VILA DO CONDE, PORTUGAL
12TH - 16TH JULY 2024

The Physics of Fermionic Portal to Vector Dark Matter

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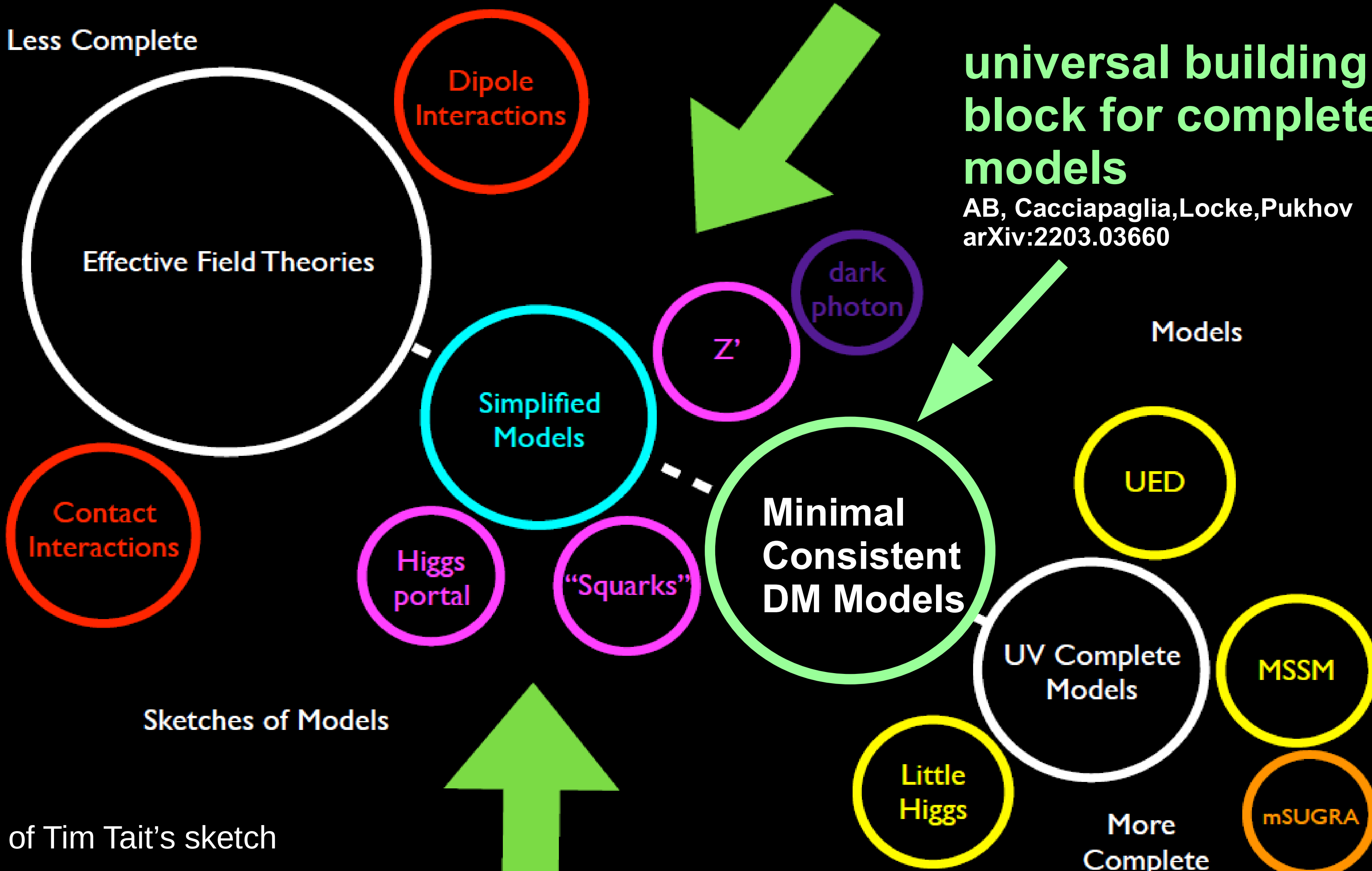
BSM 2nd Edition

BEYOND THE STANDARD MODEL BRAINSTORMING MEETING: PARTICLE PHYSICS AND COSMOLOGY INTERFACE

Theory Space with Dark Matter



Based of Tim Tait's sketch

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. $Q_D = T^3_D + Y_D$ 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: $y' \bar\Psi_L \Phi_D f_R^{\rm SM} + \cancel{y'' \bar\Psi_L \Phi^c_D f_R^{\rm SM}} + h.c$
  - **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	$-$ $+$
$\Psi = \begin{pmatrix} \Psi_D \\ \Psi \end{pmatrix} = \begin{pmatrix} \tilde F \\ F \end{pmatrix}$	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)

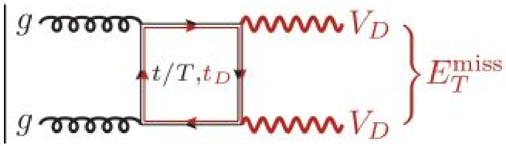
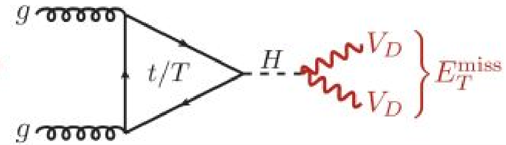
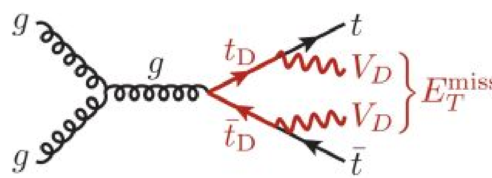
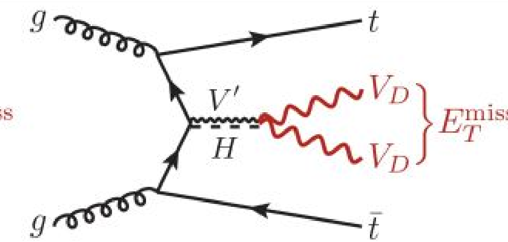
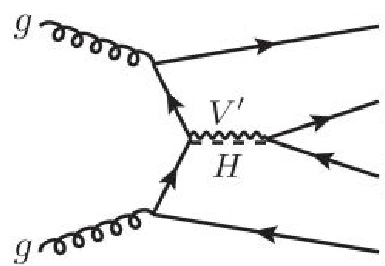
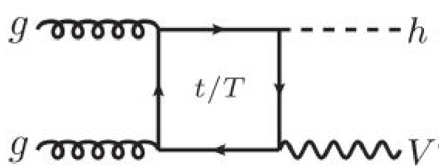
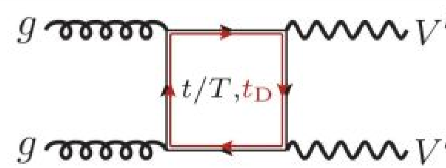
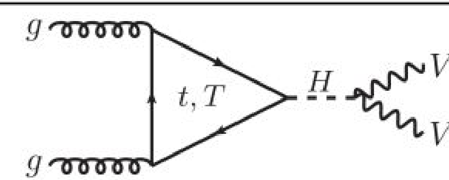
- It is the framework, representing the class of models
  (Deandrea, Moretti, Panizzi, Ross, Thongyoi, AB – arXiv:2204.03510,2203.04681)

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

$$\begin{aligned}
\mathcal{L}_{FPVDM} &= -\frac{1}{4}(V^i_{D\mu\nu})^2 + \bar{\Psi} i \not{D} \Psi + |D_\mu \Phi_D|^2 - V(\Phi_H, \Phi_D) \\
&- \underline{(y'_{\alpha\beta} \bar{\Psi}^{i\alpha}_L \Phi_D f^{\mathrm{SM}\beta}_R} + h.c) - M_\Psi{}^{ij} \bar{\Psi}^i \Psi^j \\
V(\Phi_H, \Phi_D) &= -\mu_H^2 \Phi_H^\dagger \Phi_H - \mu_D^2 \Phi_D^\dagger \Phi_D + \lambda_H (\Phi_H^\dagger \Phi_H)^2 \\
&+ \lambda_D (\Phi_D^\dagger \Phi_D)^2 + \lambda_{HD} (\Phi_H^\dagger \Phi_H)(\Phi_D^\dagger \Phi_D)
\end{aligned}$$

- $y'_{\alpha\beta}$ 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

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

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

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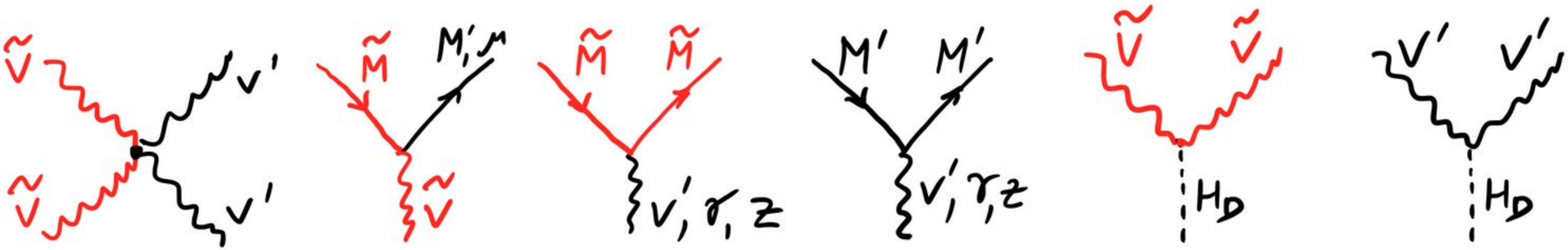
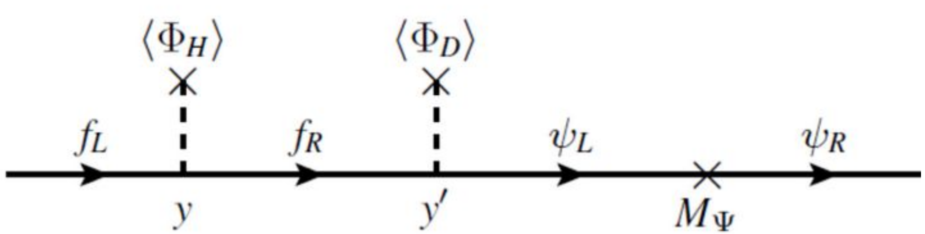
- Parameter space ($\lambda_{HD} = 0$ for simplicity): $\boxed{g_D, m_{V_D}, m_{H_D}, m_{M'}, m_{\tilde{M}}}$
- Interactions+mixing:





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

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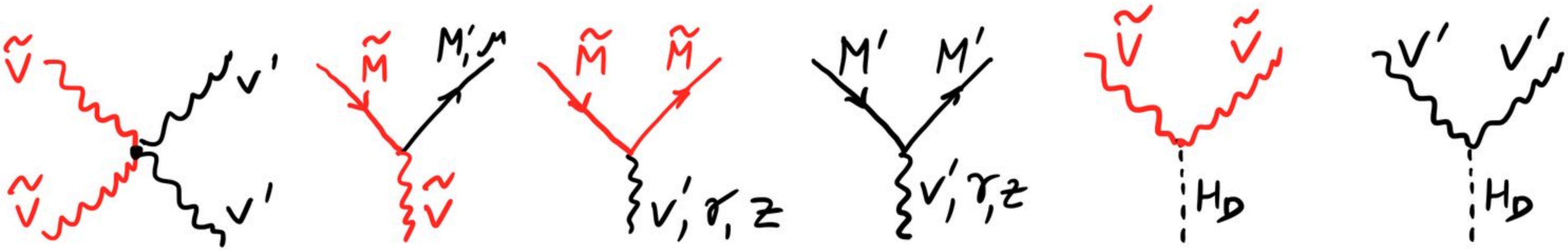
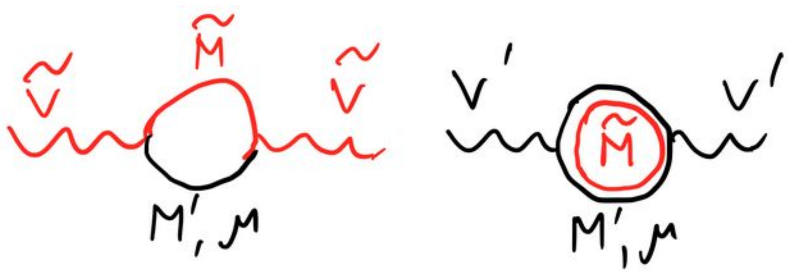
- Interactions+mass corrections:





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

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

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

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

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

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

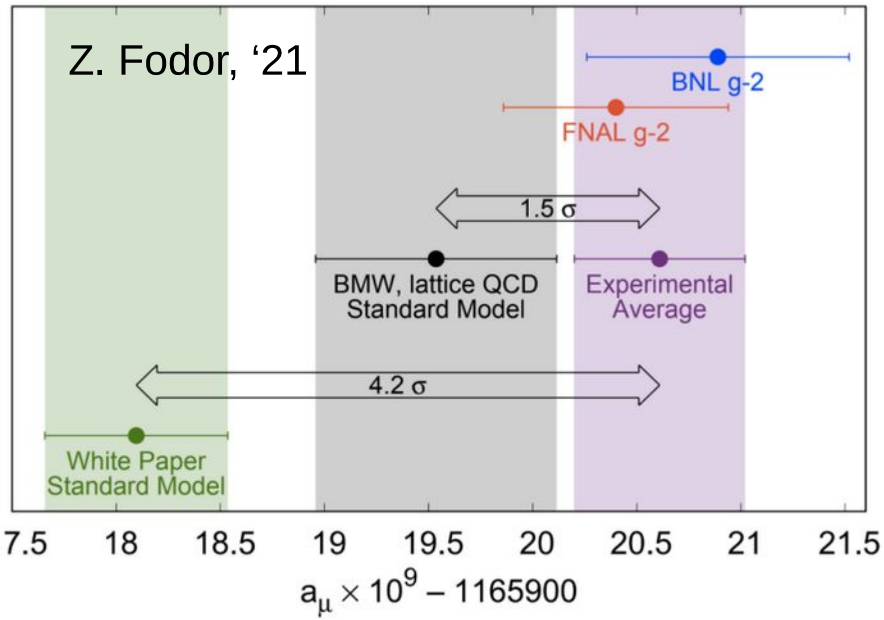
- Combining above numbers, one concludes one finds 5.1σ SM vs EXP discrepancy

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

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

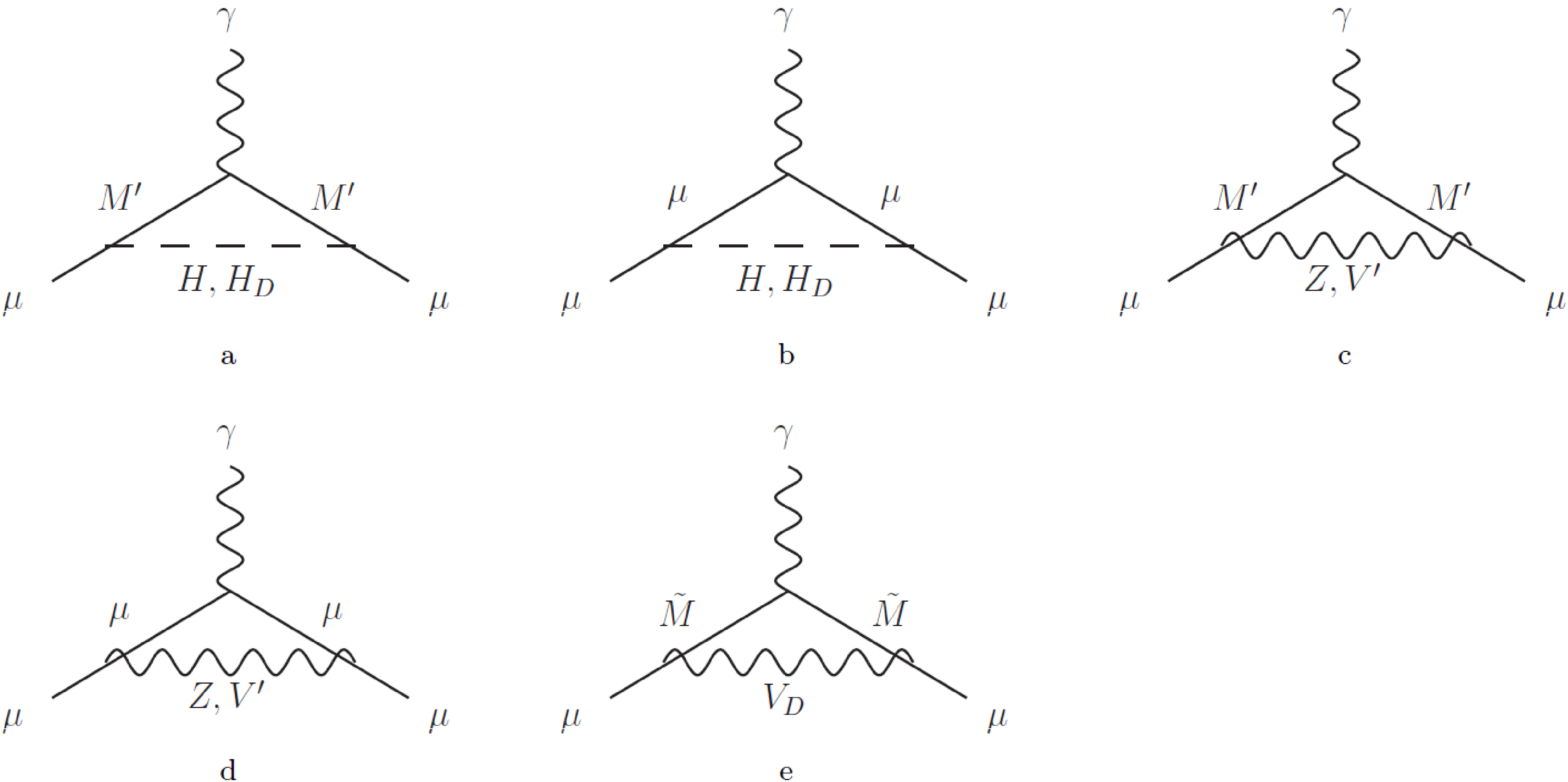
- Recent CMD3 results [arXiv:2302.08834] adds and additional intrigue here

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

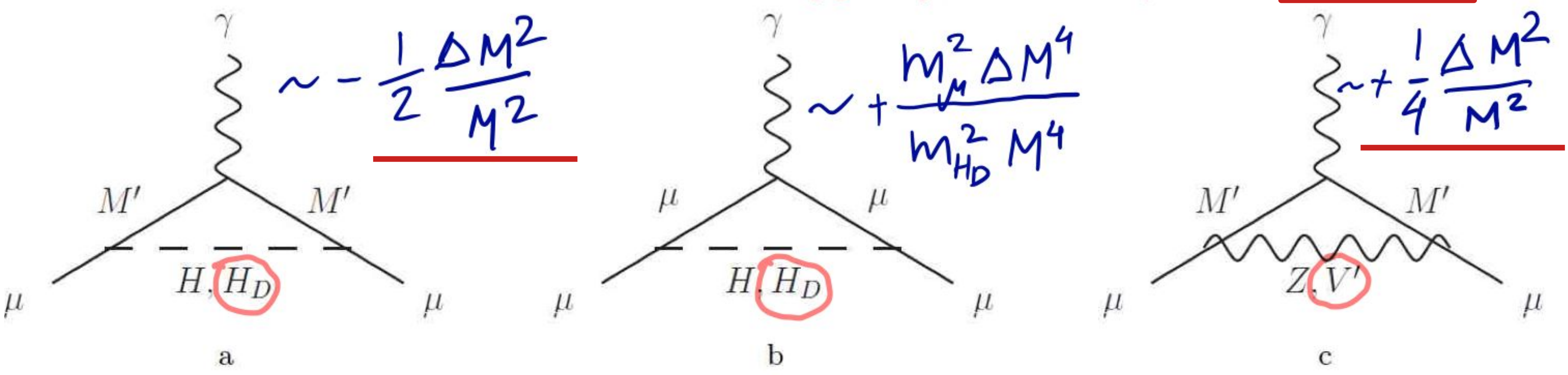


- $(g\text{-}2)\mu$ is an important puzzle to be solved including discrepancy between HVP from e+e- data and Lattice
- In our study we take Δa_μ as a real effect to be explained within our μFPVDM model

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



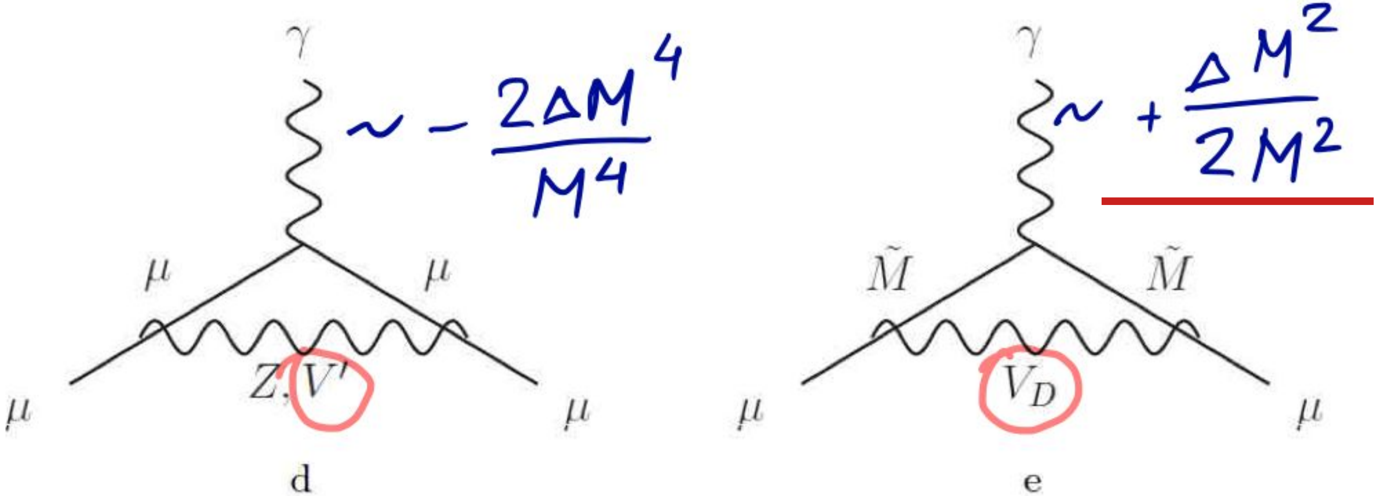
The contribution to (g-2)$_\mu$ from μPVDM x $\boxed{\dfrac{g_D^2}{96\pi^2}\dfrac{m_\mu^2}{m_{V_D}^2}}$



