Minimal Consistent Dark Matter Models(MCDM) for systematic Dark Matter exploration

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DM is very appealing even though we know almost nothing about it!

Spin ?

Mass ?

Stable

Yes ? No ?

symmetry behind stability ?

Couplings

gravity V

weak ?

higgs ?

quarks/gluons ?

leptons ?

New mediators ?

Thermal relic

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Collaborators & Projects

- U.Blumenschein, A. Freegard, D.Gupta, S.Moretti, AB arXiv:**2204.06411**
- **G.Cacciapaglia, D.Locke, A.Pukhov, AB arXiv:2203.03660**
- I.Ginzburg, D.Locke, A. Freegard, A.Pukhov, AB arXiv:**2112.15090**
- S.Prestel, F.Rojas-Abate,J.Zurita, AB arXiv:**2008.08591**
- G.Cacciapaglia, J.McKay, D. Marin, A.Zerwekh, AB arXiv:**1808.10464**

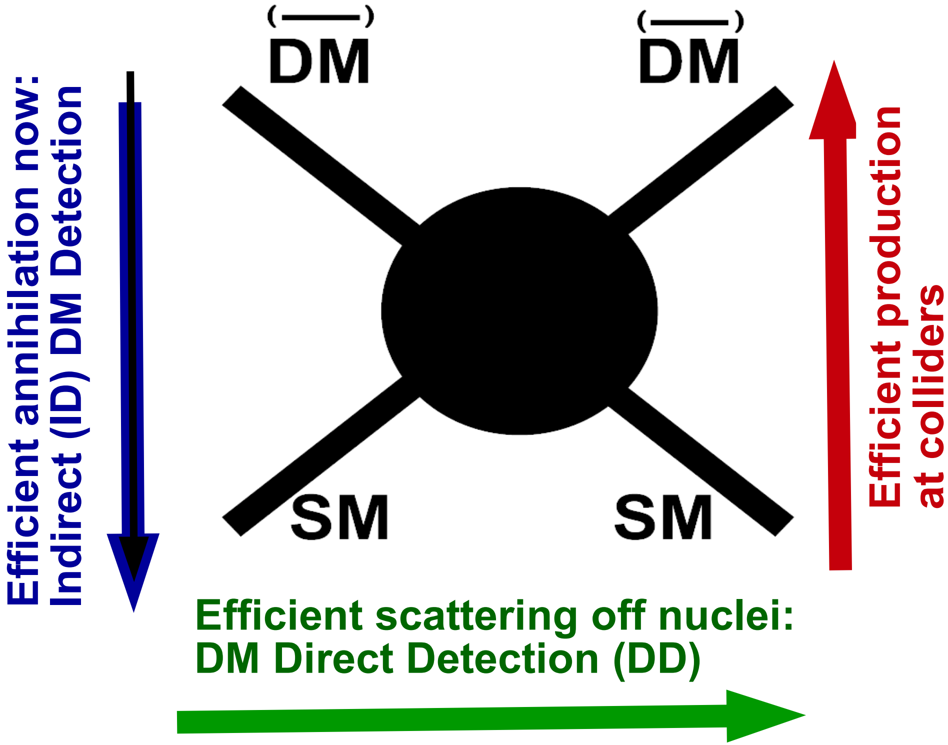
How we can explore & decode the nature of Dark Matter?

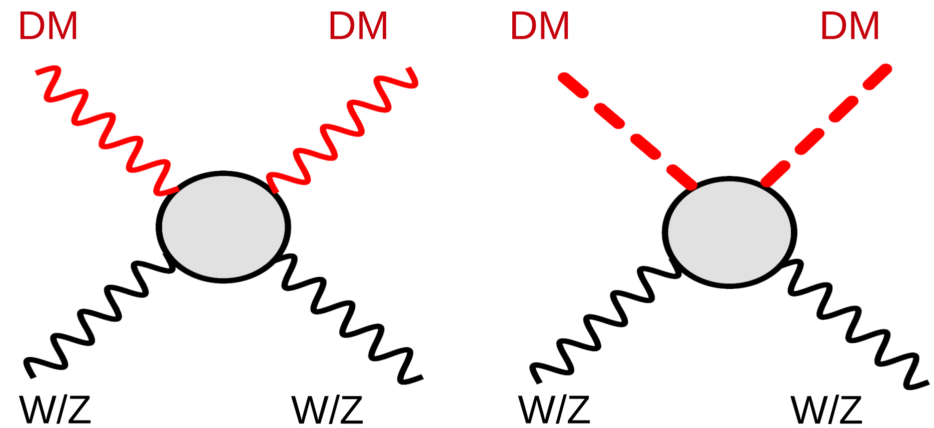
We need a DM signal first!

But at the moment we can:

understand what kind of DM is already excluded
explore and systematise the DM theory space
prepare ourselves to discovery and decoding of DM

Complementarity of DM searches

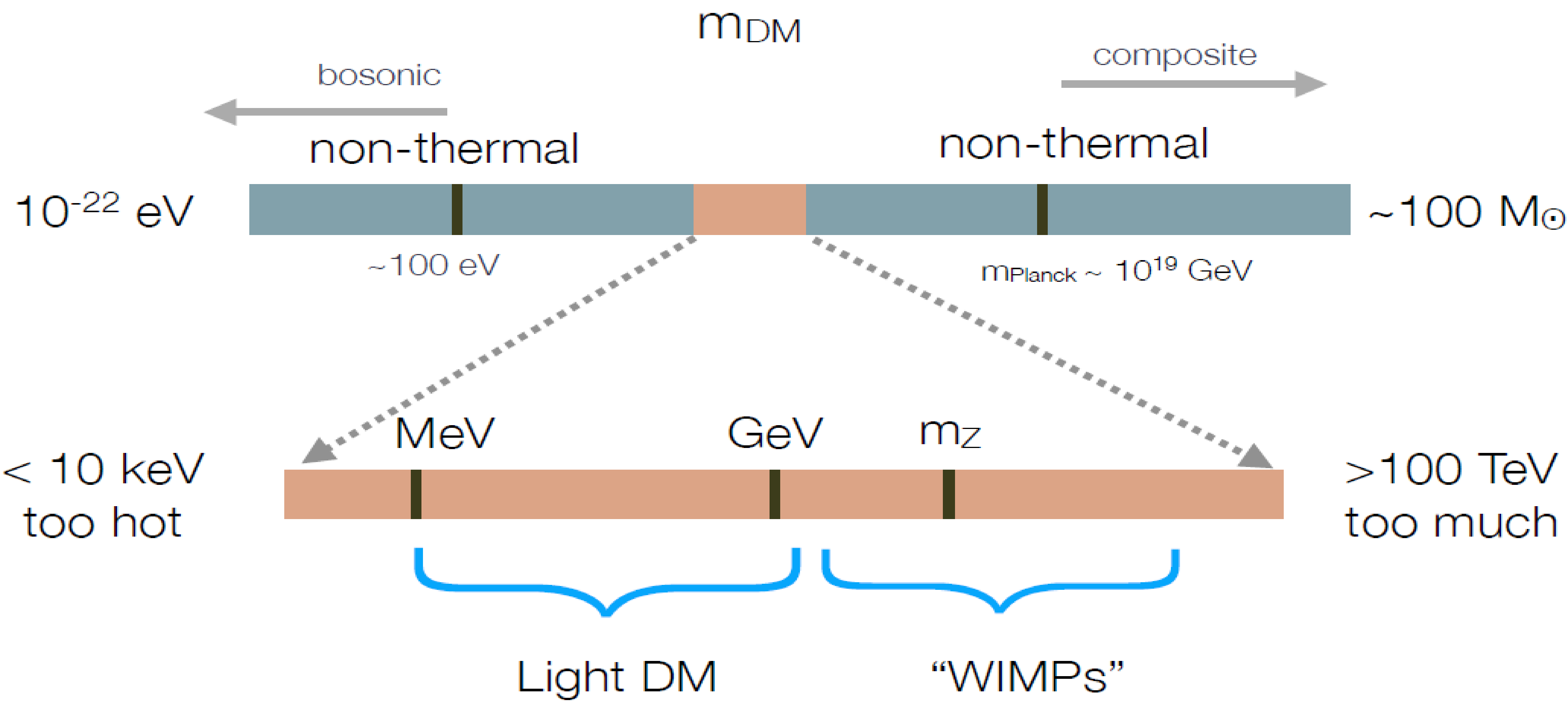




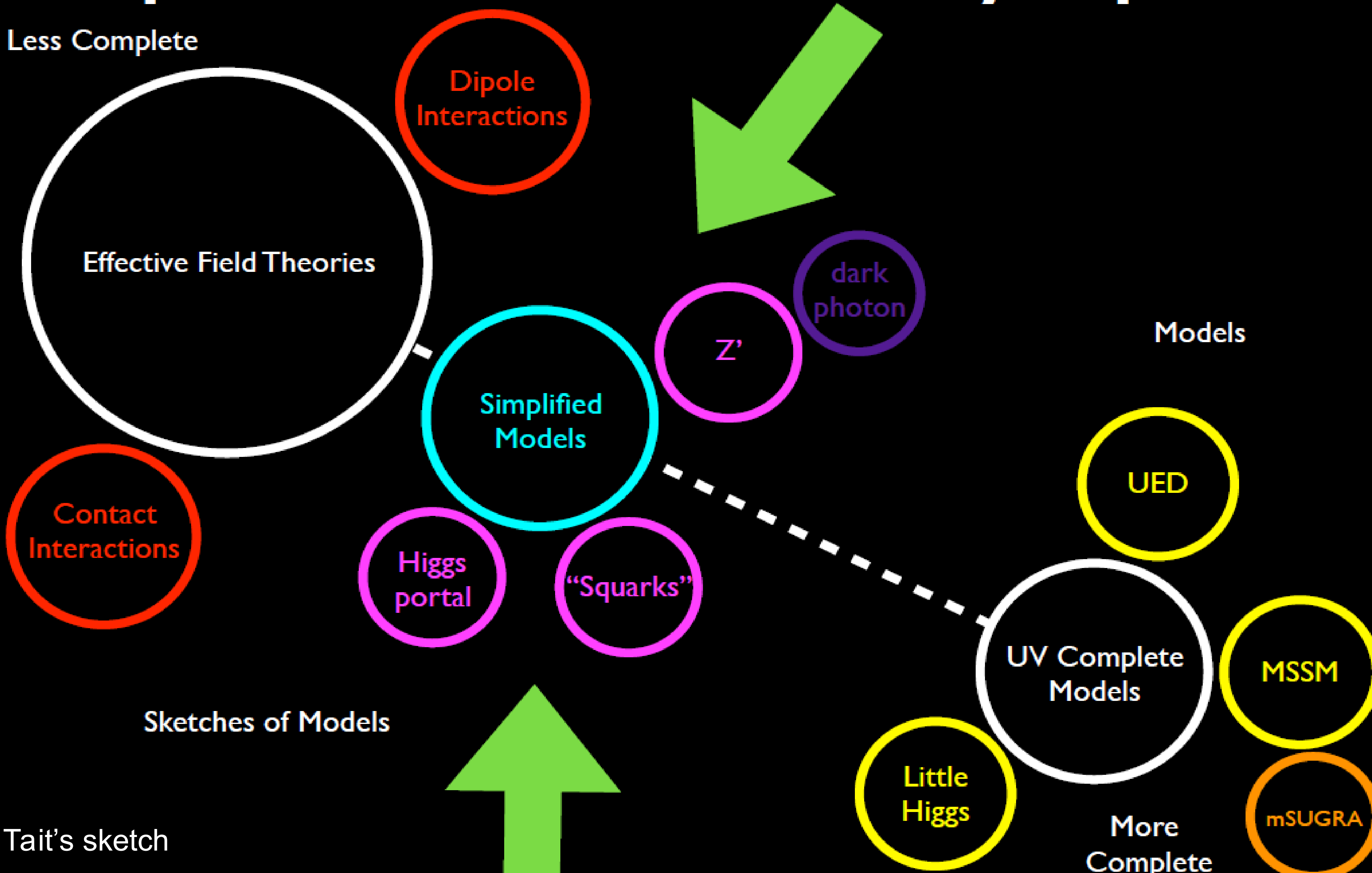
Example of DM interactions with
negligible/suppressed DD rates

Important: **there is no 100%correlation between signatures above.**
E.g. the high rate of annihilation does not always guarantee high rate for DD!

Mass range for thermal DM



Spectrum of Theory Space



Tim Tait’s sketch

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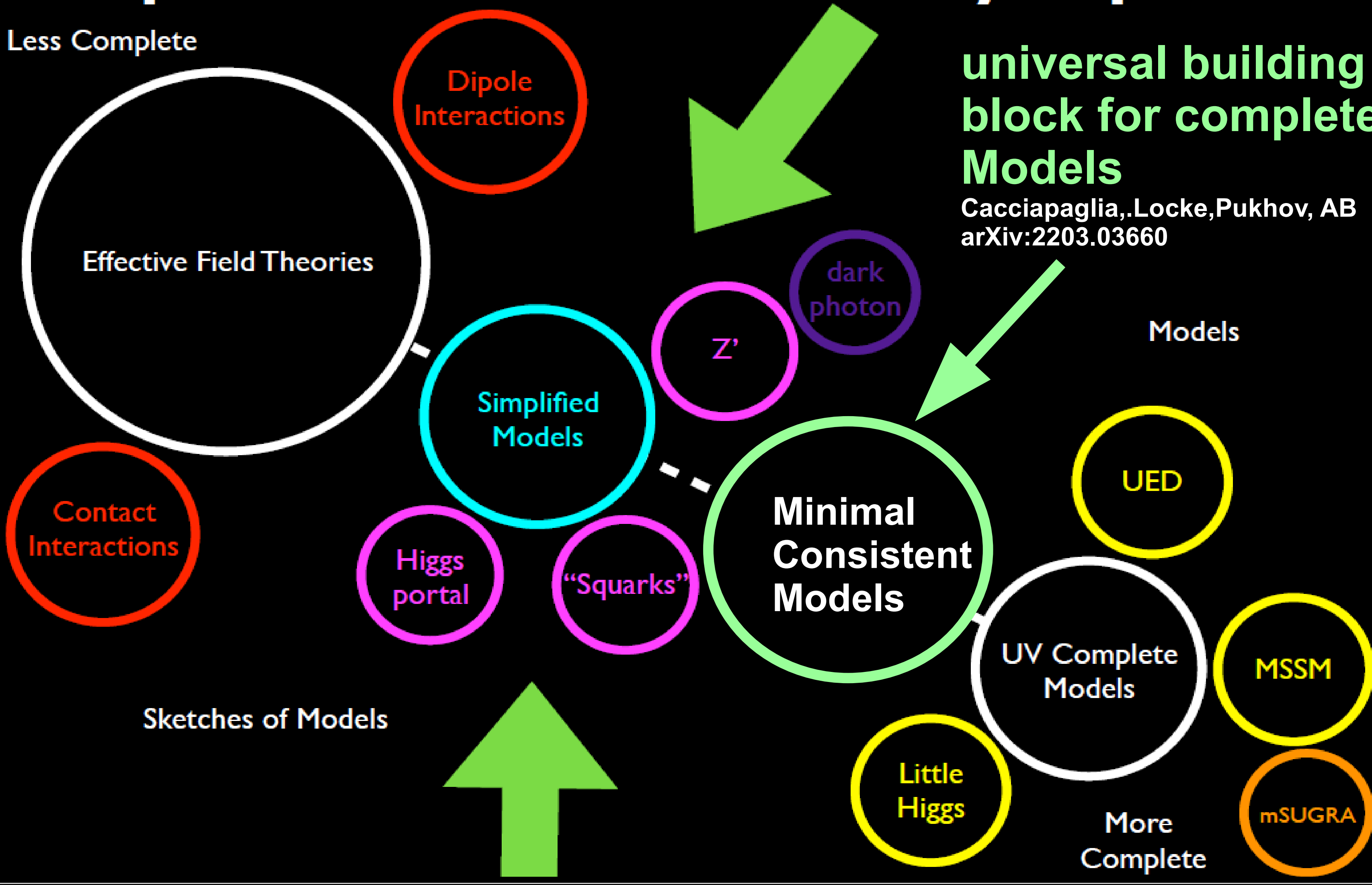

Minimal Consistent DM (MCDM) Models

Properties

- gauge-invariant
- renormalisable
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- can also be a building block of a bigger theory (e.g. SUSY)

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- DM is a part of EW multiplet
- at most one mediator multiplet
- very important for consistent exploration of DM theory space

