Probing Dark Matter with Disappearing Tracks at the LHC and future colliders

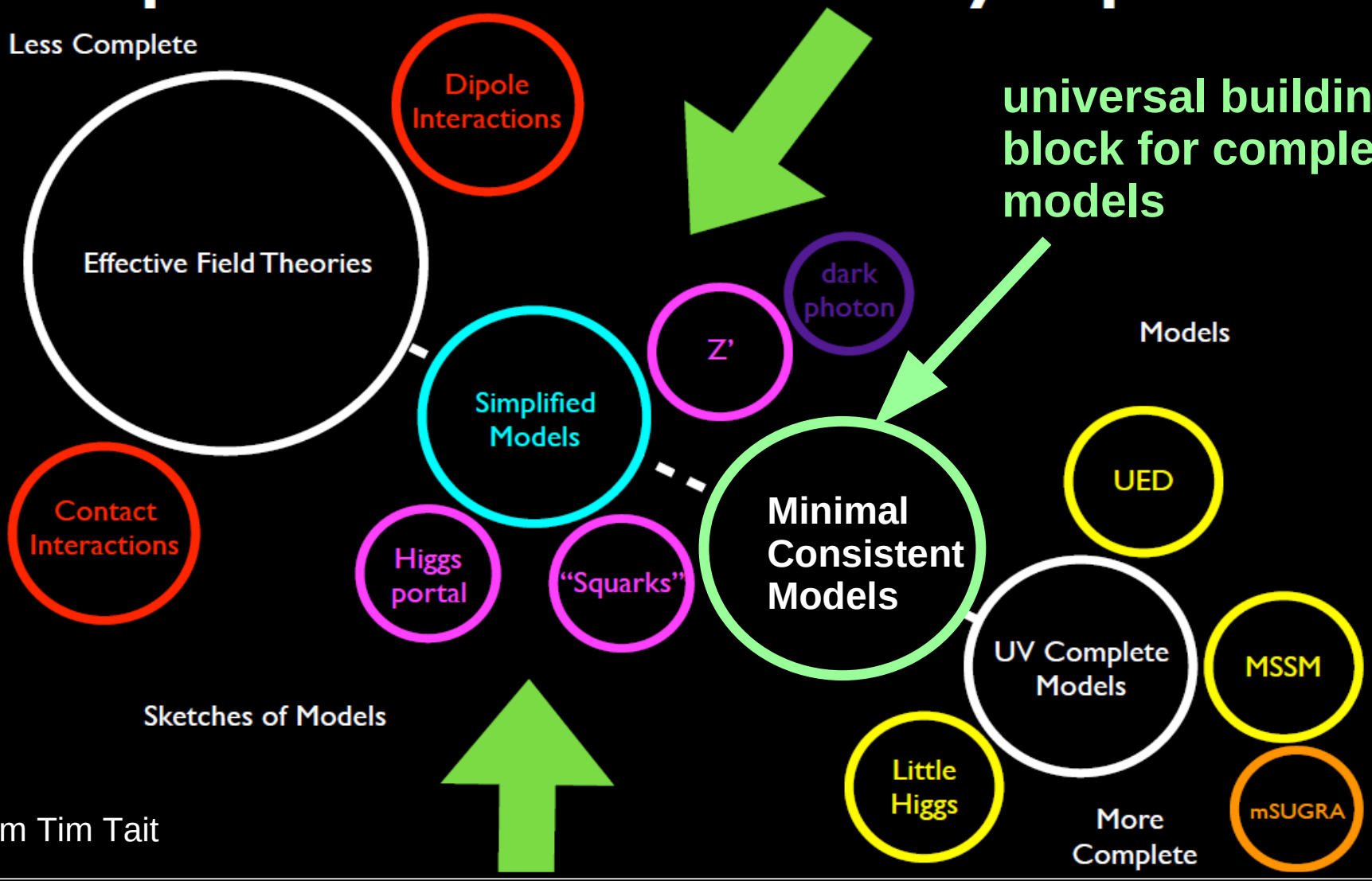
Alexander Belyaev

Southampton University & Rutherford Appleton Laboratory

LLP8 workshop:
Searching for long-lived particles at the LHC and beyond

November 19 , 2020

Spectrum of Theory Space

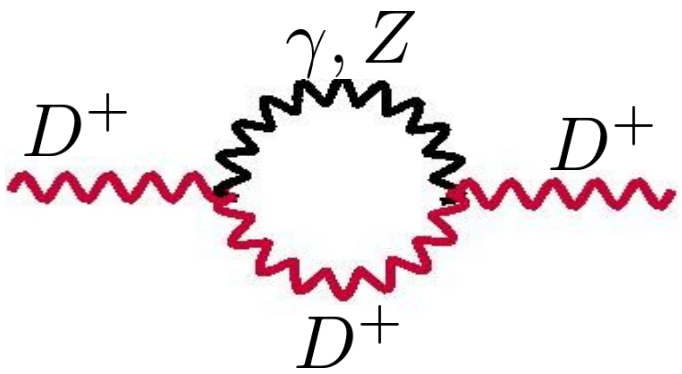


From Tim Tait

Dark Matter and Long Lived Particles

- LLPs appear in the minimal DM
- models with DM being the part of the EW multiplet: **the radiative mass split** of charged and neutral components is $\sim m_\pi$
- The **hypercharge of the multiplet**
