Six-Top Final States from the Top-Portal FPVDM: New Signature and Reinterpretation Opportunities

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The Vector DM with fermionic portal

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

Three simple ingredients

- 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

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

$$\boxed{y' \bar{\Psi}_L \Phi_D f_R^{\mathrm{SM}}}$$

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Interactions

- assign $Q_D = T_D^3 + Y_D$ and require its conservation
- $SU(2)_D \times U(1)_{\mathrm{glob}} \to U(1)^d_{\mathrm{glob}}$ pattern of dark sector breaking
- $\mathbb{Z}_2$ subgroup : $(-1)^{Q_D}$
- Yukawa portal

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

- Q_D conserved – DM is established!

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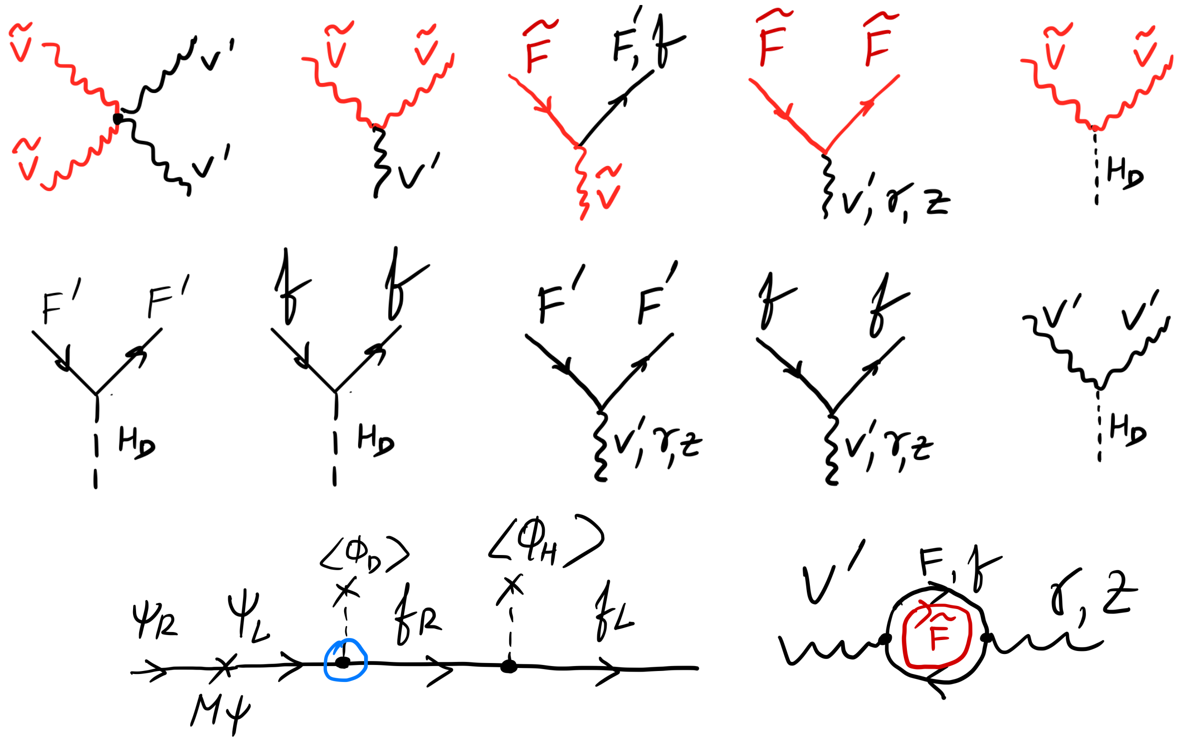

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$$\Psi = \begin{pmatrix} \tilde F \\ F \end{pmatrix} \qquad V_\mu^D = \begin{pmatrix} \tilde V_D^+ \\ V' \\ \tilde V_D^- \end{pmatrix}$$

This new class of models with fermionic portal
requires non-abelian Dark SU(2) – unique and minimal scenario

