Disappearing charged tracks for compressed Dark Sectors

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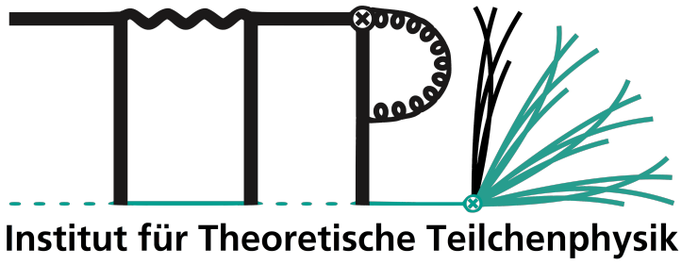


Based on:

R. Mahbubani, P. Schwaller, JZ [arXiv 1703.05327]

D. Curtin, K. Deshpande, O. Fischer, JZ [arXiv 1712.07135]

DM@LHC 2018, Heidelberg, 05.04.2018

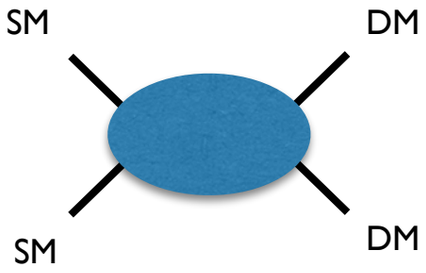
Outline

- Higgsino/Bino (Doublet/Singlet) phenomenology
- Disappearing tracks @ FCC-hh, HL-LHC.
- Displaced pions @ e-p colliders.

Higgsino/Bino (doublet/singlet) phenomenology

Particle Dark Matter?

- A plethora of cosmological and astrophysical probes of dark matter (CMB anisotropies, galaxy clusters, galaxy rotation curves, gravitational lensing, BBN, large scale structure formation,…) tell us:
  - DM is cold, non-baryonic, neutral under EM, lives in (1,N,ß).
  - Left-over abundance (relic density): $\Omega h^2 = 0.1198 \pm 0.0026$ [Planck]



SM and DM in thermal equilibrium.
Universe expands and cools down:
DM "freezes-out".

$$\Omega h^2 \sim 0.1 \left(\frac{0.01}{\alpha}\right)^2 \left(\frac{m}{100\ \mathrm{GeV}}\right)^2$$

  - Weakly Interacting (α=0.01) Massive (m=100 GeV) Particles give a relic density in the right ballpark: WIMP miracle (but only α/m is fixed!)
- Simplified models for DM as an EW multiplet:
  Minimal Dark Matter (Cirelli, Strumia, Fornengo, hep-ph/0512090)

Electroweakino Sector

$$\mathcal{M}_{\chi}^{\pm} = \begin{pmatrix} M_2 & \sqrt{2}\sin\beta M_W \\ \sqrt{2}\cos\beta M_W & \mu \end{pmatrix}$$

gauge eigenstates → mass eigenstates

$$\tilde{W}^+, \tilde{H_u}^+ \sim \chi_1^+, \chi_2^+$$

Charged winos and Higgsinos mix into *charginos* (2).

$$\mathcal{M}_{\chi}^{0} = \begin{pmatrix} M_1 & 0 & -c_\beta s_W M_Z & s_\beta s_W M_Z \\ 0 & M_2 & c_\beta c_W M_Z & -s_\beta c_W M_Z \\ -c_\beta s_W M_Z & c_\beta c_W M_Z & 0 & -\mu \\ s_\beta s_W M_Z & -s_\beta c_W M_Z & -\mu & 0 \end{pmatrix}$$

gauge eigenstates → mass eigenstates

$$\tilde{H_u}^0, \tilde{H_d}^0, \tilde{B}^0, \tilde{W_3}^0 \sim \chi_1^0, ..., \chi_4^0$$

Neutral Wino, neutral Higgsinos and bino mix into *neutralinos*

Too much hassle! Simplify by*:

1) decoupling the Wino ($M_2 \to \infty$) → 1 neutral and 1 charged state removed
2) taking a Higgsino/Bino hierarchy ($|\mu| << M_1$) → 1 neutral state removed

$$\mathcal{L} \supset -\frac{g}{c_w}\left(\frac{1}{2} - s_w^2\right)\bar{\chi}^+ \not{Z} \chi^- - e\bar{\chi}^+ \not{A} \chi^- - \frac{gI}{2c_w}\bar{\chi_1}^0 \not{Z}\gamma^5 \chi_2^0 - \frac{gm^2}{8c_w \mu M_1}\left(\frac{\bar{\chi}_2^0 \not{Z}\gamma^5 \chi_2^0}{1+\mu/M_1} - \frac{\bar{\chi}_1^0 \not{Z}\gamma^5 \chi_1^0}{1-\mu/M_1}\right)$$

$$+ \frac{em}{4c_w M_1}\left[\frac{(1+Is_{2\beta})\bar{\chi_1}^0 \chi_1^0}{1-\mu/M_1} + \frac{(1-Is_{2\beta})\bar{\chi_2}^0 \chi_2^0}{1+\mu/M_1} - \frac{2Ic_{2\beta}\bar{\chi_2}^0 \chi_1^0}{1-\mu^2/M_1^2}\right] h$$

*All pure cases and mixtures (wino/Higgsino, bino/Wino, etc) well studied in the literature.

Only "uncoverable" spot is an "almost pure" Higgsino, mass ~1.1 TeV (pure Wino 2.7 TeV).

Bino/Higgsino setup

Since EW symmetry is broken, in an EW multiplet neutral components correct their masses due to Z-loops, charged components also have W, γ-loops.

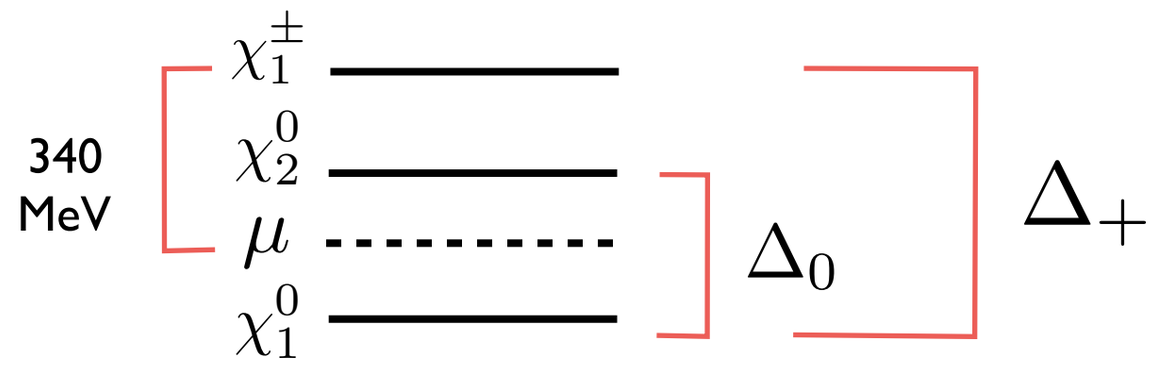
Thomas, Wells, hep-ph/9804359,
Cirelli, Formengo, Strumia, hep-ph/051209

$$\Delta_{1-\text{loop}} \to \begin{cases} \tilde{H} & 340 \text{ MeV} \\ \tilde{W} & 170 \text{ MeV} \end{cases}$$

Expanding in $\mu/M_1, m/M_1$

$$M = \begin{pmatrix} M_1 & -mc_\beta & ms_\beta \\ -mc_\beta & 0 & \mp\mu \\ ms_\beta & \mp\mu & 0 \end{pmatrix}$$

$m = m_Z s_W \approx 43.8 \text{ GeV}$



$$\Delta_0 = \frac{192 \text{ MeV}}{(M_1/10 \text{ TeV})} + \mathcal{O}\left(\frac{|\mu|}{M_1}, \frac{m}{M_1}\right)$$