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

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

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



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

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

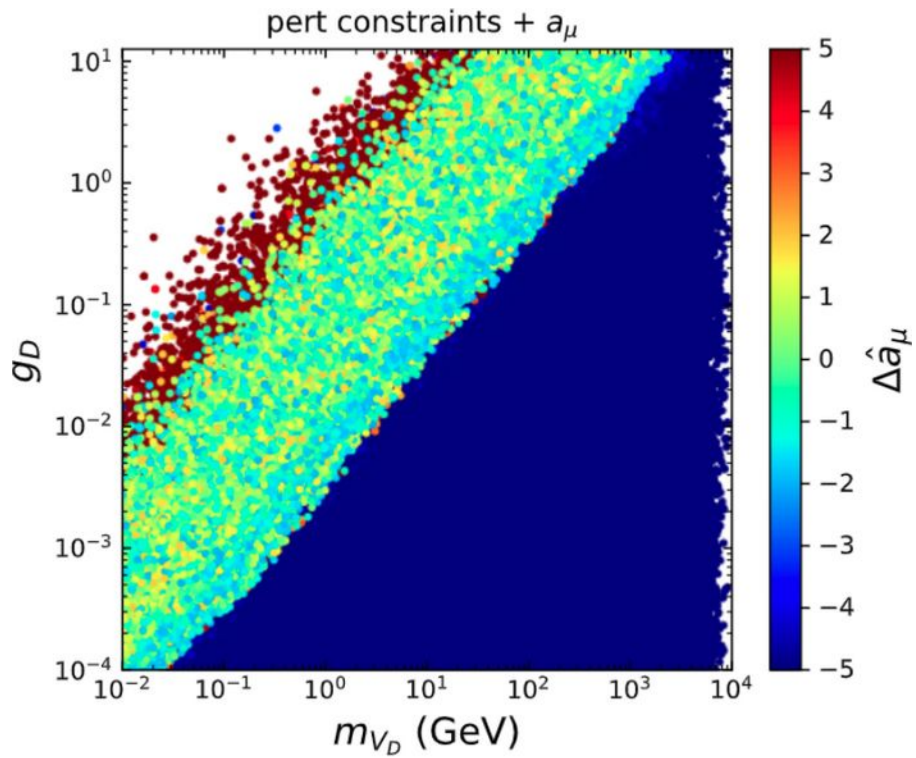
$\Delta M^2 = m_{M'}^2 - m_{\tilde{M}}^2$

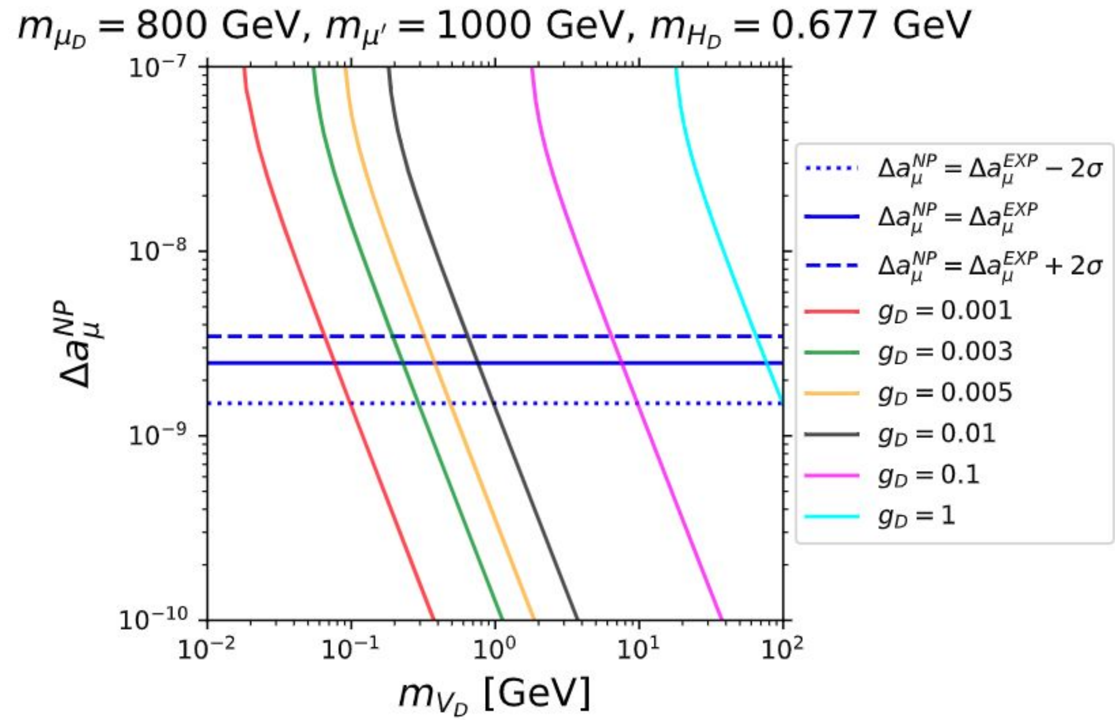
$M = m_{M'}$

$M \gg m_{V_D}$ was used

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

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



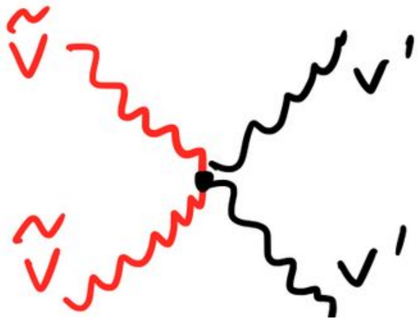


- Δa_μ can be explained within μFPVDM model $(g_D/m_{V_D} \sim 0.1)$
- $g_D - m_{V_D}$ correlation can be clearly observed as predicted by analytical calculations
- For $m_{M'} > 1\ \mathrm{TeV}$ it is hard (but possible) to explain Δa_μ because of $1/m_{M'}^2$ suppression

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

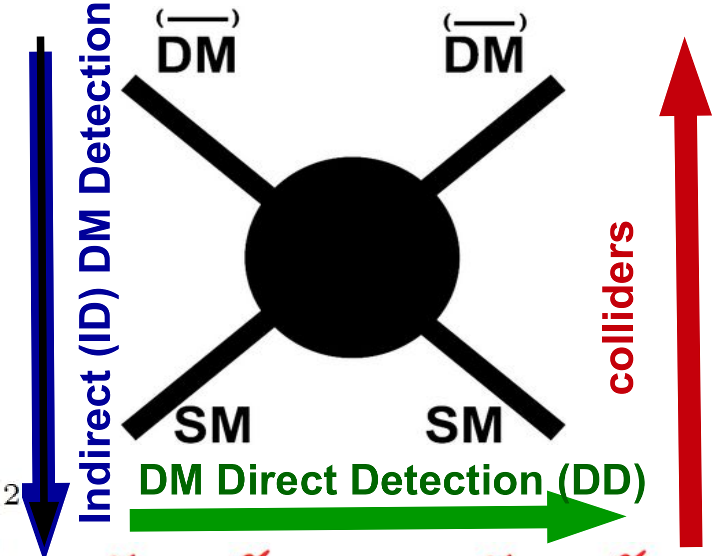
Correct Relic density: efficient (co) annihilation
annihilation to photons can affect CMB

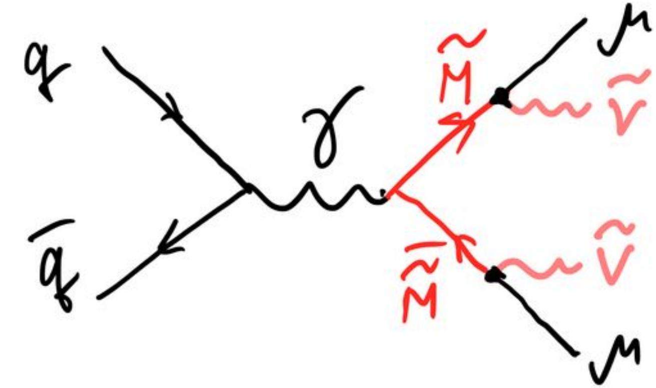
$$\Omega_{\rm DM}^{\rm Planck} h^2 = 0.12 \pm 0.0012$$

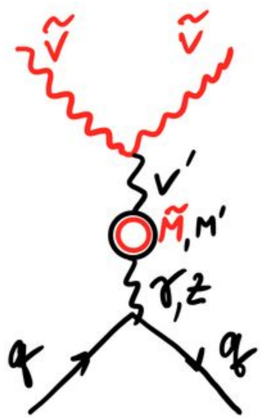


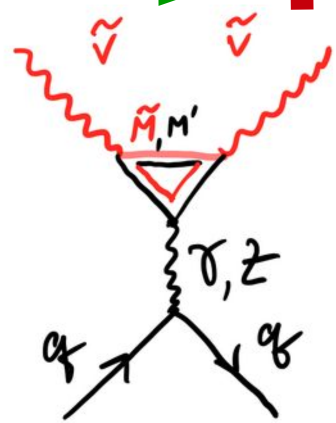
$$P_{\rm ann} < 3.2 \times 10^{-28} \, \frac{\rm cm^3}{\rm s \, GeV}$$

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









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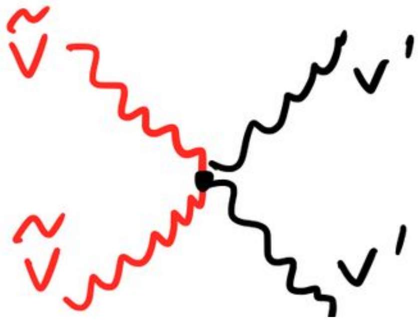

