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

Alexander Belyaev

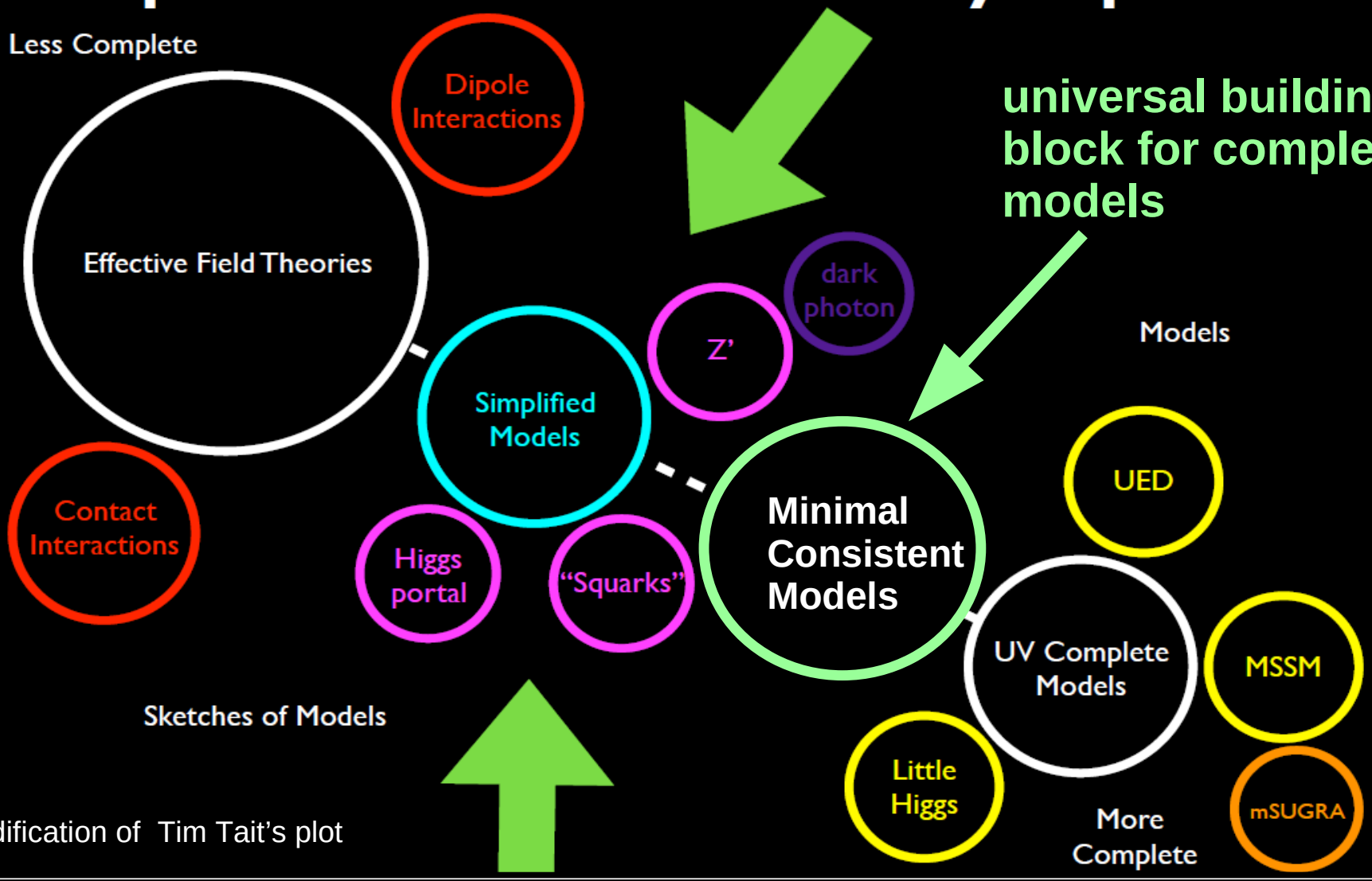
Southampton University & Rutherford Appleton Laboratory