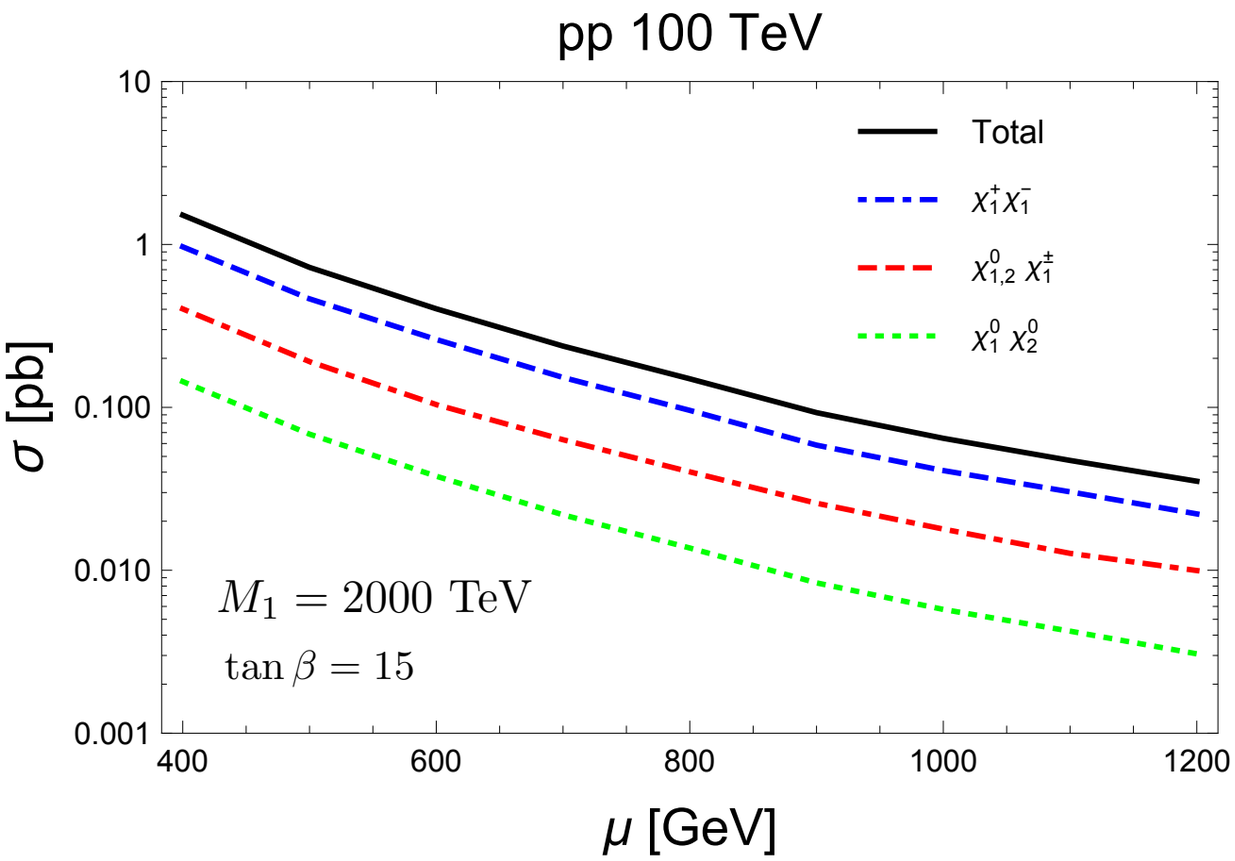
$$\Delta_+ = \Delta_{1-\text{loop}} + \frac{96 \text{ MeV}(1 \mp s_{2\beta})}{(M_1/10 \text{ TeV})} + \mathcal{O}\left(\frac{|\mu|}{M_1}, \frac{m}{M_1}\right)$$

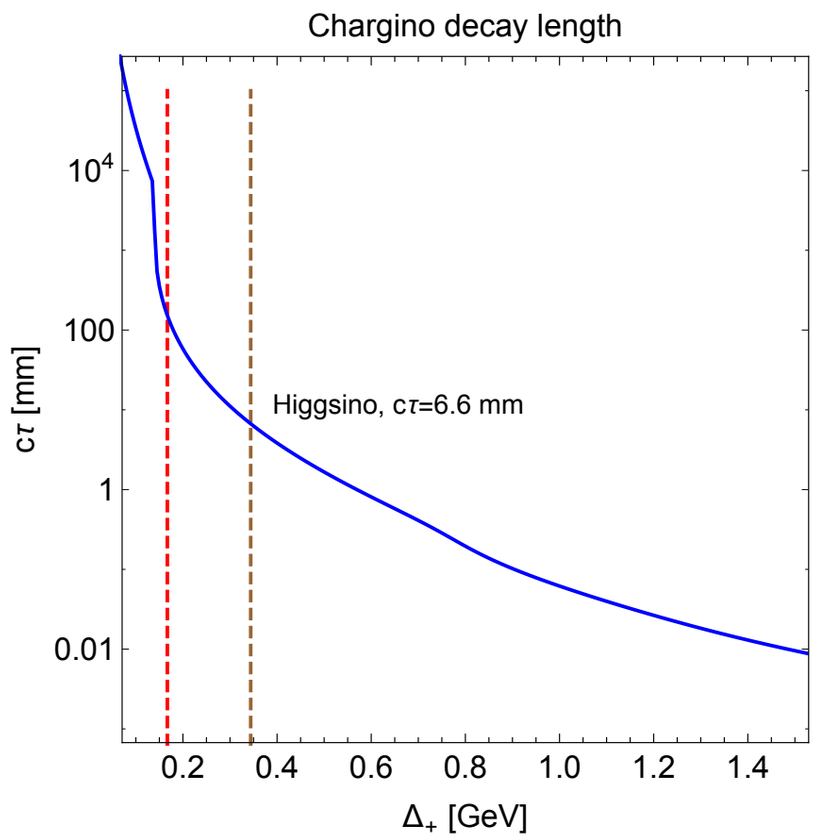
Limiting cases:

1. $\Delta_0 \geq \Delta_+$: decay open only to first neutralino for $M_1 \lesssim 3|\mu|$.
2. $\Delta_0 = 0$, $\Delta_+ = 340 \text{ MeV}$: decays to both, lifetime reduced by half.

Δ_0 < 100 KeV gives inelastic scattering @ DD → M_1 < 20 PeV.

Cross sections and decay lengths





$\sigma(1.1\ \text{TeV})[\text{fb}] = 47.23\ (39.05)\ \ \text{NLO}\ (\text{LO})\,.$

Chen, Drees, Gunion: hep-ph/951230, 9607421, 9902302.

PROSPINO Beenakker, Klasen, Krämer, Plehn, Spira, Zerwas, hep-ph/9906298

$\Delta_+ = 340\ \text{MeV} \qquad \text{BR}\ (\chi_1^\pm \to \pi^\pm \chi_0^{(1)}) \sim 97\%\,.$

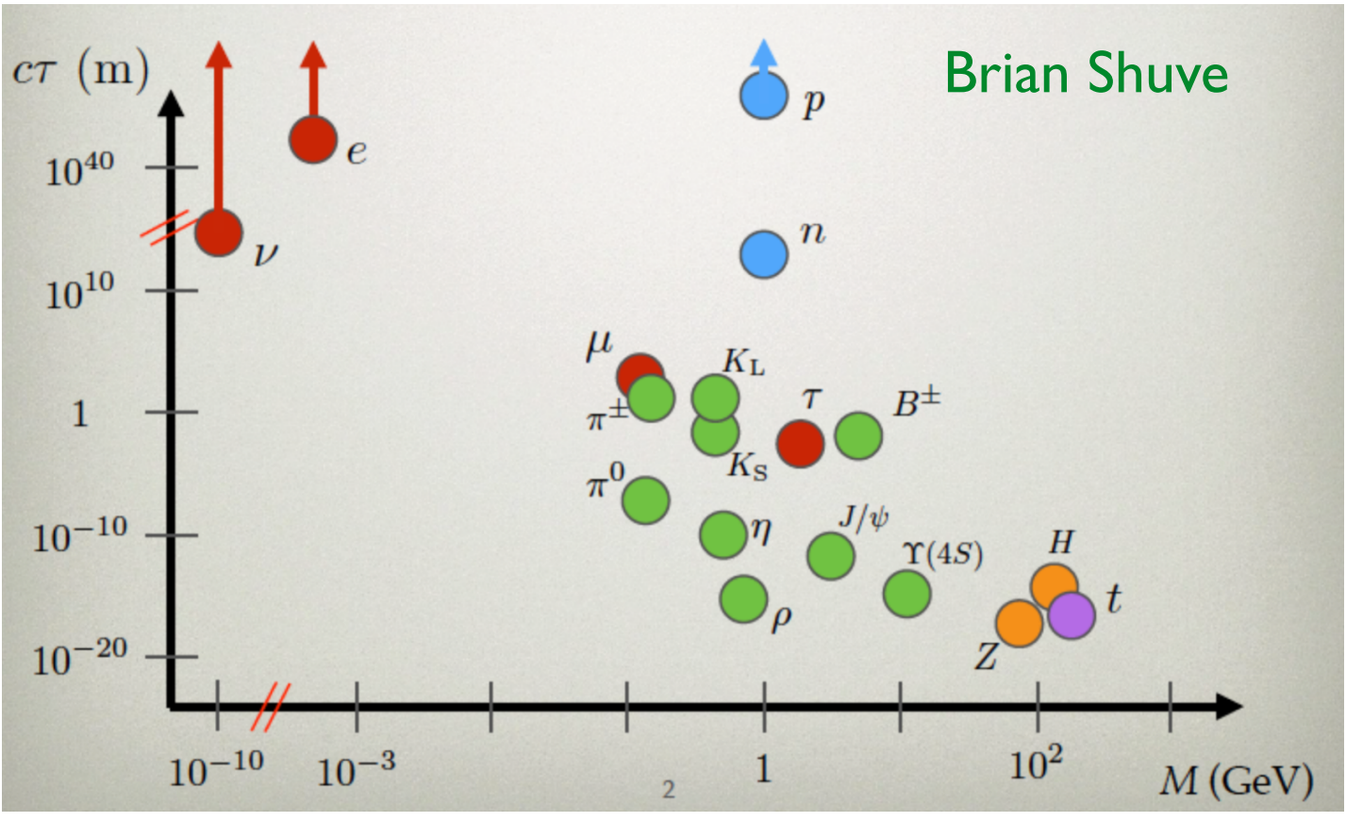
But
- 1- Lorentz boost $d = (c\tau)\gamma\beta$
- 2- Poisson process $P(d > d_0) = exp(-m_{\chi^\pm} d_0 \Gamma/|\vec{p}|)$