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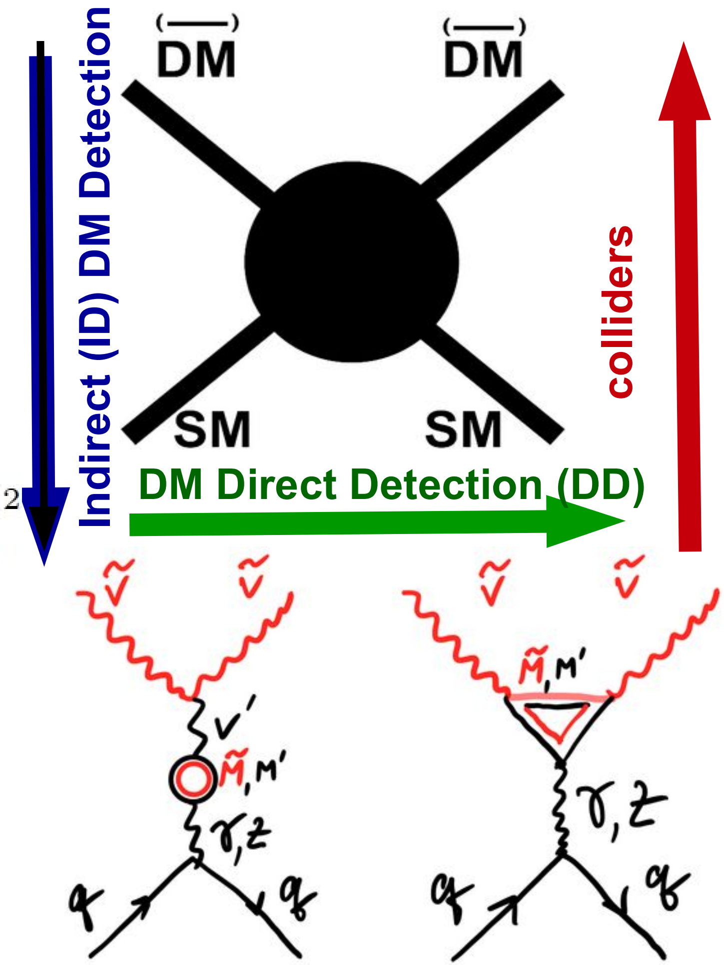
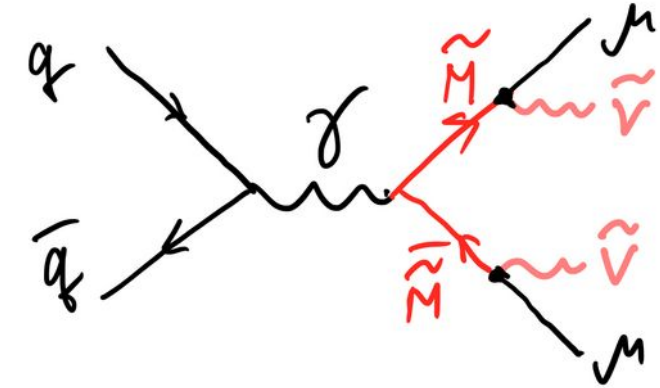
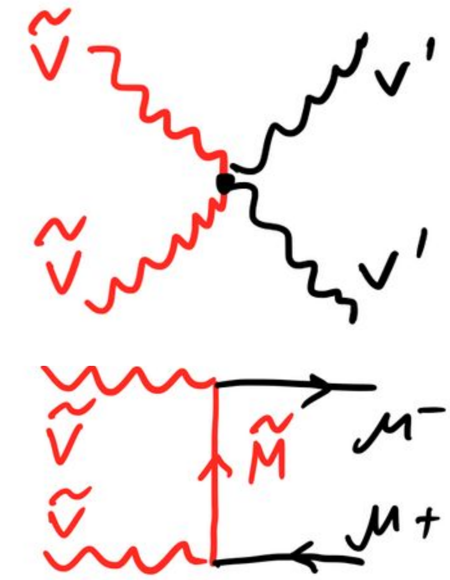




Tools used

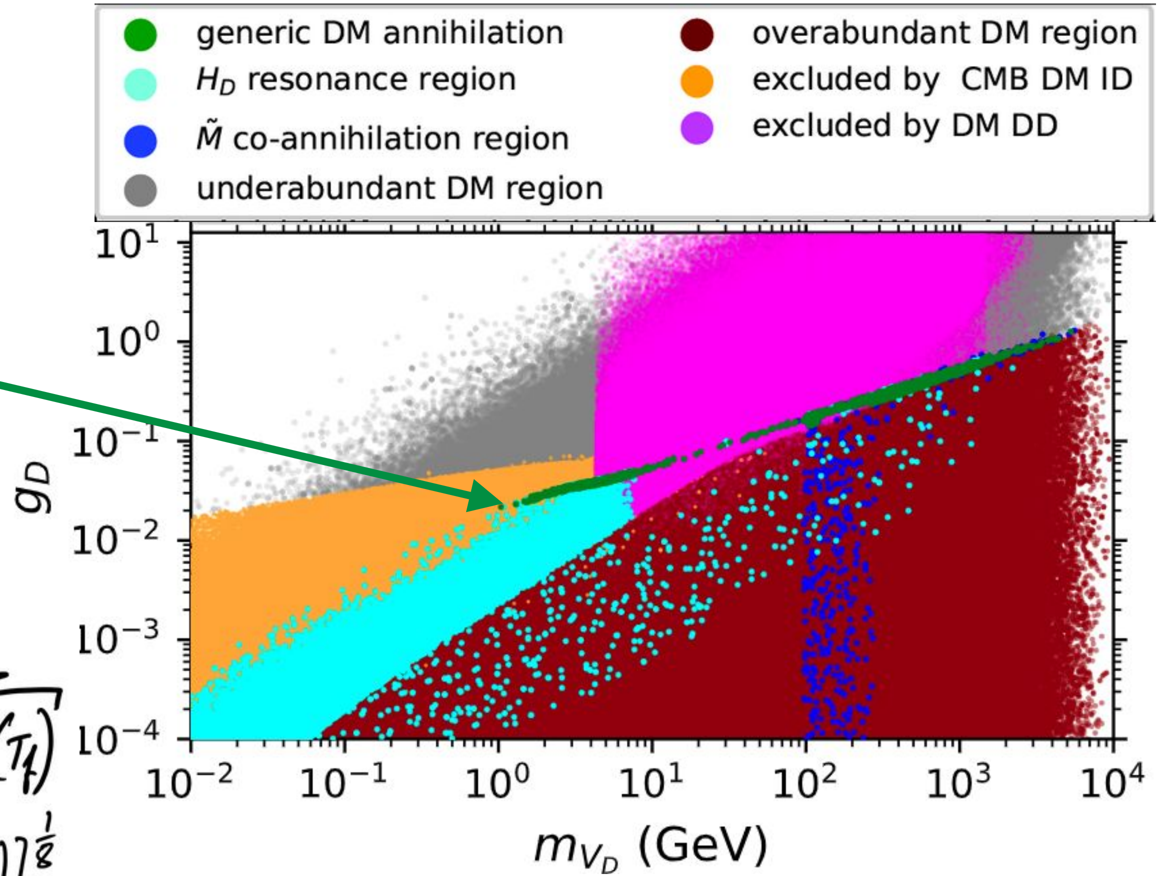
- **DM DD, ID, Relic density**
  LanHEP, CalcHEP, micrOMEGAs
- **Collider searches**
  CalcHEP, MC@NLO, PYTHIA, DELPHES, MadAnalysis, CHECKMATE

Cosmological constraints on μPVDM parameter space



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

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



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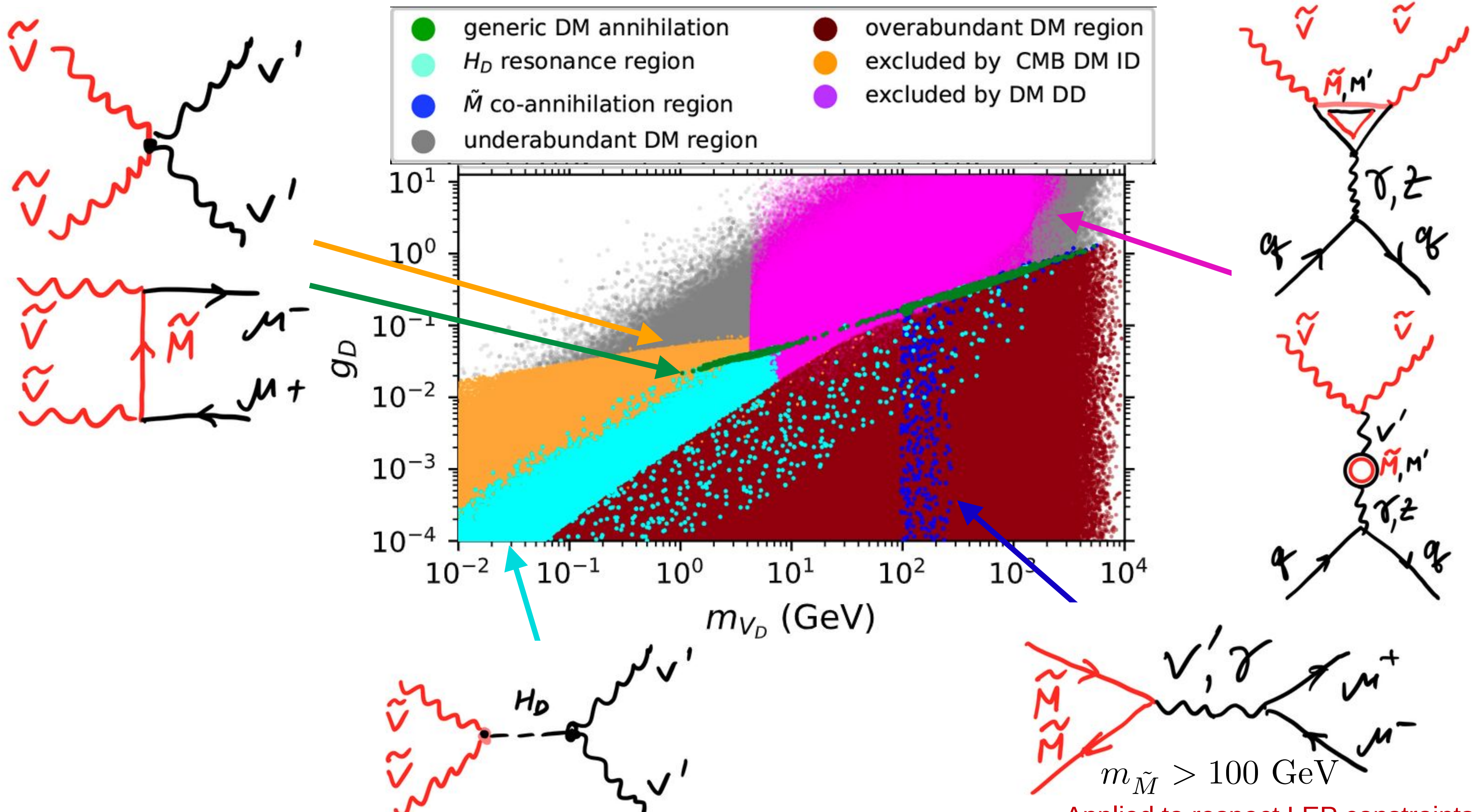
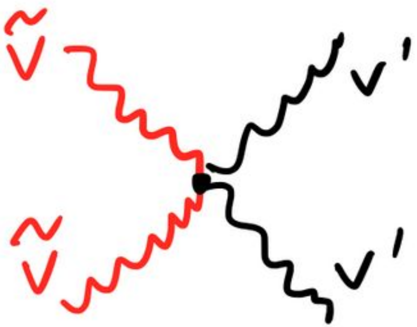
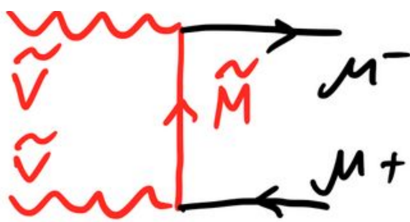


