Decoding the nature of Dark Matter at current and future experiments

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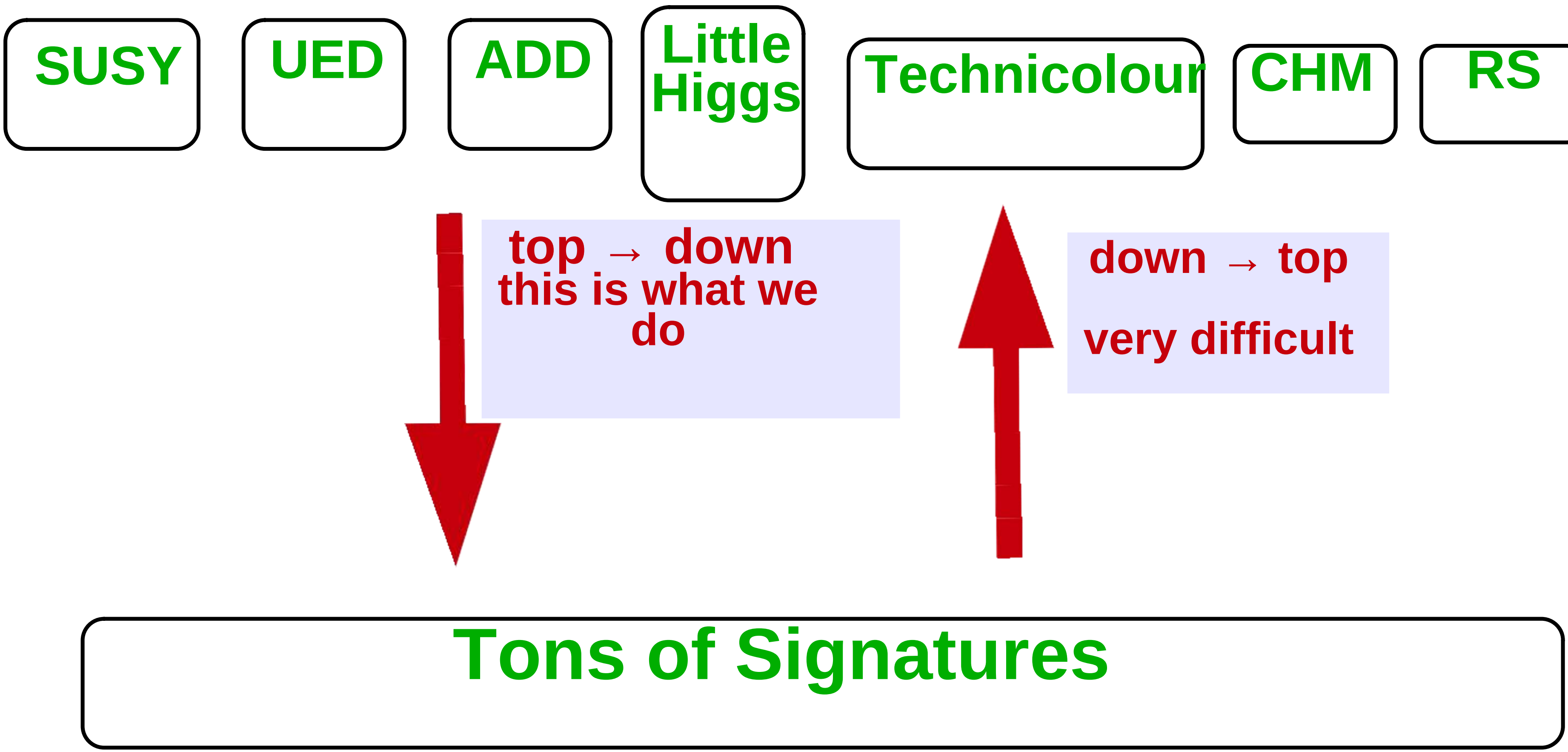
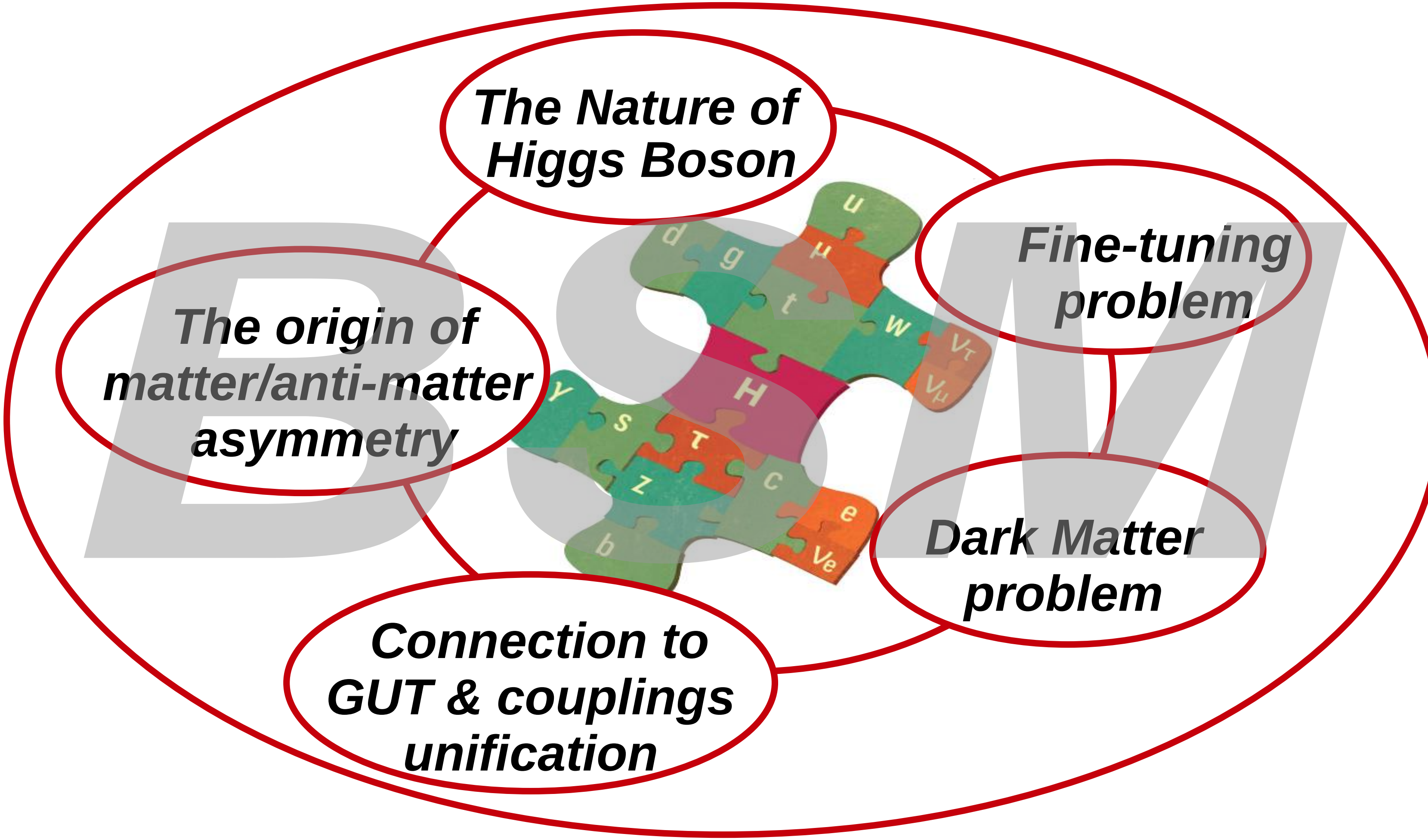
Decoding underlying theory (down → top) from the complicated set of signatures is very challenging!



The SM itself must be the piece of some (more) complete and consistent BSM theory



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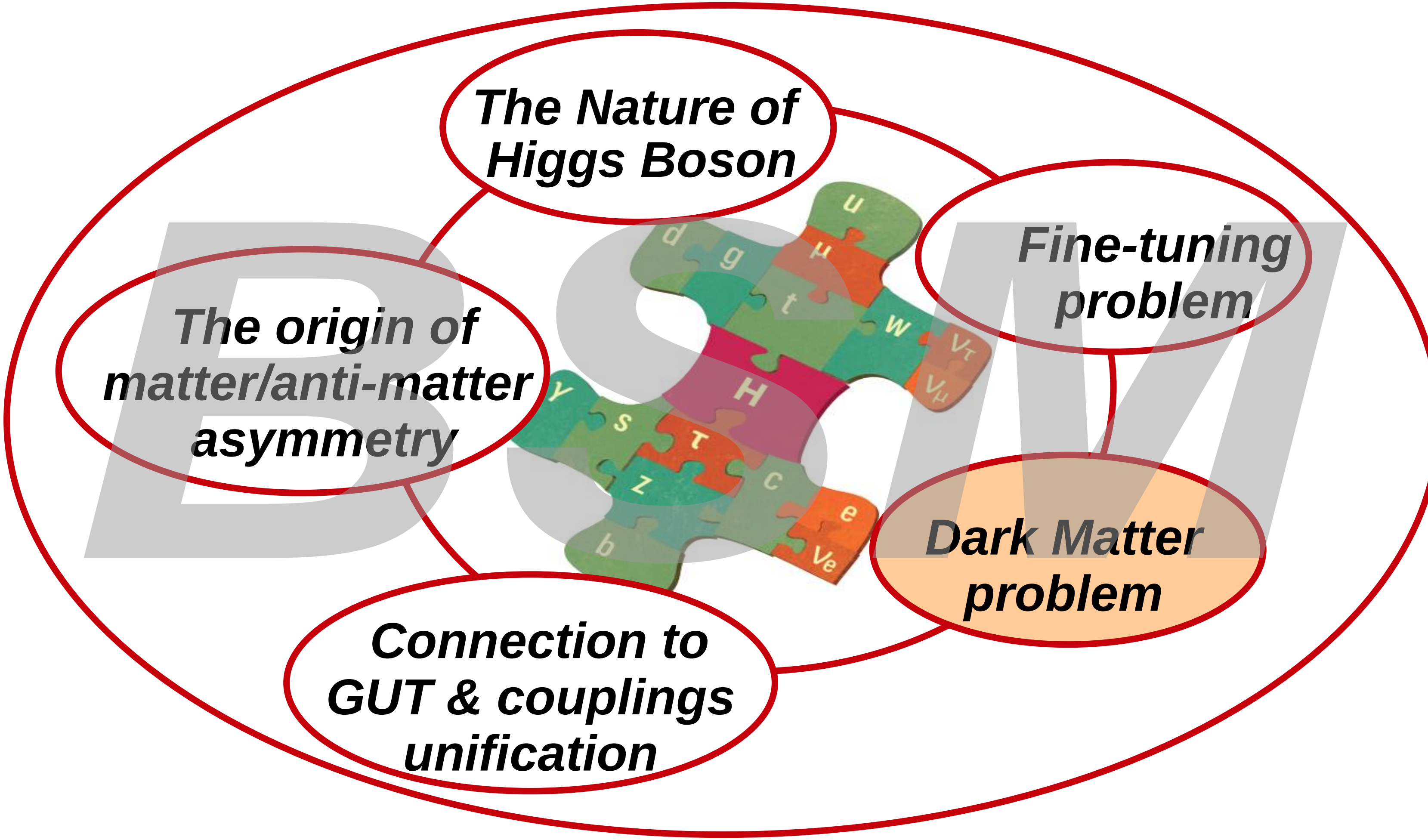


DM is very appealing even though we know almost nothing about it!

Spin ?

Mass ?

Stable

Yes ? No ?

symmetry behind stability ?

Couplings

- gravity V
- Weak ?
- Higgs ?
- Quarks/gluons ?
- Leptons ?
- New mediators ?

Thermal relic

Yes ? No ?

How we can decode the fundamental nature of Dark Matter?

How we can decode the fundamental nature of Dark Matter?

We need DM signal first!

How we can decode the fundamental nature of Dark Matter?

We need DM signal first!

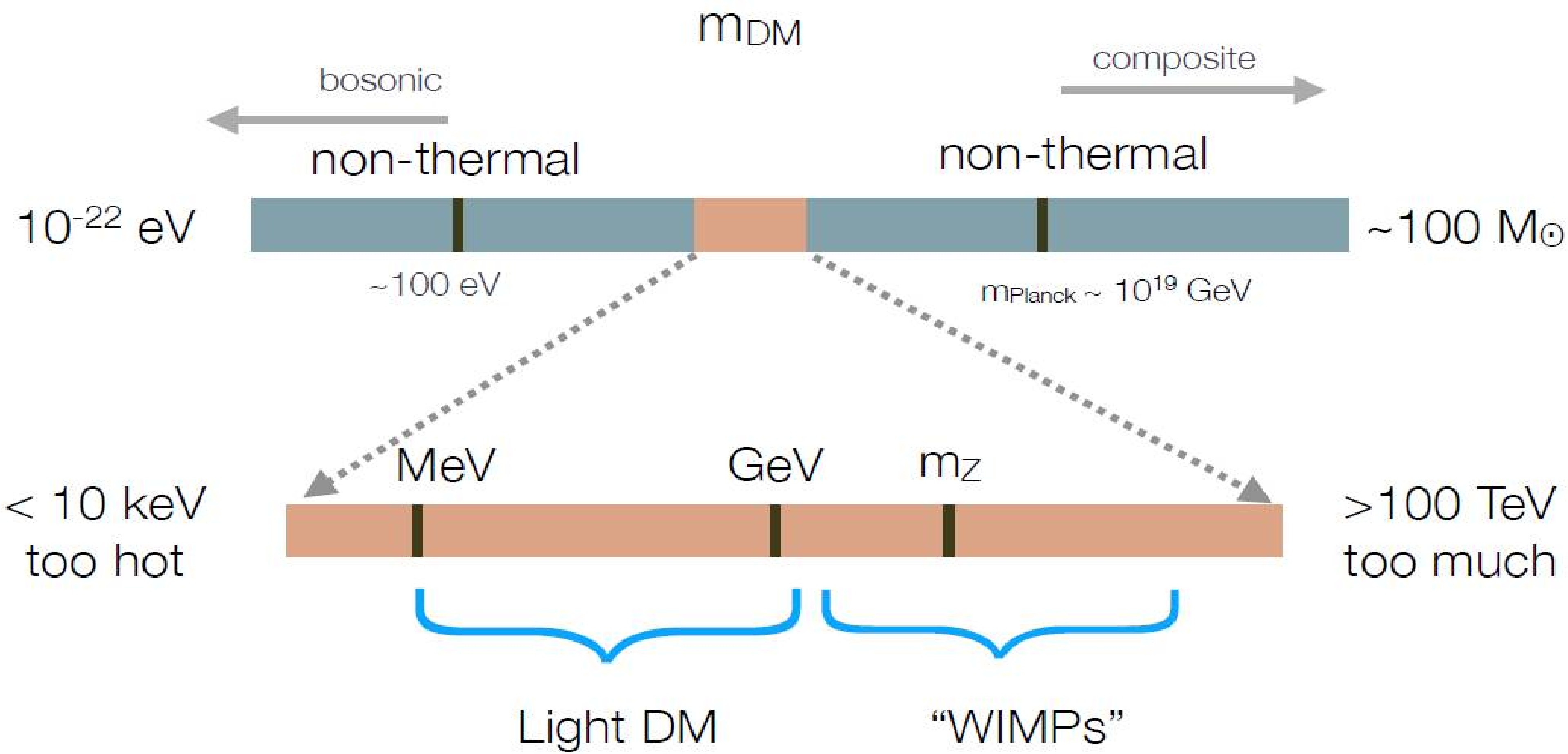
But at the moment we can:

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

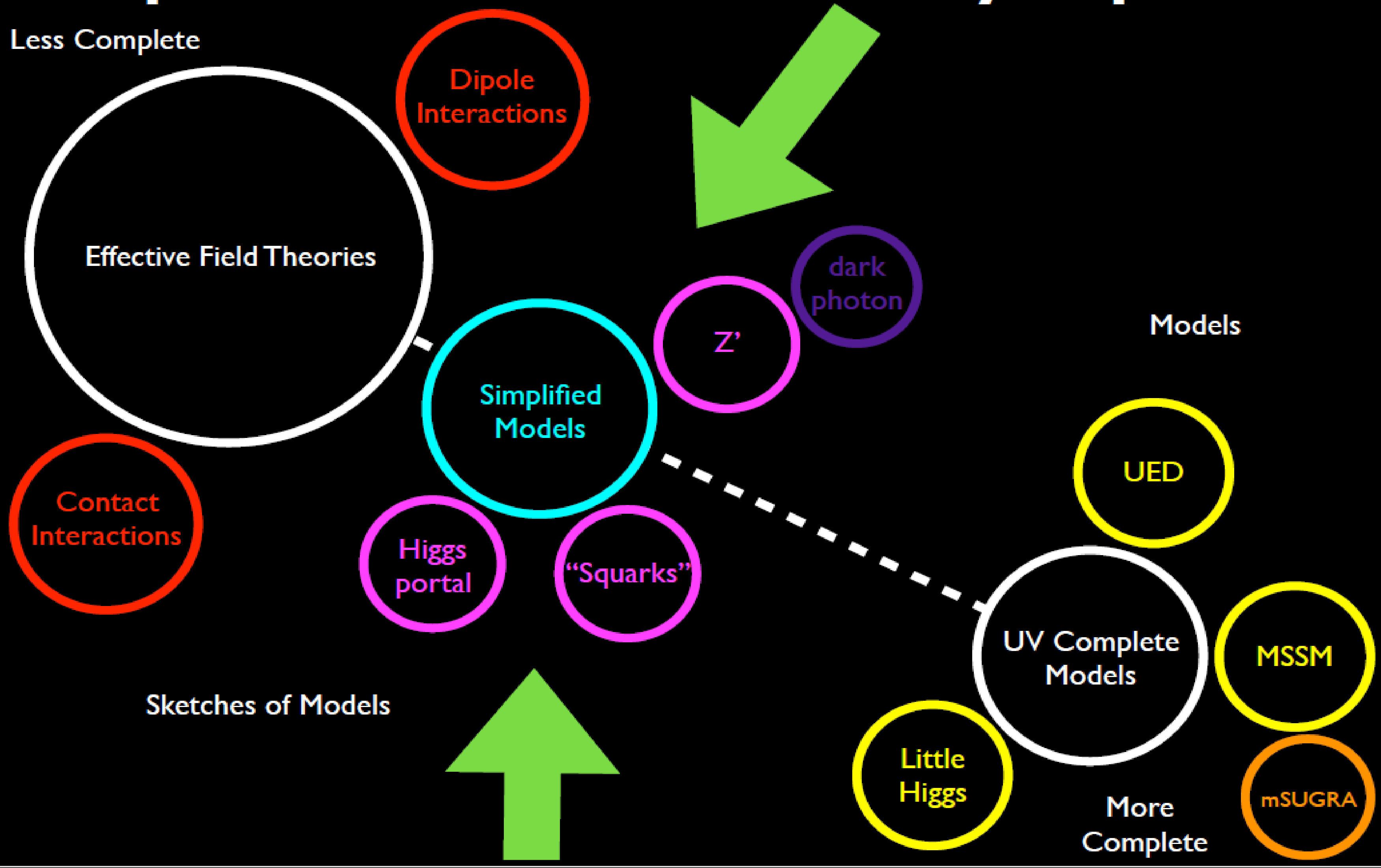
Collaborators & Projects

- I.Ginzburg, D.Locke, A. Freegard, T. Hosken, AB arXiv:**2006.xxxxx**
- S.Prestel, F.Rojas-Abate,J.Zurita, AB arXiv:**2008.08581**
- S.Novaes, P.Mercadante, C.S. Moon,T.Tomei,
  S. Moretti, M.Tomas, L. Panizzi, AB arXiv:**1809.00933**
- G.Cacciapaglia, J.McKay, D. Marin, A.Zerwekh, AB arXiv:**1808.10464**
- E.Bertuzzo, C.Caniu, G. di Cortona, O.Eboli,
  F. Iocco, A.Pukhov, AB arXiv:**1807.03817**
- T. Flacke, B. Jain, P. Schaefers, AB arXiv:**1707.07000**
- G. Cacciapaglia, I. Ivanov, F. Rojas, M. Thomas, AB arXiv:**1612.00511**
- I. Shapiro, M. Thomas, AB arXiv:**1611.03651**
- L. Panizzi, A. Pukhov, M.Thomas, AB arXiv:**1610.07545**
- D. Barducci, A.Bharucha, W. Porod, V. Sanz, AB arXiv:**1504.02472**

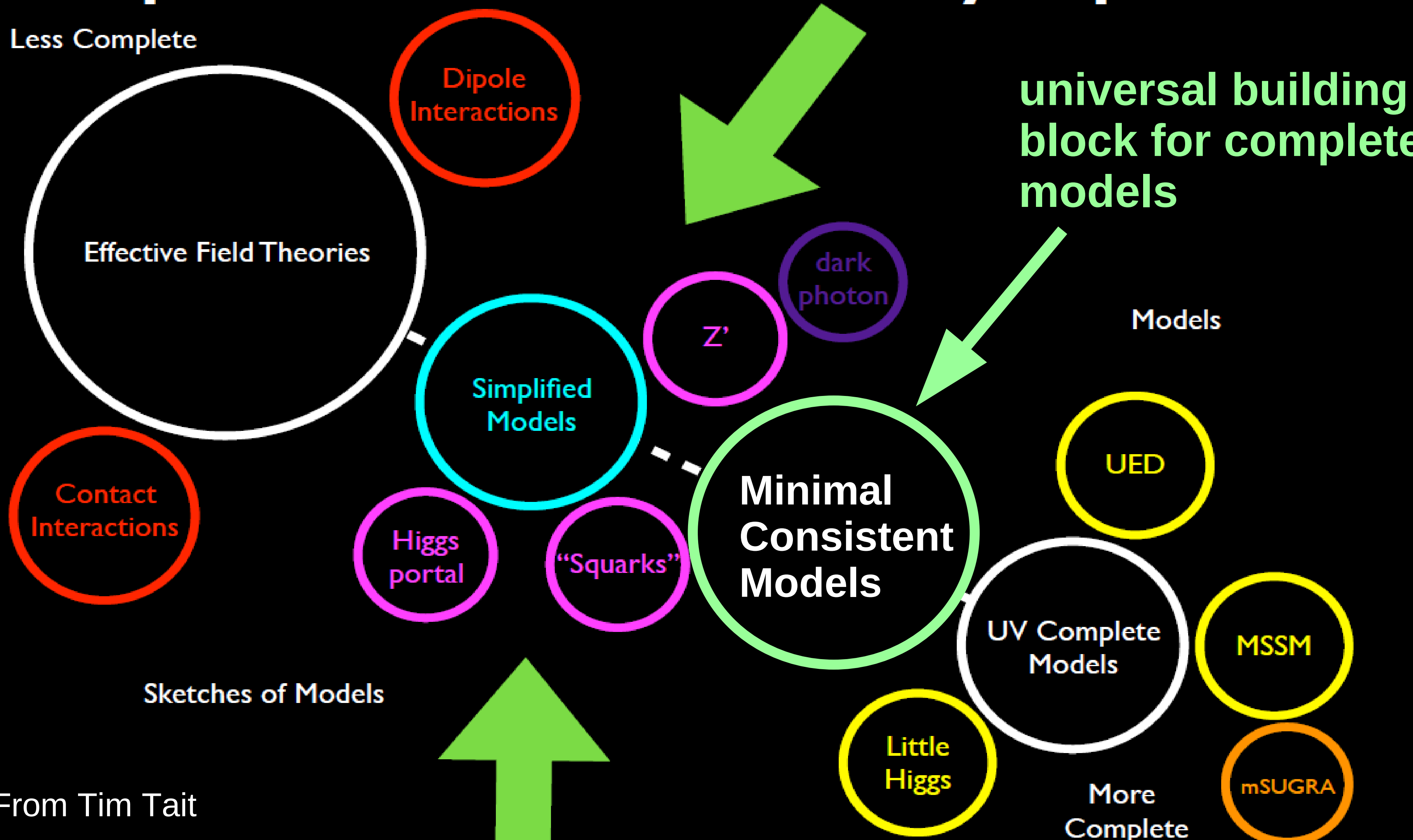
Mass range for thermal DM



Spectrum of Theory Space



Spectrum of Theory Space



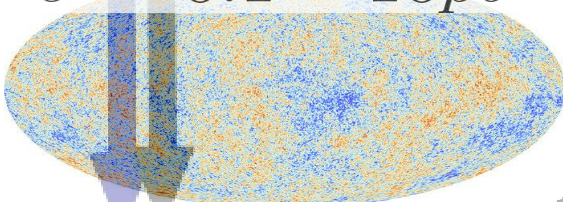
From Tim Tait

DM $\Omega h^2 \simeq 0.12$ DM

Correct Relic density: efficient (co) annihilation at the time of early Universe

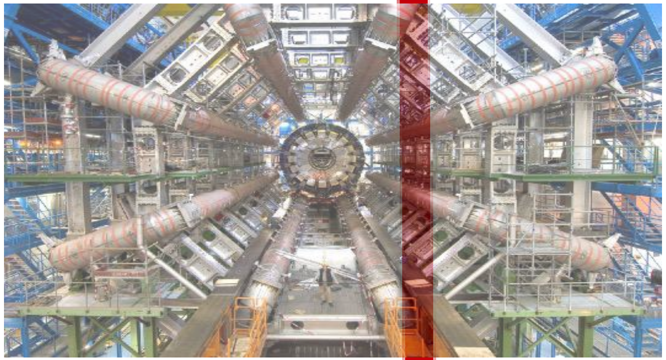
Efficient annihilation now: Indirect Detection

