BSM and Top physics with LHeC and FCC-eh

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Deep Inelastic Scattering
Santiago de Compostela
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LHeC

The Large Hadron-Electron Collider at the HL-LHC

LHeC and FCC-he Study Group

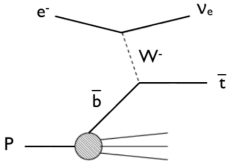
P. Agostini *et al.*, [arXiv:2007.14491 [hep-ex]]

LHeC $E_e = 50$ GeV, $\sqrt{s} \simeq 1.2$ TeV, $\mathcal{L}_{int} = 1$ ab^{-1}, parallel to HL-LHC

FCC-he $E_e = 50$ GeV, $\sqrt{s} \simeq 3.2$ TeV, $\mathcal{L}_{int} = 3$ ab^{-1}, parallel to FCC-hh

The Large Hadron-Electron Collider at the HL-LHC – section 5.3

Anomalous Wtq couplings



- Flagship measurement V_{tb}, $\sigma = 15.3$ pb
- Generic modification of Wtq interactions

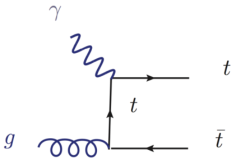
$$\delta\mathcal{L}_{Wtb} = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}V_{tb}(f_1^L P_L - f_1^R P_R)tW_{\mu}^{-} - \frac{g}{\sqrt{2}}\bar{b}\frac{-i\sigma^{\mu\nu}q_{\nu}}{M_W}(f_2^L P_L - f_2^R P_R)tW_{\mu}^{-} + \text{h.c.}$$

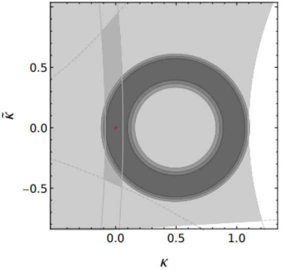
- SM: all f_i vanish at tree level.
- Analysis of $e^- p \to \nu\bar{t} + X$ at the detector level including background processes and systematic effects:

$\Rightarrow$ Precision of $\sim 10^{-3}$ for f_i^L and 10^{-2} for f_i^R at LHeC.

Mellado *et al.*, Eur. Phys. J. C **75** (2015) no.12, 577 [arXiv:1307.1688 [hep-ph]].

Top$-\gamma$ couplings





- Photoproduction of $t\bar{t}$ directly proportional to $t\bar{t}\gamma$ vertex
- Generic effective model independent parametrisation:

$$\mathcal{L}_{t\bar{t}\gamma} = e\bar{t}\left(\lambda Q_t \gamma^\mu A_\mu + \frac{1}{4m_t}\sigma_{\mu\nu}V^{\mu\nu}(\kappa_V + i\tilde{\kappa}_V\gamma_5)\right)t$$

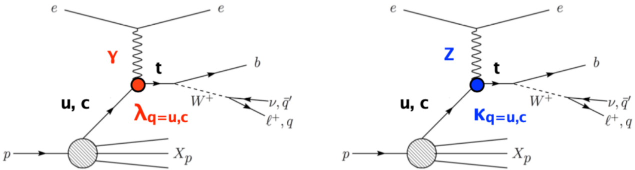
with anomalous magnetic and electric dipole moments κ and $\tilde{\kappa}$

Bouzas and Larios, Phys. Rev. D **88** (2013) no.9, 094007 [arXiv:1308.5634 [hep-ph]].

- Recent analysis (anomalous dipole moments) at the detector level incl. several backgrounds and systematics (18%).

New results from Bouzas and Larios, [arXiv:2111.04723 [hep-ph]].

Flavor changing neutral currents with top quarks



- Single top quark searches are sensitive to FCNC tqV:

$$\mathcal{L}_{FCNC}^{qV} = \frac{g}{\Lambda_V} \bar{t} \sigma^{\mu\nu} (\lambda_{qV}^L P_L + \lambda_{qV}^R P_R) q V_{\mu\nu} + \text{h.c.}$$

$q = u, c, \; V = \gamma, Z$

- These couplings also give rise to FCNC top decays: $t \to Vq$
- Process $e^- p \to e^- W^+ b + X$
- Analysis at the detector level yields sensitivity of $\lambda_{q\gamma} = 0.0025$ and $\lambda_{qZ} = 0.0037$ at 2σ for 1/ab.

