A dark path to long-lived particles

Part III: let's go practical!

Recap:
- Relic density: (freeze-out)
  - Direct detection (DD)
  - Co-annihilation as a way out:

Direct detection (DD):
- DD $\rightarrow$ $\Delta m$ small $\rightarrow$ overabundance

Co-annihilation as a way out:
- $\langle d_{DD} \rangle \neq \langle d_{ann} \rangle$
- Decoupling:
  - $\langle d_{eff} \rangle_{ann} = 10^4$ $\Rightarrow$ no overabundance
- $\langle d_{dec} \rangle > \langle d_{DD} \rangle$ $\Rightarrow$ no problems with DD

Example model: singlet-triplet DM:
- $\chi_s$ and $\chi_t$ are electroweak (SU(2)) singlet/triplet
- $\Lambda_{eff} = -\frac{m_s}{2} \chi_s \chi_s - \frac{m_t}{2} Tr[\chi_t \chi_t] + \frac{K_{st}}{\Lambda} [(H^+ \chi_t H) \chi_s + h.c.]$
  - Some effective scale of new physics; coupling $\chi_s \chi_t H$ is naturally small

Mixing:
- $\chi_T = (\chi_T^+, \chi_T^0, \chi_T^-)$
- $\chi_s = \chi_s^0$
  - Where
    - $\theta = \frac{\mu}{m_T - m_s}$
    - $\mu = \frac{\nu_s}{\nu_T} \frac{K_{st}}{\Lambda}$

Spectrum:
- Black lines: tree-level (mixing) structure
- Loop shift:
  - $\Delta m \approx 160$ MeV

Direct detection constraints:
- Small $\mu$, small $\theta$ (overabundance?)
- But from (v): $\Delta m_{cl}$ is also small
  - $\Rightarrow \chi_h$ and $\chi_+$ are very close in mass

Co-annihilation:
- $\langle d_{eff} \rangle_{ann} = \chi_s W^+ W^-$
  - Small couplings (from DD)
- For effective co-ann:
  - $\Delta m_{cl} \sim 10^{-30}$
Problem: DD+ correct relic abundance = compressed spectrum

For me = 100 GeV ÷ 1 TeV: ΔMτe ≈ ΔMχe = 15 ÷ 30 GeV

(Smaller masses are forbidden by the LEP searches of χ±)

Example: "classical" soft lepton search (CMS 1208.3949; Bharucha 1804.02557)

Z production ∝ \( \frac{1}{m_\tau^2} \)

Leptons are soft (pT\( \tau \sim 15 ÷ 30\) GeV)
- Too much background
- Can probe only light masses
  (where Z prod is decent)

But what else can we say about the decays?

Decays \( \chi^+ / \chi_h \rightarrow \chi_e \) are suppressed by the couplings W/Z

Decays \( \chi^+ / \chi_h \rightarrow \chi_h / \chi_e \) are suppressed by the available phase-space:
- \( \Delta m_{\chi h} \sim O(100\) MeV

It means that the decays might actually be displaced!

Displaced signals usually have less background, and sometimes are almost background-free.

Example of very successful search: disappearing charged tracks

Charged particles live traces in all four layers of the inner detector and decay at radii of 12 ÷ 30 cm
(\( \chi^\pm \) are lost)
Take-home message:
- DM constraints lead to extended dark sectors.
- Co-annihilation scenarios are a natural way to obtain DM through freeze-out.
- It requires compressed and weakly-coupled spectra of new physics.
- Such DM scenarios can be tested at LHC.
- Long-lived particles naturally appear, LLP searches are very promising.