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  and require its conservation
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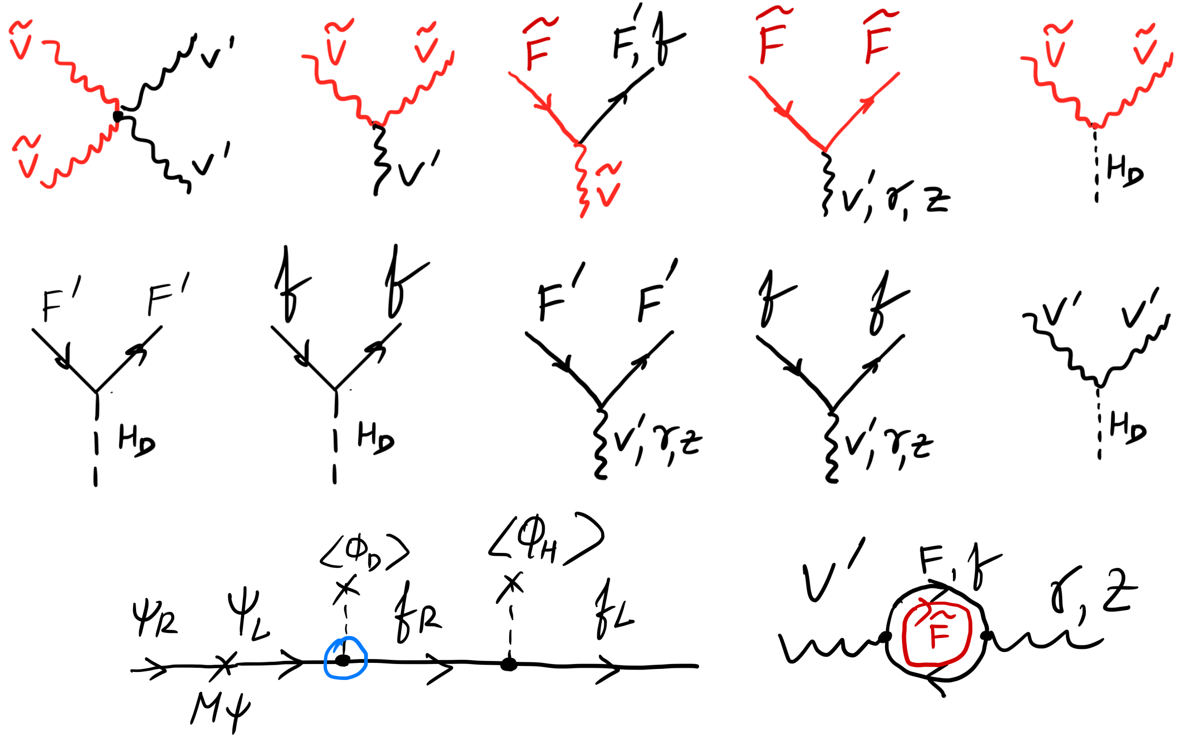
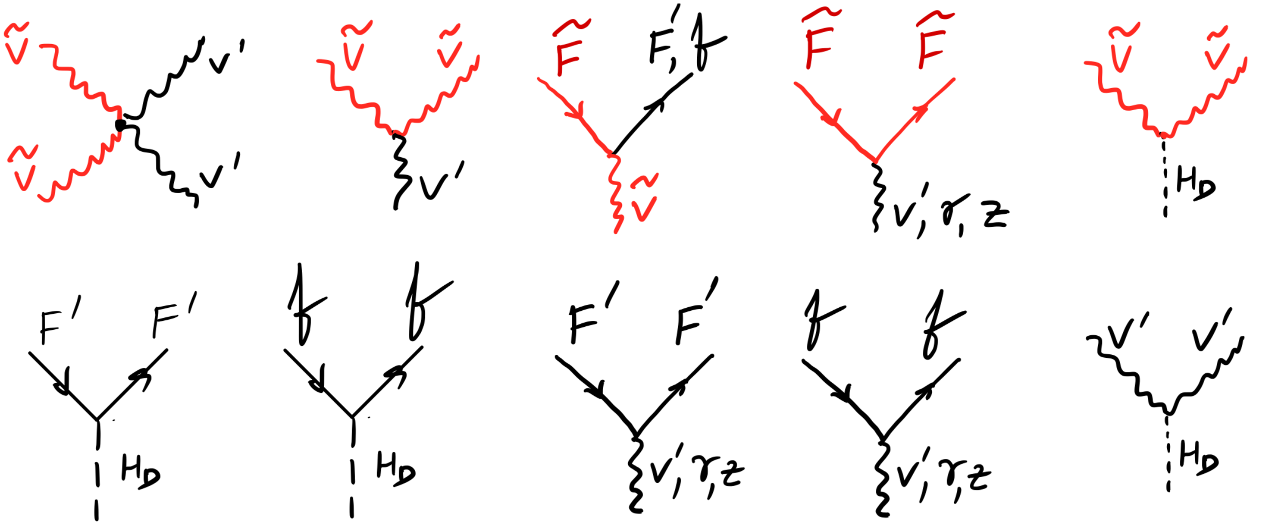
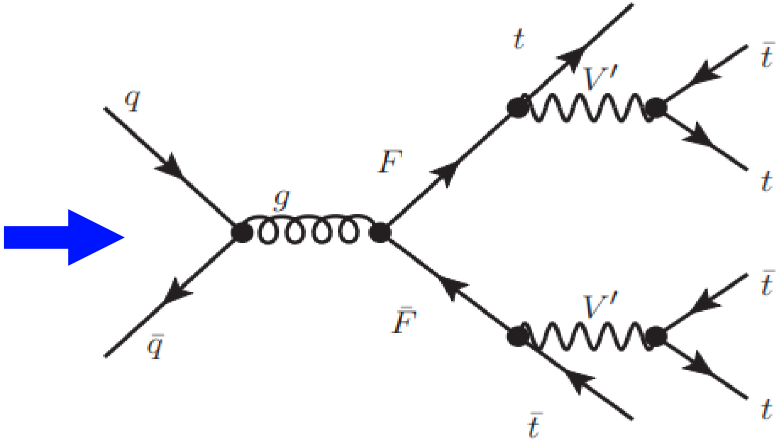


Multi-fermion signature from DM with fermionic portal

- **Has new multi-fermion signatures – we have realised this three years after the initial publication!**



