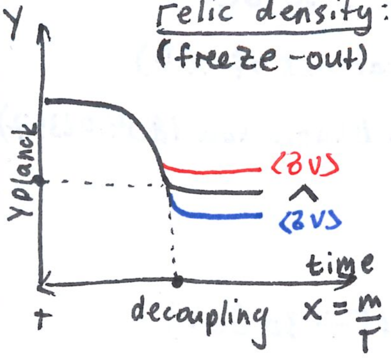
A dark path to long-lived particles

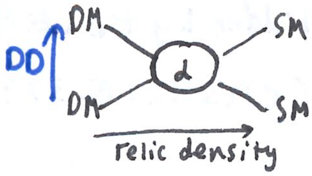
Part III: let's go practical!

Recap:

relic density: (freeze-out)



Direct detection (DD)



DD ⇒ α small

⇓

overabundance

Co-annihilation as a way out:

α_{DD} now $\neq$ α_{ann} at decoupling

decoupling:

$\langle\sigma v\rangle^{eff}_{ann}$ =  + ... $\propto (\alpha^{eff}_{dec})^2$

$\alpha^{eff}_{dec} > \alpha_{DD} \Rightarrow$ no overabundance
no problems with DD

Example model: singlet-triplet DM: χ_S & χ_T are electroweak (SU(2)) singlet/triplet

$$\mathcal{L}_{eff} = -\frac{m_S}{2}\bar{\chi}_S\chi_S - \frac{m_T}{2}\mathrm{Tr}[\bar{\chi}_T\chi_T] + \frac{k_{ST}}{\Lambda}\left[(H^+\bar{\chi}_T H)\chi_S + h.c.\right]$$

Λ - some effective scale of new physics; coupling $\chi_S\chi_T h$ is naturally small

Mixing:

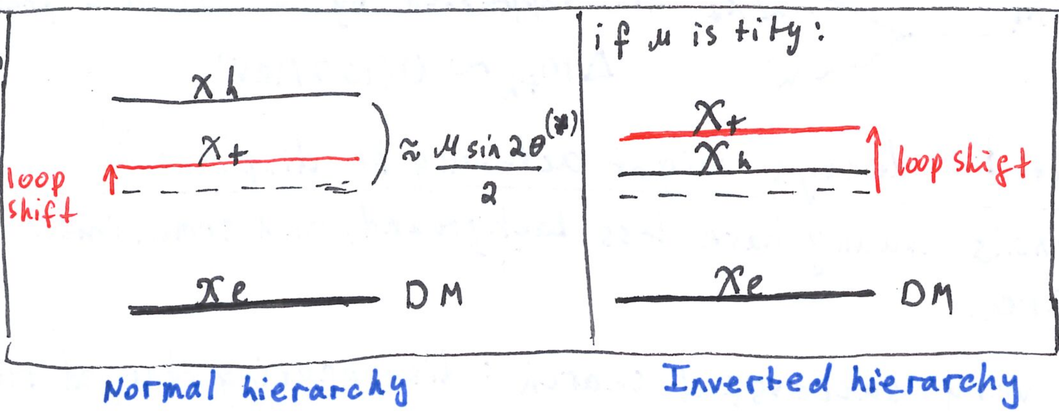
$$\chi^T = (\chi_T^+, \chi_T^0, \chi_T^-)$$
$$\chi_S = \chi_S^0$$

$$\boxed{\begin{aligned}\chi_h &= \sin\theta\,\chi_S^0 + \cos\theta\,\chi_T^0\\ \chi_\ell &= \cos\theta\,\chi_S^0 - \sin\theta\,\chi_T^0\end{aligned}}$$

where
$$\theta = \frac{\mu}{m_T - m_S}$$
$$\mu = \frac{v^2}{\sqrt{2}}\frac{k_{ST}}{\Lambda}$$