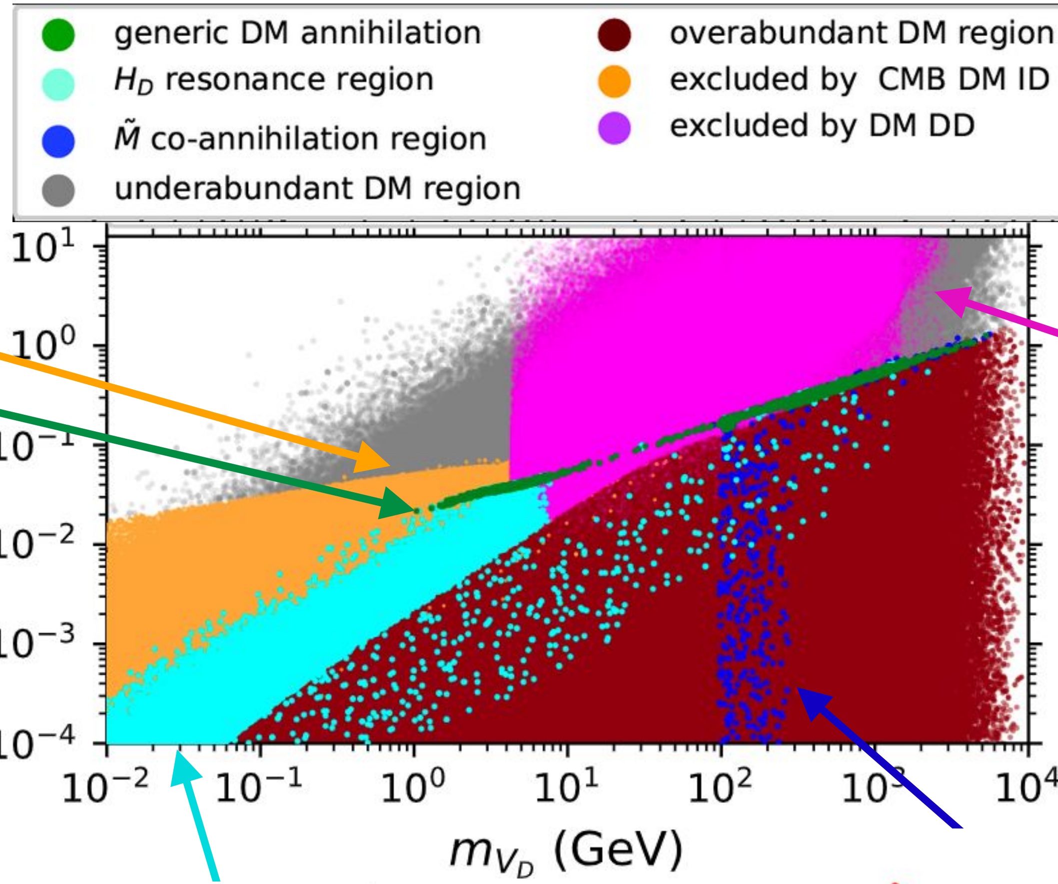
$m_{\tilde{M}} > 100$ GeV

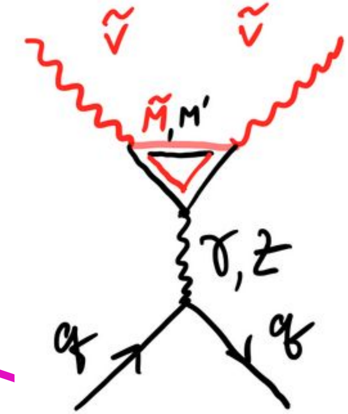
Applied to respect LEP constraints

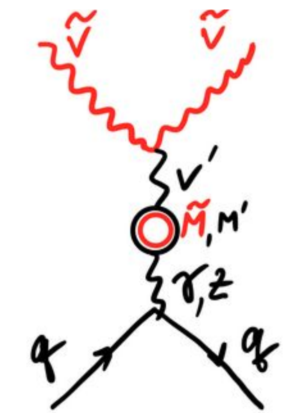
Cosmological constraints on μPVDM parameter space



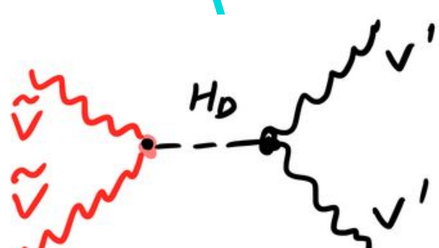








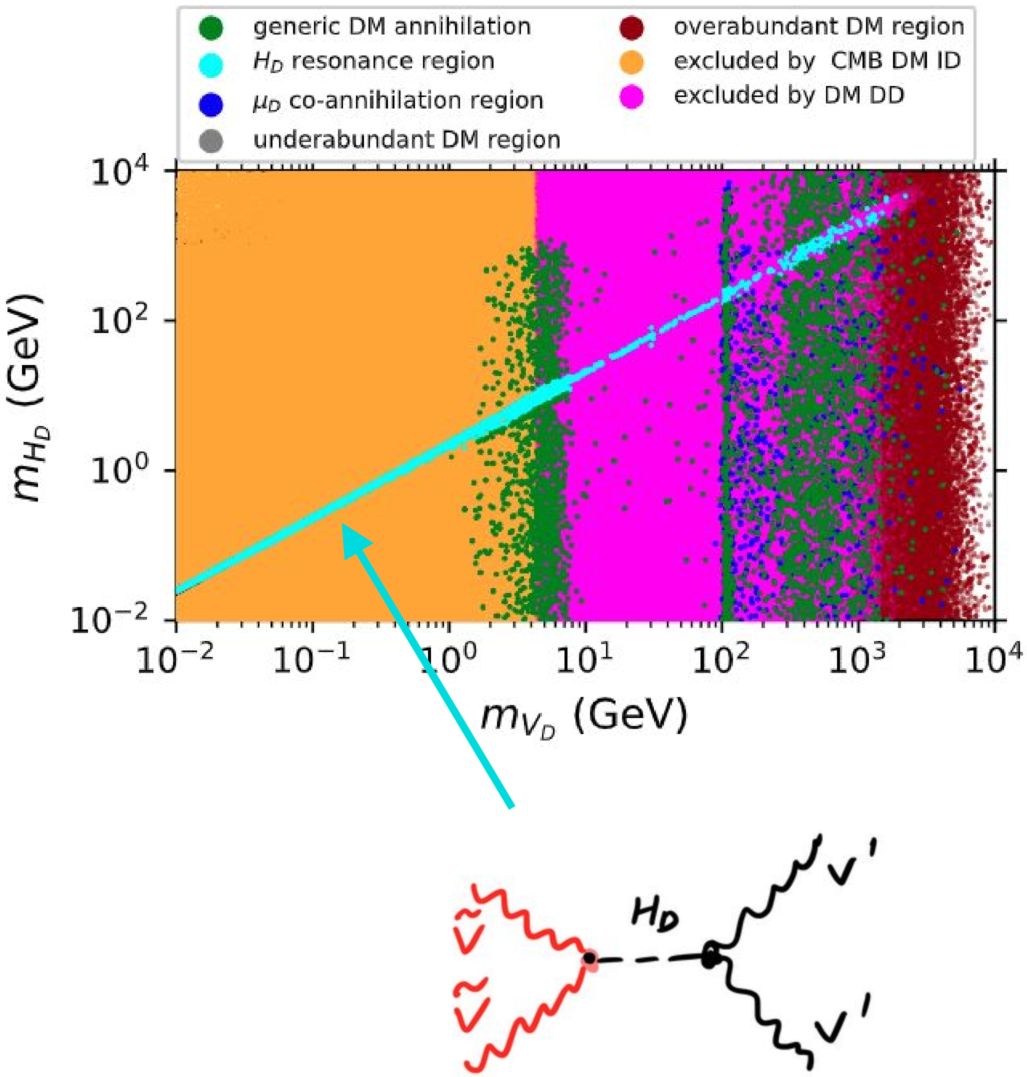
- **both DM ID and DD exclusions play an important complementary role**