  - a) should be zero, otherwise the the model is excluded by DM DD constraints from Z-boson exchange
  - b) or neutral component (DM) of the multiplet should be split by additional (e.g.Yukawa) interactions, which eliminate DM-DM-Z
  - c) multiplet for non-zero hypercharge can not be large – negatively charged component becomes the lightest particle

$$\begin{pmatrix} D^+ \\ D^0 \\ D^- \end{pmatrix} \longrightarrow \quad \Delta M = M_{D^\pm} - M_{D^0} \sim m_\pi$$



$$M_Q - M_{Q'}\big|_{m_D \gg m_W} \approx \frac{\alpha m_W}{2(1+c_W)}\left[(Q^2 - Q'^2) + \frac{2Y(Q-Q')}{c_W}\right]$$

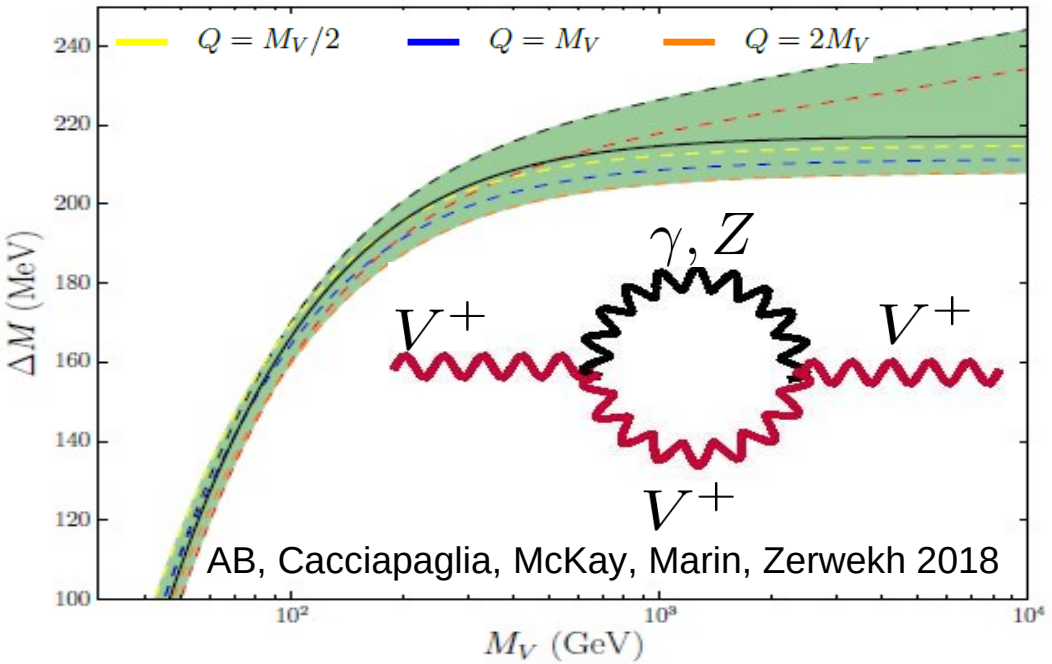
Cirelli, Fornengo,Strumia 2005 (scalar and femion DM)

