dutta, Goyal, Kumar, Mellado, arXiv:1307.1688

LHC combination preliminary

\( \sqrt{s} = 7 \text{ TeV}, \ L_{\text{int}} = 35 \text{ pb}^{-1} - 2.2 \text{ fb}^{-1} \)

ATLAS-CONF-2013-033
CMS-PAS-TOP-12-025

* SM

C. Gwenlan, High Q\(^2\) Physics at the LHeC
anomalous Wtb couplings

$$\mathcal{L}_{Wtb} = \frac{g}{\sqrt{2}} \left[ W_\mu \bar{t} \gamma^\mu (V_{tb} f_1^L P_L + f_1^R P_R) b \right] - \frac{1}{2 m_W} W_{\mu \nu} \bar{t} \sigma^{\mu \nu} \left( f_2^L P_L + f_2^R P_R \right) b + h.c.$$
**top quark PDF**

**NC:** top pair production

![Diagram showing top quark production](image)

At very high $Q^2$, the top quark becomes 'light'.

→ top PDF

**LHeC**

(Variable flavour number scheme for top)

![Graph showing $F_2^t$ vs $\tau_1$](image)

$L_{int}=10$ fb$^{-1}$

- $Q^2=100$
- $Q^2=1000$
- $Q^2=10000$

$Q^2 < 4m_t^2$

**LHeC opens up new field of research for top quark PDFs**

C. Gwenlan, High $Q^2$ Physics at the LHeC
search for anomalous tτγ couplings


LHeC: 10% and 18% accuracy

LHC: 5% uncert.

27% uncert. (with 4.6 fb^{-1}, 7 TeV)

with γp and DIS, sensitivity also to ttZ

can also measure top quark charge
FCNC in single top quark production

\[ L = -g_e \sum_{q=u,c} Q_q \frac{\kappa_q}{\Lambda} \sigma^{\mu\nu}(f_q + h_q \gamma_5) q A_{\mu\nu} + h.c. \]

- \( \kappa \) = anomalous FCNC coupling
- \( \Lambda \) = new physics scale

LHeC: operating as \( \gamma p \) collider

\[ \text{Lint} = 10 \text{ fb}^{-1} \]

- e beam: 70 GeV
- \( \gamma \): 80% of e-energy

Ref.: \( \kappa/\Lambda = 0.01 \Leftrightarrow \text{BR}(t \rightarrow u\gamma) \propto 2 \times 10^{-6} \)

(two orders of mag. better than LHC reach with 100 fb\(^{-1}\))

can also explore \( \kappa_u \neq \kappa_c \)

C. Schwanenberger, ICHEP2016

FCNC top couplings at colliders

Dimensionless coupling ($\Lambda = m_t$)
FCNC top couplings at colliders

dimensionless coupling ($\Lambda = m_t$)

test SUSY, technicolor, little Higgs, extra dimensions

C. Schwanenberger
ICHEP16
FCNC top couplings at colliders

- ZEUS
- CDF
- L3
- DØ
- ATLAS: 300 fb⁻¹
  \( \sqrt{s} = 14 \text{ TeV} \)
- FCC-he
  \( 1 \text{ ab}^{-1} \)
- ATLAS: 500 fb⁻¹
  \( \sqrt{s} = 250 \text{ GeV} \)
- 2.1 fb⁻¹, 7 TeV
- 5 fb⁻¹, 7 TeV + 20 fb⁻¹, 8 TeV

Test SUSY, technicolor, little Higgs, extra dimensions

dimensionless coupling (\( \Lambda = m_t \))
summary

• **ep future collider** has very rich high $Q^2$ analysis programme
  only selected studies shown here

• precision measurements of **proton** (and **nuclear**) structure are primary
  goals of **LHeC** (and **FCC-eh**)

• **dramatically improved precision** for LHC and FCC searches and measurements

• precision **electroweak** measurements (**light quark couplings**, $\sin^2\theta_W$)

• **new phenomena**, discovery, and / or determination of properties

• **LQs**, **contact interactions**, **excited fermions**, **RPV SUSY**, **FCNC**, **anomalous couplings**, **colour octet electron**, **ultra heavy / Majorana neutrinos**, **H+ bosons**, **heavy top**, ...