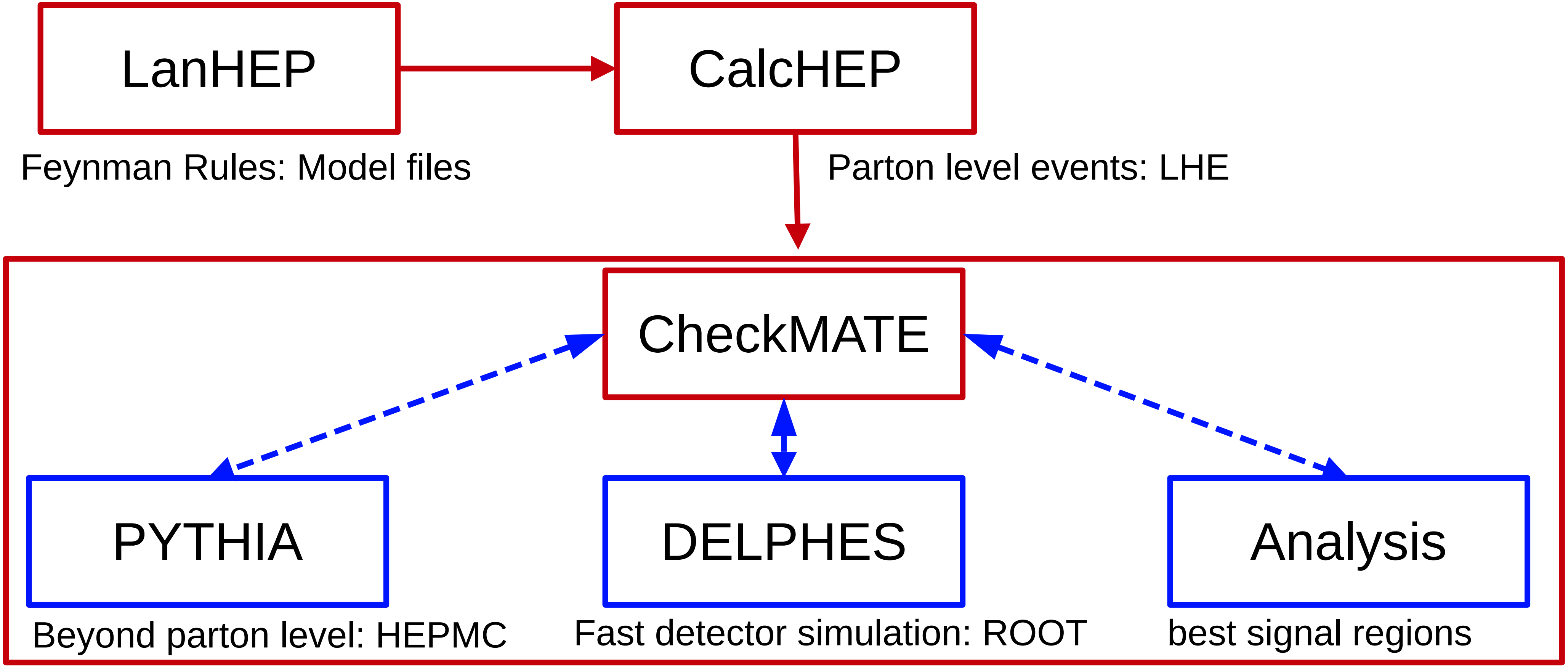
The case of top-portal realisation



Bertenstam, Gonçalves, Morais, Pasechnik, Thongyoi,AB: arXiv:**2508.04912**

- Analogous 6-muon signature takes place in the muon portal scenario
  Panizzi, Thongyoi, AB: arXiv:**2510.18564**

Tools


LanHEP
CalcHEP
Feynman Rules: Model files
Parton level events: LHE
CheckMATE
PYTHIA
DELPHES
Analysis
Beyond parton level: HEPMC
Fast detector simulation: ROOT
best signal regions

The relevant parameter space

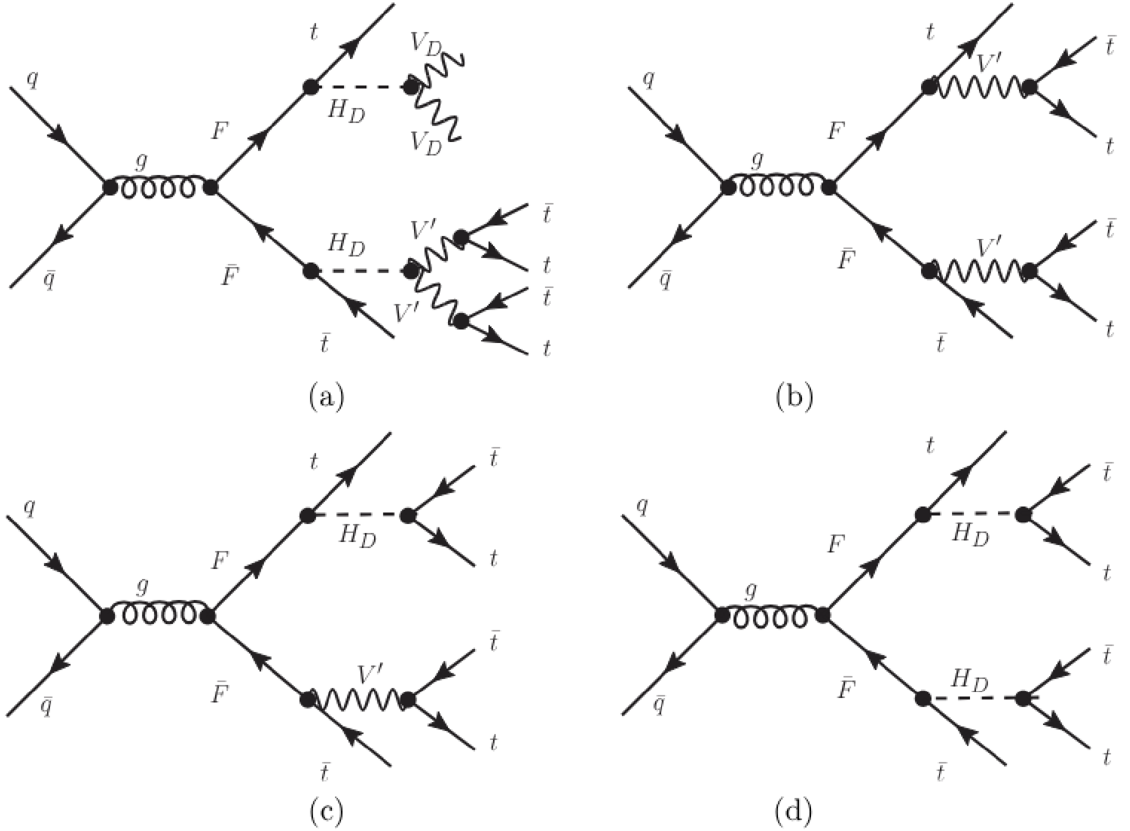
- the mass of the heavy even fermion: m_F defines the cross section and kinematics

- the mass of the V': $m_{V'}$ ($\simeq$ DM mass) can decay to two tops if $m_{V'} > 2m_t$

- the mass of the dark Higgs, $M_{HD} \ll M_{V'}$ for observable GW signature
  – is not relevant for the $6t$ signature

- the mass of the heavy odd fermion, $m_{\tilde{F}}$ ($m_{\tilde{F}} < m_F$) is not relevant for multi-fermion signature

