New physics opportunities for LLPs at ep colliders

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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

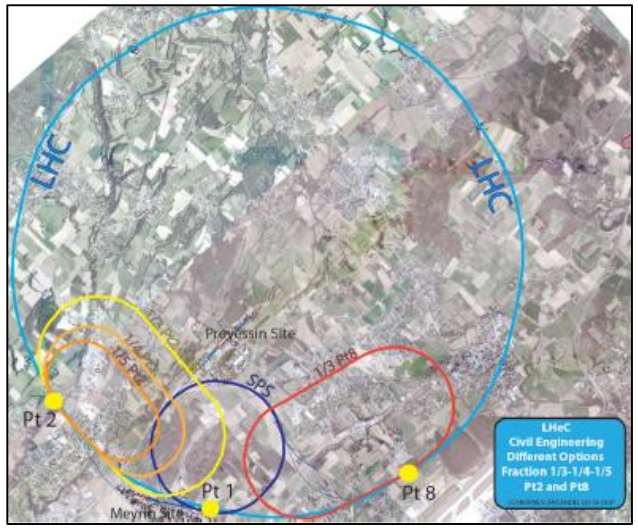
- Long lifetimes (≥ 100 m)

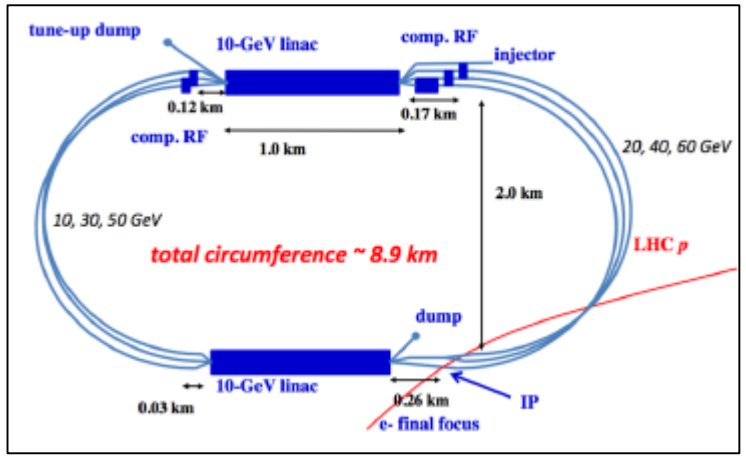
  external LLP detector e.g. MATHUSLA (Chou et al.)

Unique capabilities of electron-proton colliders (for LLPs)

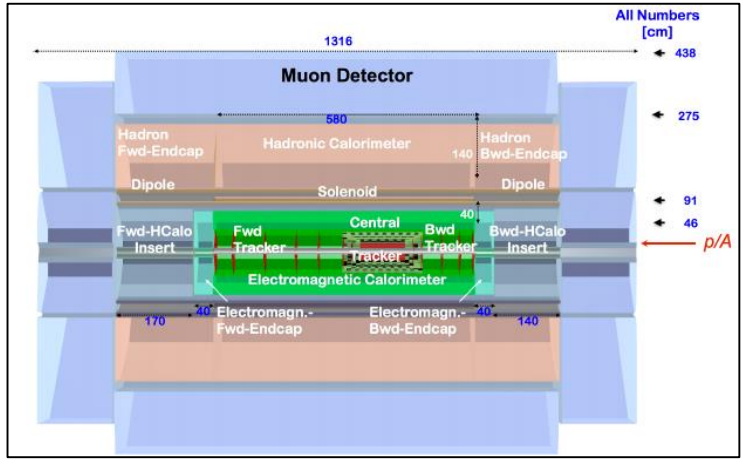
Possible layout of LHeC/FCC-he

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 µm
- FCC-he: 60 GeV e^-, 50 TeV p^+ (E_{CM} = 3.5 TeV)



BSM searches @ ep colliders

- HERA: lower E_{CM} and L_{int} → outclassed by Tevatron

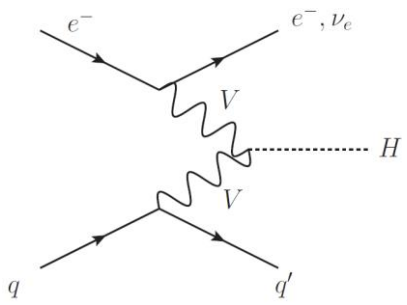
- LHeC and FCC-he: existing BSM studies

  … 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

LHeC CDR
Antusch et al.
Cakir et al.
Lindner et al. …



Any way out? What about more generic BSM??

