BSM physics at the LHeC and the FCC-eh

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Deep Inelastic Scattering Conference
13/04/21

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}, earliest start 2032

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 – chapter 8

Beyond the Standard Model studies at *ep*

- Motivation for BSM at least as strong as ever, cf.

  Website listing known anomalies:
  https://hepcomm.github.io/hepmist/

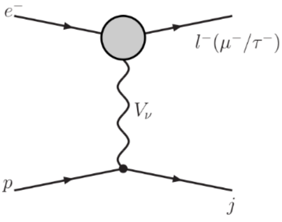
- **Electron-proton collider** ideal laboratory to study common features of electrons and quarks with EW / VBF production, LQ,multi-jet final states, forward objects
- **Upside:**
  - Small background (no QCD interaction between e and p)
  - Very low pileup
- **Downside:** low production rates for new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

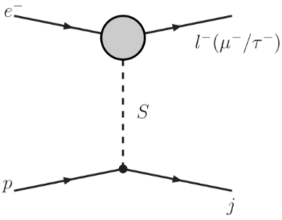
Here: short overview over some of the latest contributions.

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



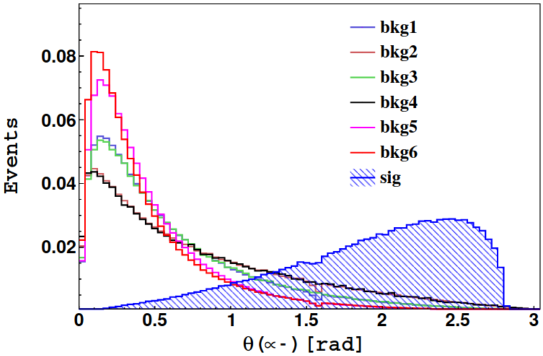


- An effective vertex couples incoming electron to a muon or a tau and a neutral scalar or vector boson.
- Flavor changing physics parametrised via an effective vertex coupling of leptons with Higgs, photon, and Z.
- Analysis at the reconstructed level.

Backgrounds: small cross sections, well separable

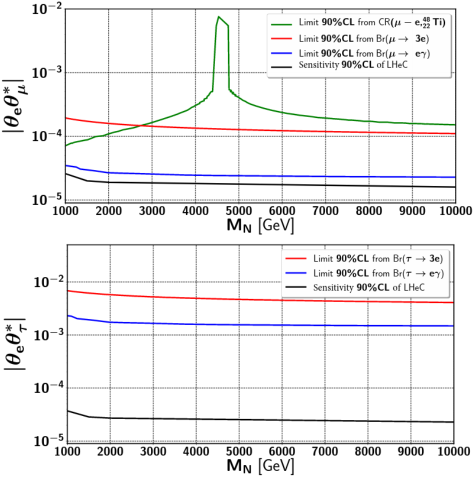
#	Backgrounds τ final state	$\sigma_{(LHeC)}[Pb]$
bkg1	$pe^- \to Z/\gamma^*(\to \tau^-\tau^+)\ \nu_l\ j$	0.0316
bkg2	$pe^- \to W^\pm(\to \tau^\pm\ \nu_\tau)\ e^-\ j$	0.2657
bkg3	$pe^- \to ZZ(\to \tau^-\tau^+)\ \nu_l\ j$	1.1×10^{-5}
bkg4	$pe^- \to Z(\to \tau^-\tau^+)W^\pm(\to \tau^\pm\ \nu_\tau)\ \nu_l\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

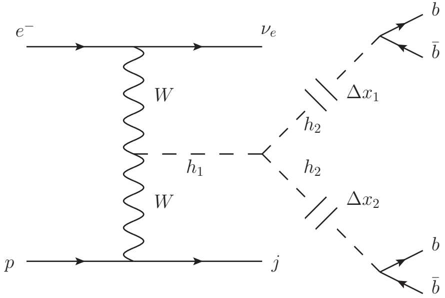


- Model independent limits on form factors.
- Recast in specific model, e.g. sterile neutrinos.
- Flavor violation proportional to $|\theta_e \theta_\alpha *|$

Exotic Higgs decays into displaced jets at the LHeC

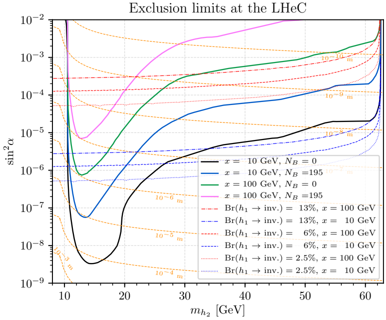
K. Cheung, O. Fischer, Z. S. Wang and J. Zurita, JHEP **02** (2021), 161 [arXiv:2008.09614 [hep-ph]].

