New physics opportunities for LLPs at ep colliders

Kaustubh Deshpande
University of Maryland, College Park

work in collaboration with
David Curtin, Oliver Fischer, Jose Zurita (1712.07135)

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Motivation for LLPs

• Null results for BSM searches so far... (@ LHC, DM detection)

• Broad range of BSM theories generically featuring LLPs!
  - approximate symmetries, sequestration of sectors, modest mass hierarchies
  - e.g. SUSY (gauge mediation, RPV, mini-split), neutral naturalness, WIMP baryogenesis,
    FIMP DM, exotic Higgs decays

• LLPs form spectacular signals @ colliders!
  - only a few events could be needed for discovery
  - but missed by standard searches ... need for “lifetime frontier” search program
Lessons from LHC (for LLPs): Challenges

• **Short lifetimes (≤ mm)**
  no tracker coverage, large background

• **Soft decay products**
  large background (b-decays), high pile-up, final state reconstruction not possible
  e.g. from compressed spectrum of Higgsino LLPs

• **Long lifetimes (≥ 100 m)**
  external LLP detector e.g. MATHUSLA (Chou et al.)
Unique capabilities of electron-proton colliders (for LLPs)
Possible layout of LHeC/FCC-he
LHeC CDR (1206.2913)

- Linac-ring configuration
- 60 GeV $e^-$, 7 TeV $p^+$ ($E_{CM} = 1.3$ TeV)
- Integrated luminosity: 1 ab$^{-1}$
- Excellent tracking resolution: few $\mu$m
- FCC-he: 60 GeV $e^-$, 50 TeV $p^+$ ($E_{CM} = 3.5$ TeV)
BSM searches @ ep colliders

• HERA: lower $E_{CM}$ and $L_{int}$ $\rightarrow$ outclassed by Tevatron

• LHeC and FCC-he: existing BSM studies
  ... **specialized scenarios** with large signal rate @ ep
    e.g. leptoquarks, SM-BSM mixing, t-channel BSM mediator
  ... in almost all cases, **corresponding pp program has greater reach**

Any way out? What about more generic BSM??

**Hint**: surprisingly good capability of ep for studying Higgs (Tang et al., ...)
  $\rightarrow$ should focus on making use of the **lepton-collider-like clean environment**
General lesson... focusing on the final state

“BSM signal which looks like hadronic noise at pp colliders can be detected at ep colliders!”

• Example: signal from softly decaying, short-lived (~μm) LLPs

→ We should expect good sensitivity @ ep colliders!
   - no (or very low) pile-up, good tracking resolution, boosted final state
   ... with larger $E_{CM}$ than most lepton colliders
This comes from broad class of BSM theories!

- New particles with electroweak charges
  → VBF production possible @ ep... but lower cross section (due to $2 \rightarrow 4$)

- Small mass splitting due to EWSB loop effects → LLPs

\[ \Delta m^2 \sim \frac{g^2}{16 \pi^2} M^2 \]
Case study: Pure Higgsinos

• MSSM: gauge eigenstates to mass eigenstates

\[
(\tilde{W}^+, \tilde{H}_u^+) \rightarrow (\chi_1^+, \chi_2^+); (\tilde{B}^0, \tilde{W}_3^0, \tilde{H}_u^0, \tilde{H}_d^0) \rightarrow (\chi_1^0, \chi_2^0, \chi_3^0, \chi_4^0)
\]

• Decoupled Wino limit \((M_2 \rightarrow \infty)\) + Higgsino/Bino hierarchy \((\mu \ll M_1)\)

\[\chi^\pm \text{ and } \chi_1^0, \chi_2^0 \text{ form “compressed spectrum”}\]

• \(O(100 \text{ MeV})\) mass splitting, \((c \tau)_{\chi^\pm} \sim 7 \text{ mm}\)

\text{... for mass splitting} \sim \text{ few GeV}, \((c \tau)_{\chi^\pm} \leq \mu \text{m}\)

Using simplified model, Higgsino mixes with Bino
Searches at future pp colliders

- Disappearing Track search: (Mahbubani et al.)
  - LLP should reach inner tracking layers
  => no sensitivity at lifetimes \( \leq \text{mm} \)

- Monojet searches: (Low et al., ...)
  - modest mass reach
  - but no info of the invisible particle!