Cakir *et al.*, Nucl. Phys. B **944** (2019), 114640 [arXiv:1809.01923 [hep-ph]].

The Large Hadron-Electron Collider at the HL-LHC – chapter 8

Beyond the Standard Model studies at *ep*

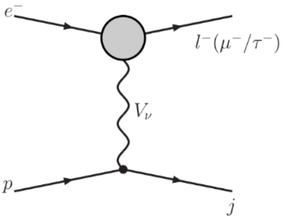
- **Electron-proton collider** ideal laboratory to study common features of electrons and quarks with EW / VBF production, LQ,multi-jet final states, forward objects
- **Upside:**
  - Small background (no QCD interaction between e and p)
  - Very low pileup
- **Downside:** low production rates for new physics processes due to small $\sqrt{s}$
- Increased engagement from theory community in recent years, summarised in "chapter 8" (almost 100 articles).

Here: brief overview over some of the "latest" contributions.

Searching for charged lepton flavor violation at ep colliders

S. Antusch, A. Hammad and A. Rashed, JHEP **03** (2021), 230 [arXiv:2010.08907 [hep-ph]].

Lepton flavor violating processes

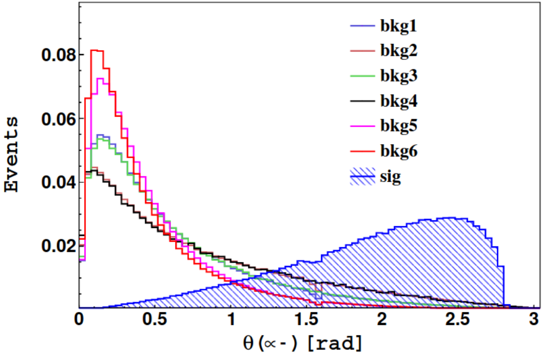


- An effective vertex couples incoming electron to a muon or a tau and a neutral scalar or vector boson.
- Flavor changing physics parametrised via an effective vertex coupling of leptons with Higgs, photon, and Z.
- Analysis for the LHeC at the detector level.

Backgrounds: small cross sections, well separable

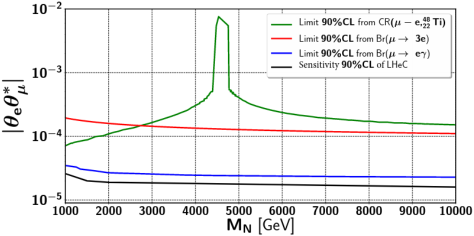
#	Backgrounds τ final state	$\sigma_{(LHeC)}[Pb]$
bkg1	$pe^- \to Z/\gamma^*(\to \tau^-\tau^+)\ \nu_l\ j$	0.0316
bkg2	$pe^- \to W^\pm(\to \tau^\pm\ \nu_\tau)\ e^-\ j$	0.2657
bkg3	$pe^- \to ZZ(\to \tau^-\tau^+)\ \nu_l\ j$	1.1×10^{-5}
bkg4	$pe^- \to Z(\to \tau^-\tau^+)W^\pm(\to \tau^\pm\ \nu_\tau)\ \nu_l\ j$	2.64×10^{-5}

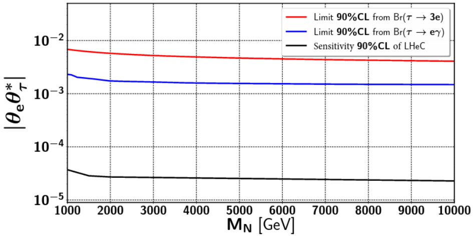
#	Backgrounds μ final state	$\sigma_{(LHeC)}[Pb]$
bkg1	$pe^- \to Z/\gamma^*(\to \mu^-\mu^+)\ \nu_l\ j$	0.0316
bkg2	$pe^- \to W^\pm(\to \mu^\pm\ \nu_\mu)\ e^-\ j$	0.2657
bkg3	$pe^- \to Z/\gamma^*(\to \tau^-\tau^+ \to \text{leptons})\ \nu_l\ j$	9.1×10^{-4}
bkg4	$pe^- \to W^\pm(\to \tau^\pm\ \nu_\tau \to \text{leptons})\ e^-\ j$	0.0451
bkg5	$pe^- \to ZZ(\to \mu^-\mu^+)\ \nu_l\ j$	1.1×10^{-5}
bkg6	$pe^- \to Z(\to \mu^-\mu^+)W^\pm(\to \mu^\pm\ \nu_\mu)\ \nu_l\ j$	2.64×10^{-5}



Cut-based optimisation of signal-to-background ratio.