- the relevant parameter space is 2D for $6t$ signature: m_F and $m_{V'}$



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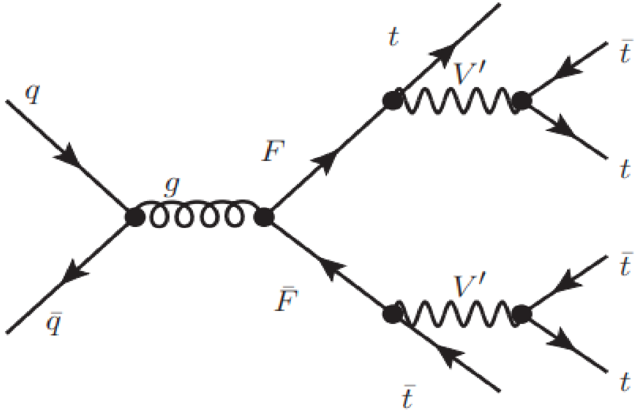
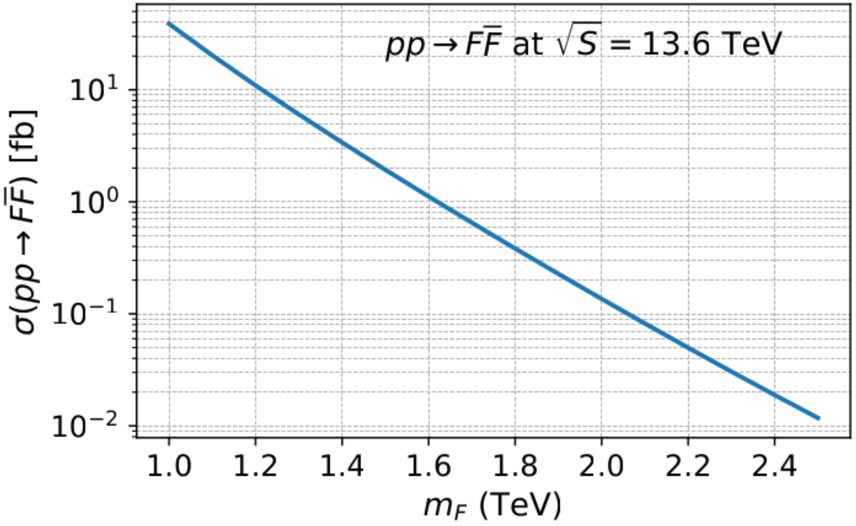




calchep_batch: to do an effective 2D scan to produce .lhe

```
Model: FPVDM_with_top
Process: p,p->Tp,tp # defines the process
Composite: p=u,U,d,D,s,S,c,C,b,B,G

pdf1:   PDT:NNPDF40_lo_as_01180(proton)
pdf2:   PDT:NNPDF40_lo_as_01180(proton)

p1:        6800
p2:        6800

Parameter: Mh2=10
Parameter: MtD=1000
Parameter: gD=0.1
Parameter: sinTs=1E-6

Run parameter: Mtp  # parameter to scan
Run begin:     1000 # can add many loops
Run step size: 100
Run n steps:   11
```

```
Run parameter: DMV # dummy parameter
Run begin:     0.025 # to define MV
Run step size: 0.1   # below
Run n steps:   10    # DMV=1-MV/Mtp

Run parameter: DM # anothet dummy parameter
Run begin:     10 # used for convenice
Run step size: 0  # to keep MtD-Mtp=10
Run n steps:   1

Parameter: MV=Mtp*(1-DMV)
Parameter: MtD=Mtp-DM

alpha Q :  Mtp

Number of events: 10000
Filename: pp_TpTp_FPVDM_example
Max number of nodes:   8
Max number of processes per node: 1
```

Finding and combining best signal regions

- **1st step**

  CheckMATE creates `evaluation/total_results.txt` **for each point of the parameter space**

  `filter_relevant_signal_regions_adaptive.py` → **to pick 10 best r_expected regions**

analysis	sr	b	db	s	ds	rexpcons
atlas_2211_08028	SR-Gtb-B	2.8	0.9	5.5528	0.38594	0.81997
atlas_2004_14060	SRA-TT	3.2	0.5	4.4529	0.34562	0.73323
atlas_2211_08028	SR-Gbb-B	3.9	1.4	5.0699	0.36878	0.66644
atlas_2211_08028	SR-Gbb-M	13	4	8.3694	0.47382	0.58402
atlas_2004_14060	SRA-TW	5.6	0.7	4.1042	0.33181	0.53135
atlas_2211_08028	SR-Gtb-M	1.2	0.6	2.307	0.24876	0.51324
cms_sus_19_005	2b_tight	12	2.8	5.1027	0.3673	0.45003
atlas_2211_08028	SR-Gbb-C	33	9	9.2546	0.49825	0.44408
atlas_2211_08028	SR-Gtt-0L-B	0.81	0.32	1.9582	0.22919	0.42651
cms_sus_19_005	2b_loose	32	4.5	6.1074	0.40184	0.36323

Finding and combining best signal regions

- **2nd step: analyse which signal regions are orthogonal (mutually exclusive) – highly non AI job!**

Analysis Code	Nature of the Search	Orthogonality/Combination
atlas_2004_14060	Inclusive SUSY, high jet multiplicity + MET	All SRs are exclusive
atlas_2101_01629	Gluino→stop→SS/4-leptons (ATLAS)	All SRs are exclusive
atlas_2211_08028	Stop→multi-b jets, 0L+1L combined	Combine one 0L+1L SR only
cms_sus_19_005	Inclusive MT2-based jets + MET (CMS)	All SRs are exclusive
cms_1908_04722	Gluino→t/b + MET, compressed spectra (CMS)	All SRs are exclusive
(ATLAS other SRs)	Individual ATLAS regions outside main sets	Treated as standalone
(CMS other SRs)	Individual CMS regions outside main sets	Treated as standalone

- We use the CL_s method to statistically combine orthogonal signal regions.
- CL_s is based on a likelihood ratio and is the standard for LHC exclusion limits.
- For each group of mutually exclusive SRs, we compute $r_{\text{exp}}^{\text{comb}} = \frac{s_{\text{tot}}}{s_{95}^{\text{exp}}}$ with uncertainties added in quadrature.