→ A tale of two tails

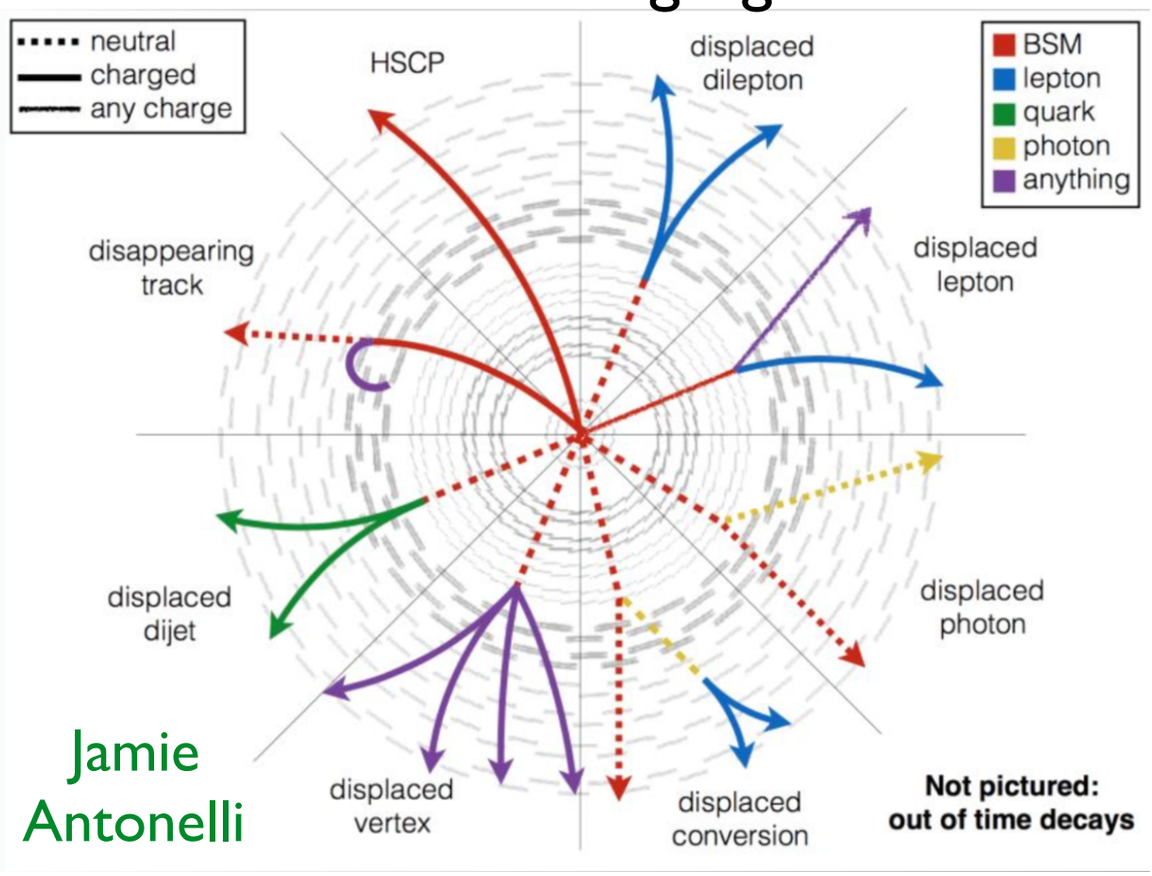
Long-Lived Particles

- LLPs: BSM states with macroscopic lifetimes (ns), theoretically well motivated.

Exist in the SM!



A lot of interesting signatures!



large cτ, small Γ

- Large mass hierarchies
- Compressed spectra
- Small couplings

BSM Models: RH neutrinos, dark QCD, stealth SUSY, Neutral Naturalness, Higgs Portal, Z' Portal, Exotic Higgs decays, Hidden Valleys, ….

LLP@LHC White Paper imminent (will be online before May 15th-18th workshop @CERN)

Disappearing tracks

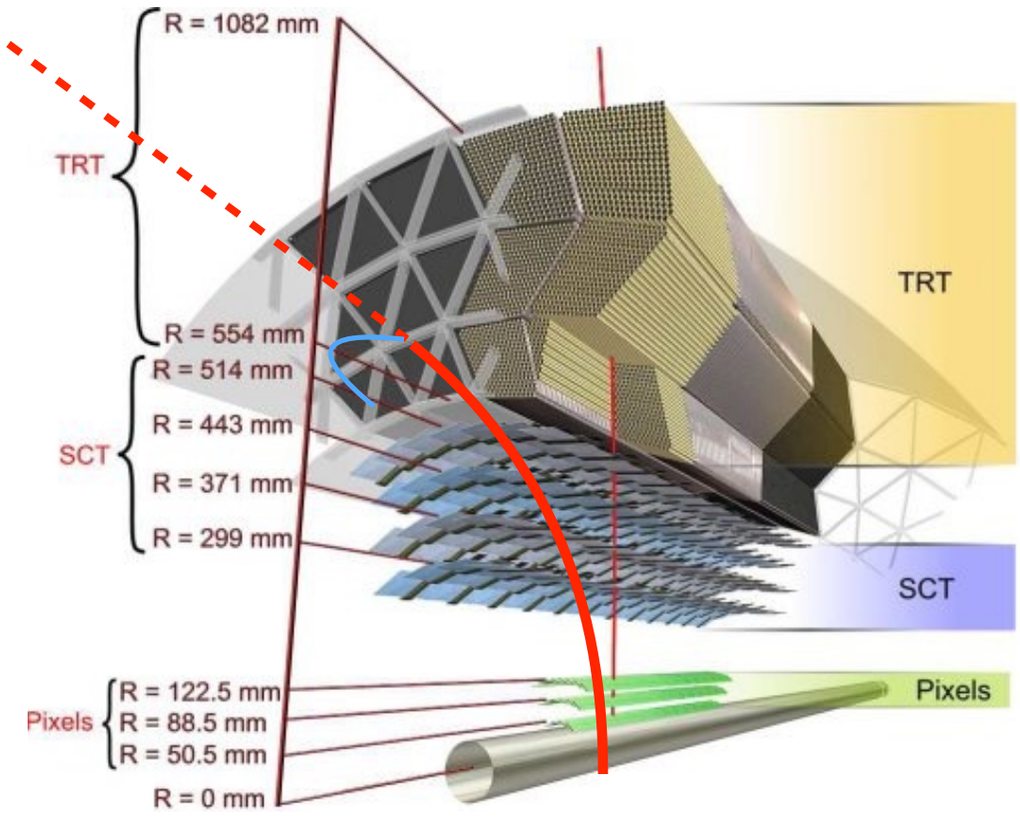
@ FCC-hh / HL-LHC

R.Mahbubani, P. Schwaller, JZ, [arXiv 1703.05327]

Disappearing tracks @ LHC

ATLAS: CERN-PH-EP-2013-155 (13 TeV: CERN-EP-2017-179) [CMS: CERN-PH-EP-2013-037]

- Charged particle (track) decays into neutral + SM (unreconstructed): disappeared!!!
- Event selection requires:
  - 1 "good quality"* (isolated, well reconstructed) track with large pT.
  - large missing transverse energy (MET > O(100 GeV)).
  - 1 hard jet, pT > 100 GeV (from initial state radiation, to trigger the event).
  - ΔΦ(jet,MET) > 1.0 (0.5) @ ATLAS (CMS) : kills mismeasured QCD multijets.



