Towards decoding the nature of Dark Matter

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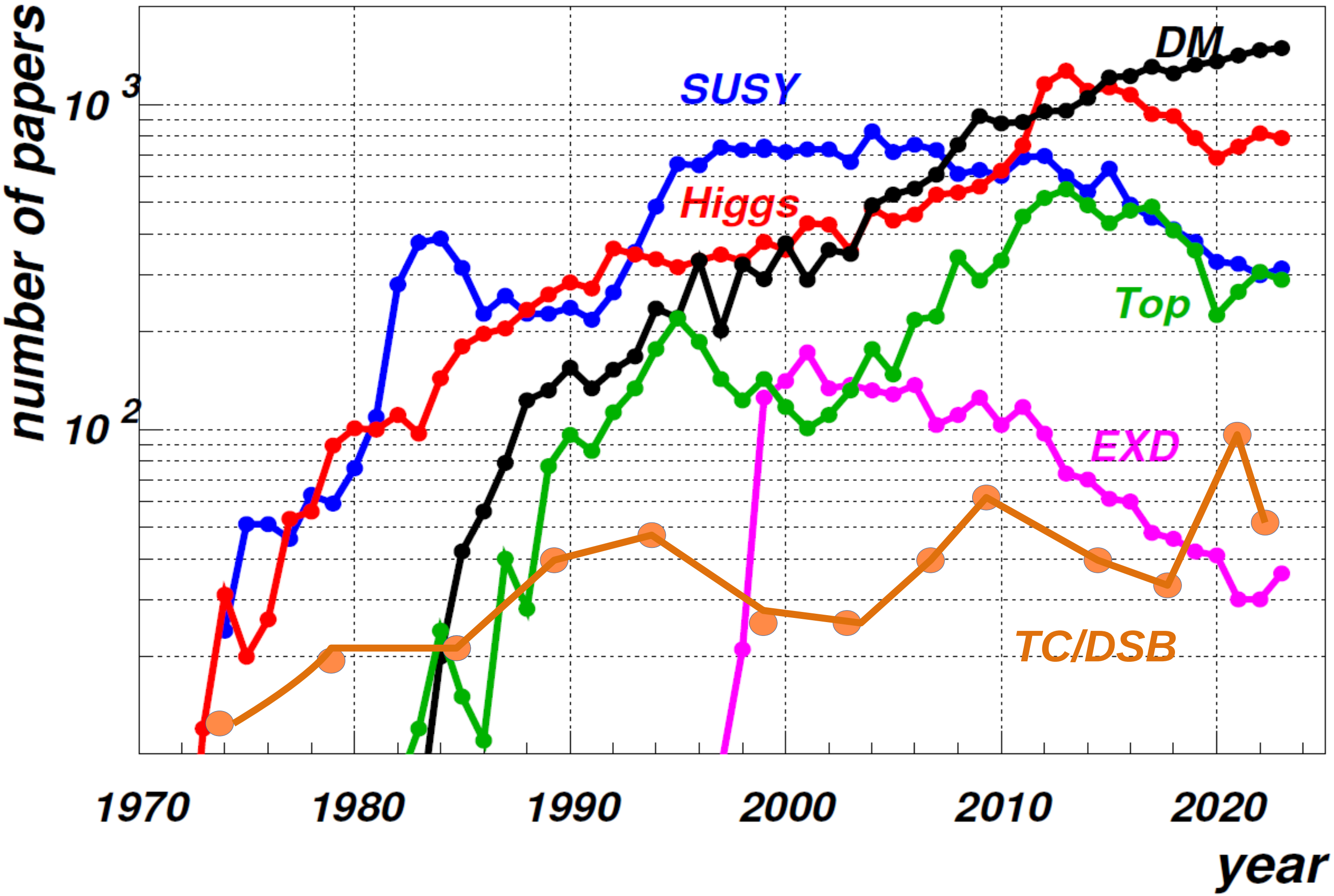
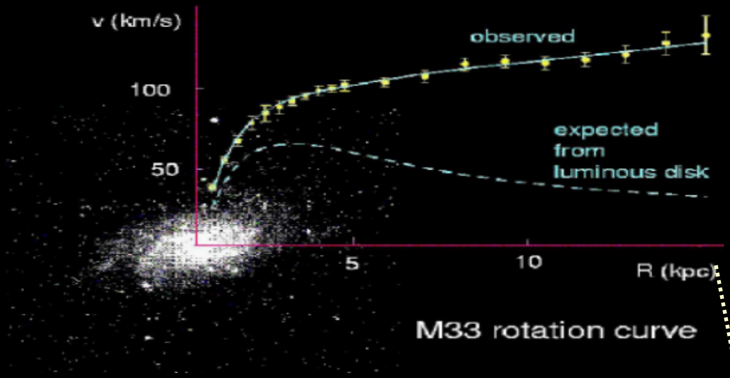
Popular directions in Particle Physics

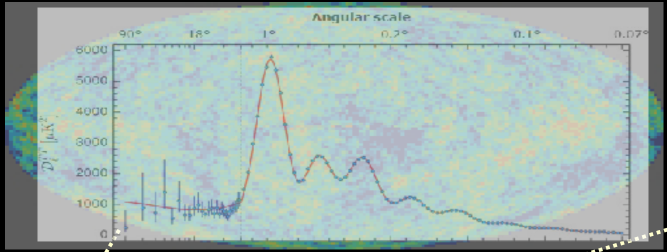


The existence of Dark Matter is confirmed by several independent observations at cosmological scale

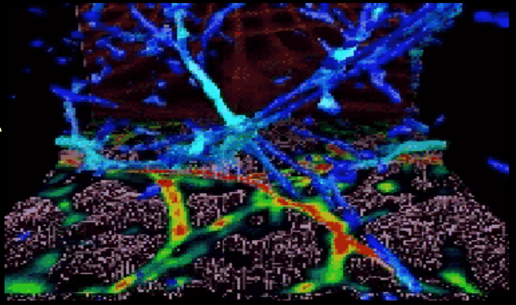
Galactic rotation curves

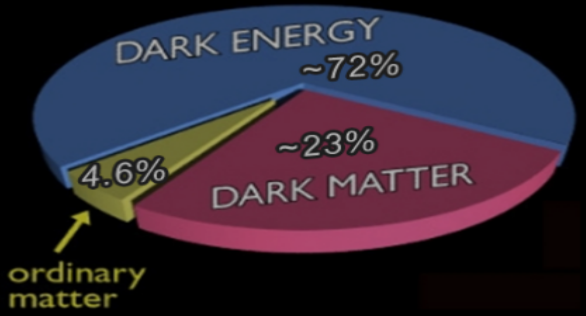


CMB: WMAP and PLANCK

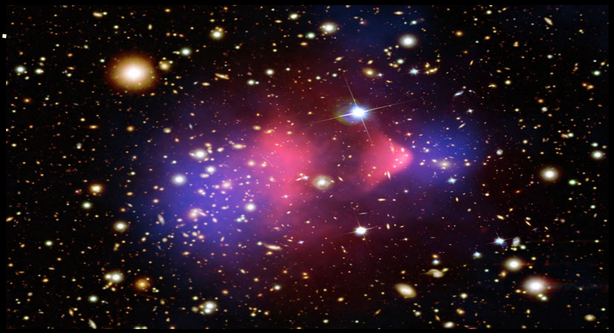


Large Scale Structures

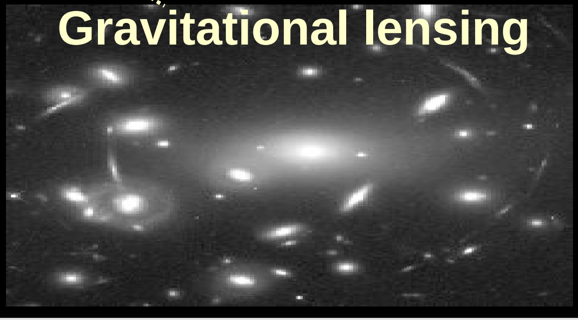




Bullet cluster



Gravitational lensing



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

Yes ? No ?

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

We need a DM signal first!

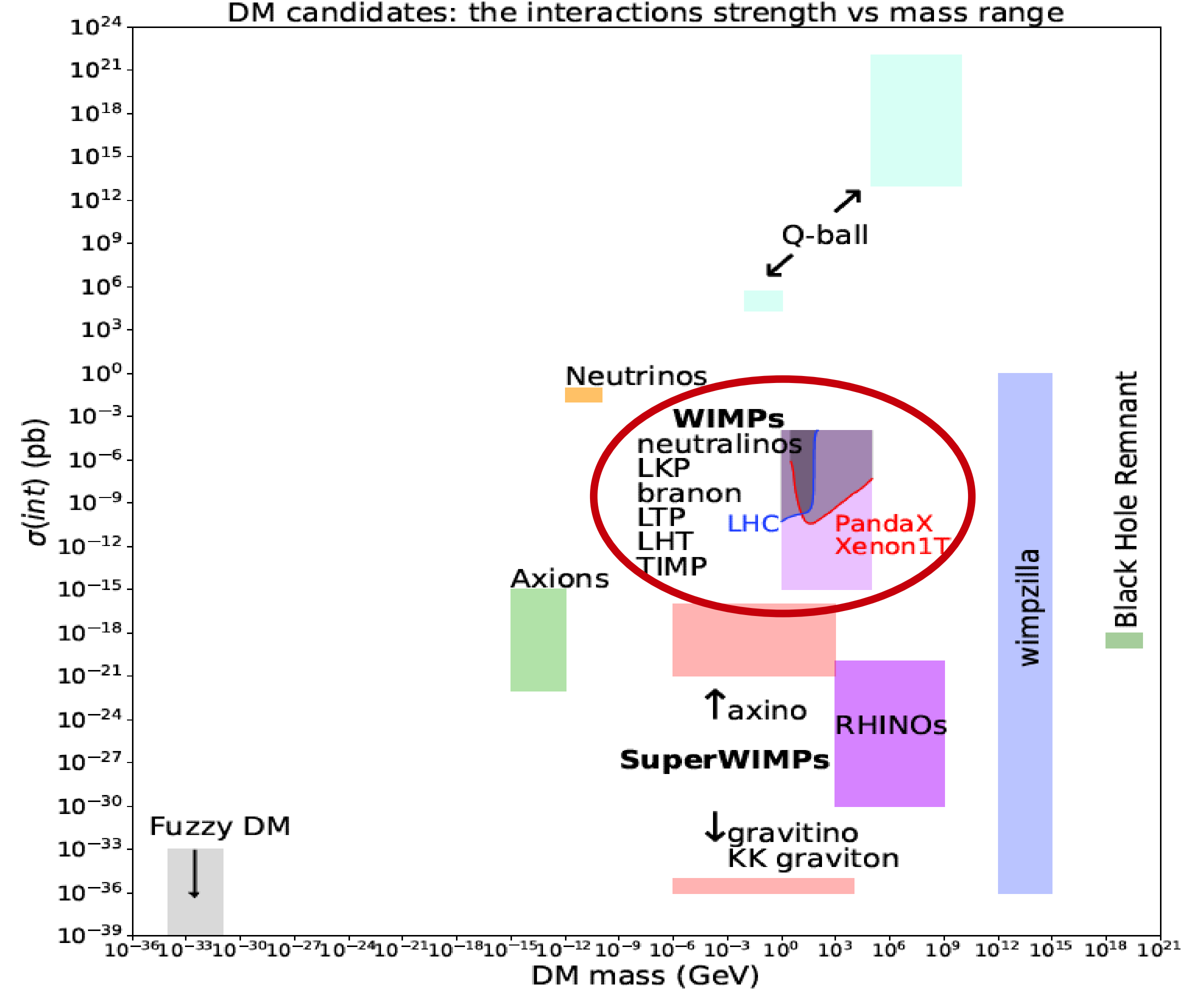
But at the moment we can:

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

Collaborators & Projects

Yao, Chakraborti,AB	arXiv:**25xx.xxxxx**
Bertenstam, Gonçalves, Morais, Pasechnik, Thongyoi,AB	arXiv:**2504.xxxxx**
Panizzi, Thongyoi, AB	arXiv:**2504.xxxxx**
Blumenschein, Freegard, Gupta, Moretti, AB	arXiv:**2204.06411**
Deandrea, Moretti, Panizzi, Ross, Thongyoi,AB	arXiv:**2204.03510,2203.04681**
Cacciapaglia, Locke, Pukhov, AB	arXiv:**2203.03660**
Ginzburg, Locke, A. Freegard, Pukhov, AB	arXiv:**2112.15090**
Prestel, Rojas-Abate, Zurita, AB	arXiv:**2008.08591**
Cacciapaglia, McKay, Marin, Zerwekh, AB	arXiv:**1808.10464**
Cacciapaglia, Ivanov, Rojas, Thomas, AB	arXiv:**1612.00511**
Panizzi, Pukhov, M.Thomas, AB	arXiv:**1610.07545**
Barducci, Bharucha, Porod, Sanz, AB	arXiv:**1504.02472**

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

DM Observables: the power of WIMP

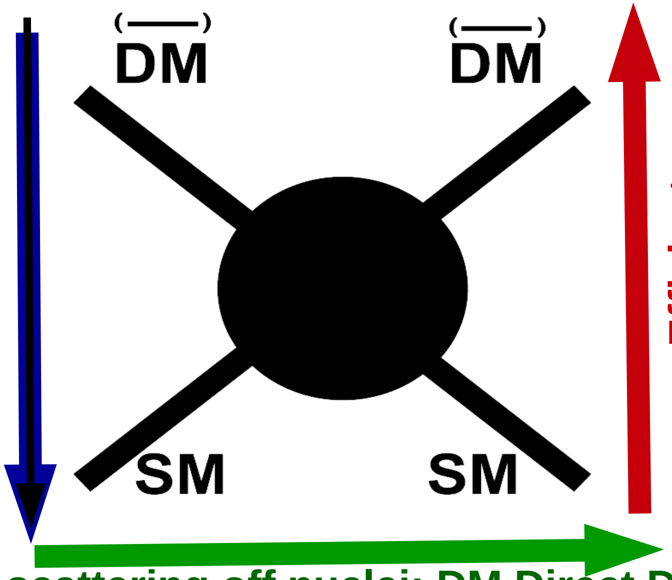
Correct Relic density: efficient (co) annihilation
WMAP, Planck ; annihilation to photons can affect CMB

Signatures from neutralino annihilation including halo, core of the Earth and Sun

- **photons,**
- **Anti-protons**
- **positrons,**
- **Neutrinos**

Neutrino telescopes:

- **Amanda**
- **Icecube**
- **Antares**



Efficient annihilation: Indirect (ID) DM Detection

Efficient production at colliders

LHC signatures

- **mono-jet**
- **mono-photon**
- **mono-Z**
- **mono Higgs**

- **VBF+MET**
- **soft leptons+MET**
- **….**

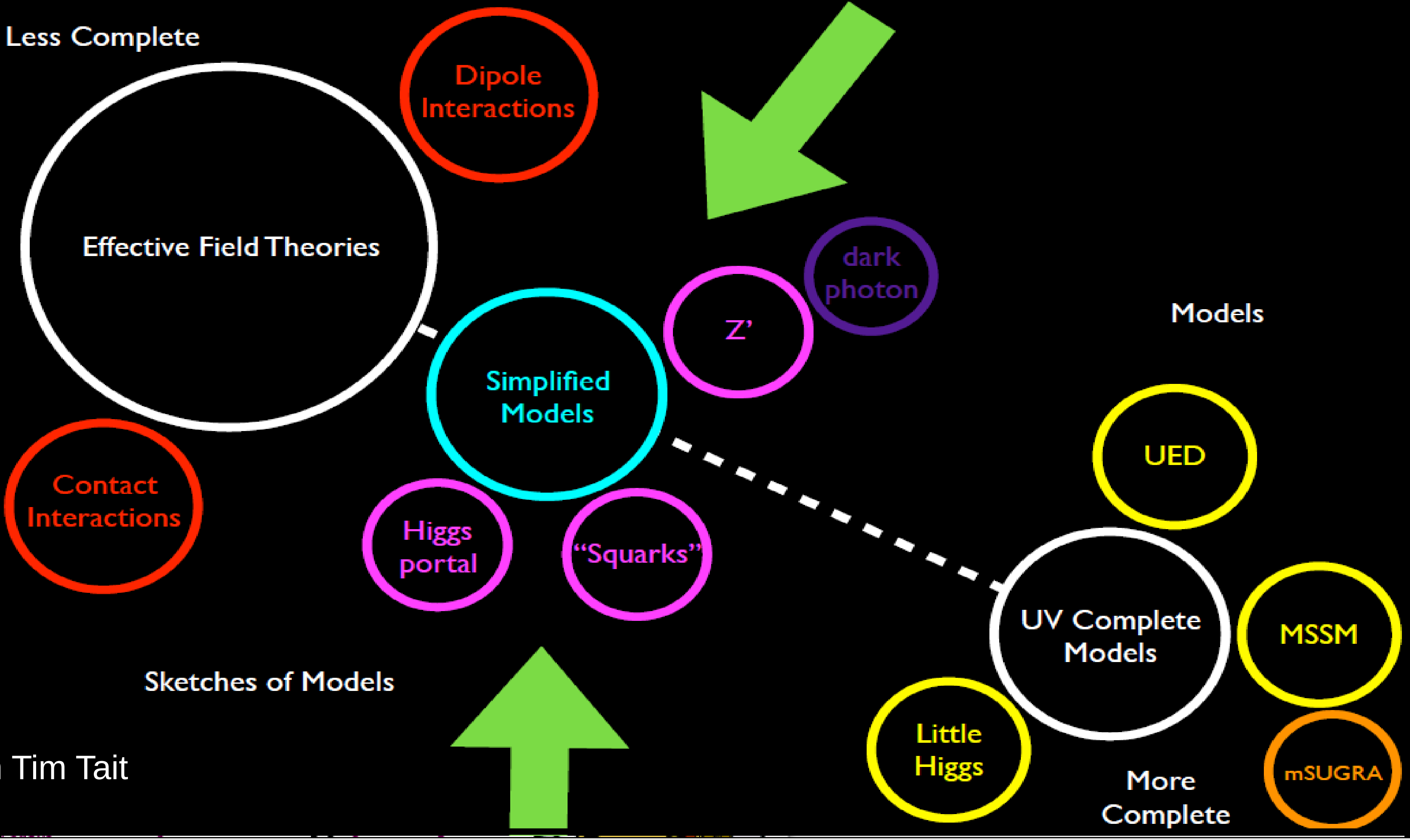
Efficient scattering off nuclei: DM Direct Detection (DD)
Signature from energy deposition from nuclei recoil: LUX, XENON, WARP, ...

Note: there is no 100%correlation between signatures above. For example, the high rate of annihilation does not always guarantee high rate for DD!

Great complementarity:

- **In case of NO DM Signal – we can efficiently exclude DM models**
- **In case of DM signal – we can efficiently determine the nature of DM**

Theory Space with Dark Matter



From Tim Tait

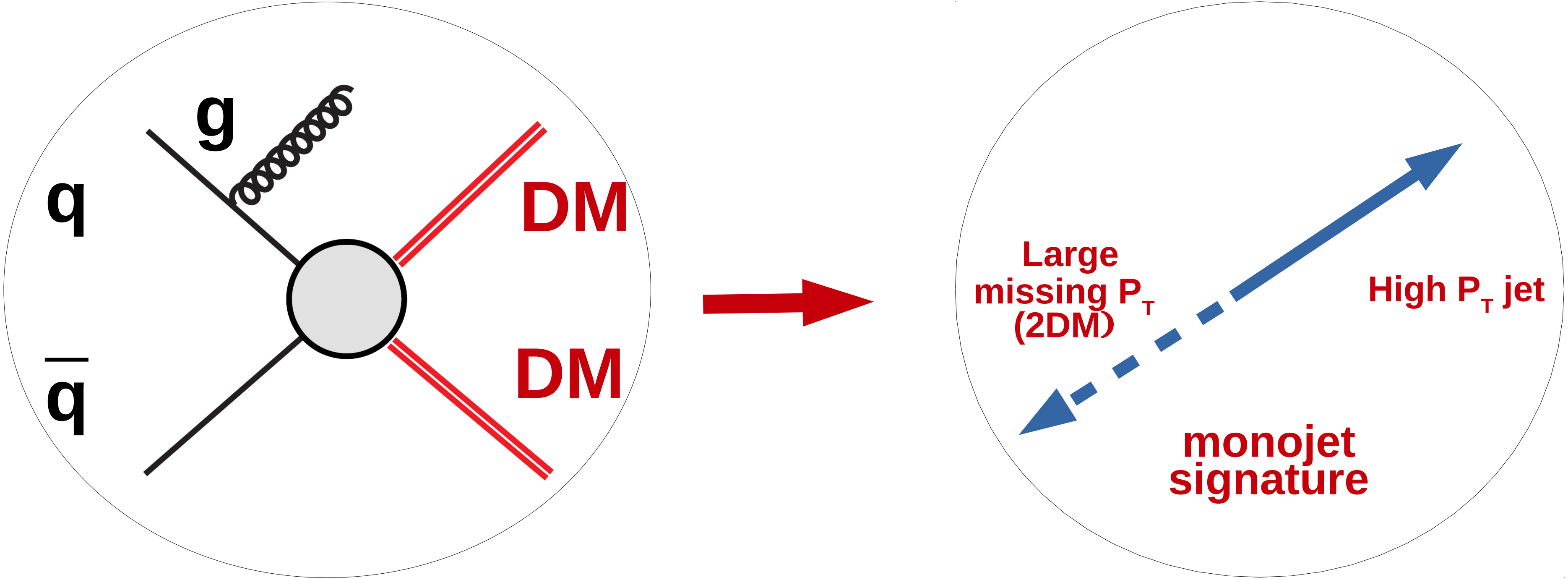
The LHC potential to probe DM

Hunting for DM at Colliders

Hunting for DM at Colliders

process

detector

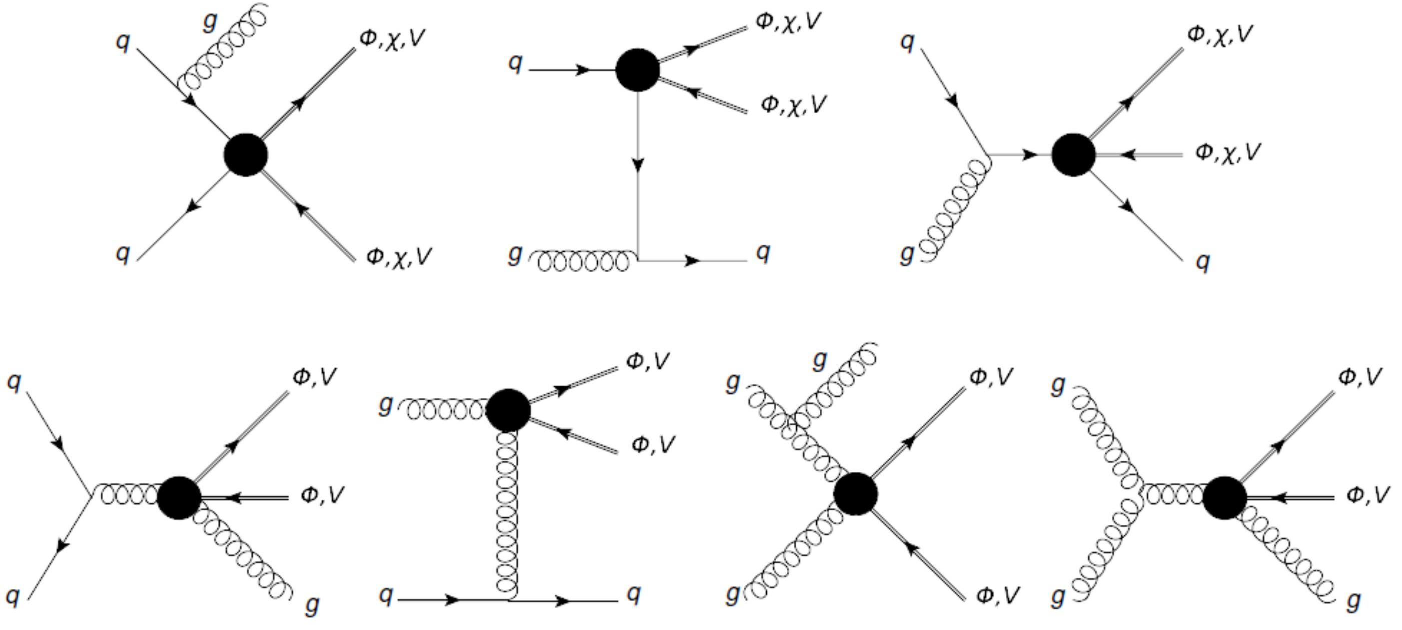


Large missing P_T (2DM)

