Physics Beyond the Standard Model - I

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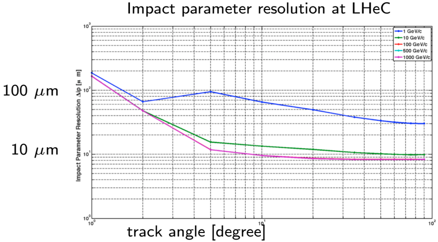
Electrons for the LHC
Chavannes de Bogis, 24.10.19

Introduction

BSM at electron-proton colliders:

- Ideal laboratory to study BSM physics with, e.g.:
  - dominant EW / VBF production;
  - signatures that are buried in QCD backgrounds;
  - Leptoquarks ($\rightarrow$ Georges Azuelos);
  - New physics in tops ($\rightarrow$ Christian Schwanenberger).
- Disadvantages compared with hadron colliders:
  - Limited $\sqrt{s}$;
  - Lower production rates (there are exceptions).
- Lately, **strong cooperation** between theory and experiment.
  $\Rightarrow$ Only few selected analyses discussed here.
- The bird's eye: systematic advantages of ep over pp.

Advantages and complementarity with pp - I



From the CDR [arXiv:1206.2913]]

No pile up; excellent tracking; triggerless:

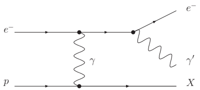
- Reconstruction of impact parameters/vertex displacements.
- Low energy thresholds $\Rightarrow$ sensitivity to soft particles.
- Excellent for: long lived particle searches.

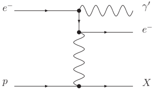
$\Rightarrow$ Examples: dark photon, Higgsinos.

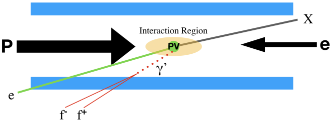
Dark Photons

M. D'Onofrio, OF, Z. S. Wang; arXiv:1909.02312 [hep-ph].

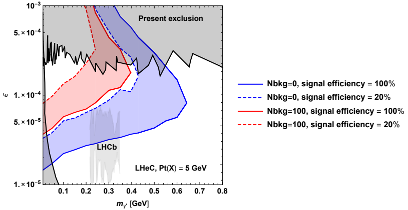
parton level analysis





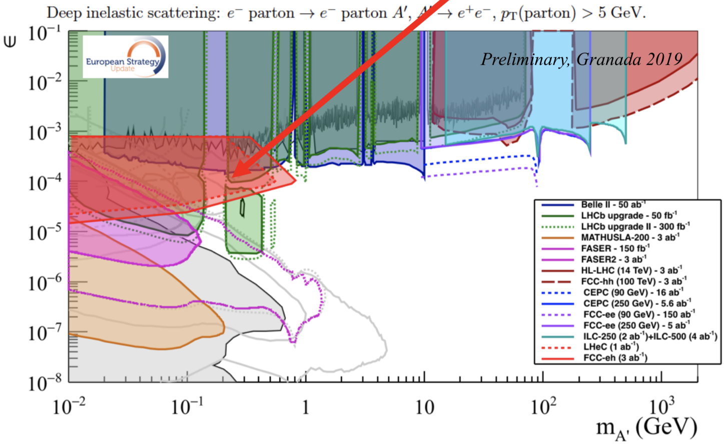


- Vector portal:
  $$\frac{-\epsilon}{2\cos\theta_W} F'_{\mu\nu} B^{\mu\nu}$$
- $e^- p \to e^- X \gamma'$ and $\gamma' \overset{\text{displaced}}{\to} x^\pm x^\mp$.
- Low momentum transfer; small scattering angles.
- γ' typically emitted from the electron with small angle.
- $x^\pm$ spiral along the beam pipe close to the scattered electron.



- No SM background process.
- Different assumptions on bkg and reconstruction efficiency.

Prospects for LHeC (1 ab^{-1}) and FCC-eh (3 ab^{-1})

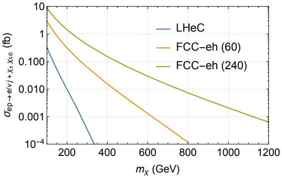


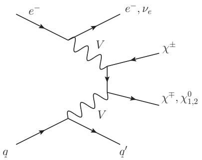
Gaia Lanfranchi; ESPP in Granada

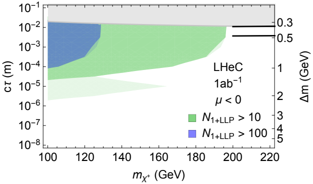
Long-lived Higgsino searches

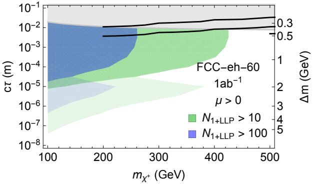
D. Curtin *et al.*; JHEP **1807** (2018) 024