Hint: surprisingly good capability of ep for studying Higgs (Tang et al., …)

→ 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

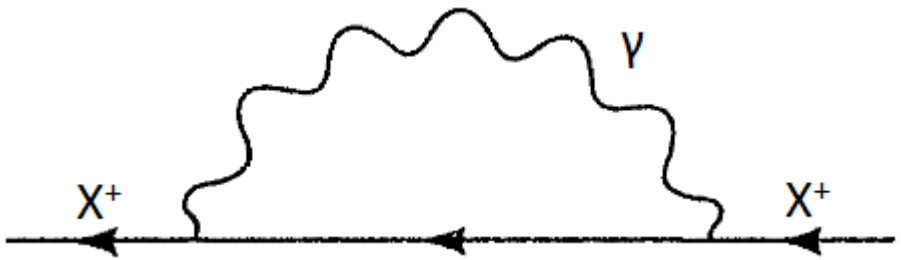
… with larger E_{CM} than most lepton colliders

This comes from broad class of BSM theories!

- New particles with electroweak charges

  → VBF production possible @ ep… but lower cross section (due to 2 → 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

$$(\widetilde{W}^{+}, \widetilde{H}_u^{+}) \rightarrow (\chi_1^{+}, \chi_2^{+})\,;\left(\widetilde{B}^{0}, \widetilde{W}_3^{0}, \widetilde{H}_u^{0}, \widetilde{H}_d^{0}\right) \rightarrow (\chi_1^{0}, \chi_2^{0}, \chi_3^{0}, \chi_4^{0})$$

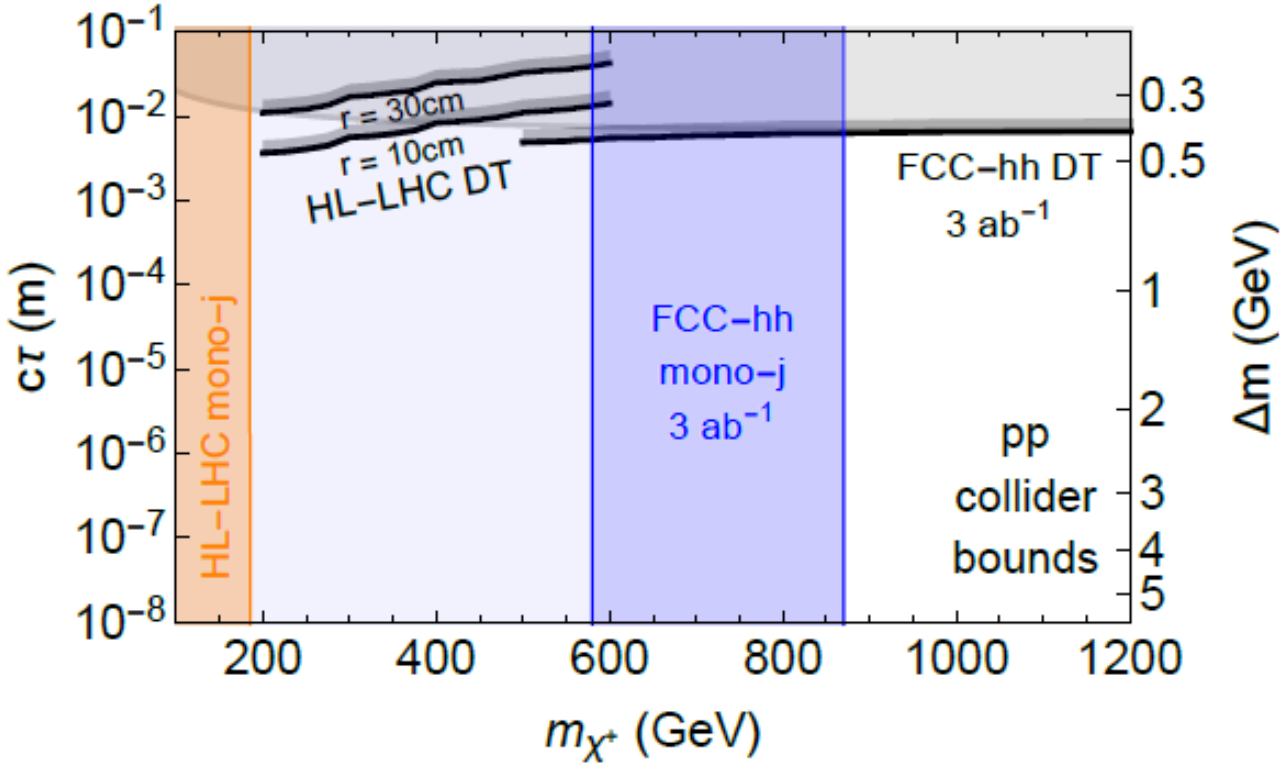
- Decoupled Wino limit ($M_2 \rightarrow \infty$) + Higgsino/Bino hierarchy ($\mu \ll M_1$)
  → $\chi^{\pm}$ and χ_1^0, χ_2^0 form "compressed spectrum"