Z_2 odd or even

spin $\tilde{X}^i_y$ isospin

hypercharge

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G.Cacciapaglia, D.Locke, A.Pukhov, AB **2203.03660**

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DM multiplet only

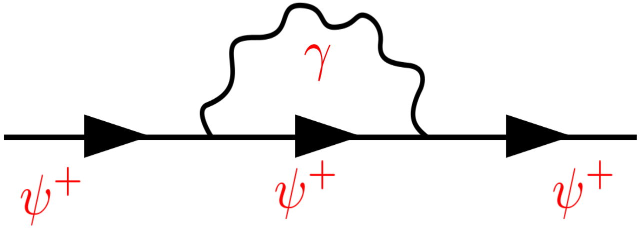
$$\mathcal{L} = i\bar{\psi}\gamma^\mu D_\mu \psi - m_D \bar{\psi}\psi$$

$$\psi = \begin{pmatrix} \psi^{n+} \\ \vdots \\ \psi^{+} \\ \psi_0 \\ \psi^{-} \\ \vdots \\ \psi^{m-} \end{pmatrix}$$

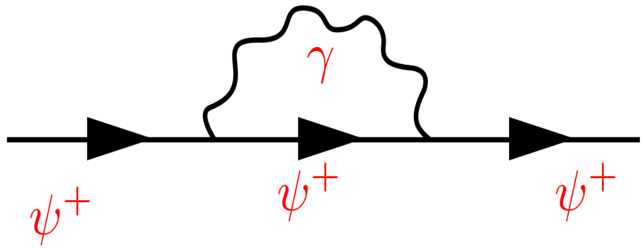
Cirelli,Fornengo,Strumia hep-ph/0512090 (Minimal Dark Matter)

- **{I,Y}={0,0}, {½,½}, {1,0}**

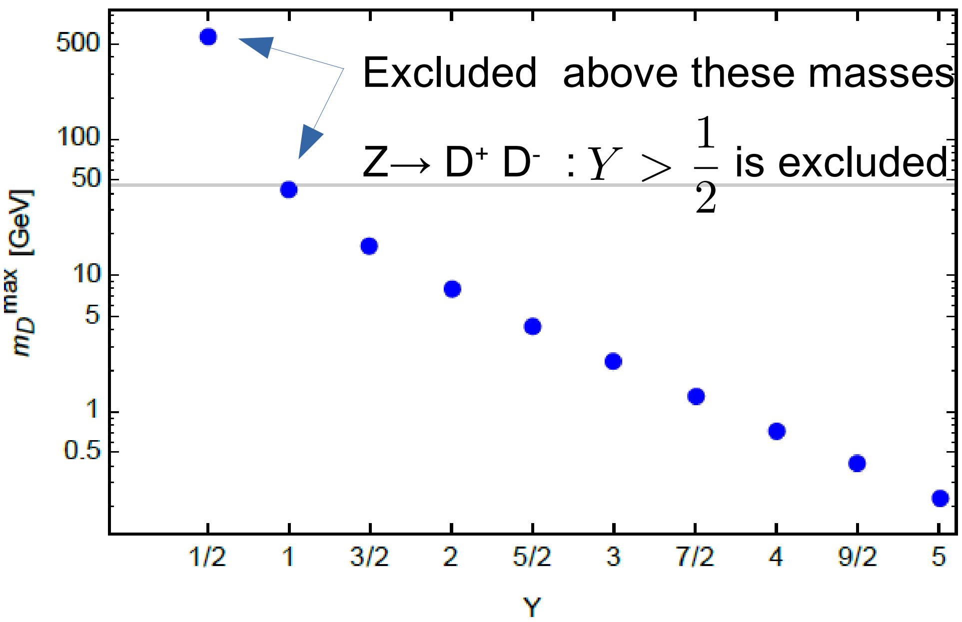
- {0,0} – no gauge-interactions – invisible to direct detection and collider but over(under) abundant if thermal (non-thermal)
- $Y \neq 0$ (Dirac DM) Is excluded by direct detection or requires additional sector – which splits the mass of ψ
- Radiative mass split – very important for the phenomenology

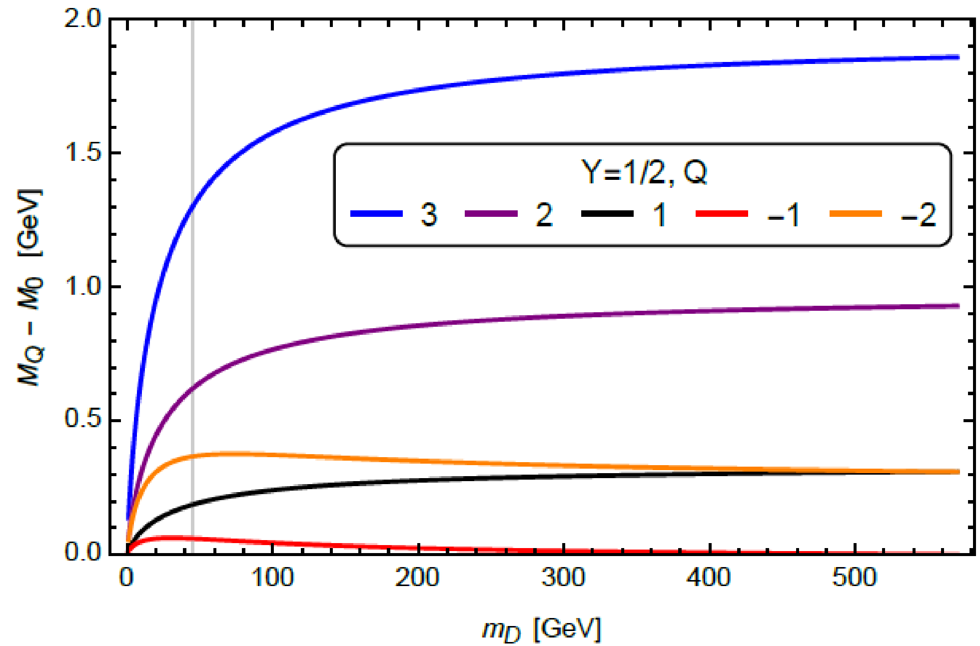


Radiative mass Split
simplest models with Y>1/2 are excluded



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





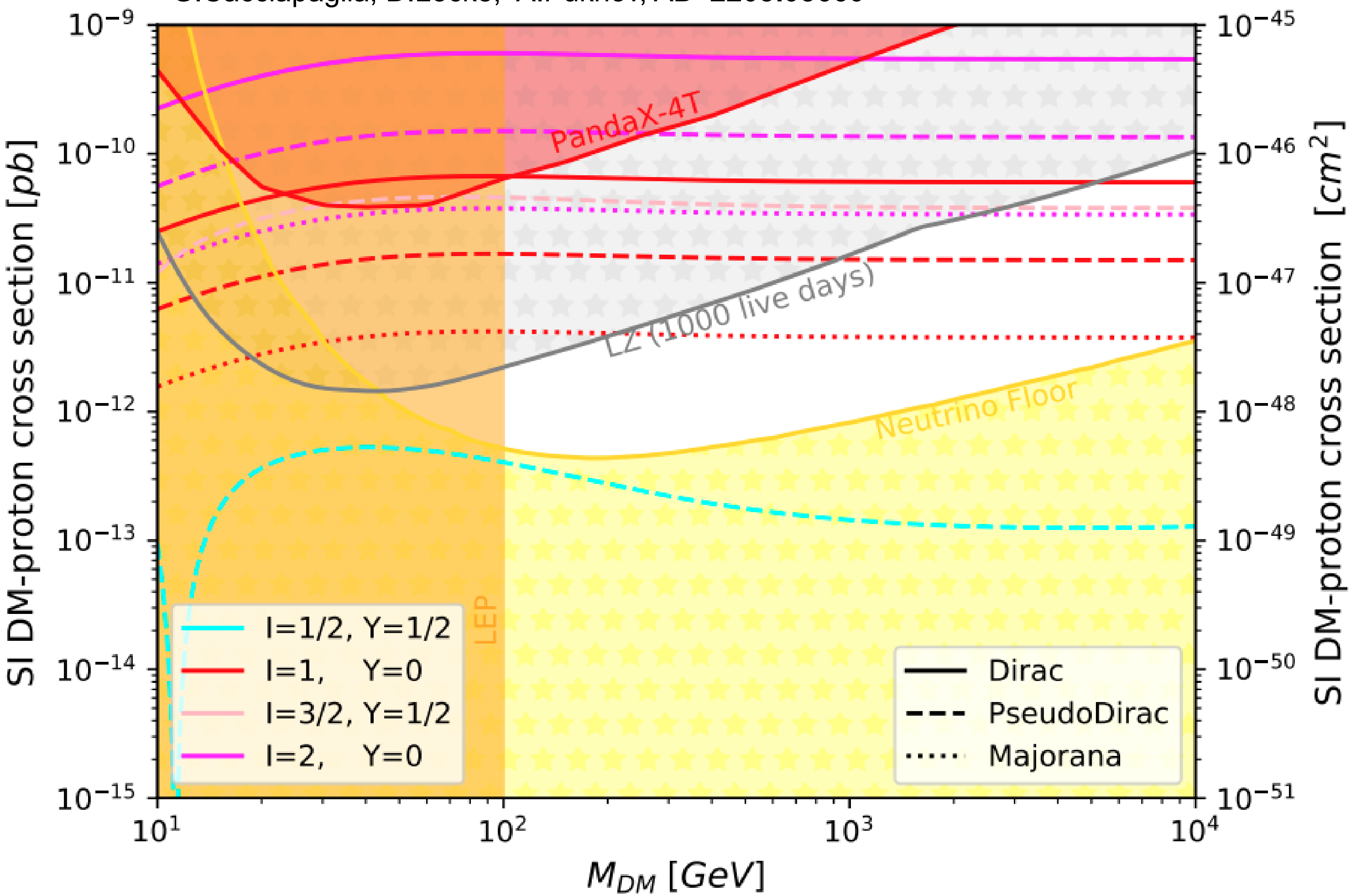
Left: maximum value of m_D above which the lightest particle has charge Q = -1 for various values of Y

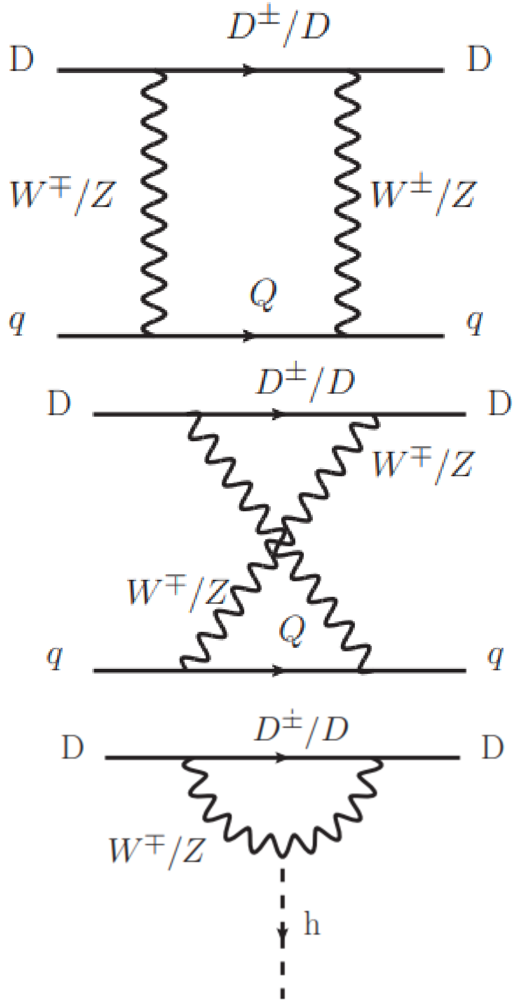
Right: spectrum for a generic multiplet with Y = 1/2, with mD < 570 GeV.

The vertical line shows $m_D \sim m_Z/2$, below which the model is excluded by the Z decays

The role of loops in DM DD

G.Cacciapaglia, D.Locke, A.Pukhov, AB **2203.03660**





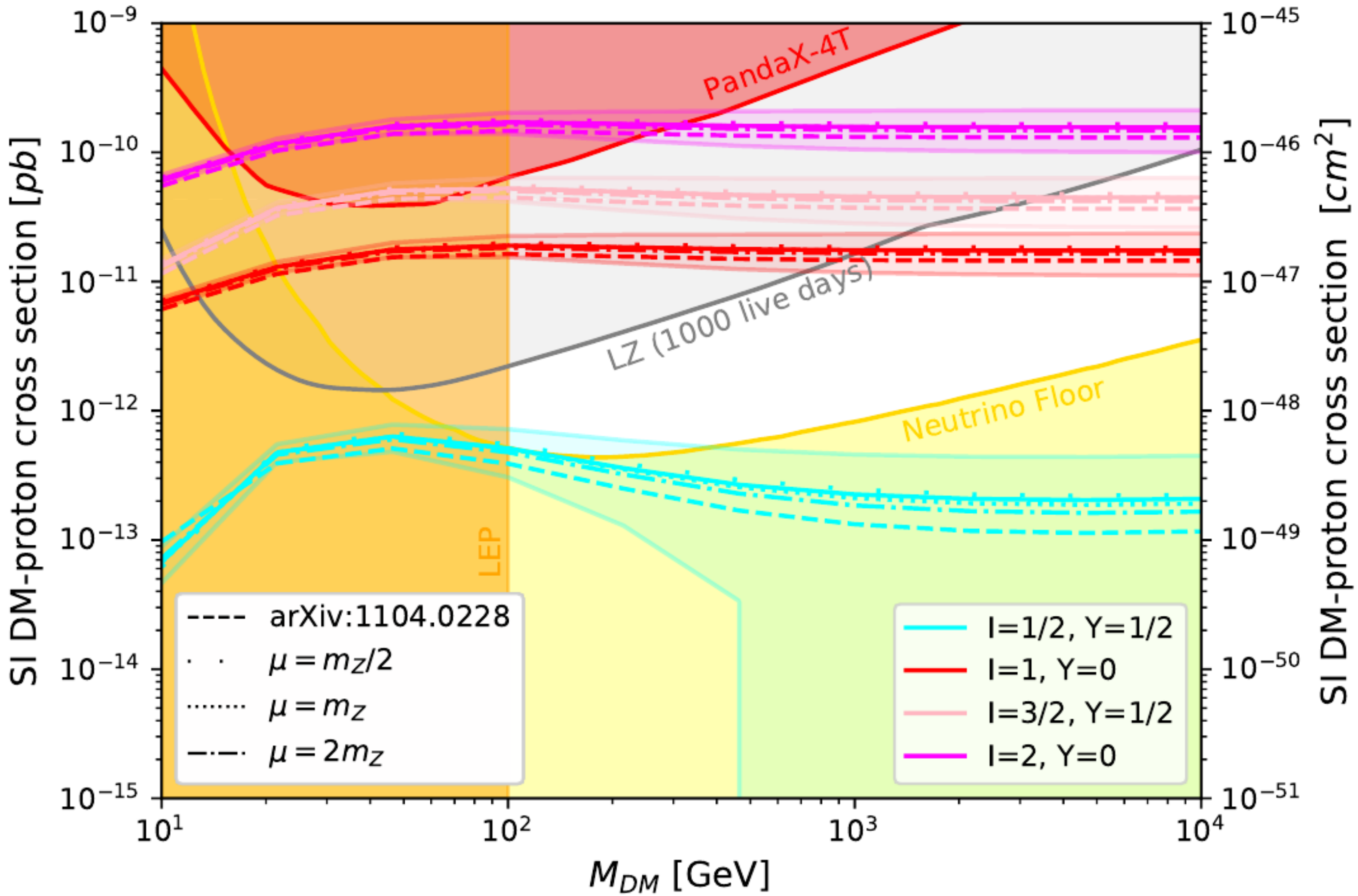
Y=0 minimal candidates may be discovered or ruled out at next generation of DD experiments. But there is a cancellation in amplitudes and some models could be accessible only at colliders!
[Initially noted by **Hisano, Ishiwata, Nagata arXiv:1004.4090**]

The impact of the PDF uncertainties on DM DD

- the uncertainties in the cross section lead to a sizeable uncertainty in the bound on the DM mass ~ several hundred GeV

- For I=1/2 a cancellation may occur for MDM > 450 GeV, hence making a prediction for the direct detection problematic

  But the cross section always remains below the reach of LZ, and will likely escape detection.