$\sigma \simeq 0.1 - 10pb$



Dark Matter (DM) Signatures

$M_{DM} \simeq 0.1 - 1TeV$



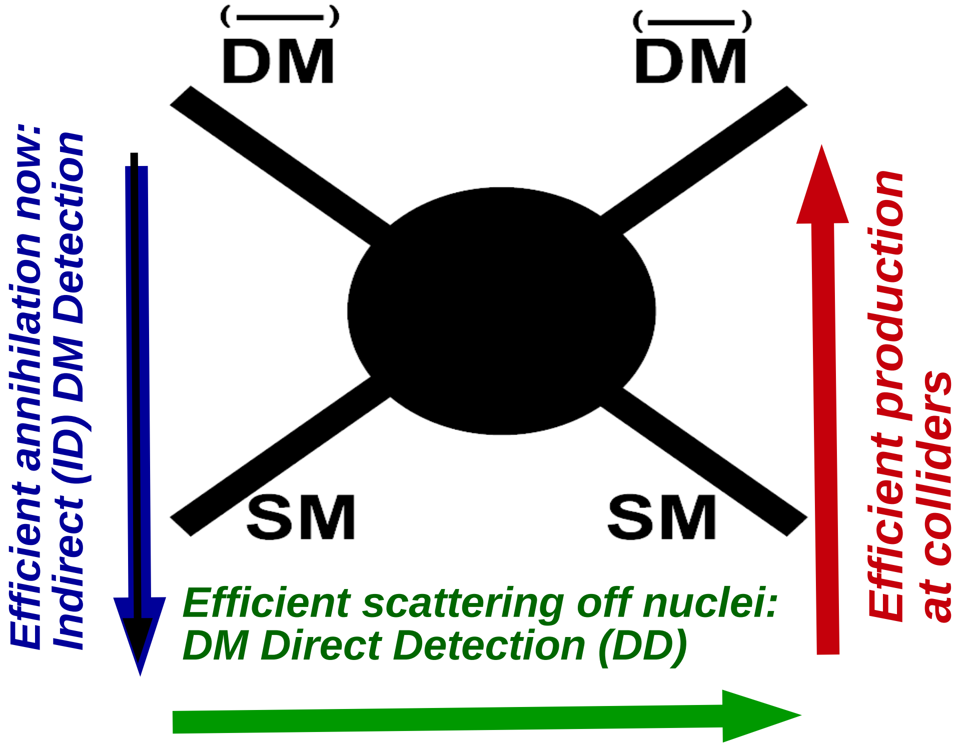
Efficient production at colliders

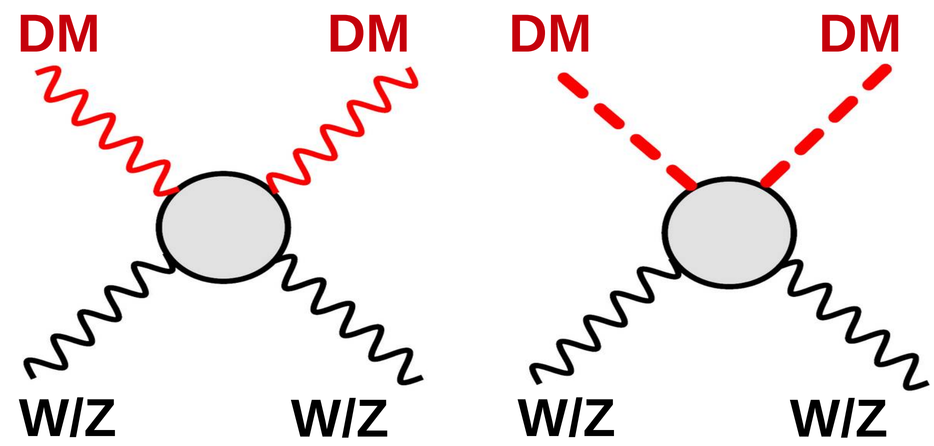
$\sigma_{SI} \simeq 10^{-10}pb$

SM  SM

Efficient scattering off nuclei: Direct Detection

Complementarity of DM searches





Example of DM interactions with 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!

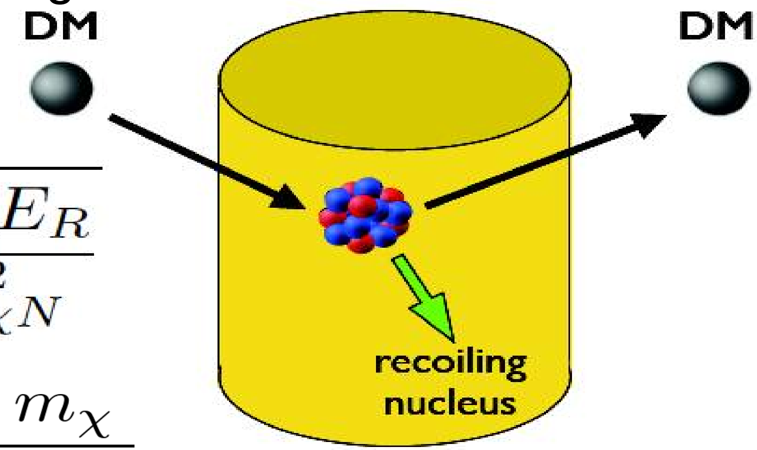
Actually there is a great complementarity in this:

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

Direct Dark Matter Detection

- Search for the recoil energy of a nucleus in an underground detector after collision with a WIMP

  Elastic recoil energy



$$E_R = \frac{2\mu_{\chi N}^2 v^2}{m_N} \cos^2\theta \qquad v_{\min} = \sqrt{\frac{m_N E_R}{2\mu_{\chi N}^2}}$$

- Minimum WIMP speed required to produce a recoil energy - **limitation in low DM mass region!**

$$\mu_{\chi N} = \frac{m_N \cdot m_\chi}{m_N + m_\chi}$$

- The differential event rate (per unit detector mass):

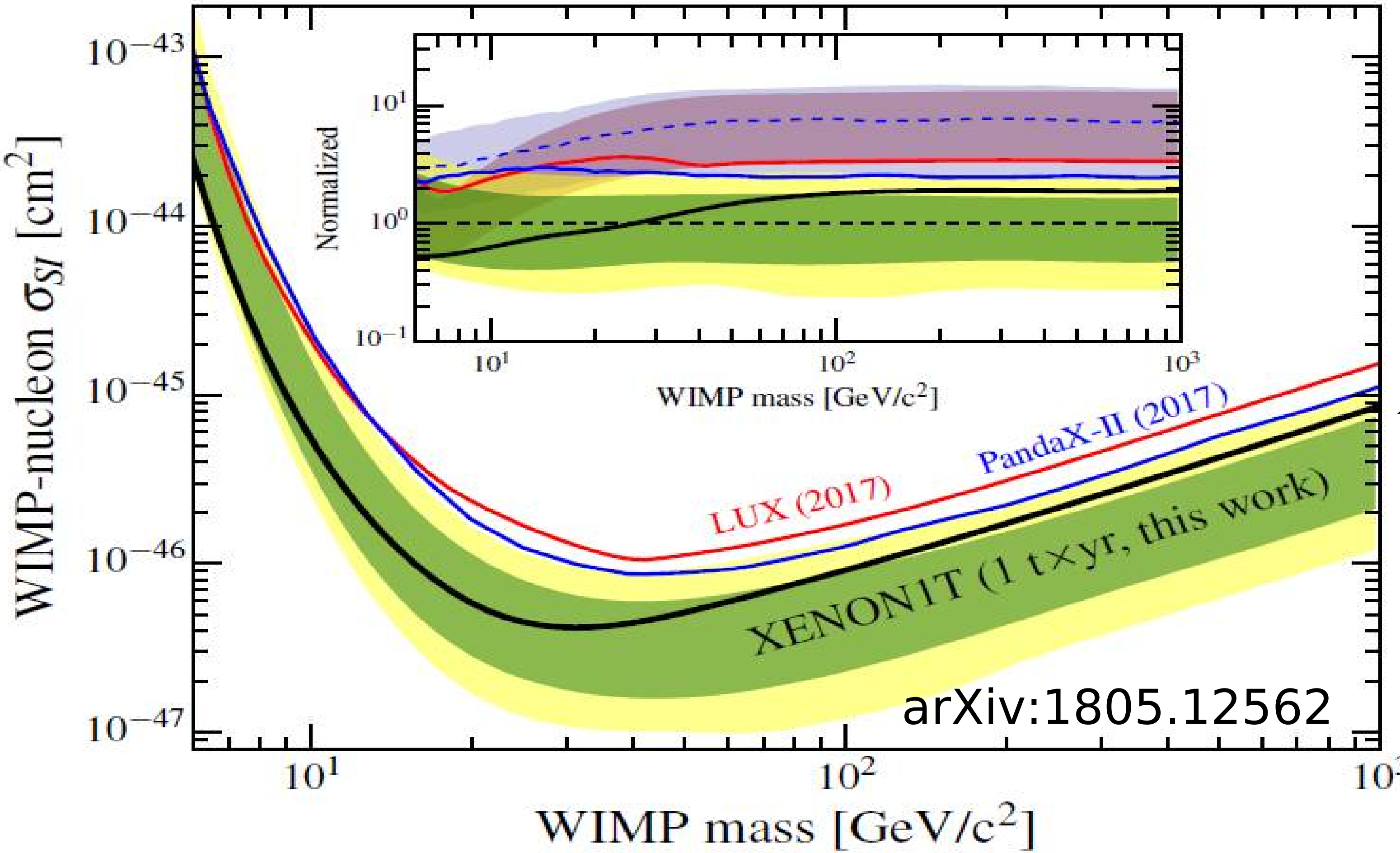
astrophysics

$$\frac{dR}{dE_R} = \frac{\rho_\chi}{m_\chi m_N} \int_{v > v_{\min}} d^3v \, \frac{d\sigma_{\chi N}}{dE_R} \, v \, f_{\rm det}(\mathbf{v}, t)$$

the source of uncertainty from the halo integral – from DM velocity and density distributions

XENON 1T results

10^{-46} cm^2 = 10^{-10} pb

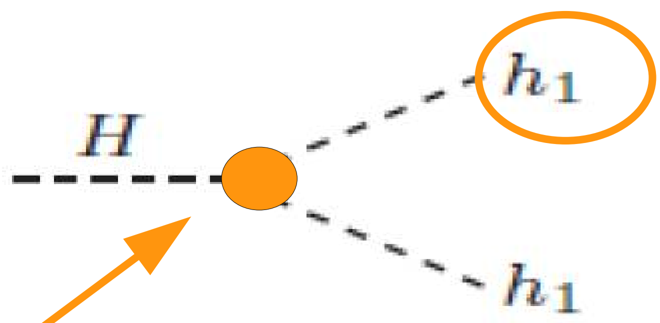


The limit scales linearly with M_{DM}

Power of DM DD to rule out theory space
Inert 2 Higgs Doublet Model

$$\phi_1 = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v+H \end{pmatrix} \qquad \phi_2 = \frac{1}{\sqrt{2}}\begin{pmatrix} \sqrt{2}h^+ \\ h_1 + ih_2 \end{pmatrix}$$

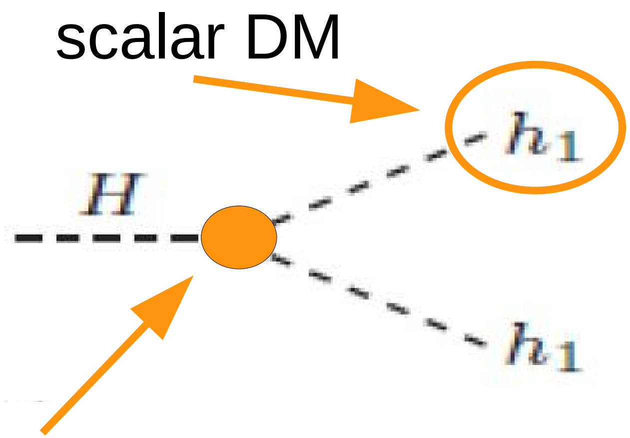
$$\begin{aligned} V &= -m_1^2(\phi_1^\dagger\phi_1) - m_2^2(\phi_2^\dagger\phi_2) + \lambda_1(\phi_1^\dagger\phi_1)^2 + \lambda_2(\phi_2^\dagger\phi_2)^2 \\ &+ \lambda_3(\phi_1^\dagger\phi_1)(\phi_2^\dagger\phi_2) + \lambda_4(\phi_2^\dagger\phi_1)(\phi_1^\dagger\phi_2) + \frac{\lambda_5}{2}\left[(\phi_1^\dagger\phi_2)^2 + (\phi_2^\dagger\phi_1)^2\right] \end{aligned}$$



scalar DM

$$\lambda_{345} = \lambda_3 + \lambda_4 + \lambda_5$$

Power of DM DD to rule out theory space
Inert 2 Higgs Doublet Model



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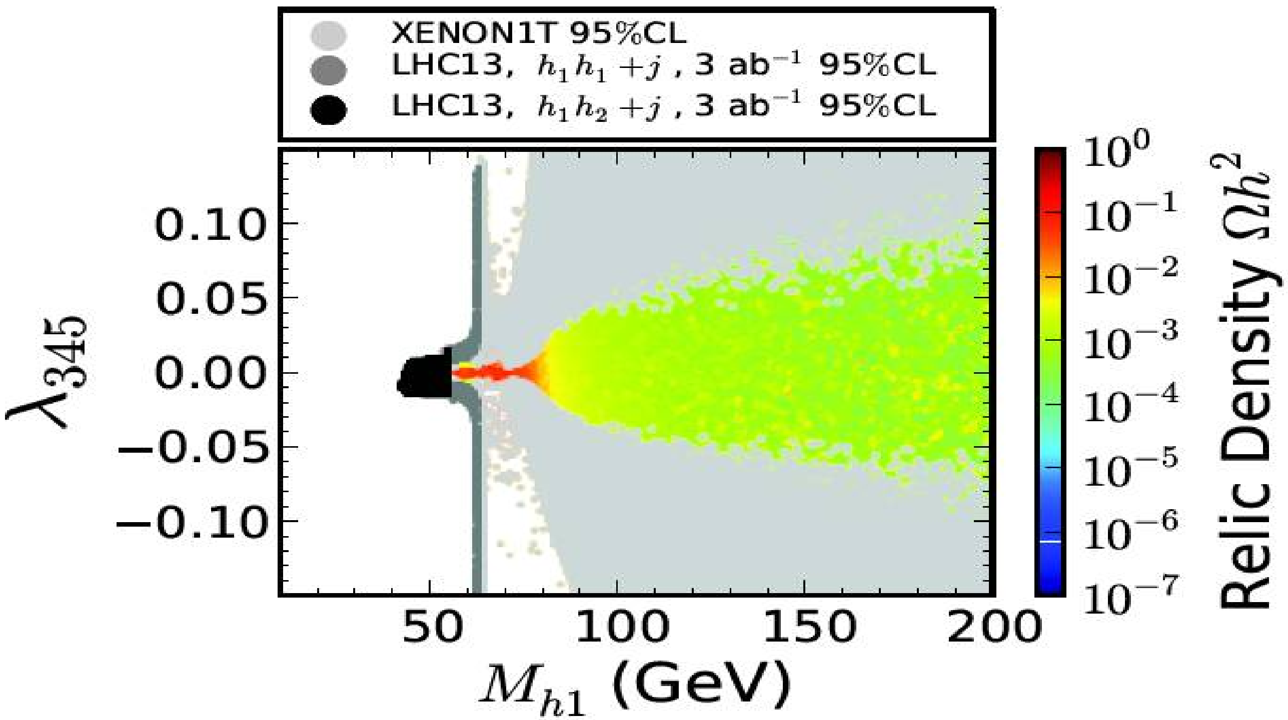
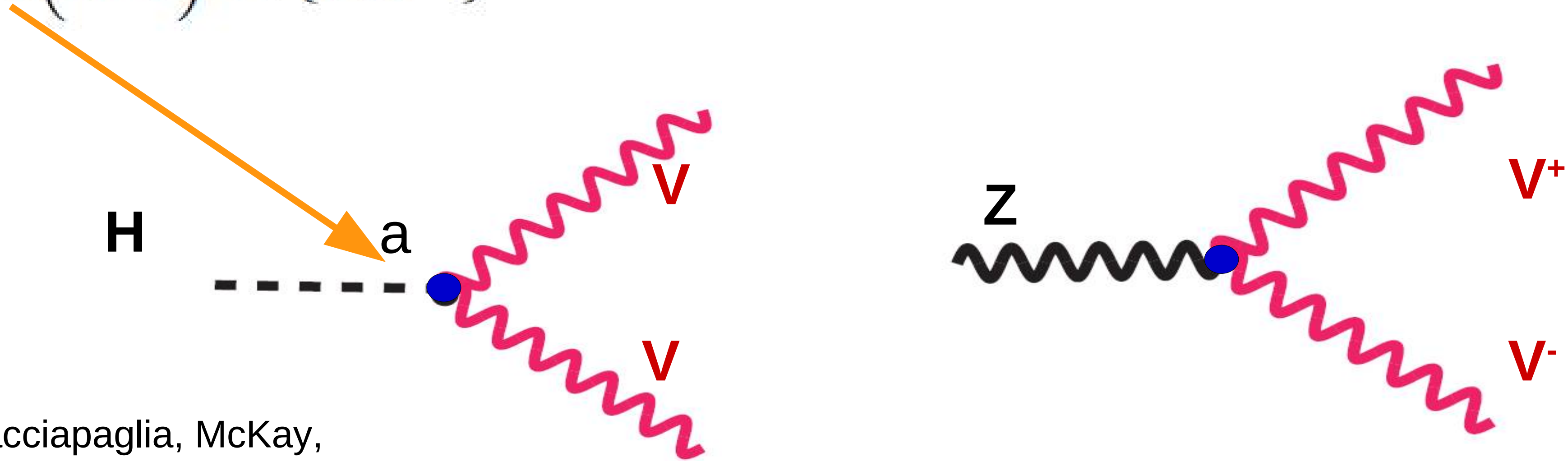


Cacciapaglia, Ivanov, Rojas, Thomas, AB arXiv:**1610.07545**
Novaes, Mercadante, Moon,Tomei, Moretti,Tomas, Panizzi, AB arXiv:**1809.00933**

Power of DM DD to rule out theory space
Vector DM (VDM) Model

$$\mathcal{L} = \mathcal{L}_{SM} - Tr\{D_\mu V_\nu D^\mu V^\nu\} + Tr\{D_\mu V_\nu D^\nu V^\mu\}$$
$$-\frac{g^2}{2} Tr\{[V_\mu, V_\nu][V^\mu, V^\nu]\}$$
$$-igTr\{W_{\mu\nu}[V^\mu, V^\nu]\} + \tilde{M}^2 Tr\{V_\nu V^\nu\}$$
$$+a\left(\Phi^\dagger \Phi\right) Tr\{V_\nu V^\nu\}$$

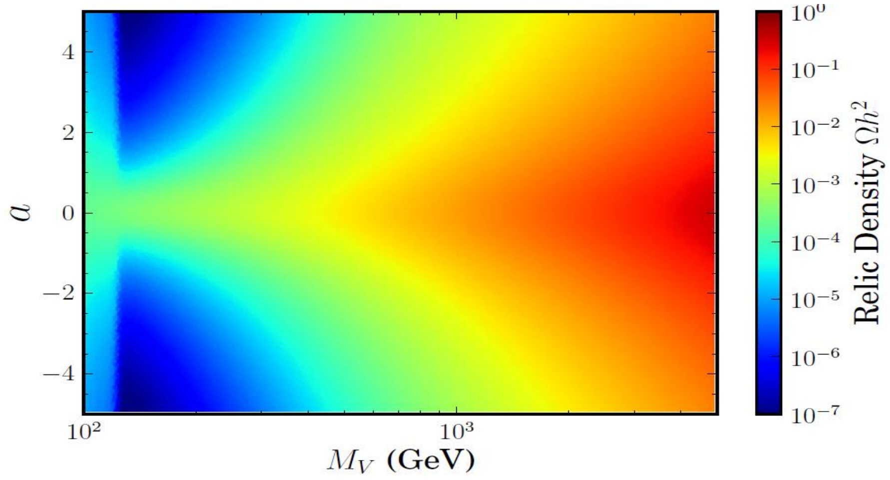
- DM from vector triplet
- SM gauge coupling
- $V_{DM}V_{DM}H$ coupling is the only free parameter



AB,Cacciapaglia, McKay, Martin, Zerwekh, arXiv:**1808.10464**

The probe of VDM parameter space

The relic density map in M_V- a parameter space



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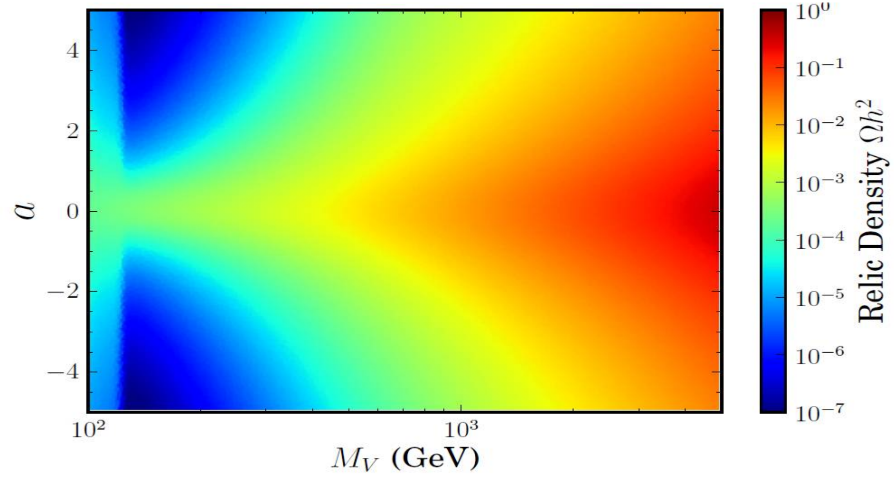