$$\Delta M = \frac{5g_W^2(M_W - c_W^2 M_Z)}{32\pi}$$

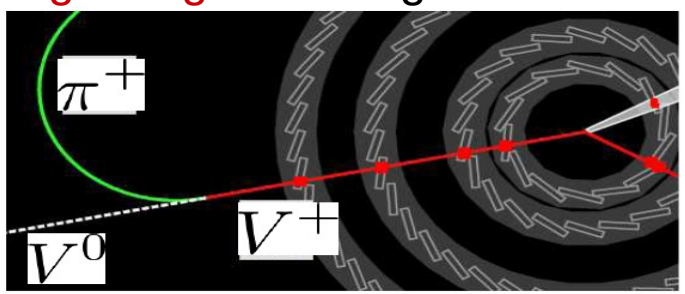
AB, Cacciapaglia, McKay, Marin, Zerwekh 2018 (vector DM)

Dark Matter and Long Lived Particles

- LLPs appear in the minimal DM
- models with DM being the part of the EW multiplet: **the radiative mass split** of charged and neutral components is $\sim m_\pi$
- The **hypercharge of the multiplet**
  - a) should be zero, otherwise the the model is excluded by DM DD constraints from Z-boson exchange
  - b) or neutral component (DM) of the multiplet should be split by additional (e.g.Yukawa) interactions, which eliminate DM-DM-Z
  - c) multiplet for non-zero hypercharge can not be large – negatively charged component becomes the lightest particle

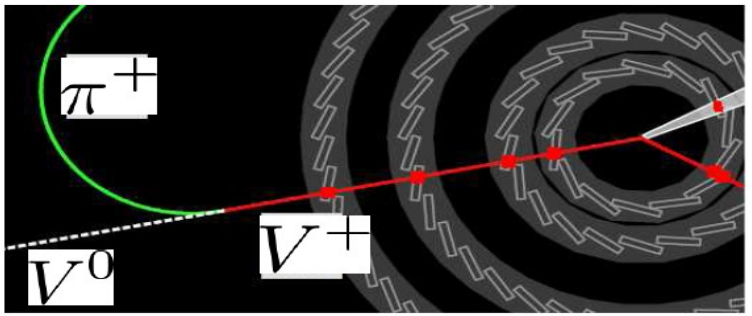


This small mass gap (~ pion mass) provides disappearing charge track signature

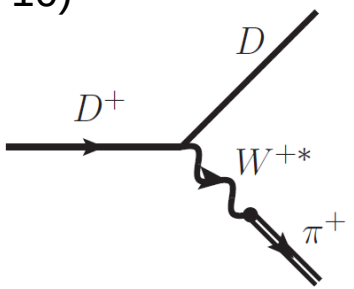


D^+ (charged partner of DM multiplet) decay

- The phase-space suppression makes DM to take away most of the energy in the process making SM particles invisible for the detector producing a Disappearing Track
- D^+ life-time should be properly evaluated using W-pion mixing
  (otherwise overestimated by factor of 10)



$$\mathcal{L}_{W\pi} = \frac{g f_\pi}{2\sqrt{2}} W_\mu^+ \partial^\mu \pi^- + \text{h.c.}$$