Compressed Higgsinos... one of the most challenging BSM scenario to probe at pp colliders!
Constraints from cosmology

- Thermal relic density: upper limit on mass
- DM direct detection:
  - DM – nuclear scattering via Higgs coupling
  - constrains short lifetimes
- DM indirect detection:
  - lower bound on thermal relic mass

But... cosmological bounds model-dependent!
e.g. if no stable DM (via hidden sector decay)

- need collider searches to confirm DM nature
- blind spots exist!
Higgsinos @ ep colliders

• Higgsino production via VBF: one or two charginos per event

\begin{align*}
\chi^\pm &\to \chi^{0}_{1,2} + \text{soft } \pi^\pm \text{ (or } e^\pm, \mu^\pm) \\
\text{- Asymmetric ep collision } &\to \text{ boosted } \chi^\pm (\gamma \beta \sim 5–10) \to (c\tau)_{\text{lab}} \text{ is more!}
\end{align*}
Analysis strategy

Jet identifies PV and provides trigger!

Search parameters/thresholds:

\[ r_0 = 5 \times \text{detector resolutions} = (25, 40, 80) \ \mu\text{m} \]

\[ p_{\text{min}}^T (\text{for pion}) = (50, 100, 400) \ \text{MeV} \]

(outgoing e\(^-\) not shown)

Disappearing track

single soft displaced pion

... unique capability!

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Analysis strategy

\[ \chi^\pm \rightarrow \chi_{1,2}^0 + (2+ \text{charged particles}) : \text{displaced vertex} \]

Only requirement... \( \chi^\pm \) decays beyond \( r_0 \)!
Results: LHeC

Can probe much shorter lifetimes (~ 10 μm) than HL-LHC (~ mm)!
Mass reach ~ monojet search at HL-LHC
Results: FCC-he

Hadronic and DV reconstruction uncertainties

HL-LHC / FCC-hh disappearing track searches

Mass reach greater than energy of (most) lepton colliders!

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Conclusions

• LLP searches are theoretically highly motivated!

• ep colliders have good sensitivity for short-lived (~μm), softly decaying LLPs
  ... inaccessible to other collider searches!

  - pure Higgsinos, exotic Higgs decays
  - 1.1 TeV Higgsino hard to probe even with FCC-he

• Covers broad class of BSM theories: new particles with electroweak charges, LLPs

General lesson:
BSM signal which looks like hadronic noise at pp colliders can be detected at ep colliders!
Thank you!
Back up slides...
Background (from tau leptons)

- ep collision $\rightarrow$ VBF production (1 or 2 tau) $\rightarrow$ beta-decay
  - same final states as charginos, $c\tau \sim 0.1 \text{ mm}$

- Tau final products are more central and energetic!
  - Kinematic cuts: $|\eta| > 1$, $\text{MET} > 30 \text{ GeV}$, $E_{\text{final}} < 1.5 \Delta m$
  - $10^{-3}$ ($10^{-4}$) background rejection for 1+LLP (2 LLP) events,
    keeping $O(1)$ fraction of the signal!

- $N_{\text{signal}}$ at $2\sigma = 50$ (10) for 1+LLP (2 LLP)
  - showing contours for $N_{\text{signal}} > 10$ and $> 100$
Tracking resolution \( r_0 \) and energy \( p_T^{\text{min}} \) thresholds

- \( r_0 \) threshold: affects reach at lowest lifetimes
- \( p_T^{\text{min}} \) threshold:
  - affects reach at larger lifetimes
  - for shorter \( c\tau \), larger mass splitting, no sensitivity to \( p_T^{\text{min}} \) cut

• Results robust w.r.t. variation in these thresholds
• Motivation to aim for \( p_T^{\text{min}} \sim 100 \text{ MeV} \), to reach \( m_\chi = 1.1 \text{ TeV} \)
Exotic Higgs decays @ ep colliders

• Highly motivated LLP production channel, BSM couplings to $|H|^2$

• VBF Higgs production, $h \rightarrow XX$, $X = BSM$ LLP

• $\text{Br}(h \rightarrow XX)$, $(c\tau)_X$ : free parameters ... focusing on $m_X \sim O(10 \text{ GeV})$

• Same search strategy as for Higgsinos...
  - $X \rightarrow 2+$ charged particles: DV signature
  - Invariant mass of DV $\sim 10$ GeV $\rightarrow$ tau background rejection
Exotic Higgs decays @ ep colliders

Can probe lifetimes \( \leq \mu m \)

Much more optimistic search...

Curtin et al.

Realistic search

ep colliders sensitive to much shorter lifetimes robustly than either projections at pp colliders!