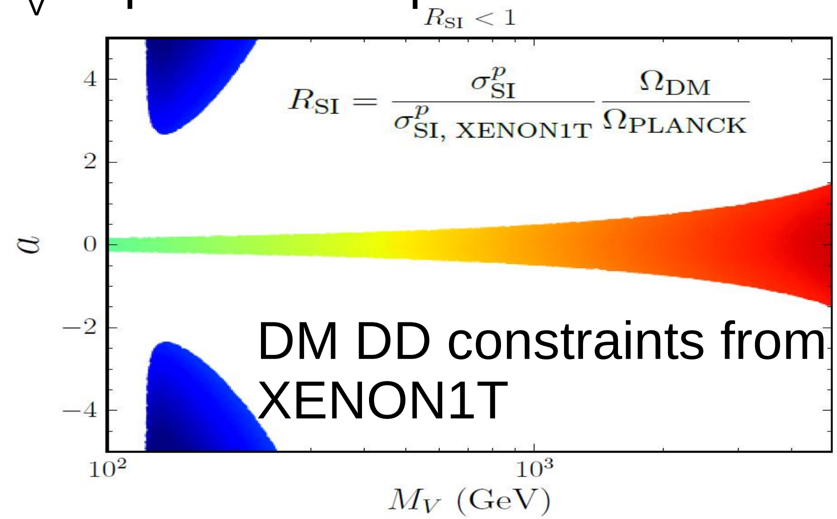

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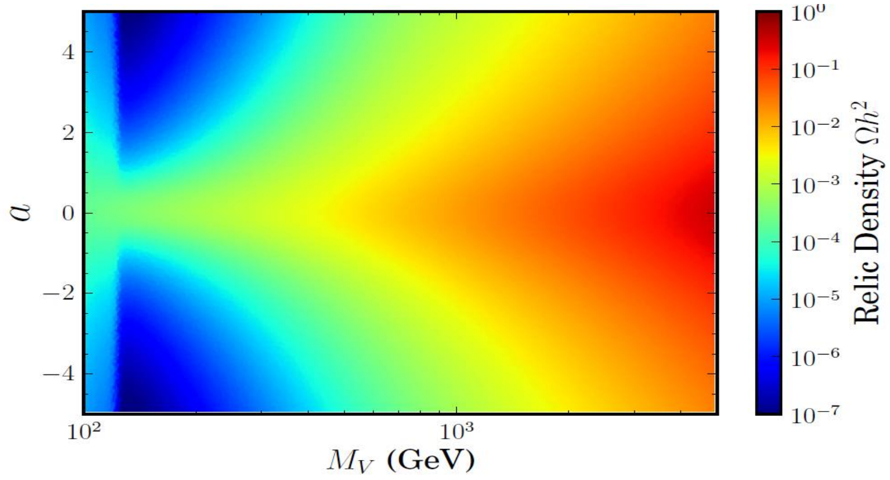
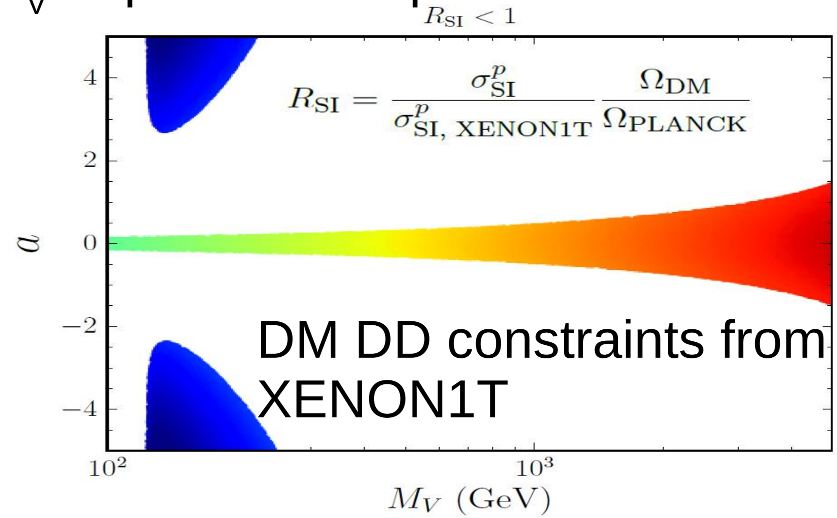
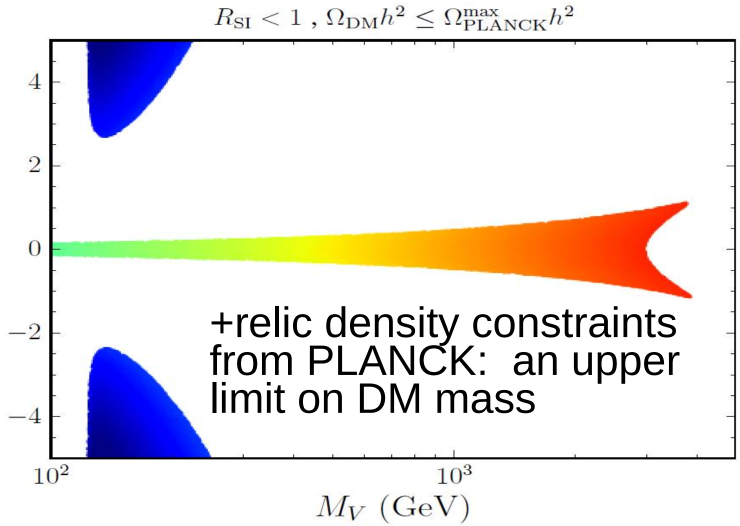




DM DD constraints from XENON1T



+relic density constraints from PLANCK: an upper limit on DM mass

- ZENON 1T + Planck excludes **both** large $HV_{DM}V_{DM}$ couplings and large M_{DM}
- The **lower masses** (rest of space) can be covered at colliders

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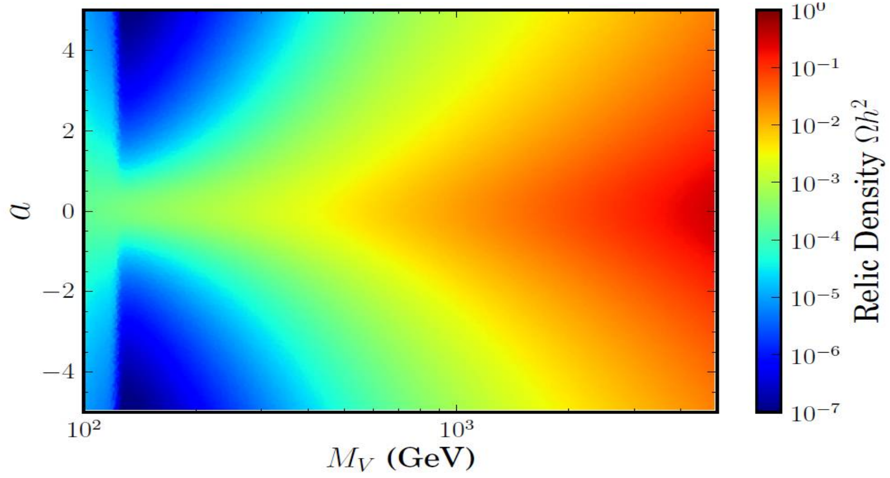
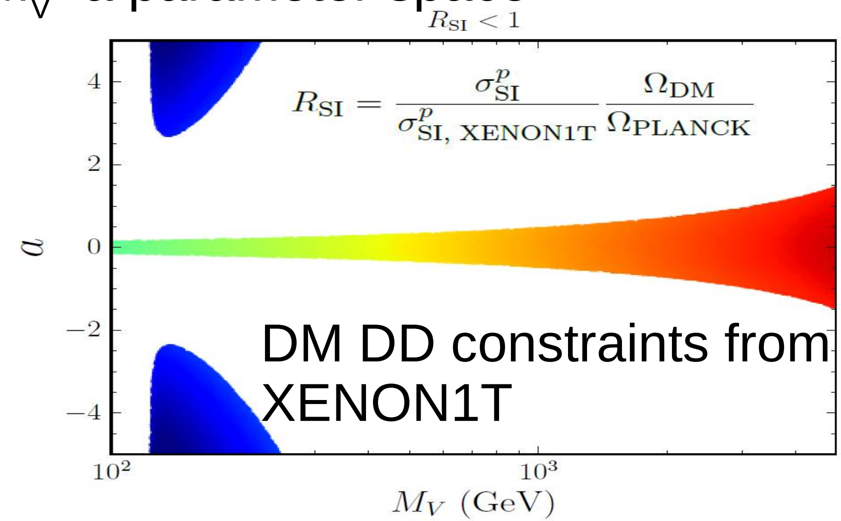
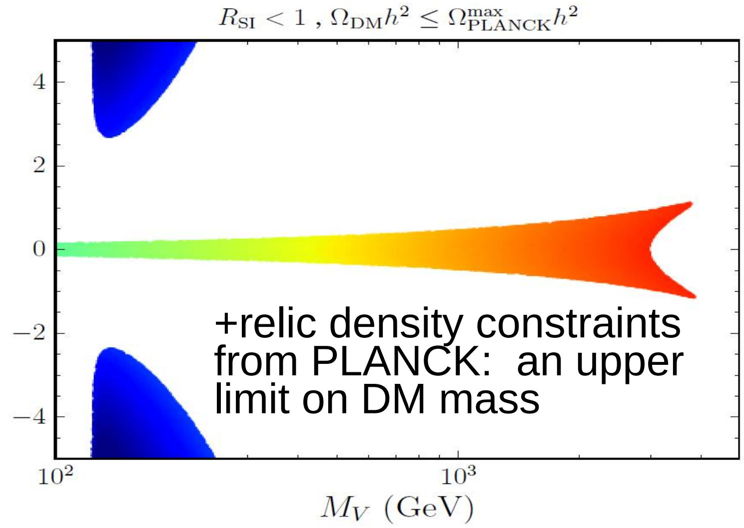
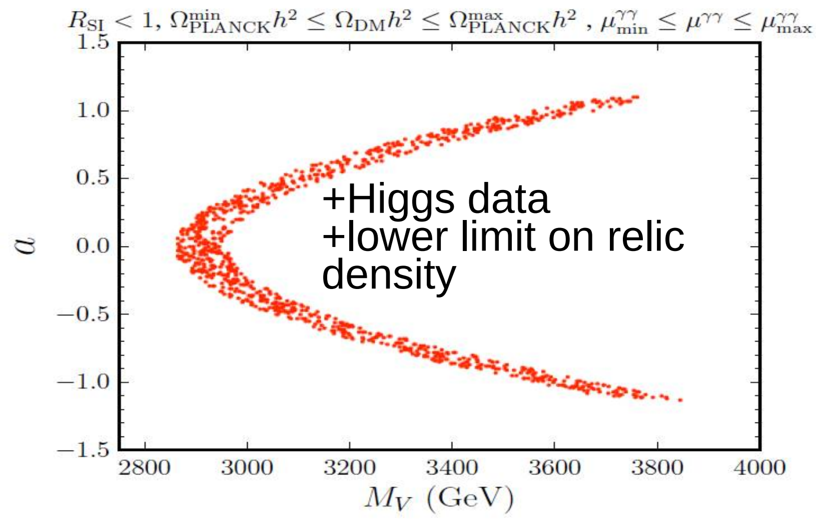
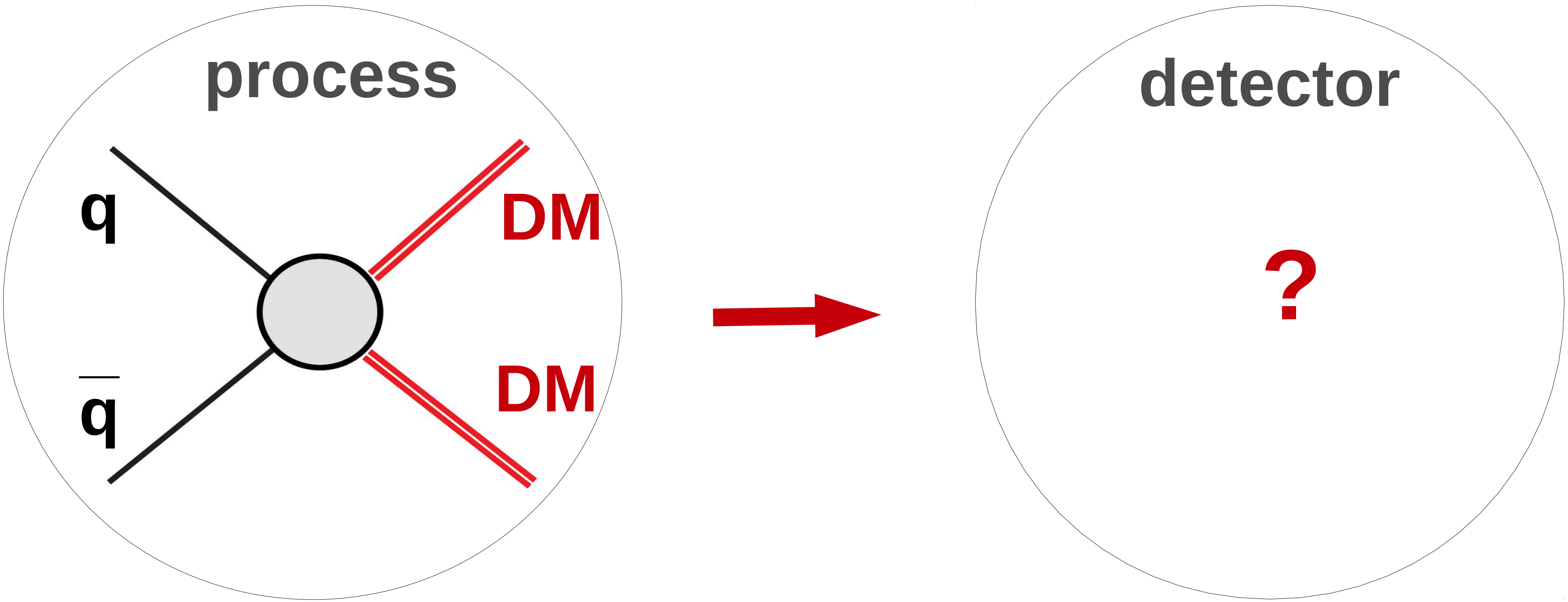




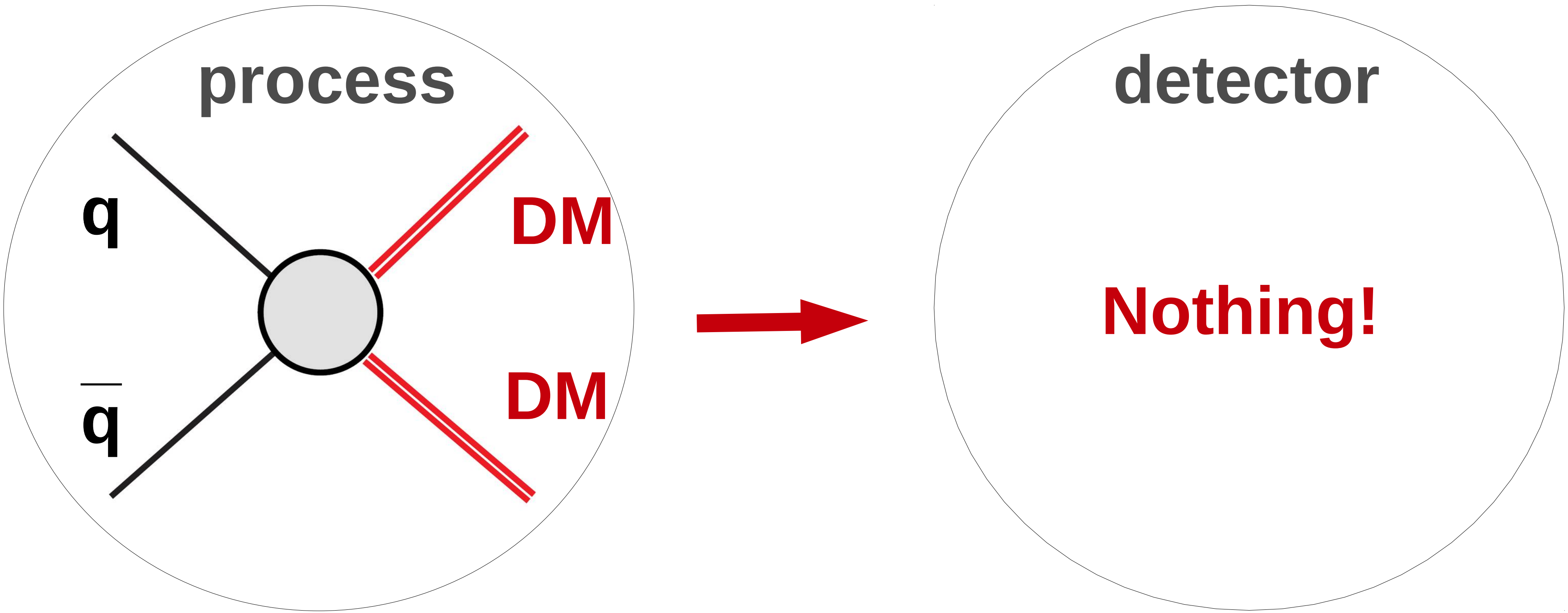




DM DD interplay with Collider Searches



Hunting for DM at Colliders



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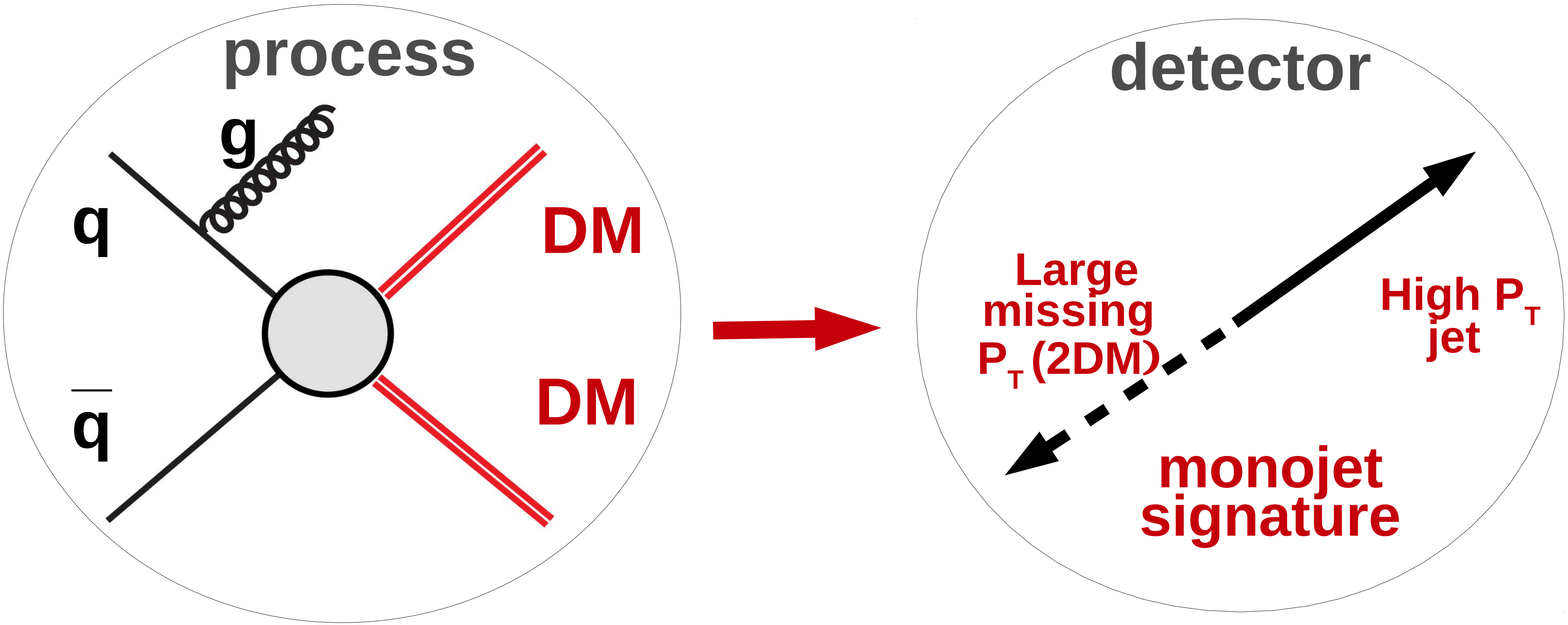


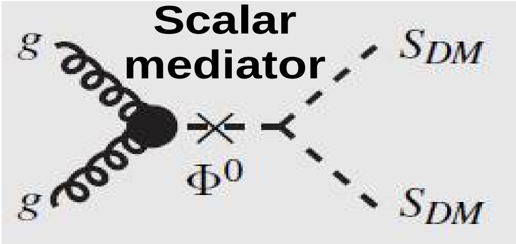
Probing DM properties at the LHC

Can we to probe DM operators with different DM spin using the shape missing transverse momentum **(MET)** only?

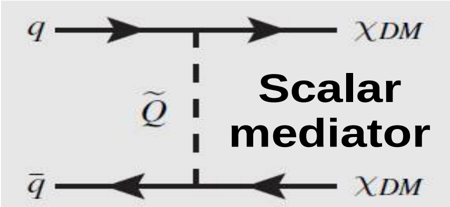
- we use the EFT approach: simplicity and model independence
- explore the complete set of DIM5/DIM6 operators involving two SM quarks (gluons) and two DM particles
- consider DM with spin=0, 1/2, 1
- use mono-jet signature at the LHC

Mapping EFT operators to simplified models

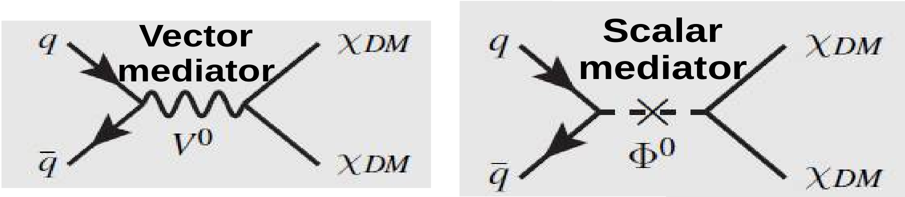
C5,C5A $\frac{1}{\Lambda^2}\phi^*\phi G^{\mu\nu}G^{\mu\nu}$ $\frac{1}{\Lambda^2}\phi^*\phi\tilde{G}^{\mu\nu}G^{\mu\nu}$ →



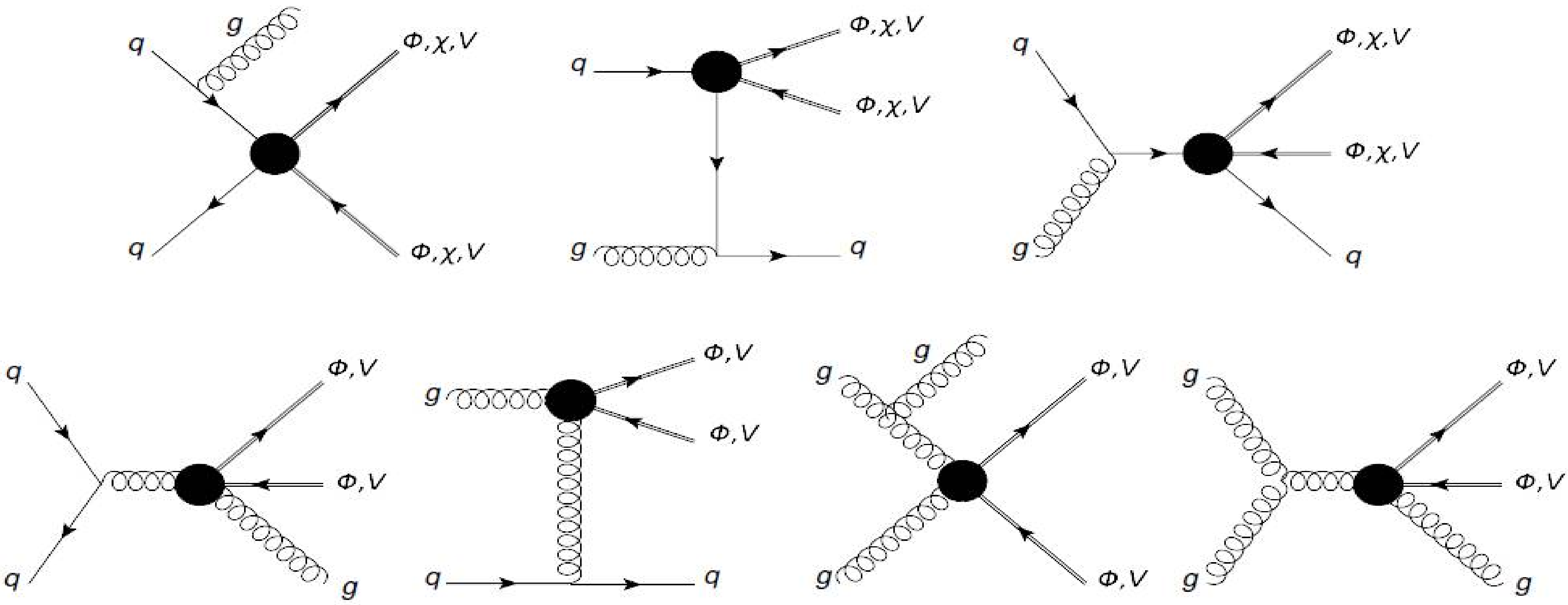
D1T-D4T $\frac{1}{\Lambda^2}\bar{\chi}q\bar{q}\chi$ →



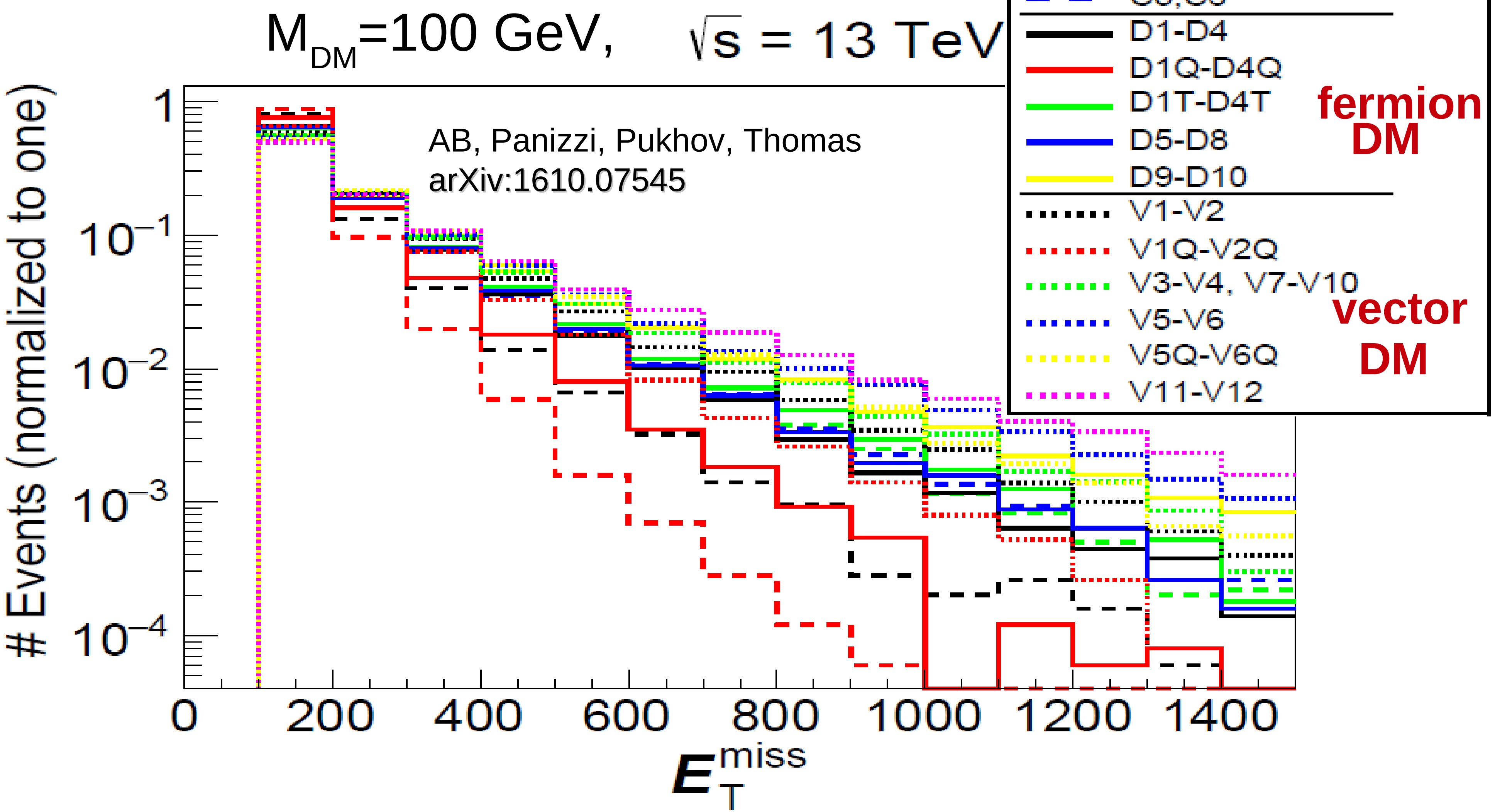
D1-D4, D5-D8 $\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$ $\frac{1}{\Lambda^2}\bar{\chi}\chi\bar{q}q$ →