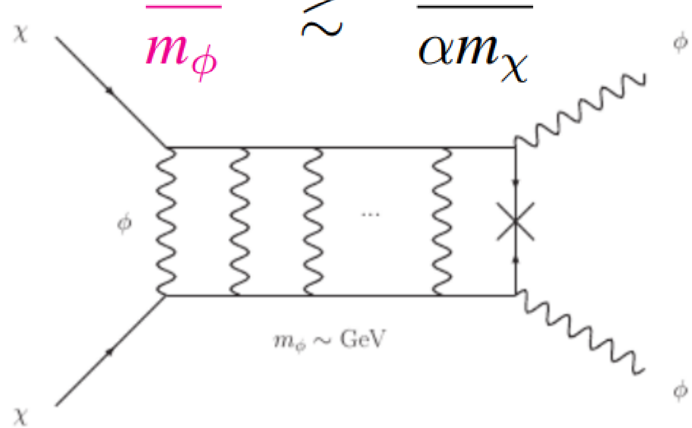
Sommerfeld effect

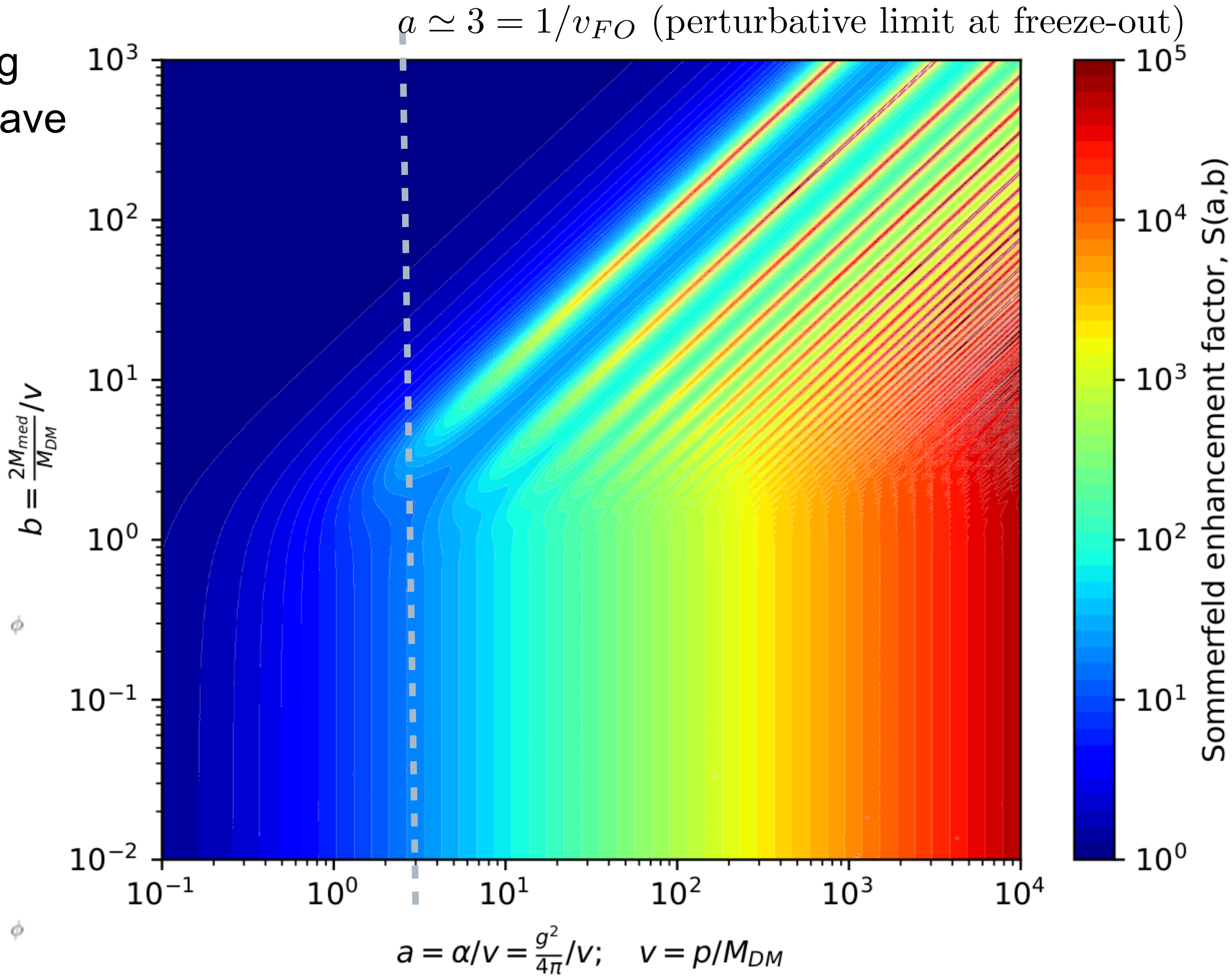
- non-relativistic effect changing the cross section due to the wave function distortion by a long range potential
- Conditions:
  - slow incoming particles

$$m_\chi v^2 \lesssim \alpha^2 m_\chi$$

  - long range force

$$\frac{1}{m_\phi} \gtrsim \frac{1}{\alpha m_\chi}$$





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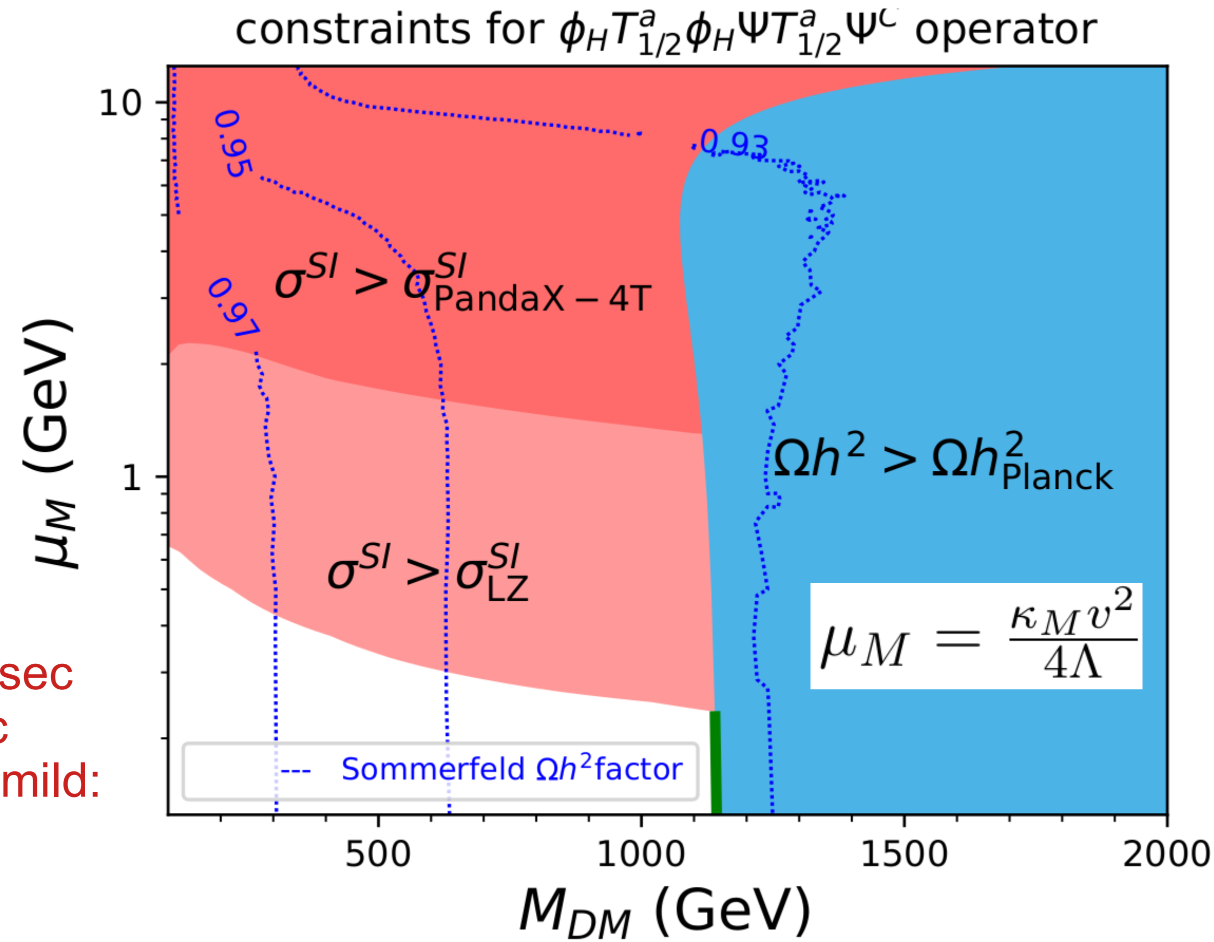
The Sommerfeld enhancement of the xsec and the respective reduction of the relic density (due to the Higgs exchange) is mild: it is (mainly) defined by the velocity at freeze-out

$$\Delta\mathcal{L}_{\rm dim-5} = -\frac{1}{2}\frac{\kappa_M}{\Lambda}\ \phi_H T^a_{1/2}\phi_H\ \bar\Psi T^a_I \Psi^C + {\rm h.c.}$$



$$\tilde{F}^0_0 S^0_0 (CP - odd)$$

Z2 odd

isospin

$$\tilde{X}^i_y$$

spin

hypercharge

Minimal fermion DM model with pseudo-scalar mediator

new model, has not been explored previously

two-component DM model (pseudoscalar is accidentally stable)

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$$\mathcal{L} \supset iY_\psi a \bar{\psi} \gamma^5 \psi - \frac{\lambda_{aH}}{4} |a|^2 \phi_H^\dagger \phi_H$$

Fermion DM Singlet

pseudoscalar

SM Higgs doublet

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- a does not acquire VEV → no linear coupling to Higgs
- $m_a < 2m_\psi$ → "secluded DM"
- Model implemented in LanHEP, and numerical scan performed using micrOMEGAs.

4 relevant parameters:

$$m_\psi,\ Y_\psi,\ m_a,\ \lambda_{aH}$$

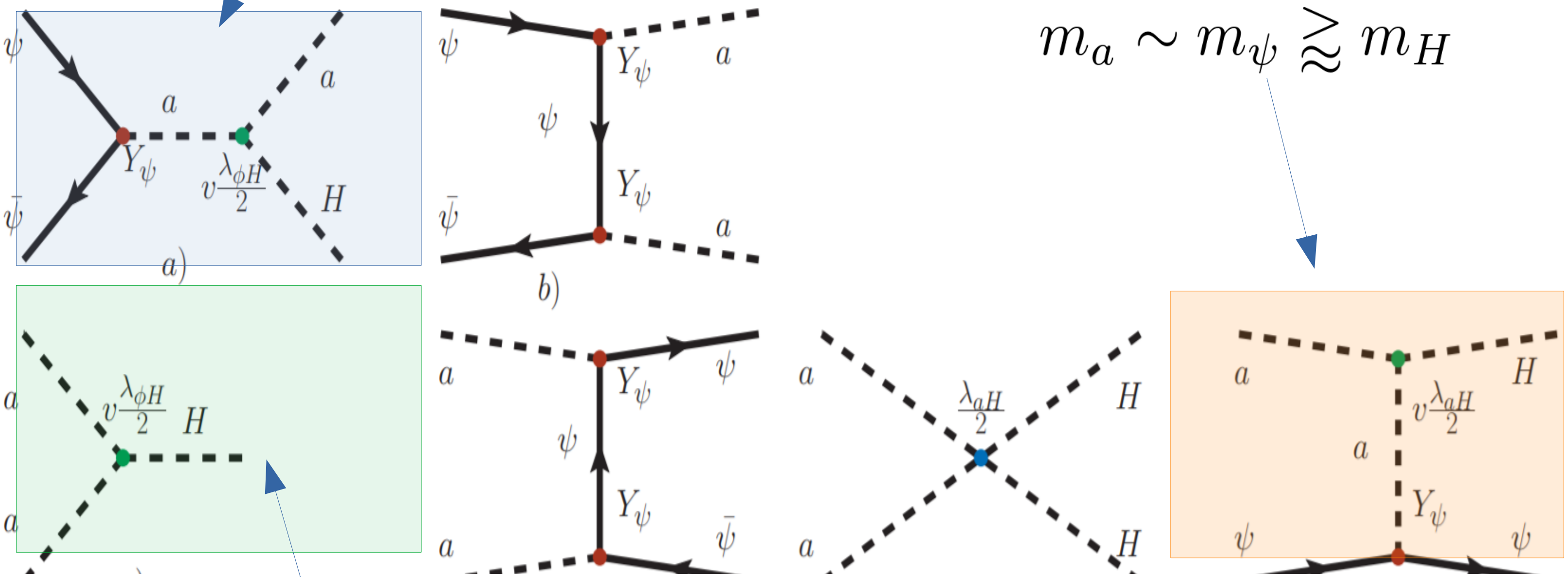
G.Cacciapaglia, D.Locke, A.Pukhov, AB arXiv:**2203.03660**
B.Diaz, P. Escalona,S.Norrero,A. Zerwekh arXiv:**2105.04255**

Minimal fermion DM model with pseudo-scalar mediator
rich phenomenology: relic density, DD, colliders

(co)Annihilation channels

$$m_\psi \gtrapprox \frac{m_a + m_h}{2} \gtrapprox \frac{3m_H}{4} \sim 90GeV$$

$$m_a \sim m_\psi \gtrapprox m_H$$



aa → WW
ma>80GeV
aa → ZZ
ma>90GeV
aa → tt
ma>173GeV

$$\sigma^{ann}_{aa\to ff} v \sim \frac{\lambda^2 m_f^2}{(4m_a^2 - m_H^2)^2 + m_H^2 \Gamma_H^2)}$$