• study **top quark** in detail for first time at **ep collider**

• couplings to gauge bosons (EG. $|V_{tb}|$, $W_{tb}$, $tt\gamma$, $ttZ$, $tH$)

• **top quark properties**: **top PDF**, **charge**, **polarisation**

• **FCC-he**: higher sensitivity in all channels, studies ongoing
High $Q^2$

Rutherford backscattering of dozens of TeV $e^-$ energy

$\theta_h = 1^\circ$

HERA

LHeC

FCC-he

175 GeV

60 GeV

$E_r = 50000$ GeV

$E_s = 175$ GeV

$\frac{Q^2}{GeV^2}$
primary measurements at high $Q^2$

**NC+CC cross sections to high precision**

- access high $x$, free of nuclear corrections
- different beam charge and polarisations:
  determination of all quark types!

---

C. Gwenlan, High $Q^2$ Physics at the LHeC

... and gluon via scaling violations (and FL)
asymmetry measurements in DIS

\[ A^\pm = \frac{\sigma_{NC}^\pm(P_R) - \sigma_{NC}^\pm(P_L)}{\sigma_{NC}^\pm(P_R) + \sigma_{NC}^\pm(P_L)} \]

\[ R^\pm = \frac{\sigma_{NC}^\pm}{\sigma_{CC}^\pm} \]

LHeC CDR,
J. Phys. G39
075001 (2012)

10 fb\(^{-1}\)
e beam:
60 GeV

mean \( x \) differs by
factor of 6 between
NC and CC

extract \( \sin^2\theta_W \) (\( \alpha, M_Z \) fixed)
single LQ production cross sections

LHeC CDR,
J. Phys. G39
075001 (2012)
LQ properties with the LHeC

- **fermion number** and **flavour structure**

\[
A = \frac{\sigma_{e^-} - \sigma_{e^+}}{\sigma_{e^-} + \sigma_{e^+}} \begin{cases} 
> 0 & \text{for } F=2 \\
< 0 & \text{for } F=0 
\end{cases}
\]

- C. Gwenlan, High $Q^2$ Physics at the LHeC
LQ properties with the LHeC

- **other properties:**
  - **spin**
  - **LHC:** pair production of LQ – LQ leads to angular distributions which depend on the g – LQ – LQ coupling
    - may need to look at spin correlations
  - **LHeC:** $\cos\theta^*$ distribution sensitive to spin
  - vector LQs can have anomalous couplings
  - **couple chirally** (i.e. to L or R but not both?)
  - could be probed by measuring sensitivity of cross sections to polarisation of the electron beam
  - **generation mixing?**
  - does LQ decay to 2$^{nd}$ generation?
  - **BR to neutrino, good S/B in vj channel** $e_L^-u_L \rightarrow S_3 \rightarrow \nu_e d_L$
quark substructure

- if contact terms originate from a model where fermions composite, scale proportional to composite object radius

\[ f(Q^2) = 1 - \frac{1}{6} \langle r^2 \rangle Q^2 \]

\[ \frac{d\sigma}{dQ^2} = \frac{d\sigma_{SM}}{dQ^2} f_e(Q^2) f_q(Q^2) \]

sensitive to fermion radius below $10^{-19}$–$10^{-20}$ m at LHeC (FCC-eh)

LHeC CDR,
J. Phys. G39
075001 (2012)
CI at the LHC and LHeC

- **LHC**: variation of Drell-Yan cross section for CI model
- cannot simultaneously determine $\Lambda$ and sign of interference of new amplitude with respect SM ($\epsilon$)

EG: negative interference too small to be disentangled


LHeC: sign $\epsilon$ from asymmetry of $\sigma/\sigma_{SM}$ in $e^+p$ and $e^-p$
excited fermions