High P_T jet

monojet signature

Mono-jet diagrams from EFT operators
Can we test DM properties at the LHC?



$$\frac{\tilde{m}}{\Lambda^2}\phi^*\phi\bar{q}q \quad \text{[C1]}$$

$$\frac{1}{\Lambda^2}\bar{\chi}\chi\bar{q}q \quad \text{[D1]}$$

$$\frac{\tilde{m}}{\Lambda^2}V^{\dagger\mu}V_\mu\bar{q}q \quad \text{[V1]}$$

$$\frac{1}{\Lambda^2}\phi^\dagger i\overleftrightarrow{\partial_\mu}\phi\bar{q}\gamma^\mu q \quad \text{[C3]}$$

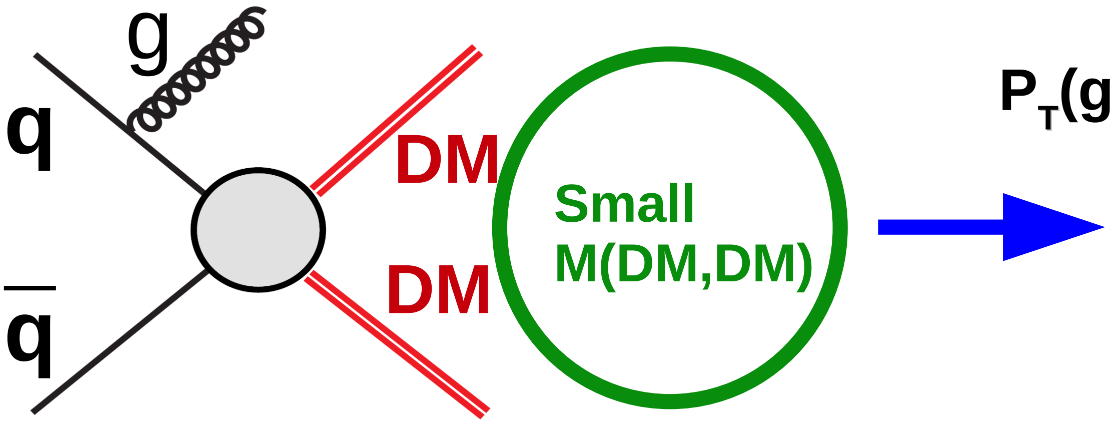
$$\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q \quad \text{[D5]}$$

$$\frac{1}{\Lambda^2}\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q \quad \text{[D9]}$$

$$\frac{\tilde{m}}{\Lambda^2}V^\dagger_\mu V_\nu\bar{q}i\sigma^{\mu\nu}q \quad \text{[V5]}$$

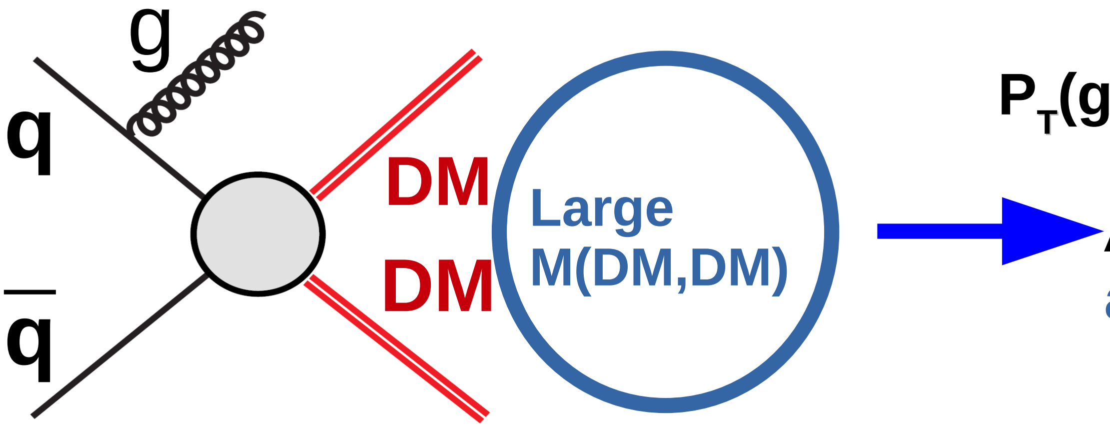
Properties of MET distributions:

- MET distributions are the same for the fixed mass of DM pair [M(DM,DM)] & fixed SM operator
- With the increase of M(DM,DM), MET slope decreases (PDF effect)



P_T(g) small → P_T(g)large

Δ (x1 x2)/(x1 x2) is large and MET slope is steep



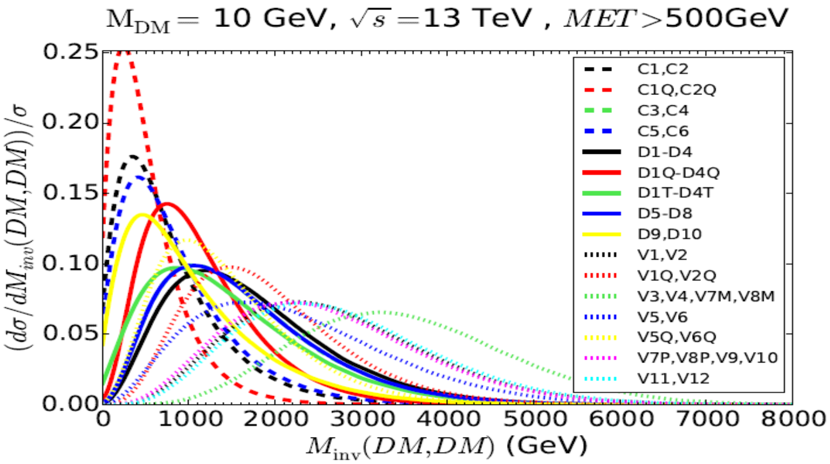
P_T(g) small → P_T(g)large

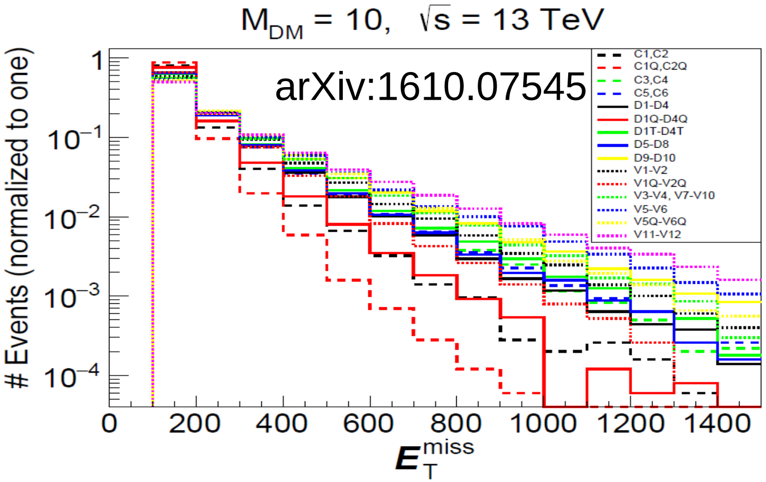
Δ (x1 x2)/(x1 x2) is small and MET slope is gradual

Distinguishing DM operators/theories

The harder M(DM,DM) distributions

The flatter MET shapes





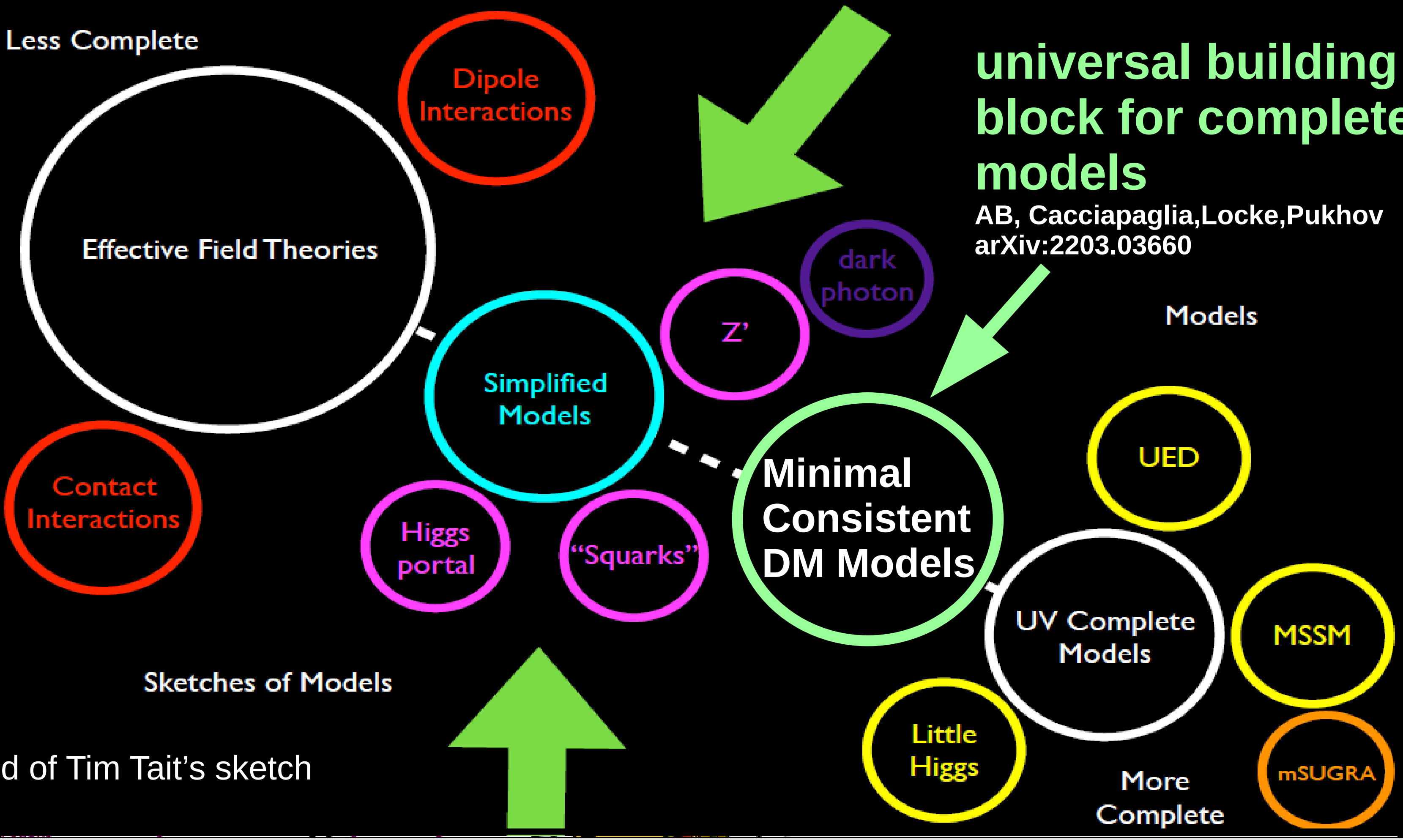
operator energy dependence → M_{DMDM} shape → MET shape

- ➪ projection for 300 fb^{-1}: some operators C1-C2,C5-C6,D9-D10,V1-V2,V3-V4,V5-V6 and V11-12 can be distinguished from each other [Panizzi, Pukhov, M.Thomas, AB, arXiv:**1610.07545]**

- ➪ Application beyond EFT: when the DM mediator is not produced on-the-mass-shell and M_{DMDM} is not fixed: t-channel mediator or mediators with mass below $2M_{DM}$

DM classification:
minimal consistent dark matter models (MCDMs)

Theory Space with Dark Matter



universal building block for complete models

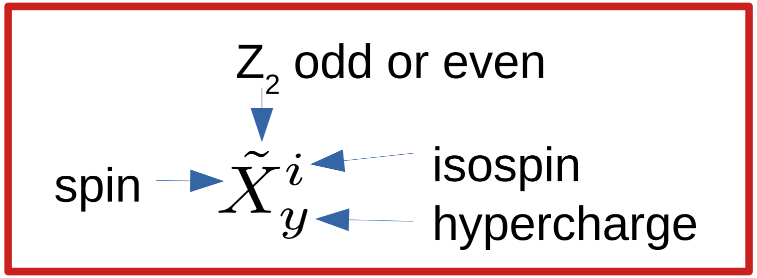
AB, Cacciapaglia,Locke,Pukhov
arXiv:2203.03660

Based of Tim Tait's sketch

Minimal Consistent DM (MCDM) Models

Properties

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



Z_2 odd or even

spin

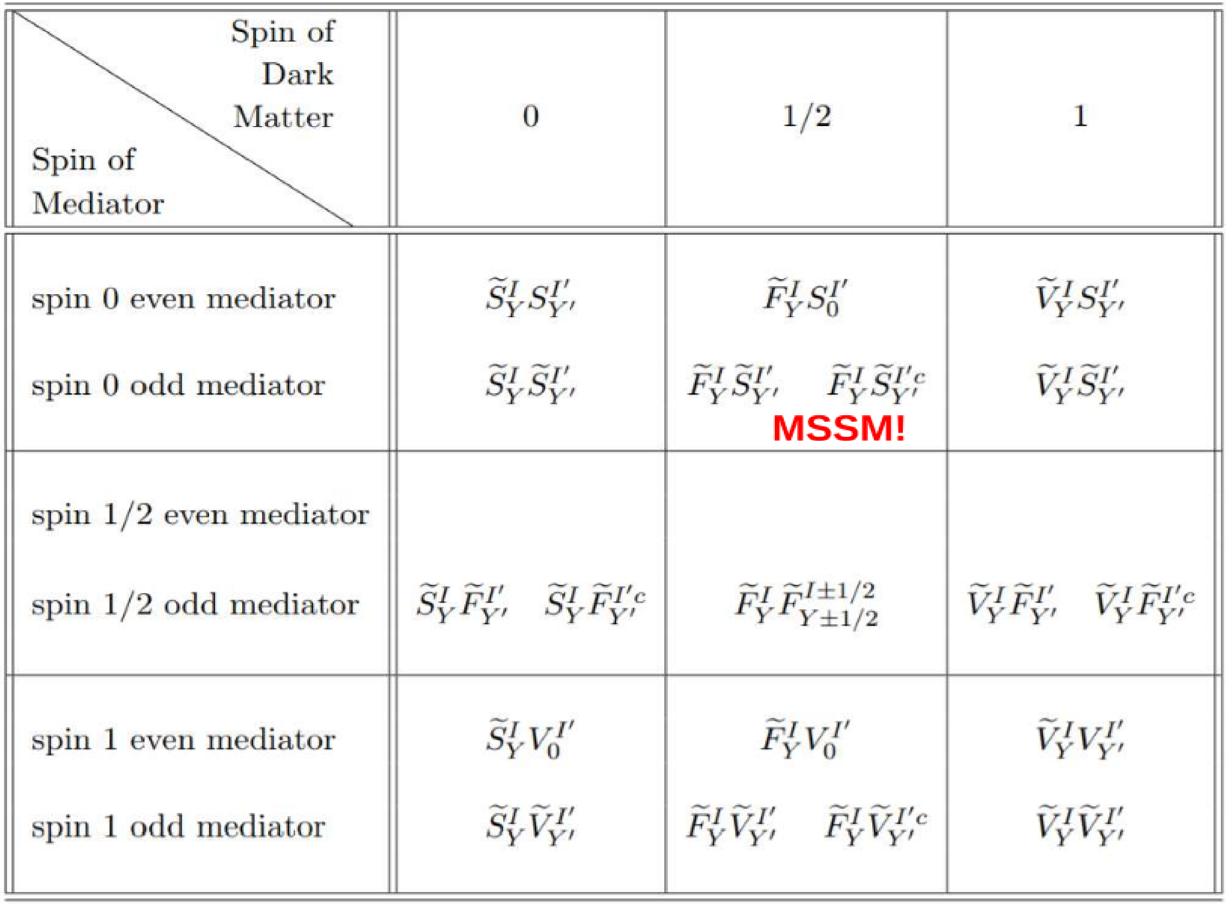
$\tilde{X}^i_y$

isospin

hypercharge

Classification

- DM is a part of EW multiplet
  - Radiative mass split
  - Disappearing track (DT) signatures
- at most one mediator multiplet



Spin of Dark Matter Spin of Mediator	0	1/2	1
spin 0 even mediator	$\tilde{S}^I_Y S^{I'}_{Y'}$	$\tilde{F}^I_Y S^{I'}_0$	$\tilde{V}^I_Y S^{I'}_{Y'}$
spin 0 odd mediator	$\tilde{S}^I_Y \tilde{S}^{I'}_{Y'}$	$\tilde{F}^I_Y \tilde{S}^{I'}_{Y'}$ $\tilde{F}^I_Y \tilde{S}^{I'c}_{Y'}$ MSSM!	$\tilde{V}^I_Y \tilde{S}^{I'}_{Y'}$
spin 1/2 even mediator			
spin 1/2 odd mediator	$\tilde{S}^I_Y \tilde{F}^{I'}_{Y'}$ $\tilde{S}^I_Y \tilde{F}^{I'c}_{Y'}$	$\tilde{F}^I_Y \tilde{F}^{I\pm1/2}_{Y\pm1/2}$	$\tilde{V}^I_Y \tilde{F}^{I'}_{Y'}$ $\tilde{V}^I_Y \tilde{F}^{I'c}_{Y'}$
spin 1 even mediator	$\tilde{S}^I_Y V^{I'}_0$	$\tilde{F}^I_Y V^{I'}_0$	$\tilde{V}^I_Y V^{I'}_{Y'}$
spin 1 odd mediator	$\tilde{S}^I_Y \tilde{V}^{I'}_{Y'}$	$\tilde{F}^I_Y \tilde{V}^{I'}_{Y'}$ $\tilde{F}^I_Y \tilde{V}^{I'c}_{Y'}$	$\tilde{V}^I_Y \tilde{V}^{I'}_{Y'}$

an important step for consistent exploration of DM theory space

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

DM multiplet only

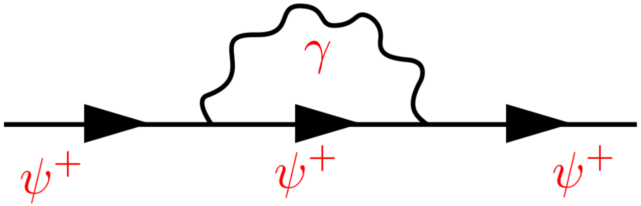
$$\mathcal{L} = i\bar{\psi}\gamma^{\mu}D_{\mu}\psi - m_D\bar{\psi}\psi$$