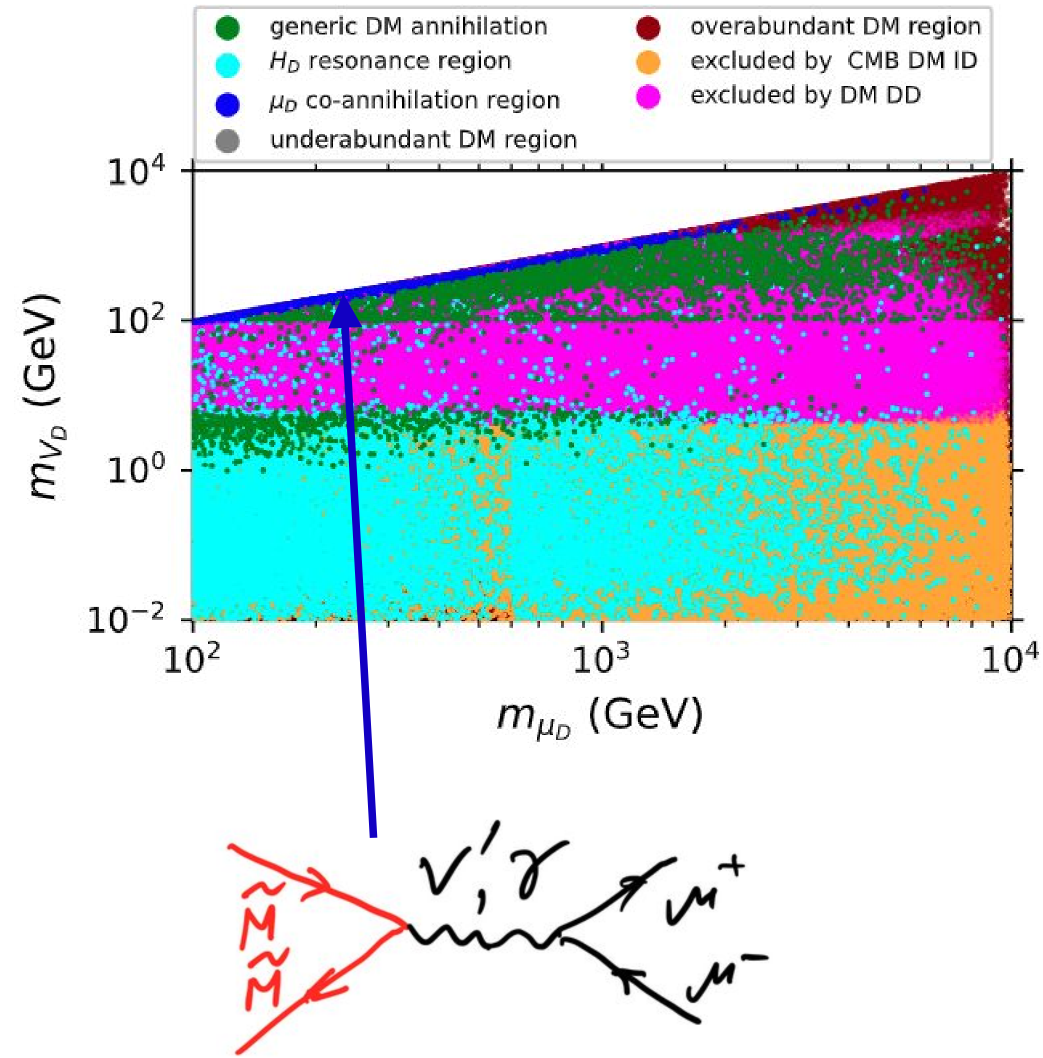


$m_{\tilde{M}} > 100$ GeV

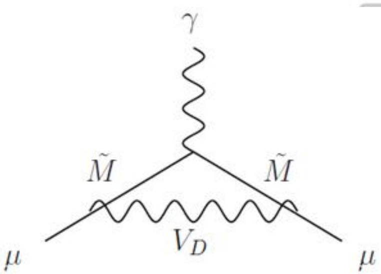
Applied to respect LEP constraints

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



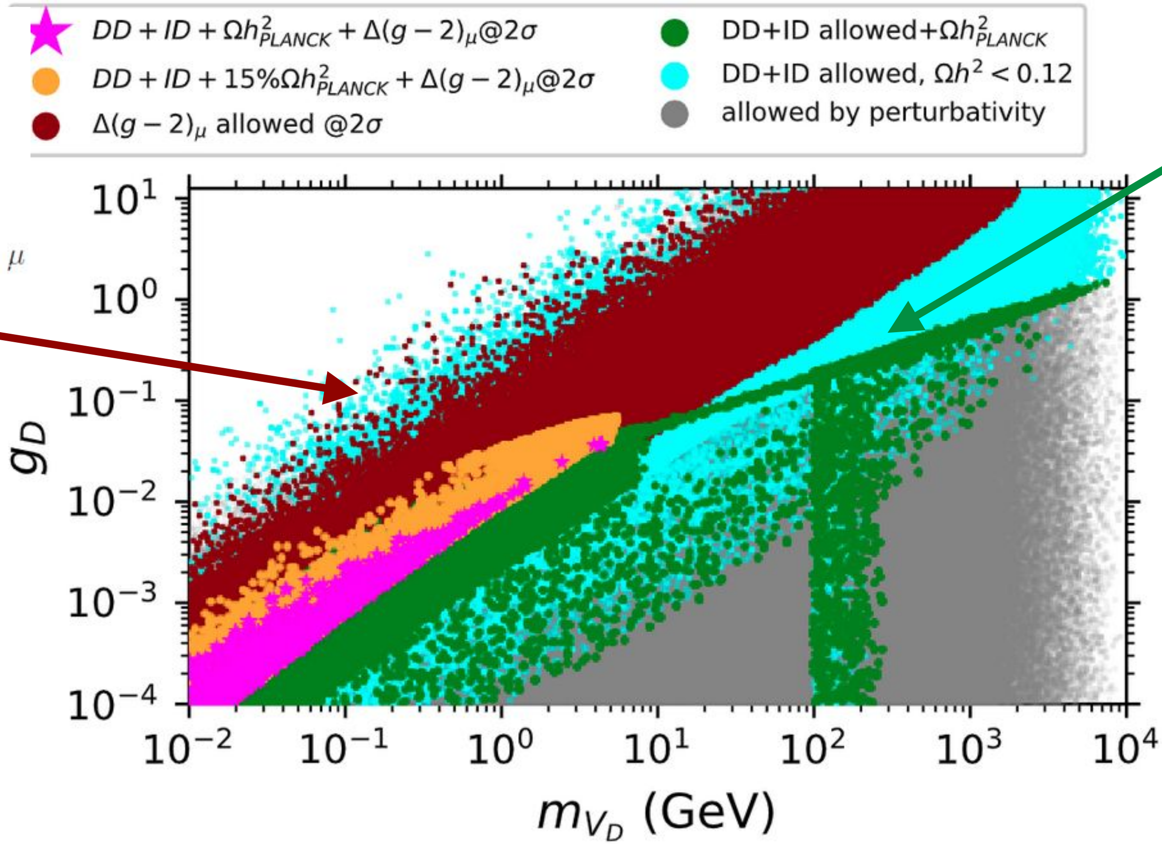


Combining (g-2)$_\mu$ and DM constraints



$g_D \sim m_{V_D}$

"trajectory" to explain Δa_μ



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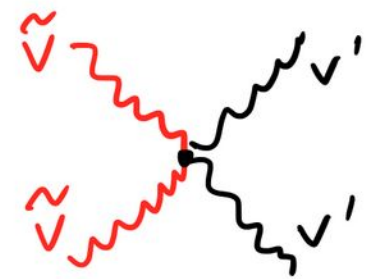
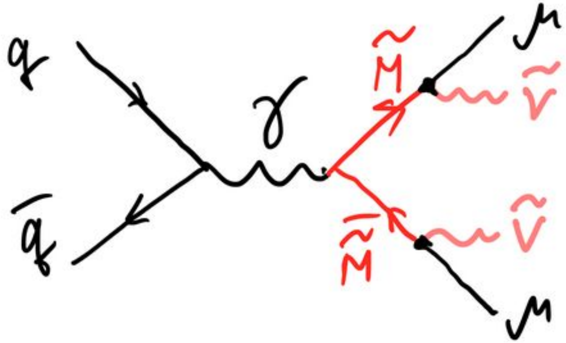
$$g_D \sim \sqrt{M_{V_D}} / [g_{eff}(T_f)]^{\frac{1}{8}}$$

Ωh^2_{PLANCK}
"trajectory" to explain DM relic density



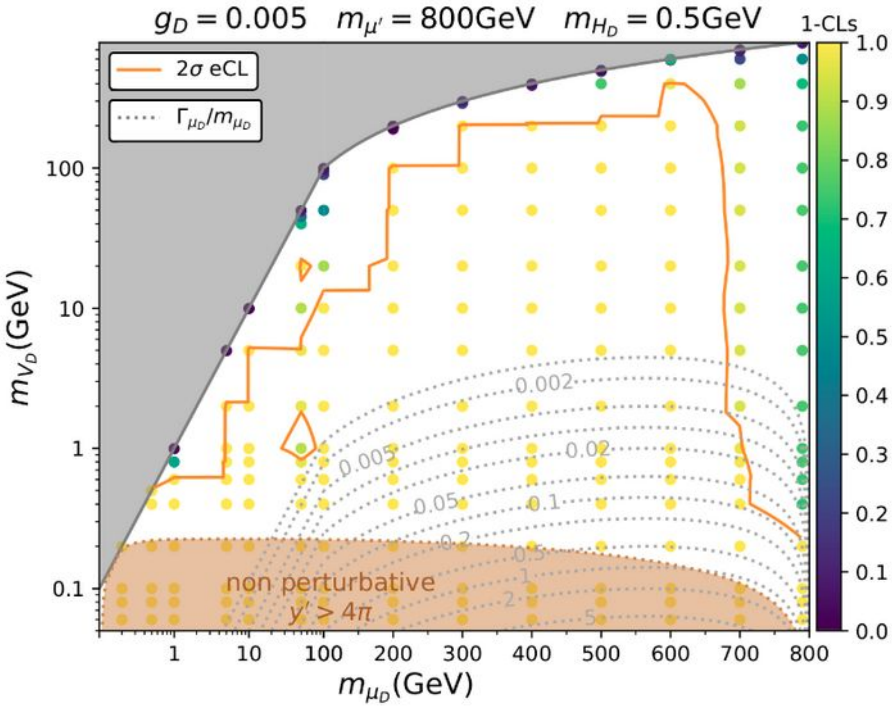
- (g-2) and DM relic density allowed bands have different slopes crossing at **0.1 – 1 GeV**
  - "dark photon"(V') kind of region
  - New collider signatures (see below)
  - very intriguing to explore further for GW effects and explaining NANOGrav results

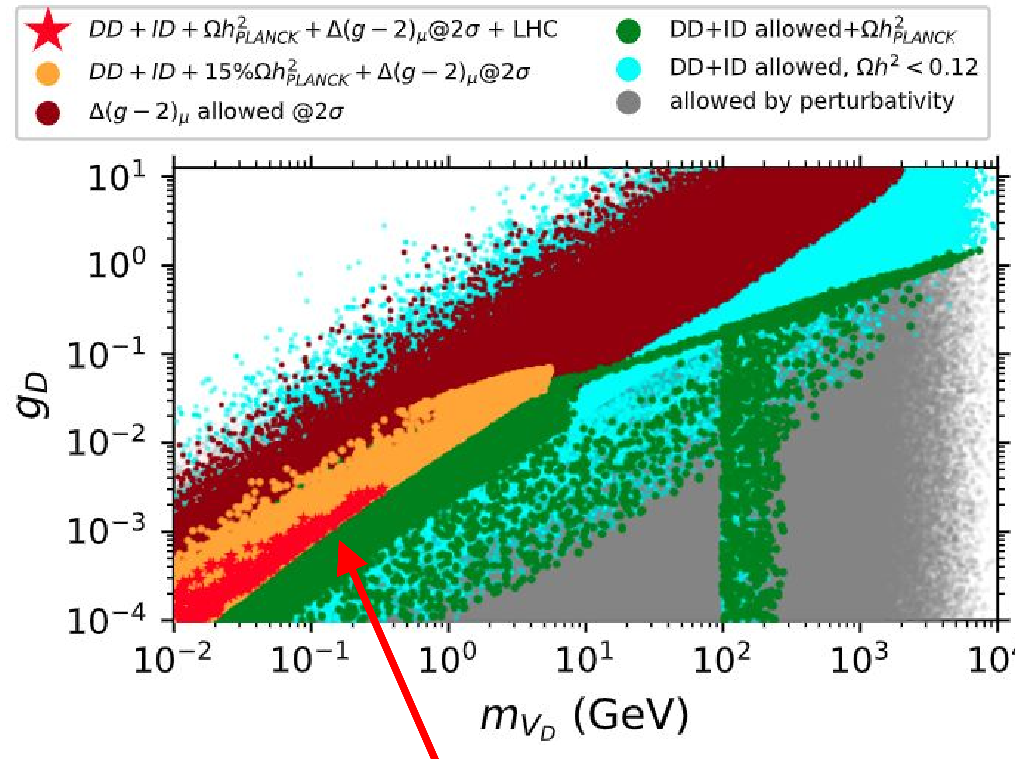
Final very set important constraints: colliders