parton level analysis incl. hadronisation







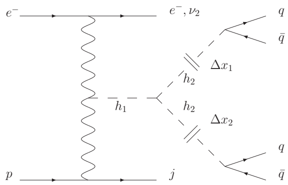


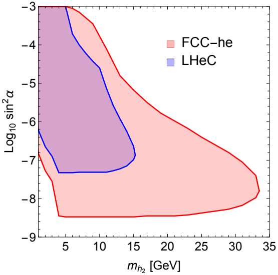
- Decay products $P_T = \mathcal{O}(100)$ MeV very short lifetime $c\tau \sim \mu$m
- Production via vector boson fusion
- Beam remnant jet $\Rightarrow$ primary vertex with $\mathcal{O}(10)\,\mu$m precision
- Signal: single soft displaced pion.
- Looks like hadronic noise@pp, but can be detected@ep!

1.1 TeV Higgsino (thermal relic DM) can be discovered with 240 GeV electron beams and 10/ab.

Exotic Higgs decays into LLPs

parton level analysis



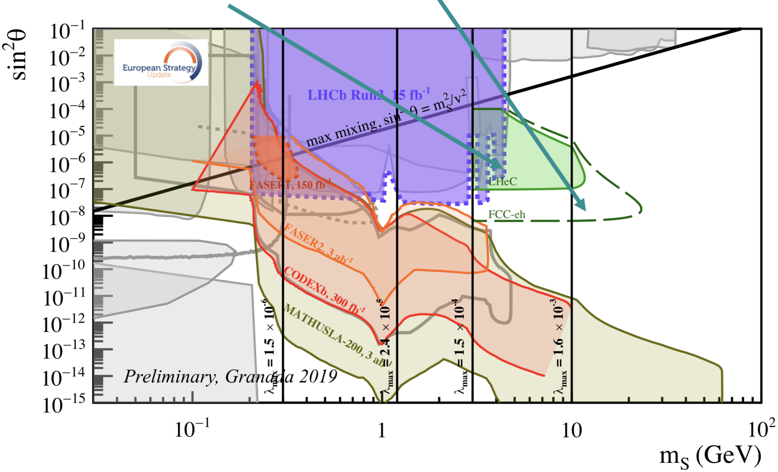


OF; *input for the ESPP*

- Scalar portal: $\lambda S^2 H^\dagger H$
- Higgs decays into a pair of long-lived scalars h_2:

  $pe^- \to \ell_e j\, h_1 \to \ell_e j\, 2h_2 \to \ell_e j\, 2(jj)_{\rm displaced}$
- Branching $\mathrm{Br}(h_1 \to 2h_2)$ and h_2 lifetime controlled by α.
- Assumption: $P_T > 400$ MeV, displacement $> 50\,\mu$m with 100% detection efficiency

Projections for LHeC (1 ab^{-1}) and FCC-eh (3 ab^{-1}) - (fixed λ=4x10^{-3}).



Gaia Lanfranchi; ESPP in Granada

Advantages and complementarity with pp - II

Large luminosity and low number of backgrounds:

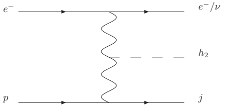
- Compared to LHC:
  - no QCD interactions between initial states,
  - no di-top and suppressed VV, VVV.
- Excellent for: BSM with mass scale $\sim v_{\mathrm{EW}}$.
- This is important: Mellado *et al.*; [arXiv:1901.05300]

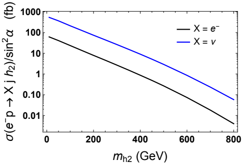
$\Rightarrow$ Examples: heavy scalar boson, sterile neutrinos.

Heavy scalar boson

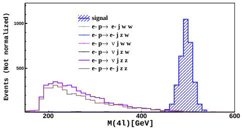
L. Delle Rose, OF, A. Hammad; Int. J. Mod. Phys. A **34** (2019) no.23, 1950127

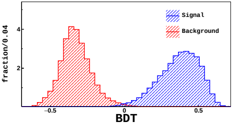
analysis at the reconstructed level; charged Higgses in George's talk

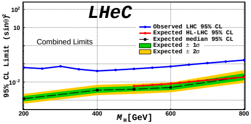




- Mass eigenstates: $\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} H \\ S \end{pmatrix}$
- h_2 interaction strength: (SM Higgs with $m_h = m_{h_2}$) $\times \sin^2\alpha$.
- Madgraph, Pythia6 (patched), Delphes, boosted decision tree.