• could be produced directly if their mass is below compositeness scale
  assume spin= ½, L, R doublets

\[
\mathcal{L} = \frac{1}{2\Lambda} \bar{f} \tau f \sigma_{\mu\nu} \left[ g_\rho \frac{\tau}{2} W_{\rho \mu} + g'_{\rho B_{\mu\nu}} + g_s f_s \frac{\lambda_{\rho}}{2} G_{\mu\nu} \right] f_L
\]

contact interaction Lagrangian

\[
\mathcal{L} = \frac{4\pi}{2\Lambda^2} j_\mu j^{\mu}; \quad j_\mu = \eta_L \bar{f}_L \gamma_\mu f_L + \eta'_L \bar{f}_L \gamma_\mu f'_L + \eta_L' \bar{f}_L \gamma_\mu f_L + h.c. + (L \leftrightarrow R)
\]

gauge interaction Lagrangian

\[ \text{LHC could probe up to 1–2 TeV} \]
for \( f = f' = 1, \Lambda = m_e^* \) (or \( f/\Lambda = 1/m_e^* \))

O. Cakir et al. PRD70 (2004) 075011
A. Belyaev et al., EPJ C41, s02 (2005) 1

**ep colliders** could extend sensitivity to \( f/\Lambda \) and mass reach to \( \lesssim \text{CM} \)
heavy fermions / coloured bosons

heavy leptons:
- vector-like leptons: L and R chiralities have same transformation properties
  - predicted in GUT theories (E6) or in Composite Higgs Models
  - couplings: $eEZ, \nu EW, eEH; \nu NZ, eNW, \nu NH$
- Majorana neutrino production in an effective approach
  (L. Duarte et al. 1412.1433)
  - SM background from $p\gamma \rightarrow \ell^+ + 3j + \nu$, $pe^- \rightarrow e^+ + 3j + 2\nu_e$
able to discover Majorana neutrinos up to 700 GeV (for $E_e = 50$ GeV)

vector-like quarks?
- single production of top partners, sensitive to couplings: $qQZ, qQW, qQH$;
- (coupling to light quarks)

diquarks
- predicted in superstring inspired E6 and composite models
- could carry charge 1/3, 2/3, 4/3 and be scalar or vector
- in gp production
  \[
  \mathcal{L}_{\beta \frac{1}{3}} = \left( g_{\beta L} \bar{Q}_L^c i \tau_2 Q_L + g_{\beta R} \bar{u}_R d_R \right) D Q_1^c + \text{h.c.}
  \]
  (M Şahin and O. Çakir, arXiv:0911.0496)
  LHeC reach excluded; vector and scalar diquarks can be distinguished by the angular distribution of their decays

G. Azuelos

C. Gwenlan, High $Q^2$ Physics at the LHeC
1. **VBF Higgs production with BSM decays**
   eg. RPV cases $H \rightarrow \chi_1^0 \chi_1^0 \rightarrow 3j \ 3\nu$ (resonances)
   need to understand backgrounds

2. **vector boson scattering at high mass**
   mass dependence of cross section
   - anomalous TGC, QGC couplings?
     I.T.Cakir et al., arXiv:1406.7697
     studies show sensitivity comparable to LHC
   - is unitarity restored only by Higgs?
     are there new resonances (composite Higgs model)?
     expect below about 2–3 TeV:
     e-q → e-qWZ, vqWZ
     search for deviations from SM predictions
   - **LHC**: hadronic modes challenging (high QCD backgrounds not present in ep, pileup, difficult if no lepton triggers used, …)
**RPV SUSY**

**single squark production, in RPV SUSY** (signal like LQs, with generation mixing)

\[ \Lambda'_{131} < 0.03 \]

- sensitivity up to 700 – 800 GeV with only 1 fb\(^{-1}\)
- LHC will also provide constraints
- very promising with high luminosity, 100 fb\(^{-1}\)
- requires good b-tagging

\[ \Lambda'_{131} < 0.02 \]

**sbottom**

Barbier hep-ph/0406039

- < 100 fb\(^{-1}\) needed for 1 TeV RPV sbottom discovery

**RPV SUSY can be probed at unprecedented levels**

- C. Gwenlan, High Q\(^2\) Physics at the LHeC
**SUSY – PDF impact on searches**

- **SUSY** – searches near HL–LHC kinematic boundary may ultimately be limited by knowledge of PDFs (esp. gluon at high x)

![](image1.png)