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

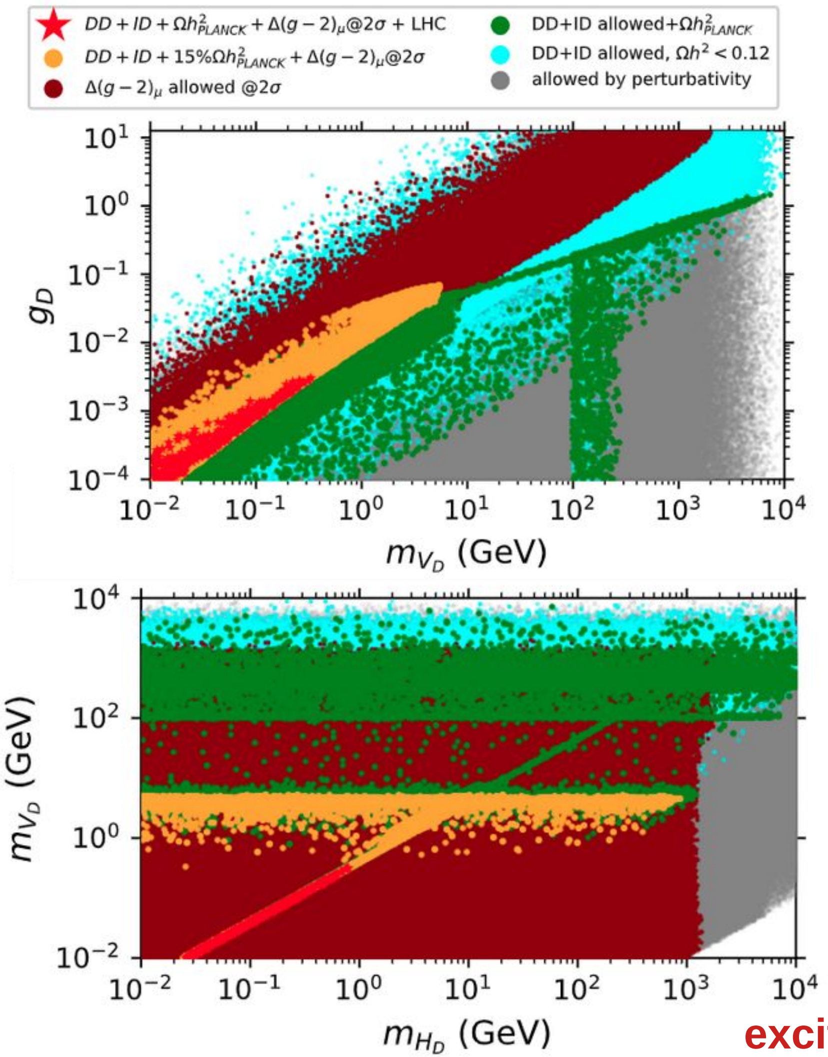
- Madgraph + PTHIA+Delphes + Madanalysis
- $\tilde{M} > 600\ \mathrm{GeV}$ comes from the main $\mu^+\mu^- +\ MET$

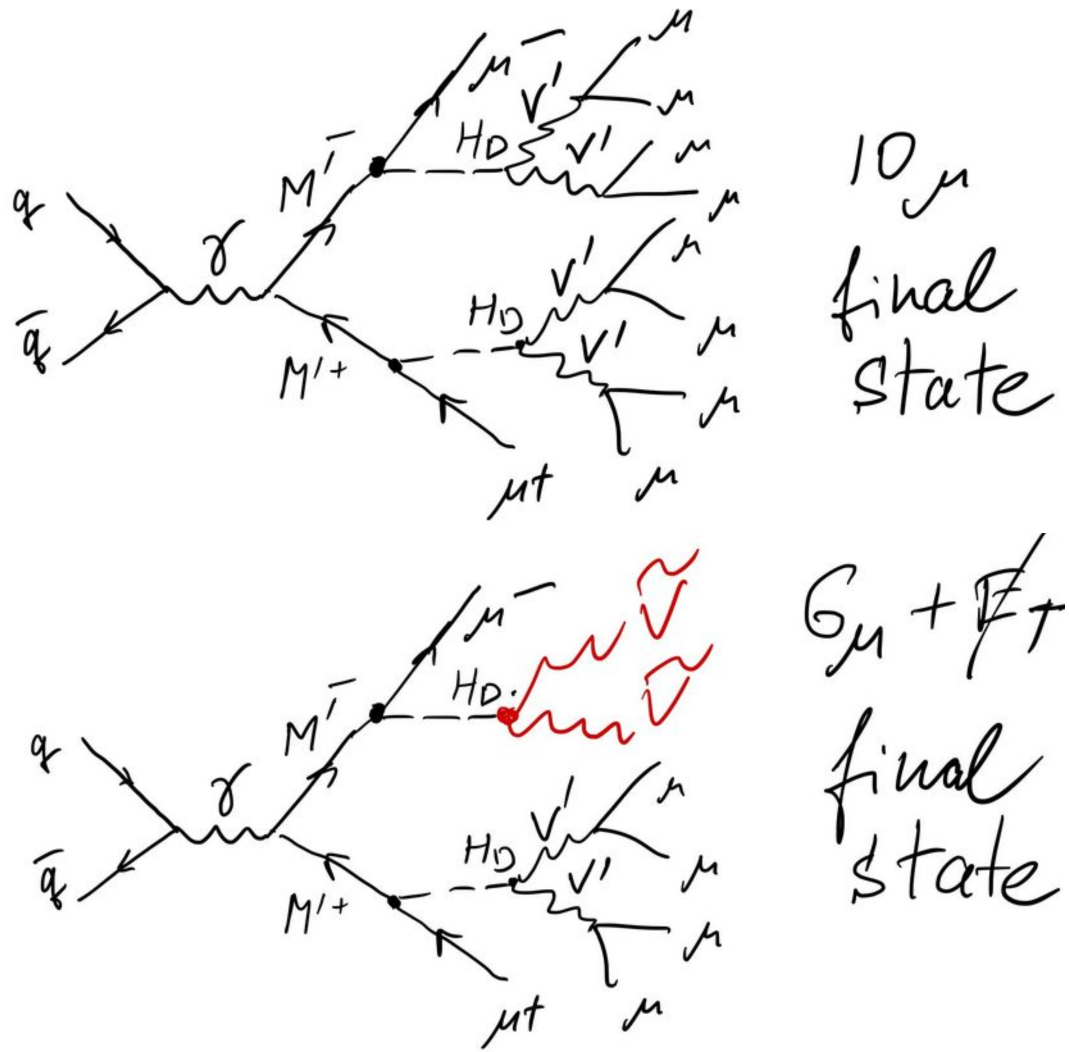




- surviving region after all constraints

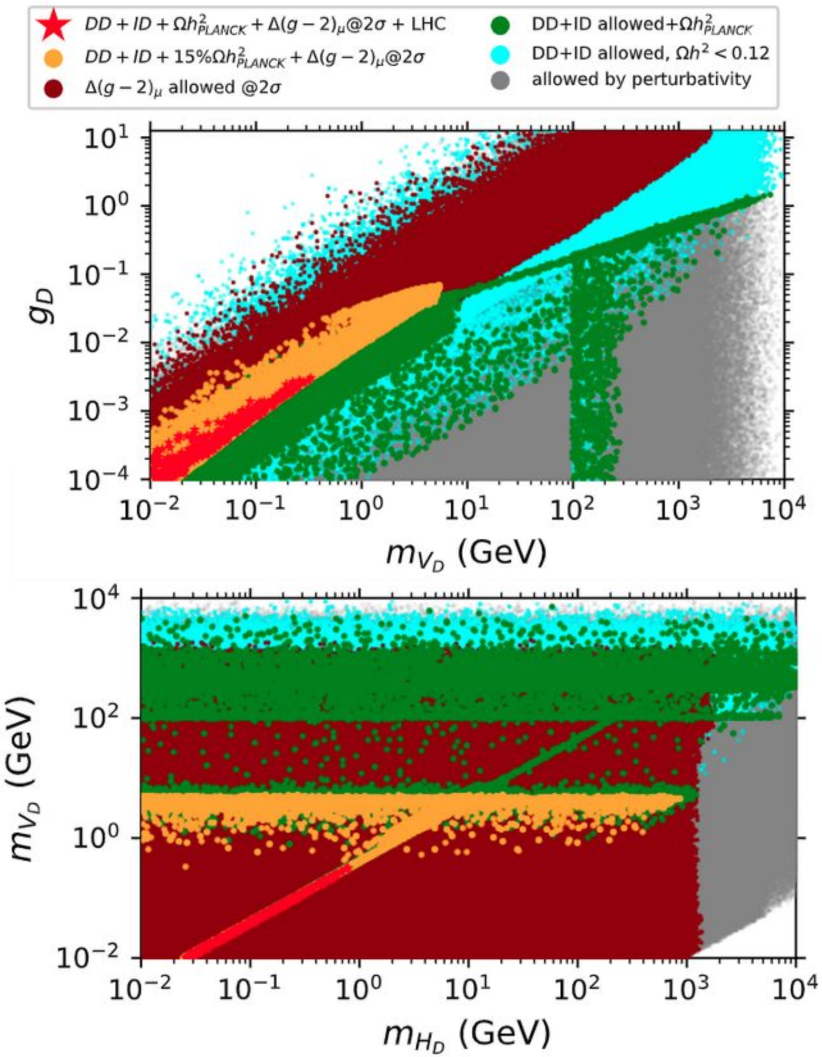
The parameter space and signatures after all constraints





exciting new signatures: 10μ, 8μ, 6μ(+MET), 4μ(+MET), 2μ+MET:
hi-PT pairs of muons (from V' decay) + single high-pT muons

The parameter space and signatures after all constraints

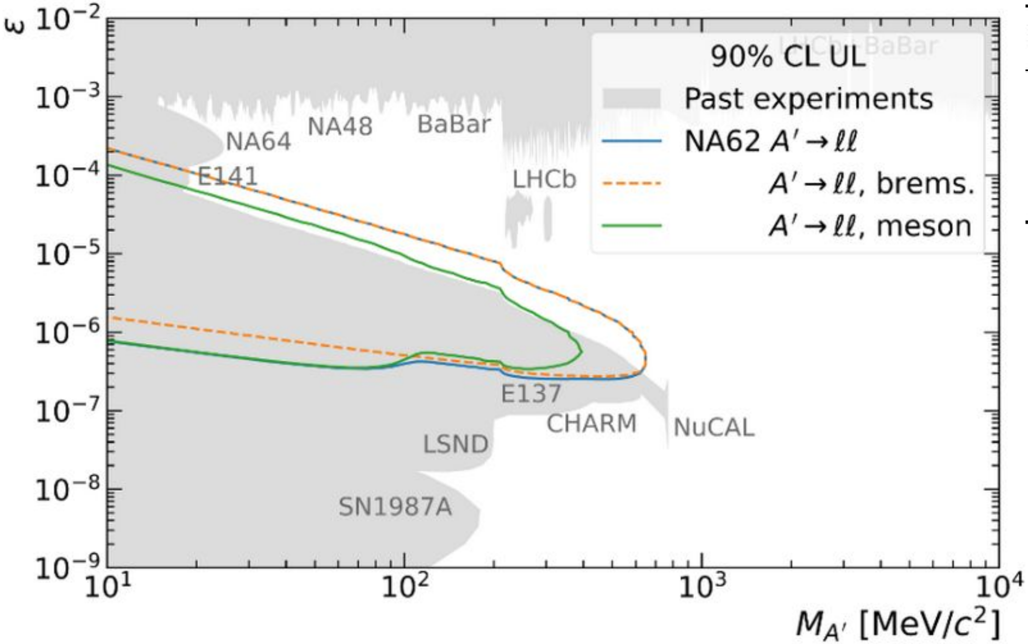


Inputs/Observables	BP1	BP2	BP3
g_D	0.003	0.003	0.003
m_{V_D} [GeV]	0.28	0.28	0.28
m_{μ_D} [GeV]	800	900	1000
$m_{\mu'}$ [GeV]	1000	1200	1400
m_{H_D} [GeV]	0.677	0.677	0.677
$m_{V'}$ [GeV]	0.2756	0.2706	0.2637
$Br(\mu' \to V'\mu)$	0.383	0.342	0.318
$Br(\mu' \to H_D\mu)$	0.371	0.319	0.282
$Br(\mu' \to V_D\mu_D)$	0.246	0.339	0.4
$Br(H_D \to V_D V_D^*)$	0.639	0.612	0.575
$Br(H_D \to V'V')$	0.352	0.375	0.409
$Br(H_D \to \mu^+\mu^-)$	9.24×10^{-3}	1.31×10^{-2}	1.54×10^{-2}
$Br(V' \to \mu^+\mu^-)$	$\sim$1	$\sim$1	$\sim$1
$Br(\mu' \to V'\mu \to 3\mu)$	0.383	0.342	0.318
$Br(\mu' \to H_D\mu \to 5\mu)$	0.131	0.12	0.115
$\sigma_{\rm tot}(pp \to \mu'\mu')$ [fb]	6.499×10^{-2}	1.867×10^{-2}	6.32×10^{-3}
$N_{\rm event}(pp \to 6\mu)$	2.86	0.655	0.192
$N_{\rm event}(pp \to 8\mu)$	0.978	0.23	0.069
$N_{\rm event}(pp \to 10\mu)$	0.335	0.08	0.025

assuming 300 fb^{-1} for the integrated luminosity

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 **avoiding existing bound on dark-photons: requires dedicated analysis**