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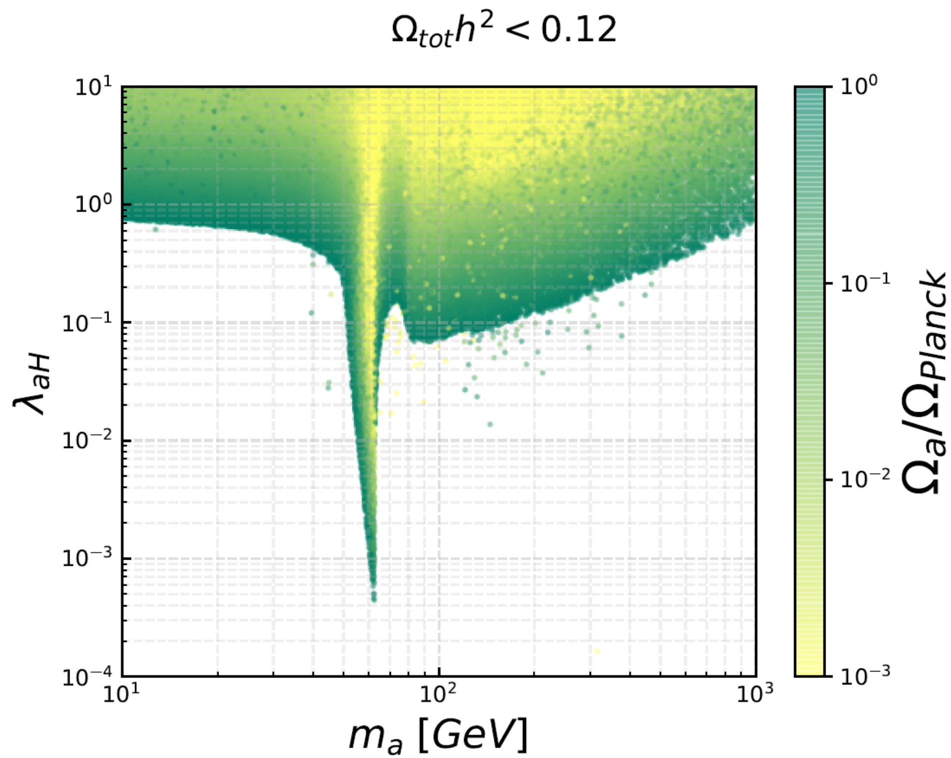
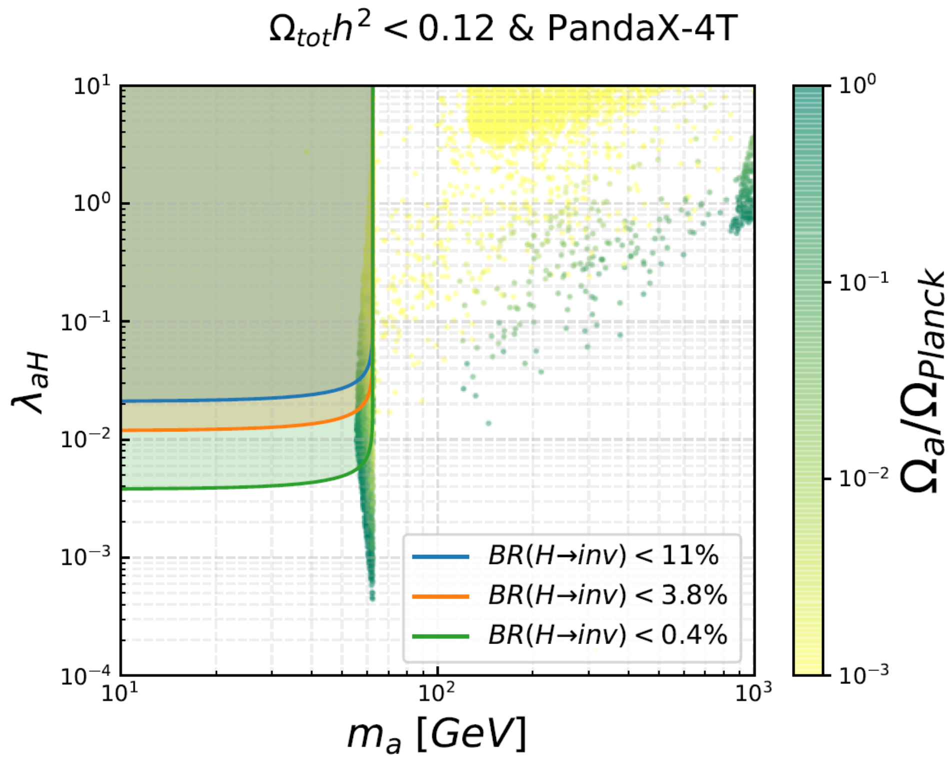
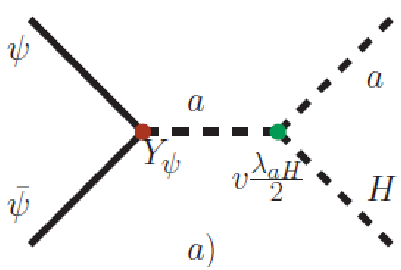
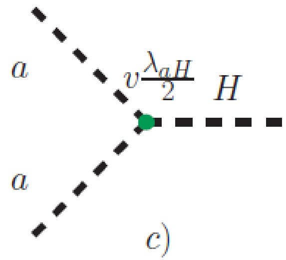
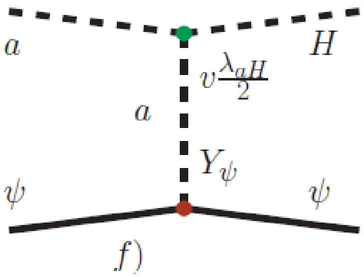


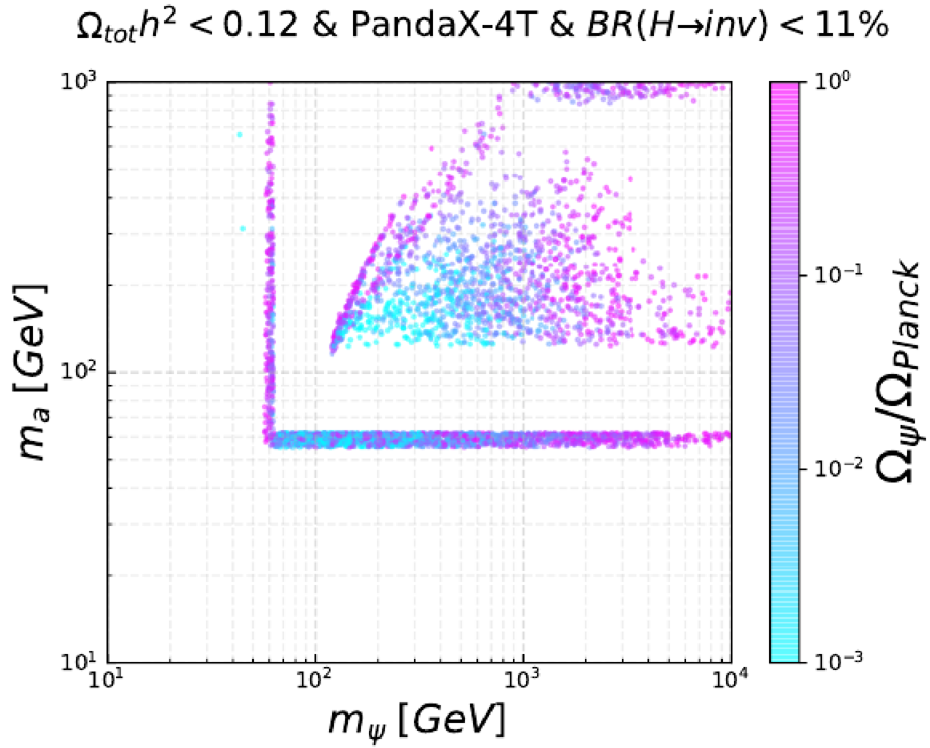


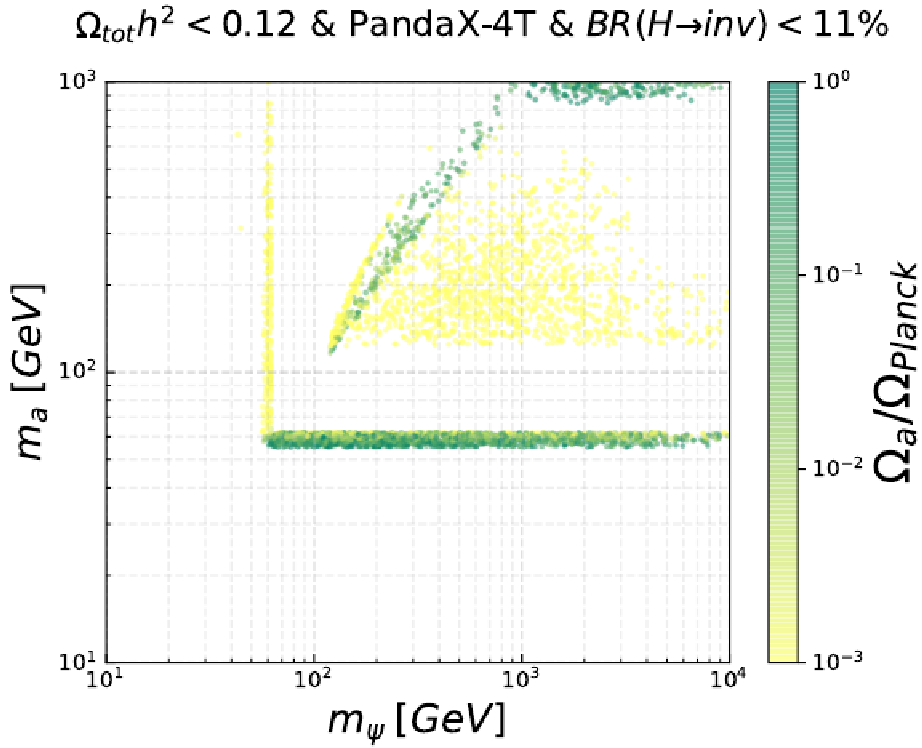


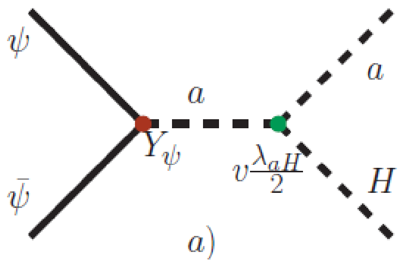


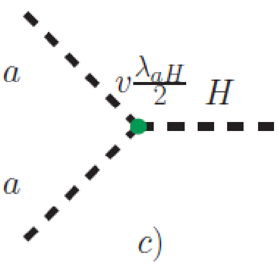


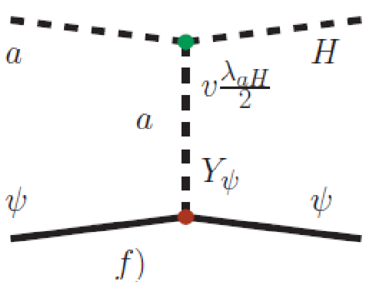
Minimal fermion DM model with pseudo-scalar mediator
Xenon1T vs LZ exclusion











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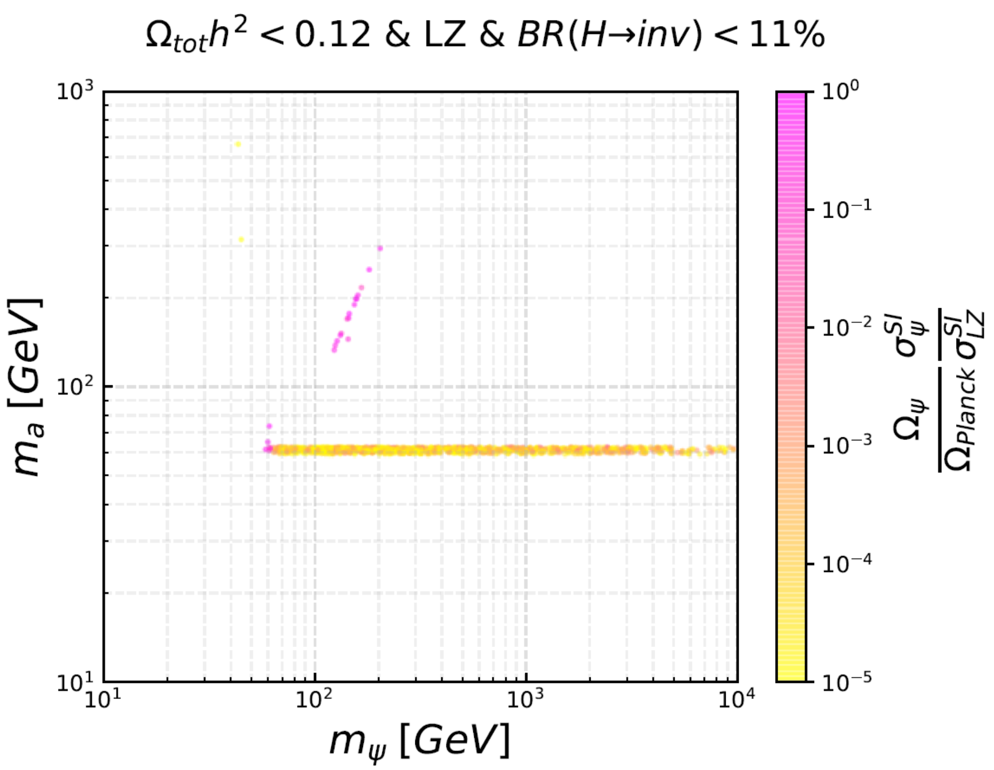