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

  … for mass splitting ~ few GeV, $(c\tau)_{\chi^{\pm}} \leq \mu\mathrm{m}$

Using simplified model, Higgsino mixes with Bino

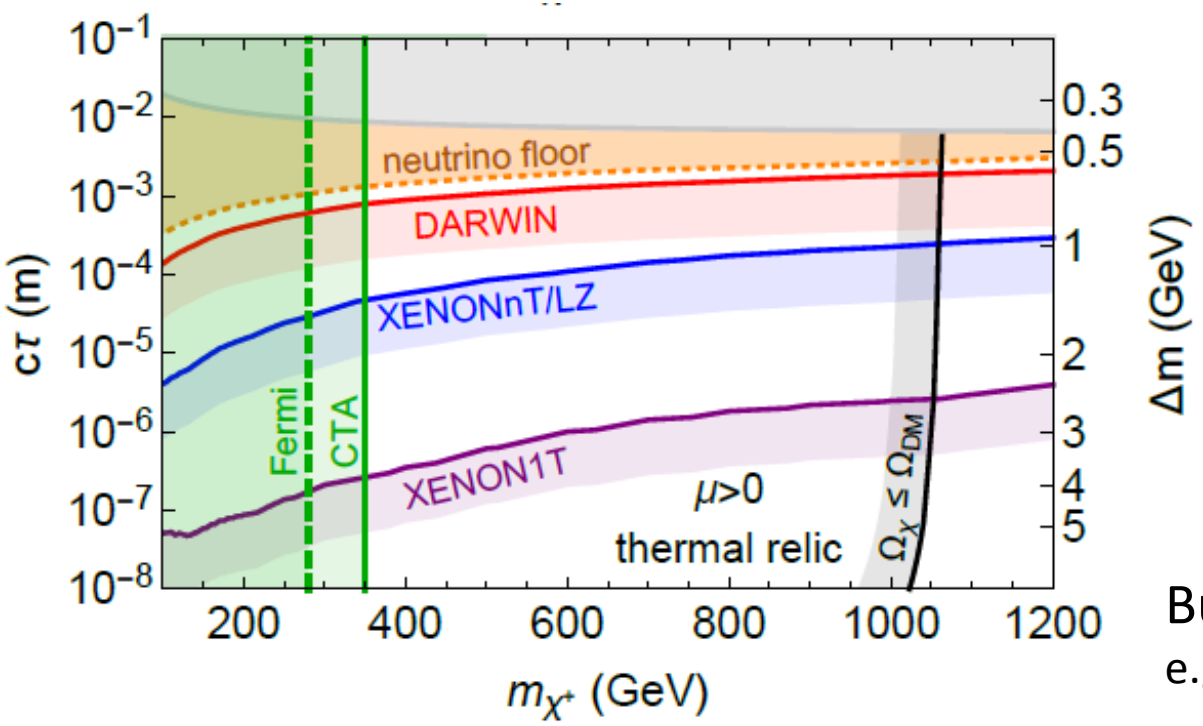
Searches at future pp colliders



- Disappearing Track search:
  (Mahbubani et al.)
  - LLP should reach inner tracking layers
  => no sensitivity at lifetimes ≤ 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



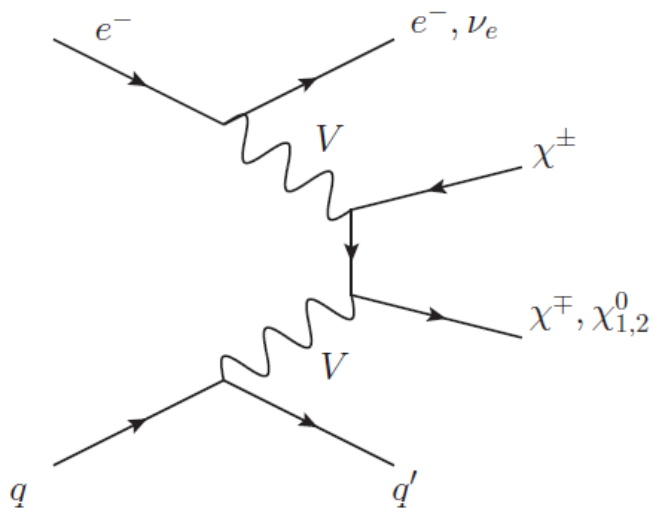
- Thermal relic density: upper limit on mass
- DM direct detection:
  - DM – nuclear scattering via Higgs coupling
  - constrains short lifetimes
- DM indirect detection:
  - lower bound on thermal relic mass