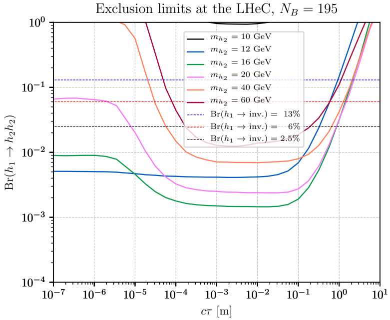
Extending the SM with a complex neutral scalar singlet S



- 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



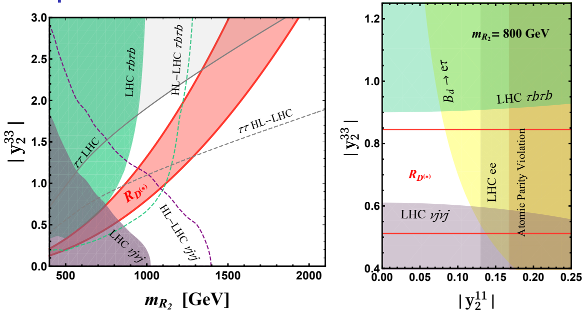


- Consider only CC Higgs production: $e^- p \to \nu_e h_1 j$.
- $h_1 \to 2h_2 \to 4b$ with two displaced vertices.
- Analysis at the reconstructed level.
- From events with $n_{jet} \geq 5$, reconstruct m_{h_2}, require displacement. "Delphes with displacement." https://sites.google.com/site/leftrighthep/delphes.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

Testing the $R_{D^{(*)}}$ Anomaly at the LHeC

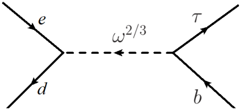
G. Azuelos, O. Fischer and S. Jana, [arXiv:2012.11514 [hep-ph]].

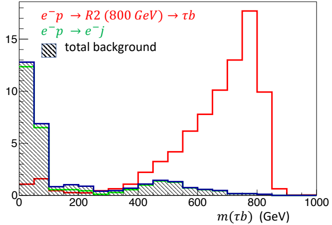
The R_2 Leptoquark



- Extend the SM with the $R_2 = \begin{pmatrix} \omega^{5/3} \\ \omega^{2/3} \end{pmatrix}$ leptoquark.
- Yukawa couplings of R_2: $q_R L_L \propto y_1$ and $Q_L \ell_R \propto y_2$
- The component $\omega^{2/3}$ can explain the R_{D^*} anomaly: $\mathrm{Br}(B^0 \to B^{*-}\tau^+\nu_\tau)/\mathrm{Br}(B^0 \to B^{*-}\mu^+\nu_\mu)$
- LHC: R_2 pair produced, limits on 3^{rd}-generation searches, di-lepton, jets plus MET, ...
- Also: atomic parity violation, rare B meson decays.

Signature at LHeC





- s-channel resonance with τb final state.
- Cross section proportional to y_1^{11}.
- Fix $y_1^{23} = 1$, y_1^{33} to explain $R_{D^{(*)}}$.
- Analysis at the reconstructed level, including several background processes, corrected LQ mass.
- LHeC is sensitive to $y_2^{11} \sim 0.02$ for $m_{R_2} = 800$ GeV.

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:

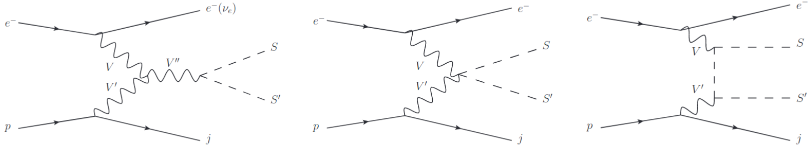
$$\mathcal{L}_{Y_\Delta} = Y_\Delta \bar{\ell^c} i\sigma^2 \Delta \ell + H.c.$$

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

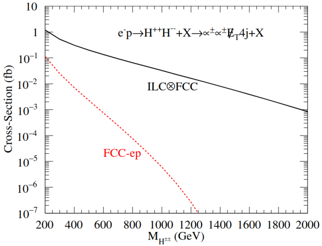
- Lepton flavor violating processes $\tau \to \bar{l}_i l_j l_k$ and $\mu \to \bar{e}ee$ mediated at tree level and constrain Y_Δ.
- Constraints from precision measurements: $v_\Delta \leq 1$ GeV.
- LHC searches for doubly charged scalars only stringent when $H^{\pm\pm} \to \ell^\pm \ell^\pm$ is the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

- M. Mitra *et al.*,
  "Displaced Neutrino Jets at the LHeC," [arXiv:2104.ASAP [hep-ph]].
- 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

- The LHeC generates a lot of interest in the pheno community.
- Driving factor: complementary to pp and ee colliders.
- 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.
- Not to forget:
  - ⋆ *ep* is essential to fully exploit pp measurements due to PDF.
  - ⋆ Adds significantly to Higgs and electroweak measurements.