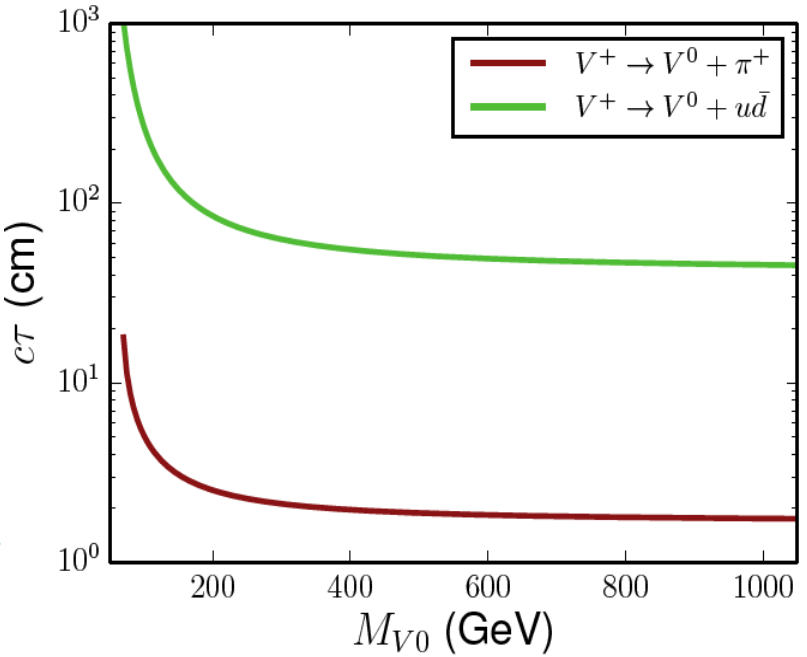


$$\mathcal{L}^{\text{i2HDM}}_{D^+D\pi^-} = -\frac{g' f_\pi}{4\sqrt{2}M_W^2}[(p_D - p_D^+)\cdot p_{\pi^-}]D^+ D\pi^- + \text{h.c.}$$

$$\mathcal{L}^{\text{MFDM}}_{D^+D\pi^-} = -\frac{g^2 f_\pi}{4\sqrt{2}M_W^2}\cos(\theta_{DD_3}) p^\mu_{\pi^-} D^+\gamma^\mu D\pi^- + \text{h.c.}$$

$$\mathcal{L}^{\text{VDM}}_{D^+D\pi^-} = -\frac{g^2 f_\pi}{2\sqrt{2}M_W^2}\left[(p_D - p_{D^+})^\mu g^{\nu\rho} - p_D^\nu g^{\mu\rho} + p_{D^+}^\rho g^{\mu\nu}\right] p_{\pi^-\mu} D^+_\nu D_\rho \pi^- + \text{h.c.}$$

$$\mathcal{L}^{\text{MSSM}}_{D^+D\pi^-} = -\frac{g^2 f_\pi}{4\sqrt{2}M_W^2} p_{\pi^-\mu} D^+ \left[g_L\gamma^\mu P_L + g_R\gamma^\mu P_R\right] D\pi^- + \text{h.c.}$$