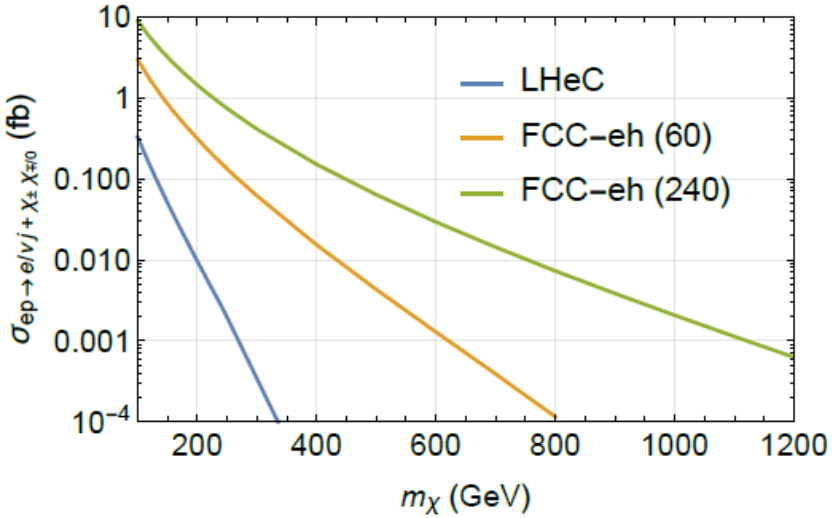
But… cosmological bounds model-dependent!
e.g. if no stable DM (via hidden sector decay)

- need collider searches to confirm DM nature
- blind spots exist!

Higgsinos @ ep colliders

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

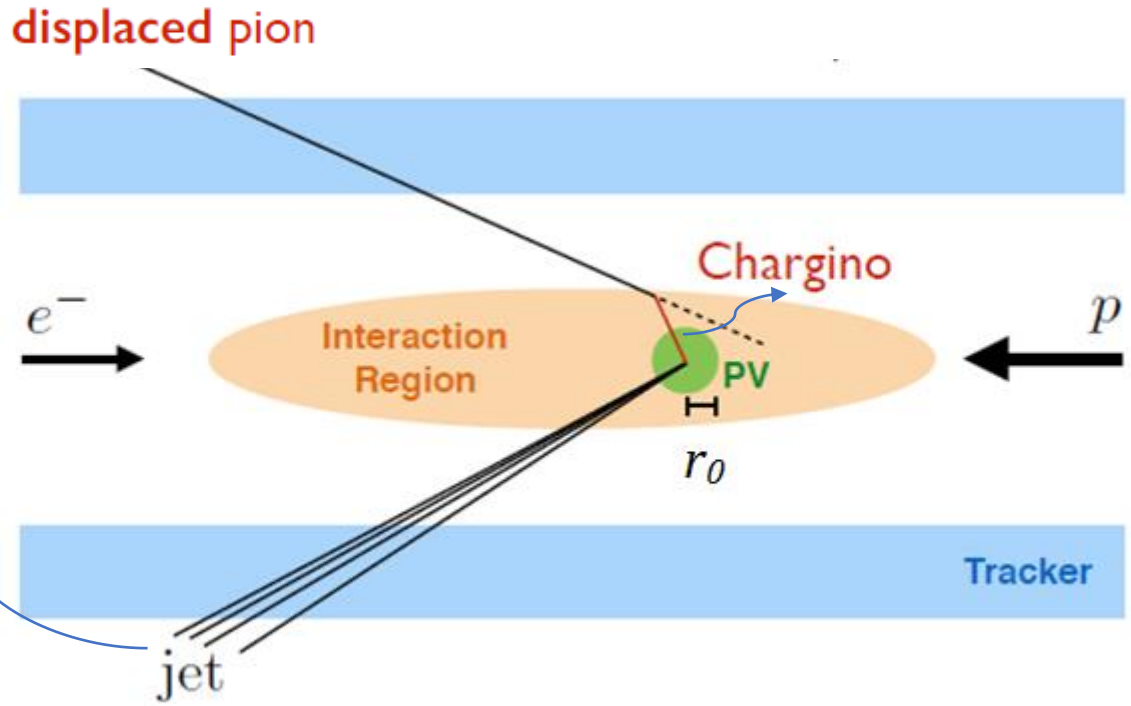




- Decay: $\chi^\pm \to \chi^0_{1,2}$ + soft $\pi^\pm$ (or $e^\pm, \mu^\pm$)

  - Asymmetric ep collision → boosted $\chi^\pm$ ($\gamma\beta \sim 5-10$) → $(c\tau)_{lab}$ is more!