**EG: gluino production at the LHC**

- **plot by C. Borschensky, M. Kramer; update to arXiv:1211.5102**

**LHeC improves sensitivity for HL-LHC**

- **also NNPDF3.0**
  - **arXiv:1410.8849**

C. Gwenlan, High $Q^2$ Physics at the LHeC
top quark production

Dutta, Goyal, Kumar, Mellado, arXiv:1307.1688

EG. **CC** with $L_{\text{int}} = 100 \text{ fb}^{-1}$ (e: 60–140 GeV):
- 2–6 × 10^5 events
- 3–10 × 10^5 events

**ep** future collider offers excellent prospects for **top quark physics**
top quark electroweak interactions

• 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 (EG. EDM, MDM)

• measurement of top isospin and search for anomalous $ttZ$ couplings (EG. EDM, MDM)

• sensitive search for FCNC couplings will constrain BSM models that predict FCNC (EG. SUSY, little Higgs, technicolour)
measurement of $|V_{tb}|$


$\Delta \beta$: luminosity uncertainty

![Diagram](image)

\[
\begin{pmatrix}
V_{ud} & V_{us} & V_{ub} \\
V_{cd} & V_{cs} & V_{cb} \\
V_{td} & V_{ts} & V_{tb}
\end{pmatrix}
\]

$e$ beam: 60 GeV
with $L_{\text{int}} = 100$ fb$^{-1}$, with simple cuts:

hadronic: $N_t = 22000$, S/B=1.2
leptonic: $N_t = 11000$, S/B=11

$LHeC$: $\Delta |V_{tb}| = 0.005$ with $L_{\text{int}}=100$ fb$^{-1}$
LHC measurements of $|V_{tb}|$

**ATLAS+CMS Preliminary**

- **LHCtopWG**
- September 2016

$|V_{tb}| \pm \sqrt{\frac{\sigma_{tot}}{N_{obs}}} = \frac{\sigma_{tot} - \sigma_{bg}}{N_{obs}}$ from single top quark production

- $\sigma_{tot}$ NLO+NLL MSTW2008nlo

- $\Delta \alpha_{PDF}$ scale @ PDF
- $m_{W} = 172.5$ GeV

**t-channel:**
- ATLAS 7 TeV
  - PRD 90 (2014) 120066 (4.59 fb$^{-1}$)
  - ATLAS 8 TeV
  - Paper in preparation (20.2 fb$^{-1}$)
  - CMS 7 TeV
  - JHEP 12 (2012) 035 (1.17 - 1.56 fb$^{-1}$)
  - CMS 8 TeV
  - JHEP 05 (2014) 090 (19.7 fb$^{-1}$)
  - CMS combined 7+8 TeV
  - JHEP 06 (2014) 090

- CMS 13 TeV
  - Paper in preparation (2.3 fb$^{-1}$)

- ATLAS 13 TeV
  - arXiv:1609.09520 (3.2 fb$^{-1}$)

**Wt:**
- ATLAS 7 TeV
  - PLB 716 (2012) 142-159 (2.05 fb$^{-1}$)
  - CMS 7 TeV
  - PRL 110 (2013) 032003 (4.9 fb$^{-1}$)
  - ATLAS 8 TeV$^{1,2}$
  - JHEP 01 (2016) 064 (20.3 fb$^{-1}$)

- CMS 8 TeV$^{1,2}$
  - PRL 112 (2014) 231802 (12.2 fb$^{-1}$)
  - LHC combined 8 TeV$^{1,2}$
  - ATLAS-COM-2016-023, CMS-PAS-TOP-15-019

- ATLAS 13 TeV
  - ATLAS-COM-2016-004 (3.2 fb$^{-1}$)

**s-channel:**
- ATLAS 8 TeV$^{1,2}$
  - PLB 756 (2016) 228 (20.3 fb$^{-1}$)

$\Delta_{N}^{\text{theo}}$ scale @ PDF

- **meas** ± (theo)

- **ATLAS+CMS Preliminary**
- **LHCtopWG**
- **September 2016**

- **C. Gwenlan, High Q$^{2}$ Physics at the LHeC**
- **47**
anomalous Wtb couplings

\[ \mathcal{L}_{Wtb} = \frac{g}{\sqrt{2}} \left[ W_\mu t^\gamma (V_{tb} f_{1L} P_L + f_{1R} P_R) b \right. \\
- \frac{1}{2m_W} W_{\mu \nu} \bar{t} \sigma_{\mu \nu} \left( f_{2L} P_L + f_{2R} P_R \right) b + h.c. \]