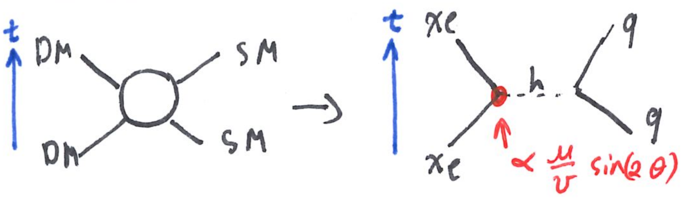
Spectrum

black lines: tree-level (mixing) structure



loop shift: $\Delta m^{loop} \approx 160$ MeV

Direct detection constraints:

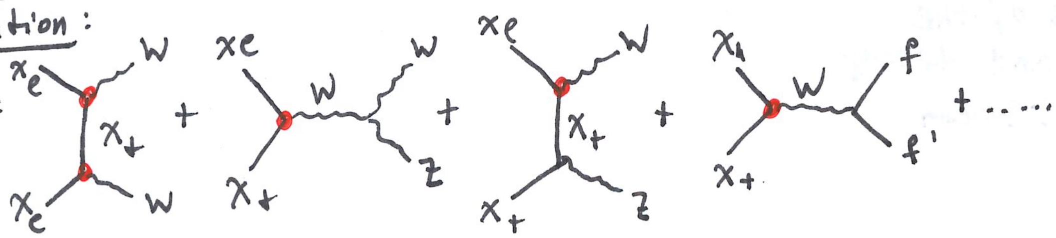


⇒ $\boxed{\text{small } \mu, \text{ small } \theta}$ (overabundance?)

But from (*): Δm_{cl} is also small

⇒ χ_h and χ_+ are very close in mass

Co-annihilation:

$\langle\sigma v\rangle^{eff}_{ann}$ =  + ...

• - small couplings (from DD)

For effective co-ann: $\boxed{\frac{\Delta m_{c\ell}}{m_c} \sim 10 \div 30\%}$

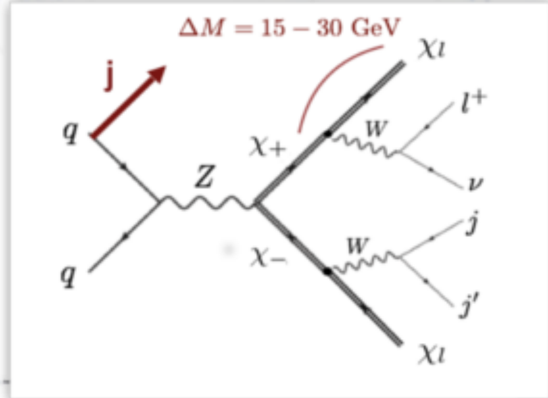
OK, we rescued DM. Let's just continue searchin @ LHC?

<u>Problem</u>: DD + correct relic abundance = comressed spectrum

For $m_\ell = 100\,\text{GeV} \div 1\,\text{TeV}$: $\Delta m_{+\ell} \approx \Delta m_{h\ell} = 15 \div 30\,\text{GeV}$

(smaller masses are forbidden by the LEP searches of $\chi^\pm$)

<u>Example</u>: „classical" soft lepton search (CMS 1206.3949, Bharuchaa 1804.02357)



$\sigma_{\text{production}} \propto \frac{1}{m_+^2}$

Leptons are soft ($p_{T\ell} \sim 15 \div 30\,\text{GeV}$)

⇓

Too much background

⇓

Can probe only light masses (where σ_{prod} is decent)

<u>But what else can we say about the decays?</u>

Decays $\chi_+/\chi_h \to \chi_\ell + W/Z$ are suppressed by the couplings

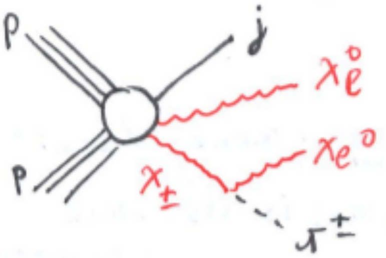
Decays $\chi_+/\chi_h \to \chi_h/\chi_+ + W$ are suppesed by the available phase-space:

$\Delta m_{+h} \sim O(100\,\text{MeV})$

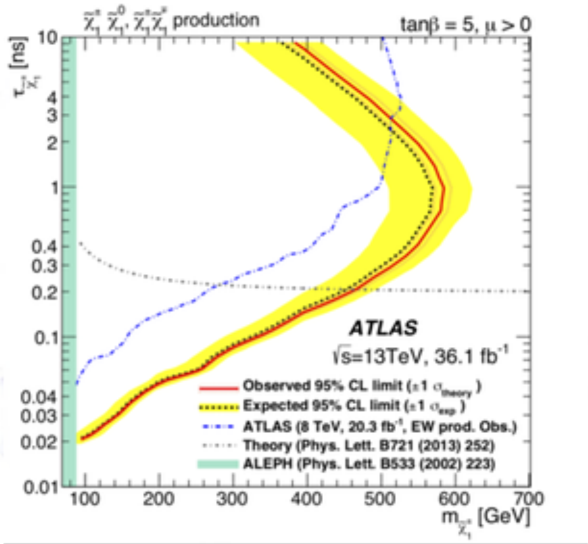
It means that the decays might actually be displaced!

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

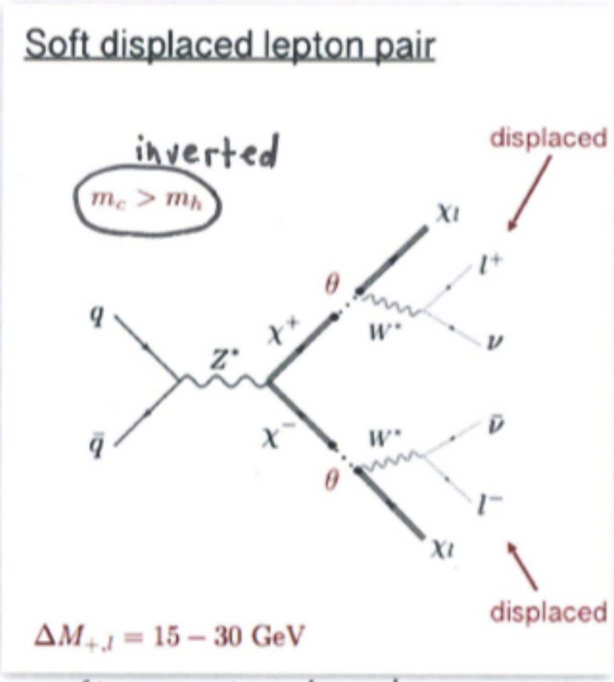
Example of very successful search: disappearing charged tracks

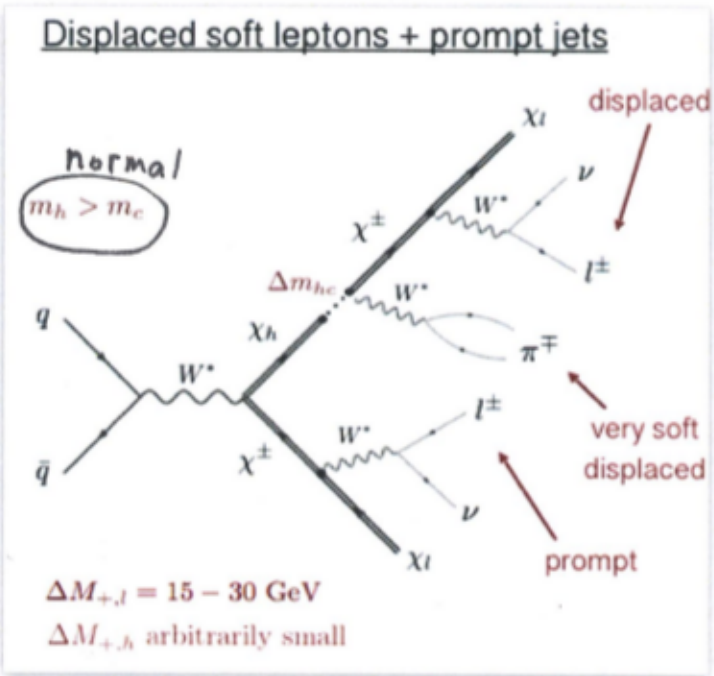


Charged particles live traces in all four layers of the inner detector and decay at radii of $12 \div 30$ cm ($\pi^\pm$ are lost)