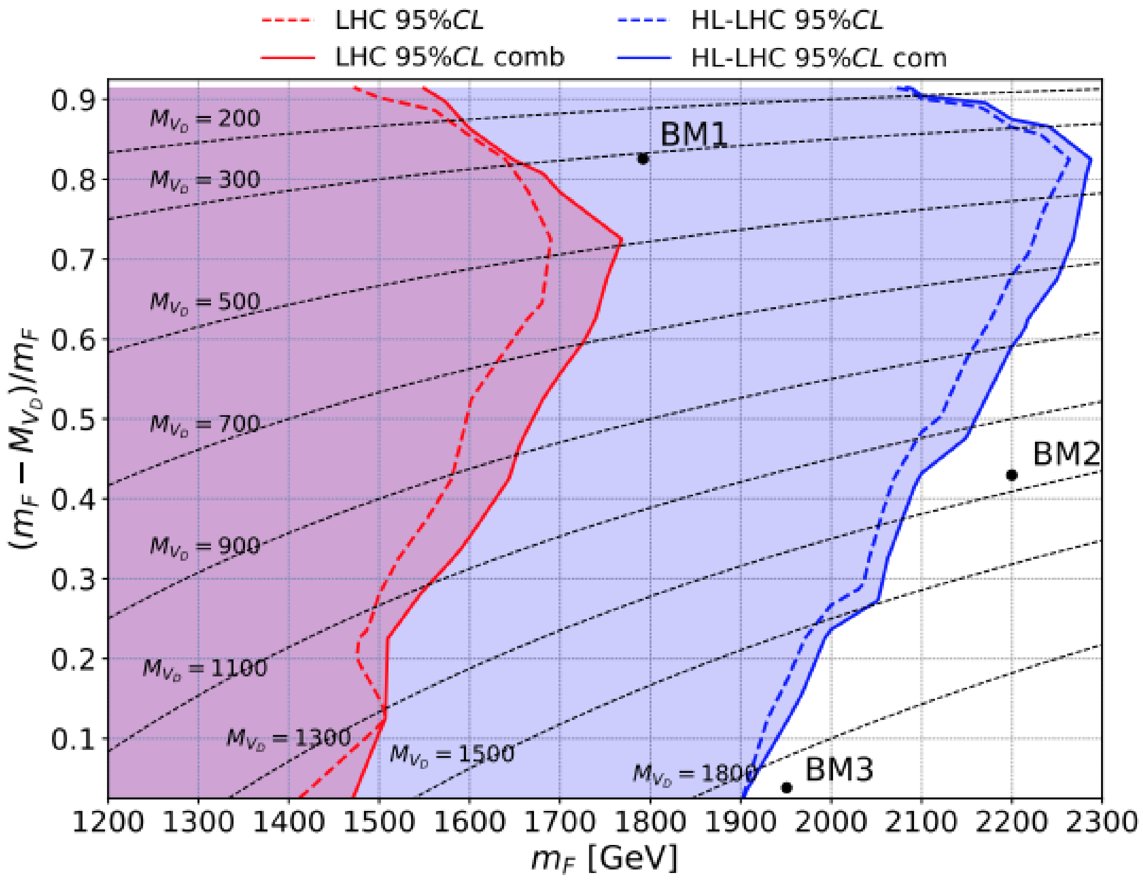
Finding and combining best signal regions

- Combination is only applied to SRs from orthogonal analyses, e.g.:
  - `atlas_2004_14060`, `cms_sus_19_005`: all SRs are exclusive
  - `atlas_2211_08028`: one 0L + one 1L only
- Final exclusion is determined from the **maximum** of:
  1. Best individual SR; 2. Best ATLAS combination;
  3. Best CMS combination; 4. Best ATLAS+CMS combined.

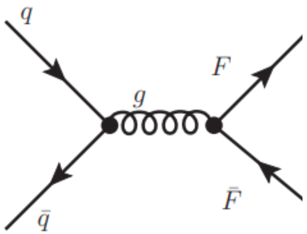
python code to combine signal regions: `batch_combine_signal_regions.py`

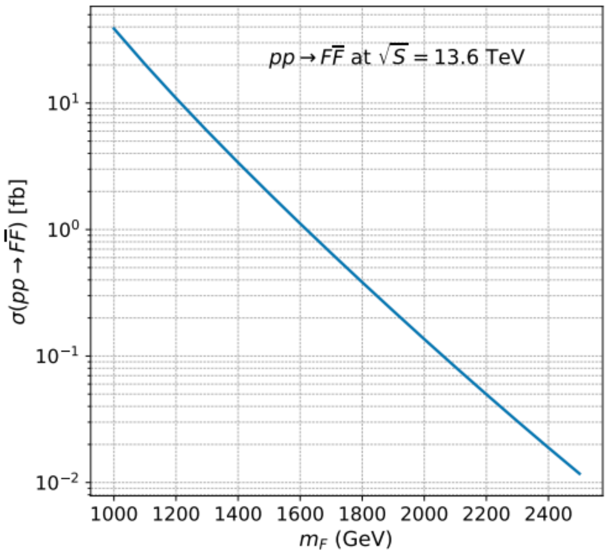
Mtp	DMV	Lumi	Best_Indiv	Best_ATL	Best_CMS	Best_Comb	Overall_Best
1200	0.025	1	2.092	3.097	1.496	2.781	3.097
1200	0.125	1	2.332	3.327	1.839	3.53	3.53
1200	0.225	1	2.848	4	2.731	4.022	4.022
1200	0.325	1	3.63	4.923	2.57	5.105	5.105

Final results



- LHC signature: **6 tops from VLQ pair**
- current sensitivity: **up to 1.8 TeV for m_F**
  up to 1.4 TeV for DM
- HL-LHC prospects: **up to 2.3 TeV for m_F**
  up to 1.8 TeV for DM
- The orthogonal combination allows us to extend sensitivity by up to 100 GeV – almost factor of two in cross section