Mono-jet diagrams from EFT operators

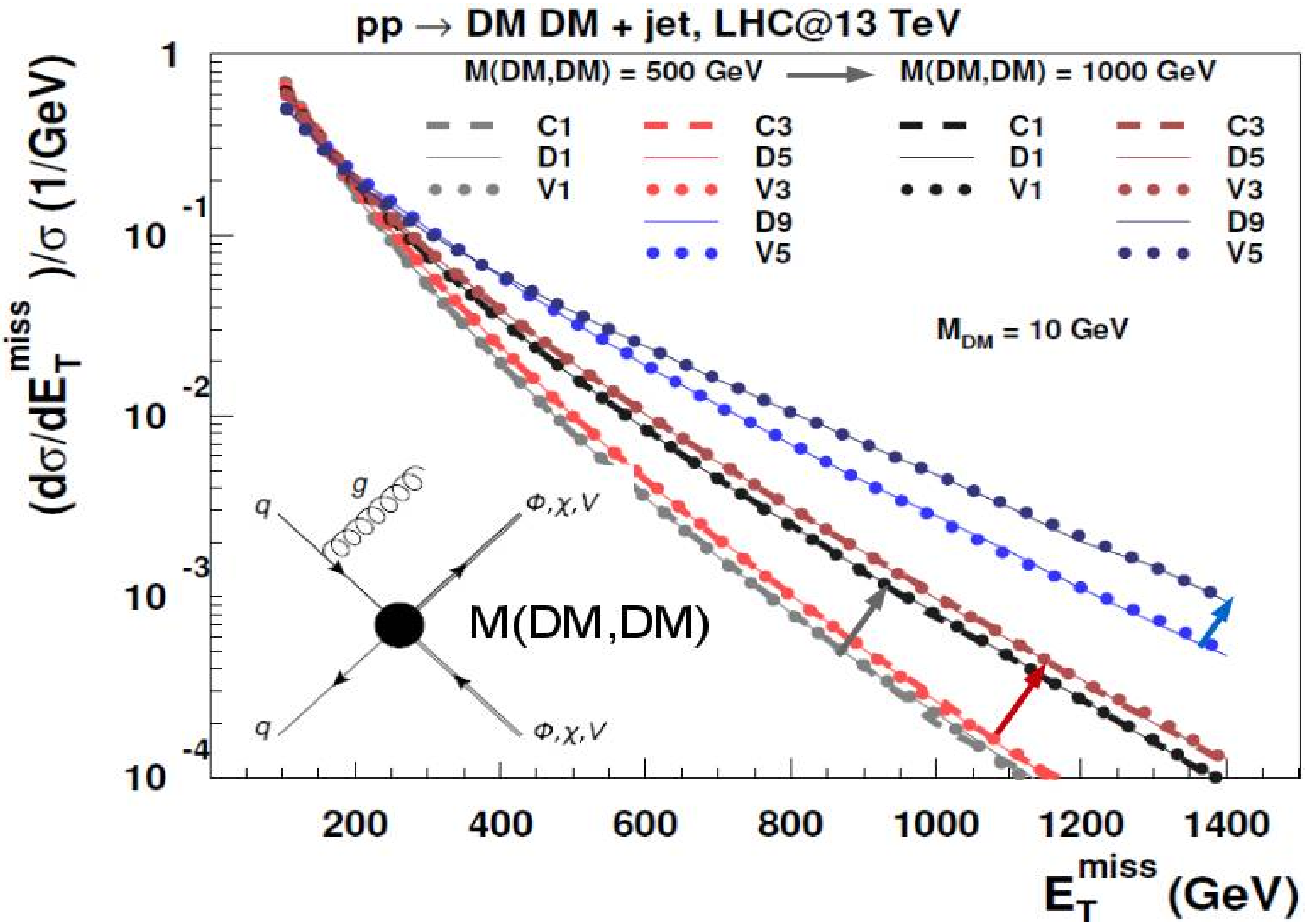


Missing E_T (MET) distributions: the large range of slopes



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)



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

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

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

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

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

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

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

Properties of MET distributions for small and large M(DM,DM)

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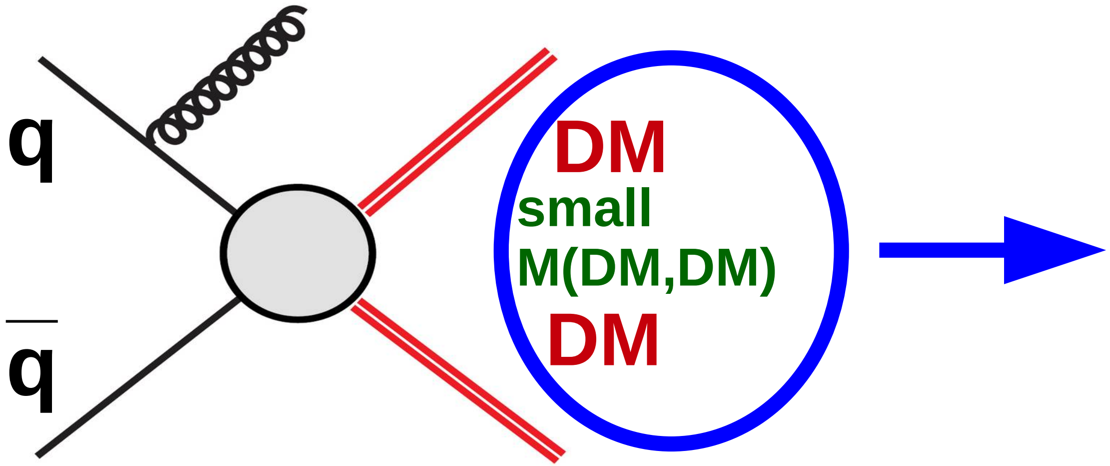

for p_T(g) increase
Δ (x1 x2)/(x1 x2) is large
and MET slope is steep

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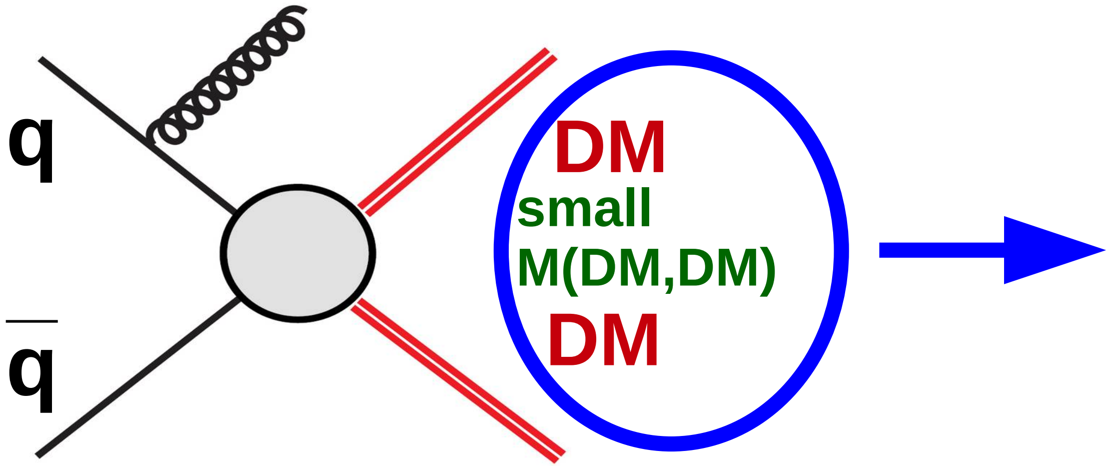

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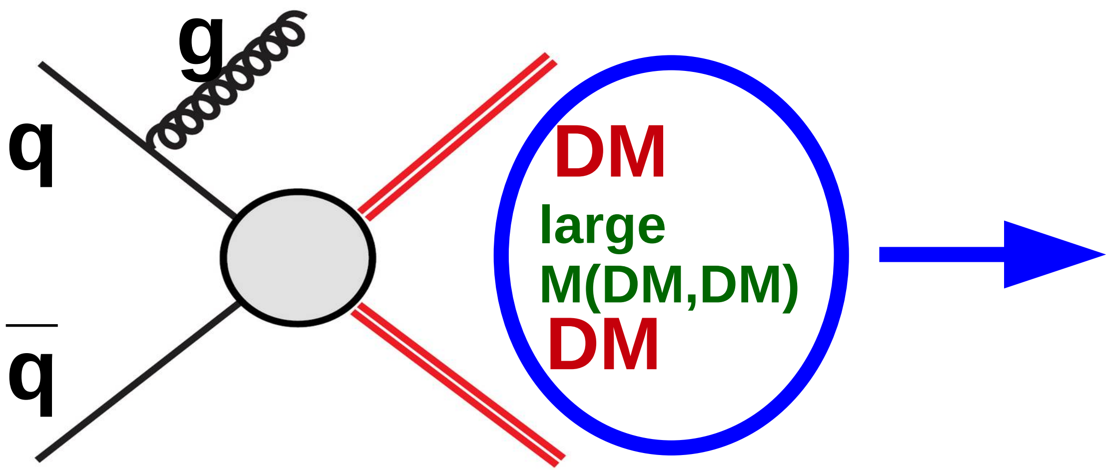
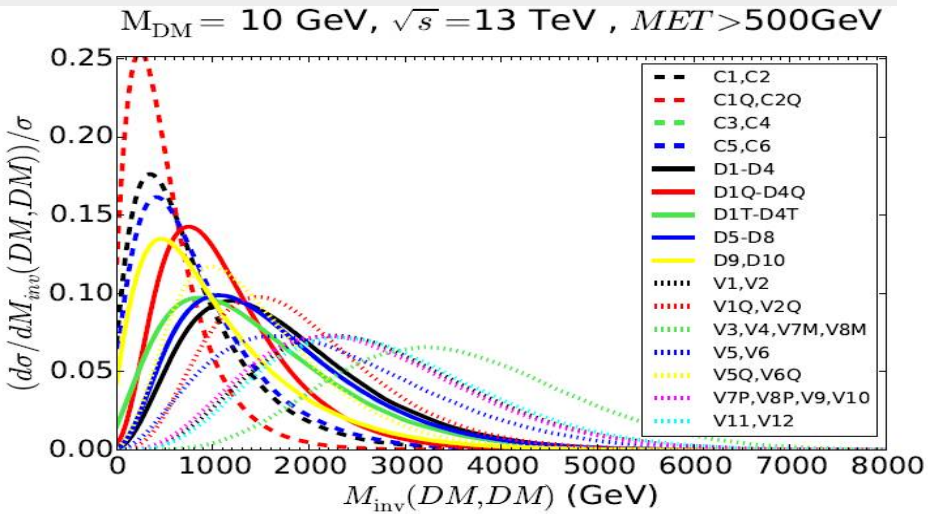
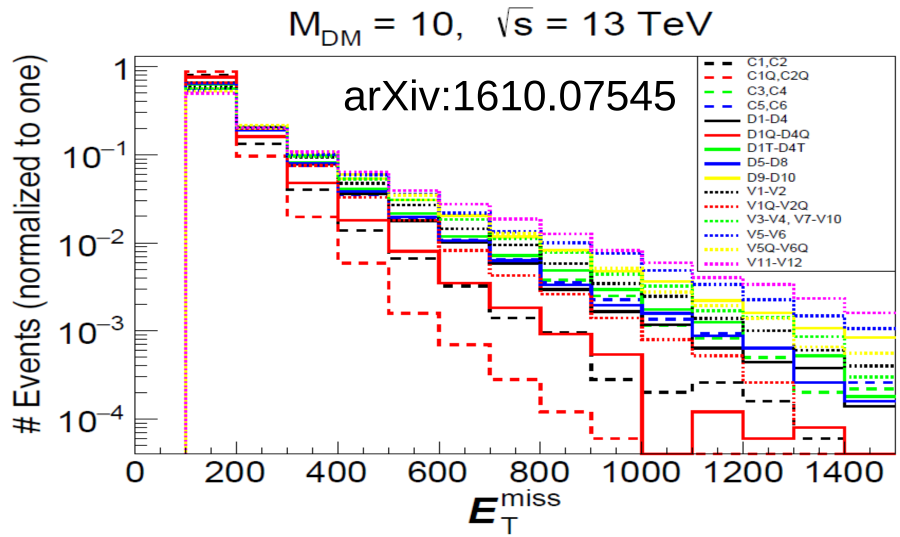


for p_T(g) increase
Δ (x1 x2)/(x1 x2) is small
and MET slope is gradual

Distinguishing DM operators/theories

The harder M(DM,DM) distributions ⟷ **The flatter MET shapes**





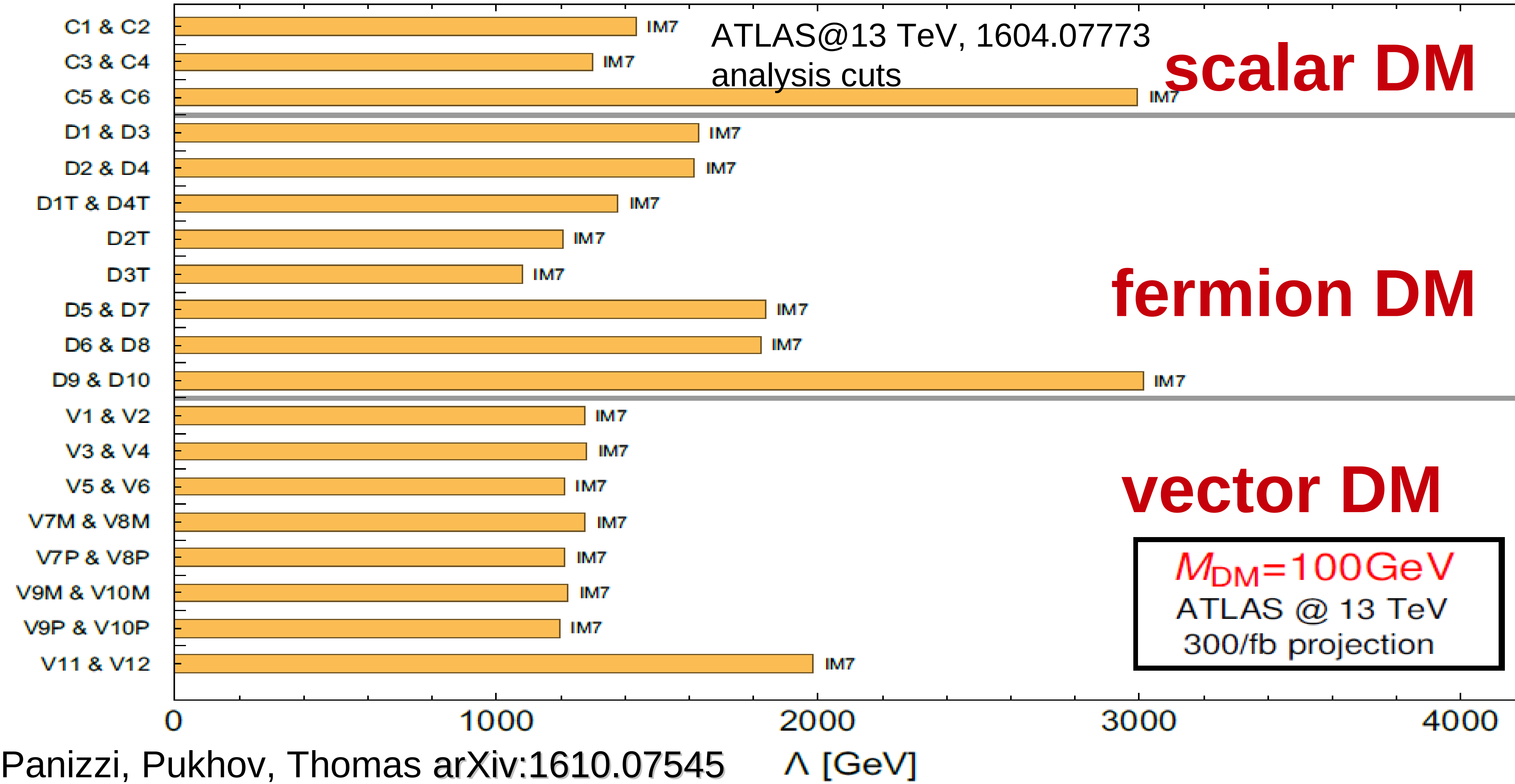
operator energy dependence → M_{DMDM} shape → MET shape

- 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

- 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 $2M_{DM}$

LHC@13TeV reach projected 100 fb^{-1}

LanHEP → CalcHEP → LHE → CheckMATE



AB, Panizzi, Pukhov, Thomas arXiv:1610.07545

Distinguishing the DM operators: χ^2 for pairs of DM operators

$$\chi^2_{k,l} = \min_{\kappa} \sum_{i=3}^{7} [(\frac{1}{2} N_i^k - \kappa \cdot N_i^l)/(10^{-2} BG_i)]^2$$

: if χ^2>9.48 (95%CL for 4 DOF) – operators can be distinguished!

			Complex Scalar DM				Dirac Fermion DM			
			100 GeV		1000 GeV		100 GeV		1000 GeV	
			C1	C5	C1	C5	D1	D9	D1	D9
Complex Scalar DM	100 GeV	C1	0.0	**19.7**	**25.54**	**74.63**	**11.73**	**41.79**	**25.78**	**52.58**
		C5	**15.74**	0.0	0.37	**16.25**	1.11	3.93	0.74	7.35
	1000 GeV	C1	**19.89**	0.36	0.0	**11.82**	2.33	2.09	0.27	4.58
		C5	**50.86**	**13.86**	**10.34**	0.0	**21.03**	3.7	**11.18**	1.53
Dirac Fermion DM	100 GeV	D1	**9.88**	1.17	2.52	**25.99**	0.0	9.23	2.4	**14.17**
		D9	**30.49**	3.59	1.96	3.96	7.99	0.0	2.71	0.52
	1000 GeV	D1	**20.31**	0.73	0.27	**12.92**	2.25	2.93	0.0	5.42
		D9	**37.38**	6.54	4.18	1.6	**11.96**	0.5	4.89	0.0

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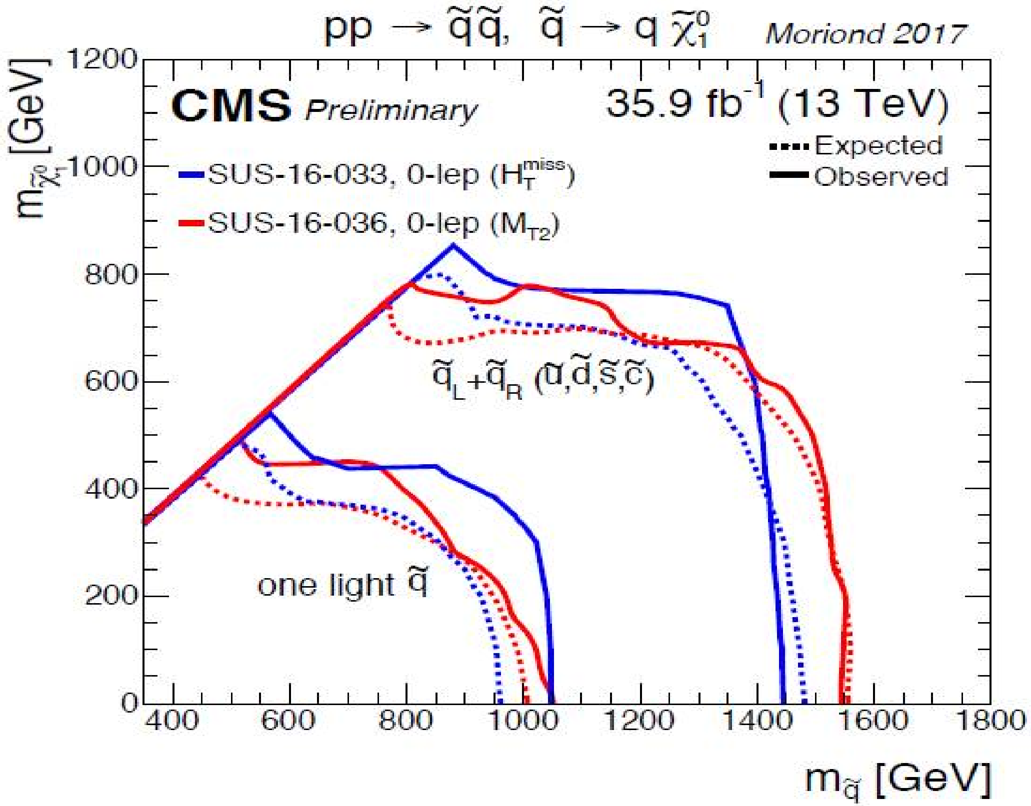
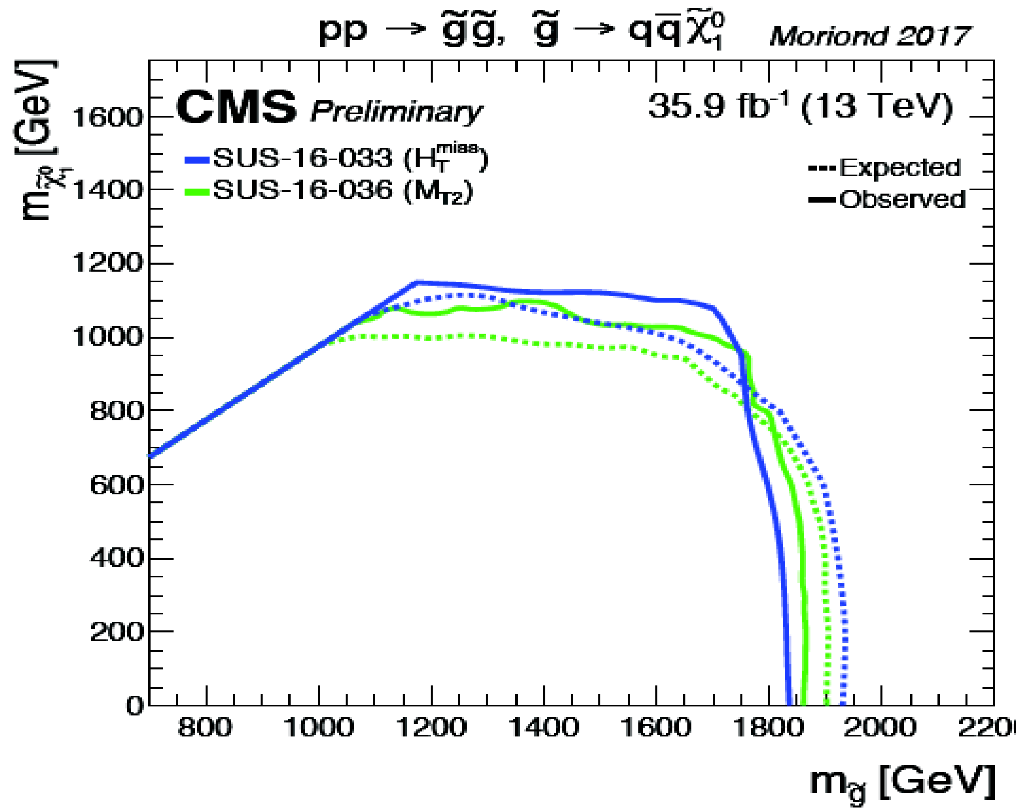
			Complex Scalar DM				Dirac Fermion DM				Complex Vector DM							
			100 GeV		1000 GeV		100 GeV		1000 GeV		100 GeV				1000 GeV			
			C1	C5	C1	C5	D1	D9	D1	D9	V1	V3	V5	V11	V1	V3	V5	V11
Complex Scalar DM	100 GeV	C1	0.0	19.7	25.54	74.63	11.73	41.79	25.78	52.58	22.97	32.89	54.35	73.34	25.18	34.61	52.34	80.85
		C5	15.74	0.0	0.37	16.25	1.11	3.93	0.74	7.35	0.18	1.53	8.2	15.73	0.44	1.9	7.24	19.13
	1000 GeV	C1	19.89	0.36	0.0	11.82	2.33	2.09	0.27	4.58	0.06	0.45	5.29	11.41	0.06	0.68	4.42	14.36
		C5	50.86	13.86	10.34	0.0	21.03	3.7	11.18	1.53	11.57	6.82	1.26	0.01	10.84	6.1	1.61	0.14
Dirac Fermion DM	100 GeV	D1	9.88	1.17	2.52	25.99	0.0	9.23	2.4	14.17	1.85	5.09	15.34	25.37	2.29	5.85	13.85	29.81
		D9	30.49	3.59	1.96	3.96	7.99	0.0	2.71	0.52	2.49	0.62	0.73	3.69	2.31	0.39	0.56	5.36
	1000 GeV	D1	20.31	0.73	0.27	12.92	2.25	2.93	0.0	5.42	0.32	0.82	6.33	12.58	0.08	1.18	5.08	15.7
		D9	37.38	6.54	4.18	1.6	11.96	0.5	4.89	0.0	4.98	2.02	0.06	1.44	4.56	1.61	0.04	2.55
Complex Vector DM	100 GeV	V1	18.06	0.17	0.06	13.34	1.72	2.68	0.32	5.5	0.0	0.77	6.25	12.9	0.1	1.06	5.34	16.03
		V3	24.86	1.45	0.44	7.57	4.57	0.65	0.79	2.14	0.74	0.0	2.68	7.25	0.57	0.03	2.04	9.59
		V5	38.36	7.24	4.79	1.3	12.86	0.7	5.67	0.06	5.61	2.5	0.0	1.14	5.24	2.04	0.13	2.13
		V11	50.03	13.43	10.0	0.01	20.55	3.45	10.89	1.39	11.2	6.54	1.11	0.0	10.52	5.83	1.49	0.16
	1000 GeV	V1	19.73	0.43	0.06	12.46	2.13	2.48	0.08	5.02	0.1	0.59	5.83	12.09	0.0	0.89	4.78	15.14
		V3	25.96	1.78	0.65	6.72	5.21	0.4	1.12	1.7	1.01	0.03	2.17	6.41	0.85	0.0	1.65	8.6
		V5	37.33	6.47	4.04	1.68	11.72	0.55	4.59	0.04	4.84	1.93	0.14	1.55	4.34	1.57	0.0	2.72
		V11	54.48	16.14	12.42	0.13	23.85	4.95	13.43	2.41	13.74	8.55	2.03	0.16	13.01	7.73	2.57	0.0