Sensitivity to flavor violation



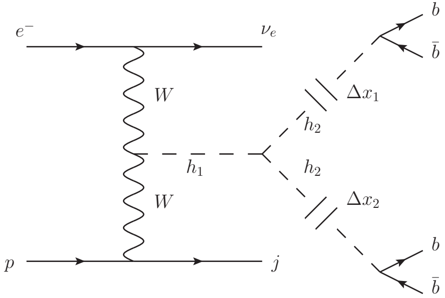


- Model independent limits on form factors for LHeC.
- Recast in specific model, here: sterile neutrinos.
- Flavor violation proportional to $|\theta_e\theta^*_\alpha|$

Exotic Higgs decays into displaced jets at the LHeC

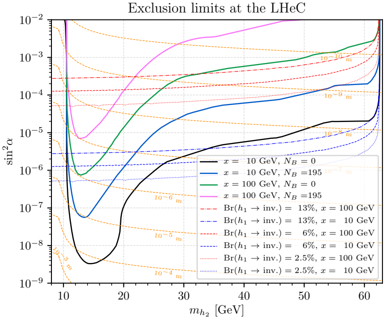
K. Cheung, O. Fischer, Z. S. Wang and J. Zurita, JHEP **02** (2021), 161 [arXiv:2008.09614 [hep-ph]].

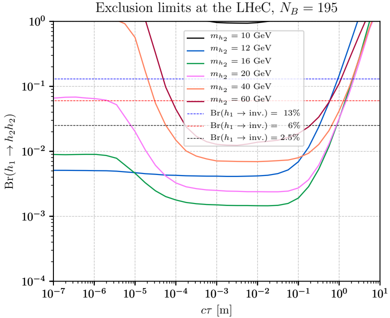
Extending the SM with a complex neutral scalar singlet S



- S can couple to and mix with the SM Higgs field.
- Physical fields: h_1 ('Higgs'), h_2 with $m_{h_2} = \mathcal{O}(10)$ GeV.
- h_2 production at LHeC: $h_1 \to 2h_2$ with small branching ratio.
- Decay rate of h_2 suppressed by mixing $\Rightarrow$ long-lived particle

Sensitivity





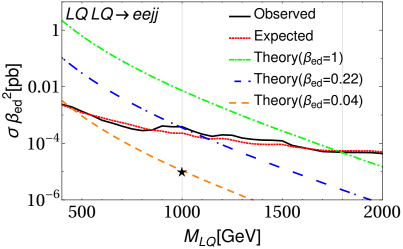
- Consider only CC Higgs production: $e^-p \to \nu_e h_1 j$.
- $h_1 \to 2h_2 \to 4b$ with two displaced vertices.
- Analysis at the detector level.
- From events with $n_{jet} \geq 5$, reconstruct m_{h_2}, require displacement. "Delphes with displacement." https://sites.google.com/site/leftrighthep/delphes.
- Inclusive backgrounds: $e^-p \to \nu_e + n_b b + n_j j + n_\tau \tau$

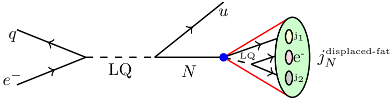
Displaced Neutrino Jets at the LHeC

G. Cottin, O. Fischer, S. Mandal, M. Mitra and R. Padhan,
[arXiv:2104.13578 [hep-ph]].

Leptoquark $\tilde{R}_2$ and longlived sterile neutrino

$$\mathcal{L}_{LQ} = -Y_{ij}\bar{d}^i_R \tilde{R}^a_2 \epsilon^{ab} L^{j,b}_L + Z_{ij}\bar{Q}^{i,a}_L \tilde{R}^a_2 N^j_R + \text{H.c.}$$





- Heavy neutrino N with mass $\sim GeV$; long lived particle.
- $\tilde{R}$ with dominant branching into qN difficult to study at LHC.
- Can be produced in ep collisions via $\tilde{R}$: $ep \to \tilde{R} \to jN$, with $N \to$ displaced fat jet.
- 5σ with 120 fb^{-1} for $M_N \sim 10$ GeV and $\tilde{R}Nq$ coupling ~ 0.1.
- Significant improvement from positron-proton scattering.