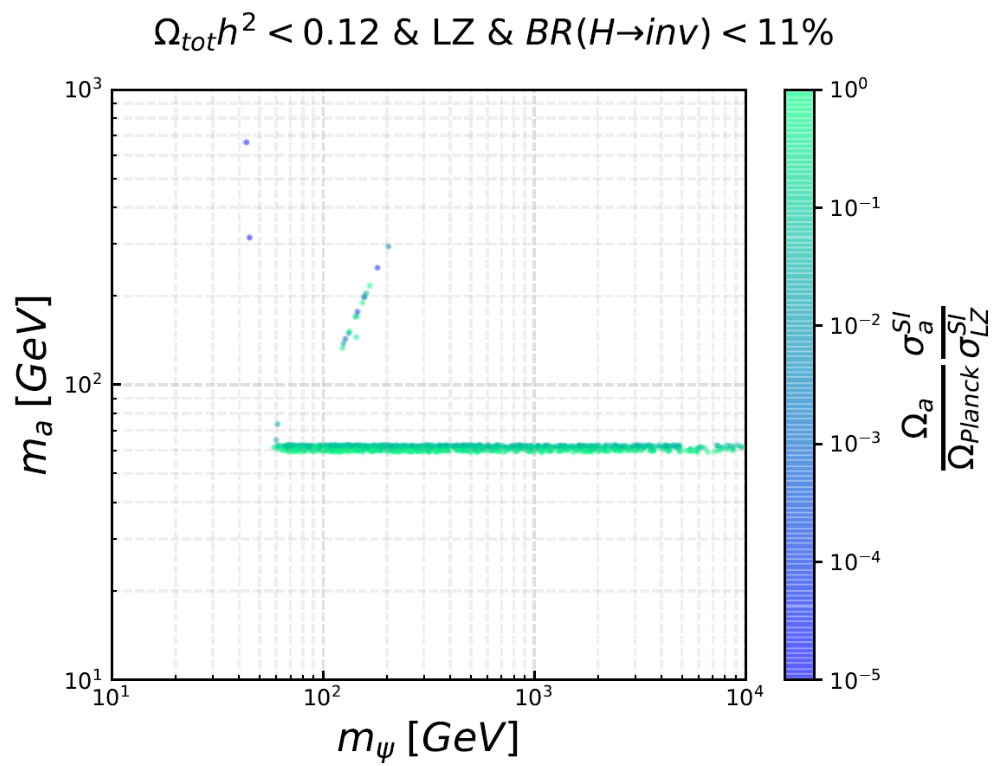

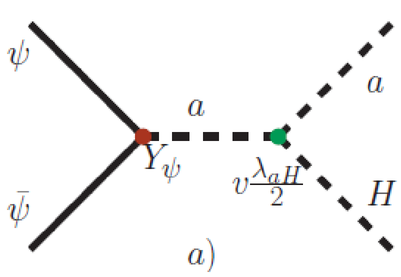

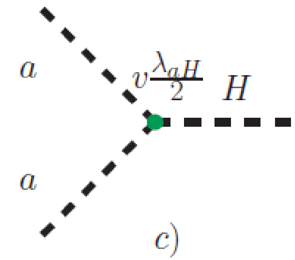

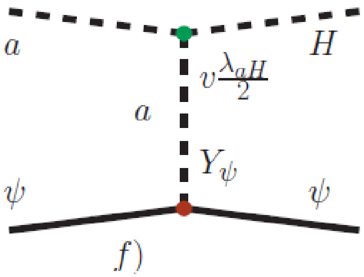

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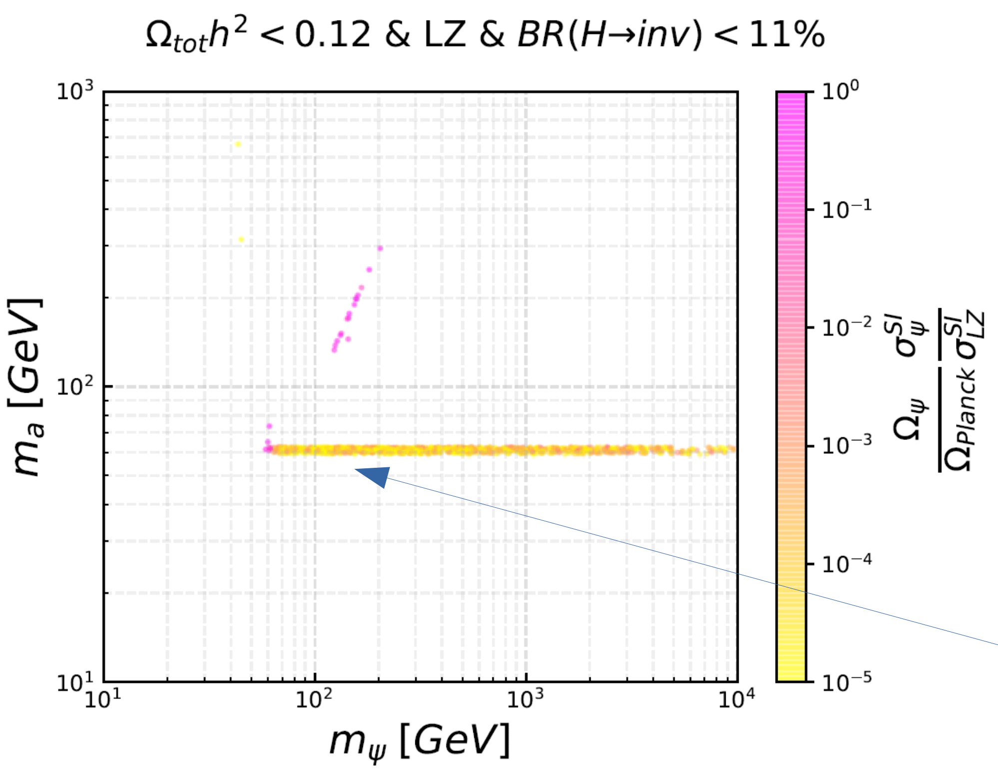
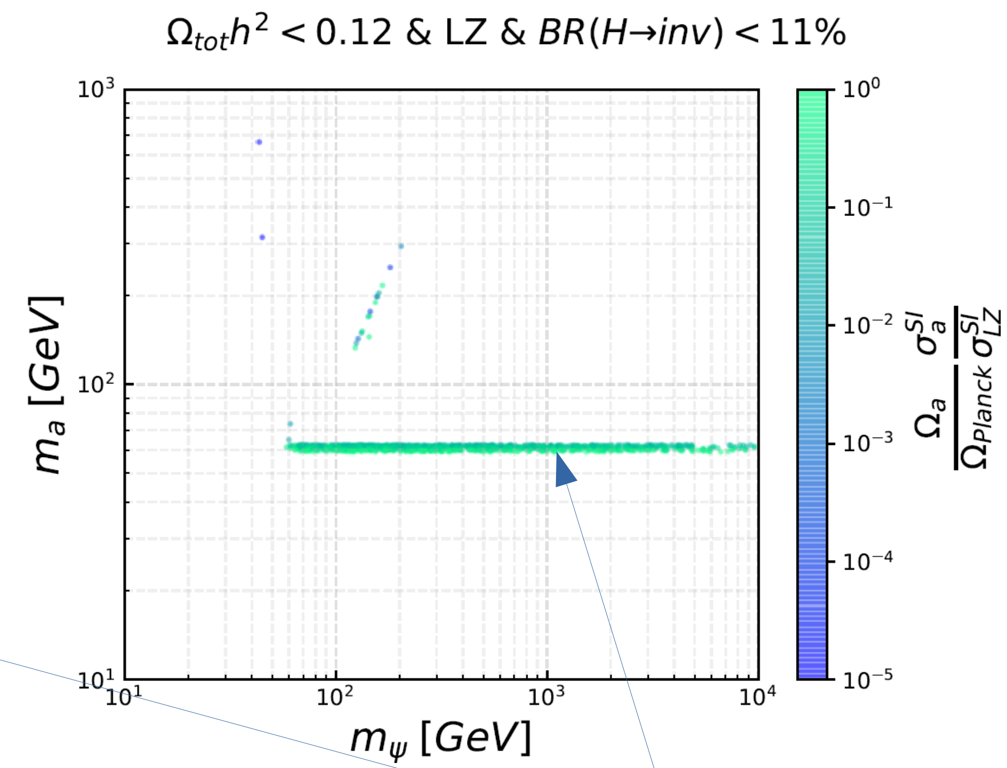
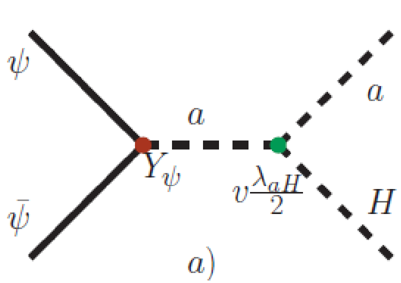
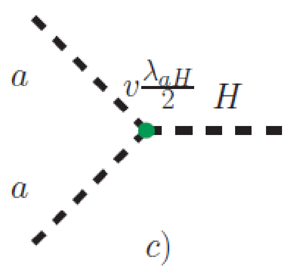
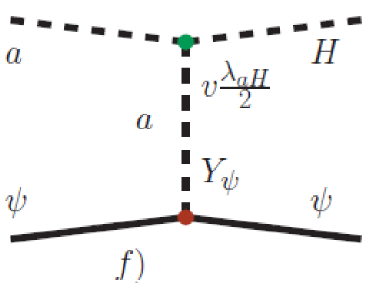




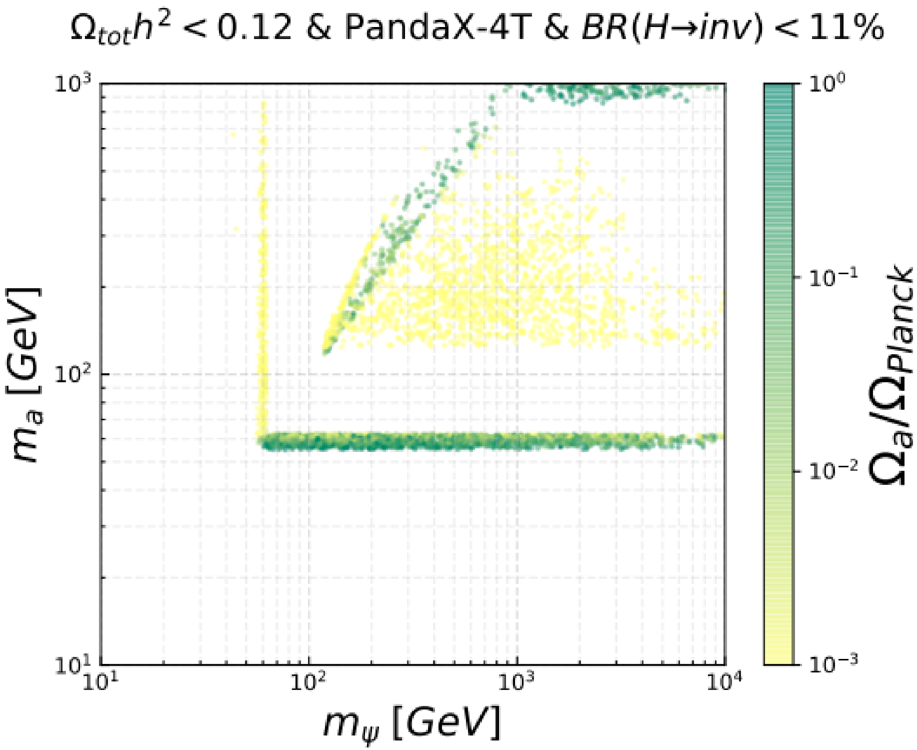


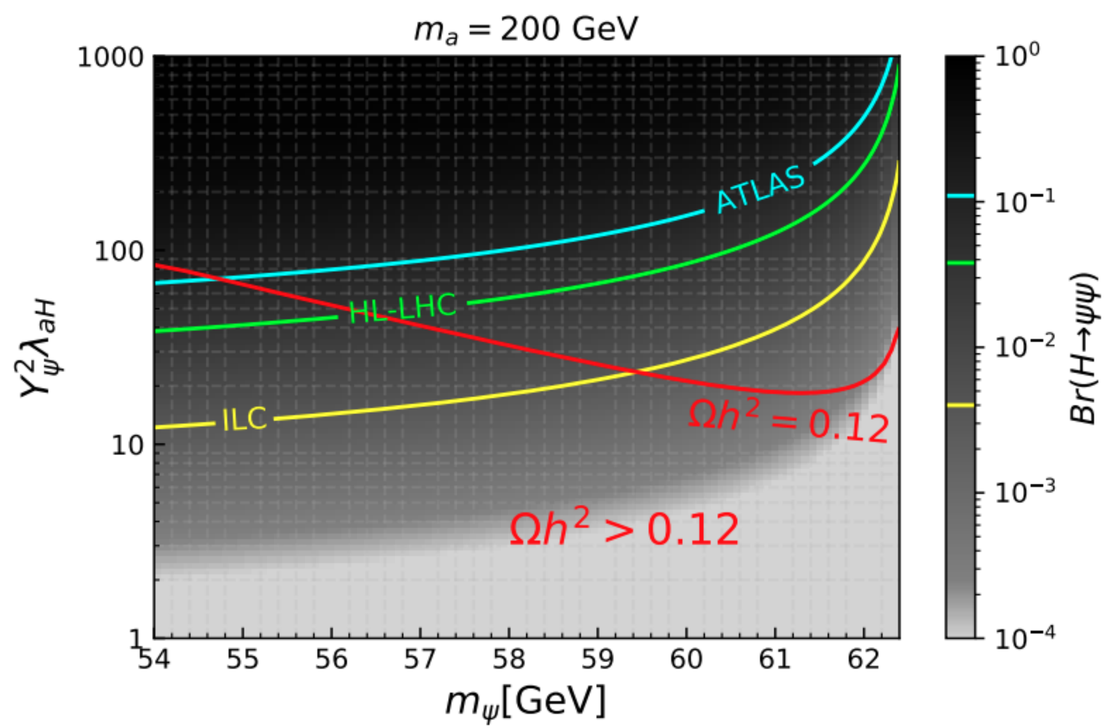


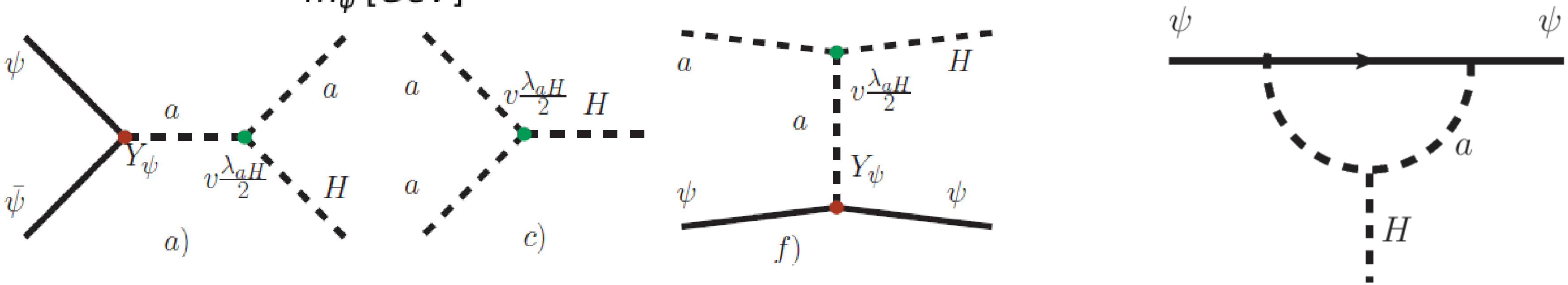


can be probed by the Higgs factories!

Minimal fermion DM model with pseudo-scalar mediator
rich phenomenology: relic density, DD, invisible H decay @colliders







Conclusions and Outlook

- To decode the nature of DM we need a signal first, **but at the moment we can** systematically explore theory/parameter space and prepare ourselves for DM discovery and identification
- **Data → Model link should be explored:**

  the exploration of all signatures (which we hope to observe soon) within the systematic model space parametrisation is the robust way to decode BSM
- **MCDM models:**

  consistent and simple, the entire parameter space can be explored
- **Systematic classification:** new simple models can be found!
- **Probing DM space**:
  - DM DD is sensitive to the loop-induced diagrams but does not exclude all models (directional DM DD should be explored for higher sensitivity)
  - sensitivity is highly dependent on mass-split
  - rich phenomenology, complementarity of DM DD, collider signals and relic density

Thank you!

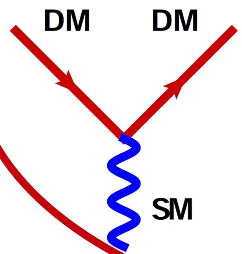
Backup slides

The ingredients of the BSM theory space

Gauge Invariant, Renormalizable, Anomaly Free

DM

Z2 symmetry, an upper limit on the mass from relic density



LHC signatures: mono-X, invisible Higgs decays, disappearing tracks, multi-leptons, Z', VLQs, ...

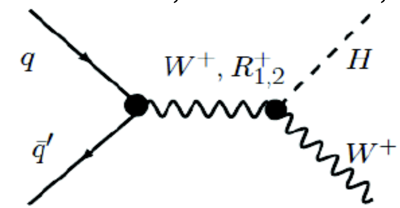
HIGGS

Which one?

Fundamental: SUSY, UED, …

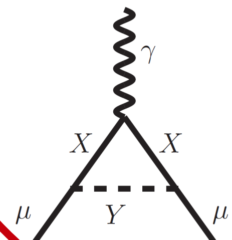
OR

Composite: CHM, Technicolor, RS, ...



LHC signatures: VBF/VH resonances deviations from SM couplings, ttH, invisible decays, Z', VLQs, ...

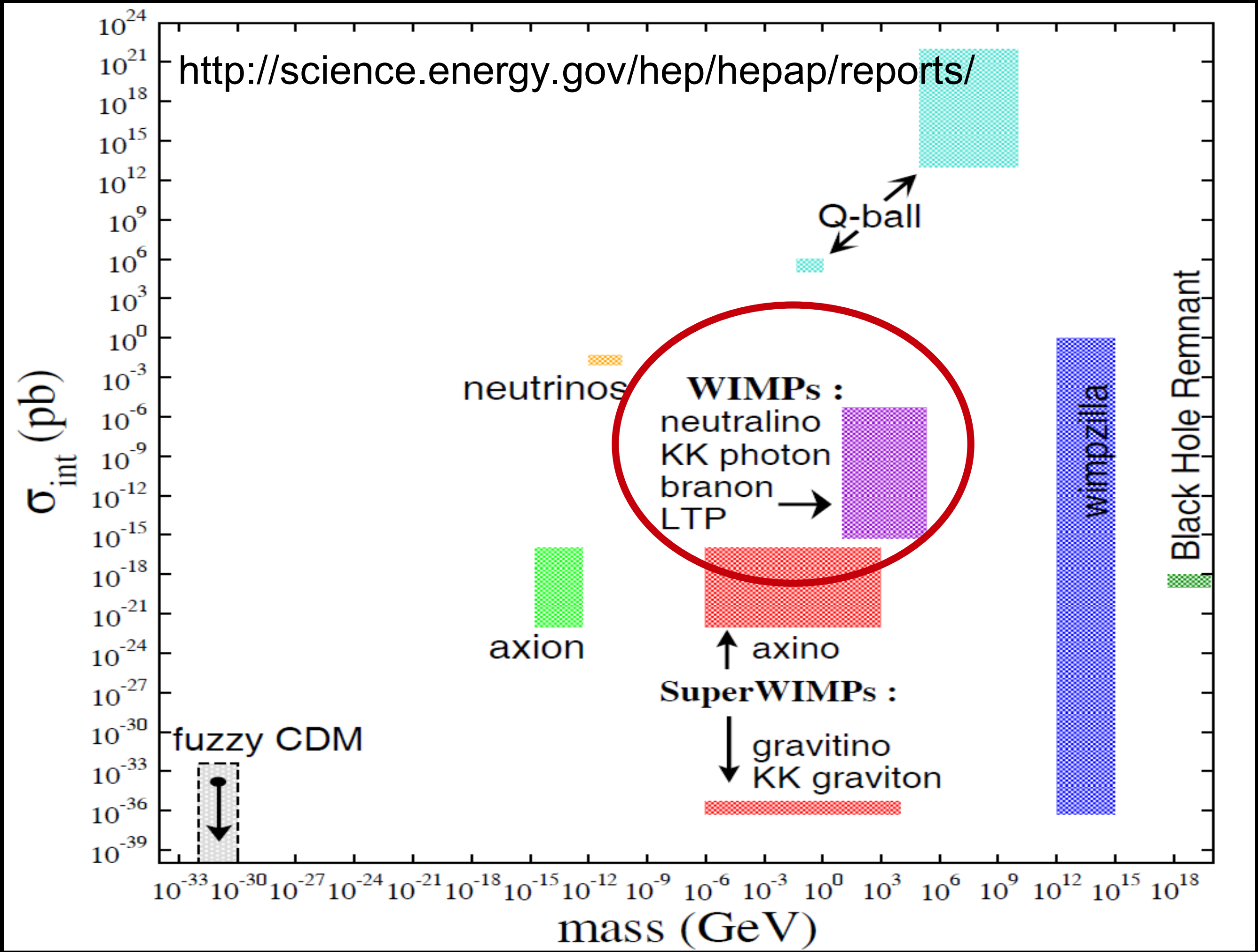
$(g-2)_\mu$ and flavour



An upper limit on the scale of new physics

LHC signatures: multi-leptons, LVUV, LQ's, Z', ...