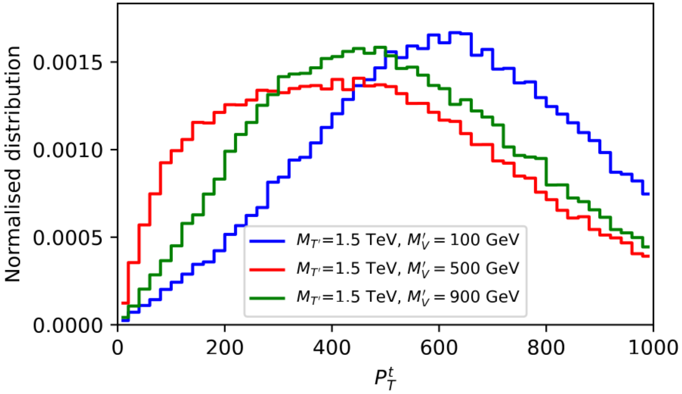




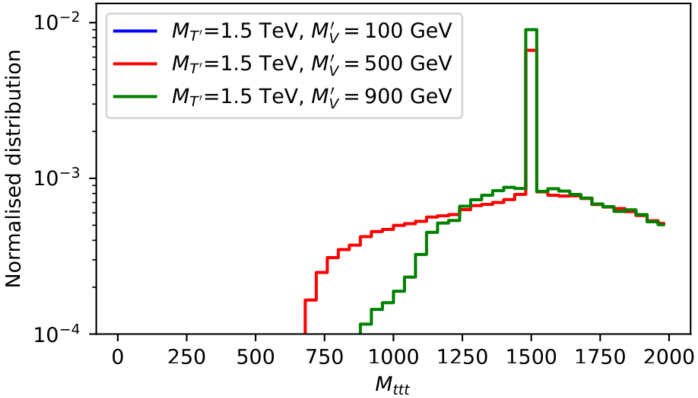
Bertenstam, Gonçalves, Morais,
Pasechnik, Thongyoi,AB: arXiv:**2508.04912**

Conclusions and Outlook

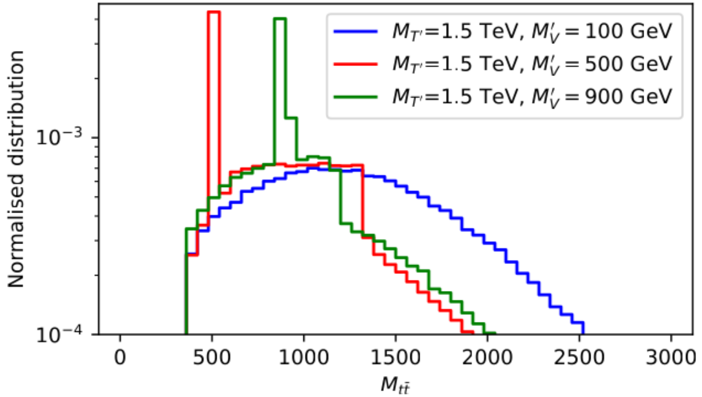
- New 6-fermion signature is very promising but has not been yet explored experimentally
- Dedicated experimental analysis will further enhance sensitivity to the model and to the 6-top signature



High P_T tops



3t – resonant signal from T



2t – resonant signal from V′

- The map of the efficiencies is ready for T → 3t topology – can be used by SMODELS or by other codes
- The set orthogonal regions is ready to be used through the python code – can be used in other codes
  The combination allows to enhance sensitivity to the cross section almost by a factor of two
- The model is initially motivated only by vector DM and new fermionic portal, but reveals new signatures and new opportunities for the BSM exploration

Thank you!

Backup Slides

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

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

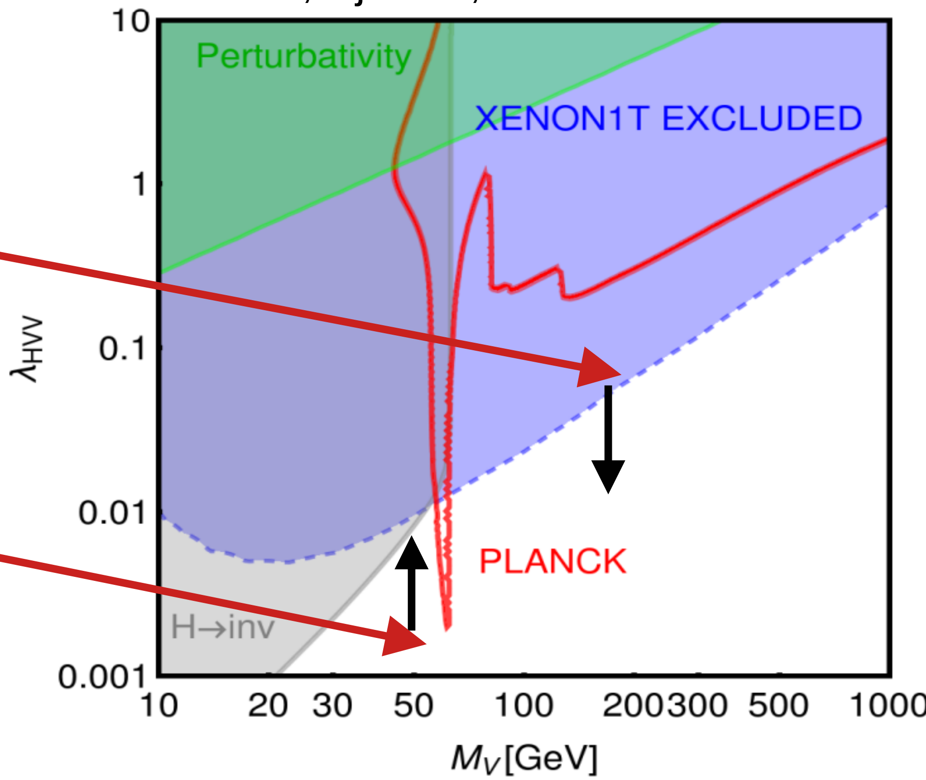
- Quite a few papers:

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**
- The Higgs portal VDM parameter space is very limited by interplay of collider, DD and DM relic density

Arcadi, Djouadi, Kado 2001.10750



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- Q_D conserved – DM is established!