Doubly Charged Higgs Production at Future ep Colliders

X. H. Yang and Z. J. Yang, [arXiv:2103.11412 [hep-ph]].

Extending the SM with a $SU(2)_L$ triplet scalar: Δ

- Motivation: type II seesaw for neutrino masses:

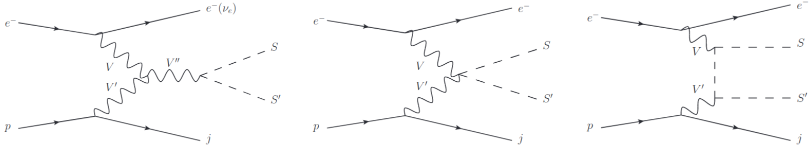
$$\mathcal{L}_{Y_\Delta} = Y_\Delta \overline{\ell^c} i\sigma^2 \Delta \ell + H.c.$$

$$\Rightarrow m_\nu = Y_\Delta \sqrt{2} v_\Delta$$

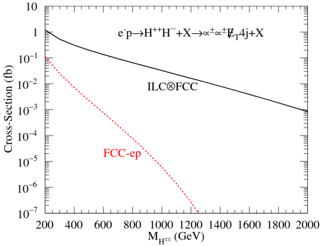
- Lepton flavor violating processes $\tau \to \bar{l}_i l_j l_k$ and $\mu \to \bar{e}ee$ mediated at tree level and constrain Y_Δ.
- Constraints from precision measurements: $v_\Delta \leq 1$ GeV.
- LHC searches for doubly charged scalars only stringent when $H^{\pm\pm} \to \ell^\pm \ell^\pm$ is the dominant decay mode.

cf. also S. Antusch et al., JHEP **02** (2019), 157 [arXiv:1811.03476 [hep-ph]].

Searching doubly charged scalars at FCC-he



- Scalar production via vector boson fusion.
- Search for two doubly (and singly) charged scalars, decaying to 2SSμ plus jets.
- Signal: analytical calculation $\rightarrow$ simulation with vegas.
- Background: $e^- p \rightarrow e(\nu_2)t\bar{t}W^{\pm}j \rightarrow$ Madgraph5.

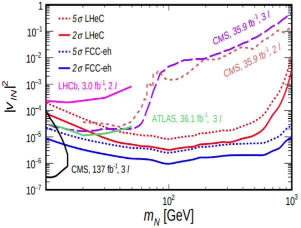


Other recent articles

"Search for heavy Majorana neutrinos at electron-proton colliders," [arXiv:2201.12997 [hep-ph]].

- By H. Gu and K. Wang.
- Analysis at detector level with boosted decition tree.
- Sensitivity similar to lepton-number conserving signatures,

$\Rightarrow$ Background free to excellent approximation.



- A. Jueid, J. Kim, S. Lee and J. Song, **"Studies of nonresonant Higgs pair production at electron-proton colliders,"** [arXiv:2102.12507 [hep-ph]].
- K. Cheung and Z. S. Wang, **"Physics potential of a muon-proton collider,"** [arXiv:2101.10476 [hep-ph]].
- G. D. Kribs, D. McKeen and N. Raj, **"Breaking up the Proton: An Affair with Dark Forces,"** Phys. Rev. Lett. **126** (2021) no.1, 011801 [arXiv:2007.15655 [hep-ph]].
- A. Gutiérrez-Rodríguez, M. A. Hernández-Ruíz, E. Gurkanli, V. Ari and M. Köksal, **"Study on the anomalous quartic $W^+W^-\gamma\gamma$ couplings of electroweak bosons in e^-p collisions at the LHeC and the FCC-he,"** Eur. Phys. J. C **81** (2021) no.3, 210 [arXiv:2005.11509 [hep-ph]].

Conclusions

- Top and BSM in electron-proton generated a lot of interest in the pheno community.
- Driving factor: complementary to pp and ee colliders.
- Opportunities for precision measurements of top physics:
  - Single top and $t\bar{t}$ production;
  - top couplings to γ, Z, W, and FCNC interactions.
- Opportunities for BSM that is hidden at the LHC:
  - Displaced vertices from long lived particles;
  - Lepton flavor violation (electron-tau);
  - Not-too-heavy scalars;
  - GeV-scale bosons.