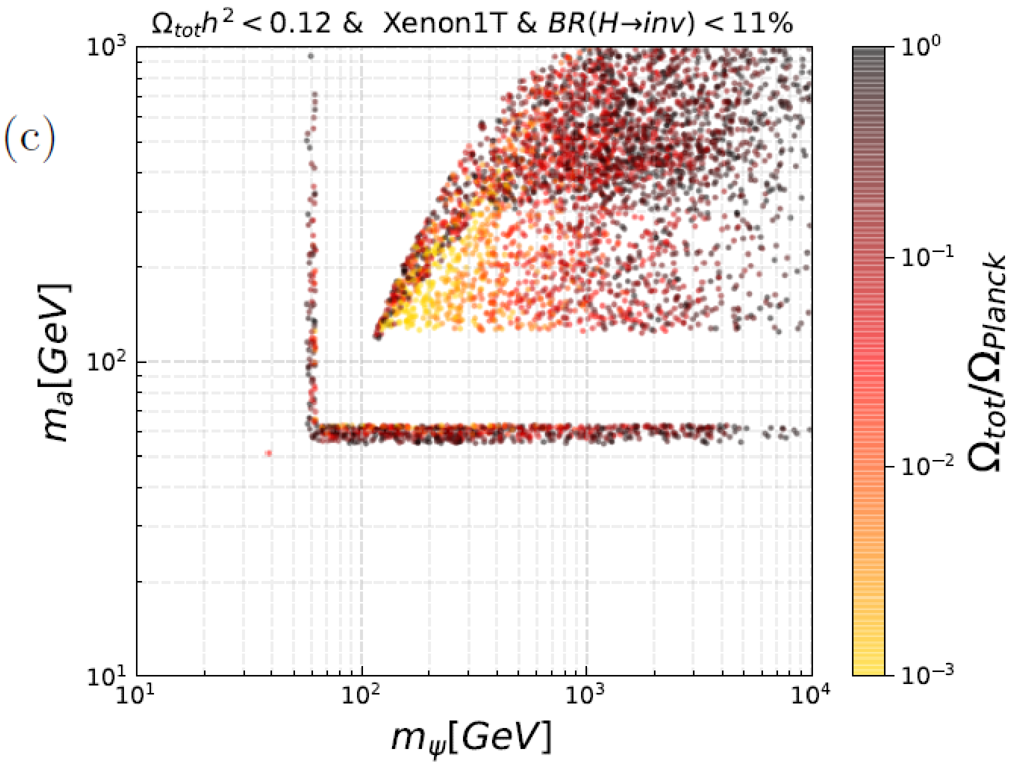
DM candidates: interaction vs mass

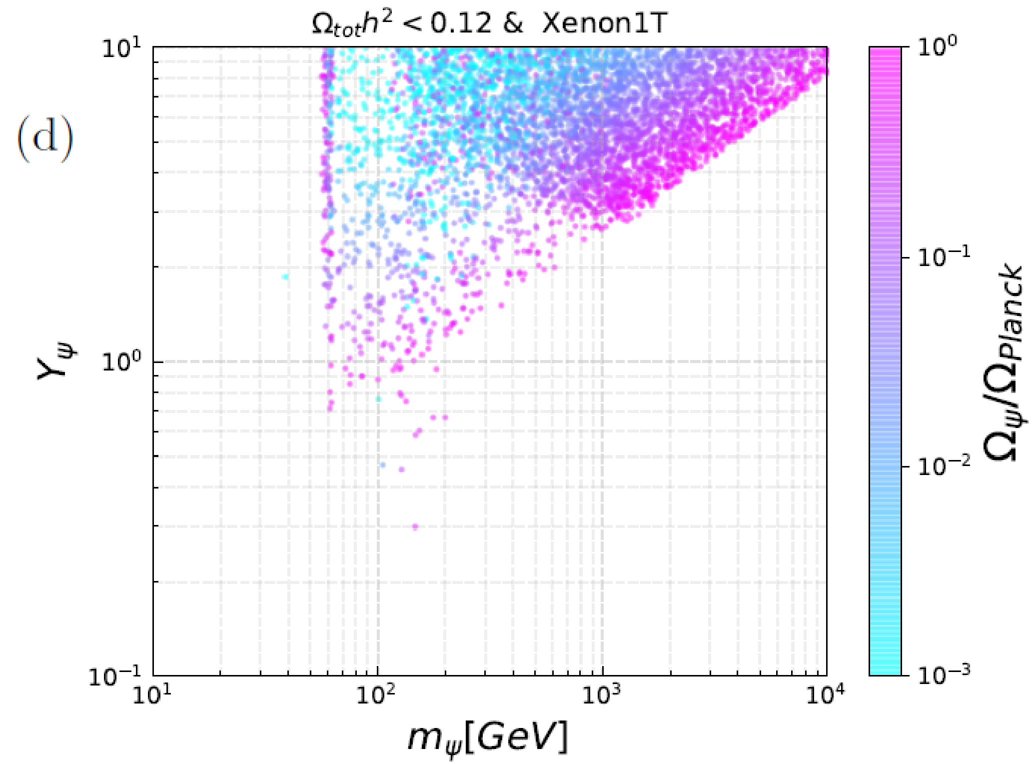


- Planck mass BH remnants: tiny black holes protected by gravity effects [Chen '04] from decay via Hawking radiation
- Wimpzillas: very massive non-thermal WIMPs [Kolb,Chung,Riotto'98]
- Q-balls: topological solitons that occur in QFT [Coleman '86]
- EW scale WIMPs, protected by parity – LSP, LKP, LTP particles
- SuperWIMPs: electrically and color neutral DM interacting with much smaller strength (perhaps only gravitationally)
- Neutrinos: usual neutrinos are too light- HDM, subdominant component only (to be consistent with large scale structures); but heavier gauge singlet neutrinos can be CDM
- Axions: $\frac{\theta_{QCD}}{32pi^2} F^{\mu\nu} \tilde{F}^{\mu\nu}$

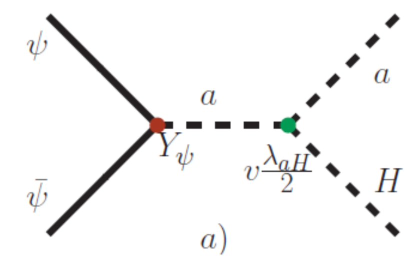
θ_{QCD} is replaced by a quantum field, the potential energy allows the field to relax to near zero strength, axion as a consequence

Minimal fermion DM model with pseudo-scalar mediator:
rich phenomenology: relic density, DD, colliders

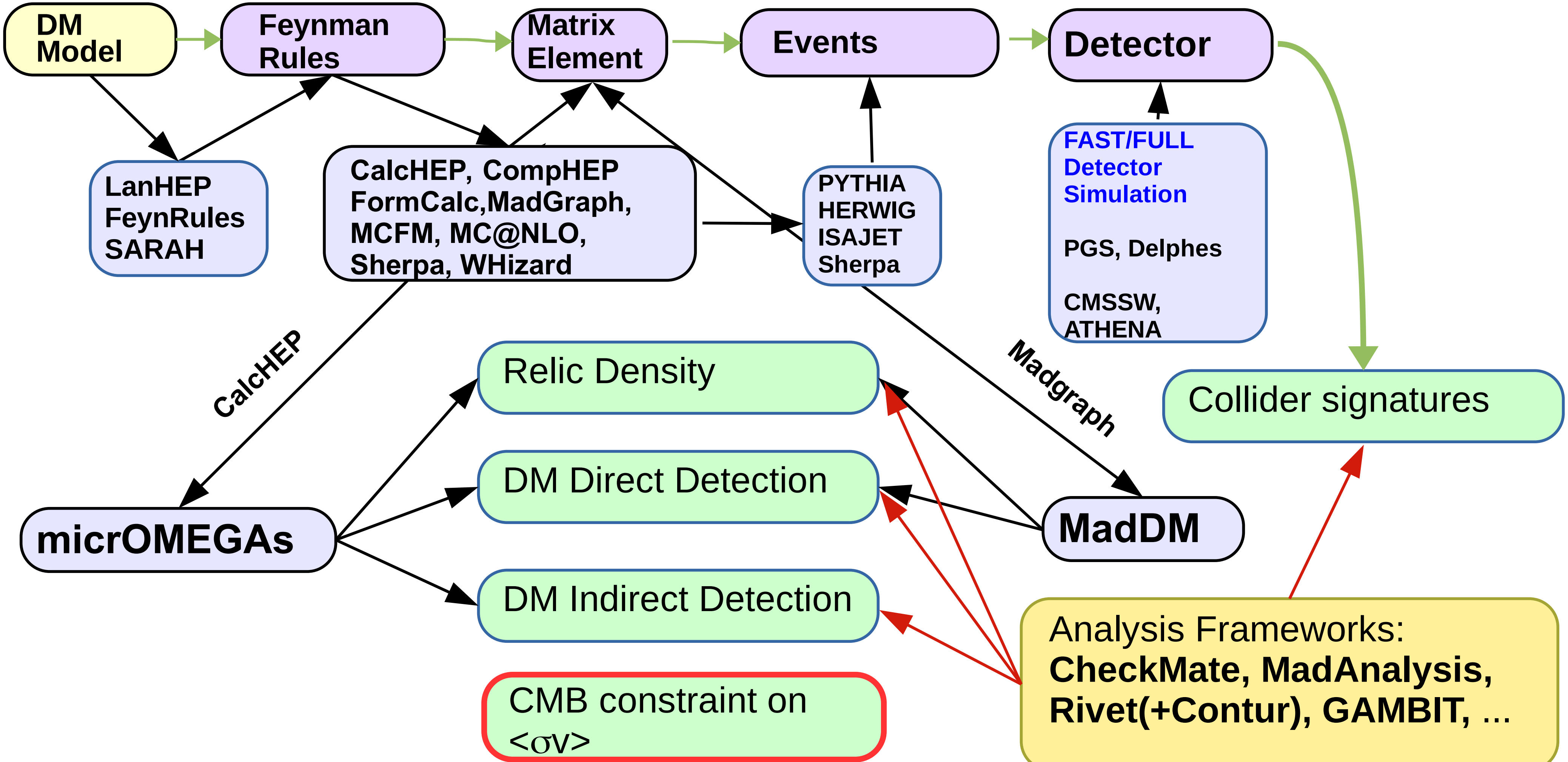




Parameter similar to that of typical portal models, however stable mediator causes “leakage” of points with FDM mass above ~90GeV caused by channel a) opening



Tools are important to make theory → observables link !



Long Lived Particles (LLPs)

- 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 of the order of pion mass
- 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

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

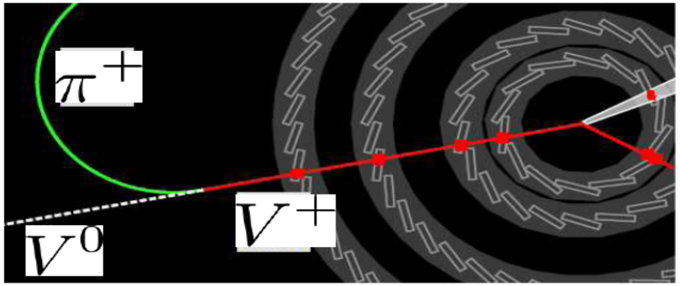
$$M_Q - M_{Q'}\big|_{m_D \gg m_W} \approx \frac{\alpha m_W}{2(1+c_W)}\left[(Q^2 - Q'^2) + \frac{2Y(Q-Q')}{c_W}\right]$$

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

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

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

$\boxed{D^+ \rightarrow D^0 \pi^+}$ is the dominant decay, D^+ is LLP



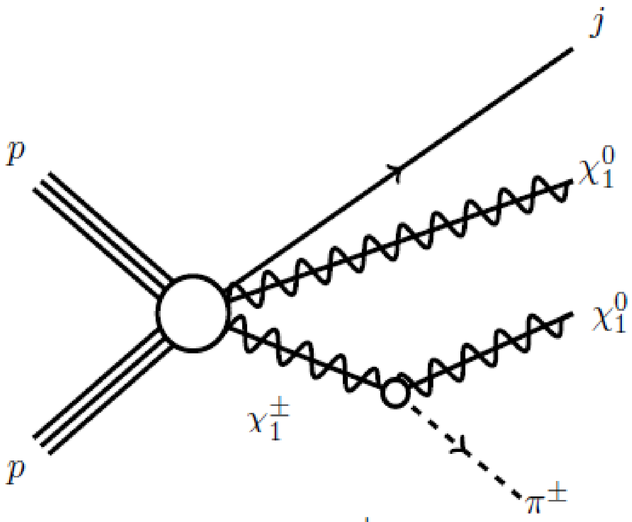
This small mass gap (~ pion mass) provides disappearing track signature

Using DT to probe minimal DM models

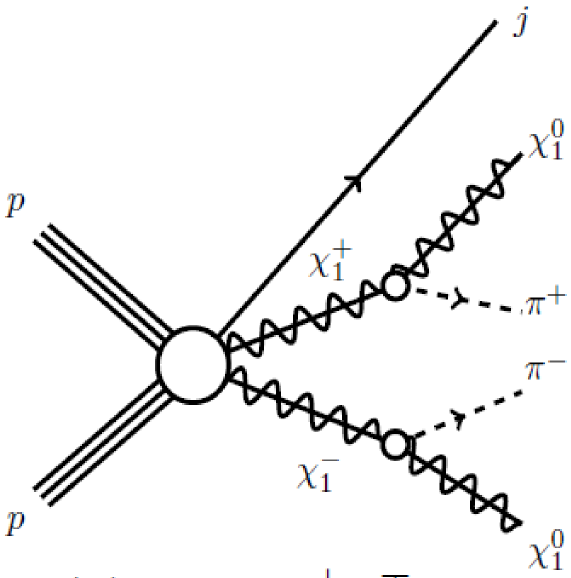
We apply our validated analysis to minimal consistent models

- 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



(a) $pp \to \chi_1^\pm \chi_1^0 j$



(b) $pp \to \chi_1^\pm \chi_1^\mp j$

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

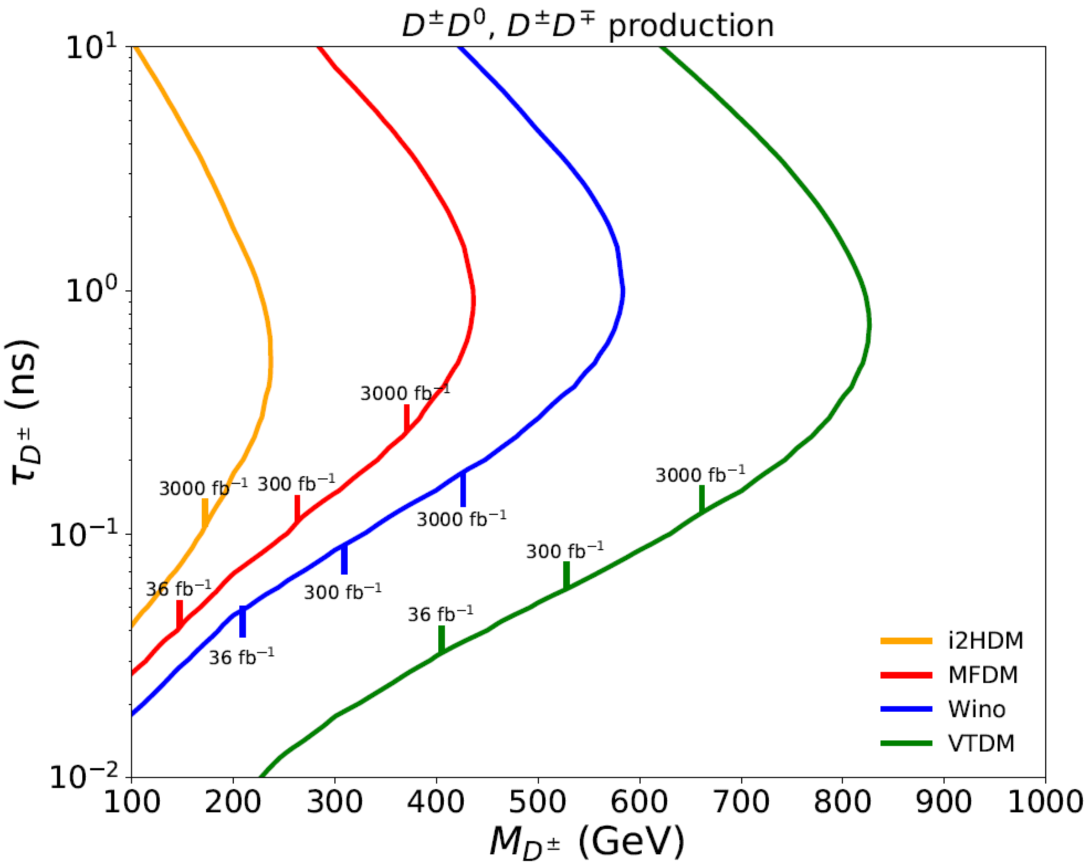
- New DT limits for DM models with different spin

- 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

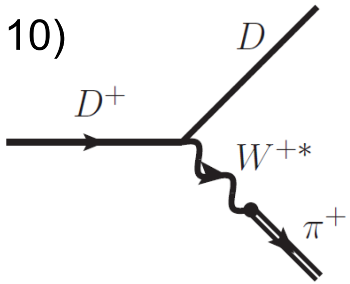
AB, Prestel, Rojas, Zurita [arXiv 2008.08581]



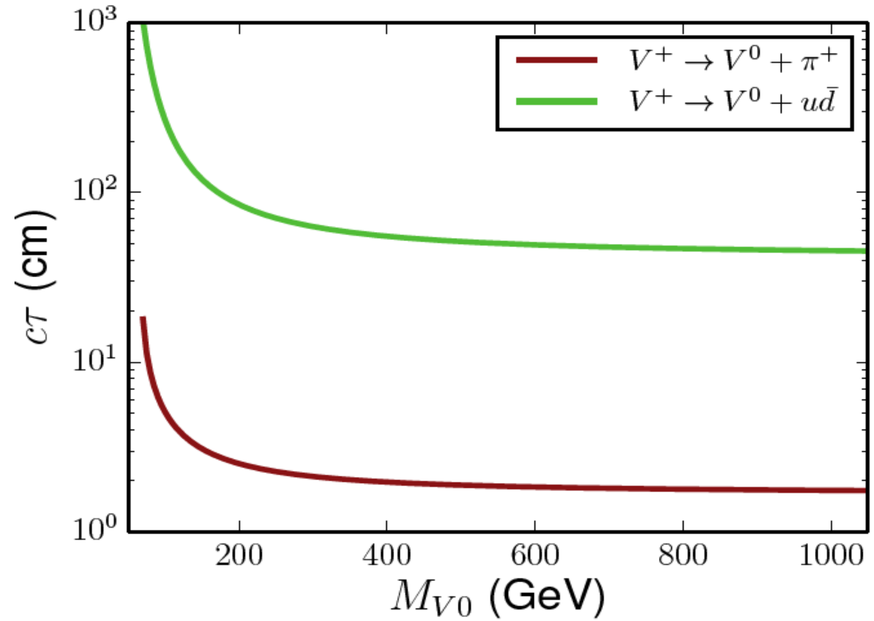
An impressive sensitivity from 36 fb^{-1} ATLAS results interpretation!