Analysis strategy



(outgoing e^- not shown)

Disappearing track

↓

single soft displaced pion

… unique capability!

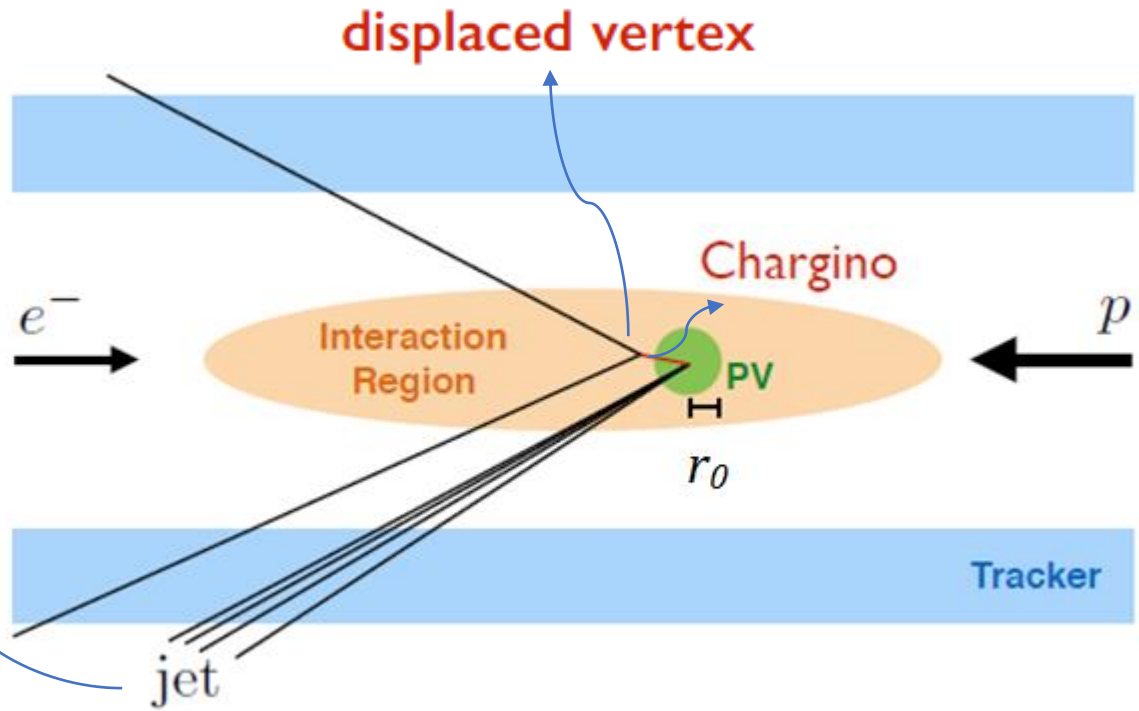
Jet identifies PV and provides trigger!

Search parameters/thresholds:

r_0 = 5 × detector resolutions = (25, 40, 80) μm

p^T_{min} (for pion) = (50, 100, 400) MeV

Analysis strategy



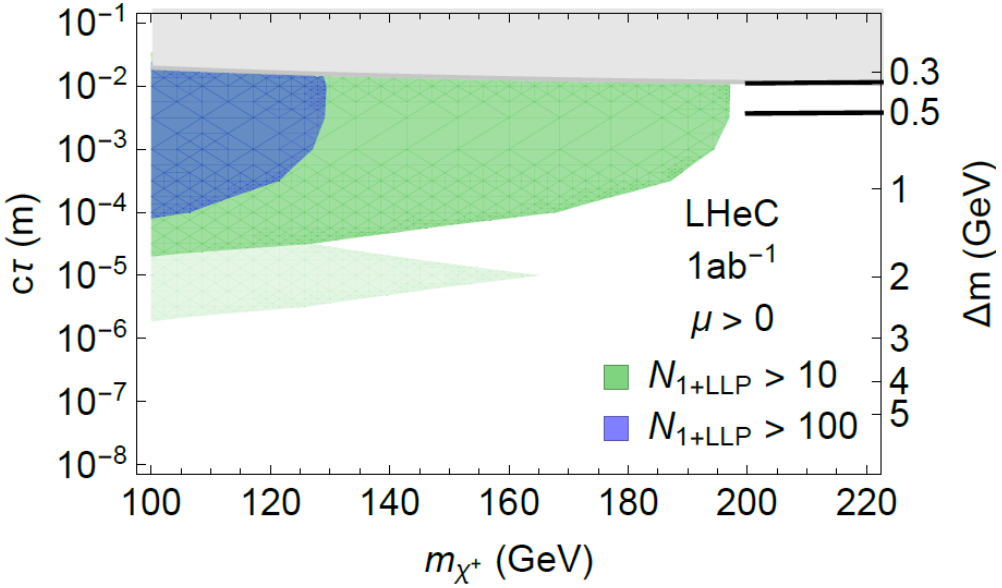
(outgoing e^- not shown)