Based on: AB,S.Prestel,F.Rojas-Abatte,J.Zurita [arXiv:2008.08581]

(Re)interpreting the results of new physics searches at the LHC

15-19 February , 2021

Spectrum of Theory Space



modification of Tim Tait's plot

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 $\sim m_\pi$

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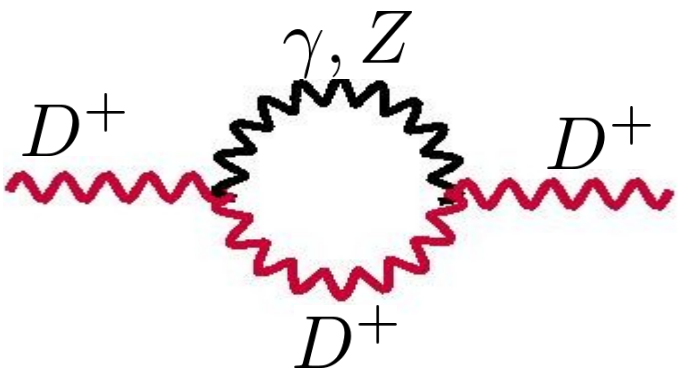

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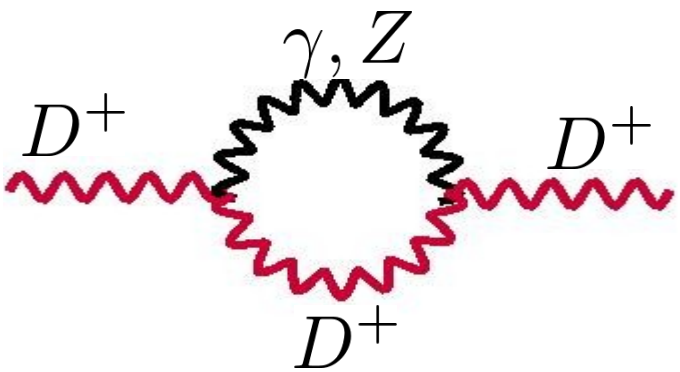

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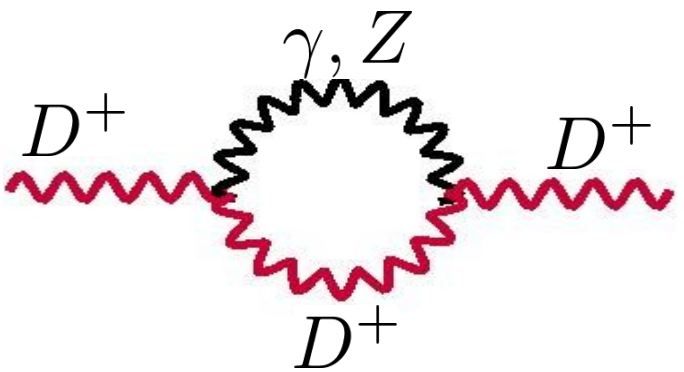

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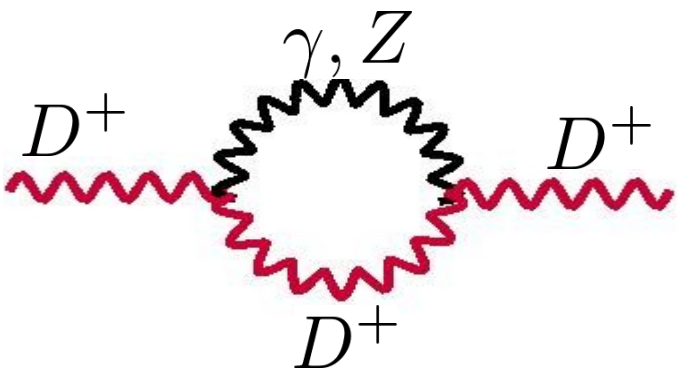