* Quality track

- At least 3 hits in pixel detectors.
- At least 2 hits in the SCT.
- Less than 5 hits in the TRT**

$d_{min} \approx 30$ cm

- pT > 15 GeV, 0.1 < |η| < 1.9 (hard and central)

ATLAS-CONF-2017-017: new pixel layer (r=3.33cm)

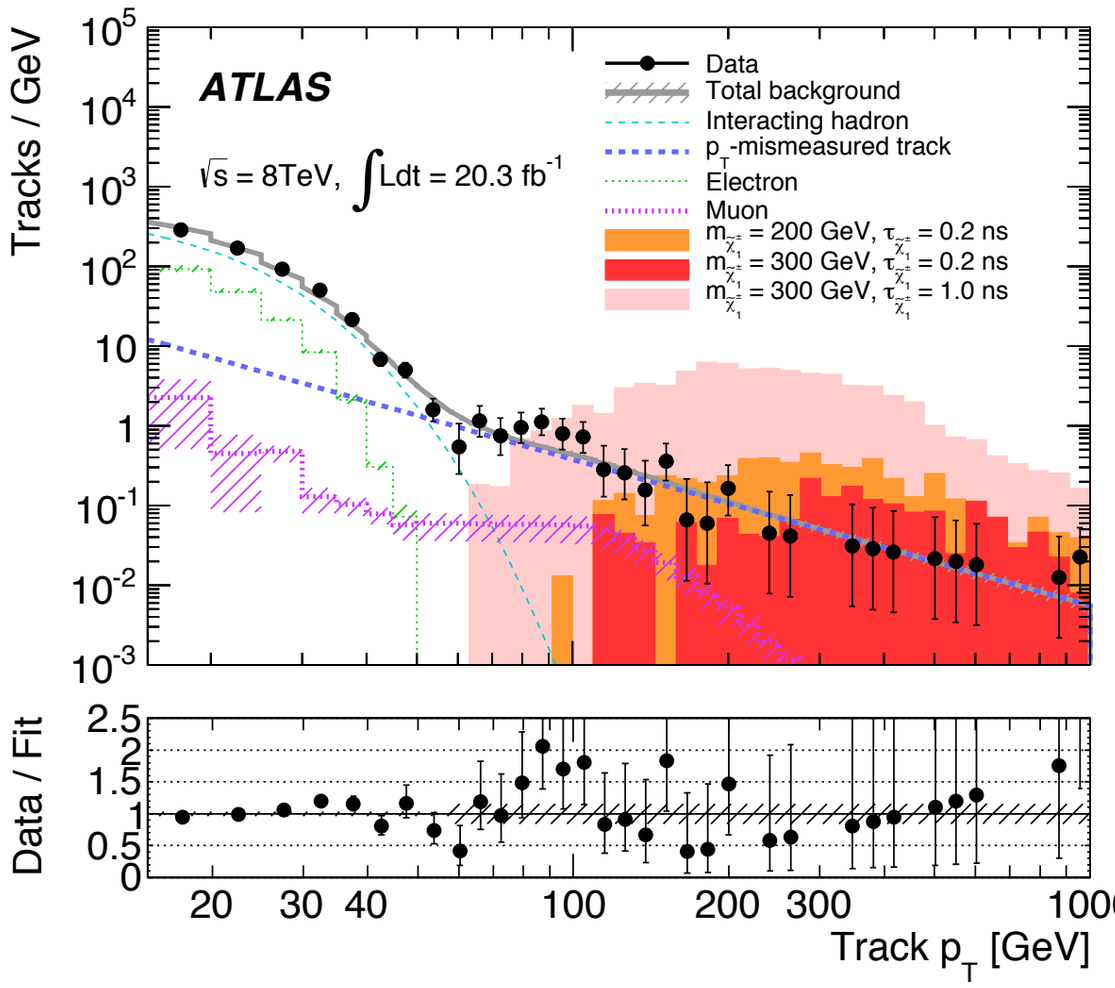
** SM particle leaves (on average) 32 hits in TRT

Don’t forget about backgrounds!

- <u>Background sources:</u>
  - Interacting hadron-tracks
  - Lepton tracks
  - pT-mismeasured tracks

    (dominant if pT >100 GeV)

    CMS: cuts on E_{calo} < 10 GeV



- Bgds @ 100 TeV estimated by:

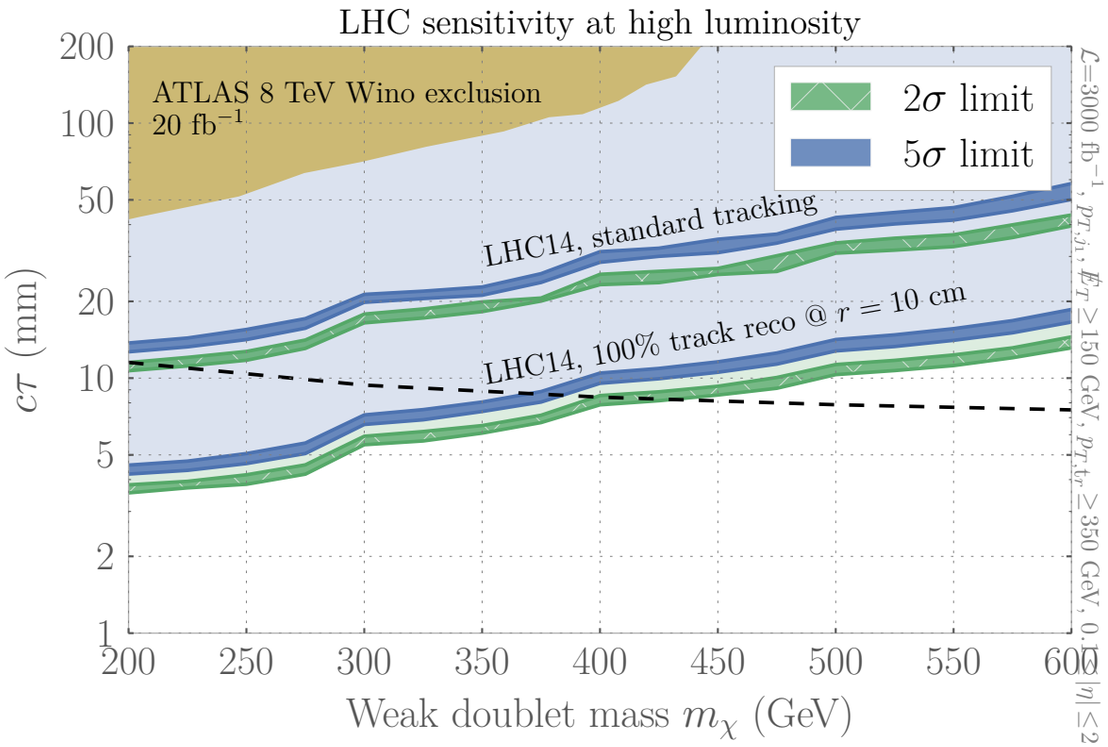
a) Taking distribution shape $(pT)^{-a}$ from LHC data (a = 1.78 ± 0.05).

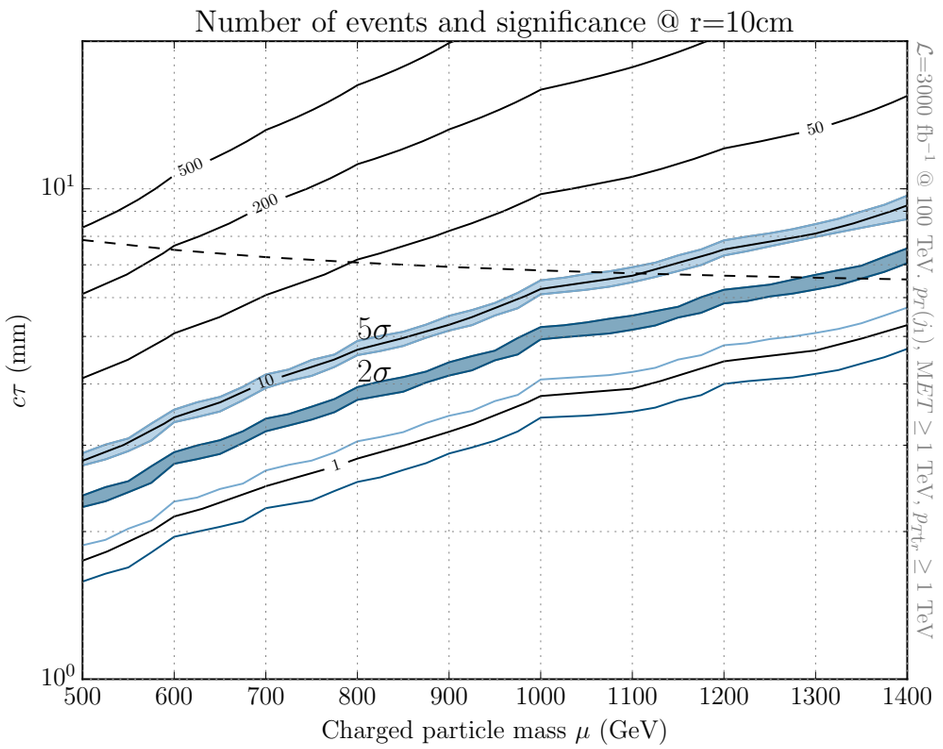
b) Normalize to known process:

1- Z+jets (used in Low, Wang: 1404.0682, Cirelli, Sala, Taoso, 1407.7058).