	$SU(2)_L$	$U(1)_Y$	$SU(2)_D$	Q_D	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)

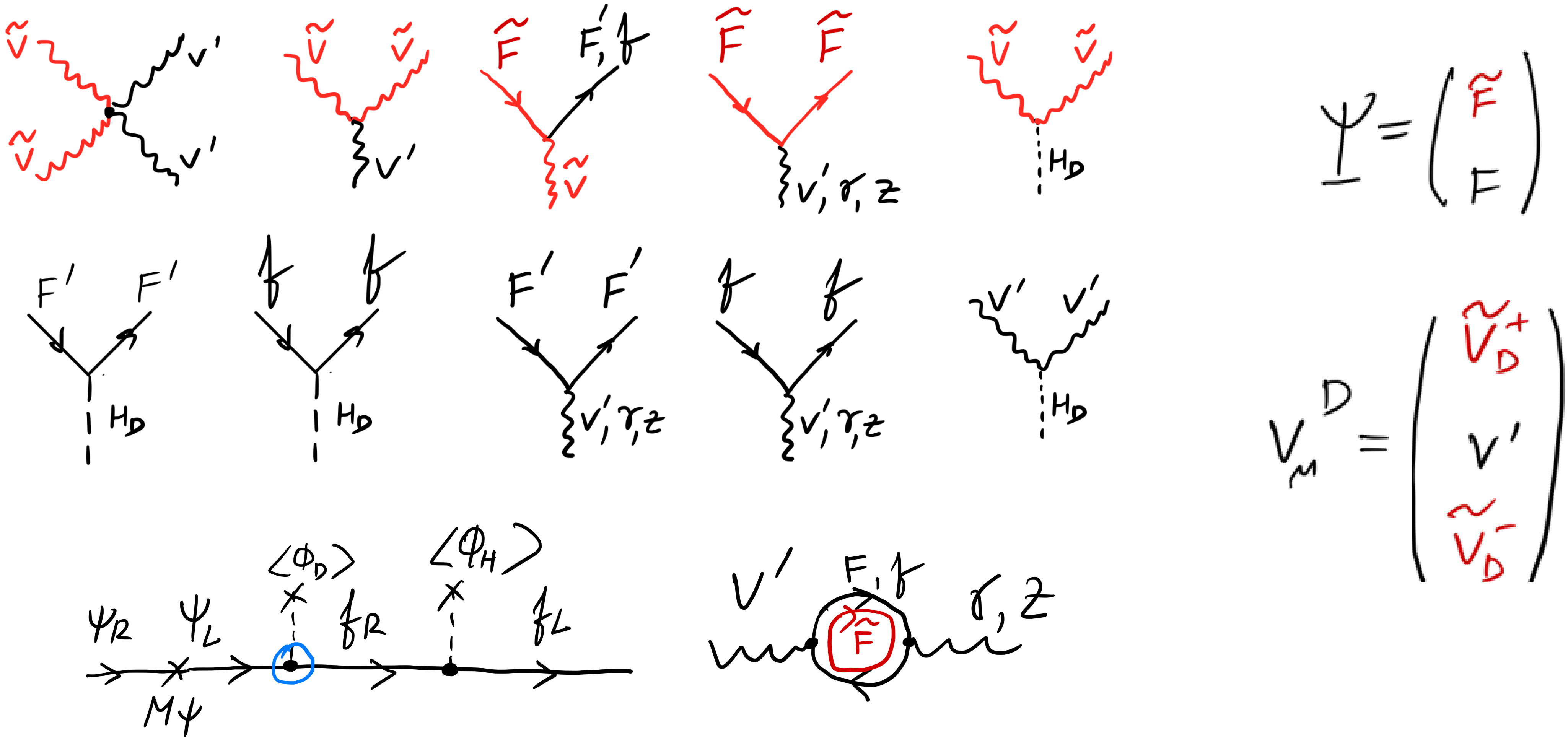
- It is the framework, representing the class of models
  [Deandrea, Moretti, Panizzi, Ross, Thongyoi, AB – arXiv:2204.03510,2203.04681]

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

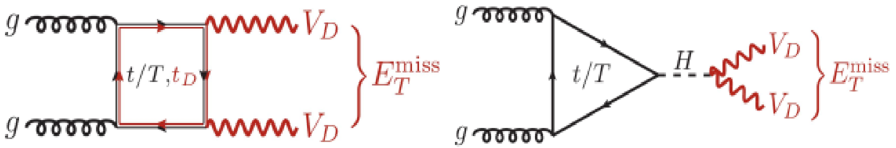
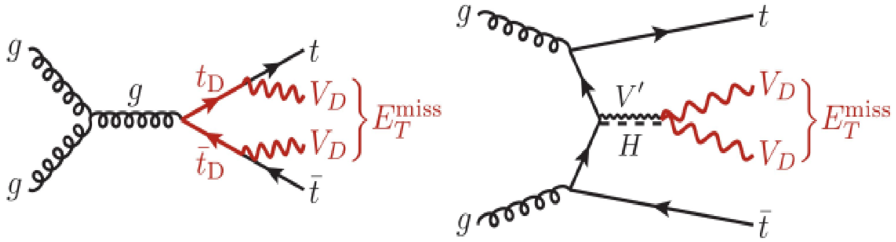
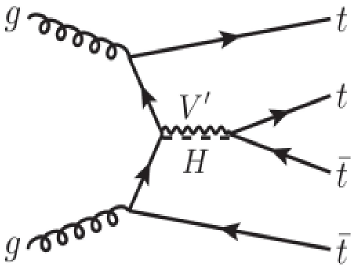
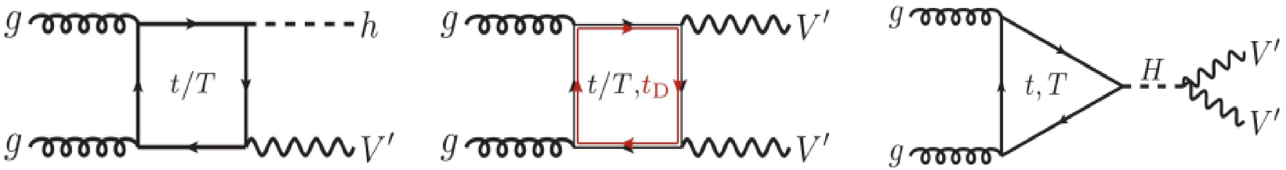
$$\begin{aligned}\mathcal{L}_{FPVDM} &= -\frac{1}{4}(V^i_{D\mu\nu})^2 + \bar{\Psi} i D\Psi + |D_\mu \Phi_D|^2 - V(\Phi_H, \Phi_D) \\ &- \quad \underline{(y'_{\alpha\beta}\bar{\Psi}^{i\alpha}_L \Phi_D f^{\mathrm{SM}\beta}_R} + h.c) - M_\Psi{}^{ij}\bar{\Psi}^i\Psi^j \\ V(\Phi_H, \Phi_D) &= -\mu^2_H \Phi^\dagger_H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