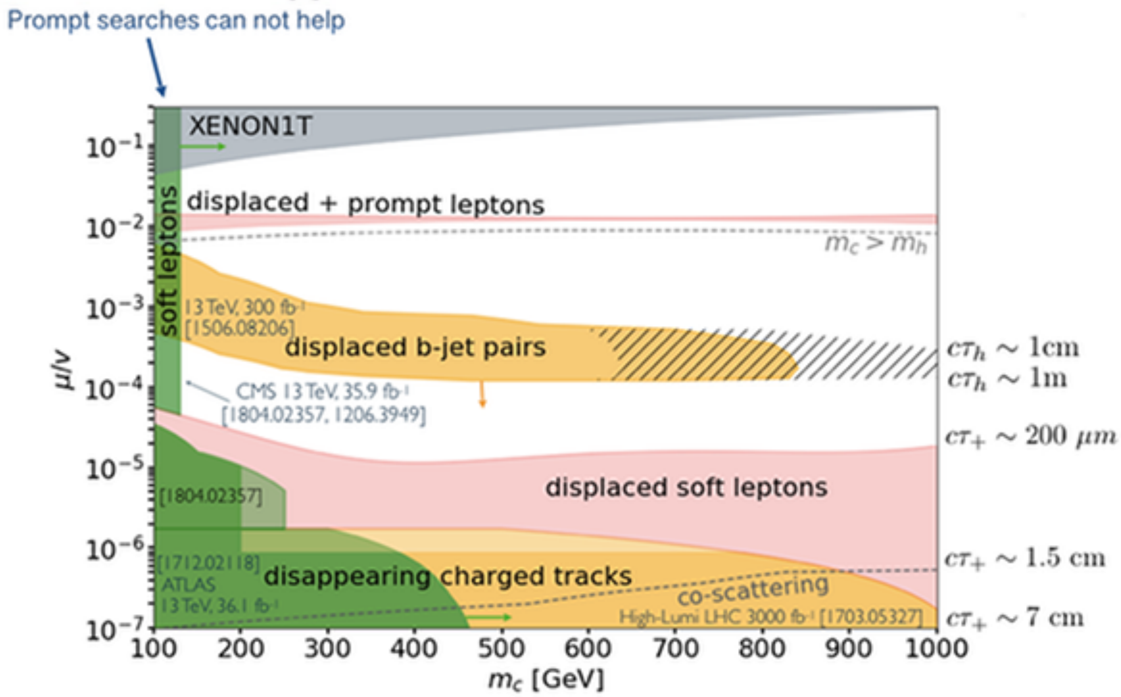


Promissing displaced signatures



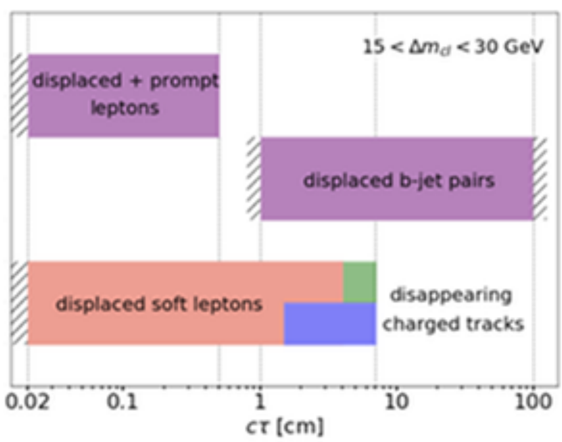


symmetric topology



Take-home message:

Lifetimes accessible @ LHC



- DD constraints lead to extended dark sectors.
- Co-annihilation scenarios are a natural way to obtain DM through freeze-out.
- It requires compressed & weakly-coupled spectra of new physics.
- Such DM scenarios can be tested @ LHC
- Long-lived particles naturally appear, LLP searches are very promissing