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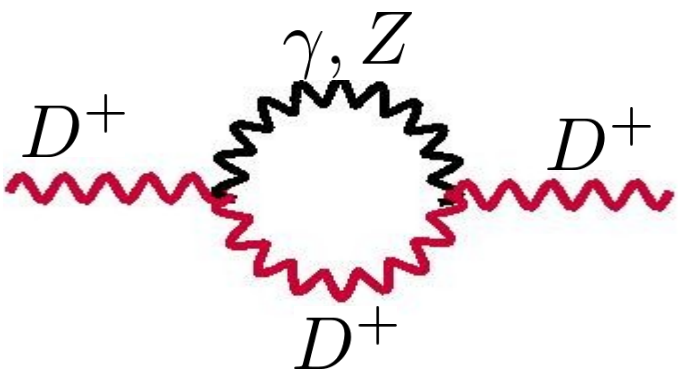

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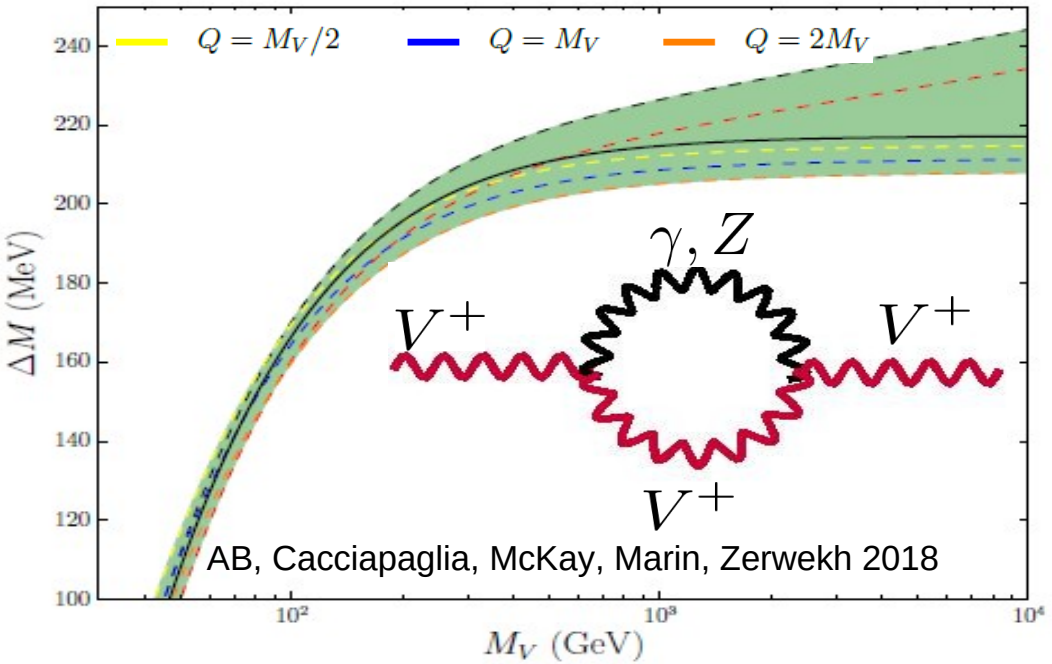
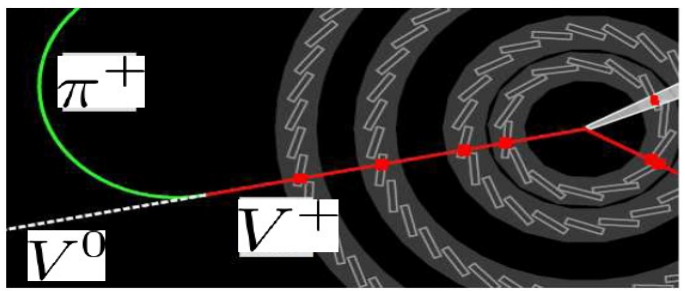
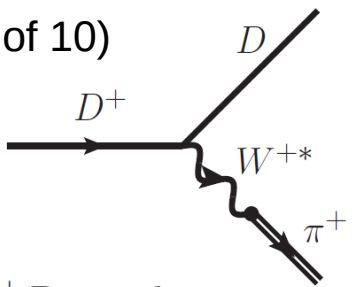