Beyond the EFT

There is no limit on the LSP mass if the mass of strongly interacting SUSY particles above ~ 1.9 TeV

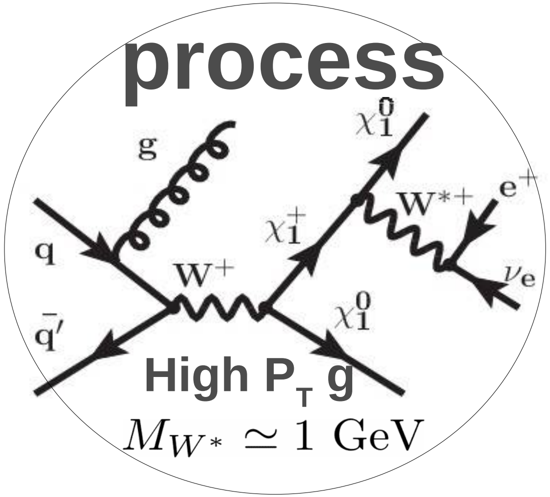


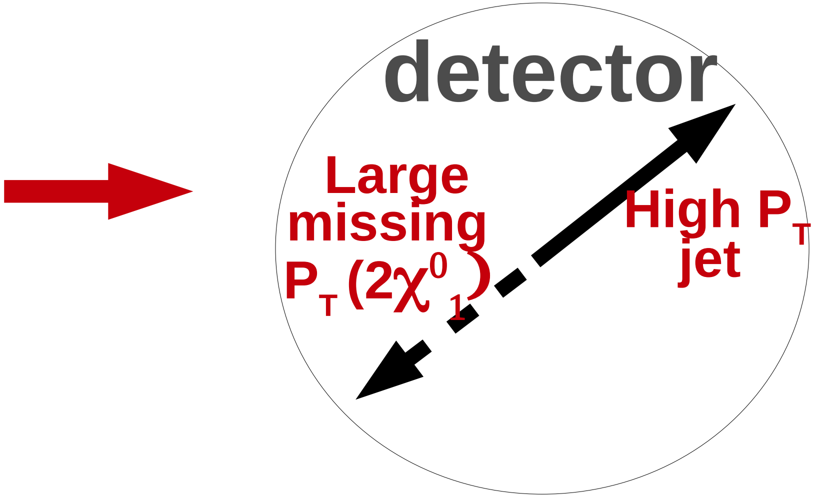


SUSY Compressed Mass Spectrum scenario

- The most challenging case takes place when only $\chi^0_{1,2}$ and $\chi^\pm$ are accessible at the LHC, and the mass gap between them is not enough for leptonic signatures

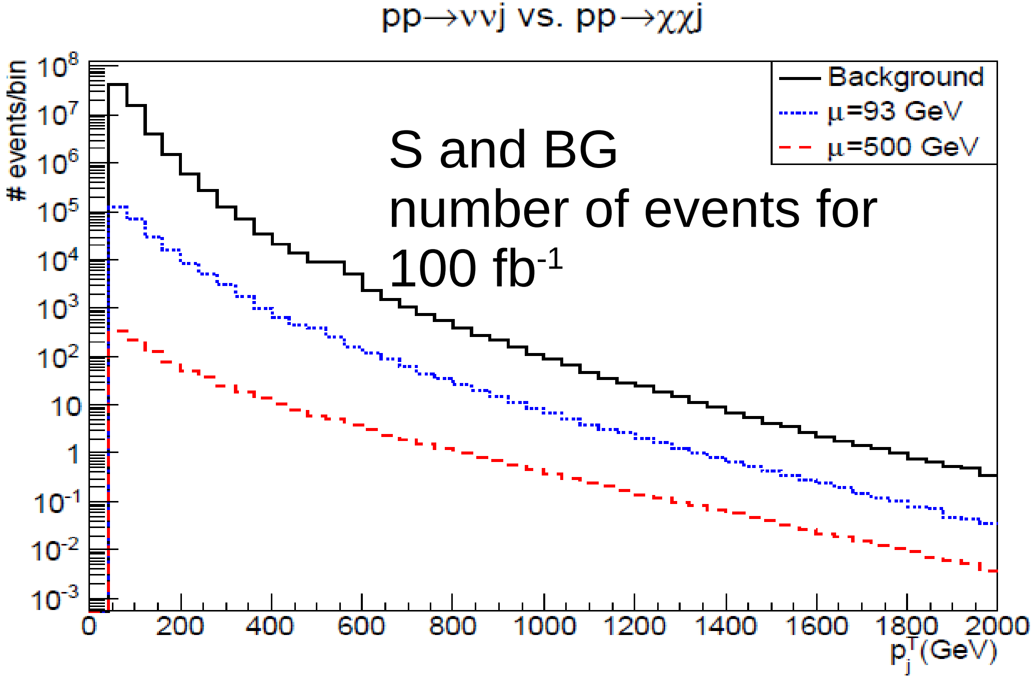
- The only way to probe CHS is a mono-jet signature
  [“Where the Sidewalk Ends? ...” Alves, Izaguirre,Wacker '11] ,
  which has been used in studies on compressed SUSY spectra, e.g.
  Dreiner,Kramer,Tattersall '12; Han,Kobakhidze,Liu,Saavedra,Wu'13; Han,Kribs,Martin,Menon '14



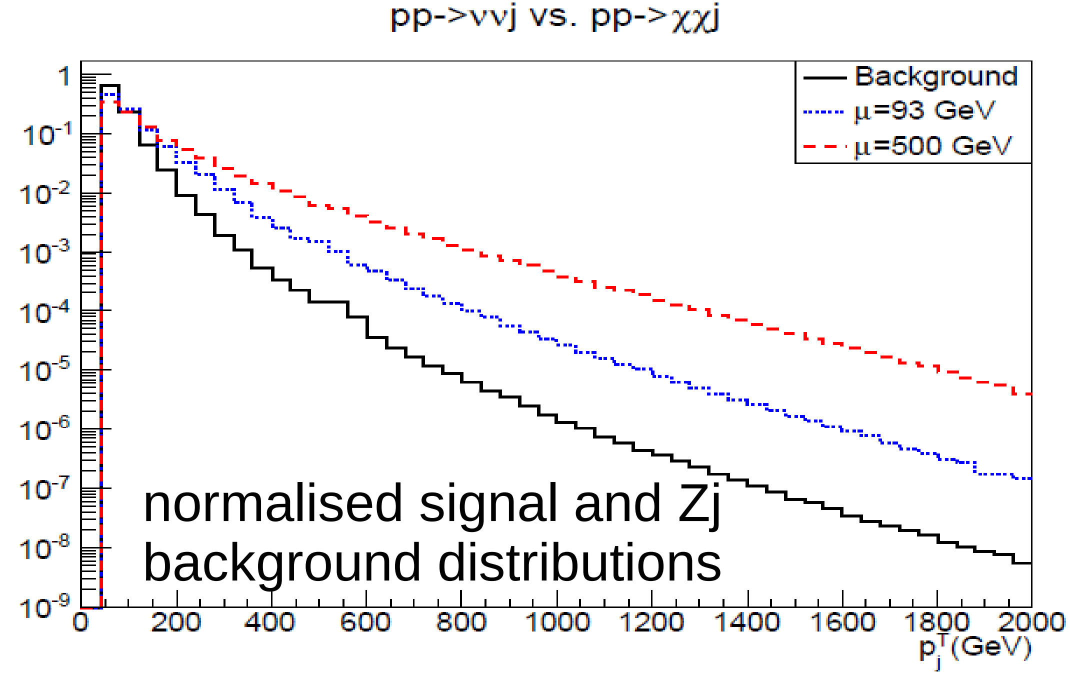


Signal vs Background

- difference in rates is pessimistic ...

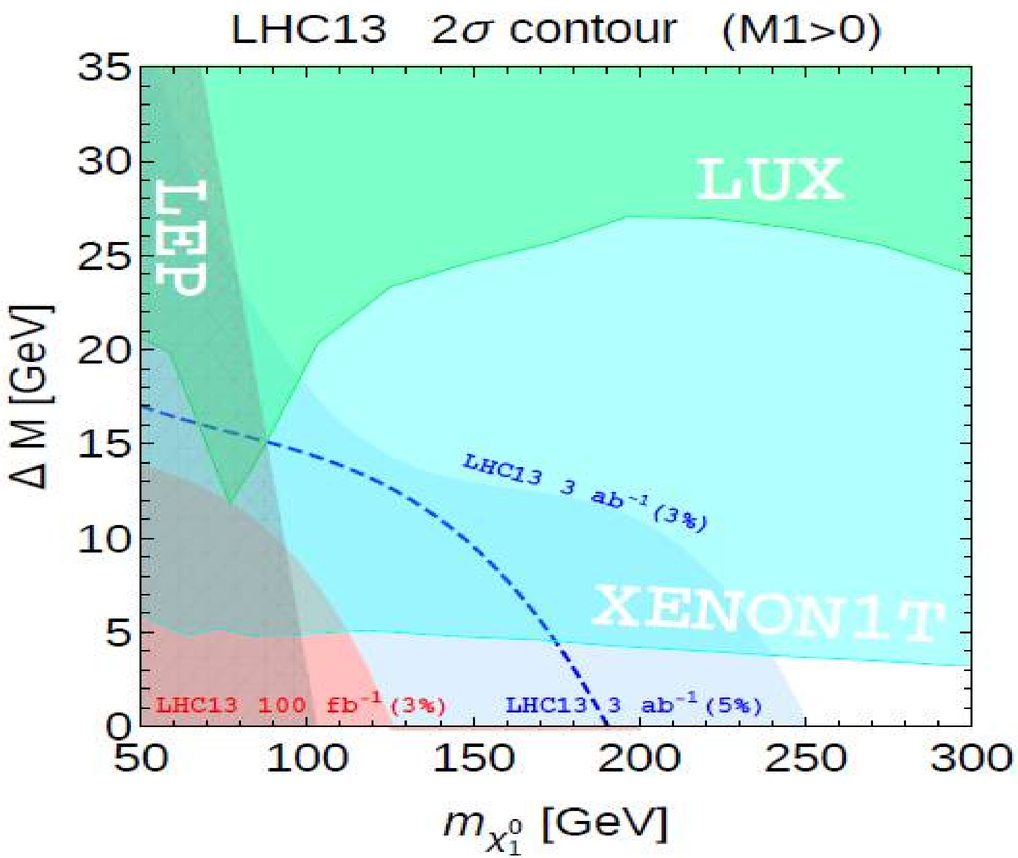


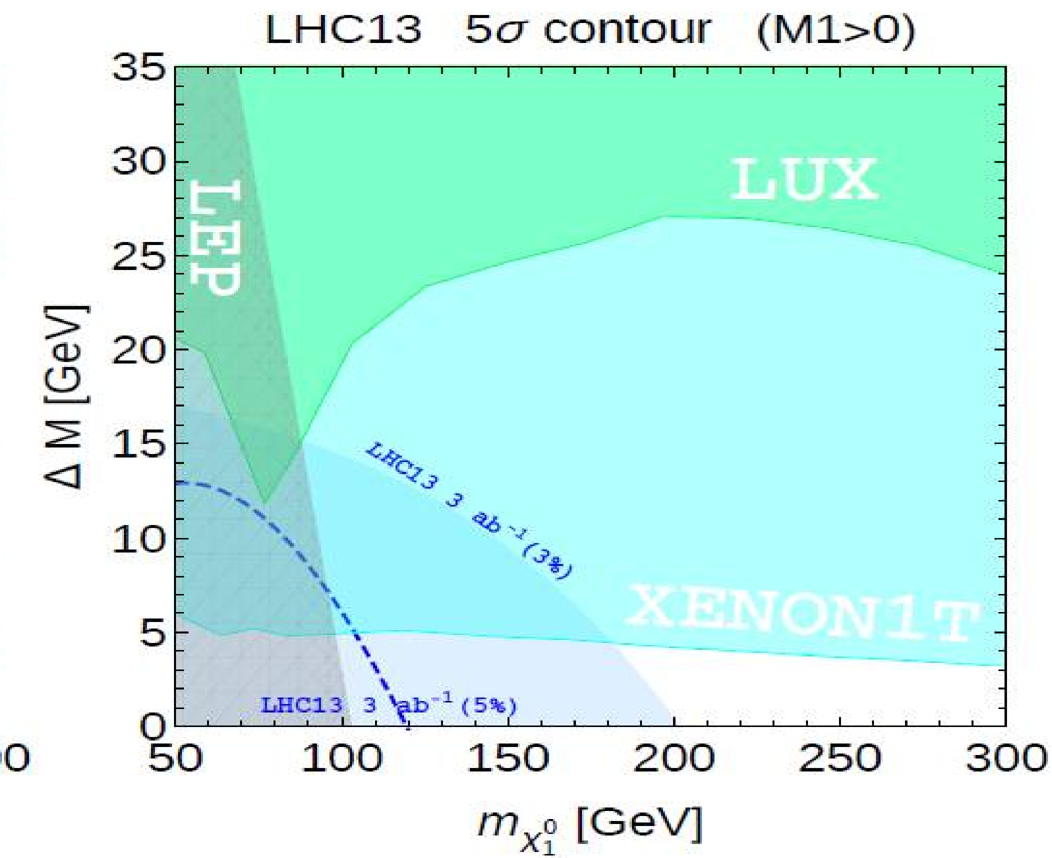
- but the difference in shapes is encouraging: large DM mass → biger M(DM,DM) → flatter MET



Signal and Zj background p_T^j distributions for the 13 TeV LHC

LHC/DM direct detection sensitivity





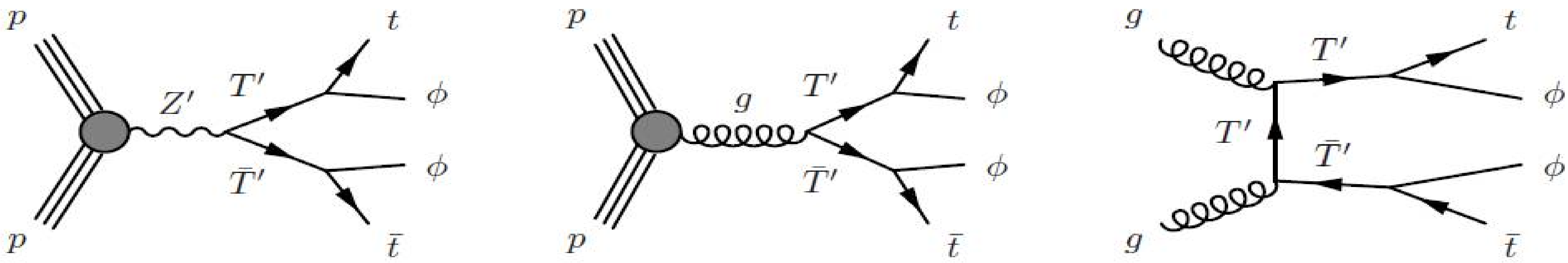
AB, Barducci,Bharucha,Porod,Sanz JHEP, 1504.02472

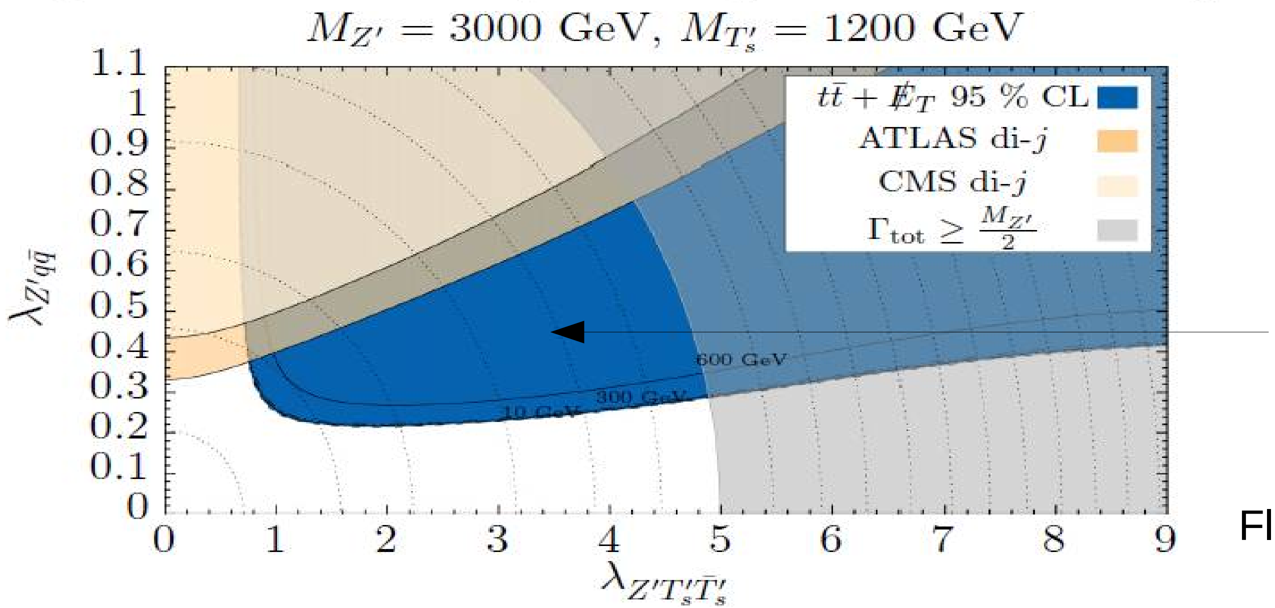
- SUSY DM, can be around the corner (~100 GeV), but it is hard to detect it!
- Great complementarity of DD and LHC for small DM (natural)SUSY region

Beyond monojet signature

Beyond the mono-jet signature

Example of the vector resonance in the Composite Higgs model:
Z' → TT → t t DM DM signature

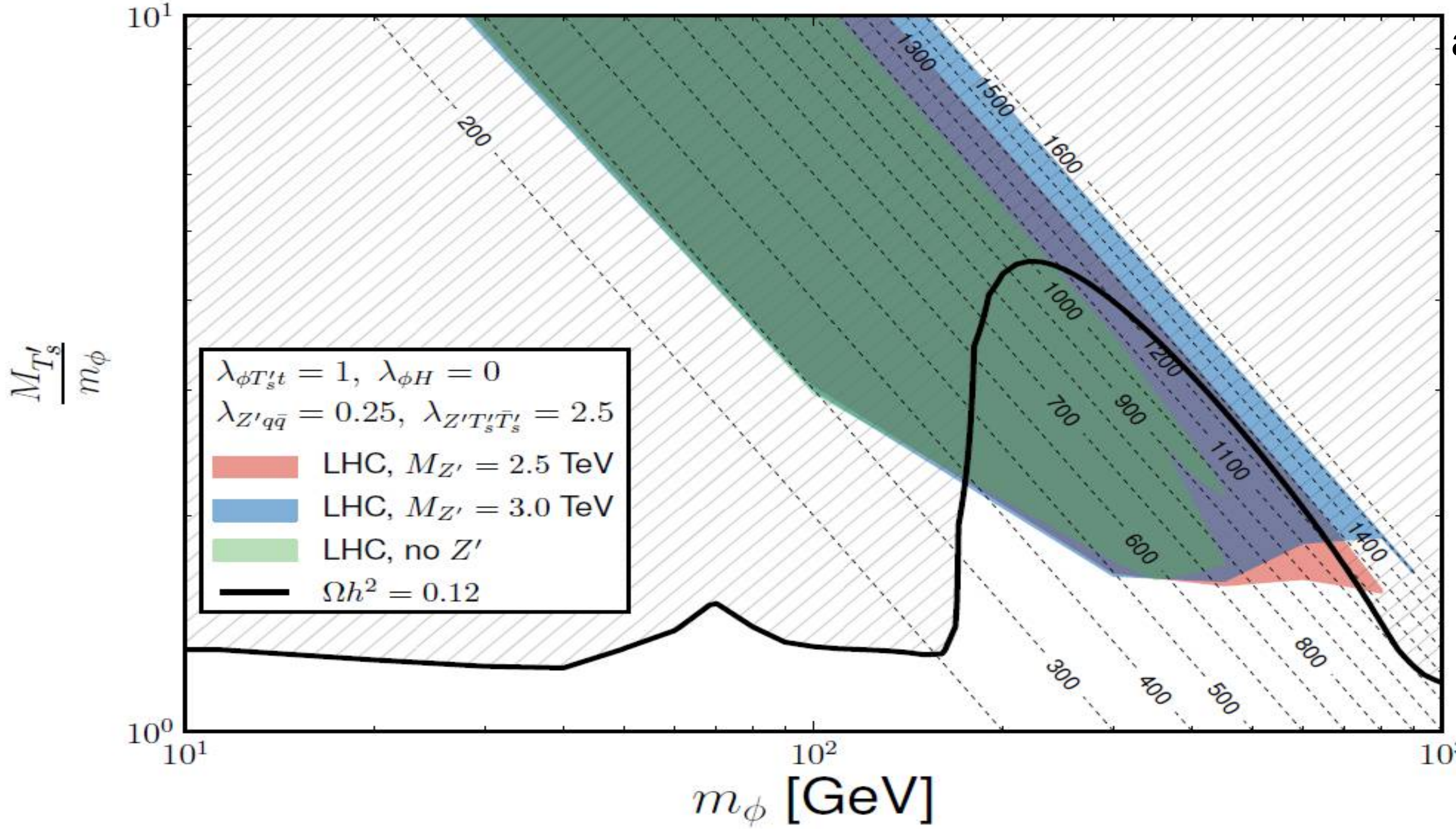




Current LHC reach with tt+ MET signature based on ATLAS_CONF_2016_050 results

Flacke, Jaine, Schaefers, AB, 2017

The role of Z' vs QCD for pp → TT → t t DM DM



arXiv: 1707.07000

Z' + QCD TT production

- LHC is probing now DM and top partner masses up to about 0.9 and 1.5 TeV respectively
- bounds from QCD production alone are extended by ~ factor of two
- DM DD rates are loop-suppressed