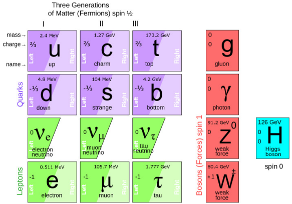


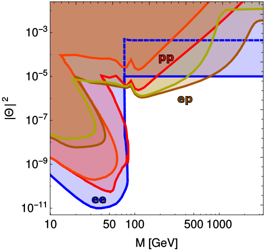




Sterile neutrinos - I

S. Antusch, E. Cazzato, OF; Int. J. Mod. Phys. A **32** (2017) no.14, 1750078

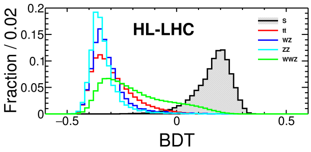




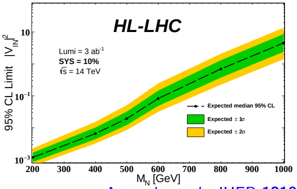
- Neutrino oscillations $\rightarrow$ type I seesaw
- Present constraints: $|\theta_e| \lesssim 10^{-5}$ to 10^{-3}
- Searches in many experiments possible:
  - Electroweak precision measurements
  - Higgs boson properties
  - Displaced vertices
  - "Bump hunt" for masses bigger than $\mathcal{O}(100)$ GeV.

Sterile neutrinos - II

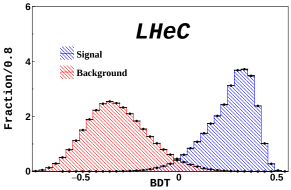
- Electron-positron colliders are ideal for $m_N < v_{\rm EW}$.
- Analyses: reconstructed level, 10^9 (10^7) events at pp (ep).
- Comparing sterile neutrino searches: pp vs. ep:



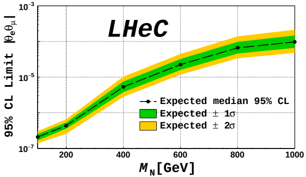
Background cross section $\mathcal{O}(10)$ pb



Antusch *et al.*; JHEP **1810** (2018) 067



Background cross section $\mathcal{O}(10)$ fb

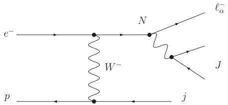


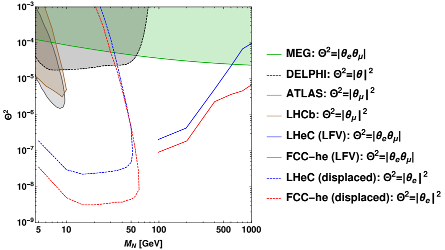
Antusch *et al.*; arXiv:1908.02852 [hep-ph]

Including 2% systematic uncertainty and 1/ab

Sterile neutrinos - III

Antusch *et al.*; arXiv:1908.02852 [hep-ph]





Promising signatures in electron-proton collisions:

- NB: production cross section not very much suppressed.
- Lepton-flavor violating final states: μ +jets, τ + jets (no MET):

  Tiny SM backgrounds, large signal-to-background ratio.
- Displaced vertices for $M_N < m_W$ (*parton level analysis*):

  Excellent vertexing and almost no conceivable backgrounds.

Recent other studies

- Light Sleptons and EWkinos — Wang, Iwamoto, D'Onofrio, Azuelos; *to be published*
- Lorentz invariance breaking — Michel, Sher; [arXiv:1909.10627]
- Doubly-charged Higgs bosons — Dev, Khan, Mitra, Rai, [arXiv:1903.01431]
- Axion-like particles — Yue, Liu and Guo, [arXiv:1904.10657]
- The Light gluino gap — Curtin, Deshpande, Fischer, Zurita, [arXiv:1812.01568].
- Leptoquarks and heavy neutrinos — Mandal, Mitra, Sinha; [arXiv:1807.06455].
- Prompt EWkinos — Han, Li, Pan, Wang, [arXiv:1802.03679]
- Effective Majorana Neutrinos — Duarte, Zapata, Sampayo; [arXiv:1802.07620]
- Georgi-Machacheck model — Azuelos, Sun, Wang; [arXiv:1712.07505]
- Extended Higgs sectors — Sun, Luo, Wei, Liu; [arXiv:1710.06284]
- ...

Many of these employ "standard LHC cut-and-count" analyses.

Conclusions

- Essential to fully exploit pp measurements $\rightarrow$ Claire Gwenlan.
- They offer a variety of opportunities for BSM searches:
  - Long lived particles;
  - Signals that are buried in hadronic backgrounds;
  - New physics with masses around $v_{\rm EW}$.
- Key features:
  - Excellent tracking and particle reconstruction;
  - Clean environment, low/no pile up;
  - Large luminosity.
- ep collider are complementary to pp and ee colliders.