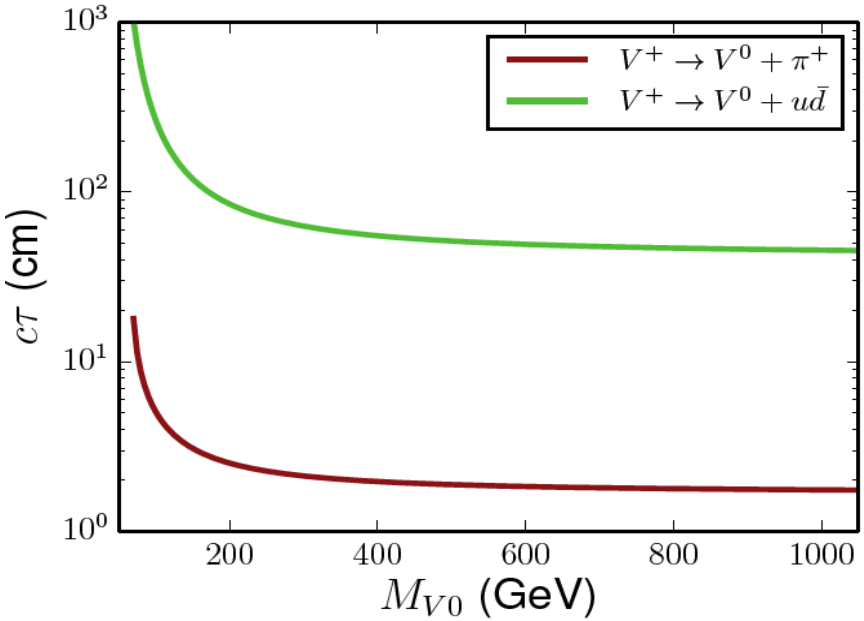
This small mass gap (~ pion mass) provides disappearing charge track signature



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)





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

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

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

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

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

AB, Prestel, Rojas, Zurita [arXiv 2008.08581]