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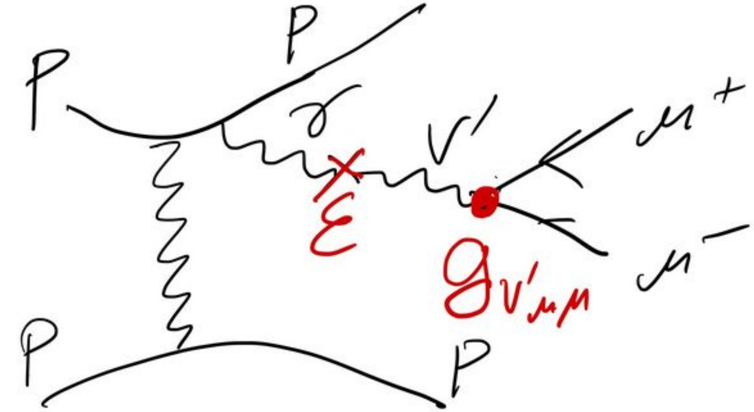
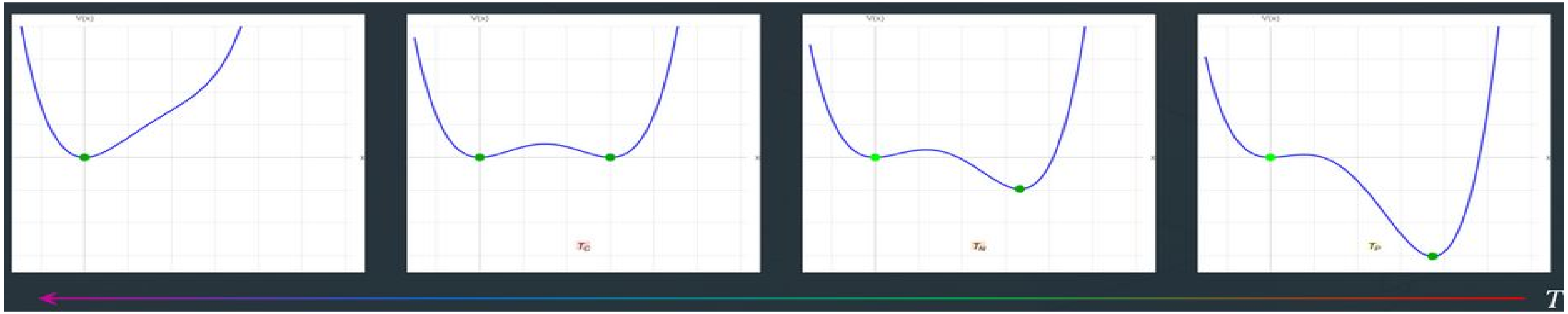
Inputs/Observables	BP1	BP2	BP3
$\tau_{V'}$ [ns]	1.10×10^{-6}	7.85×10^{-7}	6.77×10^{-7}
$\ell_{V'}$ [μm]	0.33γ	0.24γ	0.20γ
$\epsilon_{AV'}$	1.13×10^{-5}	1.39×10^{-5}	1.578×10^{-5}



Gravitational Waves from Dark sector

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

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

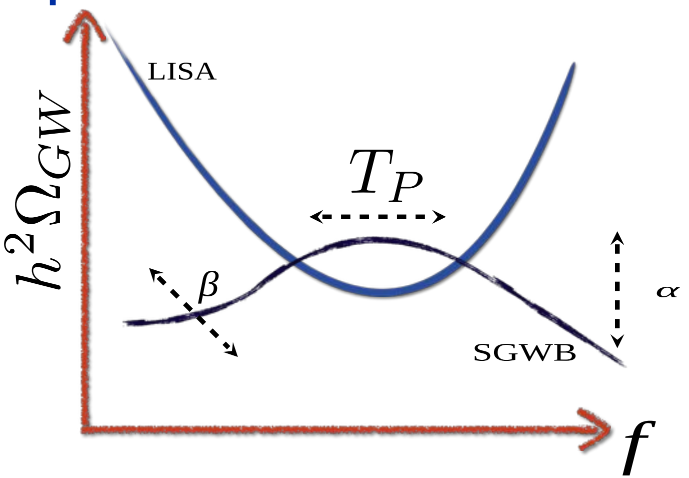


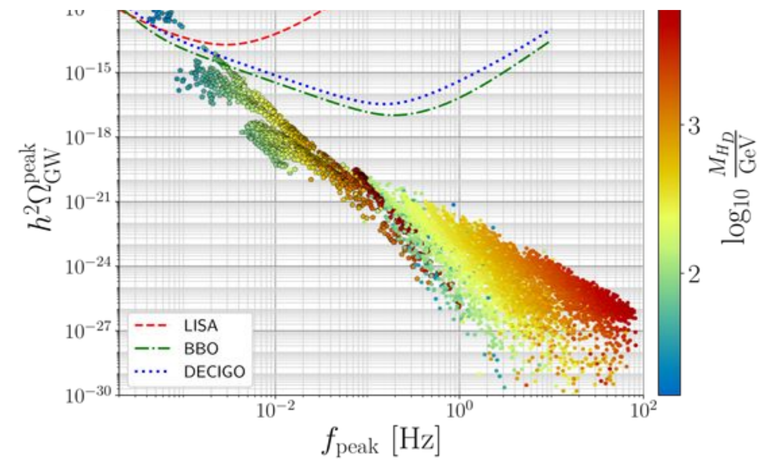
Strength: α

Inverse Duration β/H

Percolation temperature T_P

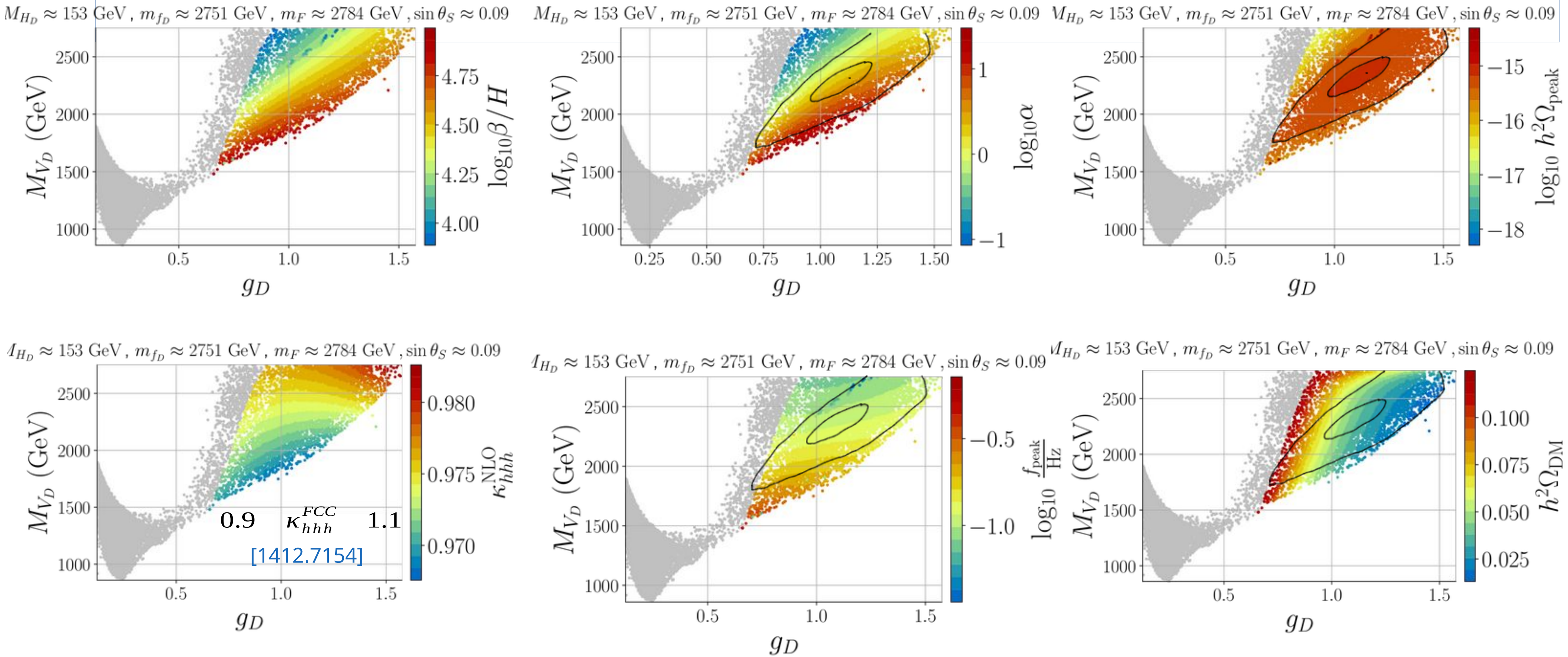
- **Tools: DRalgo+CosmoTransitions, "Dralgo to python interfacer"** **(more in Marten's tutorial)**
  - **correct implementation of dimensionally reduced effective potentials from DRAlgo**
  - **the scale dependence of the numerical solution is greatly reduced**





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

Summary on FPVDM

models are available at **hepmdb.soton.ac.uk**

- FPVDM is a very promising new framework for VDM, not requiring Higgs portal
- Incorporates many possibilities with new collider and cosmological implications
  - great potential to explain dark matter
  - collider signatures: ff+ET miss, V', Z'H, long-lived V'
- Great potential to explore flavour anomalies, was not deliberately designed for this
- The model with VL partner of muon (AB, Panizzi, Thongyoi – to appear)
  - **can explain relic density and Δa_μ**
  - Provides multi-lepton signatures, up to 10 SM fermions – new smoking gun signature!
  - non-standard "dark-photon" (V'): escapes present constraints, requires dedicated searches
- Dark sector exhibits SFOPT which could lead to STGW signals
  (AB, Bertenstam, Gonçalves, Morais, Pasechnik, Thongyoi – to appear)
  - specific parameter space can be tested by LISA and future facilities
  - GW signals can be correlated with collider and DM DD signals and can be further connected to the precision measurements of the hhh coupling