D⁺ (charged partner of DM multiplet) decay

- D⁺ life-time should be properly evaluated using W-pion mixing (otherwise overestimated by factor of 10)



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



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

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

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

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

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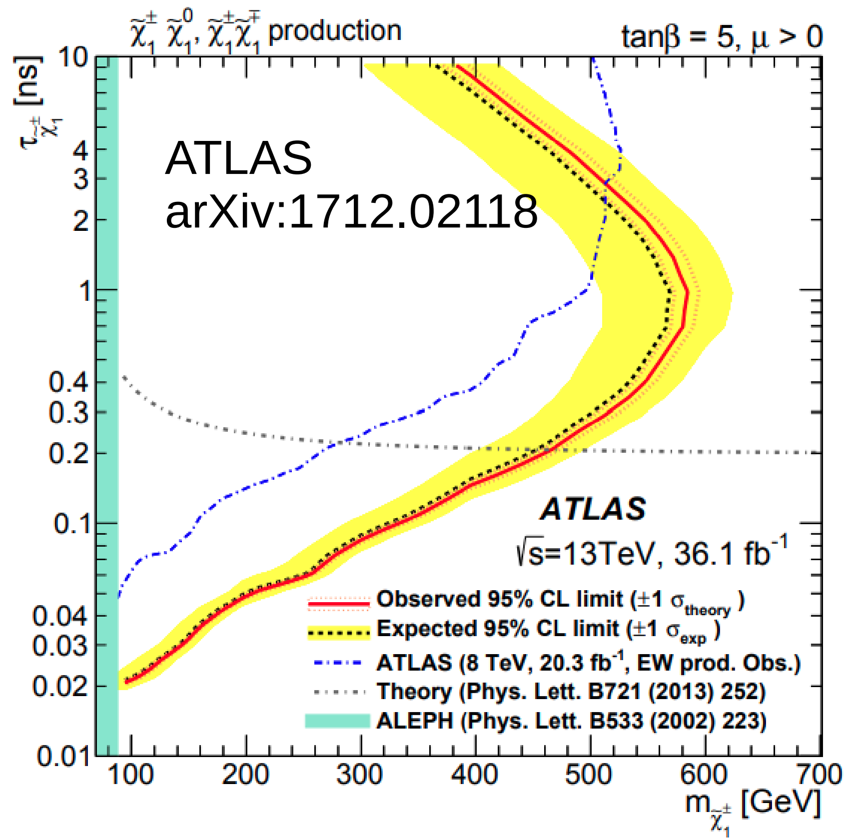


Tools to Study Disappearing Track Signature

- The strategy used [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

$\widetilde{F}^{1/2}_{1/2}\widetilde{M}^{0}_{0}$

Minimal fermion DM model

+Mediator

Z2 odd

isospin

$\tilde{X}^{i}_{y}$

spin

hypercharge

Spin of Dark Matter / ...of ...ator	0	1/2	1
...) even mediator	$\widetilde{S}^{I}_{Y}S^{I'}_{Y'}$	$\widetilde{F}^{I}_{Y}S^{I'}_{0}$	$\widetilde{V}^{I}_{Y}S^{I'}_{Y}$...
...) odd mediator	$\widetilde{S}^{I}_{Y}\widetilde{S}^{I'}_{Y'}$	$\widetilde{F}^{I}_{Y}\widetilde{S}^{I'}_{Y'}$ $\widetilde{F}^{I}_{Y}\widetilde{S}^{I'c}_{Y'}$	$\widetilde{V}^{I}_{Y}\widetilde{S}^{I'}_{Y}$...
.../2 even mediator			
.../2 odd mediator	$\widetilde{S}^{I}_{Y}\widetilde{F}^{I'}_{Y'}$ $\widetilde{S}^{I}_{Y}\widetilde{F}^{I'c}_{Y'}$	$\widetilde{F}^{I}_{Y}\widetilde{F}^{I\pm1/2}_{Y\pm1/2}$	$\widetilde{V}^{I}_{Y}\widetilde{F}^{I'}_{Y'}$ $\widetilde{V}$...
... even mediator	$\widetilde{S}^{I}_{Y}V^{I'}_{0}$	$\widetilde{F}^{I}_{Y}V^{I'}_{0}$	$\widetilde{V}^{I}_{Y}V^{I}_{Y}$...
... odd mediator	$\widetilde{S}^{I}_{Y}\widetilde{V}^{I'}_{Y'}$	$\widetilde{F}^{I}_{Y}\widetilde{V}^{I'}_{Y'}$ $\widetilde{F}^{I}_{Y}\widetilde{V}^{I'c}_{Y'}$	$\widetilde{V}^{I}_{Y}\widetilde{V}^{I}_{Y}$...

- **ILC:**
  I.Ginzburg, D.Locke, A. Freegard, A.Pukhov, AB
  arXiv:**2112.15090**

- **LHC**:
  U.Blumenschein, A. Freegard, D.Gupta, S.Moretti, AB
  arXiv:**2204.06411**

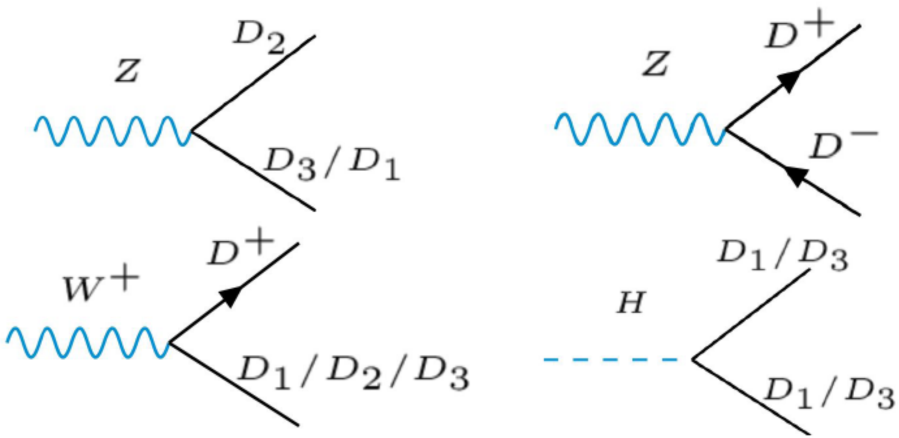
$\widetilde{F}^{1/2}_{1/2}\widetilde{M}^{0}_{0}$

Minimal fermion DM model (MFDM)

gives 2/3 -lepton signatures at the LHC

$$\mathcal{L}_{FDM} = \mathcal{L}_{SM} + \bar{\psi}(i\not{D} - m_\psi)\psi + \frac{1}{2}\bar{\chi}^0_s(i\not\partial - m_s)\chi^0_s - (Y(\bar{\psi}\Phi\chi^0_s) + h.c.)$$

$$\psi = \begin{pmatrix} \chi^+ \\ \frac{1}{\sqrt{2}}\left(\chi^0_1 + i\chi^0_2\right) \end{pmatrix}$$, additional Majorana singlet fermion χ^0_s



$$[M_{D1}, \Delta M_{D+}, \Delta M_{D3}]$$

only three parameters (effectively two for the LHC)

$\widetilde{F}^{1/2}_{1/2}\widetilde{M}^{0}_{0}$

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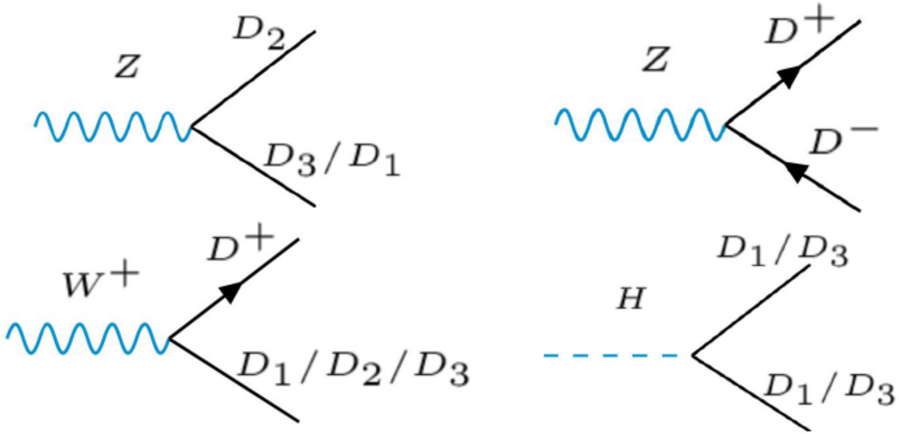

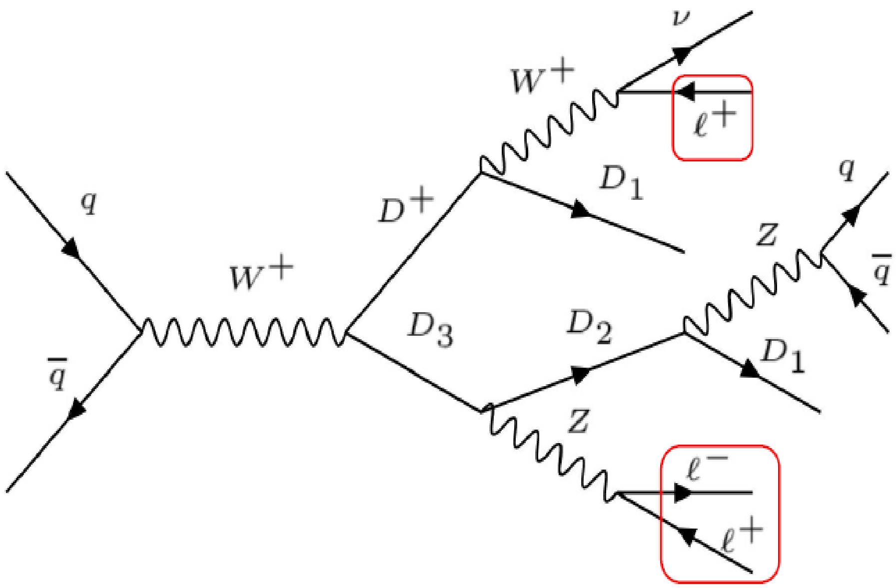

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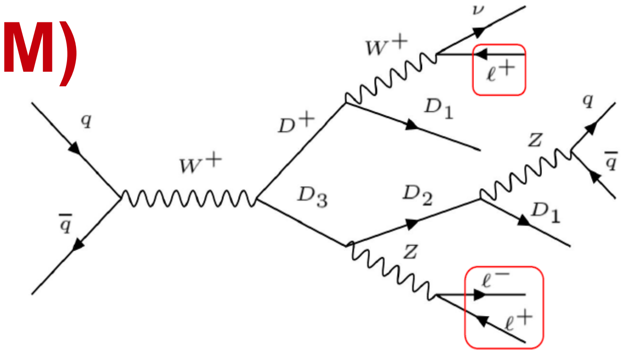

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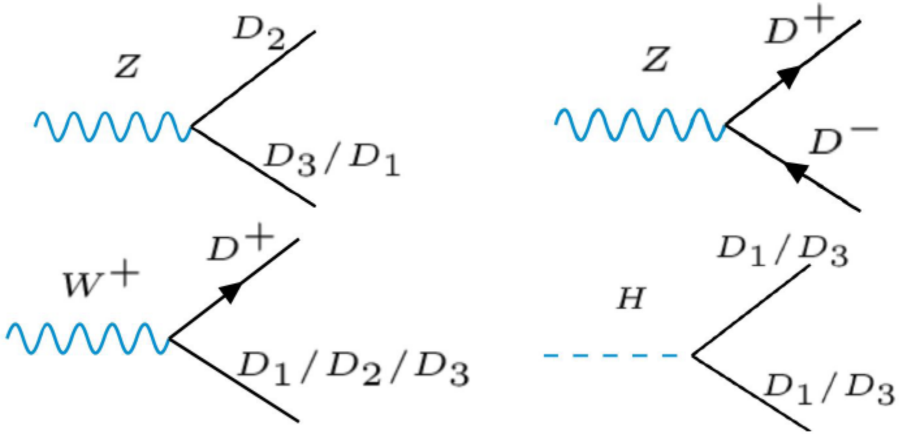

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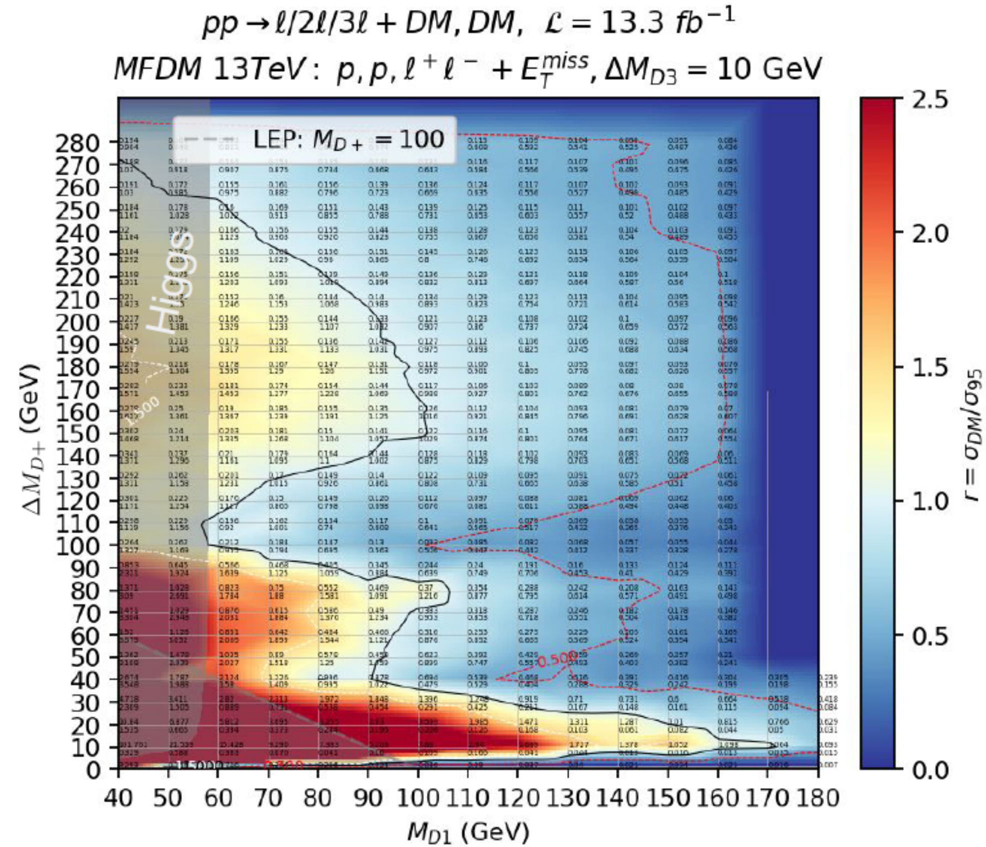