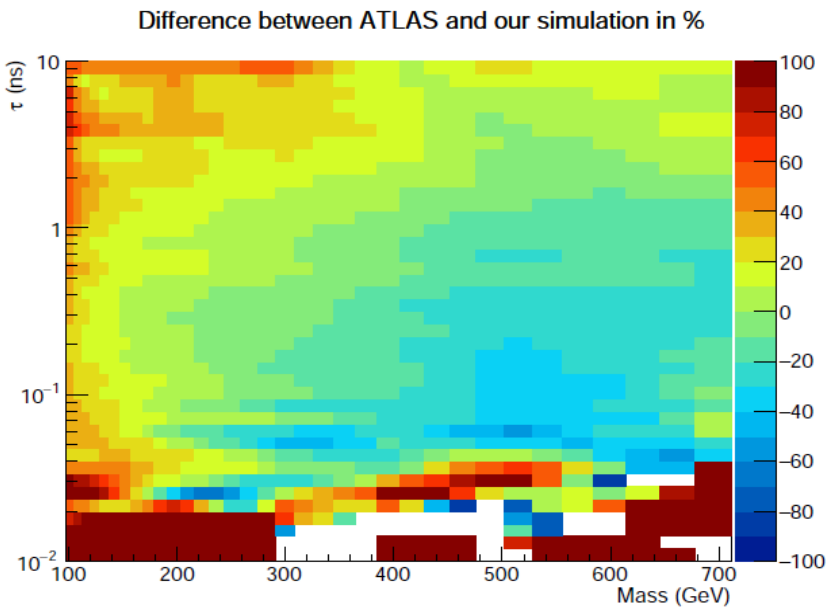
The aim of our study

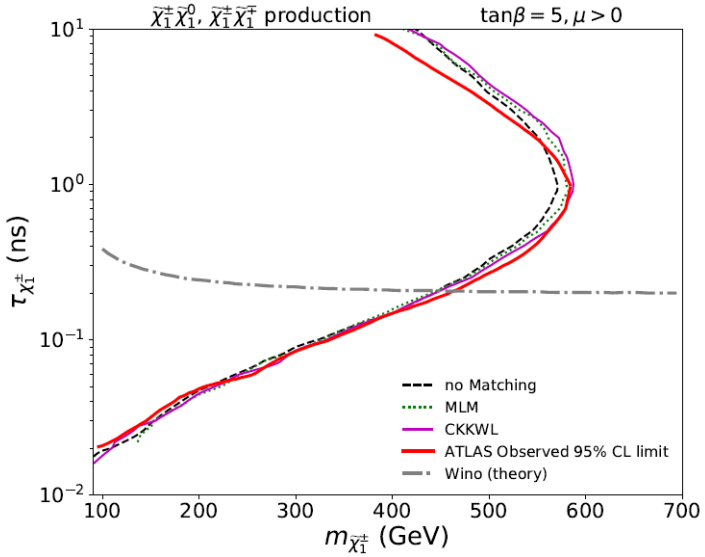
- To reinterpret ATLAS disappearing track search [arXiv:1712.02118] for long-lived charginos with disappearing-track signature for generic models with DM of different spins: 0, ½, 1

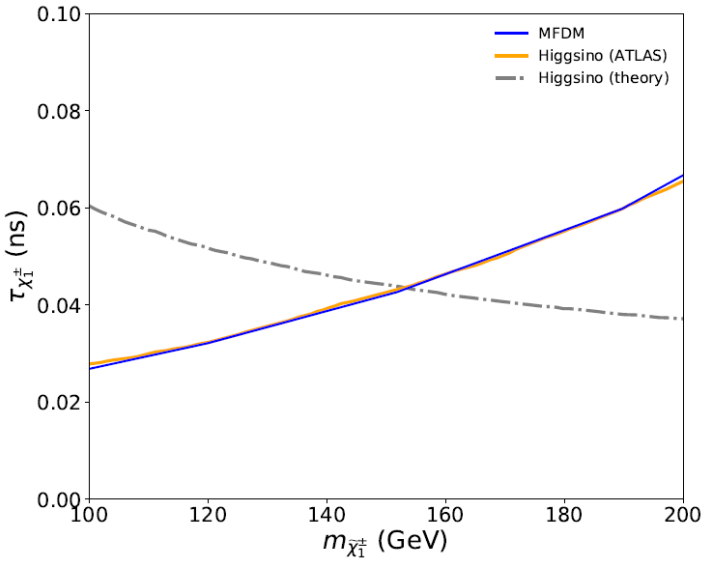
- What we do [arXiv:2008.08581]
  - LanHEP → CalcHEP (LHE) → PYTHIA 8.245 (Latest CKK merging) → Delphes 3.4.1 → analysis code
    - LanHEP/CaclHEP: i2HDM, MFDM, VTDM models with the correct W-pion mixing, models are public at HEPMDB https://hepmdb.soton.ac.uk/ (0820.0330, 0820.0329, 0820.0331)
    - PYTHIA 8.245: improved CKK merging (Stefan Prestel)