J.A. Aguilar-Saavedra, NP B812 (2009) 181

- RH vector
- LH and RH tensor

\( f_{2} \) in SM

kinematic observables sensitive to the couplings free two couplings at a time
anomalous Wtb couplings

\[ L_{Wtb} = \frac{g}{\sqrt{2}} [ W_{\mu} \bar{t} \gamma^\mu (V_{tb} f_1^L P_L + f_1^R P_R) b 
- \frac{1}{2m_W} W_{\mu\nu} \bar{t} \sigma^{\mu\nu} (f_2^L P_L + f_2^R P_R) b ] + h.c. \]

=1 in SM

LH and RH tensor

68% CL syst. (1–10%)

from asymmetry of distributions of kinematic variables

<table>
<thead>
<tr>
<th>Property</th>
<th>Precision</th>
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<tbody>
<tr>
<td>( f_1^L )</td>
<td>0.001 – 0.01</td>
</tr>
<tr>
<td>( f_1^R, f_2^L, f_2^R )</td>
<td>0.01 – 0.1</td>
</tr>
</tbody>
</table>

C. Gwenlan, High Q^2 Physics at the LHeC

LHeC: hadronic mode

similar sensitivity with leptonic mode
top quark polarisation

\[ \cos \theta: \text{angle between charged lepton and spin quantisation axis in top frame} \]

using simple e-beam axis polarisation \( P_t = 96\% \)

19.7 fb\(^{-1} \): \( A_{\uparrow \downarrow} = 0.26 \pm 0.11 \)

Atag, Sahin, PRD 73, 074001 (2006)
top quark PDF

LHeC opens up new field of research for top PDFs
search for anomalous ttZ couplings


<table>
<thead>
<tr>
<th>property</th>
<th>10% (18%) accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>EDM: $\tilde{\kappa} / \tilde{\kappa}_Z$</td>
<td>0.20–0.28 / 0.6–0.8</td>
</tr>
<tr>
<td>MDM: $\kappa / \kappa_Z$</td>
<td>0.05–0.09 / 0.9–1.3</td>
</tr>
</tbody>
</table>

tt photoproduction (grey lines)

dd DIS (black lines)

**LHeC:** 10% and 18% accuracy

C. Gwenlan, High Q$^2$ Physics at the LHeC
anomalous FCNC tHu coupling

H. Sun, X. Wang, arXiv:1602.04670

\[ e^- p \rightarrow \nu_e t \rightarrow \nu_e h q \rightarrow \nu_e b \bar{b} q \quad q = u, c \]

- object resolutions taken as ATLAS values
- b-tag rate (60%), c- and light-tag fake rates (10% and 1%)
- S/(S+B)\^2 optimised for LHeC and FCC-he scenarios
- cut- and MVA-based analyses

improves sensitivity c.f. HL–LHC

C. Gwenlan, High Q^2 Physics at the LHeC
**CP nature of tH coupling**

\[ \mathcal{L} = -i \frac{m_t}{v} \left[ \cos \zeta_t + i \gamma_5 \sin \zeta_t \right] t H \]

\[ \zeta_t = \text{phase of } tH \text{ coupling} \]

EG. \( \zeta_t = 0, \pi \) (pure scalar); \( \zeta_t = \pi/2 \) (pure pseudo-scalar)

channel: \( H \rightarrow b \bar{b}, t \rightarrow \text{leptonic} \)

**LHeC**: study new physics contributions to tH coupling

**Exclusion contour** (region above curves excluded)

\[ S/(S+B)^{1/2} \], cross section depends on \( \zeta_t \)

also studies of \( \zeta_t \) dependence of various observables
NC vector and axial vector couplings

- most recent constraints from combined analysis of HERA I + II data

C. Gwenlan, High Q^2 Physics at the LHeC

ZEUS coll.,
Phys Rev D93 (2016) no.9 092002
NC vector and axial vector couplings

- most recent constraints from combined analysis of HERA I + II data

ZEUS

C. Gwenlan, High Q^2 Physics at the LHeC

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