2- multi-jets (better description of processes with “a high density of silicon hits, hadronic interactions and scattering”).

Results





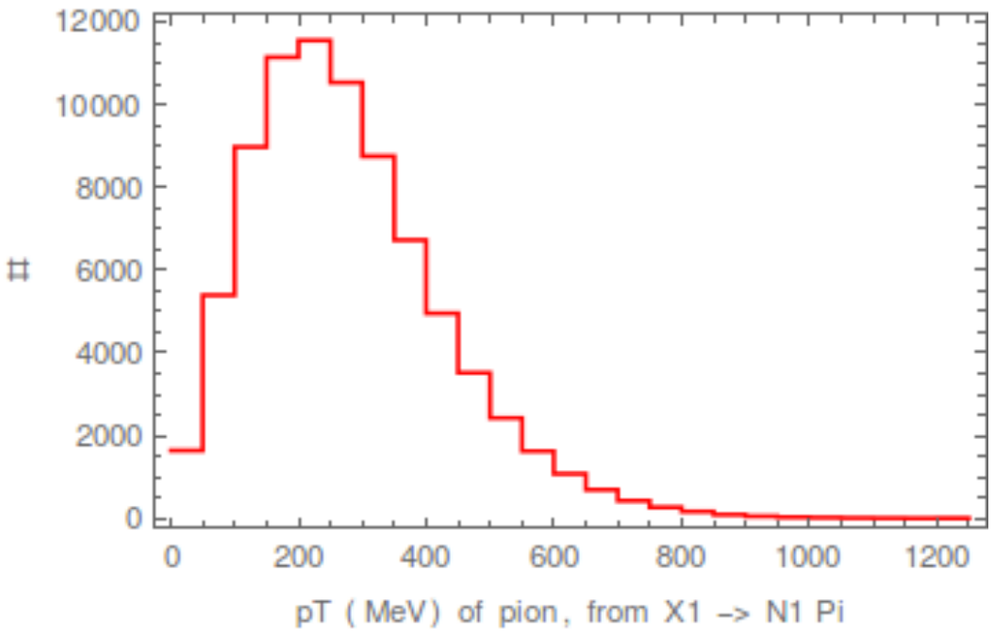
- Discovery (5σ) with 35 events @ HL-LHC: 50% systematics, bgd extrapolation with di-jet XS.
- HL-LHC: Reducing the track distance from 30 to 10 cm moves the Higgsino reach to 370 GeV. Beats the LHC reach in mono-jet of 200 -250 GeV [see e.g Schwaller, JZ 1312.7350, Barducci, Belyaev, Bharucha, Porod, Sanz, 1504.02472, Ismail, Izaguirre, Shuve, 1605.00658, …].
- FCC: m_χ < 1070 (1290) GeV for discovery (exclusion) for pure Higgsino, 50% systematics. If using Z+jets (q-qbar), the reach moves to 1.5 (1.6) TeV.

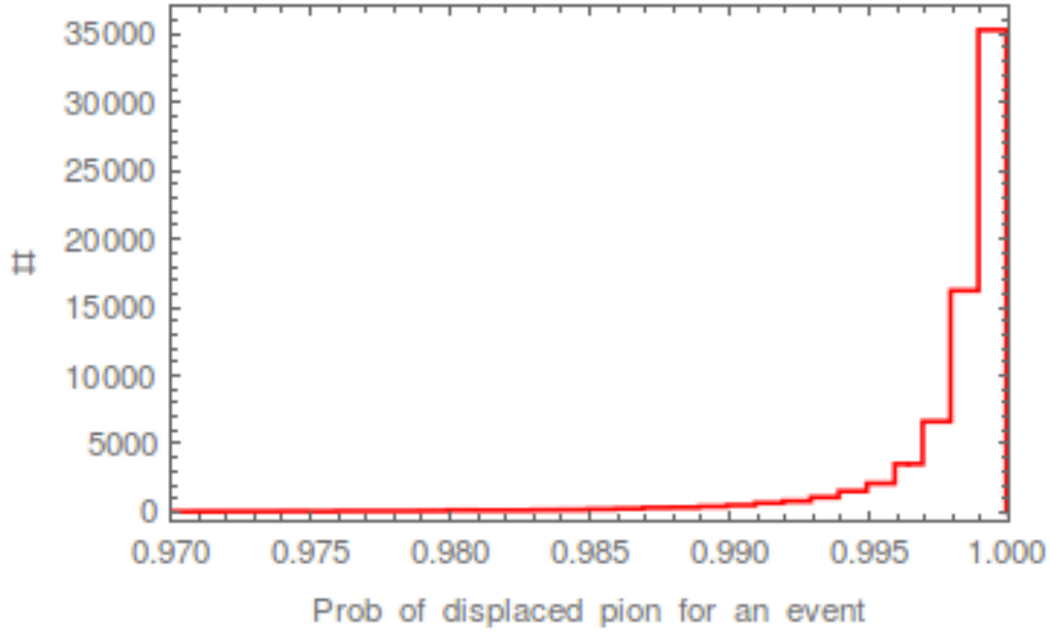
Displaced pions @ e-p colliders

David Curtin, Kaustubh Deshpande, Oliver Fischer, JZ, [arXiv 1712.07135]