    - Delphes 3.4.1: ATLAS card, in particular, to simulate correctly MET from visible ET leptons and jets
    - analysis code (Felipe Rojas): implements ATLAS cuts and efficiency "heatmap" for tracklet ID, evaluates efficiencies and limits for general models
  - Validate our code by comparing with ATLAS limits
  - Find new limits for generic DM models with spin 0, ½ , 1
  - Provide publicly the code and efficiency/limits map in (MDM-τ) plane

Validation of our code/results against ATLAS

- Total acceptance x efficiency check in MDM-τ plane







- Compare Limits in MDM-τ plane for pure wino and higgsino models

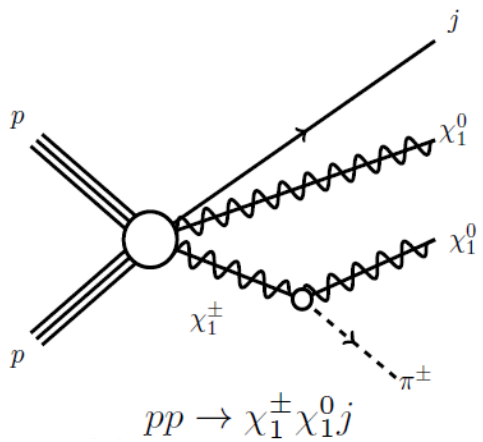
- The difference in limits on chargino mass is less than 5%