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

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

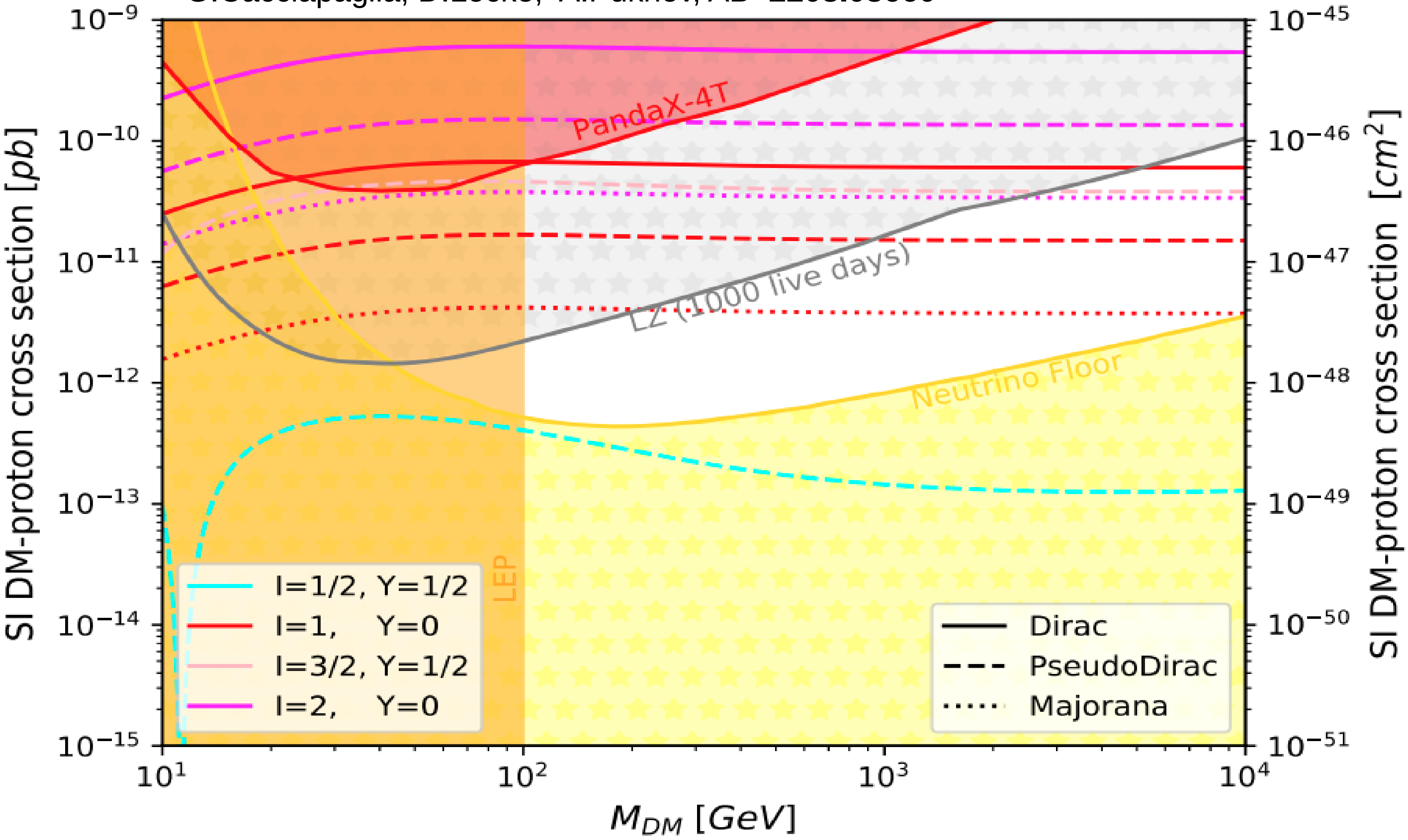
- **{I,Y}={0,0}, {½,½}, {1,0}**

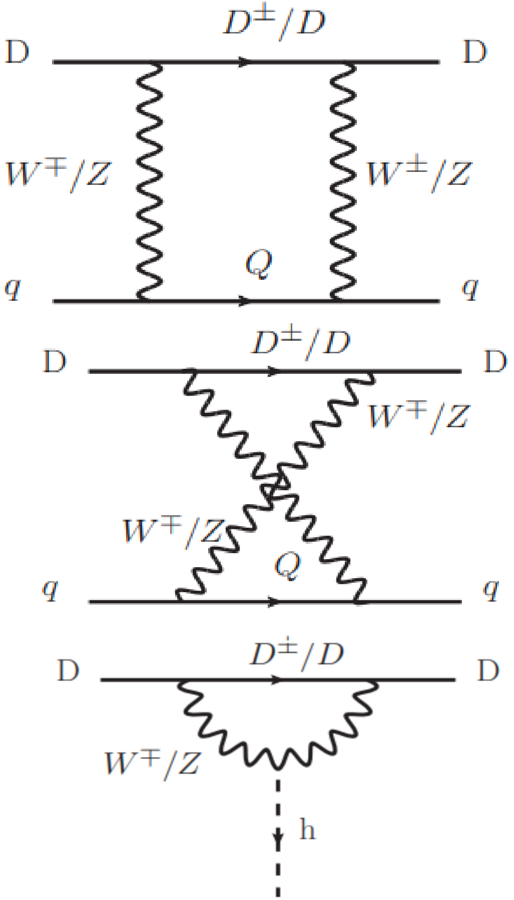
- {0,0} – no gauge-interactions – invisible to direct detection and collider but over(under) abundant if thermal (non-thermal)
- $Y \neq 0$ (Dirac DM) Is excluded by direct detection or requires additional sector – which splits the mass of ψ
- Radiative mass split – very important for the phenomenology



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!

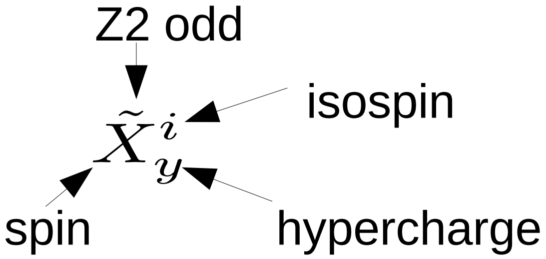
[Initially noted by Hisano, Ishiwata, Nagata arXiv:1004.4090]

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

Minimal fermion DM model with pseudo-scalar mediator

new model, has not been explored previously

two-component DM model (pseudoscalar is accidentally stable)



Z2 odd

$\tilde{X}^i_y$

isospin

spin

hypercharge

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

Fermion DM Singlet

pseudoscalar

SM Higgs doublet

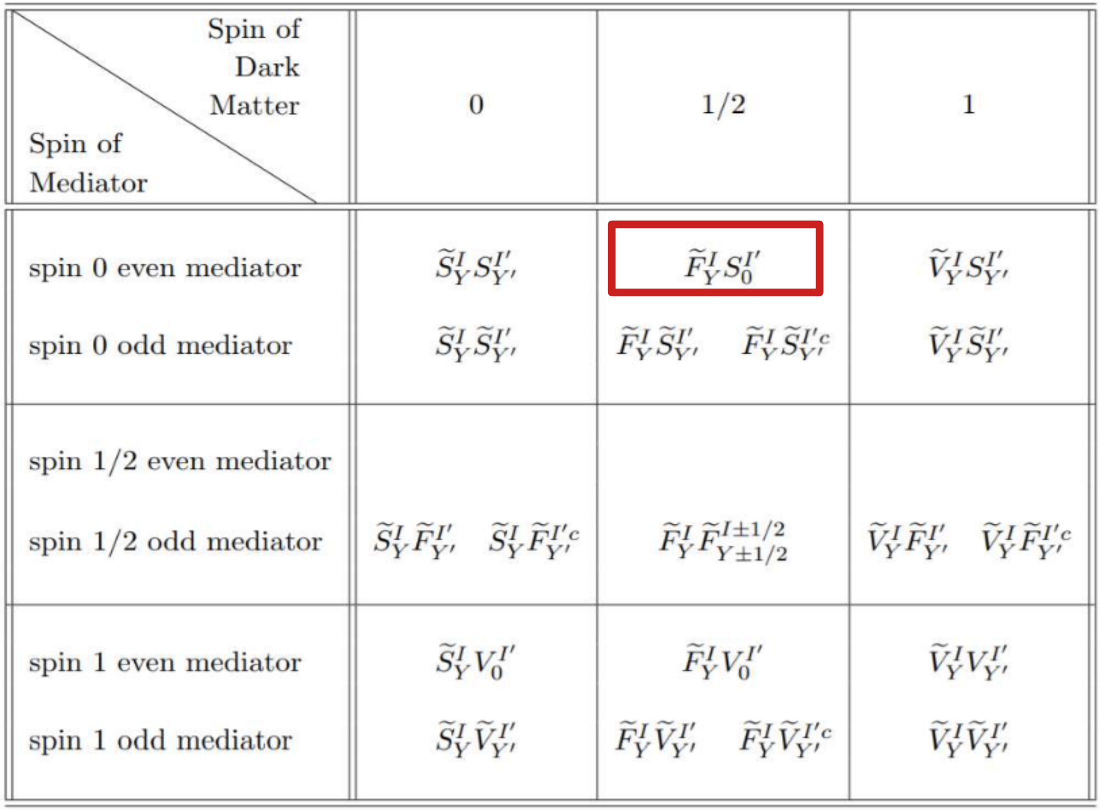
- a does not acquire VEV → no linear coupling to Higgs
- $m_a < 2m_\psi$ → “secluded DM”
- Model implemented in LanHEP, and numerical scan performed using micrOMEGAs.

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**



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spin 0 odd mediator	$\widetilde{S}^I_Y \widetilde{S}^{I'}_{Y'}$	$\widetilde{F}^I_Y \widetilde{S}^{I'}_{Y'}$ $\widetilde{F}^I_Y \widetilde{S}^{I'c}_{Y'}$	$\widetilde{V}^I_Y \widetilde{S}^{I'}_{Y'}$
spin 1/2 even mediator			
spin 1/2 odd mediator	$\widetilde{S}^I_Y \widetilde{F}^{I'}_{Y'}$ $\widetilde{S}^I_Y \widetilde{F}^{I'c}_{Y'}$	$\widetilde{F}^I_Y \widetilde{F}^{I\pm1/2}_{Y\pm1/2}$	$\widetilde{V}^I_Y \widetilde{F}^{I'}_{Y'}$ $\widetilde{V}^I_Y \widetilde{F}^{I'c}_{Y'}$
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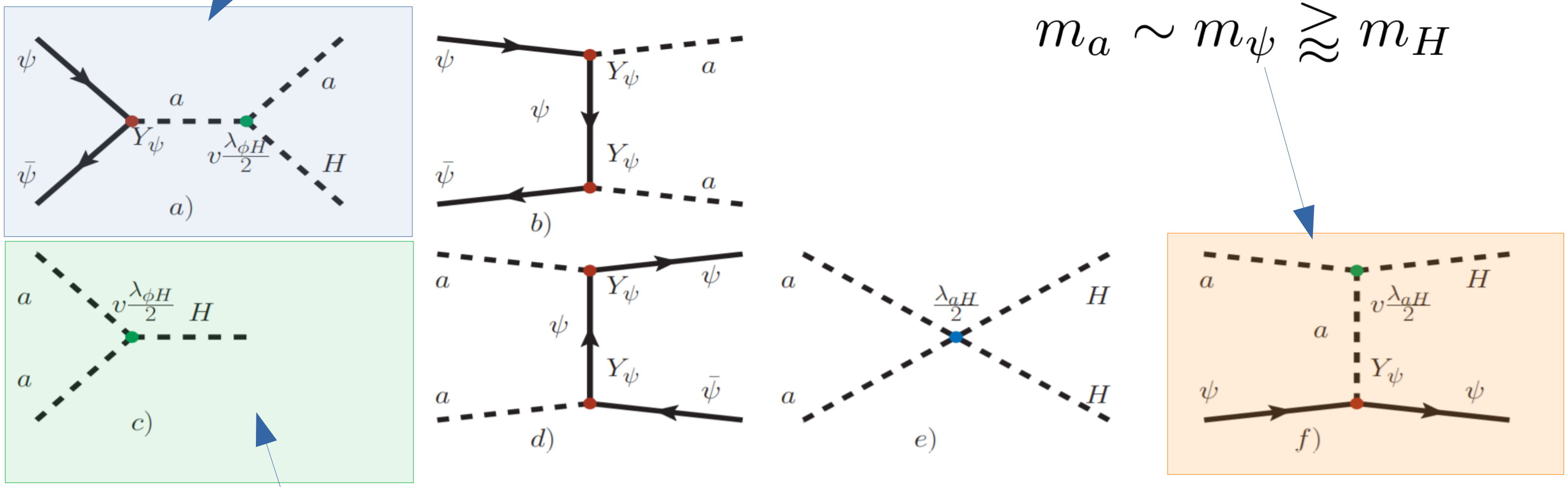
Minimal fermion DM model with pseudo-scalar mediator
rich phenomenology: relic density, DD, colliders

(co)Annihilation channels

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

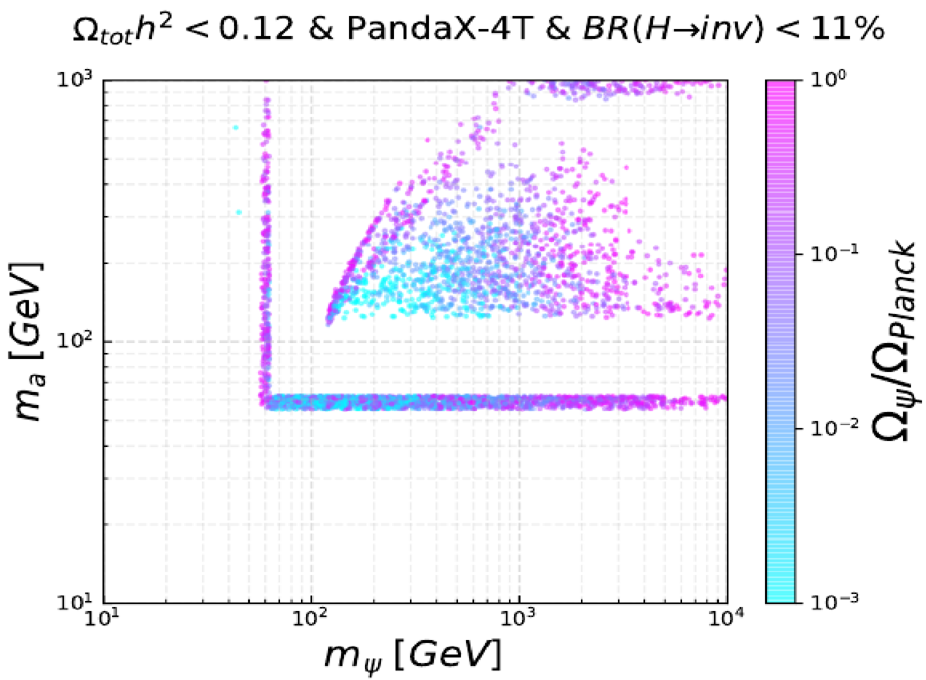


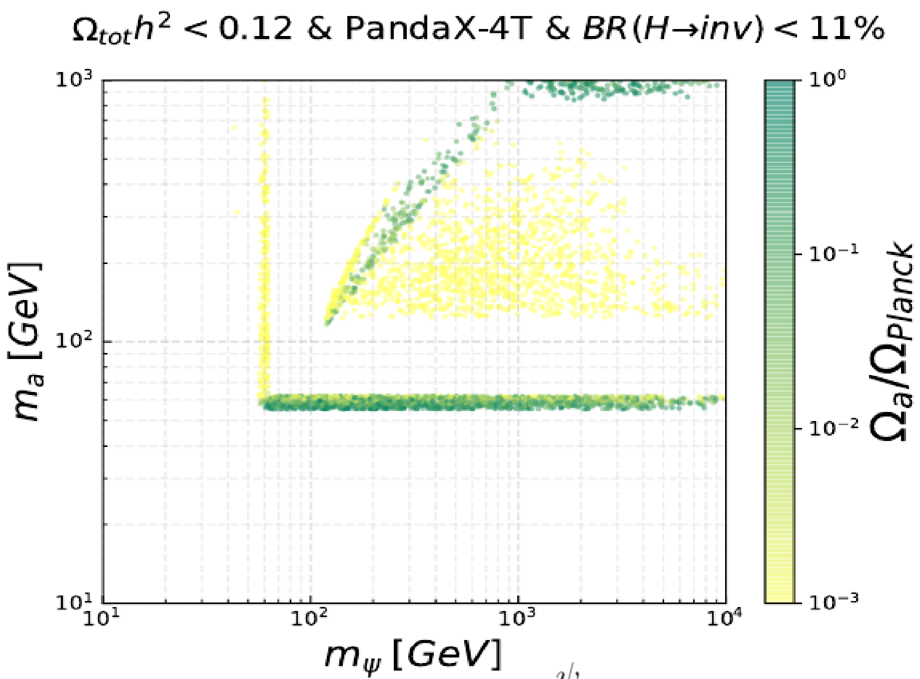
$$m_a \sim m_\psi \gtrapprox m_H$$

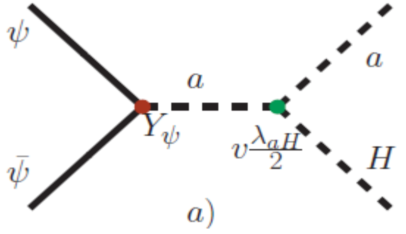
aa → WW ma>80GeV
aa → ZZ
ma>90GeV
aa → tt
ma>173GeV

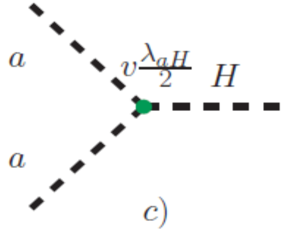
$$\sigma^{ann}_{aa\to ff} v \sim \frac{\lambda^2 m_f^2}{(4m_a^2 - m_H^2)^2 + m_H^2 \Gamma_H^2)}$$

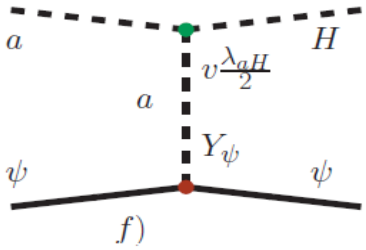
Minimal fermion DM model with pseudo-scalar mediator PandaX-4T exclusion

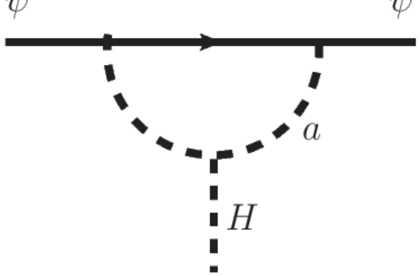






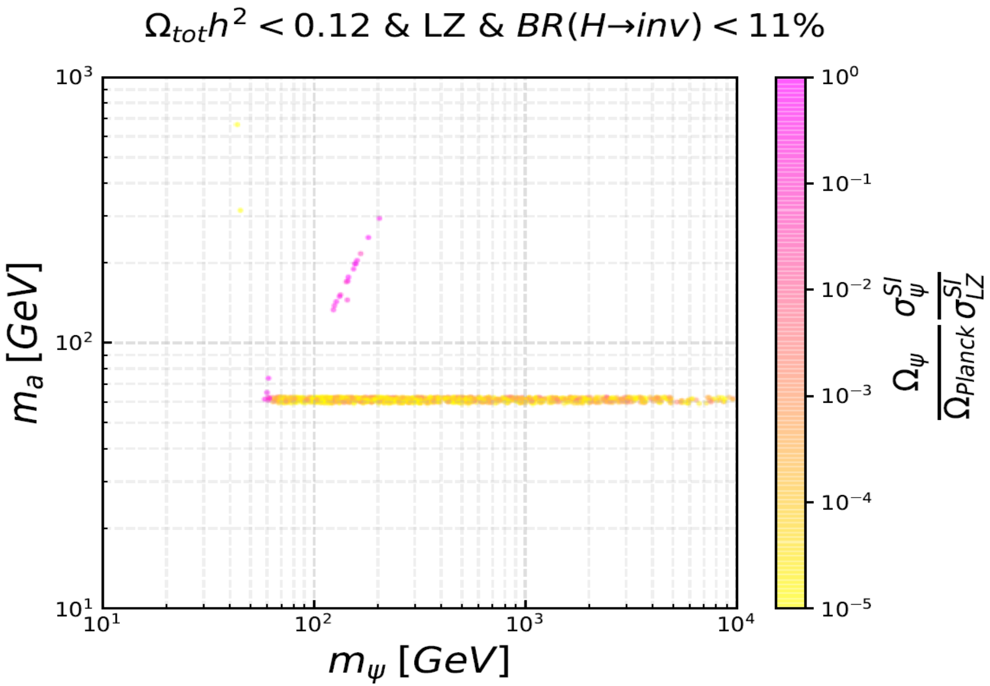


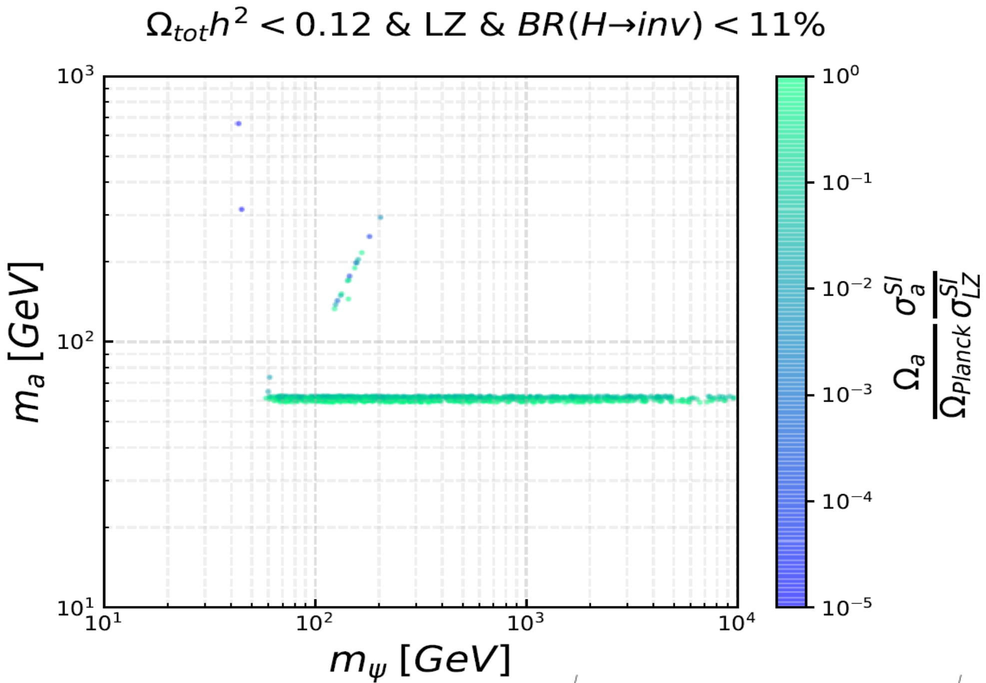


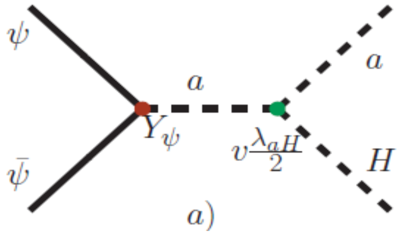


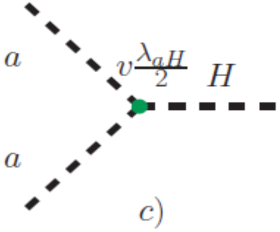
Minimal fermion DM model with pseudo-scalar mediator