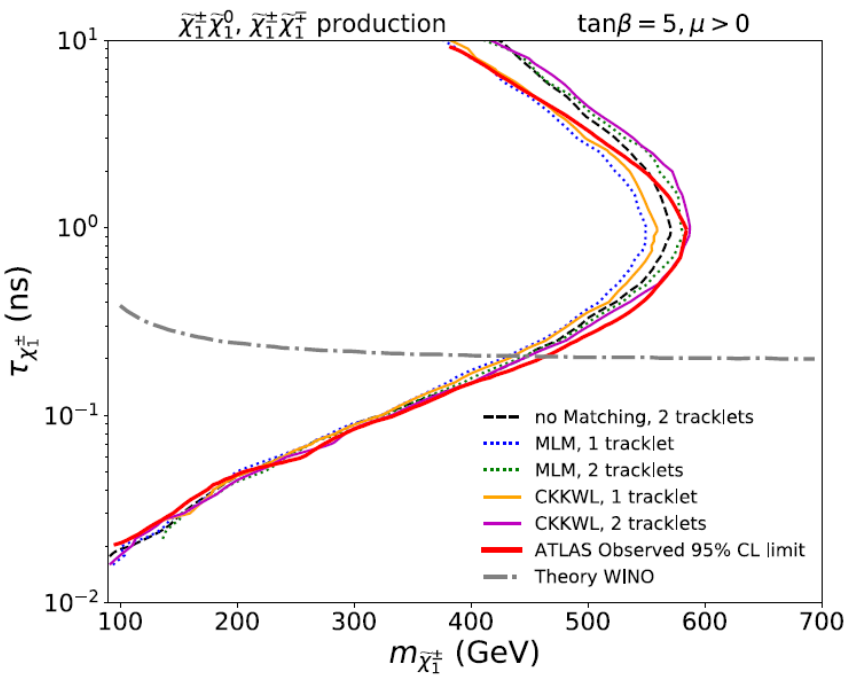


Validation of our analysis

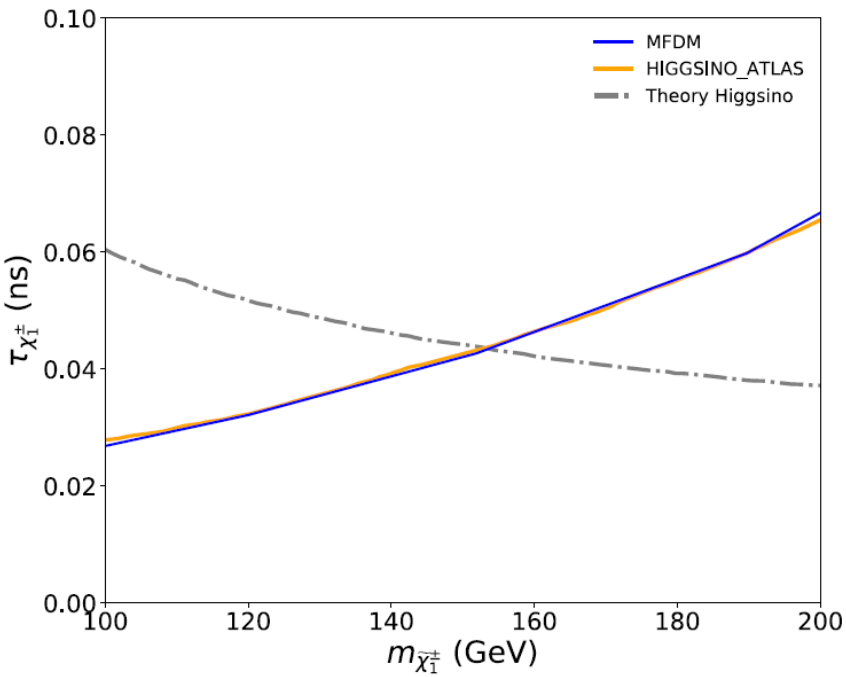
A. Belyaev, S. Prestel, F. Rojas-Abatte, J. Zurita [arXiv 2008.08581]

We first validate our approach by comparing our results for the MSSM wino and MSSM Higgsino scenarios used by ATLAS [arXiv:1712.02118] as benchmark models.

Pure wino



Pure Higgsino



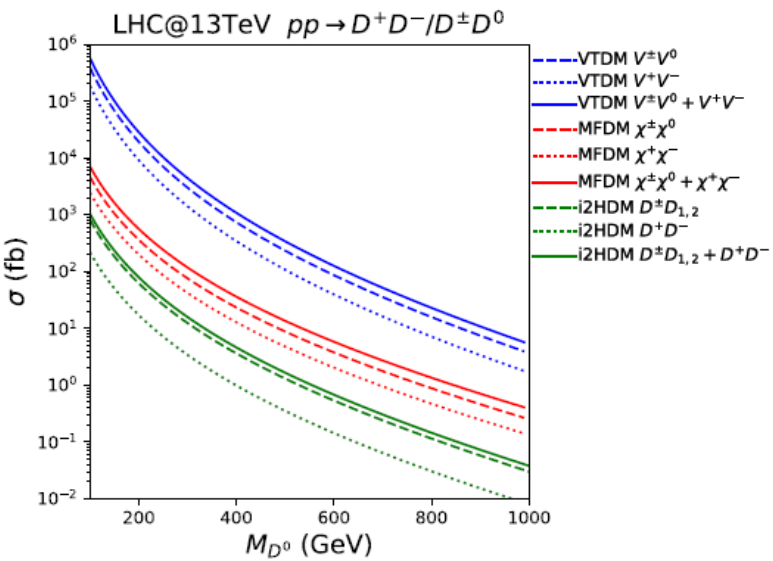
Reinterpretation of the LHC analysis

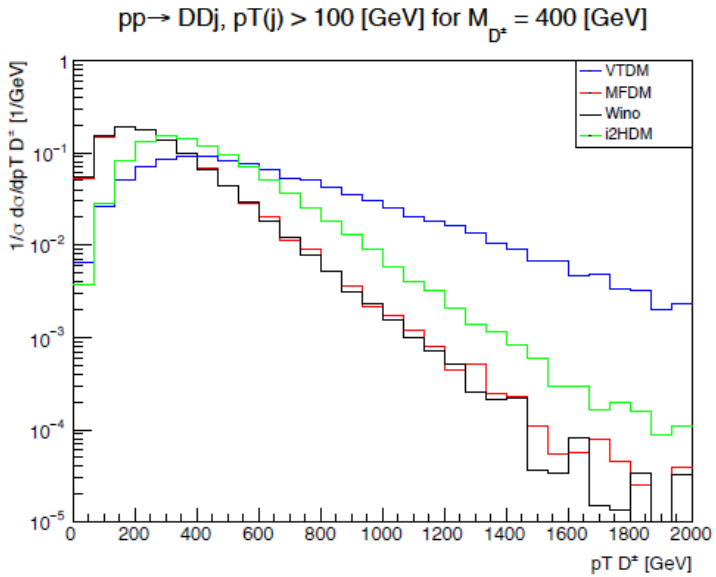
We apply our validated procedure to minimal models where DM is either:

- Scalar: Inert two-Higgs doublet model (i2HDM)
- Fermion: Minimal Fermion Dark Matter model (MFDM)
- Vector: Minimal Vector Triplet Dark Matter model (VTDM)

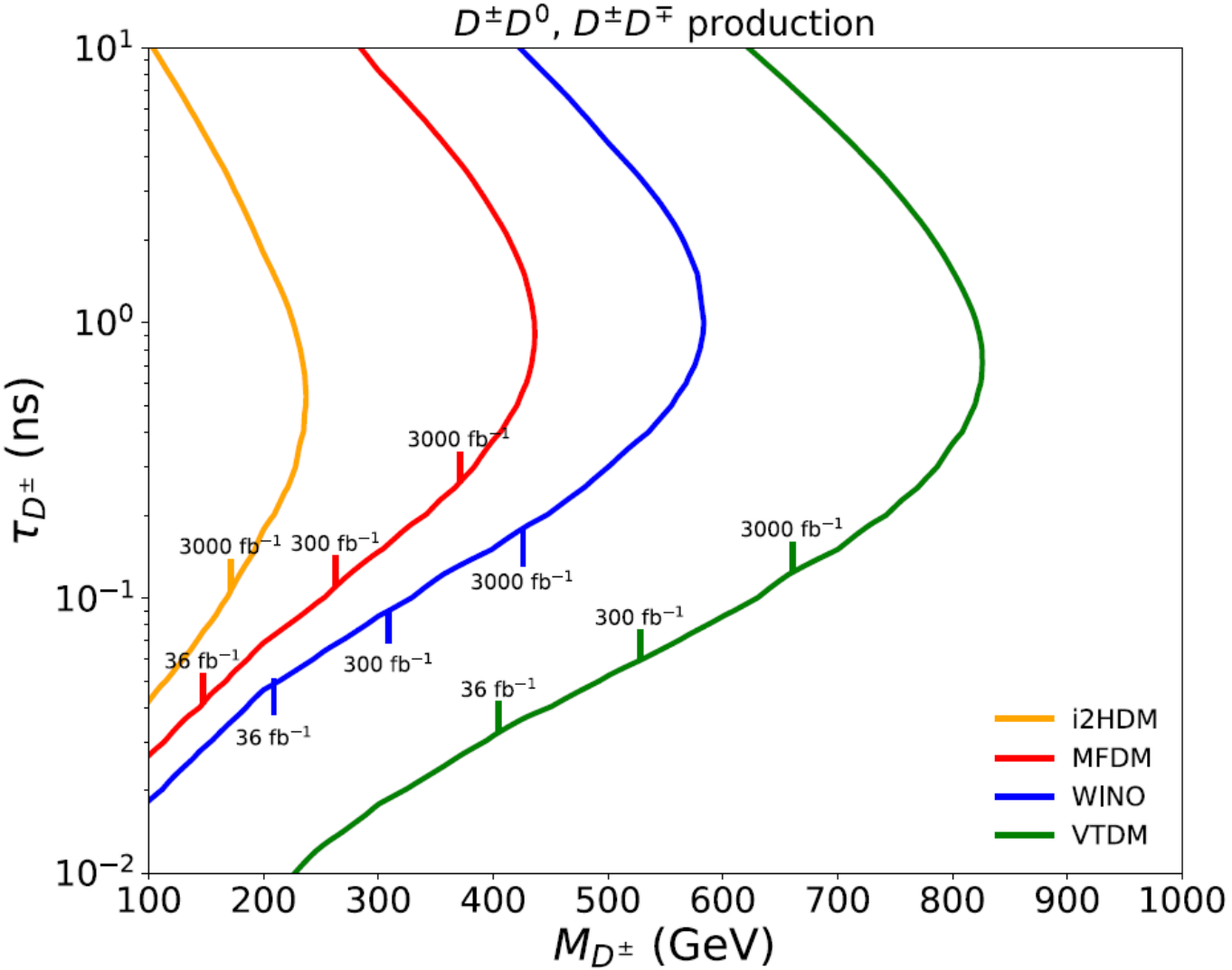
Considering the double production cross section and the Transverse momentum distribution of $D^{\pm}$ we can expect that the constraint hierarchy goes like:

$$\text{VTDM} \rightarrow \text{MFDM} \rightarrow \text{i2HDM}$$

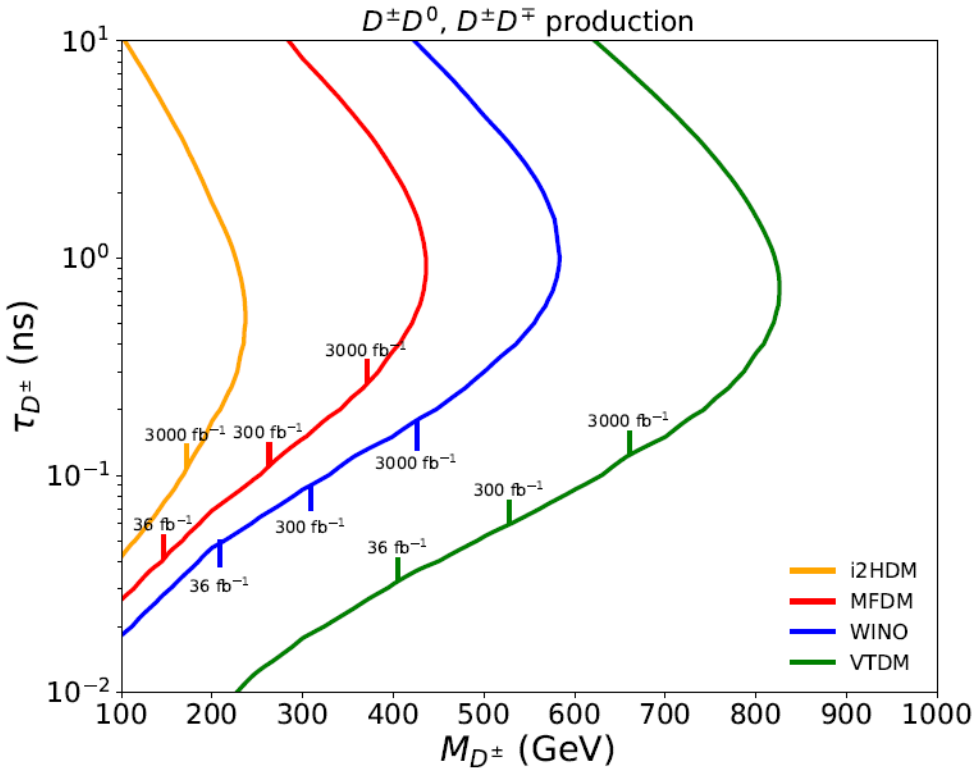




The power of DT for DM probe



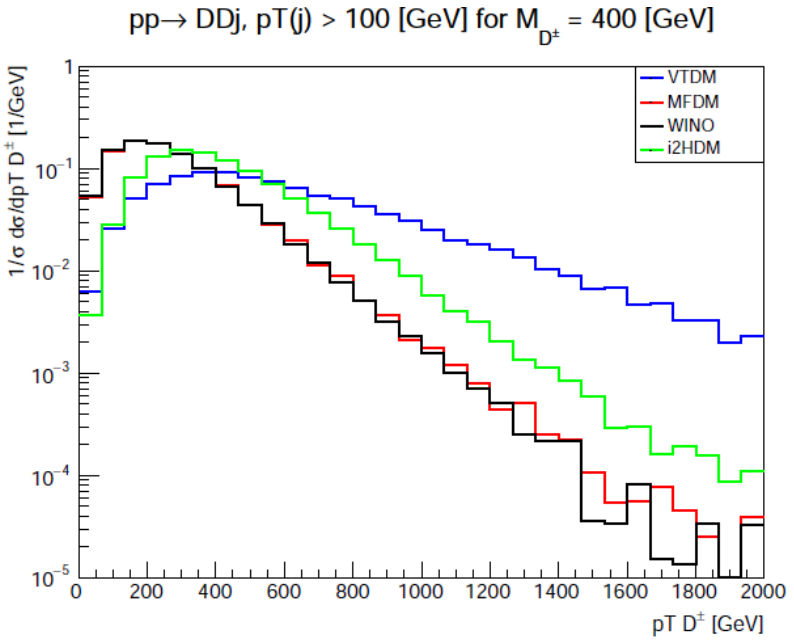
The power of Disappearing Tracks to probe DM models