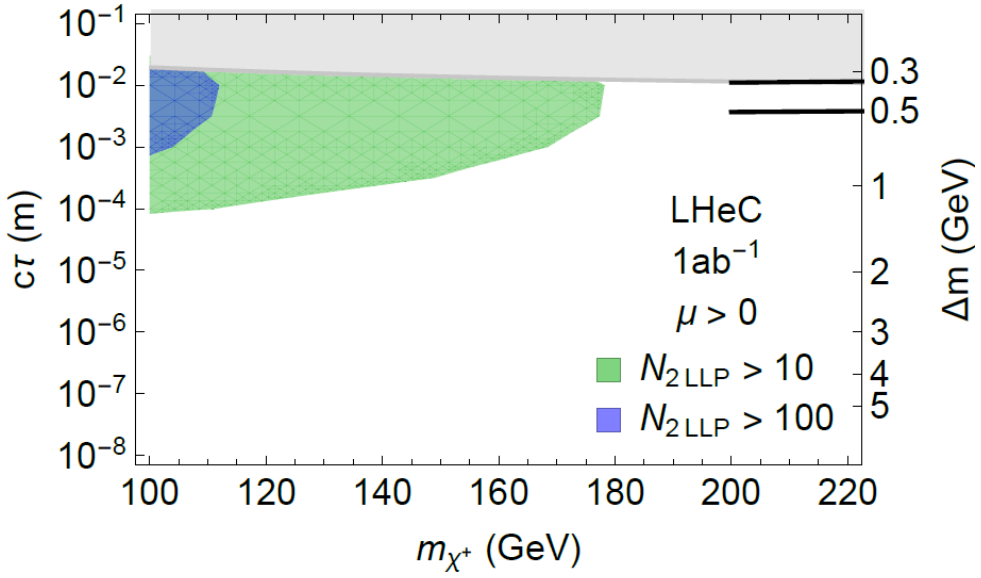
Jet identifies PV and provides trigger!

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

Only requirement… $\chi^{\pm}$ decays beyond r_0!