U.Blumenschein, A. Freegard, D.Gupta, S.Moretti, AB, arXiv:**2204.06411**

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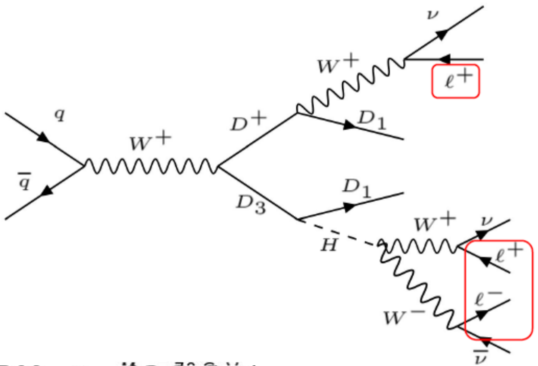

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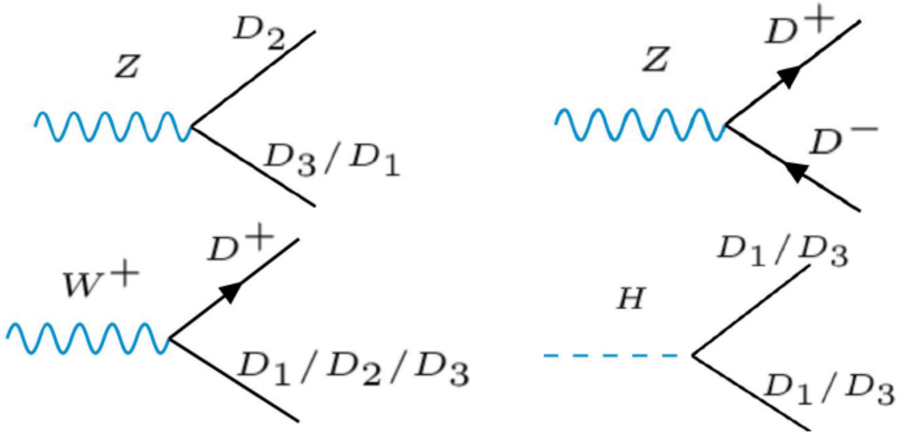

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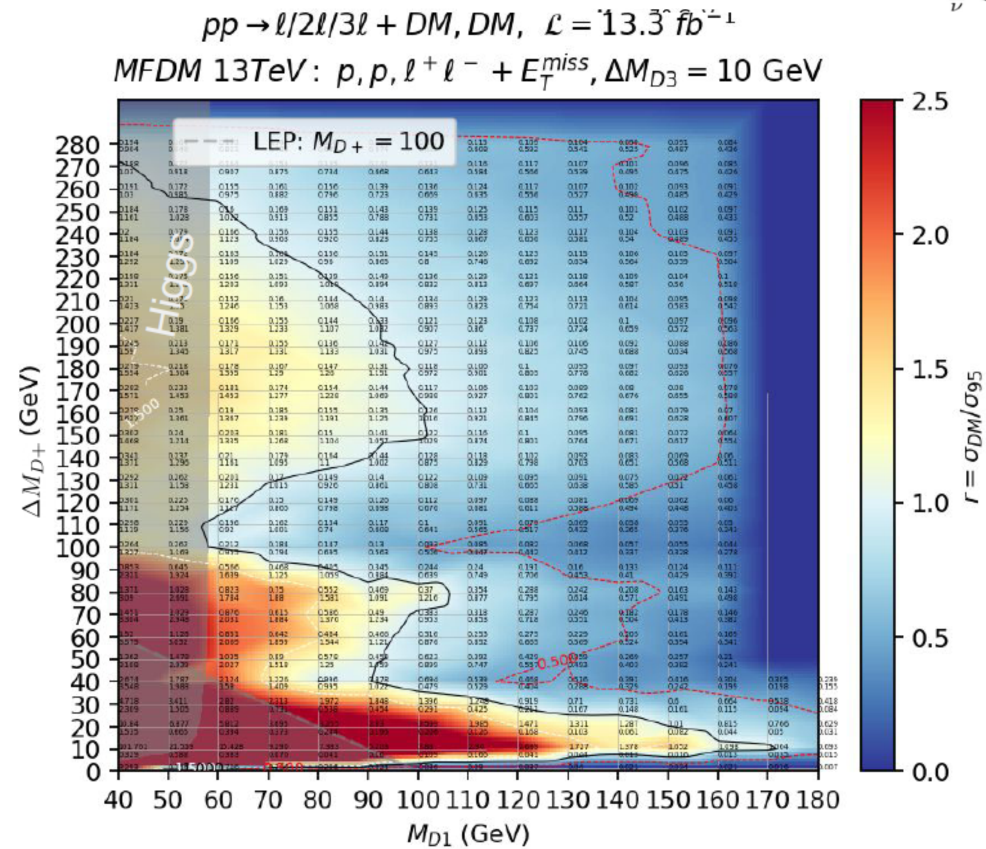
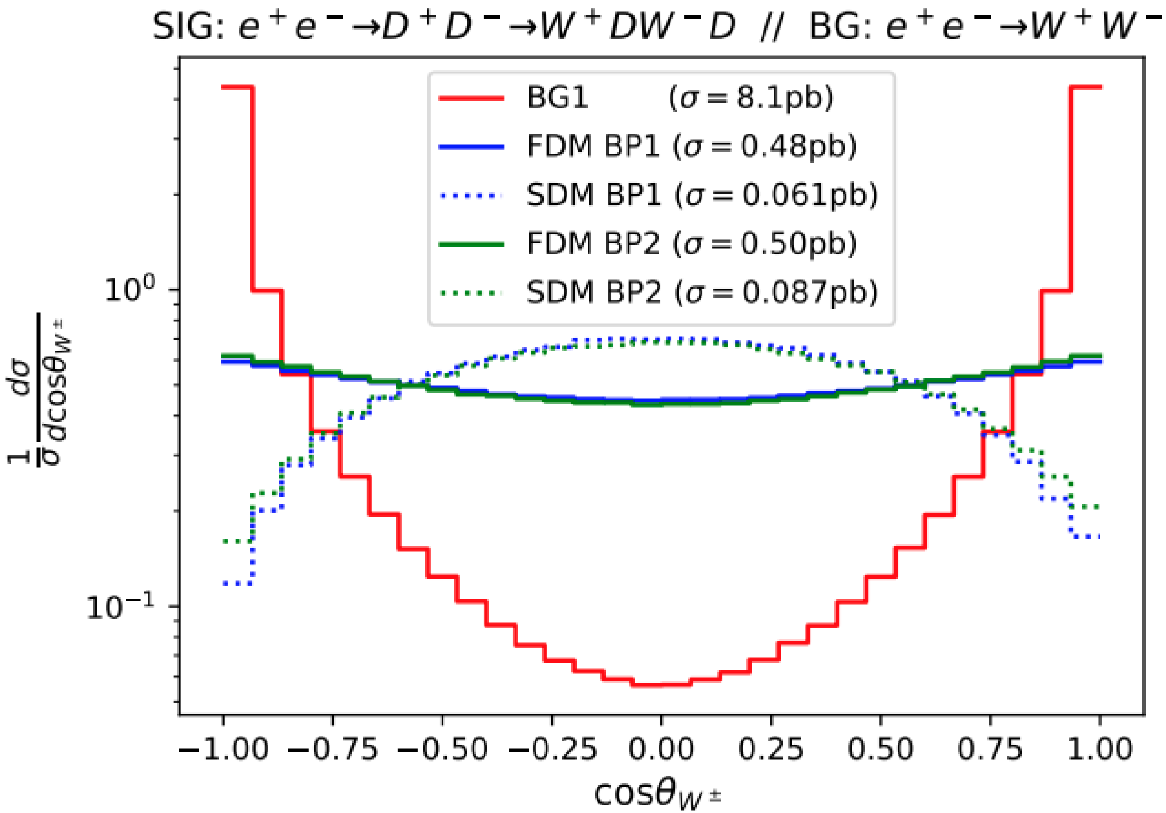


U.Blumenschein, A. Freegard, D.Gupta, S.Moretti, AB, arXiv:**2204.06411**

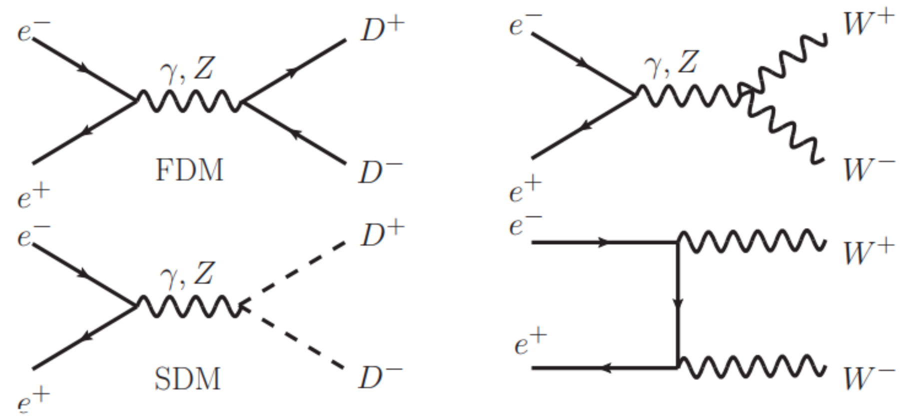
The role of the ILC in decoding the spin of DM

e+e- → D+ D- → DM DM W+ W- → DM DM jj μ ν



AB, Ginzburg, Locke, Freegard, Pukhov arXiv:**2112.15090**

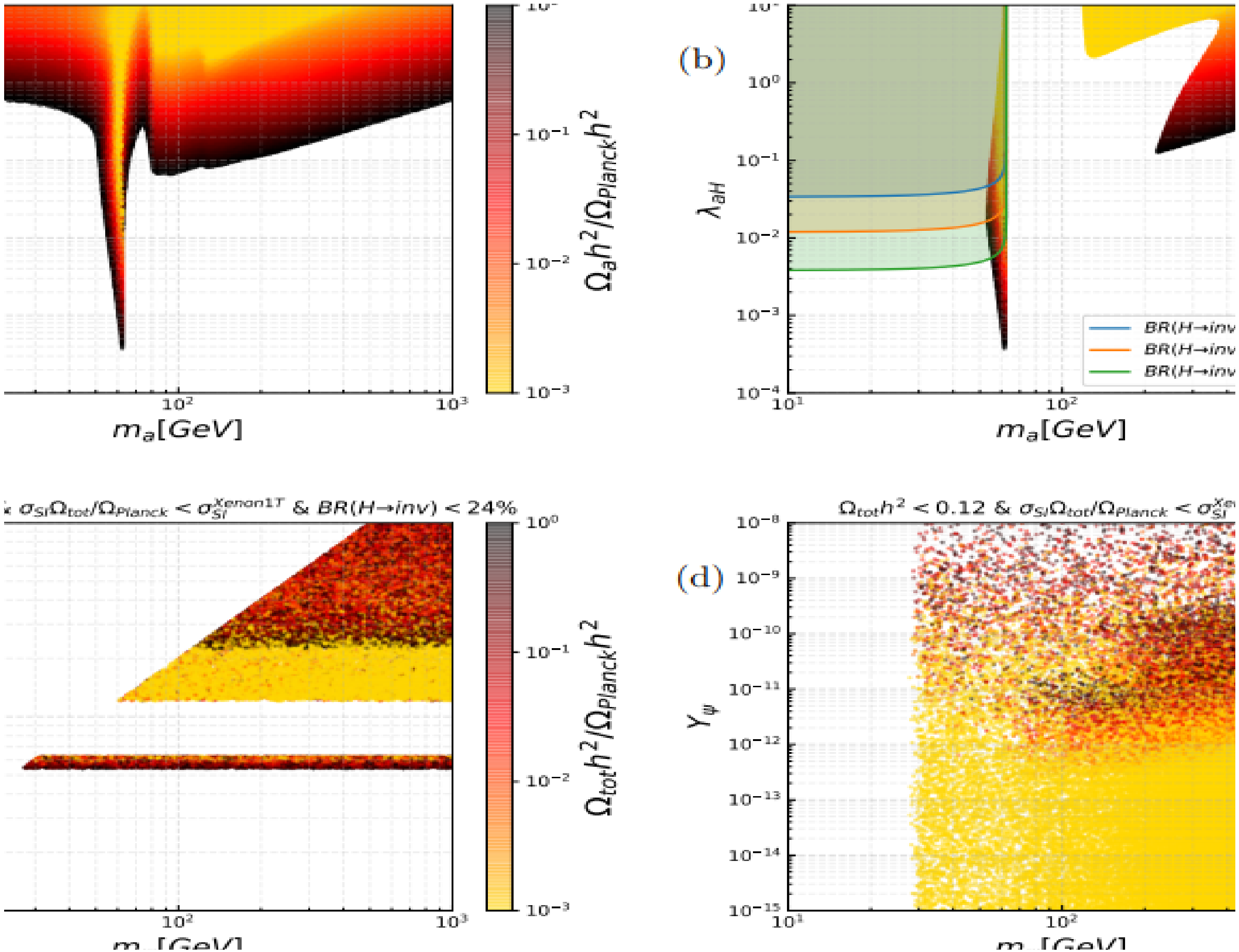
- The angular W-boson distribution (either for real or virtual W) is found to be very important discriminator between DM spin as well as the main BG
- The shape of angular W-boson distribution is the same for two benchmarks for DM of the same spins
- The $\cos\theta_W$ distribution for SDM is the most distinct one

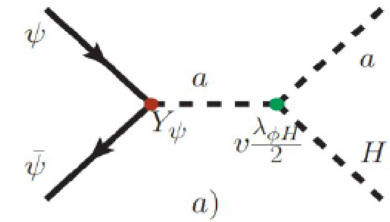


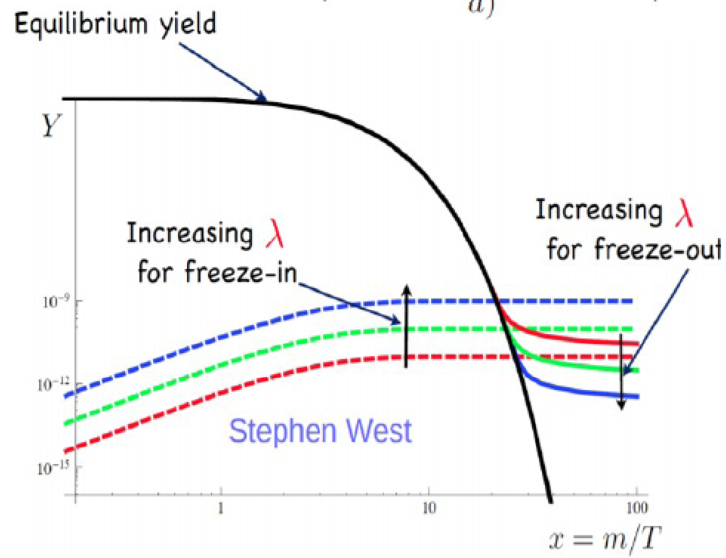
Minimal fermion DM model with pseudo-scalar mediator

non-thermal ψ

$$m_a < 2m_\psi$$







Small Y – FDM initially decoupled from SM+a bath, freezes in whilst a freezes out

Decoding Problem: Data → Theory link

- probably the most challenging problem to solve:
  the inverse problem
  - this is the problem of decoding of the underlying theory from data which requires database of models, database of signatures
  - It is based on machine learning of matching signal from data with the pattern of the signal from data

- **HEPMDB (High Energy Physics Model Database)** was created in 2011
  hepmdb.soton.ac.uk
  - convenient centralized storage environment for HEP models
  - it allows to evaluate the LHC predictions and perform event generation using CalcHEP, Madgraph for any model stored in the database
  - you can upload there your own model and perform simulation