Disappearing Charged Tracks (DCT): VDM as an example

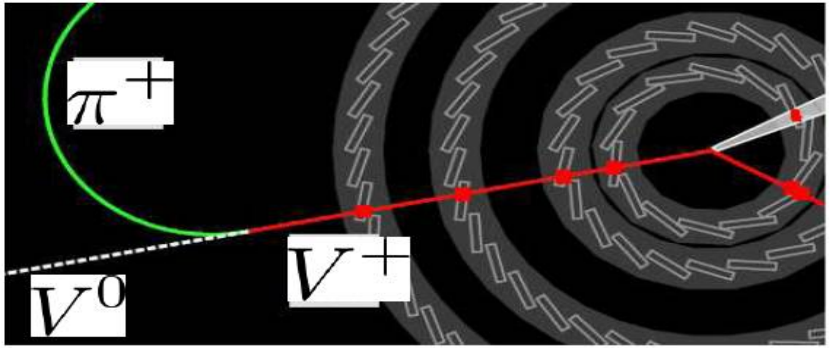
$$
\begin{aligned}
\mathcal{L} = \mathcal{L}_{SM} &- Tr\left\{D_\mu V_\nu D^\mu V^\nu\right\} + Tr\left\{D_\mu V_\nu D^\nu V^\mu\right\} \\
&-\frac{g^2}{2} Tr\left\{\left[V_\mu, V_\nu\right]\left[V^\mu, V^\nu\right]\right\} \\
&-igTr\left\{W_{\mu\nu}\left[V^\mu, V^\nu\right]\right\} + \tilde{M}^2 Tr\{V_\nu V^\nu\} \\
&+a\left(\Phi^\dagger\Phi\right) Tr\{V_\nu V^\nu\}
\end{aligned}
$$

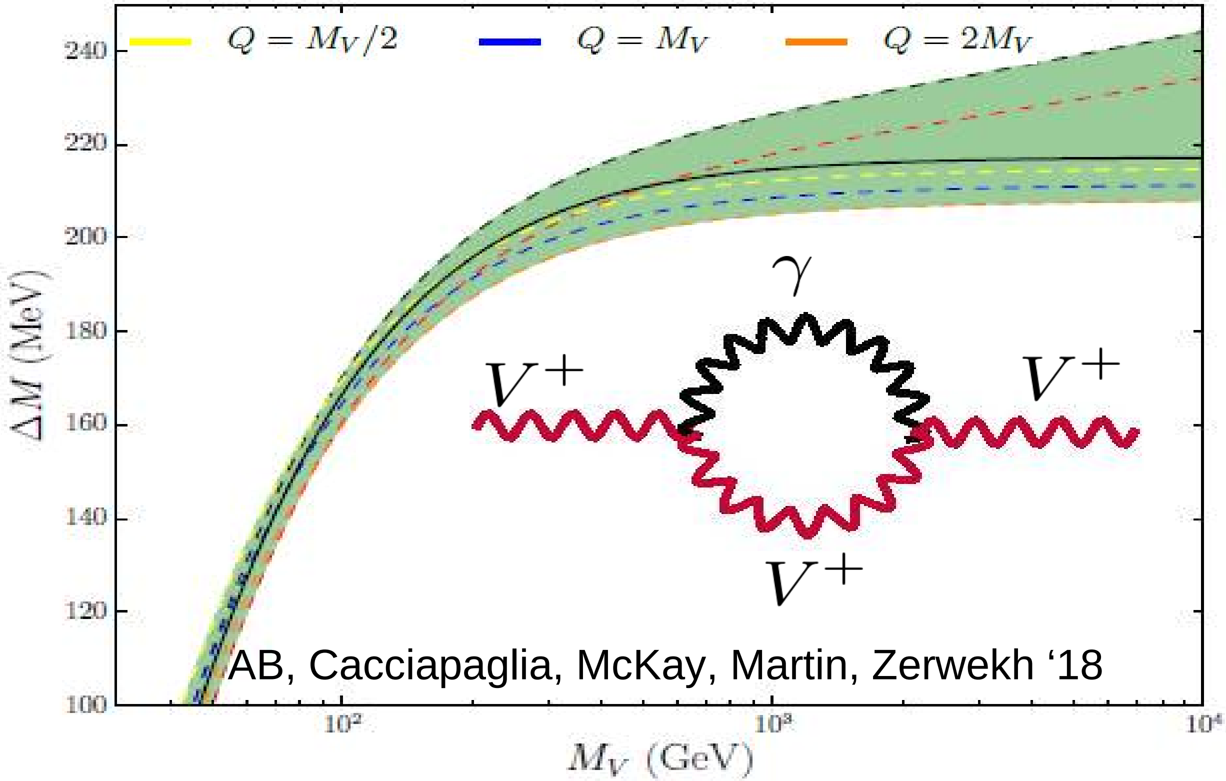
V^0 and V^+ which are degenerate at tree-level are split due to the quantum corrections

for $M_V \gg M_W$

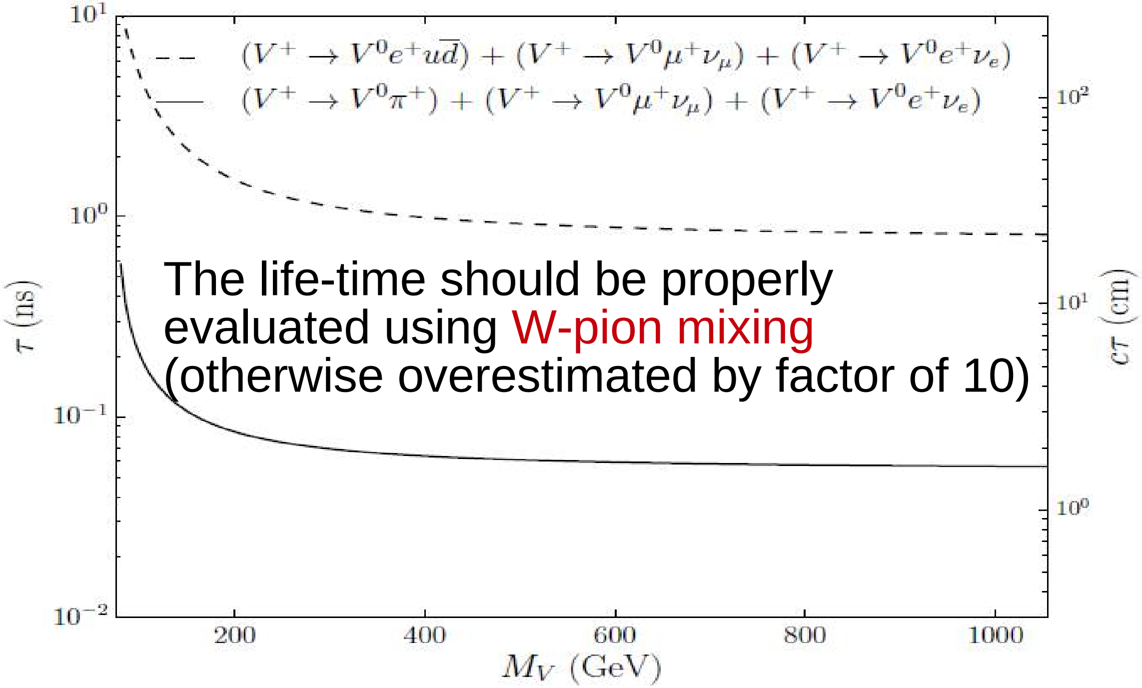
$$\Delta M = \frac{5 g_W^2 (M_W - c_W^2 M_Z)}{32\pi} \approx 217.3\,\mathrm{MeV}$$

The small mass gap (~ pion mass) between DM and its charged partner will lead to the disappearing charge tracks signatures



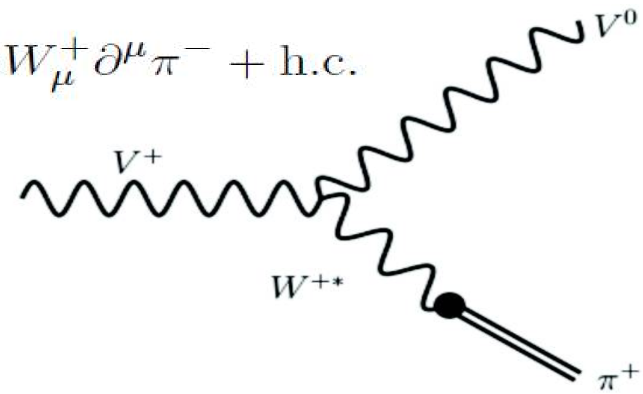


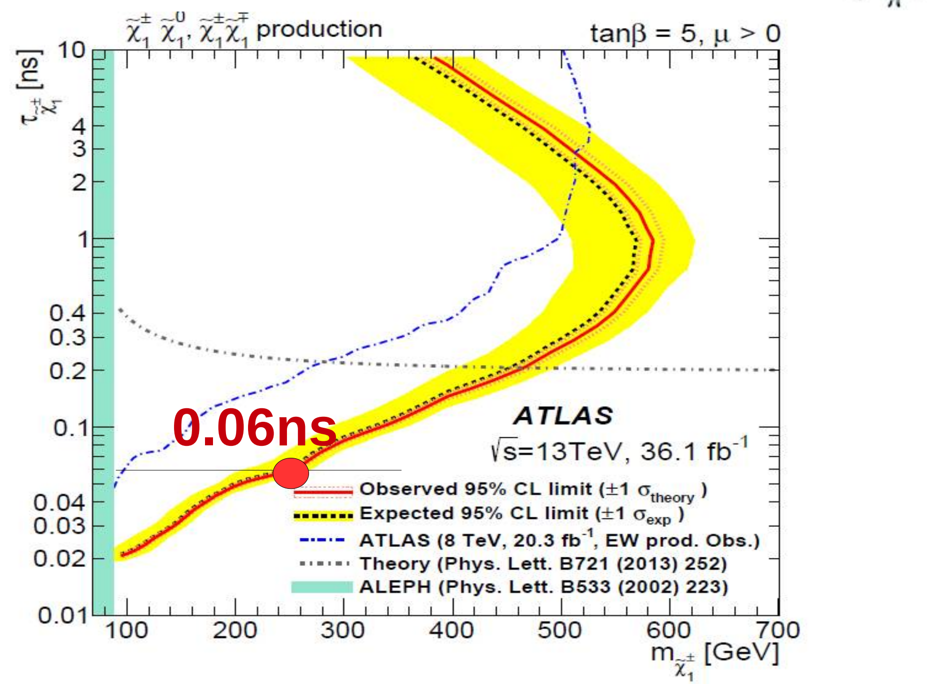
Collider sensitivity to VDM mass



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

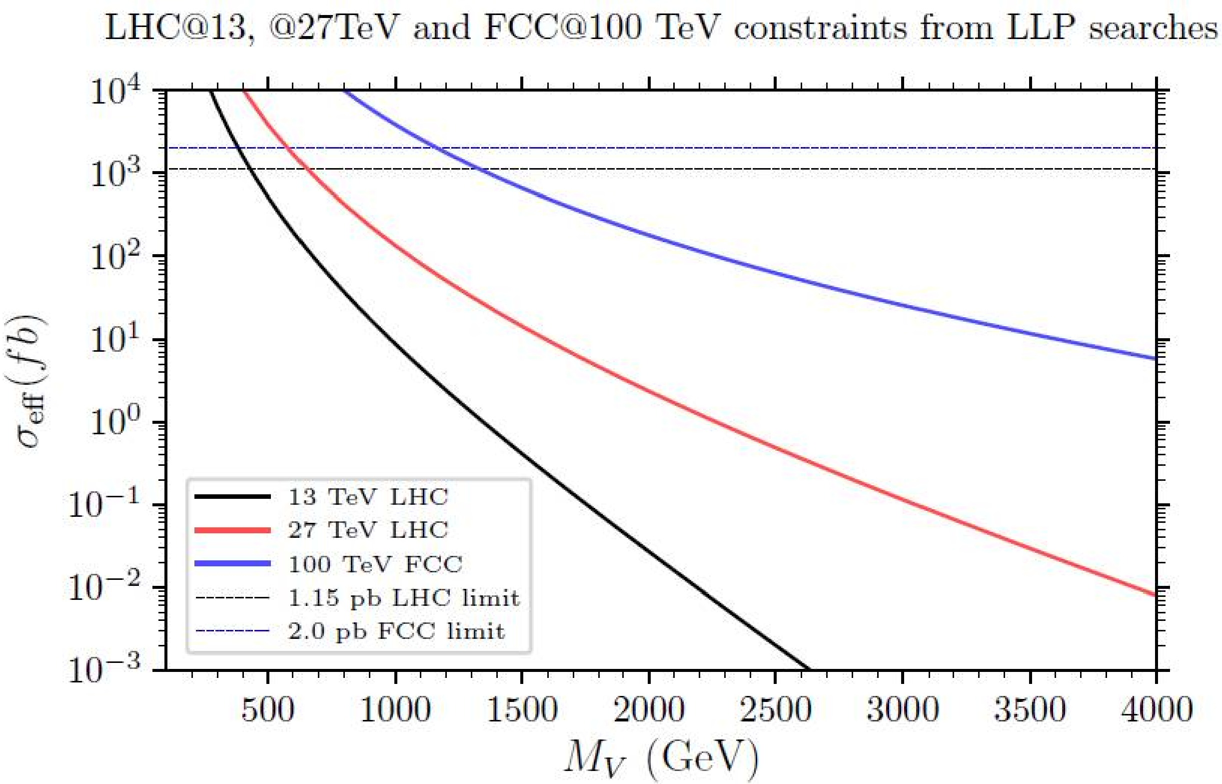
$$\mathcal{L}_{W\pi} = \frac{g f_\pi}{2\sqrt{2}} W^+_\mu \partial^\mu \pi^- + \text{h.c.}$$





Using ATLAS arXiv:1712.02118 for LHC interpretation and Mahbubani,Schwaller, Zurita ArXiv:1703.05327 For 100 TeV FCC projections

Collider sensitivity to VDM mass

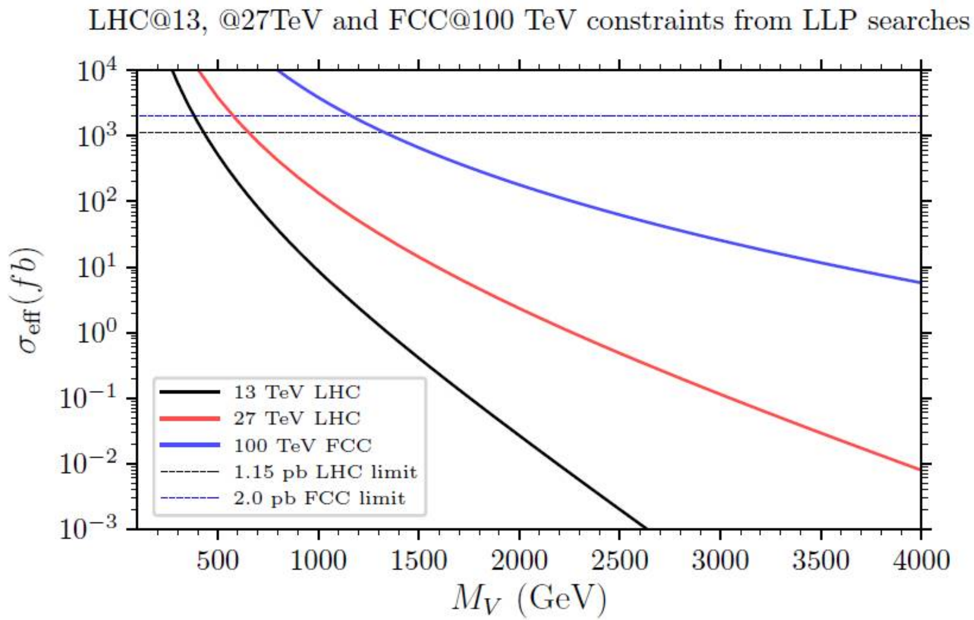


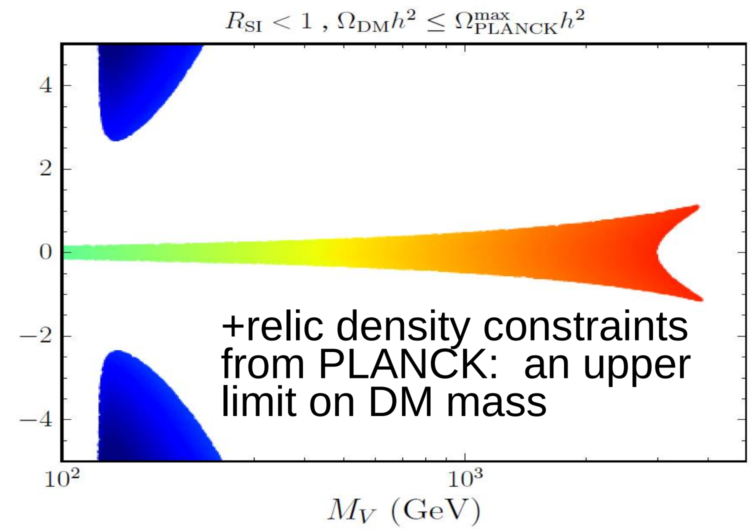
AB, Cacciapaglia, McKay, Martin, Zerwekh arXiv:**1808.10464**

Current bound from LHC on DM mass from the minimal vector triplet model is around **500 GeV**

100 TeV FCC will cover DM mass up to **1.2 TeV**

Collider sensitivity to VDM mass

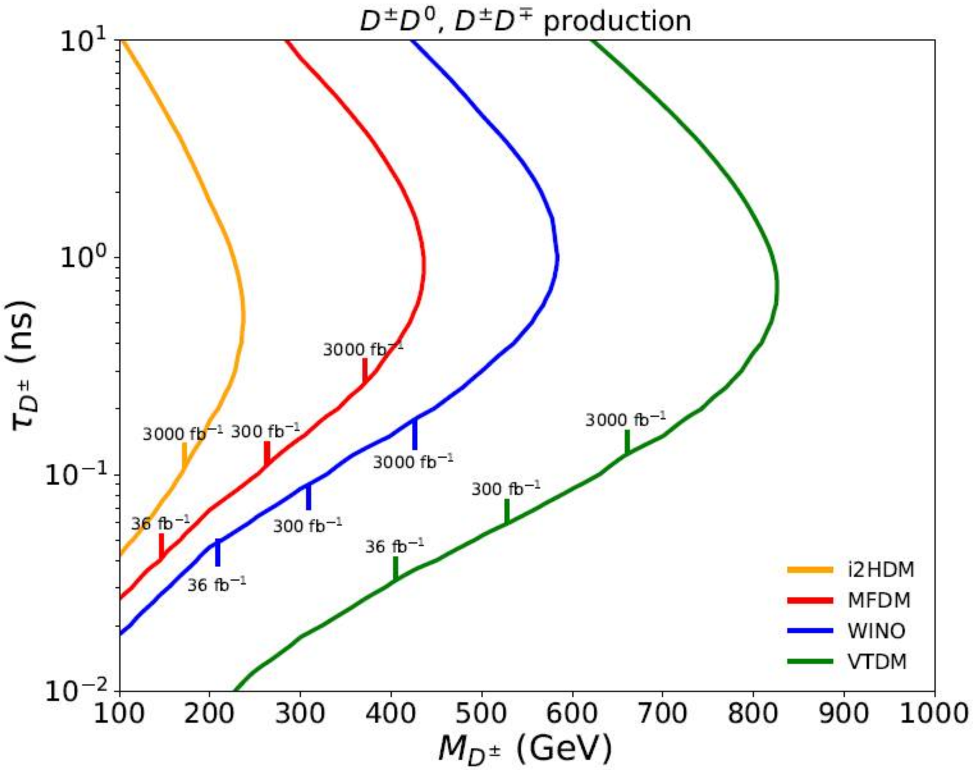




Current bound from LHC on DM mass from the minimal vector triplet model is around **500 GeV**

100 TeV FCC will cover DM mass up to **1.2 TeV** but will not fully exclude it

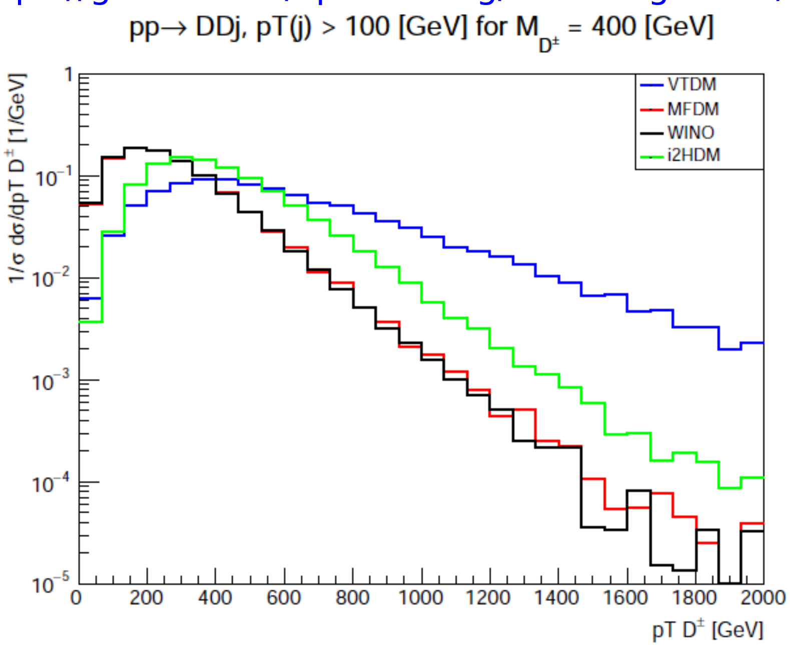
The power of Disappearing Tracks to probe DM models



S.Prestel, F.Rojas-Abate,J.Zurita, AB,
arXiv:**2008.08581**

- Delphes simulation & reinterpretation of ATLAS DT 36 fb $^{-1}$ results
- Present DT sensitivity goes even beyond HL LHC monojet sensitivity
- The sensitivityy also depends on PT of D+

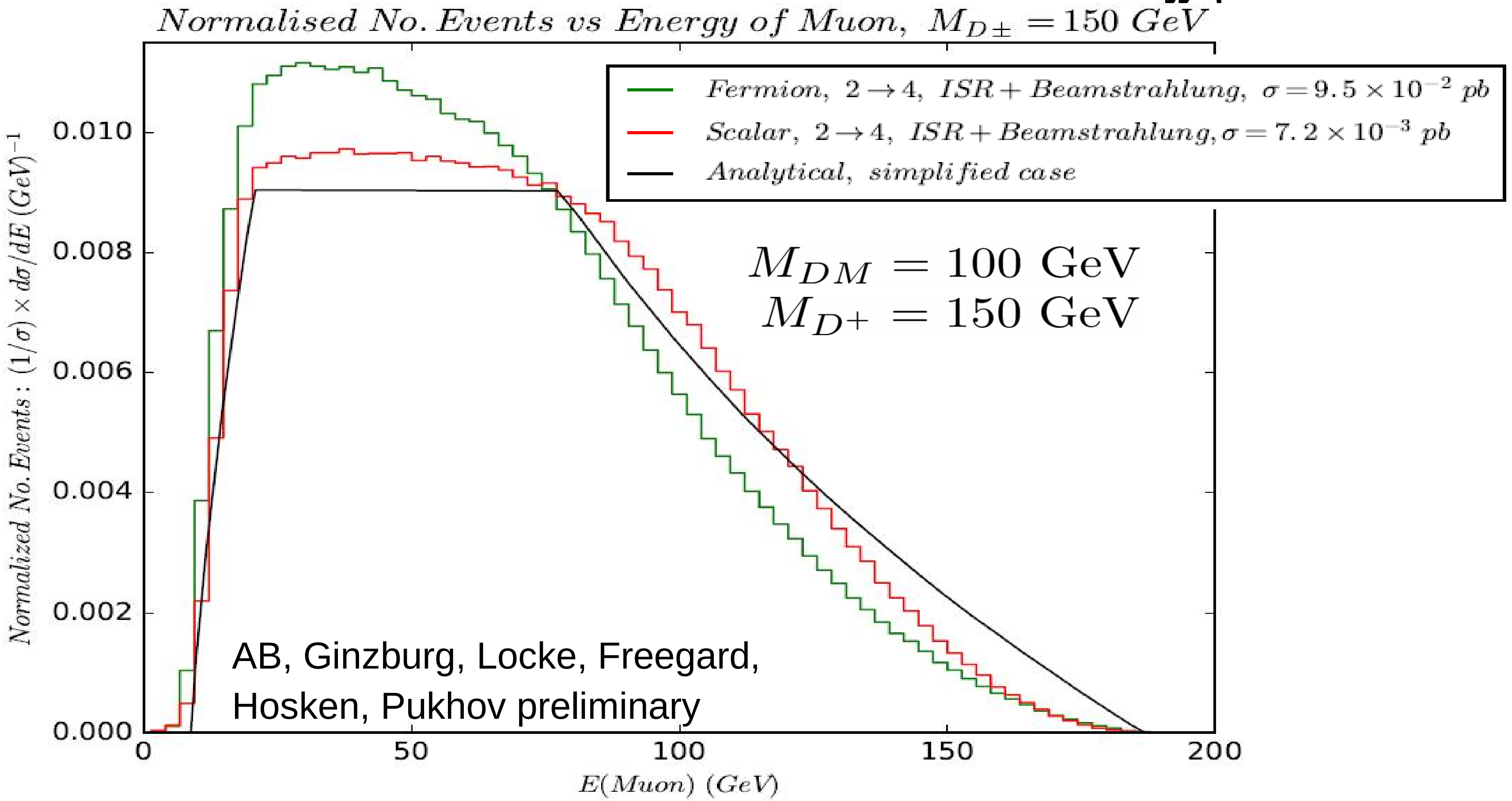
- The reinterpretation code is public at https://github.com/llprecasting/recastingCodes/



Decoding the nature of DM at the ILC

muon spectrum from the models with scalar and fermion DM

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



Decoding Problem: Data → Theory link

- probably the most challenging problem to solve – **the inverse problem of decoding of the underlying theory from signal**
  - requires database of models, database of signatures
  - requires smart procedure based on machine learning of matching signal from data with the pattern of the signal from data

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- **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 their own model and perform simulation

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- As a HEPMDB spin-off the **PhenoData** project was created **hepmdb.soton.ac.uk/phenodata**
  - stores data (digitized curves from figures, tables etc) from those HEP papers which did not provide data in arXiv or HEPData
  - has an easy search interface and paper identification via arXiv, DOI or preprint numbers

Summary

- DM DD detection provides a very powerful probe of DM theory space – in general provides DM mass probe beyond the collider reach
- Colliders – provide DM detection power in the region “blind” for DM DD, typically below 1 TeV
- Several ways to decode DM nature from the signal which we hope to observe soon (slopes of MET, cross sections, signatures, …)
- New prospects: new DD experiments, new ideas, prospects for directional DM detection, new signatures at colliders (VFB, LL, …), future colliders (great potential of ILC and FCC)
- Great synergy of collider and non-collider experiments (DD, CMB, relic density)

Thank you!