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

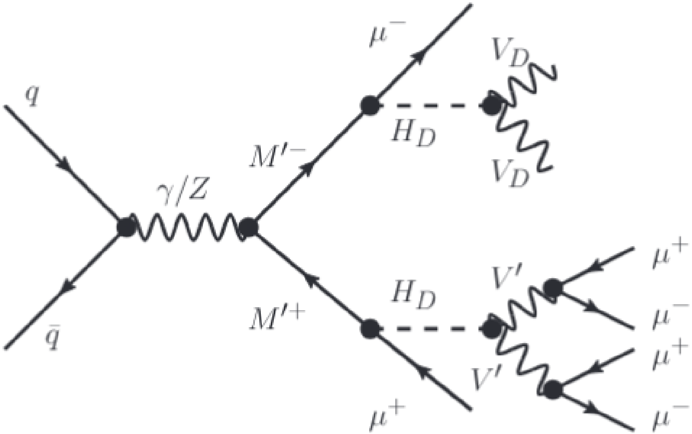
FPVDM Interactions and loop-induced kinetic mixing

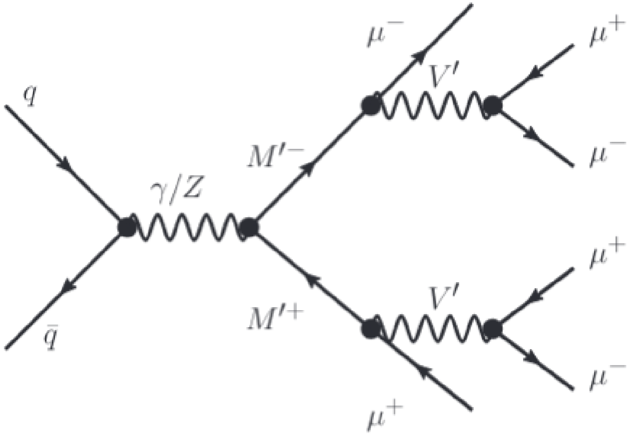


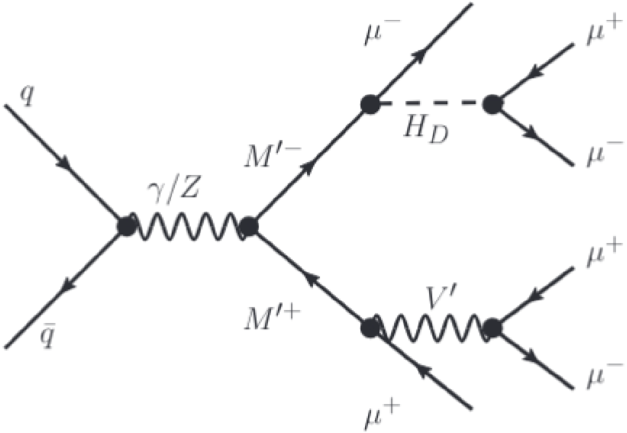
Minimal VL top portal VDM: collider signatures

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)	

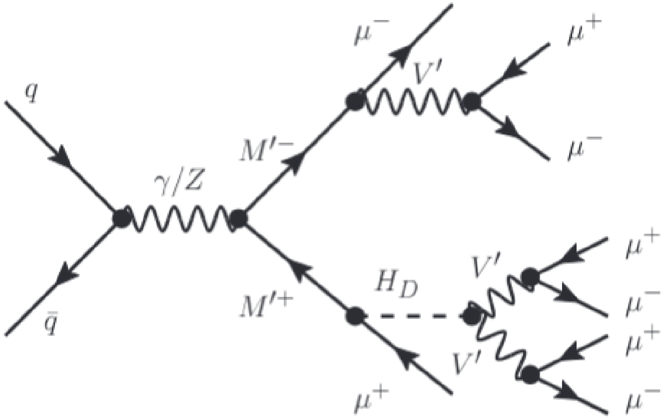
Novel multilepton (multi-fermion) signatures



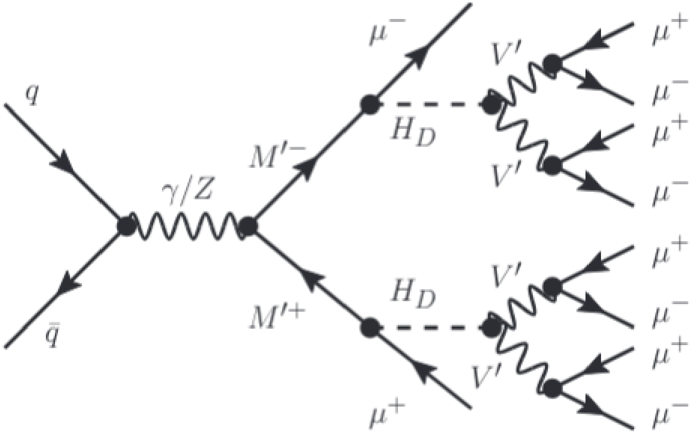




6μ(+MET): hi-PT two boosted pairs of muons (from V' decay) + two single high-pT muons



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**