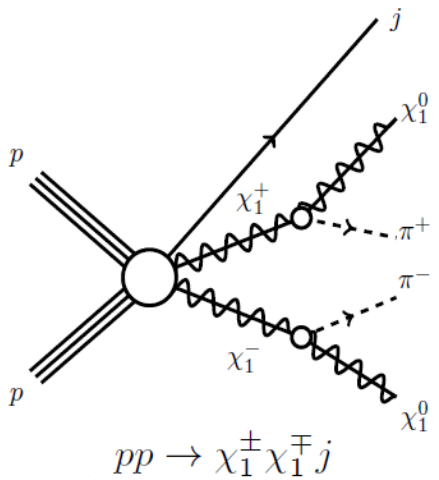
Reinterpretation of the LHC analysis

We apply our validated analysis to minimal consistent models

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

- Two classes of processes: D^+D^- and D^+D^0/D^-D^0 production mediated by s-channel Z/γ and W^+/W^- respectively





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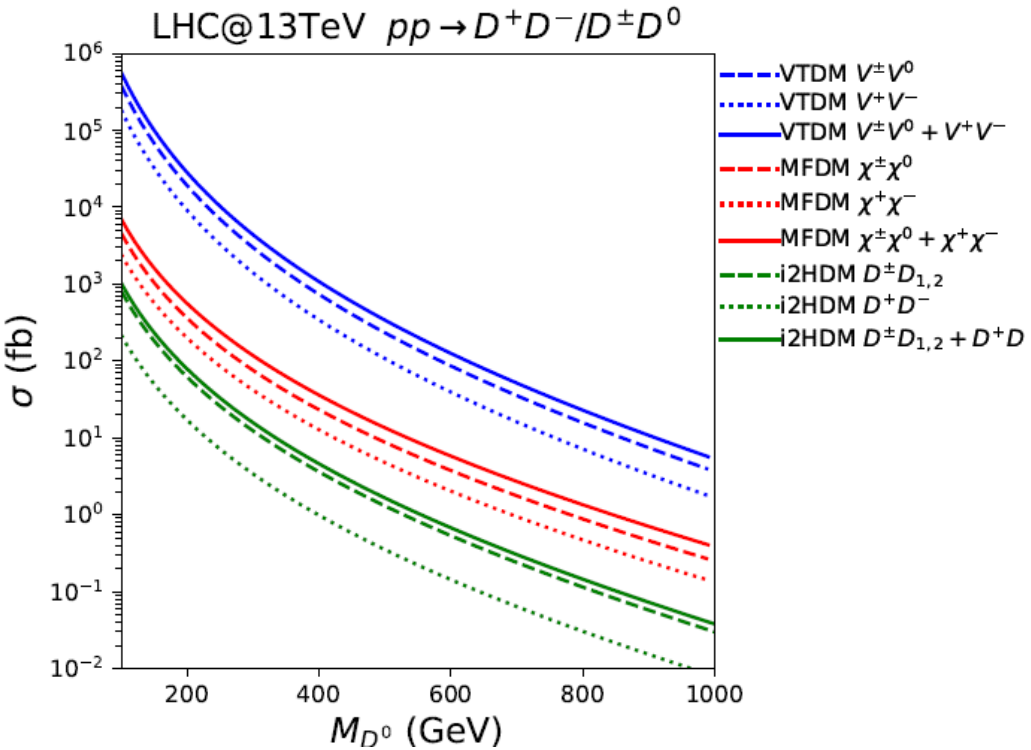
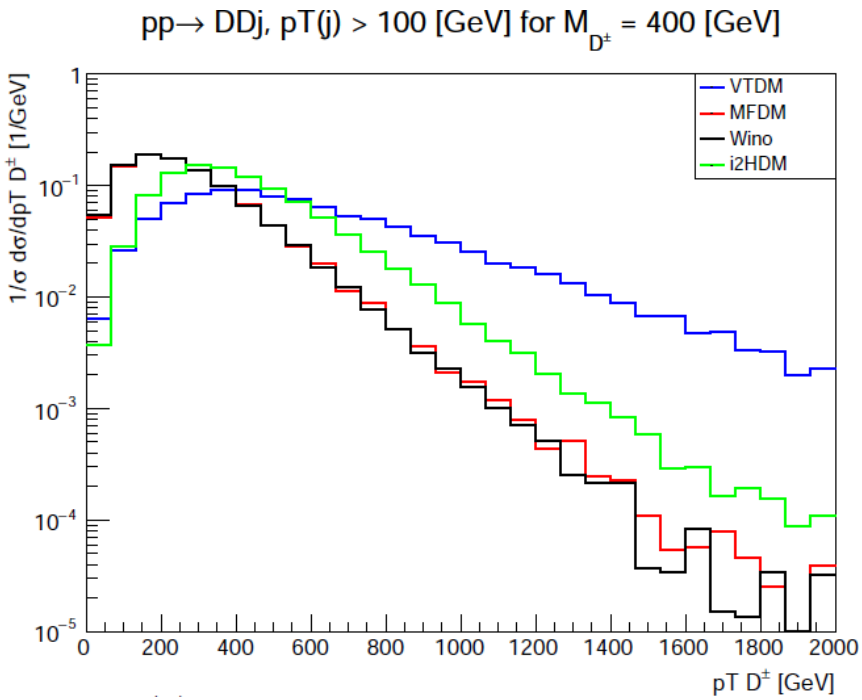
- Cross section and Transverse momentum distribution hierarchy: VTDM → MFDM → i2HDM defines the respective hierarchy of the efficiencies and the LHC sensitivity