Results: LHeC

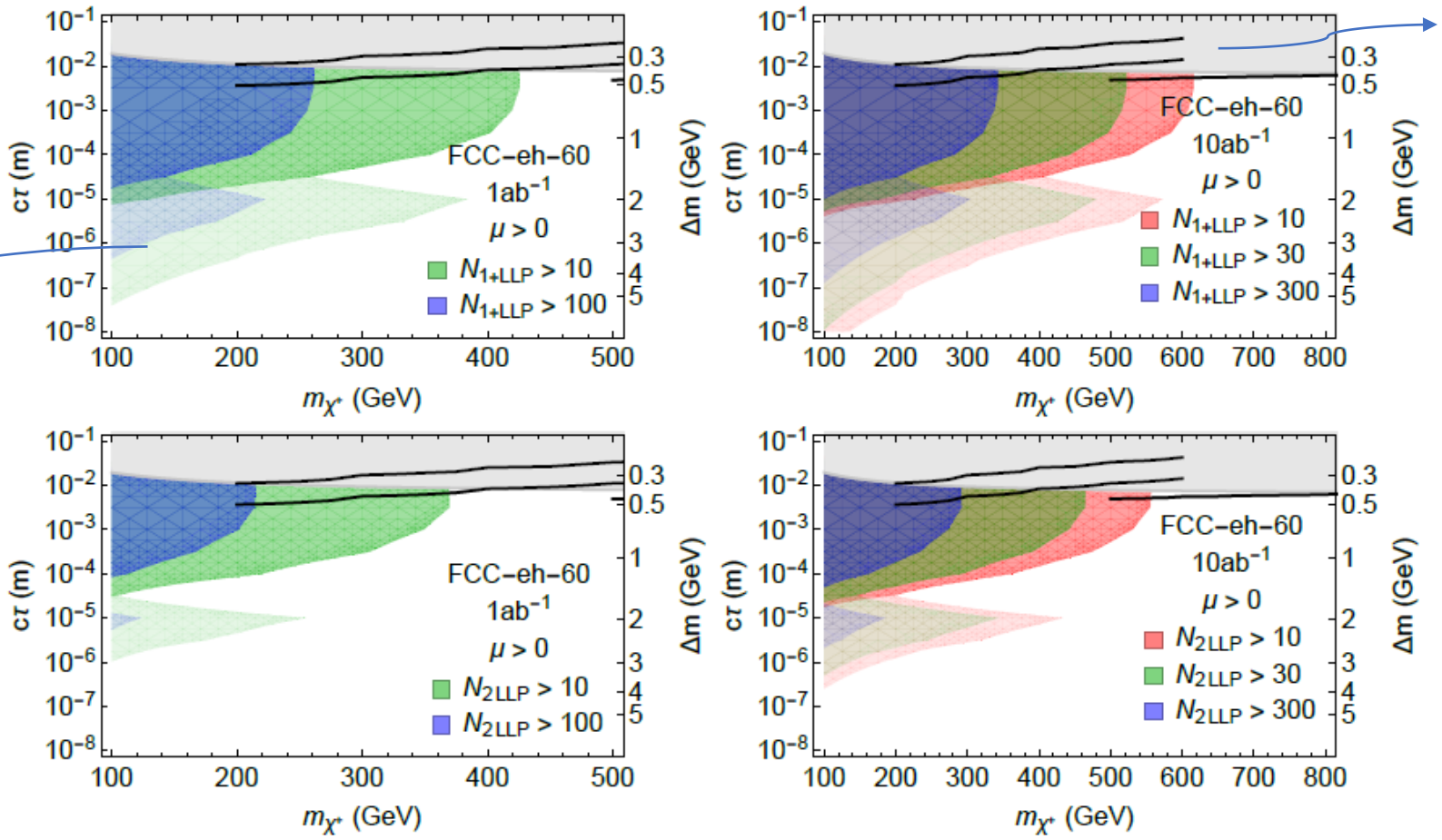




Can probe much shorter lifetimes (~ 10 μm) than HL-LHC (~ mm)!

Mass reach ~ monojet search at HL-LHC

Results: FCC-he



HL-LHC / FCC-hh disappearing track searches

Hadronic and DV reconstruction uncertainties

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

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)

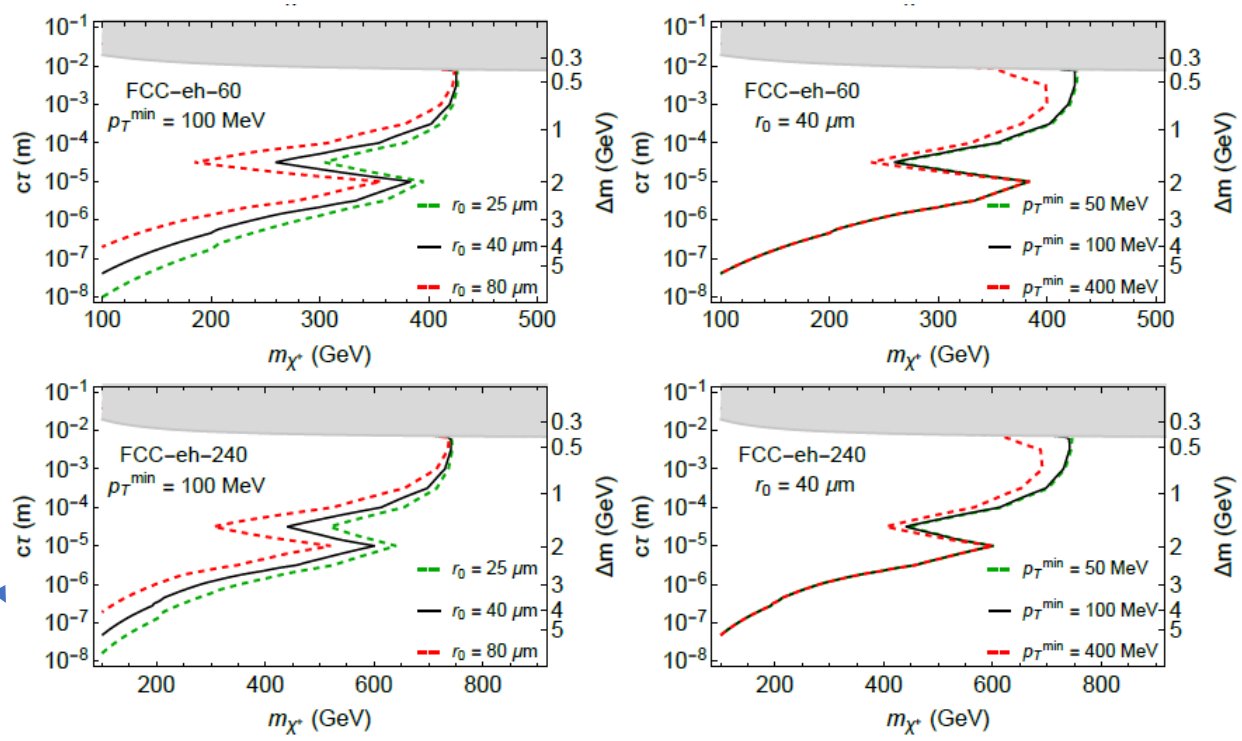
- ep collision → VBF production (1 or 2 tau) → beta-decay
  - same final states as charginos, $c\tau \sim 0.1\ \mathrm{mm}$