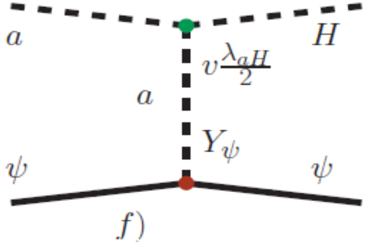
LZ exclusion

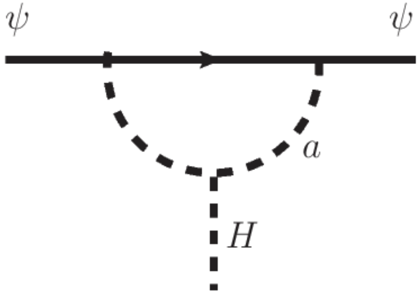




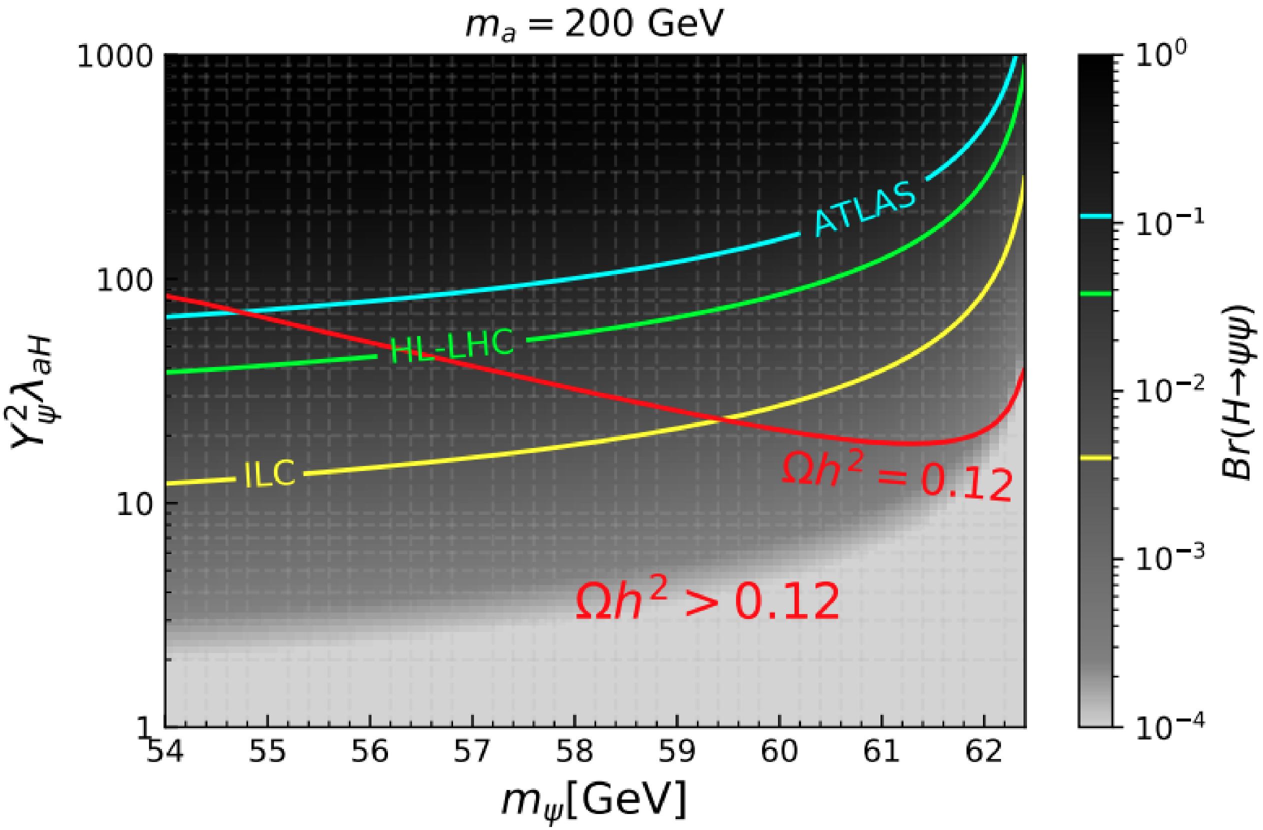


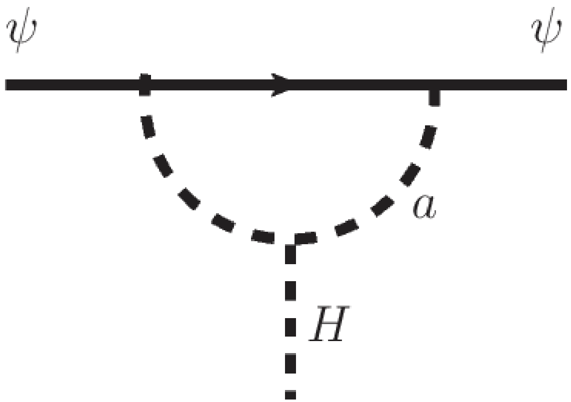






Minimal fermion DM model with pseudo-scalar mediator
relic density, DD, invisible H decay @colliders





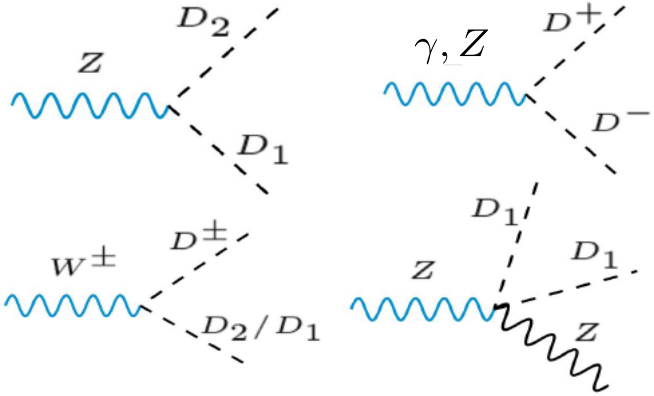
Decoding Dark Matter at future e^+e^- colliders

Inert 2 Higgs Doublet model (i2HDM)

$\tilde{S}^{1/2}_{1/2}$

$$\mathcal{L}_\phi = |D_\mu \phi_1|^2 + |D_\mu \phi_2|^2 - V(\phi_1, \phi_2)$$

$$\phi_1 = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v + H \end{pmatrix}, \quad \phi_2 = \frac{1}{\sqrt{2}}\begin{pmatrix} \sqrt{2} D^+ \\ D_1 + i D_2 \end{pmatrix}$$



$$M_{D1}, \quad \Delta M^+ = M_{D+} - M_{D1}, \quad \Delta M^0 = M_{D2} - M_{D+}$$

Minimal fermion DM model (MFDM)

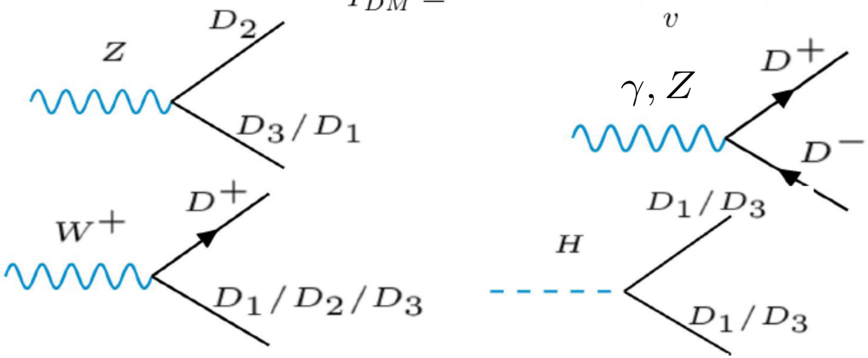
$\widetilde{F}^{1/2}_{1/2}\widetilde{M}^0_0$

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

$$\psi = \begin{pmatrix} \chi^+ \\ \frac{1}{\sqrt{2}}(\chi^0_1 + i\chi^0_2) \end{pmatrix}$$

Majorana singlet χ^0_s

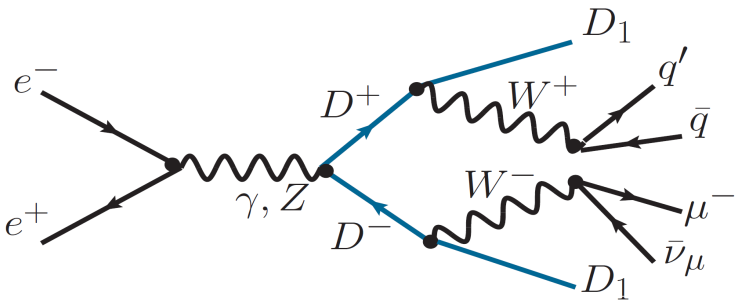
$$Y_{DM} = \frac{\sqrt{(m_{D3} - m_{D+})(m_{D+} - m_{D1})}}{v}$$



$$M_{D1} \quad \Delta M^+ = M_{D+} - M_{D1}, \quad \Delta M^0 = M_{D3} - M_{D+}$$

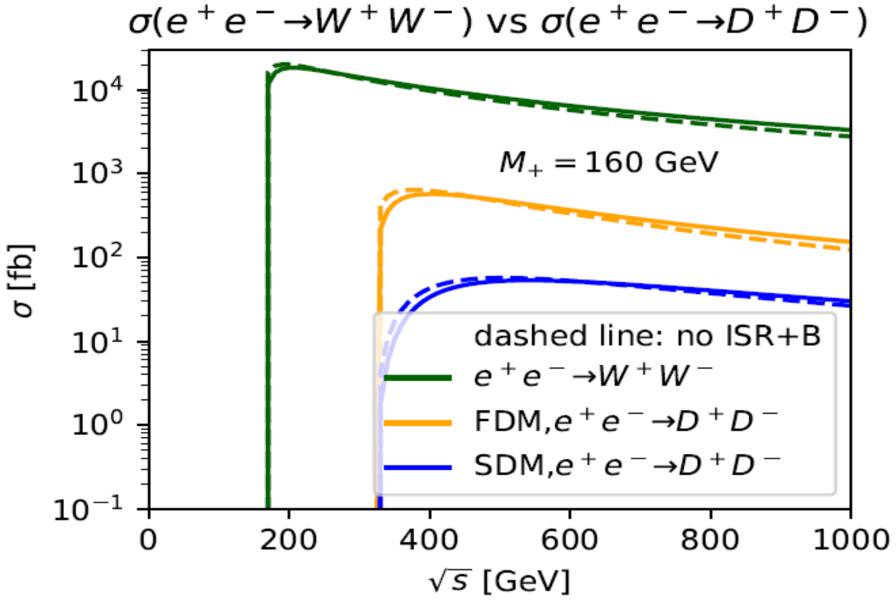
The process under study

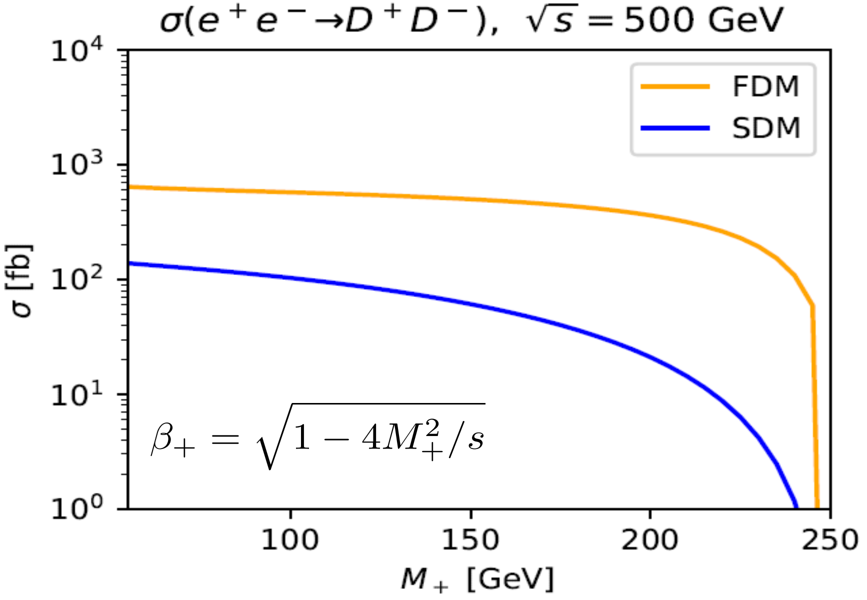
$$e^+e^- \to D^+D^- \to D_1D_1W^+W^- \to D_1D_1q'\bar{q}\mu\bar{\nu}$$



- Di-jet + muon + MET signature

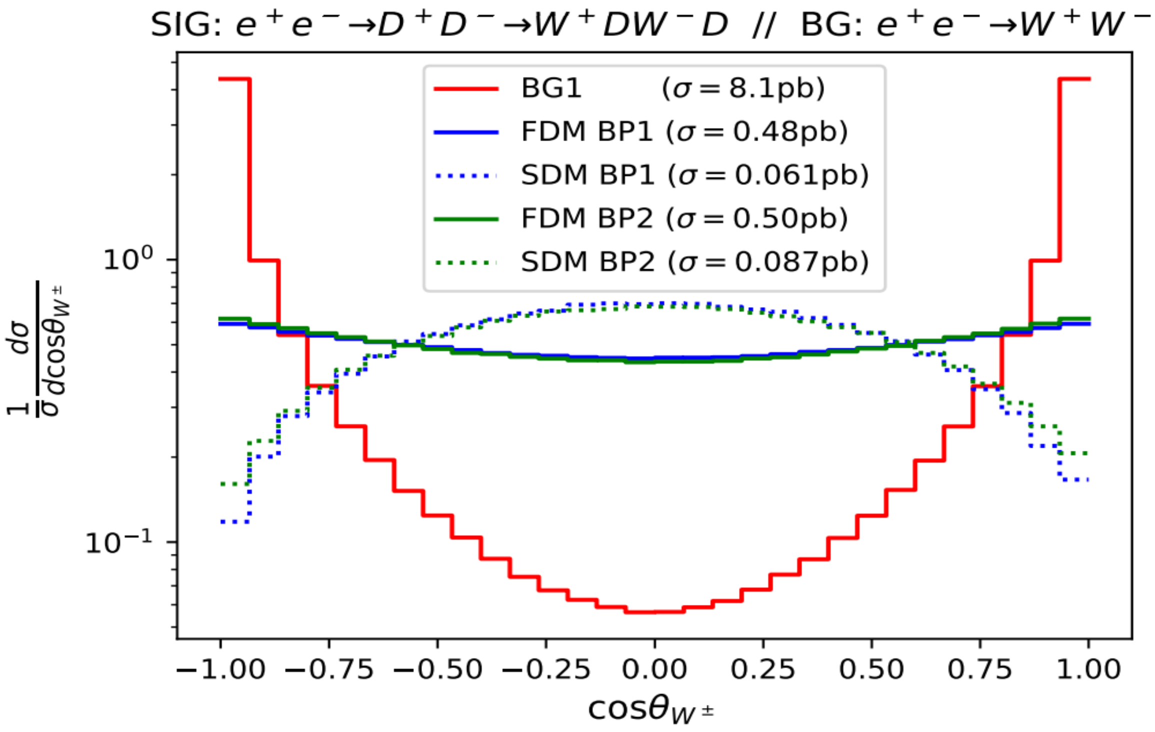
$$\sigma_{\gamma\gamma} = \begin{cases} \sigma_0\beta_+\left[1+\frac{2M_+^2}{s}\right] & \text{if } s_D = \frac{1}{2} \\ \sigma_0\frac{\beta_+^3}{4} & \text{if } s_D = 0 \end{cases}$$



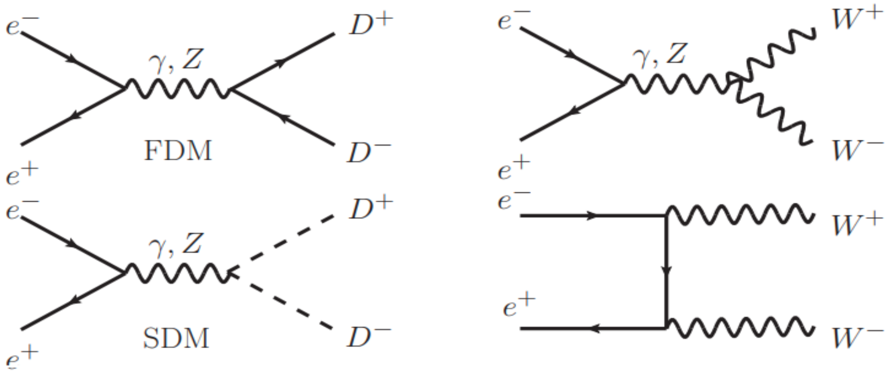


The role of the ILC in decoding the spin of DM

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



$$\frac{d\sigma}{d\cos\theta_{D^\pm}} \propto \begin{cases} 1-\cos^2\theta_{D^\pm}, & \text{for SDM} \\ 1+\frac{s-4M_+^2}{s+4M_+^2}\cos^2\theta_{D^\pm}, & \text{for FDM} \end{cases}$$



- 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 different benchmarks for DM of the same spin

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

Beyond the weak interactions: Vector Dark Matter (VDM) from dark SU(2)

Deandrea, Moretti, Panizzi, Ross, Thongyoi,AB arXiv:**2204.03510,2203.04681**

The abelian/non-abelian Vector DM was realised via Higgs portal

- $U(1)_D$ Group
- $V_D^\mu \leftrightarrow -V_D^\mu$ Explicit Z_2 symmetry plus a Higgs portal to provide the stability and the mass for VDM and connect it to the SM

$$\mathcal{L} \supset -\frac{1}{4}V_{\mu\nu}V^{\mu\nu} + (D_\mu\Phi)^\dagger (D^\mu\Phi) - V(\Phi) + \lambda_P |H|^2|\Phi|^2$$

with $D_\mu\Phi \equiv \partial_\mu\Phi - gQ_\Phi V_\mu\Phi$, after SSB → $\Phi = \frac{1}{\sqrt{2}}(v_\Phi + \varphi(x))$

so one has $m_V^2 = g^2 Q_\Phi^2\ v_\phi^2$

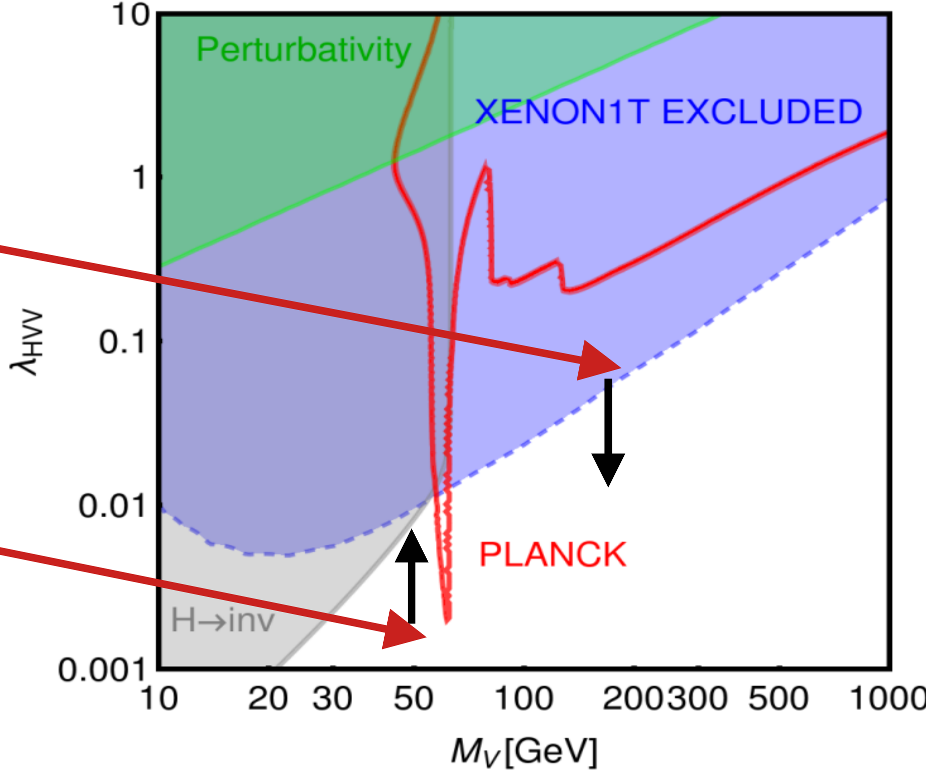
- Quite a few papers:

Lebedev, Lee, Mambrini 1111.4482,
Baek, Ko, Park , Senaha 1212.2131
DiFranzo, Fox,Tait 1512.06853

Farzan, Akbarieh 1207.4272
Duch, Grzadkowski, McGarrie 1506.08805
………………………..