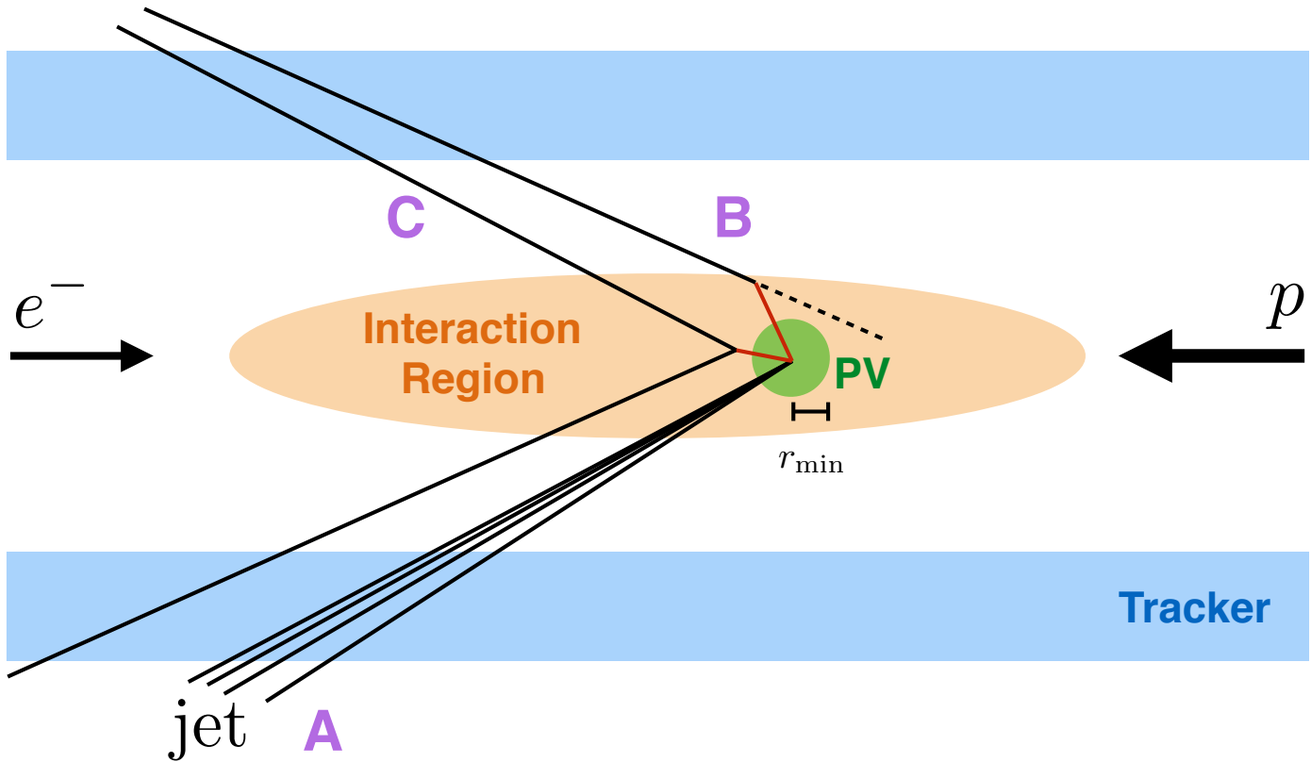
The e-p magic in action

- Disappearing tracks at hadron colliders rely on $\chi^+ \longrightarrow \chi^0 \pi^+$ (the pion is lost).
- e-p provides a clean environment (1 bunch/crossing, event reconstruction, …)
- Our strategy is to have a <u>displaced pion:</u>
  - p_T > 100 MeV .
  - Live in a 40 microns sphere from the IP (displacement wrt PV is enough? Is this region BG free?)
- Highly likely to occur! (pion reconstruction efficiency set to 100%)





Displaced objects at e-p colliders



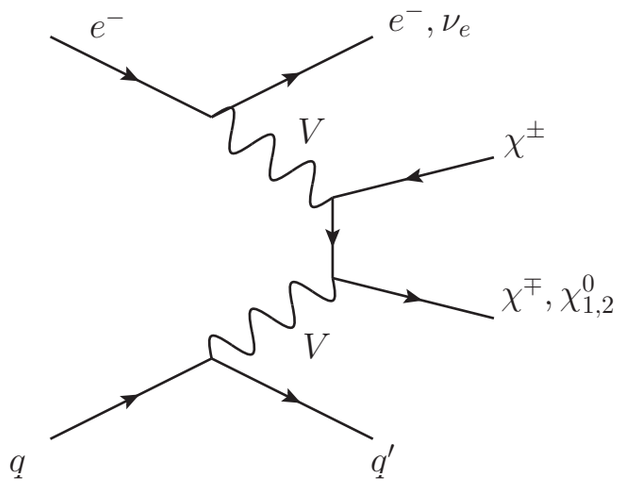
- (A) Hard jet, $pT_j > 20$ GeV, $|\eta_j| < 4.7$: identifies the PV and provides trigger.
- (B) 1 charged particle (π,μ) is displaced if the charged track has impact parameter > r_{min}
- (C) 2+ Charged particles (a,a) give a displaced vertex (DV) if d(PV,DV) > r_{min}

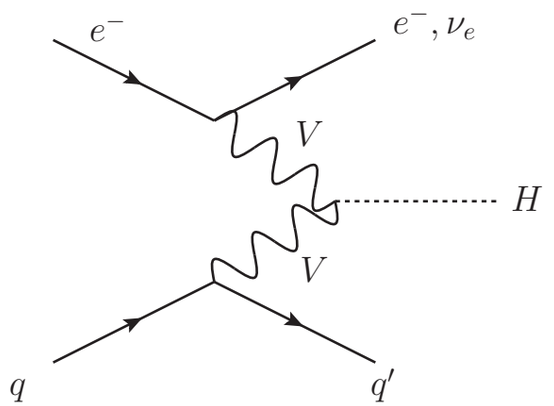
  - Charged track: $p_T > 100$ MeV, 100% reconstruction efficiency.
    (corresponds to O(0.1m) curvature in a B=3.5 T field)

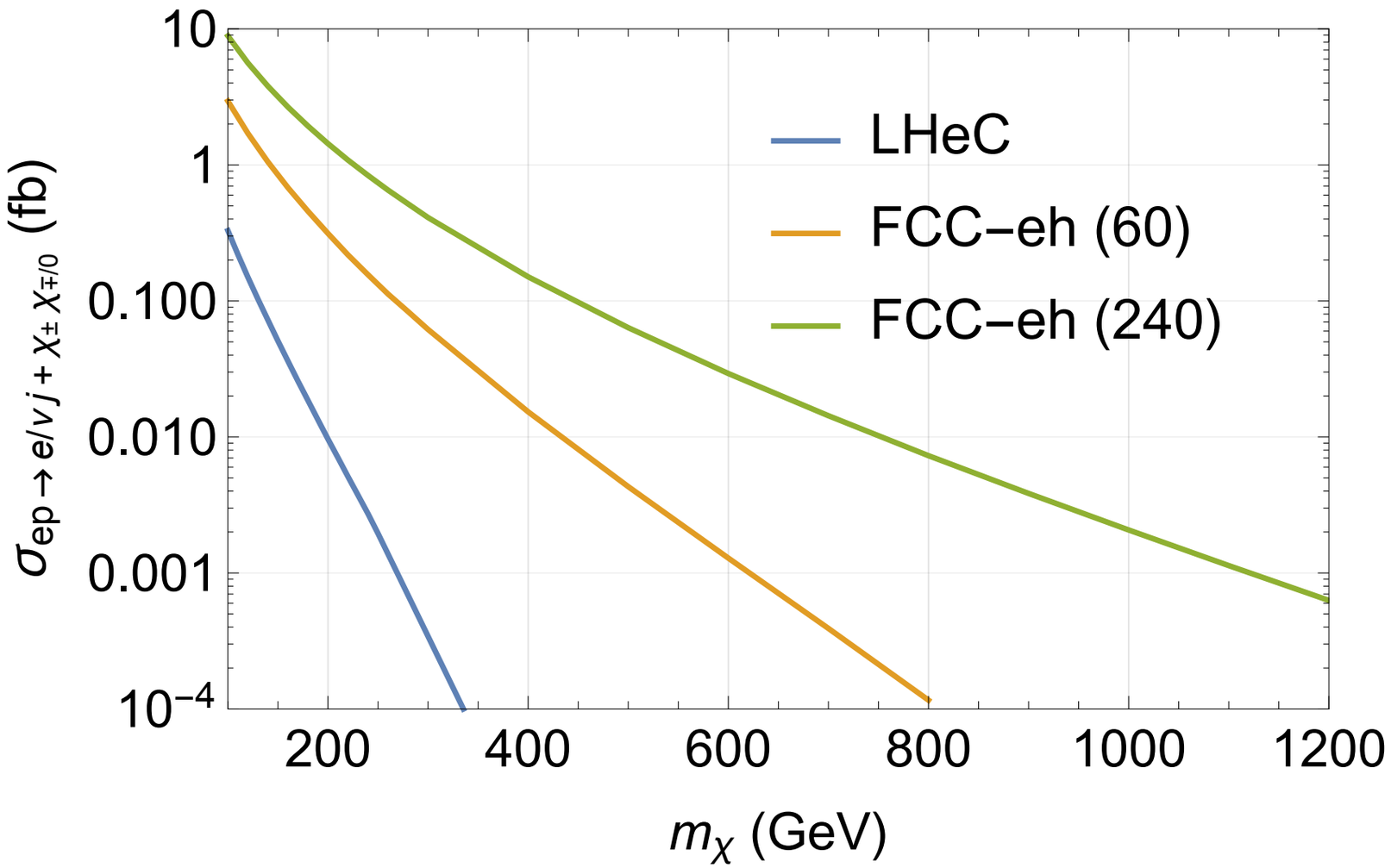
e-p phenomenology

We take (e/GeV,p/TeV) energies to be: (60,7) [LHeC], (60,50) [FCC-eh(60)] (240,50) [FCC-eh(240)]