Backup Slides

DIM5/6 operators (spin 0,1/2,1)

Complex scalar DM†	
$\frac{\tilde{m}}{\Lambda^2}\phi^\dagger\phi\bar{q}q$	$[C1]^*$
$\frac{\tilde{m}}{\Lambda^2}\phi^\dagger\phi\bar{q}i\gamma^5 q$	$[C2]^*$
$\frac{1}{\Lambda^2}\phi^\dagger i\overleftrightarrow{\partial_\mu}\phi\bar{q}\gamma^\mu q$	$[C3]$
$\frac{1}{\Lambda^2}\phi^\dagger i\overleftrightarrow{\partial_\mu}\phi\bar{q}\gamma^\mu\gamma^5 q$	$[C4]$
$\frac{1}{\Lambda^2}\phi^\dagger\phi G^{\mu\nu}G_{\mu\nu}$	$[C5]^*$
$\frac{1}{\Lambda^2}\phi^\dagger\phi\tilde{G}^{\mu\nu}G_{\mu\nu}$	$[C6]^*$

Dirac fermion DM†	
$\frac{1}{\Lambda^2}\bar{\chi}\chi\bar{q}q$	$[D1]^*$
$\frac{1}{\Lambda^2}\bar{\chi}i\gamma^5\chi\bar{q}q$	$[D2]^*$
$\frac{1}{\Lambda^2}\bar{\chi}\chi\bar{q}i\gamma^5 q$	$[D3]^*$
$\frac{1}{\Lambda^2}\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$	$[D4]^*$
$\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	$[D5]$
$\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	$[D6]$
$\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5 q$	$[D7]$
$\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$	$[D8]$
$\frac{1}{\Lambda^2}\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$	$[D9]^*$
$\frac{1}{\Lambda^2}\bar{\chi}\sigma^{\mu\nu}i\gamma^5\chi\bar{q}\sigma_{\mu\nu}q$	$[D10]^*$

Complex vector DM‡	
$\frac{\tilde{m}}{\Lambda^2}V_\mu^\dagger V^\mu\bar{q}q$	$[V1]^*$
$\frac{\tilde{m}}{\Lambda^2}V_\mu^\dagger V^\mu\bar{q}i\gamma^5 q$	$[V2]^*$
$\frac{1}{2\Lambda^2}(V_\nu^\dagger\partial_\mu V^\nu - V^\nu\partial_\mu V_\nu^\dagger)\bar{q}\gamma^\mu q$	$[V3]$
$\frac{1}{2\Lambda^2}(V_\nu^\dagger\partial_\mu V^\nu - V^\nu\partial_\mu V_\nu^\dagger)\bar{q}i\gamma^\mu\gamma^5 q$	$[V4]$
$\frac{\tilde{m}}{\Lambda^2}V_\mu^\dagger V_\nu\bar{q}i\sigma^{\mu\nu}q$	$[V5]$
$\frac{\tilde{m}}{\Lambda^2}V_\mu^\dagger V_\nu\bar{q}\sigma^{\mu\nu}\gamma^5 q$	$[V6]$
$\frac{1}{2\Lambda^2}(V_\nu^\dagger\partial^\nu V_\mu + V^\nu\partial^\nu V_\mu^\dagger)\bar{q}\gamma^\mu q$	$[V7P]$
$\frac{1}{2\Lambda^2}(V_\nu^\dagger\partial^\nu V_\mu - V^\nu\partial^\nu V_\mu^\dagger)\bar{q}i\gamma^\mu q$	$[V7M]$
$\frac{1}{2\Lambda^2}(V_\nu^\dagger\partial^\nu V_\mu + V^\nu\partial^\nu V_\mu^\dagger)\bar{q}\gamma^\mu\gamma^5 q$	$[V8P]$
$\frac{1}{2\Lambda^2}(V_\nu^\dagger\partial^\nu V_\mu - V^\nu\partial^\nu V_\mu^\dagger)\bar{q}i\gamma^\mu\gamma^5 q$	$[V8M]$
$\frac{1}{2\Lambda^2}\epsilon^{\mu\nu\rho\sigma}(V_\nu^\dagger\partial_\rho V_\sigma + V_\nu\partial_\rho V_\sigma^\dagger)\bar{q}\gamma_\mu q$	$[V9P]$
$\frac{1}{2\Lambda^2}\epsilon^{\mu\nu\rho\sigma}(V_\nu^\dagger\partial^\nu V_\mu - V^\nu\partial^\nu V_\mu^\dagger)\bar{q}i\gamma_\mu q$	$[V9M]$
$\frac{1}{2\Lambda^2}\epsilon^{\mu\nu\rho\sigma}(V_\nu^\dagger\partial_\rho V_\sigma + V_\nu\partial_\rho V_\sigma^\dagger)\bar{q}\gamma_\mu\gamma^5 q$	$[V10P]$
$\frac{1}{2\Lambda^2}\epsilon^{\mu\nu\rho\sigma}(V_\nu^\dagger\partial^\nu V_\mu - V^\nu\partial^\nu V_\mu^\dagger)\bar{q}i\gamma_\mu\gamma^5 q$	$[V10M]$
$\frac{1}{\Lambda^2}V_\mu^\dagger V^\mu G^{\rho\sigma}G_{\rho\sigma}$	$[V11]^*$
$\frac{1}{\Lambda^2}V_\mu^\dagger V^\mu\tilde{G}^{\rho\sigma}G_{\rho\sigma}$	$[V12]^*$

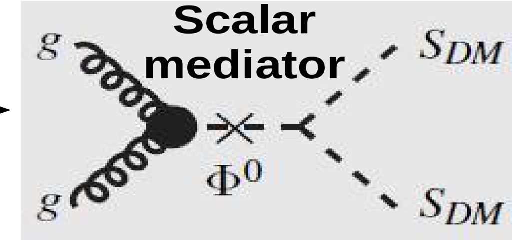
* operators applicable to real DM fields, modulo a factor $1/2$

† Listed in J. Goodman *et al.*, *Constraints on Dark Matter from Colliders*, Phys.Rev. **D82** (2010) 116010, [arXiv:1008.1783]

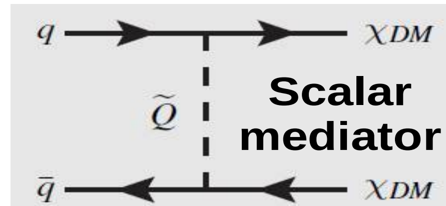
‡ All but V11 and V12 listed in Kumar *et al.*, *Vector dark matter at the LHC*, Phys. Rev. **D92** (2015) 095027, [arXiv:1508.04466]

Mapping EFT operators to simplified models

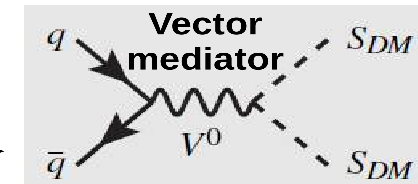
C5,C5A $\frac{1}{\Lambda^2}\phi^*\phi G^{\mu\nu}G^{\mu\nu}$ $\frac{1}{\Lambda^2}\phi^*\phi\tilde{G}^{\mu\nu}G^{\mu\nu}$ →



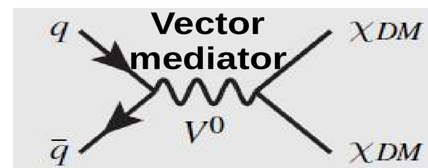
D1T-D4T $\frac{1}{\Lambda^2}\bar{\chi}q\bar{q}\chi$ →

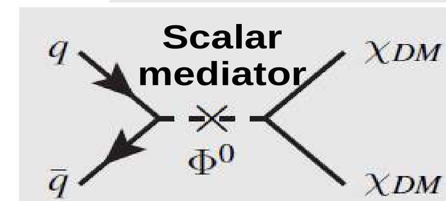


C3 $\frac{i}{\Lambda^2}[\phi^*(\partial_\mu\phi - (\partial_\mu\phi^*)\phi]\bar{q}\gamma^\mu q$ →

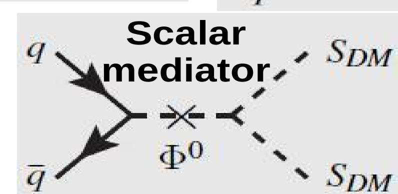


D1-D4, D5-D8 $\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$ $\frac{1}{\Lambda^2}\bar{\chi}\chi\bar{q}q$ →



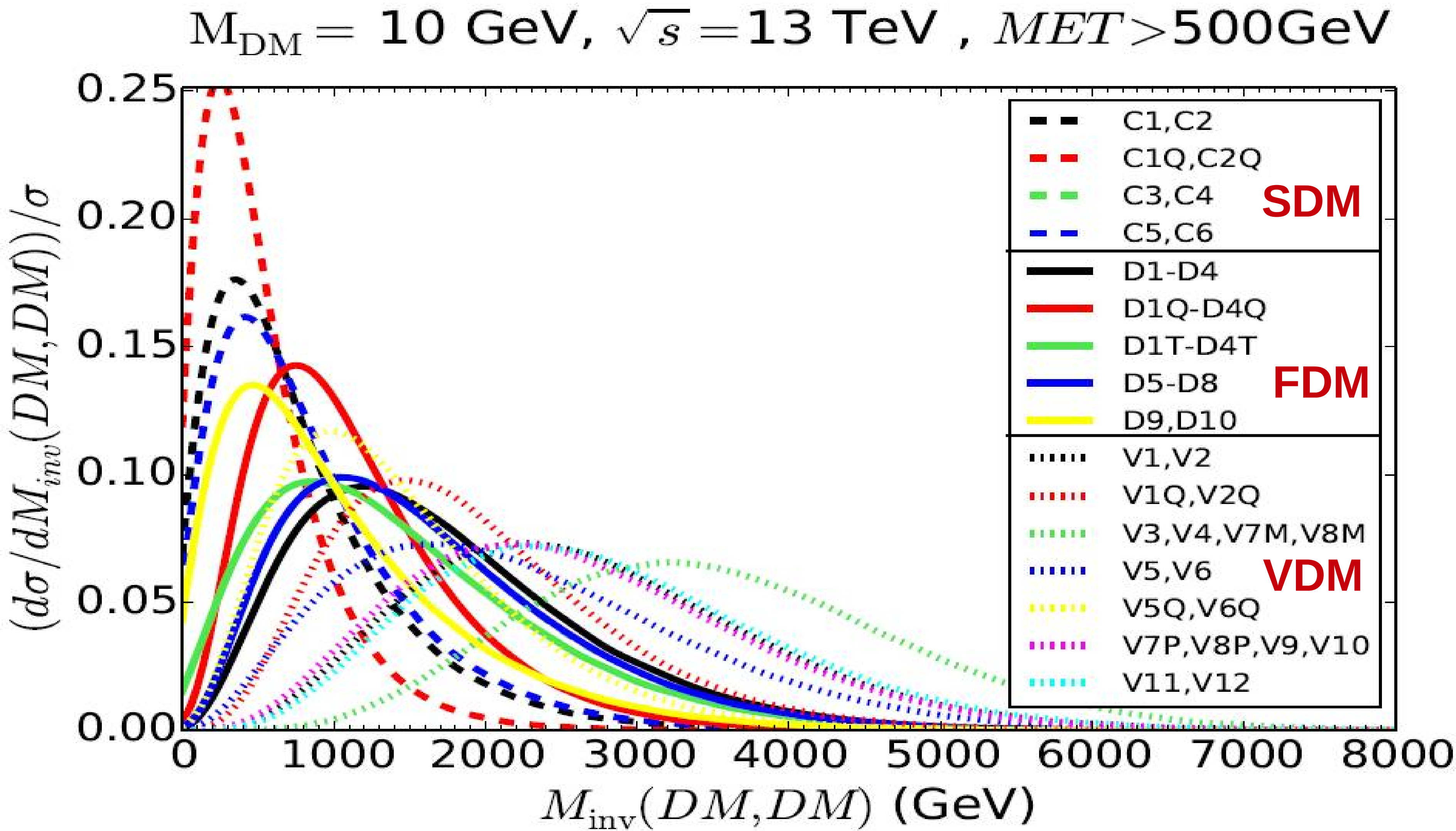


C1 $\frac{1}{\Lambda^2}\phi^*\phi\bar{q}q\Phi \Longrightarrow \frac{v}{\Lambda^2}\phi^*\phi\bar{q}q$ →

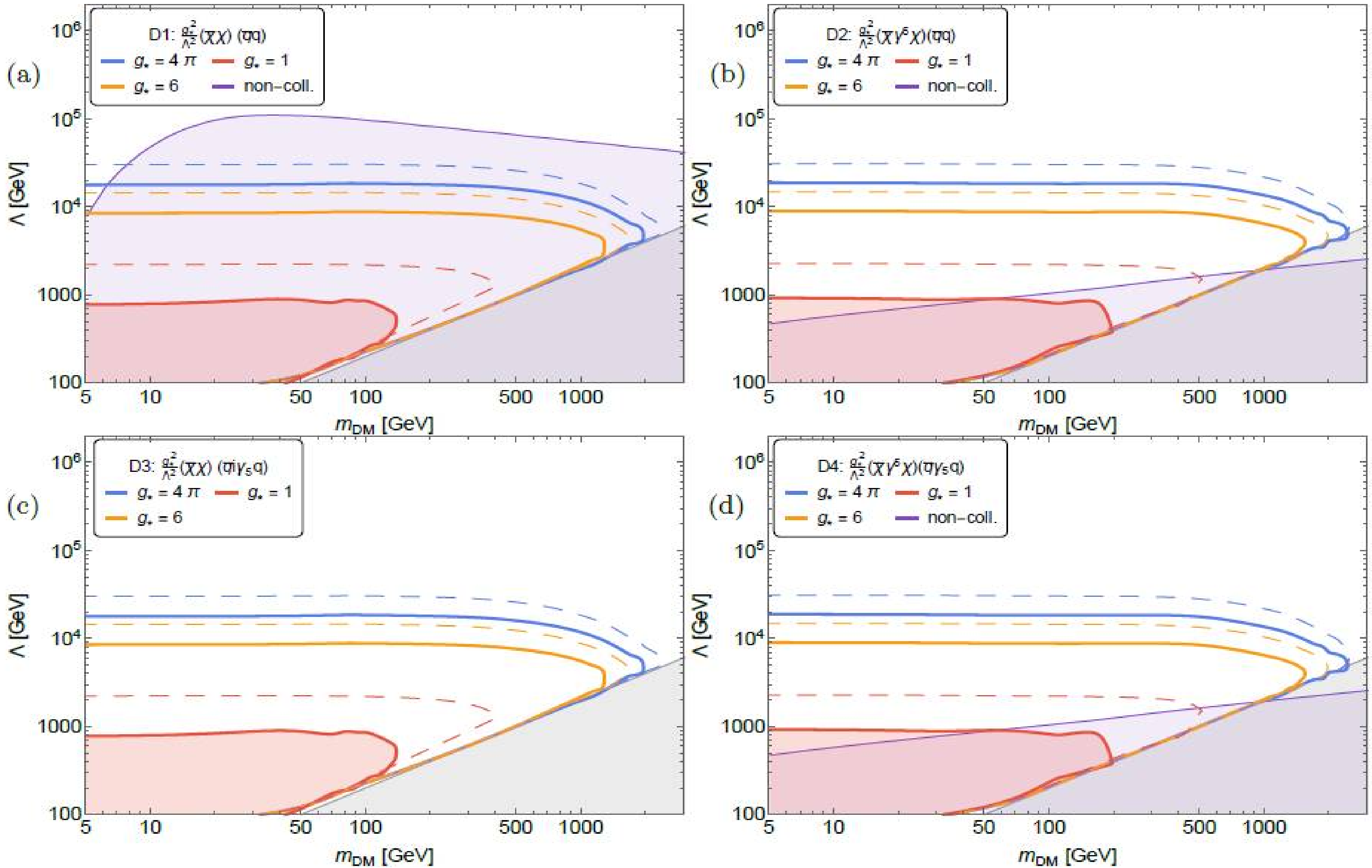


D9,D10 $\frac{1}{\Lambda^2}\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$ → $\frac{8}{\Lambda^2}\Big[\bar{\chi}q\bar{q}\chi - \frac{1}{4}\big(\bar{\chi}\chi\bar{q}q + \bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q + \bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q - \bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5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

On the other hand, M(DM,DM) distributions, defined by the EFT operators are different!



DM DD ↔ Collider interplay



Relation of the actual dimension (D) and the naive one (d) for VDM operators

V_{DM} Operator	Λ_d	d	Λ_D	D	$\Delta_\sigma(\sigma_{2\to 2} \propto E^{\Delta_\sigma})$	Amplitude Enhancement
V1,V2,V5,V6	$\frac{1}{\Lambda}$	5	$\frac{M_{DM}^2}{\Lambda^3}$	7	4	$(E/M_{DM})^2$
V3,V4,V7M,V8M,V11,V12	$\frac{1}{\Lambda^2}$	6	$\frac{M_{DM}^2}{\Lambda^4}$	8	6	$(E/M_{DM})^2$
V7P,V8P,V9,V10	$\frac{1}{\Lambda^2}$	6	$\frac{M_{DM}}{\Lambda^3}$	7	4	E/M_{DM}

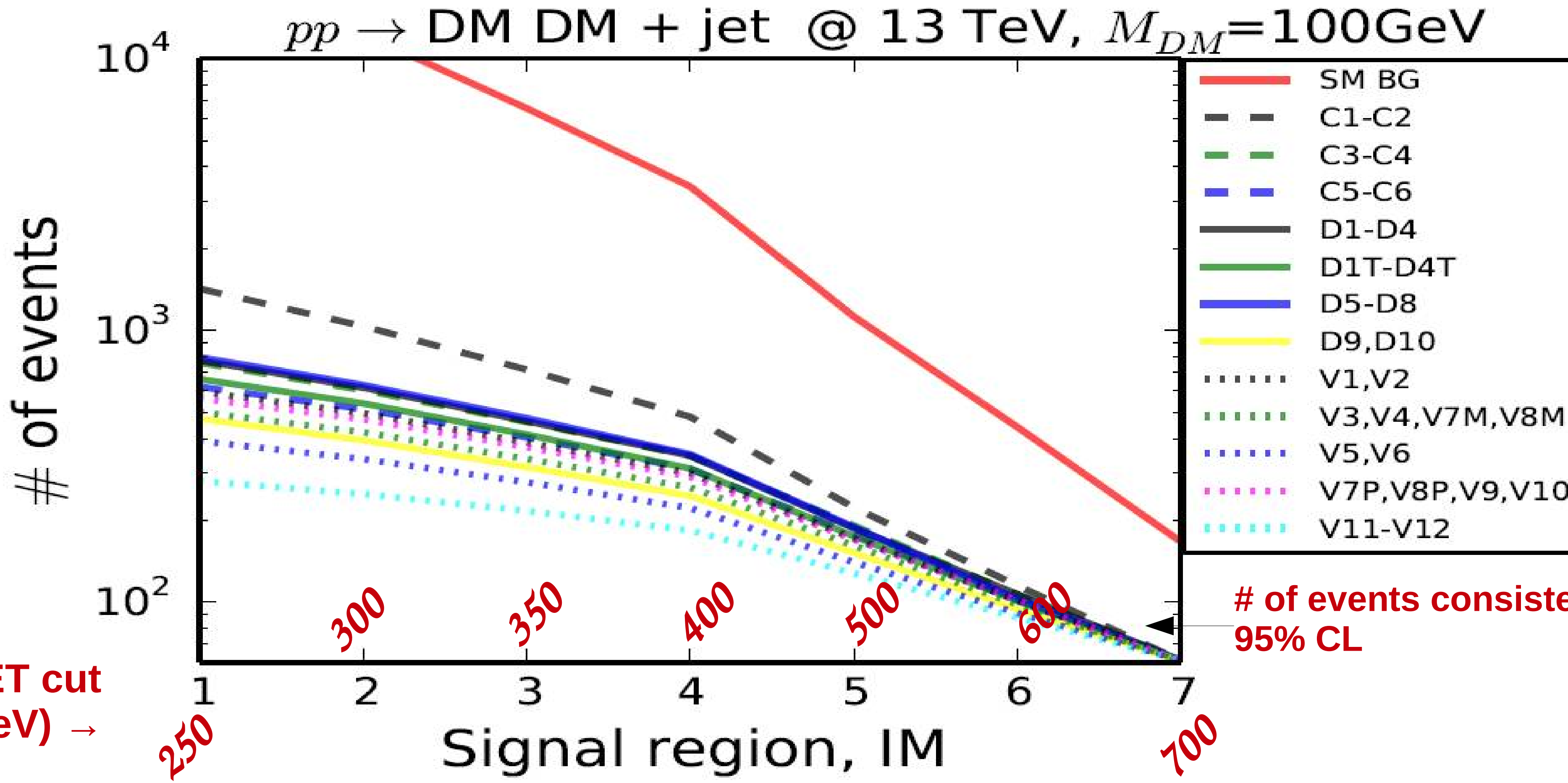
- we suggest a **new parametrisation** of VDM operators: since the energy E and the collider limit on L are of the same order, it is natural to use an additional $\mathbf{M_{DM}/\Lambda}$ factor for each power of $\mathbf{E/M_{DM}}$ enhancement, so collider limits are **not artificially enhanced** **[~100 TeV !!! for MDM =1 GeV, see Kumar, Marfatia, Yaylali 1508.04466]** and will be of the same order as limits for other operators

- Dictionary between limits on Λ in different parametrisations:

$$\Lambda_D = (\Lambda_d^{d-4} M_{DM}^{D-d})^{\frac{1}{D-4}} \quad \textit{and} \qquad \Lambda_d = (\Lambda^{D-4} M_{DM}^{d-D})^{\frac{1}{d-4}}$$

Distinguishing DM operators

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



# of events consistent with 95% CL

MET cut (GeV) →

On the BG uncertainty

- **The BG is statistically driven, e.g. pp-> Zj → nnj BG is defined from the pp → Zj → l^+l^-j one**