Vector DM with the Higgs portal

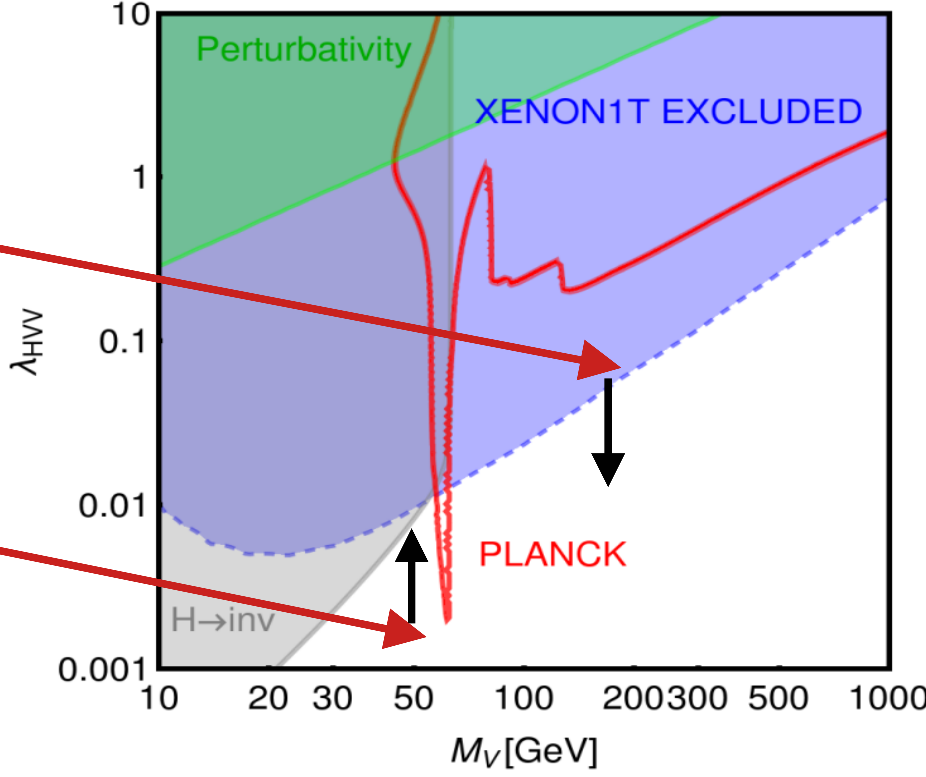
- Since VDM ‘talks’ to SM via Higgs, $V_D V_D H$ coupling is **limited from above** by DM direct detection and H → DM DM Br
- Since DM Relic density should be equal or below the PLANCK relic density limit $\Omega h^2 \simeq 0.11$ $V_D V_D H$ coupling is **limited from below**


Arcadi, Djouadi, Kado 2001.10750

Vector DM with the Higgs portal

- Since VDM ‘talks’ to SM via Higgs, $V_D V_D H$ coupling is **limited from above** by DM direct detection and H→ DM DM Br
- Since DM Relic density should be equal or below the PLANCK relic density limit $\Omega h^2 \simeq 0.11$ $V_D V_D H$ coupling is **limited from below**
- The Higgs portal VDM parameter space is very limited by interplay of collider, DD and DM relic density

Arcadi, Djouadi, Kado 2001.10750



Vector DM and Vector-Like Fermionic Portal

- Higgs portal : the parameter space for minimal scenarios is almost excluded
- **Vector Like(VL) fermionic portal for Vector Dark Matter**
  - $SU(2)_D$ gauge triplet (new dark gauge) V_μ^D
  - Complex scalar doublet charged under $SU(2)_D$, Φ_D – to break gauge group
  - Vector-Like fermion doublet of $SU(2)_D$, Ψ – to “talk” to SM

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  - Complex scalar doublet charged under SU(2)$_D$, Φ_D – to break gauge group
  - Vector-Like fermion doublet of SU(2)$_D$, Ψ – to “talk” to SM
  - we assign the “dark charge” to the components

    of the doublets, e.g. $Q_D = T_D^3 + Y_D$ and require its conservation
  - we have $SU(2)_D \times U(1)_{\rm glob} \to U(1)^d_{\rm glob}$ pattern of dark sector breaking
  - $\mathbb{Z}_2$ subgroup can be defined as : $(-1)^{Q_D}$
  - The portal is driven by Yukawa interactions: $y'\bar\Psi_L \Phi_D f_R^{\rm SM} + \xcancel{y''\bar\Psi_L \Phi^c_D f_R^{\rm SM}} + h.c$
  - **Choosing e.g. $Y_D = +1/2$ for Φ_D and Ψ , make the second term above (y'') to disappear under the requirement of Q$_D$ conservation: DM is established!**

Vector DM and Vector-Like Fermionic Portal

- V_μ^D SU(2)$_D$ gauge triplet
- Complex scalar SU(2)$_D$ doublet Φ_D to break gauge group
- VL fermion doublet of SU(2)$_D$ Ψ to “talk” to SM
- assign $Q_D = T_D^3 + Y_D$ and require its conservation
- $SU(2)_D \times U(1)_{\rm glob} \to U(1)^d_{\rm glob}$ pattern of dark sector breaking
- $\mathbb{Z}_2$ subgroup $: (-1)^{Q_D}$
- Yukawa portal

$$y'\bar\Psi_L\Phi_D f_R^{\rm SM} + \cancel{y''\bar\Psi_L\Phi_D^c f_R^{\rm SM}}$$

- Q$_D$ conserved – DM is established!

	$SU(2)_L$	$U(1)_Y$	$SU(2)_D$	Q_D	$\mathbb{Z}_2$
$\Phi_D = \begin{pmatrix}\varphi_D+\frac{1}{2}\\ \varphi_D-\frac{1}{2}\end{pmatrix} \to \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ H_D+v_D\end{pmatrix}$	1	0	2	+1 0	− +
$\underline{\Psi} = \begin{pmatrix}\Psi_D\\ \Psi\end{pmatrix} = \begin{pmatrix}\tilde{F}\\ F\end{pmatrix}$	1	Q_{EM}	2	+1 0	− +
$V_\mu^D = \begin{pmatrix}V_\mu^{D+}\\ V_\mu^{D0}\\ V_\mu^{D-}\end{pmatrix} = \begin{pmatrix}\tilde{V}_D^+\\ V'\\ \tilde{V}_D^-\end{pmatrix}$	1		3	+1 0 −1	− + −

Fermionic Portal for Vector Dark Matter (FPVDM)

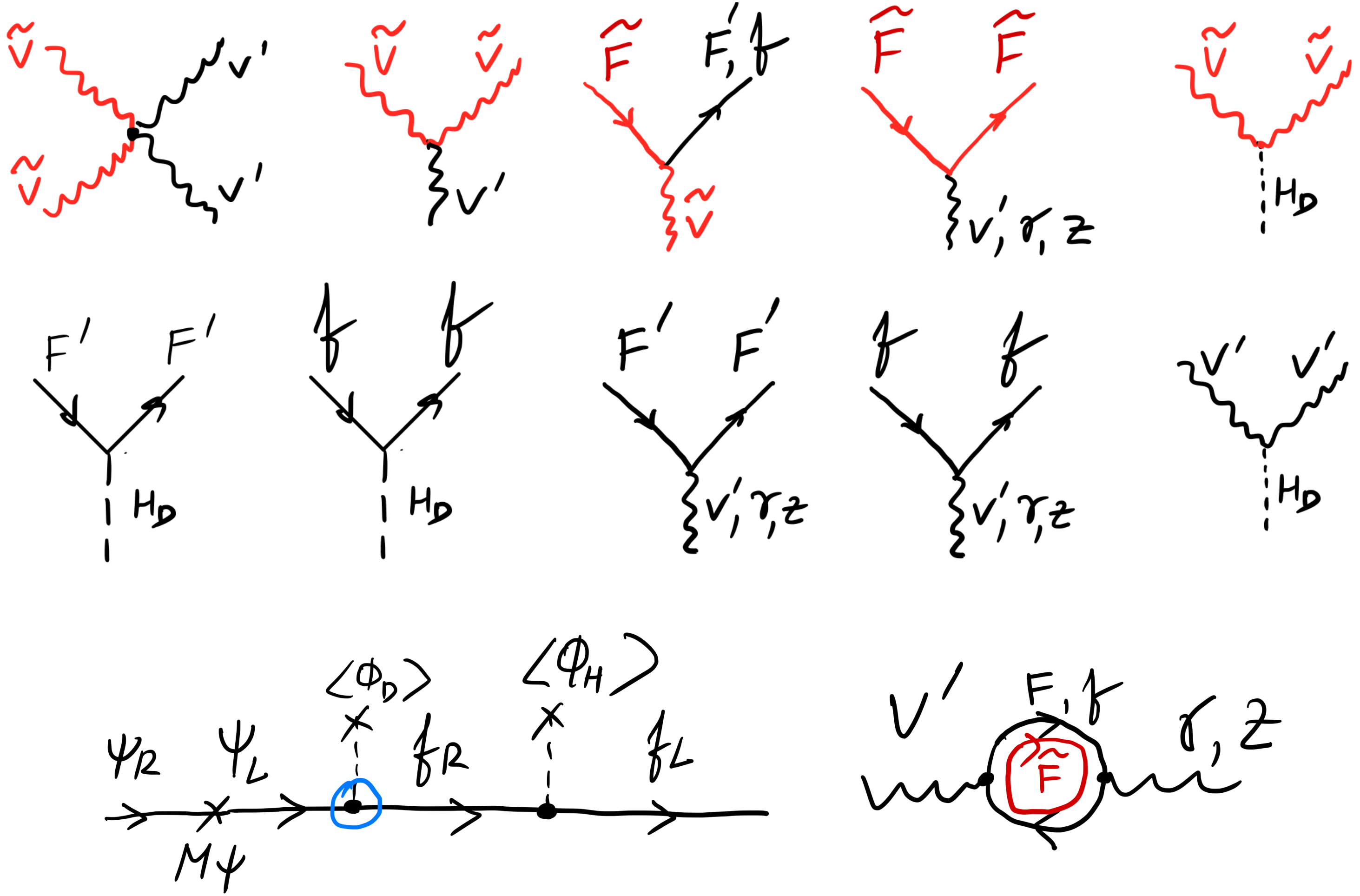
- It is the framework, representing the class of models
  [Deandrea, Moretti, Panizzi, Ross, Thongyoi, AB – arXiv:2204.03510,2203.04681]

- Various realisations are possible, including one or several VL fermions

$$\begin{aligned}
\mathcal{L}_{FPVDM} &= -\frac{1}{4}(V^i_{D\mu\nu})^2 + \bar{\Psi} i D \Psi + |D_\mu \Phi_D|^2 - V(\Phi_H, \Phi_D) \\
&- \underline{(y'_{\alpha\beta}\bar{\Psi}^{i\alpha}_L \Phi_D f^{\mathrm{SM}\beta}_R} + h.c) - M_\Psi{}^{ij}\bar{\Psi}^i\Psi^j \\
V(\Phi_H, \Phi_D) &= -\mu^2_H \Phi^\dagger_H \Phi_H - \mu^2_D \Phi^\dagger_D \Phi_D + \lambda_H(\Phi^\dagger_H \Phi_H)^2 \\
&+\lambda_D(\Phi^\dagger_D \Phi_D)^2 + \lambda_{HD}(\Phi^\dagger_H \Phi_H)(\Phi^\dagger_D \Phi_D)
\end{aligned}$$

- $y'_{\alpha\beta}$ can have a flavour structure – to explain flavour anomalies
- λ_{HD} can be negligible at tree-level, DM can be well-generated via FP
- the model with $\Psi = \begin{pmatrix} \tilde{T} \\ T \end{pmatrix}$ and $\lambda_{HD} = 0$ was explored

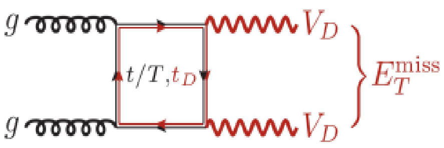
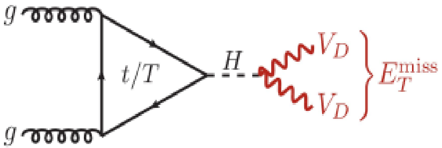
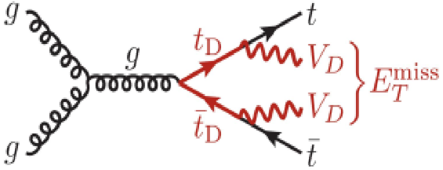
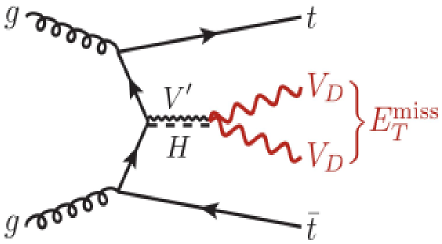
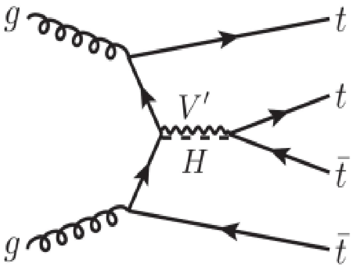
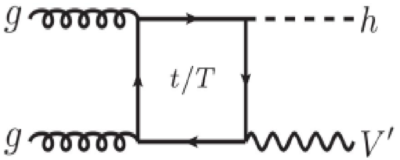
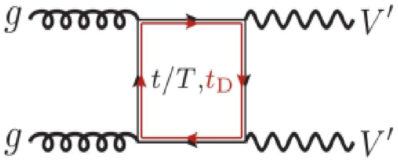
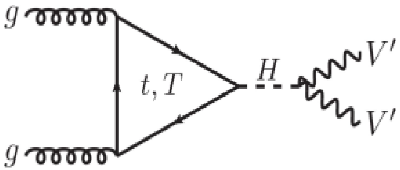
FPVDM Interactions and loop-induced kinetic mixing



$$\Psi = \begin{pmatrix} \tilde{F} \\ F \end{pmatrix}$$

$$V_\mu^D = \begin{pmatrix} \tilde{V}_D^+ \\ V' \\ \tilde{V}_D^- \end{pmatrix}$$

Minimal VL top portal VDM: collider signatures

Process	Representative diagrams
mono-jet (only loop)	  + jet from ISR or from loop
$t\bar{t} + E_T^{\rm miss}$	 
$t\bar{t}t\bar{t}$	
hV' and $V'V'$ (only loop)	  

FPVDM model with $\Psi_M = \begin{pmatrix} \tilde{M} \\ M' \end{pmatrix}$, the partner of muon

$$\mathcal{L}_{\mu PVDM} \supset -y'\bar{\Psi}_{ML}\Phi_D\mu_R + h.c \qquad \text{with} \quad \tilde{V}_D, \quad V', \quad H_D, \quad M', \quad \tilde{M}$$

- has potential to explain DM relic density and $(g\text{-}2)_\mu$ anomaly

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- one should ensure
  - consistency with DD and ID DM search experiments
  - consistency with collider searches

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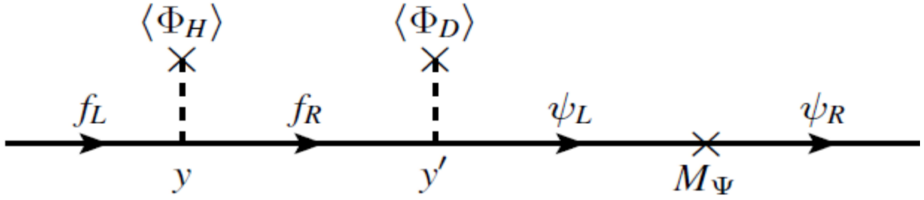
- Parameter space ($\lambda_{HD} = 0$ for simplicity): $\boxed{g_D, m_{V_D}, m_{H_D}, m_{M'}, m_{\tilde{M}}}$
- Interactions+mixing:



$$y'\bar{\Psi}_L\Phi_D f_R^{\mathrm{SM}} + h.c$$

FPVDM model with $\Psi_M = \begin{pmatrix} \tilde{M} \\ M' \end{pmatrix}$, the partner of muon

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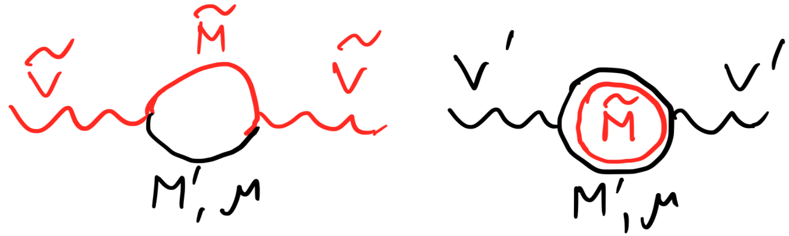
- Interactions+mass corrections:



$$m_{V_D} - m_{V'} = \frac{g_D^2 m_{M'}^2}{32\pi^2 m_{V_D}} \left(\frac{m_{M'}^2 - m_{\tilde{M}}^2}{m_{M'}^2} \right)^2$$

The status of $(g\text{-}2)_\mu$ and our approach here

- The combined experimental value from BNL +FNAL(from August 2023):

$$a_\mu^{\mathrm{EXP}} = 116592059(22) \times 10^{-11}$$

- The SM Theory Initiative 2020 prediction [arXiv:2006.04822] provides

$$a_\mu^{\mathrm{SM}} = 116591810(43) \times 10^{-11}$$

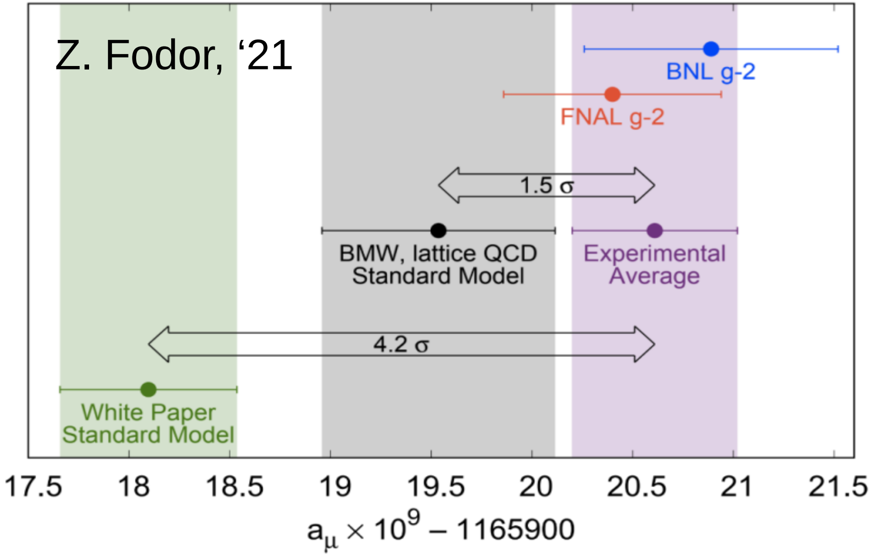
- Combining above numbers, one concludes one finds 5.1σ SM vs EXP discrepancy

$$\Delta a_\mu = a_\mu^{\mathrm{EXP}} - a_\mu^{\mathrm{SM}} = 249(48) \times 10^{-11}$$

- Theory: for three contributions to (g-2)μ – QED, EW and Hadronic – the Hadronic Vacuum Polarisation (HVP) is taken from the experimental data and it has the biggest contribution to the uncertainty

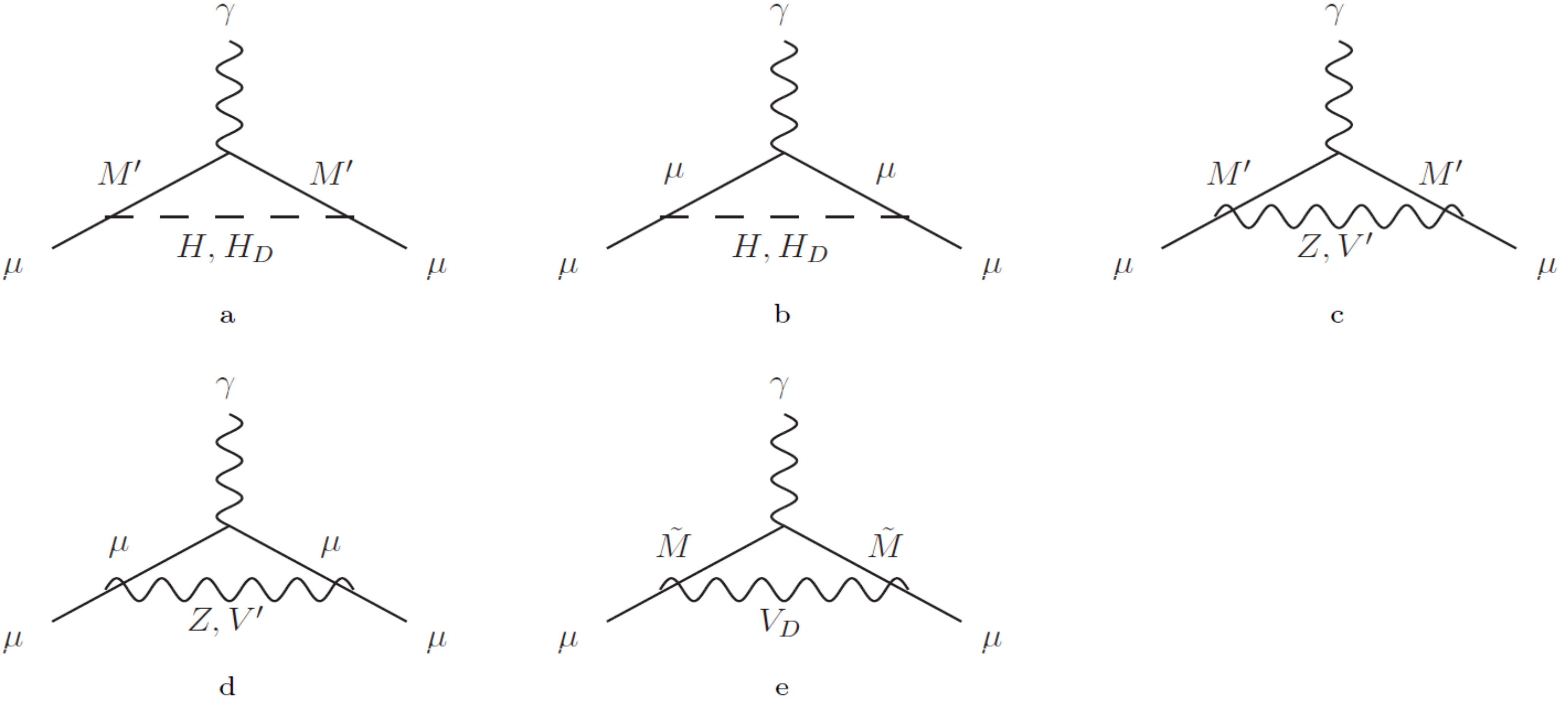
- Recent CMD3 results [arXiv:2302.08834] adds and additional intrigue here

- Of course recent Lattice results from BMW [Nature 593, 51 (2021)] must be add here