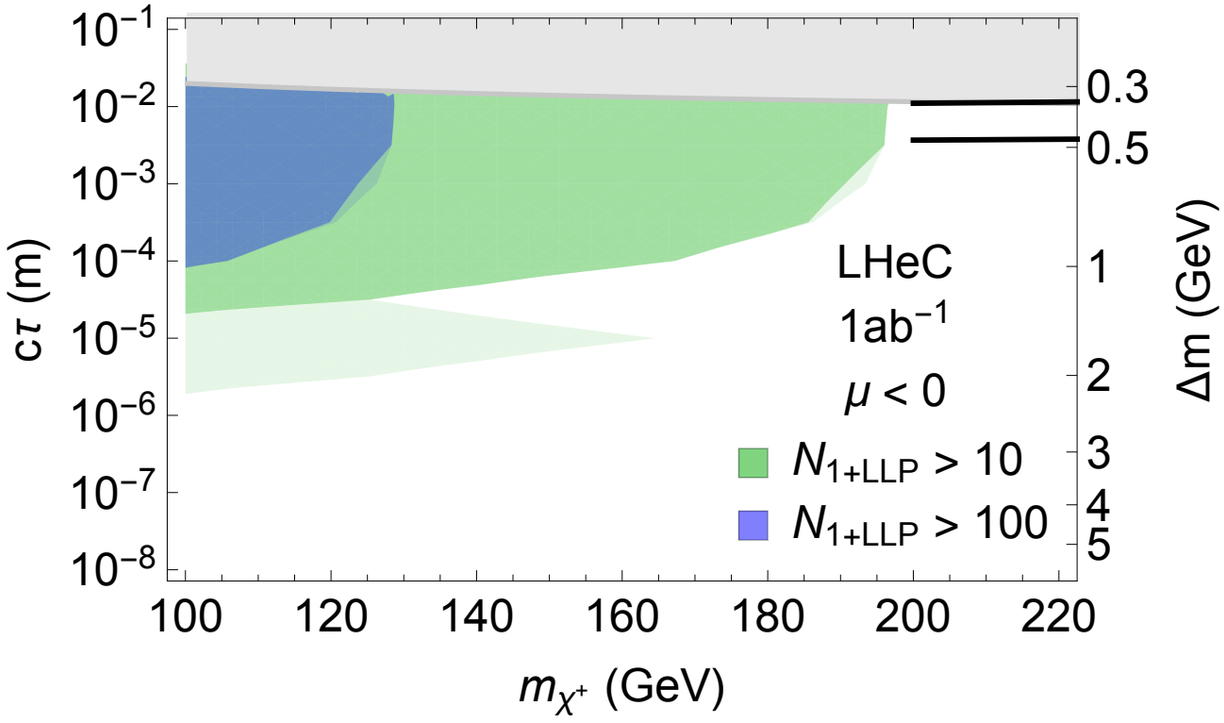
[The latter option uses the highest achievable e-beams discussed for FCC-ee]