CMS-PAS-EXO-16-013

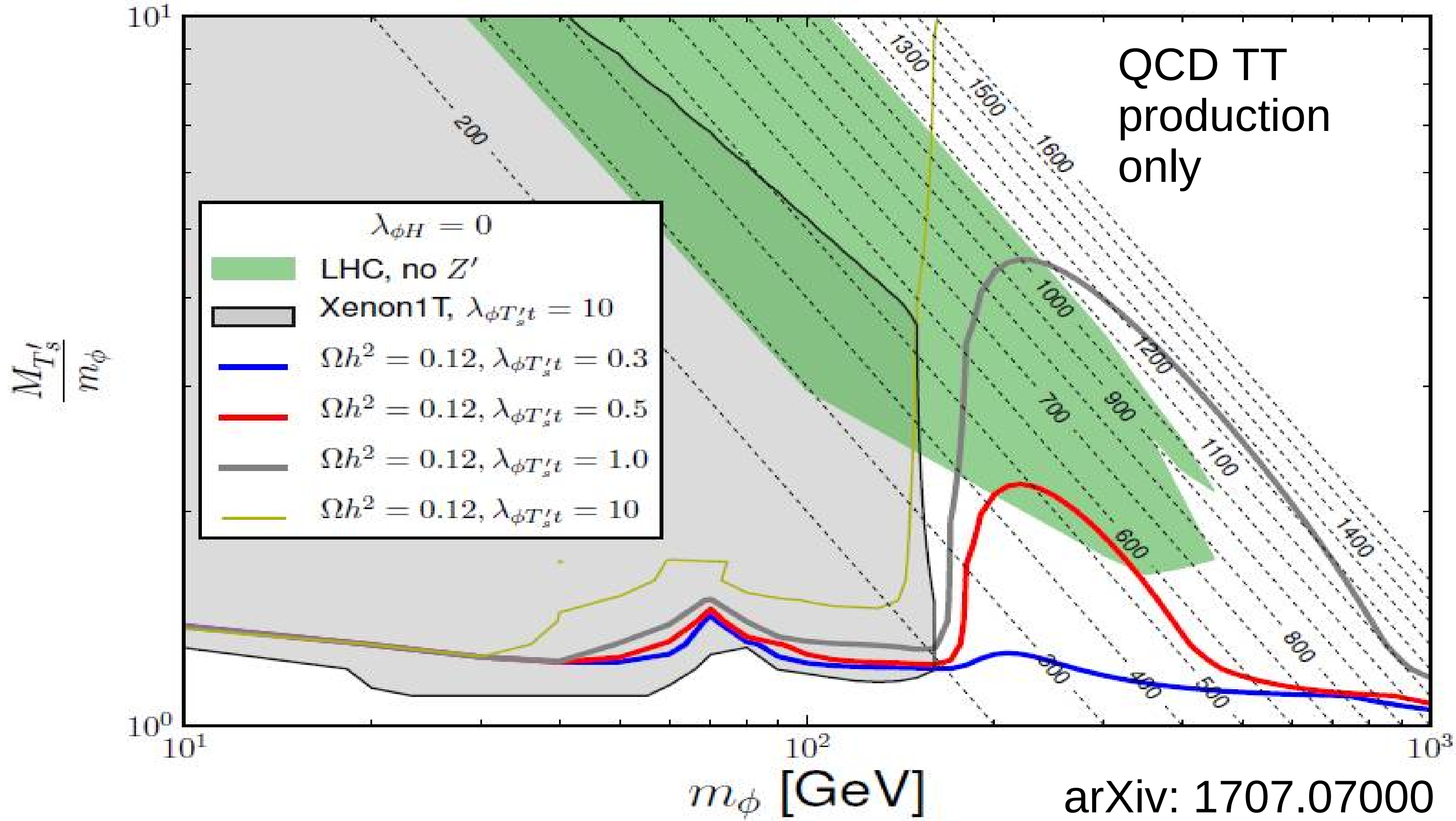
E_T^{miss} Range (GeV)	$Z(\nu\nu)$+jets	$W(\ell\nu)$+jets	$Z(\ell\ell)$+jets	γ+jets	Top	Diboson	QCD	Total (Pre-fit)	Total (Post-fit)	Data
$200-230$	14919 ± 221	11976 ± 196	207 ± 13	230 ± 14	564 ± 55	251 ± 41	508 ± 171	27761 ± 1464	28654 ± 171	28601
$230-260$	7974 ± 116	5776 ± 101	92.9 ± 5.7	101 ± 6	267 ± 26	157 ± 26	308 ± 104	14114 ± 757	14675 ± 97	14756
$260-290$	4467 ± 70	2867 ± 50	37.9 ± 2.3	63.7 ± 3.9	116 ± 11	77.3 ± 12.7	38.3 ± 21.0	7193 ± 351	7666 ± 68	7770
$290-320$	2518 ± 46	1520 ± 34	18.4 ± 1.1	29.6 ± 1.8	56.7 ± 5.6	42.9 ± 7.1	29.8 ± 10.5	4083 ± 204	4215 ± 48	4195
$320-350$	1496 ± 35	818 ± 20	10.0 ± 0.6	19.7 ± 1.2	33.6 ± 3.3	25.4 ± 4.2	9.0 ± 5.4	2385 ± 118	2407 ± 37	2364
$350-390$	1204 ± 31	555 ± 15	3.9 ± 0.2	12.7 ± 0.8	24.5 ± 2.4	22.1 ± 3.6	6.0 ± 3.5	1817 ± 87	1826 ± 32	1875
$390-430$	684 ± 20	275 ± 9	2.1 ± 0.1	8.3 ± 0.5	9.8 ± 1.0	13.9 ± 2.3	3.0 ± 1.6	978 ± 45	998 ± 23	1006
$430-470$	382 ± 14	155 ± 6	0.96 ± 0.06	4.9 ± 0.3	9.4 ± 0.9	6.6 ± 1.1	1.0 ± 0.8	589 ± 30	574 ± 17	543
$470-510$	248 ± 11	87.3 ± 3.8	0.47 ± 0.03	3.7 ± 0.2	0.22 ± 0.02	5.1 ± 0.8	0.65 ± 0.44	337 ± 15	344 ± 12	349
$510-550$	160 ± 8	52.2 ± 2.7	0.23 ± 0.01	2.0 ± 0.1	2.7 ± 0.3	2.2 ± 0.4	0.28 ± 0.19	211 ± 9	219 ± 9	216
$550-590$	99.5 ± 6.0	29.2 ± 1.9	0.12 ± 0.01	1.8 ± 0.1	0.94 ± 0.09	2.0 ± 0.3	0.19 ± 0.14	134 ± 6	134 ± 7	142
$590-640$	77.3 ± 4.9	18.9 ± 1.4	0.09 ± 0.01	0.46 ± 0.03	< 0.13	1.7 ± 0.3	0.11 ± 0.08	100 ± 4	98.5 ± 5.8	111
$640-690$	44.8 ± 3.5	11.2 ± 0.9	0.017 ± 0.001	0.19 ± 0.01	< 0.13	1.5 ± 0.2	0.06 ± 0.05	59.6 ± 2.6	58.0 ± 4.1	61
$690-740$	27.8 ± 2.5	6.1 ± 0.6	0.013 ± 0.0008	0.57 ± 0.04	< 0.13	0.69 ± 0.11	0.02 ± 0.02	36.6 ± 1.5	35.2 ± 2.9	32
$740-790$	21.8 ± 2.3	5.3 ± 0.6	< 0.005	0.28 ± 0.02	0.23 ± 0.02	0.11 ± 0.02	0.02 ± 0.02	23.8 ± 1.0	27.7 ± 2.7	28
$790-840$	13.5 ± 1.9	2.8 ± 0.4	< 0.005	0.18 ± 0.01	0.27 ± 0.03	0.010 ± 0.001	0.008 ± 0.007	15.3 ± 0.7	16.8 ± 2.2	14
$840-900$	9.5 ± 1.4	2.0 ± 0.3	< 0.005	0.28 ± 0.02	< 0.13	0.25 ± 0.04	< 0.008	12.2 ± 0.6	12.0 ± 1.6	13
$900-960$	5.4 ± 1.0	1.1 ± 0.2	< 0.005	< 0.08	< 0.13	0.37 ± 0.06	< 0.008	7.6 ± 0.3	6.9 ± 1.2	7
$960-1020$	3.3 ± 0.8	0.77 ± 0.21	< 0.005	0.12 ± 0.01	< 0.13	0.23 ± 0.04	< 0.008	5.2 ± 0.3	4.5 ± 1.0	3
$1020-1160$	2.5 ± 0.8	0.52 ± 0.16	< 0.005	< 0.08	< 0.13	0.16 ± 0.03	< 0.008	3.6 ± 0.2	3.2 ± 0.9	1
$1160-1250$	1.7 ± 0.6	0.3 ± 0.11	< 0.005	< 0.08	< 0.13	0.16 ± 0.03	< 0.008	2.3 ± 0.1	2.2 ± 0.7	2
> 1250	1.4 ± 0.5	0.19 ± 0.08	< 0.005	< 0.08	< 0.13	0.06 ± 0.01	< 0.008	1.6 ± 0.1	1.6 ± 0.6	3

http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/EXO-16-013/#AddFig

Complementarity of LHC and non-LHC DM searches

for the model with Vector Resonances, Top Partners and Scalar DM

TT→ t t DM DM



arXiv: 1707.07000

LHC@13TeV Reach for spin 0 and ½ DM

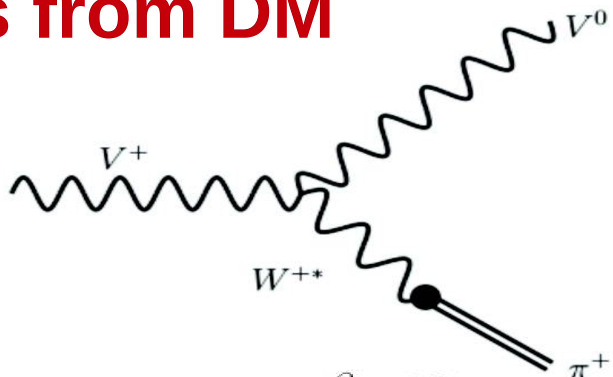
	Operators	Coefficient	Excluded Λ (GeV) at 3.2 fb^{-1}			Excluded Λ (GeV) at 100 fb^{-1}		
			DM Mass			DM Mass		
			10 GeV	100 GeV	1000 GeV	10 GeV	100 GeV	1000 GeV
Complex Scalar DM	C1 & C2	$1/\Lambda$	456	424	98	1168	1115	267
	C3 & C4	$1/\Lambda^2$	750	746	400	1134	1131	662
	C5 & C6	$1/\Lambda^2$	1621	1576	850	2656	2611	1398
Dirac Fermion DM	D1 & D3	$1/\Lambda^2$	931	940	522	1386	1405	861
	D2 & D4	$1/\Lambda^2$	952	936	620	1426	1399	1022
	D1T & D4T	$1/\Lambda^2$	735	729	476	1217	1199	780
	D2T	$1/\Lambda^2$	637	638	407	1053	1052	670
	D3T	$1/\Lambda^2$	586	625	391	969	938	644
	D5 & D7	$1/\Lambda^2$	1058	967	721	1580	1591	1190
	D6 & D8	$1/\Lambda^2$	978	1050	579	1608	1585	955
	D9 & D10	$1/\Lambda^2$	1587	1592	958	2613	2619	1580

LHC@13TeV Reach for spin 1 DM

	Operators	Coefficient	Excluded Λ (GeV) at 3.2 fb^{-1}			Excluded Λ (GeV) at 100 fb^{-1}		
			DM Mass			DM Mass		
			10 GeV	100 GeV	1000 GeV	10 GeV	100 GeV	1000 GeV
Complex Vector DM	V1 & V2	M_{DM}^2/Λ_D^3	831	833	714	1162	1161	997
	V3 & V4	M_{DM}^2/Λ_D^4	930	931	833	1196	1193	1070
	V5 & V6	M_{DM}^2/Λ_D^3	784	791	711	1095	1104	993
	V7M & V8M	M_{DM}^2/Λ_D^4	930	926	882	1195	1193	1130
	V7P & V8P	M_{DM}/Λ_D^3	796	791	652	1112	1102	911
	V9M & V10M	M_{DM}/Λ_D^3	796	799	737	1109	1114	1027
	V9P & V10P	M_{DM}/Λ_D^3	794	782	609	1110	1089	850
	V11 & V11A	M_{DM}^2/Λ_D^4	1435	1442	1309	1844	1850	1683

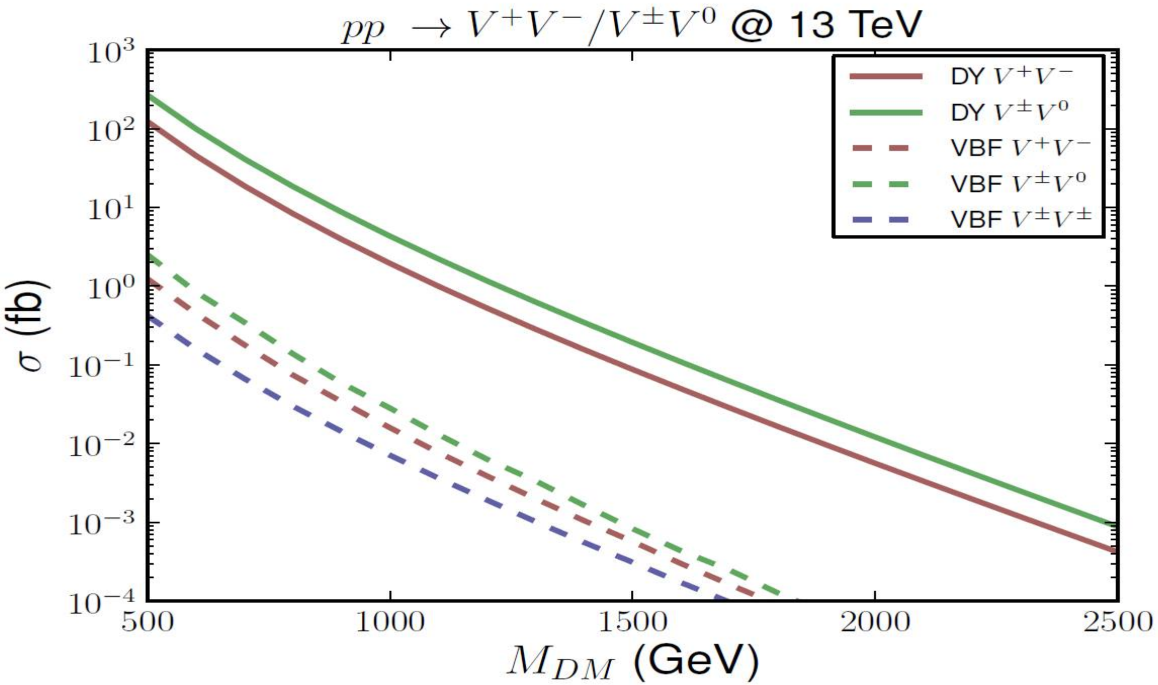
Disappearing Charged Tracks from DM

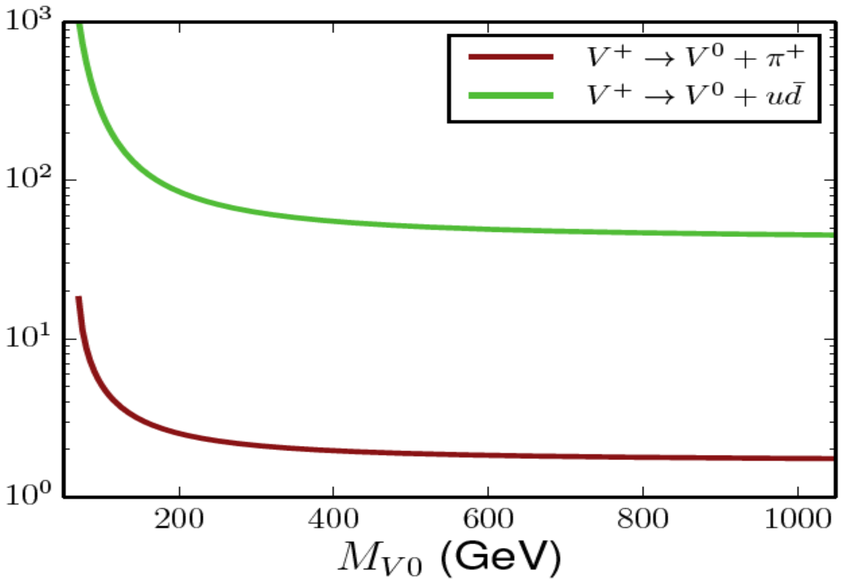
The small mass gap between (~ pion mass) DM and its charged partner will lead to the disappearing charge tracks



The life-time should be properly evaluated using W-pion mixing

$$\mathcal{L}_{\pi^- V^+ V^0} = \frac{g^2 f_\pi}{2\sqrt{2} M_W^2} [g_{\beta\gamma}(p_{V^+} - p_{V^0})_\alpha + g_{\alpha\gamma}(p_{V^+} - p_{V^0})_\beta] p^\alpha_{\pi^-} \pi^- V^{+\beta} V^{0\gamma}$$



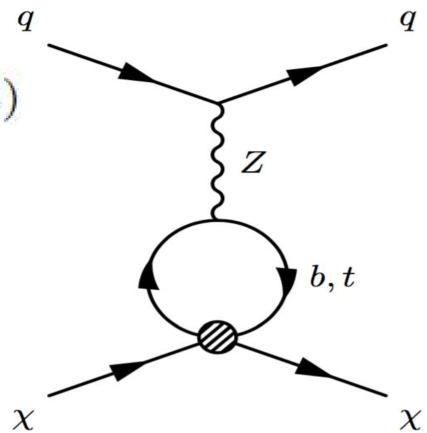


Importance of the operator running in the DM DD ↔ Collider interplay

- In case of axial operators, e.g

$c_A^{(q)} c_\chi \overline{\chi}\gamma^\mu \chi \overline{q}\gamma_\mu \gamma_5 q \quad (D7)$ or $c_A^{(q)} c_\phi \phi^\dagger \overleftrightarrow{\partial}_\mu \phi \overline{q}\gamma^\mu \gamma_5 q \quad (C4)$

couplings $\mathbf{c}_V^{(q)}$ arise due to the running of the wilson coefficient $\mathbf{c}_A^{(q)}$ leading to sizable constraints on the DM DD constraints



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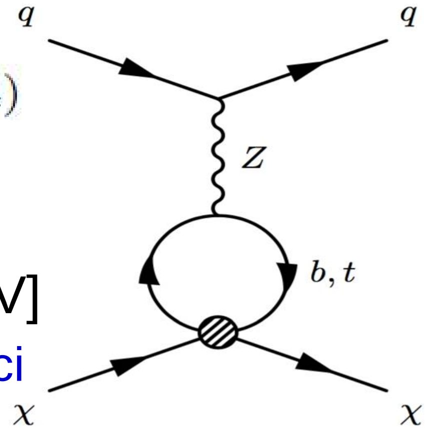

$\mathbf{c_A^{(u)}, c_A^{(d)}, c_V^{(u)}, c_V^{(d)}}=\mathbf{(1,1,0,0)}$[1TeV] → (**1.1, 1.1, 0.04, -0.07**)[1GeV]

runDM program (**github.com/bradkav/runDM**) by D'Eramo, Kavanagh Panci

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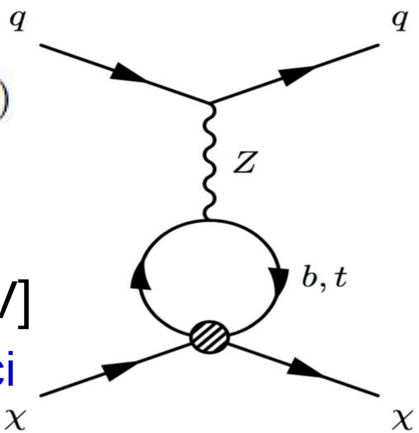
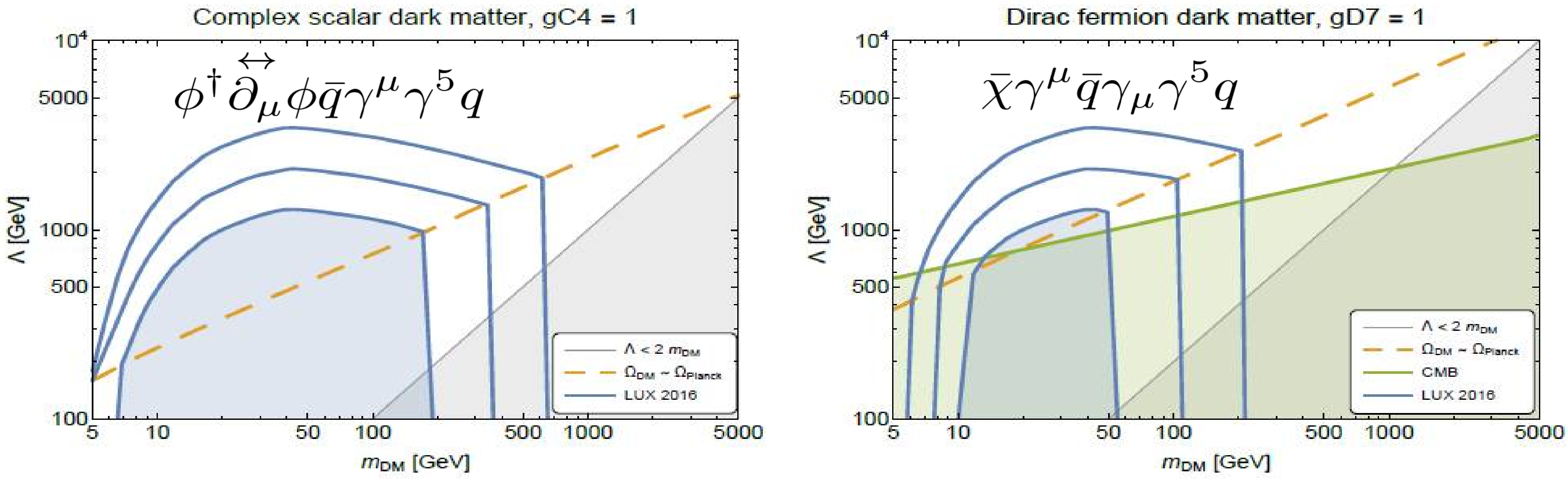
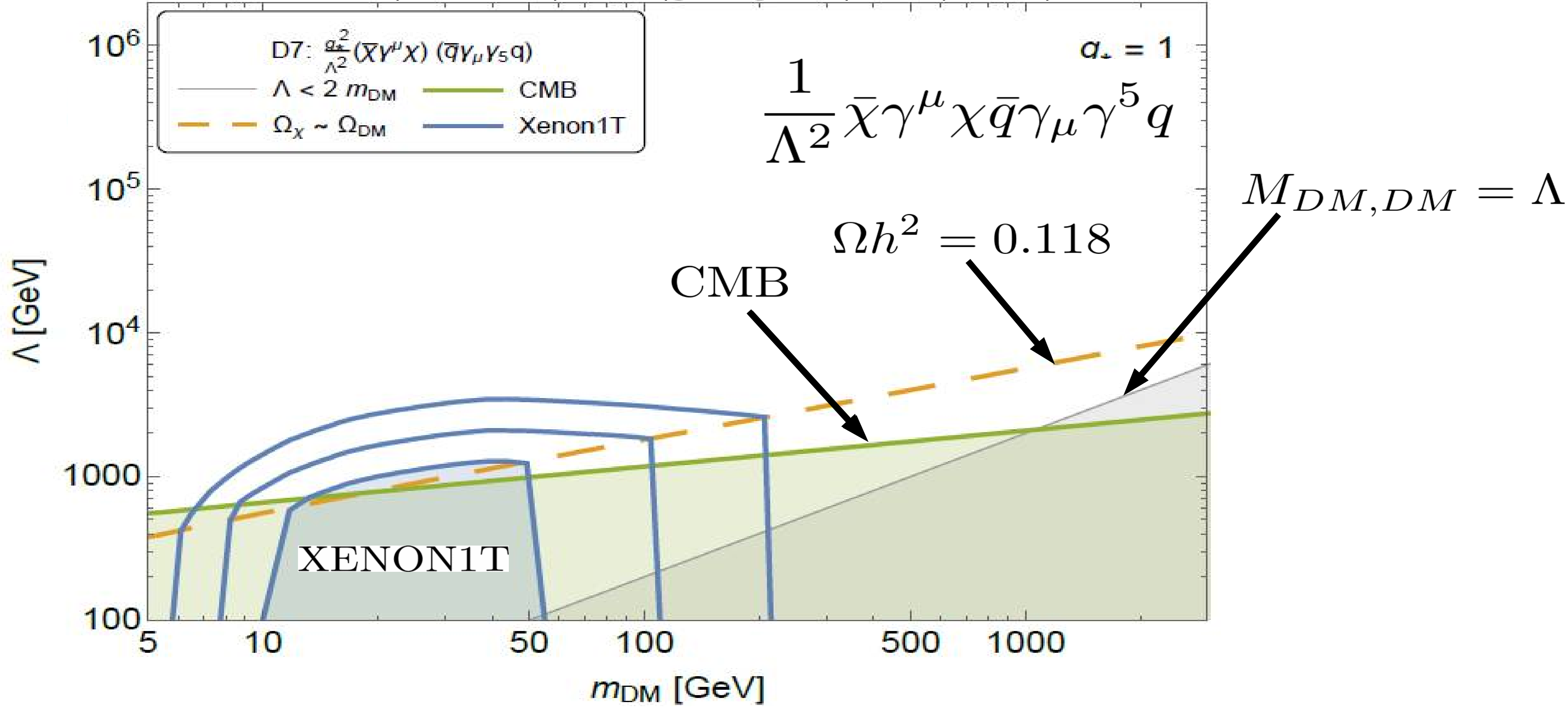




AB, Bertuzzo, Caniu, di Cortona, Eboli, Iocco, Pukhov 2018

DM DD ↔ Collider interplay

AB, Bertuzzo, Caniu, di Cortona, Eboli, Iocco, Pukhov 2018



$$\text{CMB:} \quad p_{ann} < 4.1 \times 10^{-28}\ \frac{\text{cm}^3}{\text{s GeV}}\ \text{at 95\% C.L.}\ ,\ \text{where}\quad p_{ann} = \sum_j f_j(600, m_{DM})\frac{\langle\sigma v\rangle_j(600)}{m_{DM}}$$

DM DD ↔ Collider interplay

AB, Bertuzzo, Caniu, di Cortona, Eboli, Iocco, Pukhov 2018