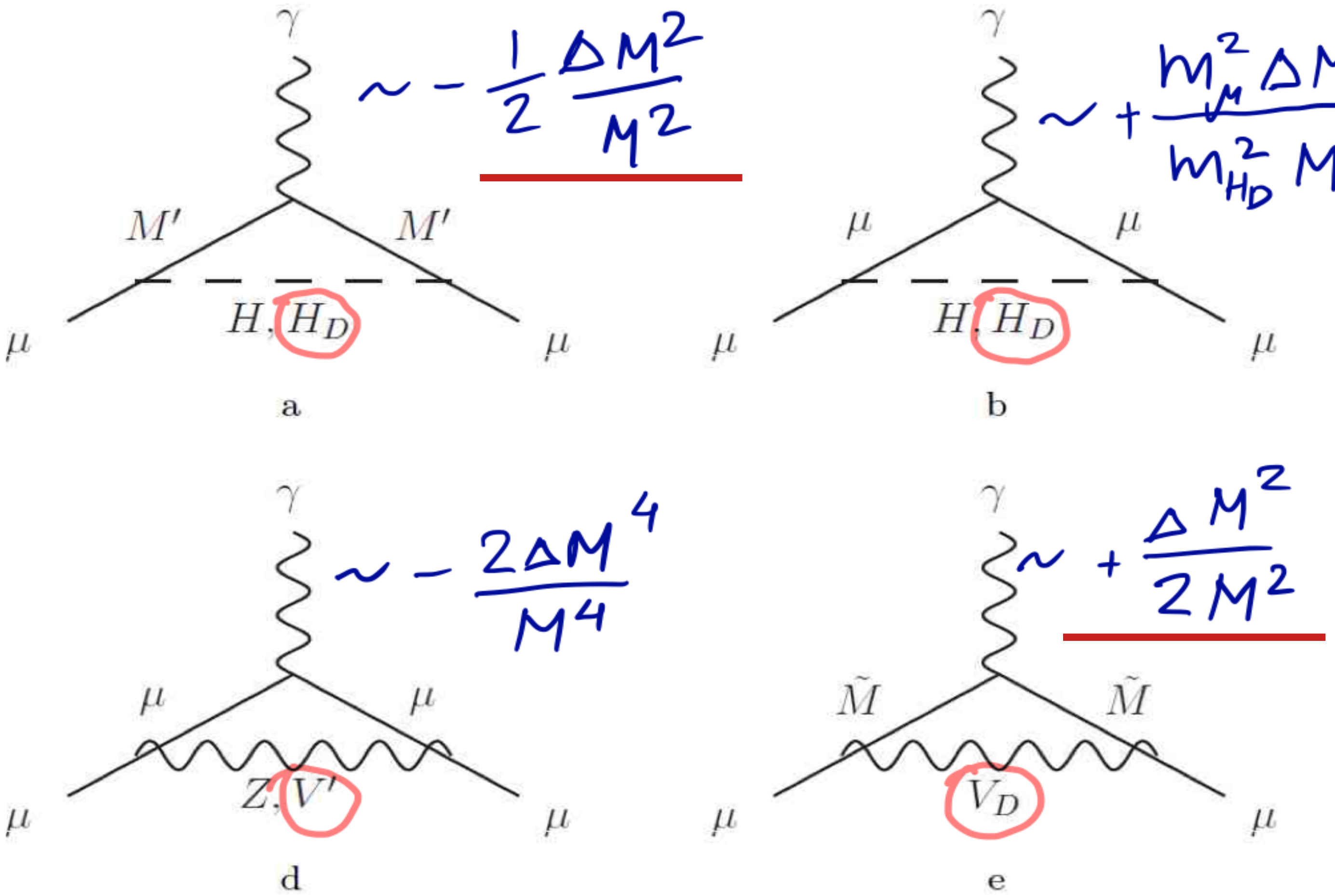


- (g-2)μ is an important puzzle to be solved including discrepancy between HVP from e+e- data and Lattice
- In our study we take Δa_μ as a real effect to be explained within our μFPVDM model

The contribution to (g-2)$_\mu$ from μPVDM



The contribution to $(g-2)_\mu$ from μPVDM $\times \boxed{\frac{g_D^2}{96\pi^2}\frac{m_\mu^2}{m_{V_D}^2}}$



a: $\sim -\frac{1}{2}\frac{\Delta M^2}{M^2}$

b: $\sim +\frac{m_\mu^2 \Delta M^4}{m_{H_D}^2 M^4}$

c: $\sim +\frac{1}{4}\frac{\Delta M^2}{M^2}$

d: $\sim -\frac{2\Delta M^4}{M^4}$

e: $\sim +\frac{\Delta M^2}{2M^2}$

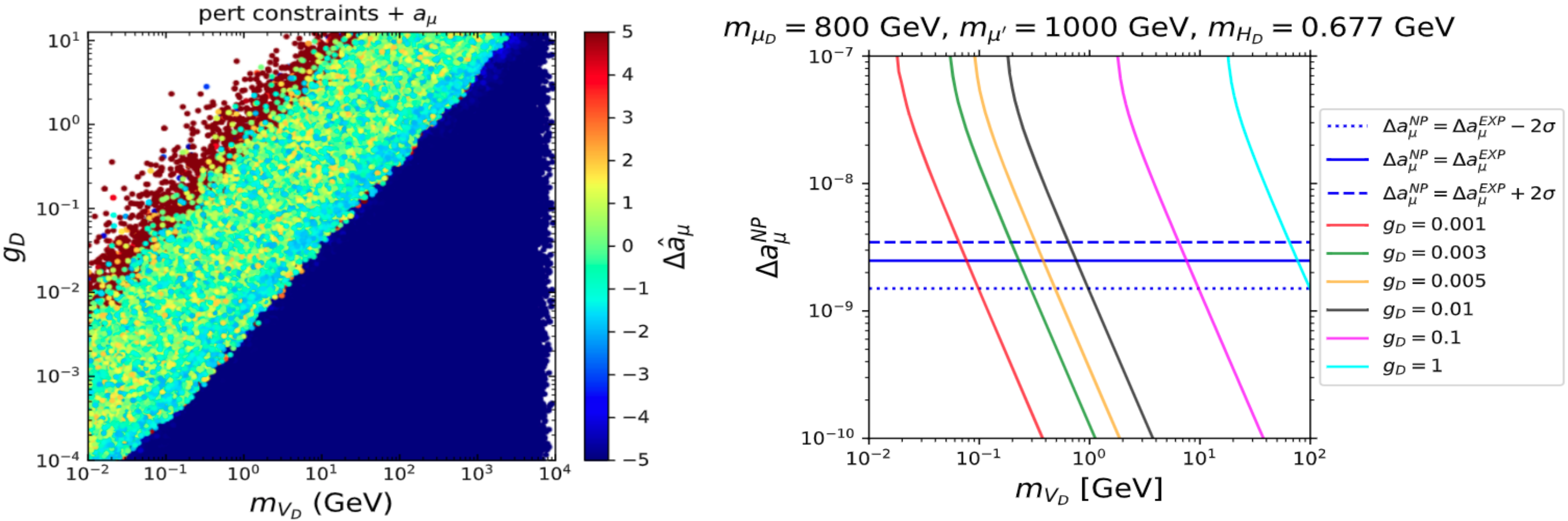
$\Delta M^2 = m_{M'}^2 - m_{\tilde{M}}^2$

$M = m_{M'}$

$M \gg m_{V_D}$ was used

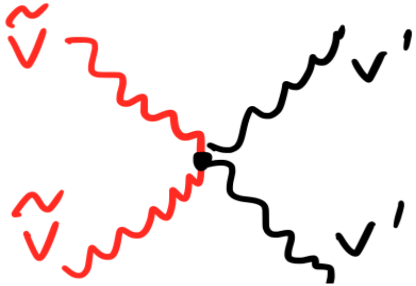
(g-2)$_\mu$ results from scan of $\boxed{g_D, m_{V_D}, m_{H_D}, m_{M'}, m_{\tilde{M}}}$ space

$$\Delta\hat{a}_\mu = (\Delta a_\mu^{\mu PVDM} - \Delta a_\mu)/\sigma_{a_\mu} \equiv \frac{\Delta a_\mu^{\mu PVDM} - 249}{48} \times 10^{-11}$$



- Δa_μ can be explained within μFPVDM model $(g_D/m_{V_D} \sim 0.1)$
- $g_D - m_{V_D}$ correlation can be clearly observed as predicted by analytical calculations
- For $m_{M'} > 1\ \mathrm{TeV}$ it is hard (but possible) to explain Δa_μ because of $1/m_{M'}^2$ suppression

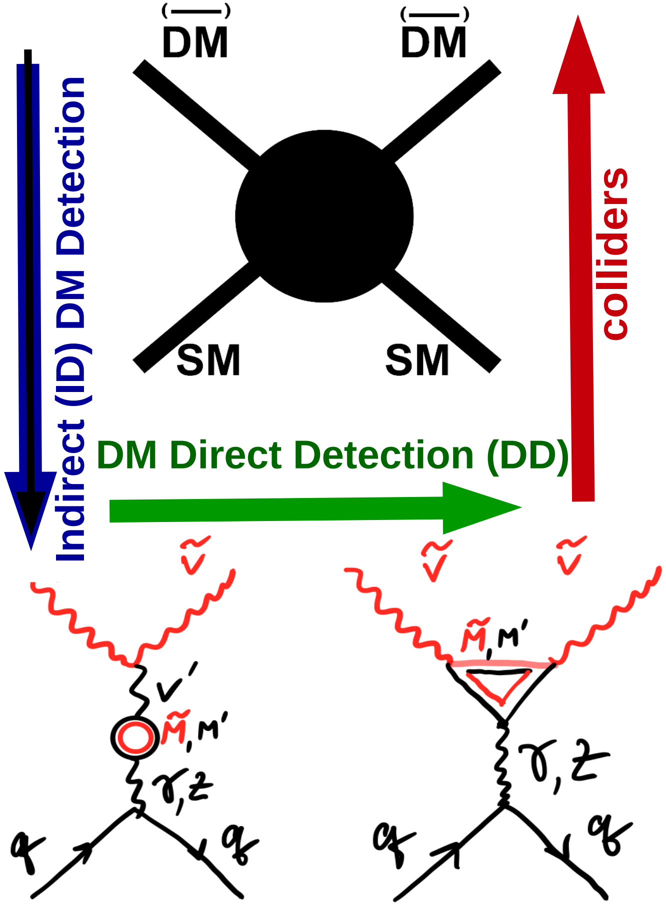
We also aim to explain DM relic density & to be consistent with DM DD and ID as well as with collider searches



$$P_{\rm ann} < 3.2 \times 10^{-28}\ \frac{\rm cm^3}{\rm s\, GeV}$$

$$P_{\rm ann} = \sum_j \frac{f_j^{\rm eff}\langle\sigma v\rangle_j}{M_{\rm DM}}\left(\frac{\Omega_{\rm DM}}{\Omega_{\rm DM}^{\rm Planck}}\right)^2$$

DM annihilation can affect CMB



$\overset{(-)}{\rm DM}$ $\overset{(-)}{\rm DM}$

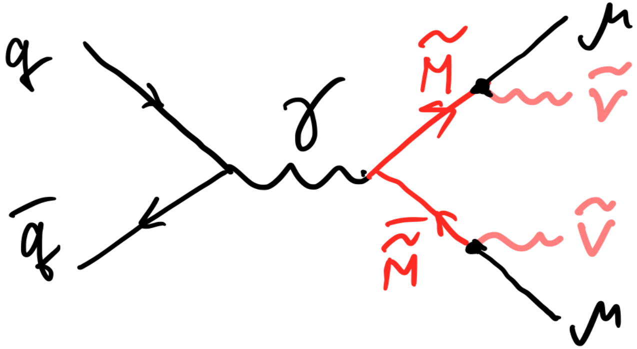
SM SM

Indirect (ID) DM Detection

DM Direct Detection (DD)

colliders

$$\Omega_{\rm DM}^{\rm Planck} h^2 = 0.12 \pm 0.0012$$



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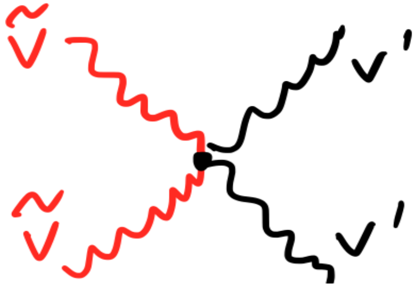

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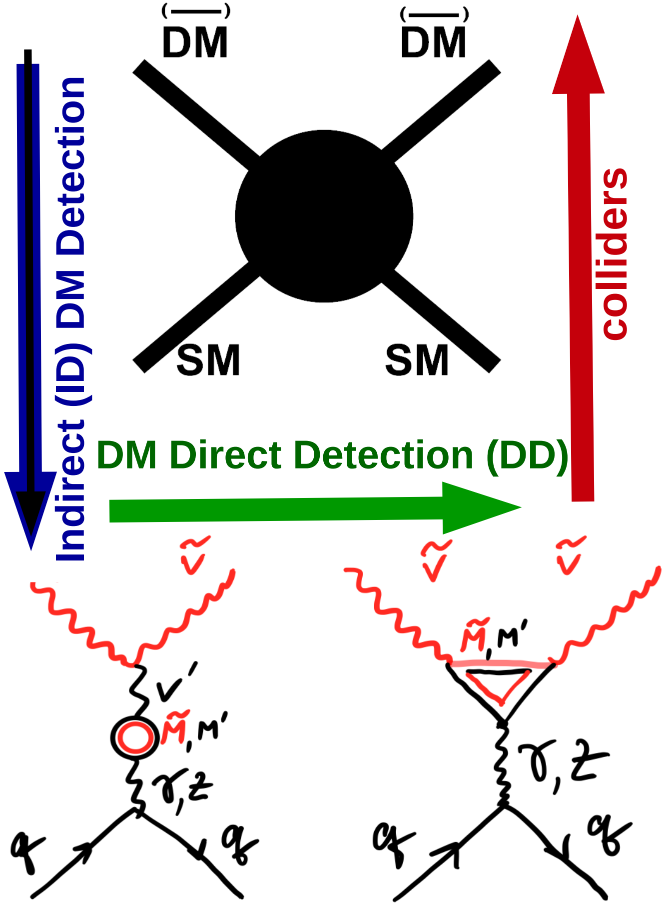
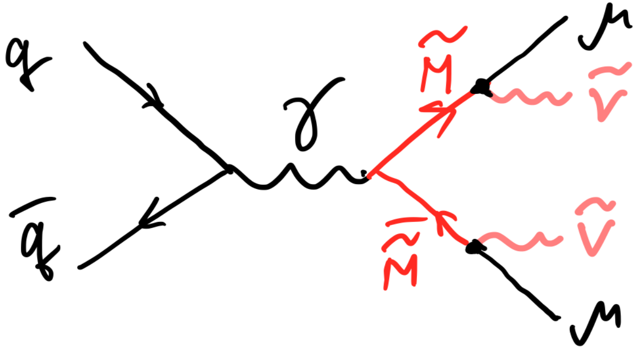


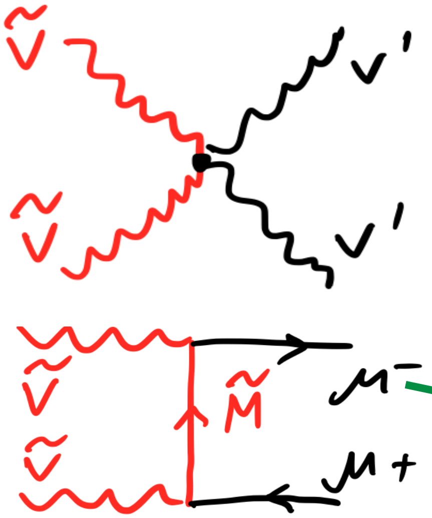
$$\Omega_{\rm DM}^{\rm Planck} h^2 = 0.12 \pm 0.0012$$



Tools used

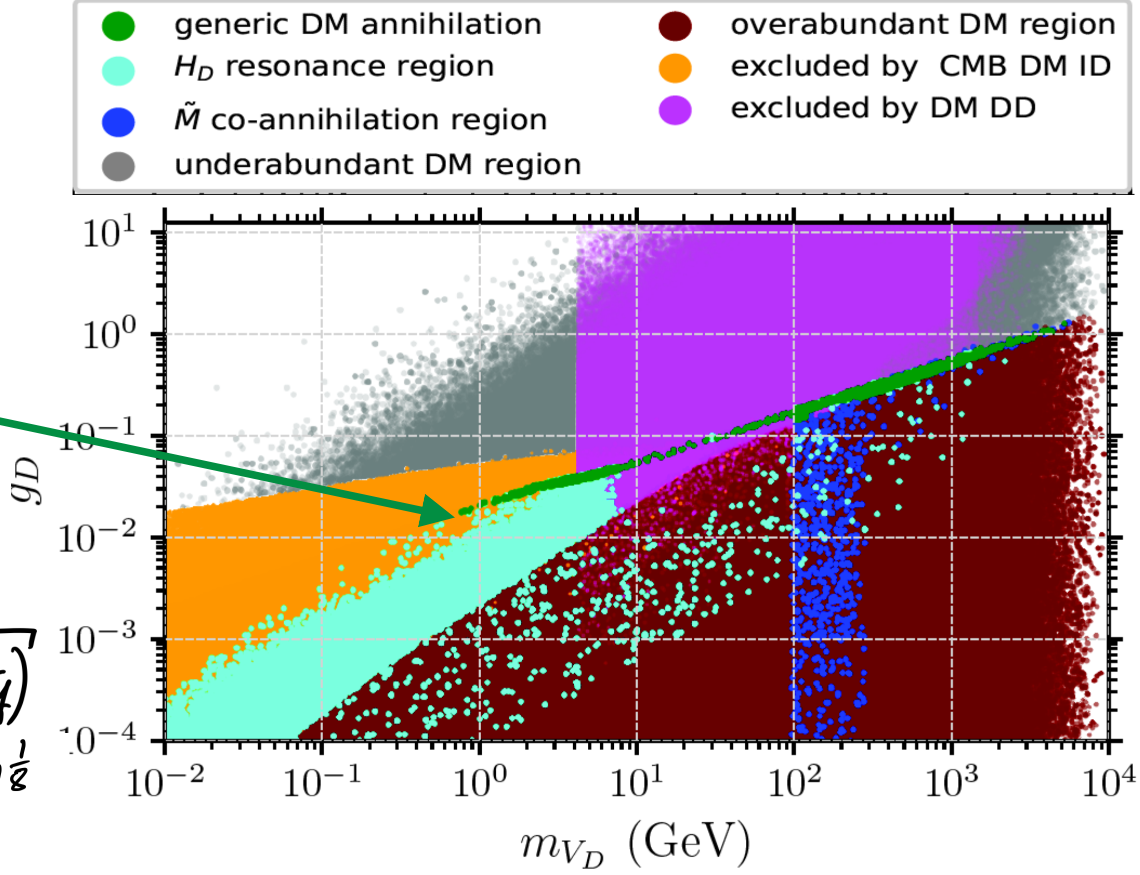
- **DM DD, ID, Relic density**
  LanHEP,CalcHEP, micrOMEGAs
- **Collider searches**
  CalcHEP, MC@NLO, PYTHIA, DELPHES, MadAnalysis, CHECKMATE