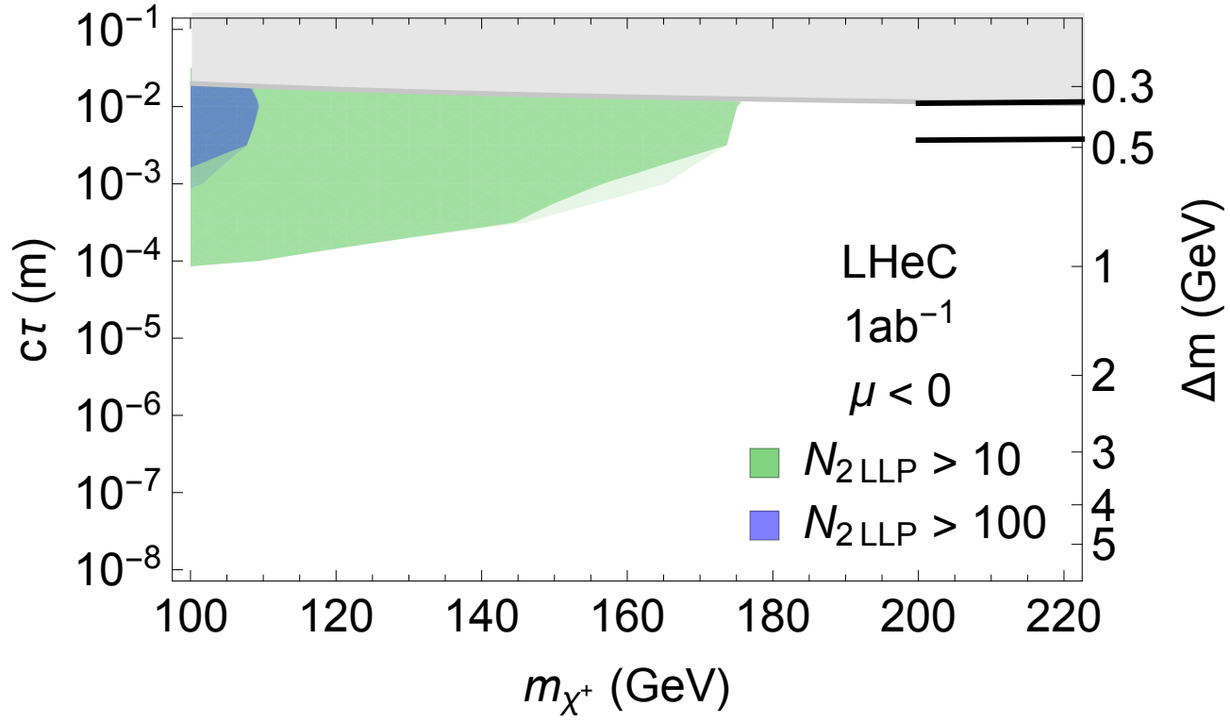






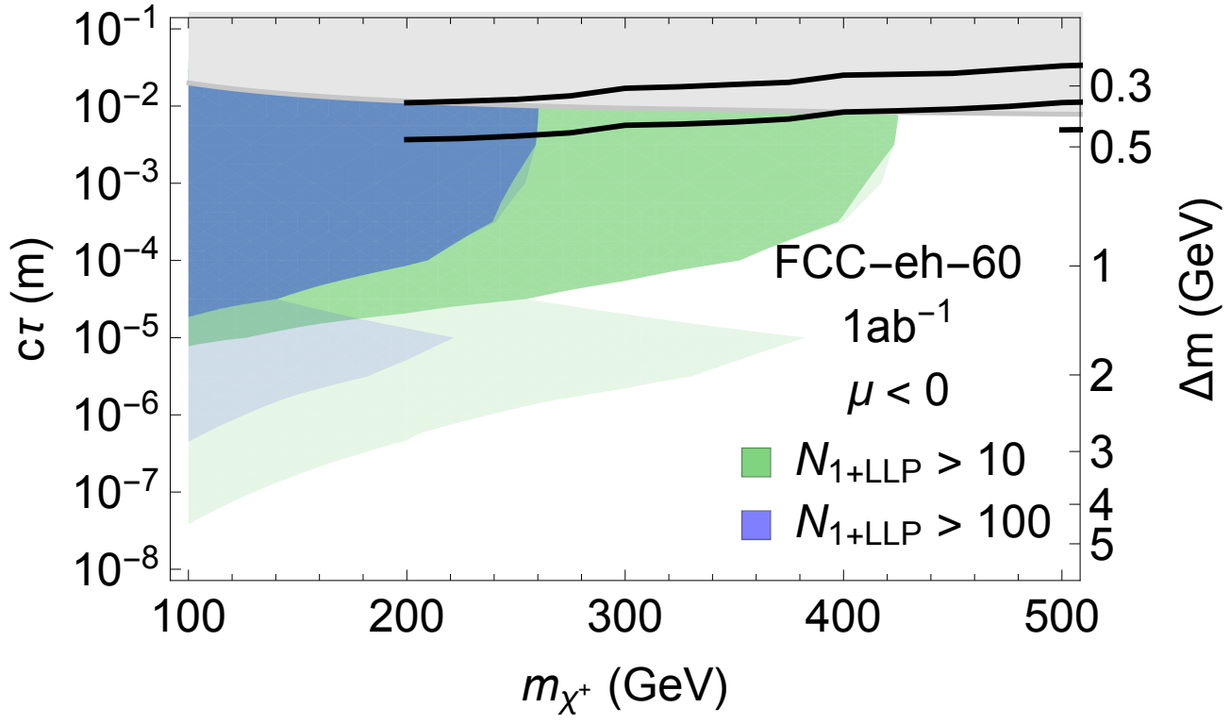
Higgsinos @ LHeC

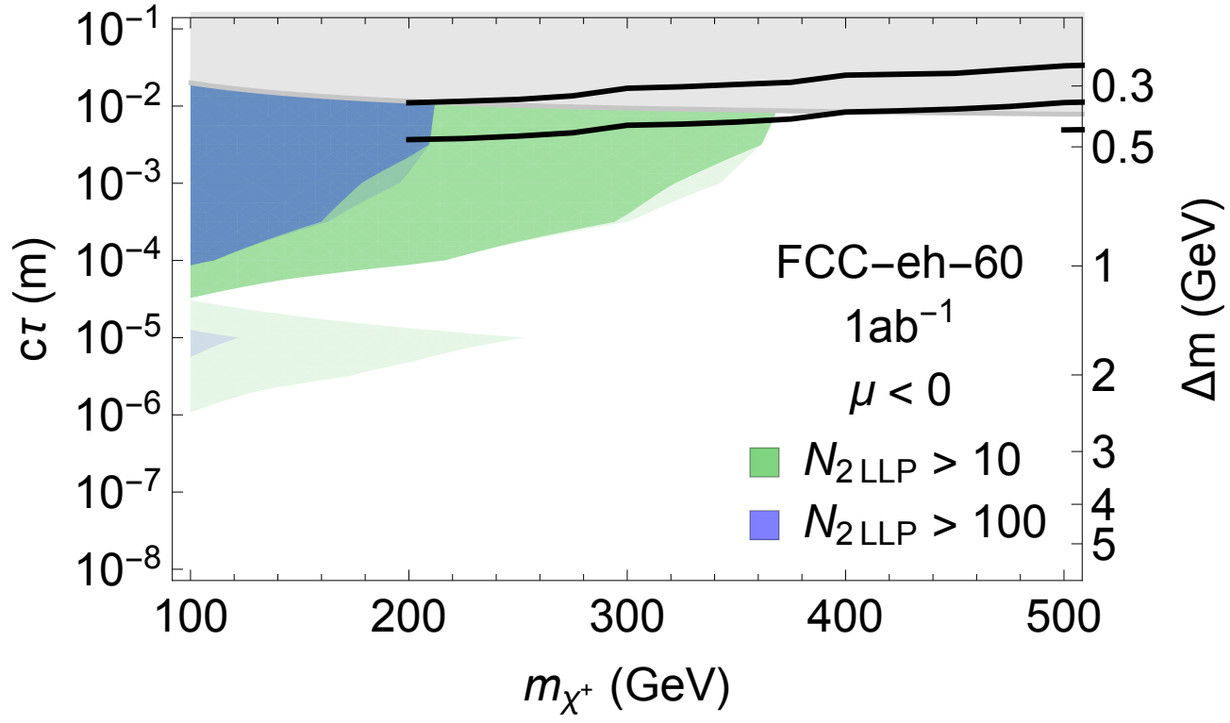




LHeC does not compete with LHC mono-jet reach or disappearing tracks for nominal lifetimes, but it can probe sub-mm distances!

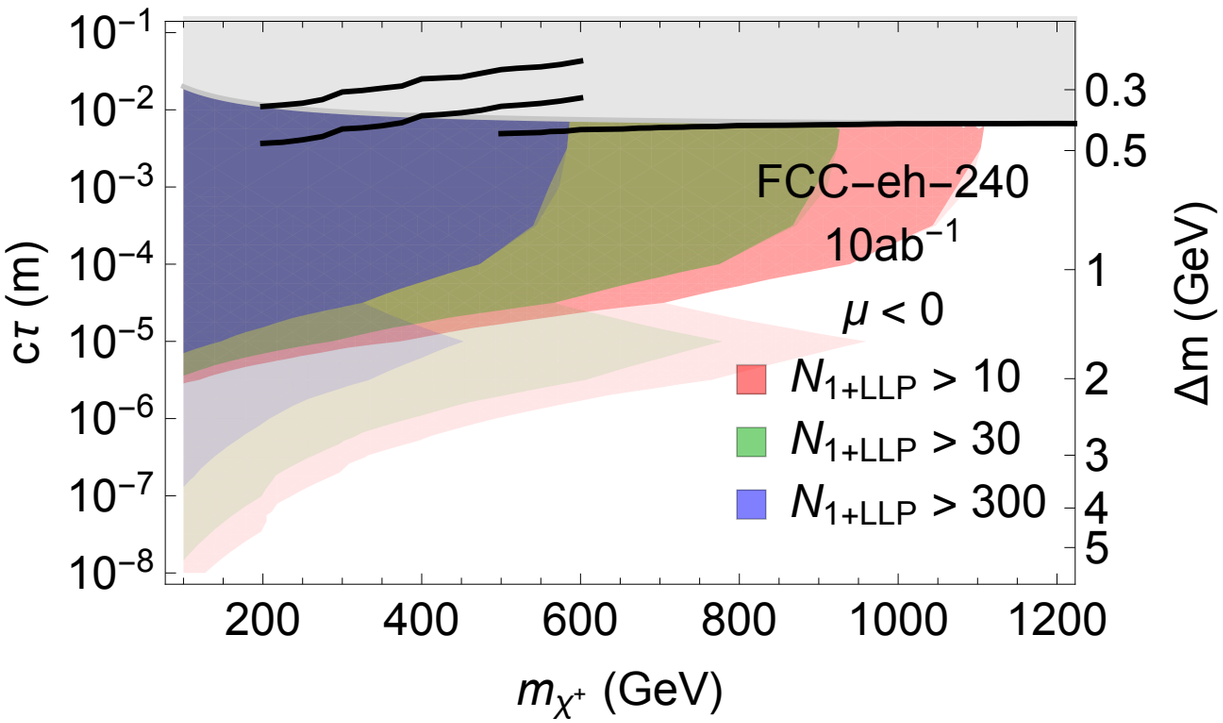
Higgsinos @ FCC-eh (60)

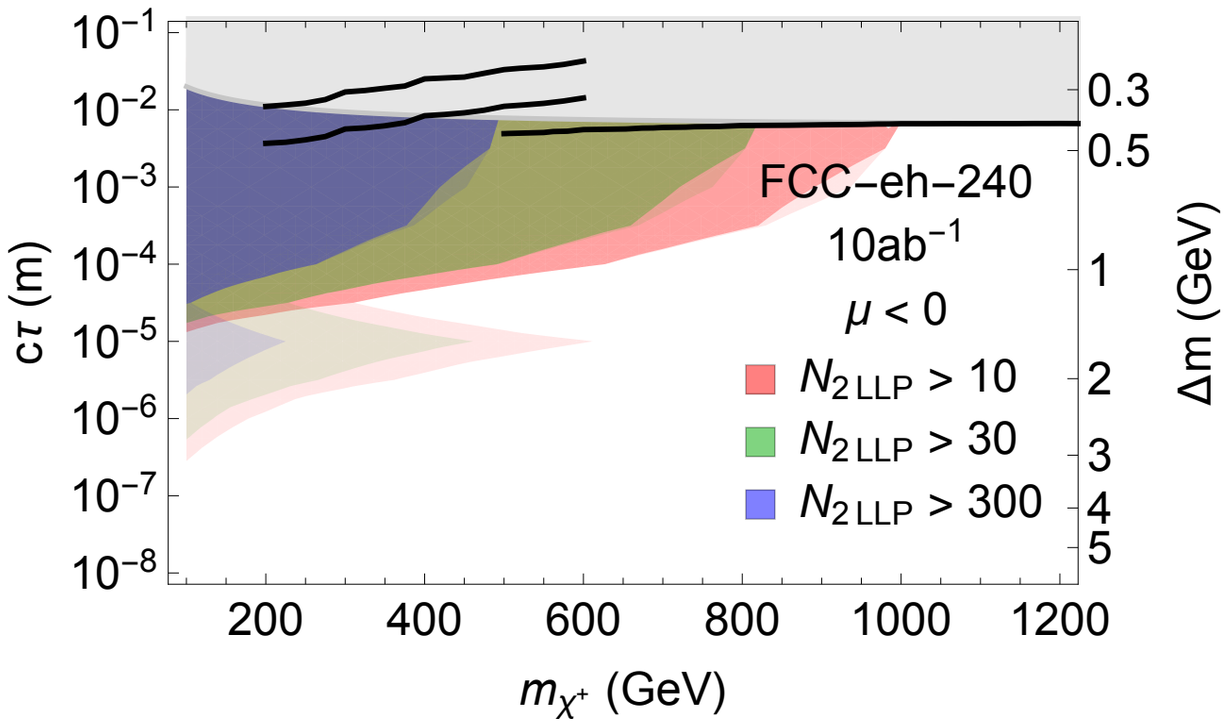




FCC-eh (60) has a lower mass teach than FCC,
but now we can probe cτ ~ μm!

Higgsinos @ FCC-eh (240)





This very optimistic setup would allow to probe thermal Higgsinos!

Conclusions

• I have discussed how to close the window on thermal Minimal Dark Matter (MSSM dark matter) at several colliders in the last standing corner of model space: doublet-singlet (Higgsino-Bino).

•Tracker improvements in HL-LHC / FCC have the potential to fully test the thermal hypothesis for a highly decoupled singlet ("pure case"), trumping over the mono-jet search.
Other strategies under scrutiny (mono-Z, mono-γ, …).

•Electron-proton colliders provide a highly clean environment and allow to see the soft-pion as a displaced object, probing lifetimes at the micron level.
Unlike at p-p collider, the mass splittings could then be accessible (work in progress!).