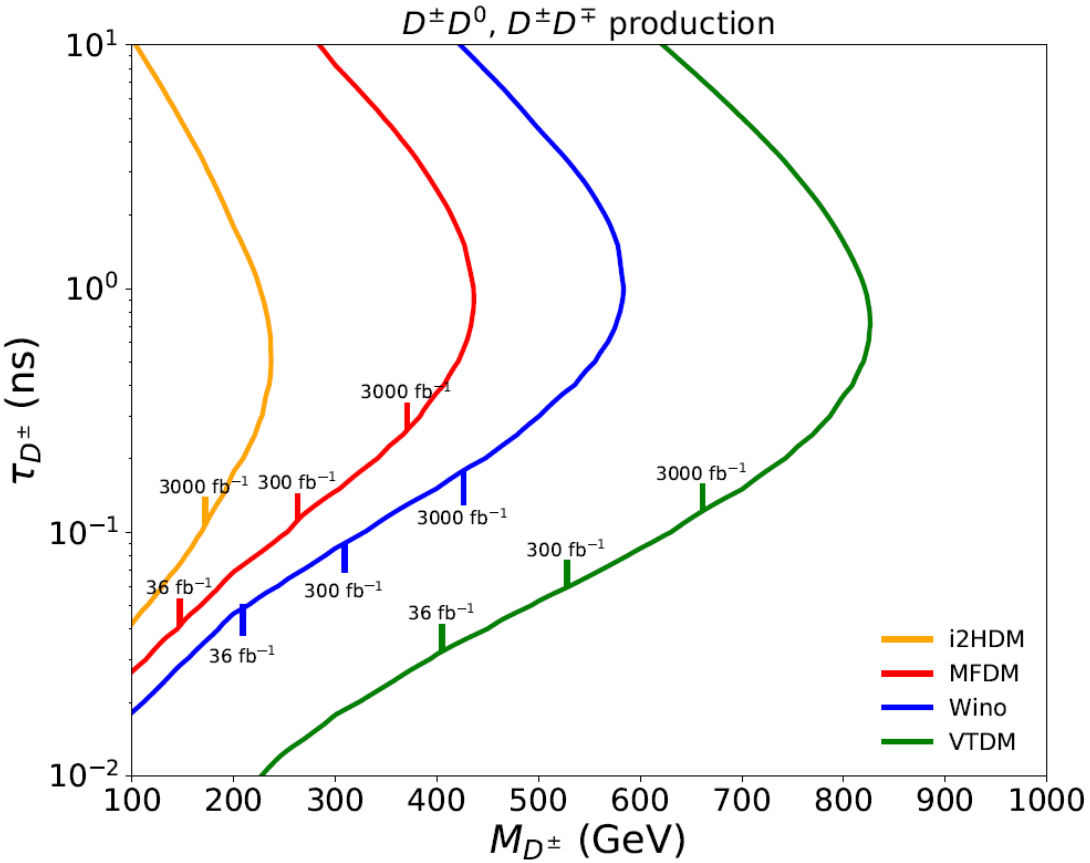


The power of DT for DM probe versus mono-jet limits

- New DT limits for DM models with different spin
- The limits are well beyond those from mono-jet signature analysis for $\tau \sim 1$ ns

Models	Mass (GeV)	tau (ns)
i2HDM	237	0.5
MFDM	436	0.9
VTDM	822	0.7
WINO	587	1.0

- VTDM → MFDM → i2HDM hierarchy is defined by CS and PT



Public source for the interpretation

- The reinterpretation code is public at https://github.com/llprecasting/recastingCodes/ [reads root file after LHE → PYTHIA → Delphes simulation]

- Tables of efficiencies and limits in MDM-τ plane allow to quickly find the reach for your own model in a simple code

tau	Mass (GeV)						
(ns)	100	200	300	400	500	600	700
0.01	1.37e-06	1.90e-07	5.64e-08	1.86e-08	1.17e-08	2.59e-11	2.41e-09
0.02	2.31e-05	9.19e-06	4.13e-06	2.26e-06	1.46e-06	6.29e-07	3.84e-07
0.03	8.67e-05	5.20e-05	3.10e-05	2.06e-05	1.43e-05	8.99e-06	6.72e-06
0.04	1.90e-04	1.43e-04	1.02e-04	7.52e-05	5.61e-05	4.06e-05	3.24e-05
0.05	3.19e-04	2.83e-04	2.27e-04	1.77e-04	1.42e-04	1.10e-04	9.33e-05

efficiencies

tau	Mass (GeV)							
(ns)	91	200	300	400	500	600	700	800
0.01	968.4	10390	63800	318700	1.44e+06	4.17e+06	2.08e+07	1.993e+09
0.02	187.4	753.3	2580	6434	15530	31210	64850	1.272e+05
0.03	99.06	256.7	649.0	1246	2324	3940	7094	11360
0.04	70.91	142.5	293.7	482.5	768.2	1179	1909	2814
0.05	58.26	97.35	173.7	259.1	377.6	538	797.9	1107
0.06	51.03	74.99	120.8	167.5	227.3	305.9	427.8	568.8

Limits in fb

- available at zenodo https://zenodo.org/record/4288736 (thanks to Sabine for idea about zenodo)
- efficiencies for separate channels of D^+D^- and D^+D^0/D^-D^0 production are important for more general interpretation – being produced now (thanks to Felipe Rojas)

Conclusions and Outlook

- The first accurate interpretation of DT
- New limits on DM mass are beyond mono-jet ones for $\tau \sim 1$ ns
- The code is validated and public. Available for being used by HEPM community and in public frameworks, e.g. CheckMATE, MADanalysis etc.
- Tables with limits and efficiencies are also public and can be effectively (e.g. in SmodelS, CheckMATE), especially for individual channels
- The models, including LanHEP source code are at HEPMDB – W-pion mixing is essential to predict correct D^+ decay width/life-time
- The next step is to explore DT for HL-LHC and future colliders

Thank you!