Cosmological constraints on μPVDM parameter space

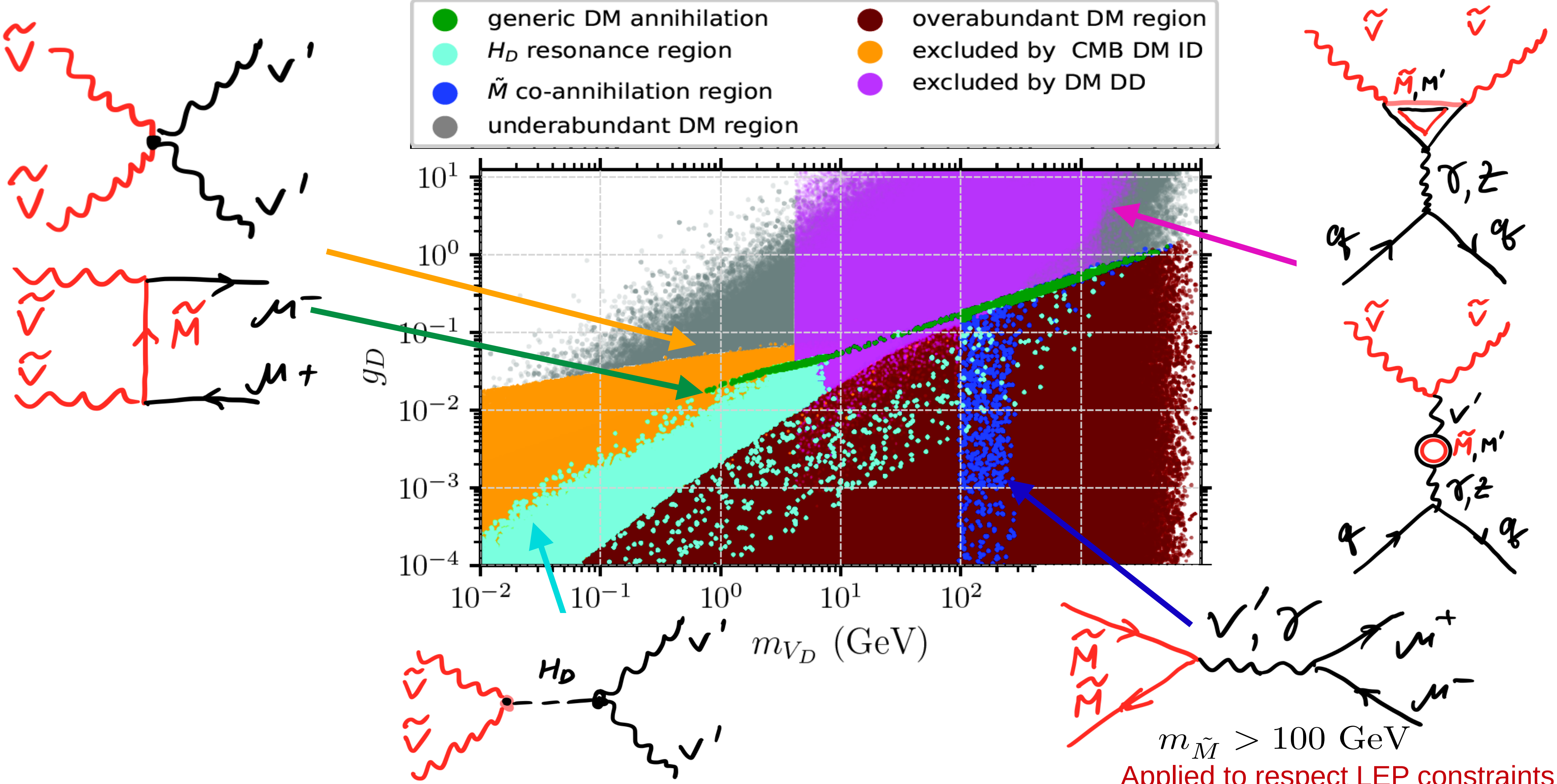


$$\Omega h^2 \propto \frac{M_{V_D}^2}{g_D^4}\frac{1}{\sqrt{g_{eff}(T_f)}}$$

$$g_D \sim \sqrt{M_{V_D}}\,/[g_{eff}(T_f)]^{\frac{1}{8}}$$



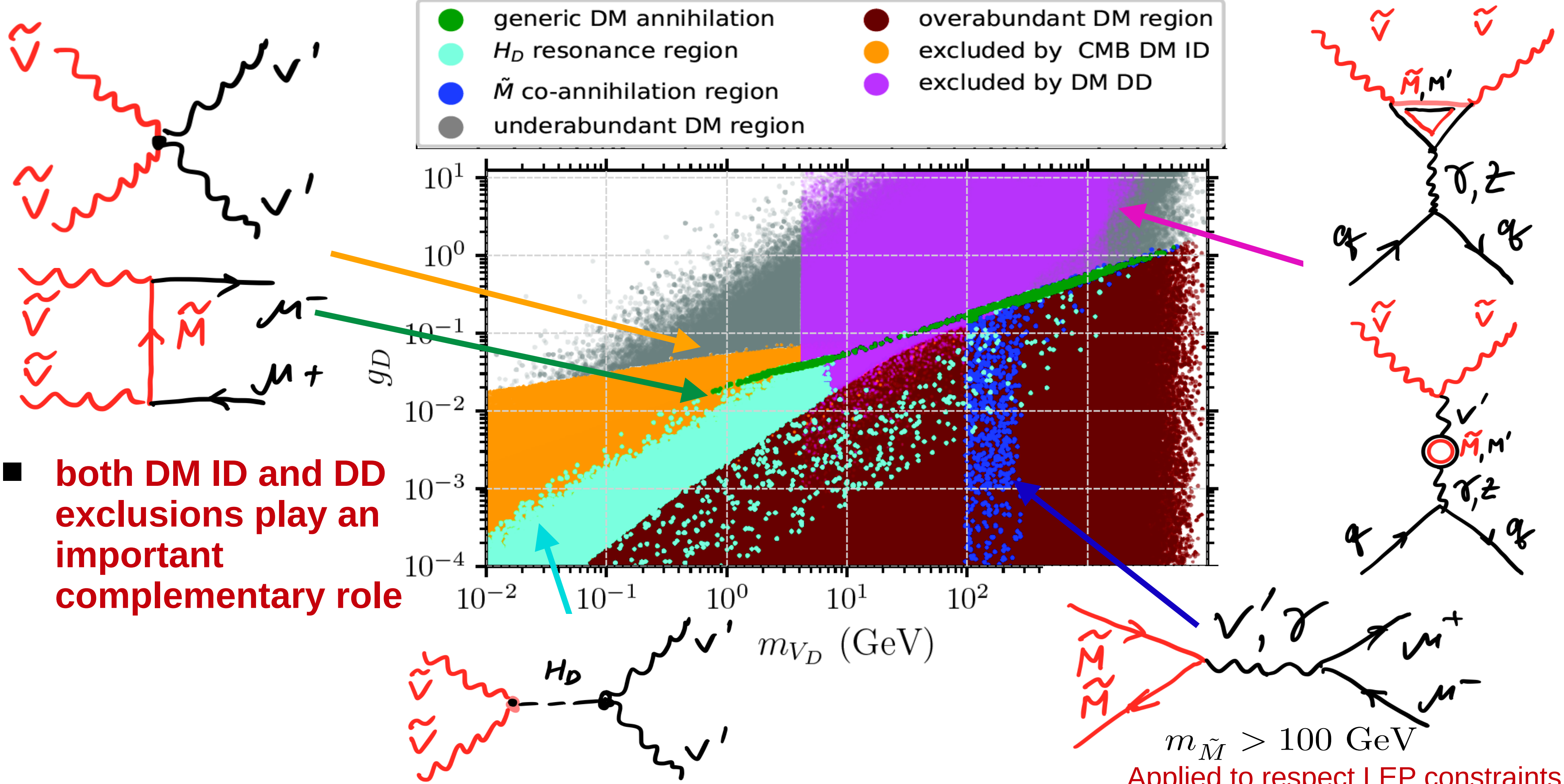
Cosmological constraints on μPVDM parameter space



$m_{\tilde{M}} > 100$ GeV

Applied to respect LEP constraints

Cosmological constraints on μPVDM parameter space

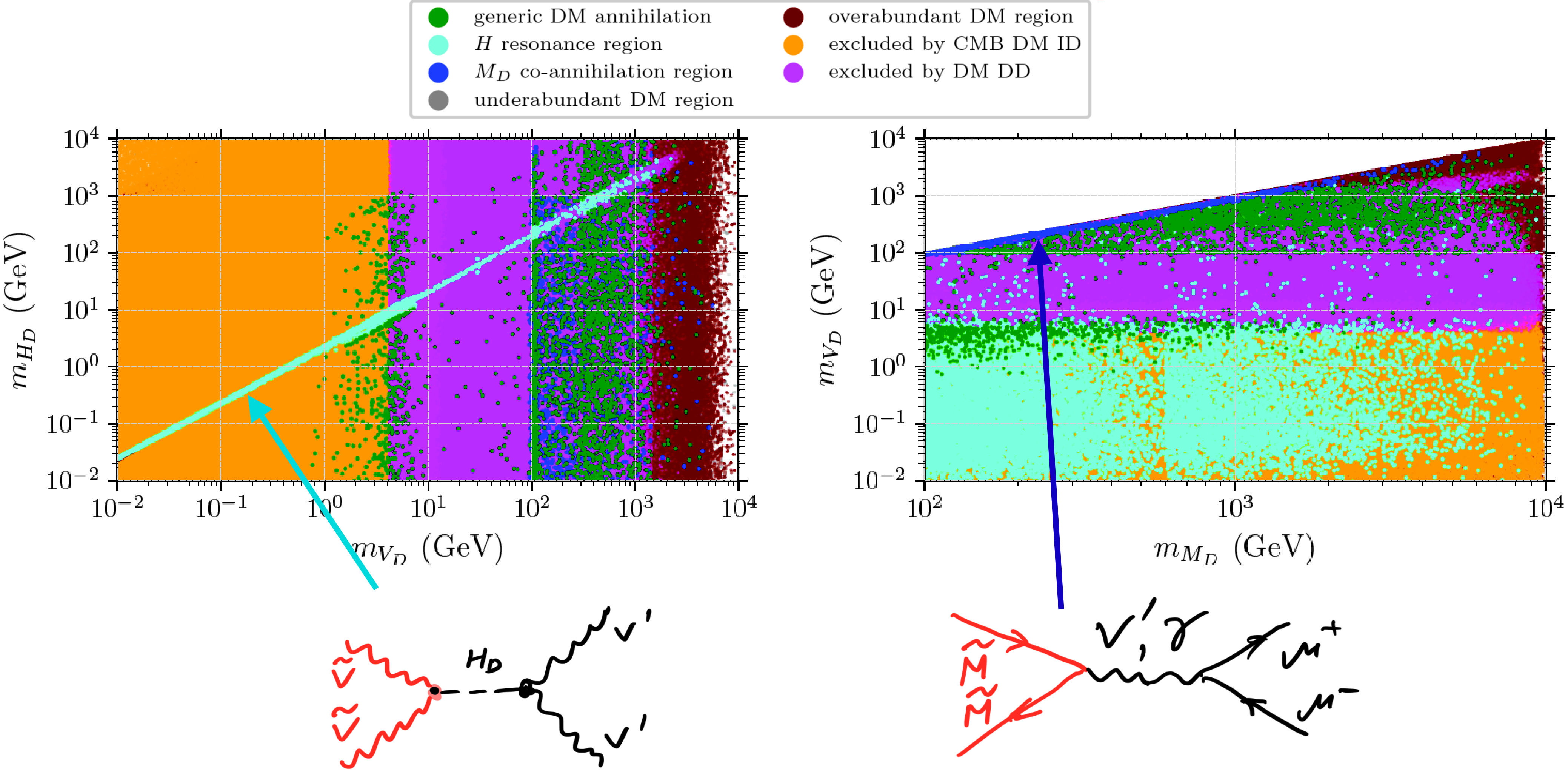


- **both DM ID and DD exclusions play an important complementary role**

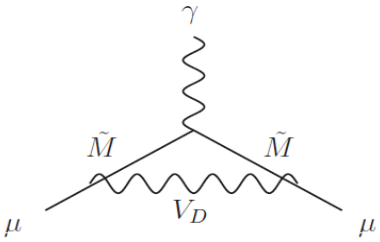
$m_{\tilde{M}} > 100$ GeV

Applied to respect LEP constraints

m_{HD} vs m_{VD} and m_{VD} vs m_M planes

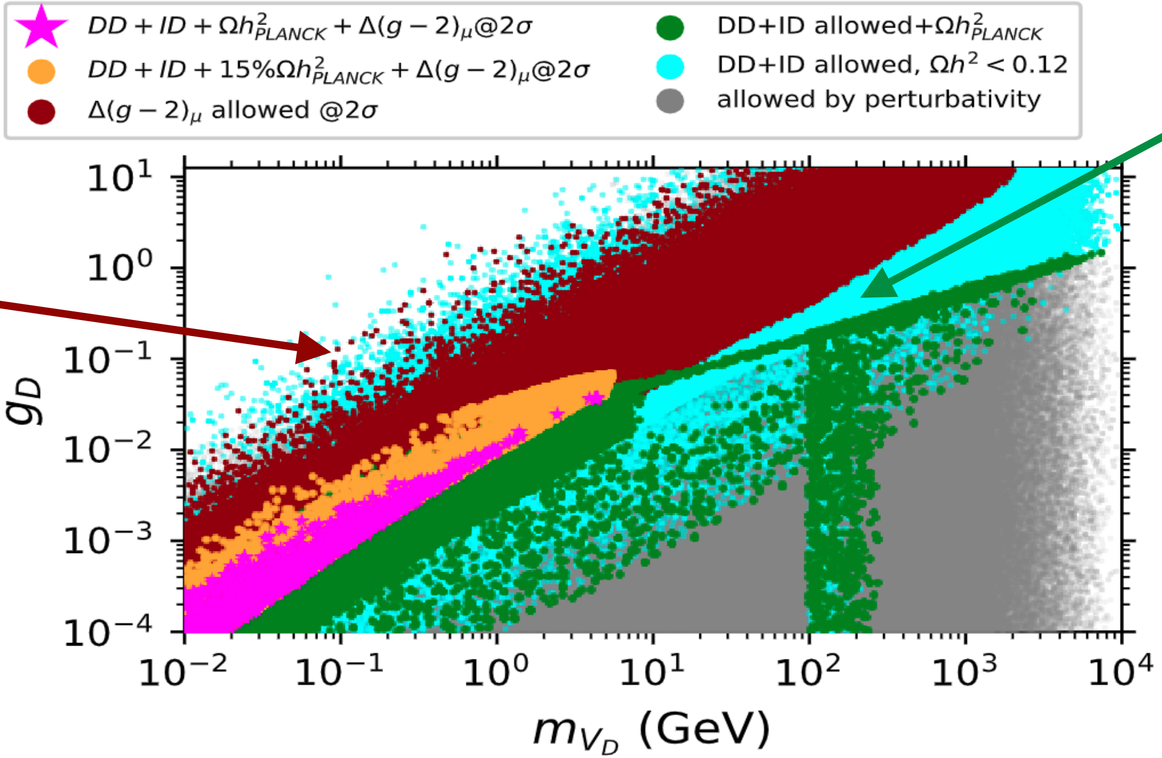


Combining $(g\text{-}2)_\mu$ and DM constraints



$g_D \sim m_{V_D}$

“trajectory” to explain Δaμ

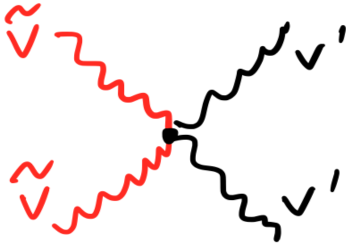


$$\Omega h^2 \propto \frac{M_{V_D}^2}{g_D^4} \frac{1}{\sqrt{g_{eff}(T_f)}}$$

$$g_D \sim \sqrt{M_{V_D}} \Big/ [g_{eff}(T_f)]^{\frac{1}{8}}$$

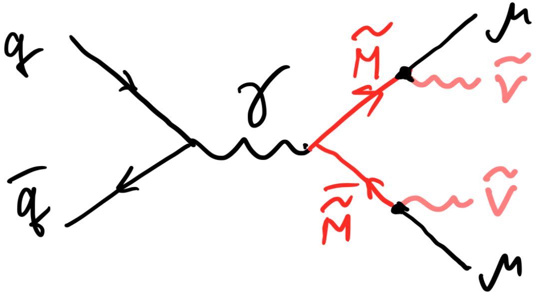
Ωh^2_{PLANCK}

“trajectory” to explain DM relic density



- (g-2) and DM relic density allowed bands have different slopes crossing at **0.1 – 1 GeV**
  - “dark photon”(V’) kind of region
  - New collider signatures (see below)
  - very intriguing to explore further for GW effects and explaining NANOGrav results

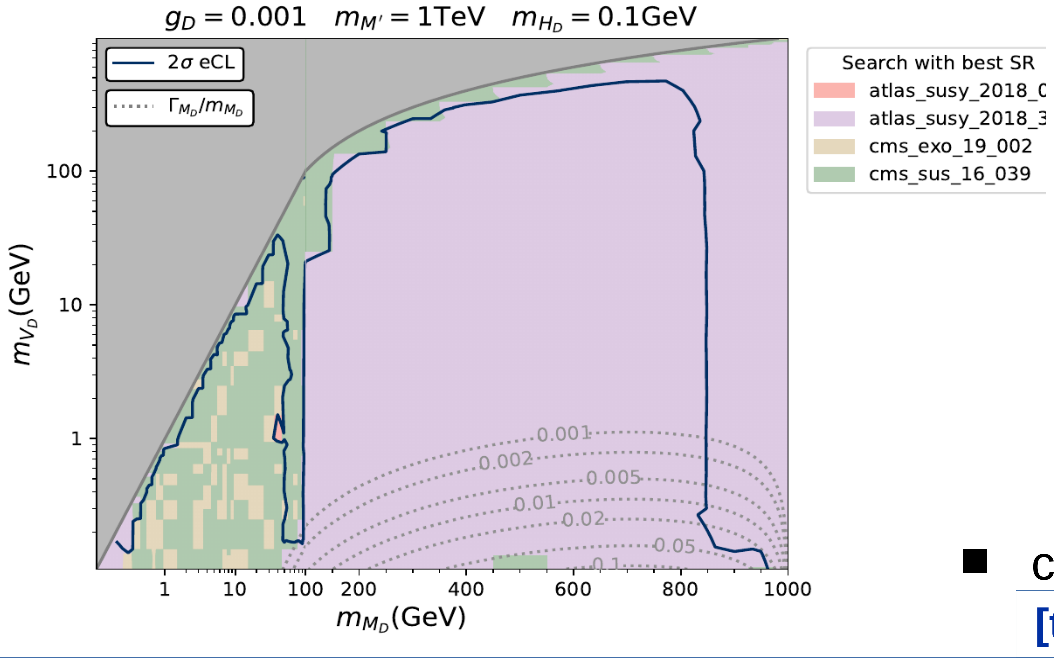
Final set of very important constraints: colliders

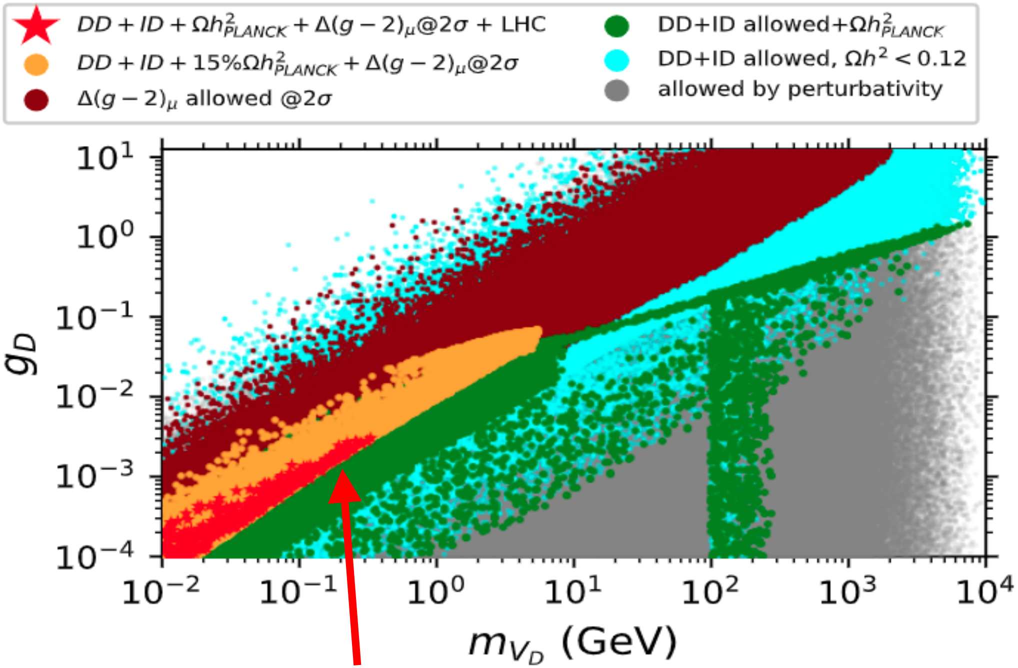


$$pp \to \tilde{M}^-\tilde{M}^+ \to \tilde{V}_D\tilde{V}_D\mu^+\mu^-$$

- Madgraph + PTHIA+Delphes + Madanalysis
- $\tilde{M} > 600$ GeV comes from the main $\mu^+\mu^- + MET$

atlas-susy-2018-32, cms-sus-16-039, cms-exo-19-010

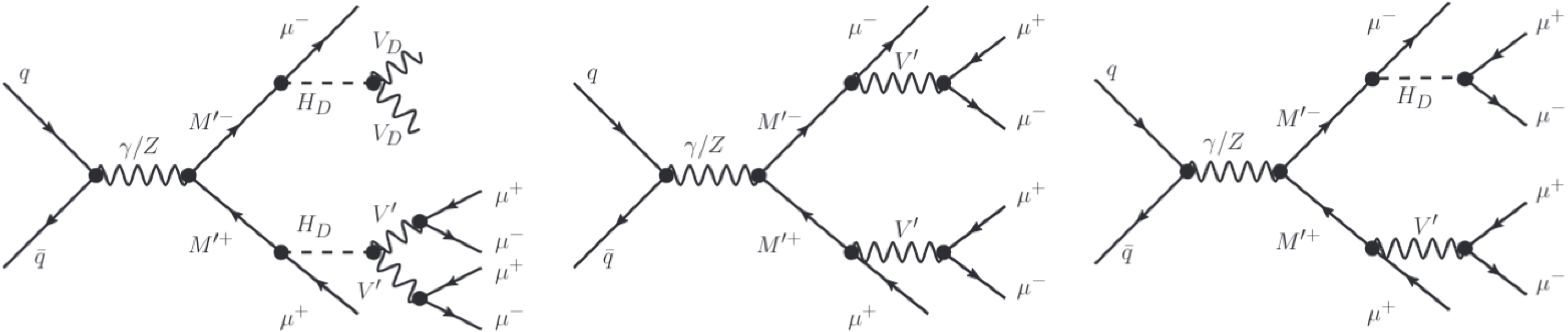




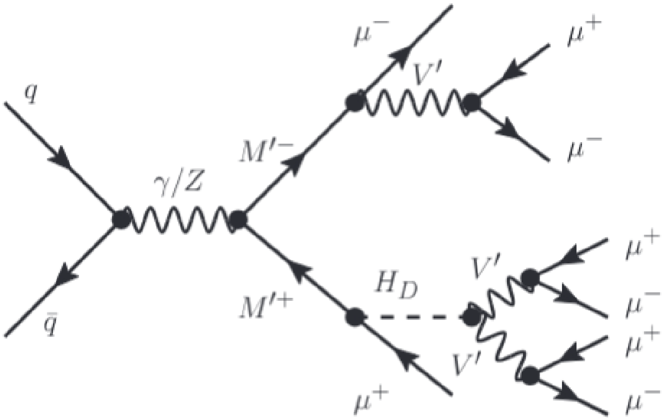
- combinedconstraints require M_{DM} below 1 GeV

[to appear] Panizzi, Thongyoi,AB

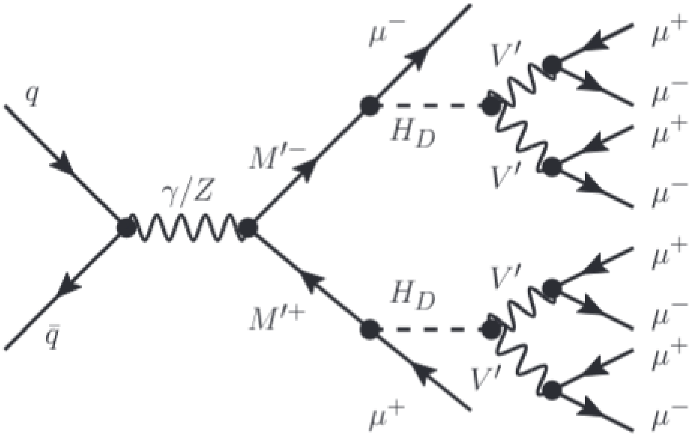
Novel multilepton (multi-fermion) signatures



6μ(+MET): hi-PT two boosted pairs of muons (from V’ decay) + two single high-pT muons



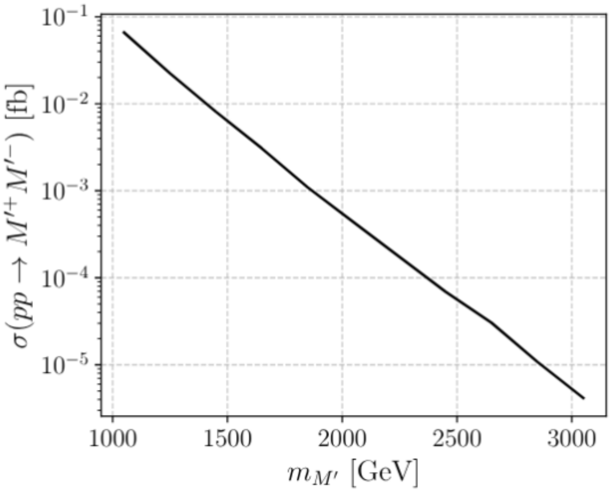
Note:
depending on the portal, there will be analogous multi-fermion signatures, e.g.
muti-tops, multi-bquarks etc.