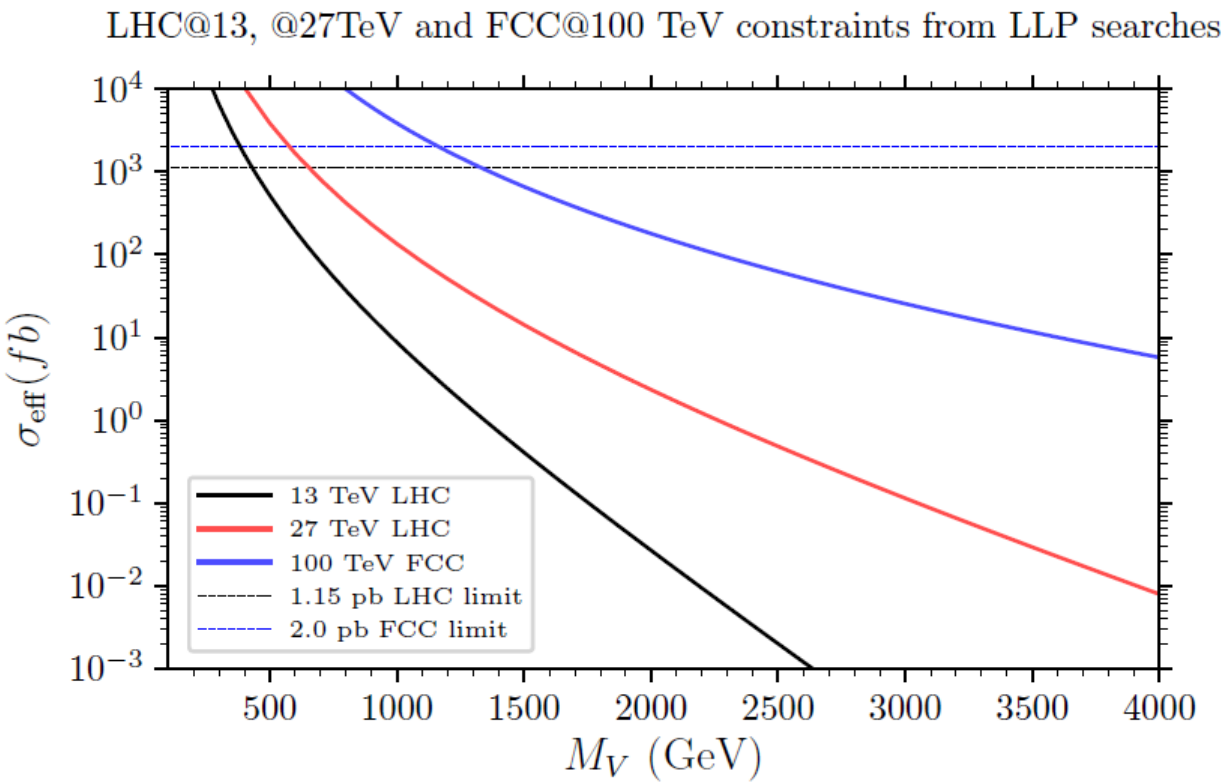
S.Prestel, F.Rojas-Abate,J.Zurita, AB, arXiv:**2008.08581**

- Delphes simulation & reinterpretation of ATLAS DT 36 fb $^{-1}$ results
- Present DT sensitivity goes even beyond HL LHC monojet sensitivity
- The sensitivityy also depends on PT of D+

- The reinterpretation code is public at https://github.com/llprecasting/recastingCodes/



Future Collider sensitivity to VDM mass



AB, Cacciapaglia, McKay, Martin, Zerwekh arXiv:**1808.10464**

Current bound from LHC on DM mass from the minimal vector triplet model is around **500 GeV**

100 TeV FCC will cover DM mass up to **1.2 TeV**

Thank you!