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

- N_{signal} at 2σ = 50 (10) for 1+LLP (2LLP)
  - showing contours for $N_{signal} > 10$ and > 100

Tracking resolution (r_0) and energy (p_T^{min}) thresholds

r_0 threshold:
affects reach at lowest lifetimes



p_T^{min} threshold:
- affects reach at larger lifetimes
- for shorter cτ, larger mass splitting, no sensitivity to p_T^{min} cut

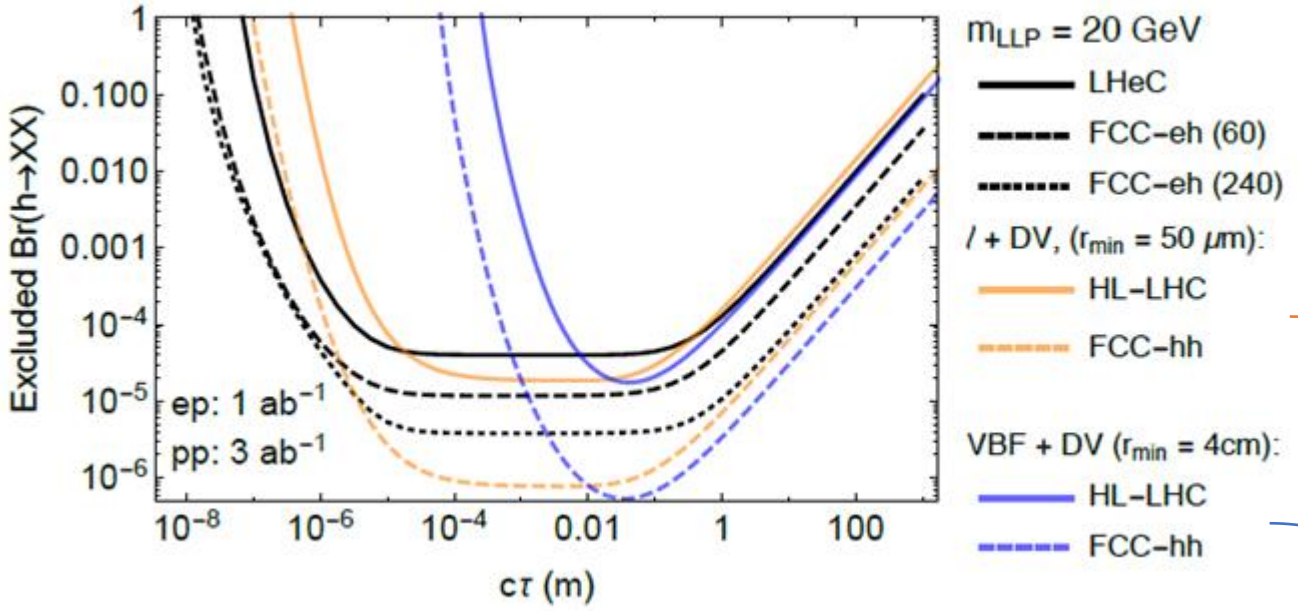
- Results robust w.r.t. variation in these thresholds
- Motivation to aim for $p_T^{min} \sim 100$ MeV, to reach $m_\chi = 1.1$ TeV

Exotic Higgs decays @ ep colliders

- Highly motivated LLP production channel, BSM couplings to $|\mathrm{H}|^2$
- VBF Higgs production, h → X X , X = BSM LLP
- Br(h → X X), $(c\tau)_X$: free parameters … focusing on $m_X \sim O(10\ \mathrm{GeV})$
- Same search strategy as for Higgsinos…
  - X → 2+ charged particles: DV signature
  - Invariant mass of DV ~ 10 GeV => tau background rejection

no soft decay products here!

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!