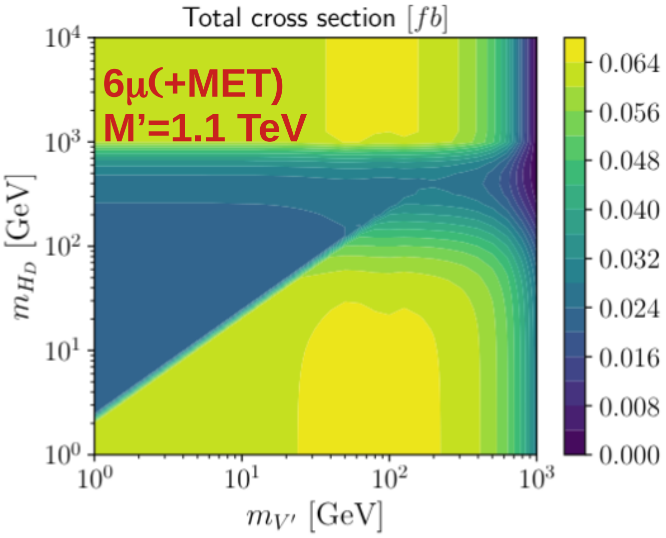


8μ: hi-PT three boosted pairs of **μ’s** + 2 isolated **μ’s**

10μ: hi-PT four boosted pairs of **μ’s** + 2 isolated **μ’s**

The rates for multi-lepton signatures





6μ(+MET)
M'=1.1 TeV

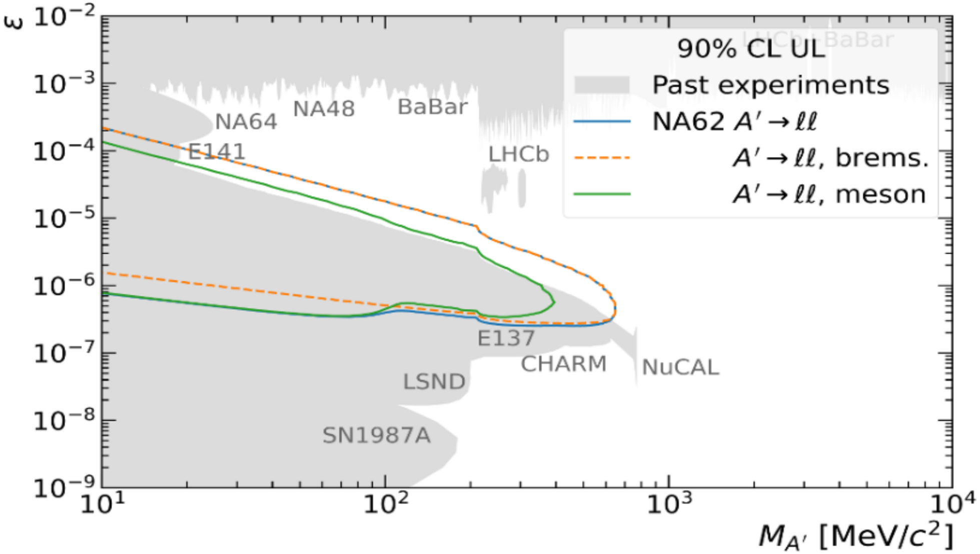
Inputs/Observables	BP1	BP2
g_D	0.003	0.003
m_{V_D} [GeV]	0.28	0.28
m_{μ_D} [GeV]	800	900
$m_{\mu'}$ [GeV]	1000	1200
m_{H_D} [GeV]	0.677	0.677
$m_{V'}$ [GeV]	0.2756	0.2706
$Br(\mu' \to V'\mu)$	0.383	0.342
$Br(\mu' \to H_D\mu)$	0.371	0.319
$Br(\mu' \to V_D\mu_D)$	0.246	0.339
$Br(H_D \to V_D V_D^*)$	0.639	0.612
$Br(H_D \to V'V')$	0.352	0.375
$Br(H_D \to \mu^+\mu^-)$	9.24×10^{-3}	1.31×10^{-2}
$Br(V' \to \mu^+\mu^-)$	$\sim$1	$\sim$1
$Br(\mu' \to V'\mu \to 3\mu)$	0.383	0.342
$Br(\mu' \to H_D\mu \to 5\mu)$	0.131	0.12
$\sigma_{\rm tot}(pp \to \mu'\mu')$ [fb]	6.499×10^{-2}	1.867×10^{-2}
$N_{\rm event}(pp \to 6\mu)$	2.86	0.655
$N_{\rm event}(pp \to 8\mu)$	0.978	0.23
$N_{\rm event}(pp \to 10\mu)$	0.335	0.08

# of events for 300 fb^{-1} integrated luminosity

Yao, Chakraborti, AB [work in progress]

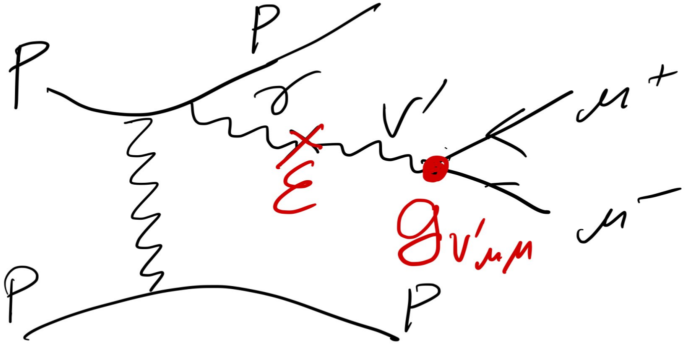
The model predicts sub-GeV V′ bosons which look like dark-photons, but not quite...

- V′ bosons **have kinetic mixing** with photons and Z-bosons similarly to dark-photons
- At the same time V′ bosons have **significant coupling to SM fermion** which is the partner of VL dark fermion
- As a result, V′ bosons will can promptly decay (if kinematically allowed) to SM fermions **leading to a relaxed/different bounds on dark-photons: requires dedicated analysis**



JHEP 09 (2023) 035, 2303.08666 [hep-ex]

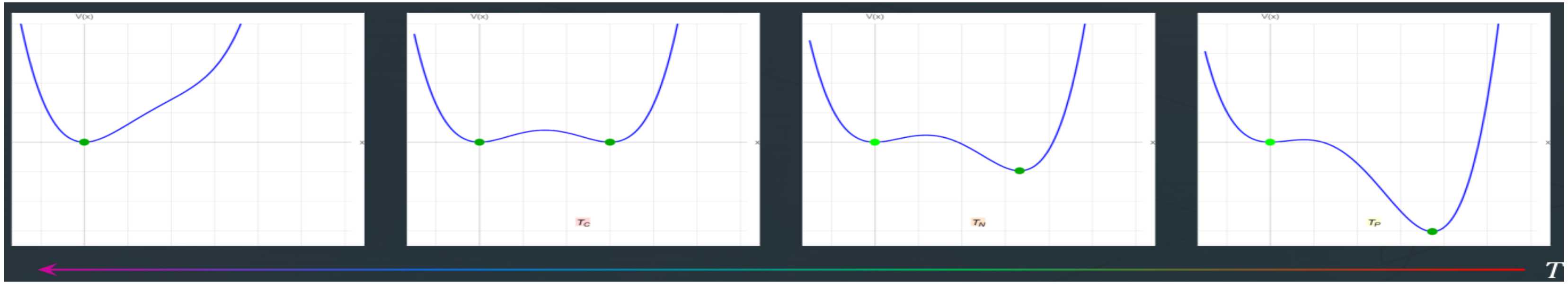
Inputs/Observables	BP1	BP2
$\tau_{V'}$ [ns]	1.10×10^{-6}	7.85×10^{-7}
$\ell_{V'}$ [μm]	0.33γ	0.24γ
$\epsilon_{AV'}$	1.13×10^{-5}	1.39×10^{-5}



Gravitational Waves from Dark sector

[to appear] Bertenstam, Gonçalves, Morais, Pasechnik, Thongyoi, AB

- **$SU_D(2)$ symmetry breaking can induce Strong First Order Phase Transition (SFOPT)**

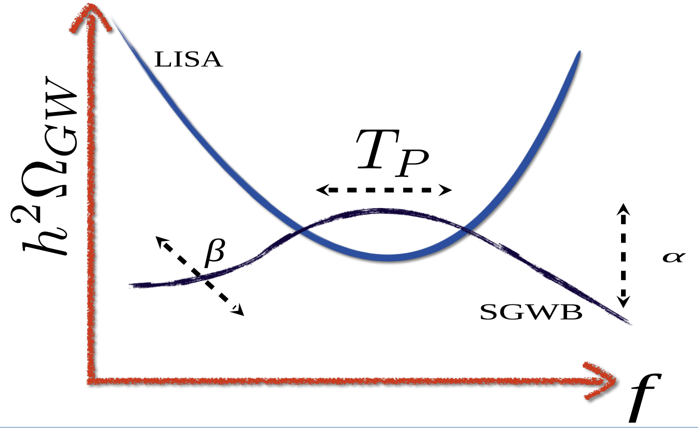


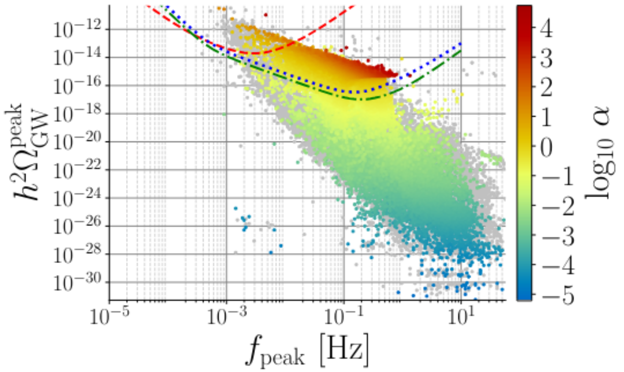
Strength: α

Inverse Duration β/H

Percolation temperature T_P

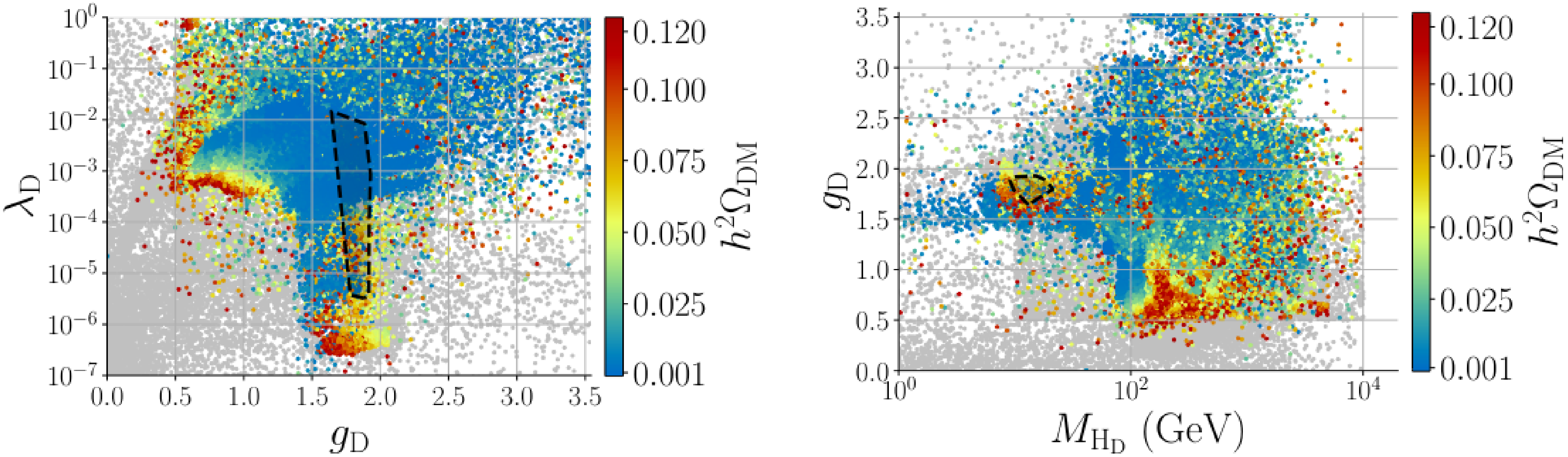
- **Tools: DRalgo+CosmoTransitions, “Dralgo to python interfacer”**
  - **correct implementation of dimensionally reduced effective potentials from DRAlgo**
  - **the scale dependence of the numerical solution is greatly reduced**





Gravitational Waves from Dark sector

specific parameter space can be tested by LISA and/or future facilities



- **Typical mass of DM is few TeV since the g_D value required by SFOPT is of the order of one**
- **DM can be tested by DD experiments or from coloured fermions production at hadron colliders**
- **Dark Higgs production at colliders**
- **hhh coupling can be potentially probed at FCC's**

Conclusions and Outlook

- **To decode the nature of DM** we need a signal first! But at the moment we should **systematically explore theory/parameter space and prepare ourselves for DM decoding**

- **Systematic classification** is important – one should cover consistently the theory space

- **Probing DM space**
  - non-singlets can be probed via DT searches or multi-lepton signatures at colliders
  - DM DD is sensitive to the loop-induced diagrams but does not exclude all models
  - rich phenomenology, complementarity of DM DD, collider signals and relic density

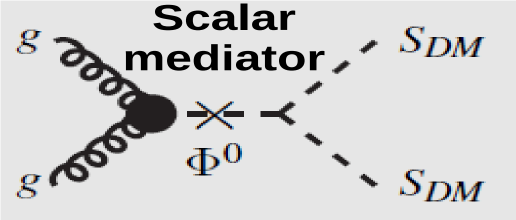
- **FPVDM** (available at HEPMDB) – new class of models beyond weak group: an elegant solution of DM, $(g-2)_\mu$ and flavour problems via VL fermion portal, new multi-fermion signatures and promising projects

- **Decoding the underlying theory**: requires joint effort of theorists and experimentalists as well as ML approach, to find the **link between signatures and underlying theory**

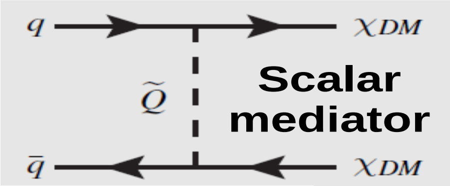
Backup slides

Mapping EFT operators to simplified models

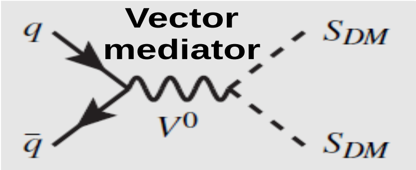
C5,C5A $\frac{1}{\Lambda^2}\phi^*\phi G^{\mu\nu}G^{\mu\nu}$, $\frac{1}{\Lambda^2}\phi^*\phi\tilde{G}^{\mu\nu}G^{\mu\nu}$ →



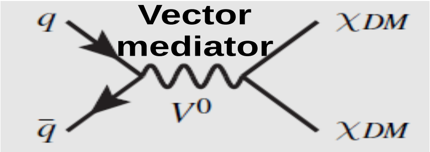
D1T-D4T $\frac{1}{\Lambda^2}\bar{\chi}q\bar{q}\chi$ →

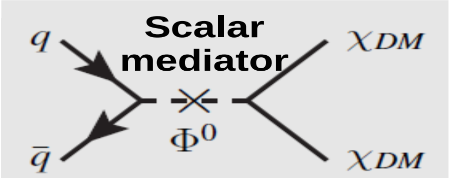


C3 $\frac{i}{\Lambda^2}[\phi^*(\partial_\mu\phi - (\partial_\mu\phi^*)\phi]\bar{q}\gamma^\mu q$ →

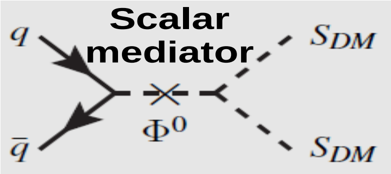


D1-D4, D5-D8 $\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$ $\frac{1}{\Lambda^2}\bar{\chi}\chi\bar{q}q$ →





C1 $\frac{1}{\Lambda^2}\phi^*\phi\bar{q}q\Phi \Longrightarrow \frac{v}{\Lambda^2}\phi^*\phi\bar{q}q$ →



D9,D10 $\frac{1}{\Lambda^2}\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$ → $\frac{8}{\Lambda^2}\Big[\bar{\chi}q\bar{q}\chi - \frac{1}{4}\big(\bar{\chi}\chi\bar{q}q + \bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q + \bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q - \bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q\big)\Big]$

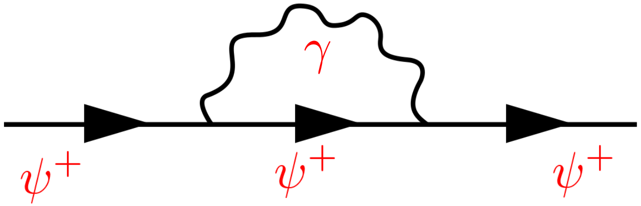
DM multiplet only

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

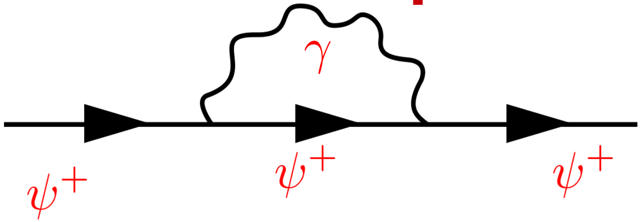
Cirelli,Fornengo,Strumia hep-ph/0512090 (Minimal Dark Matter)

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

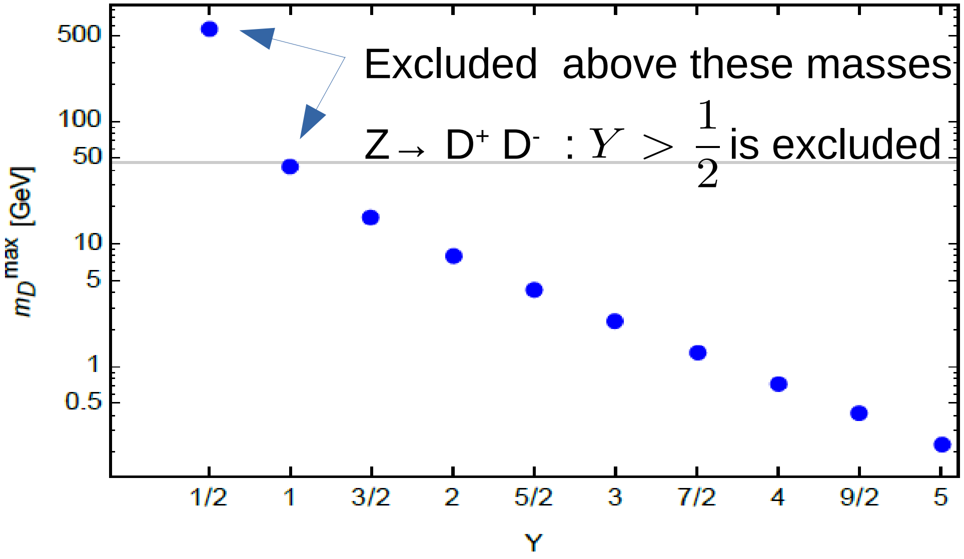
- **{I,Y}={0,0}, {½,½}, {1,0}**
- {0,0} – no gauge-interactions – invisible to direct detection and collider but over(under) abundant if thermal (non-thermal)
- $Y \neq 0$ (Dirac DM) Is excluded by direct detection or requires additional sector – which splits the mass of ψ
- Radiative mass split – very important for the phenomenology



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

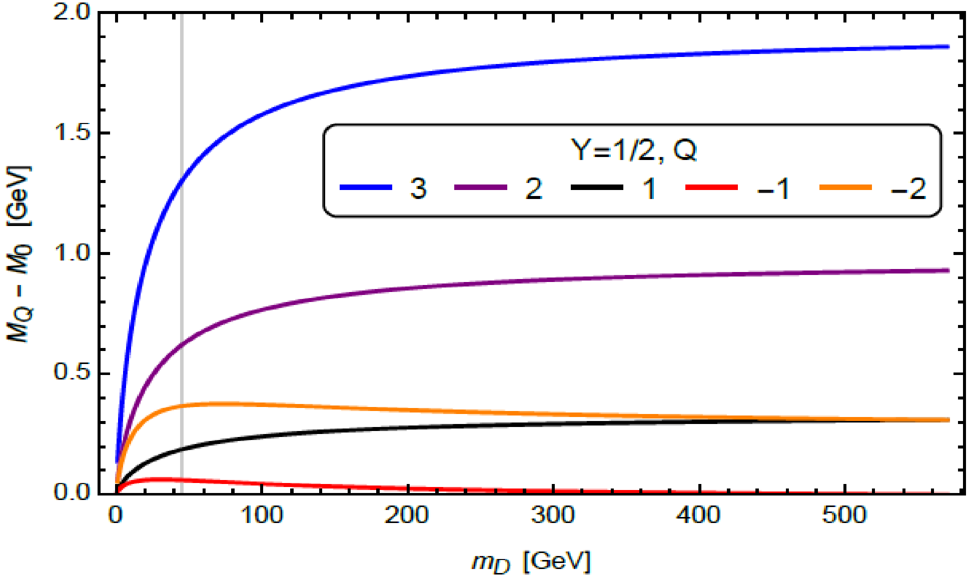


$$M_Q - M_{Q'}\big|_{m_D \gg m_W} \approx \frac{\alpha m_W}{2(1+c_W)}\left[(Q^2 - Q'^2) + \frac{2Y(Q-Q')}{c_W}\right]$$



Excluded above these masses

Z→ D⁺ D⁻ : $Y > \frac{1}{2}$ is excluded



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

Sommerfeld effect

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

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

  - long range force

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