

# Decoding the nature of Dark Matter

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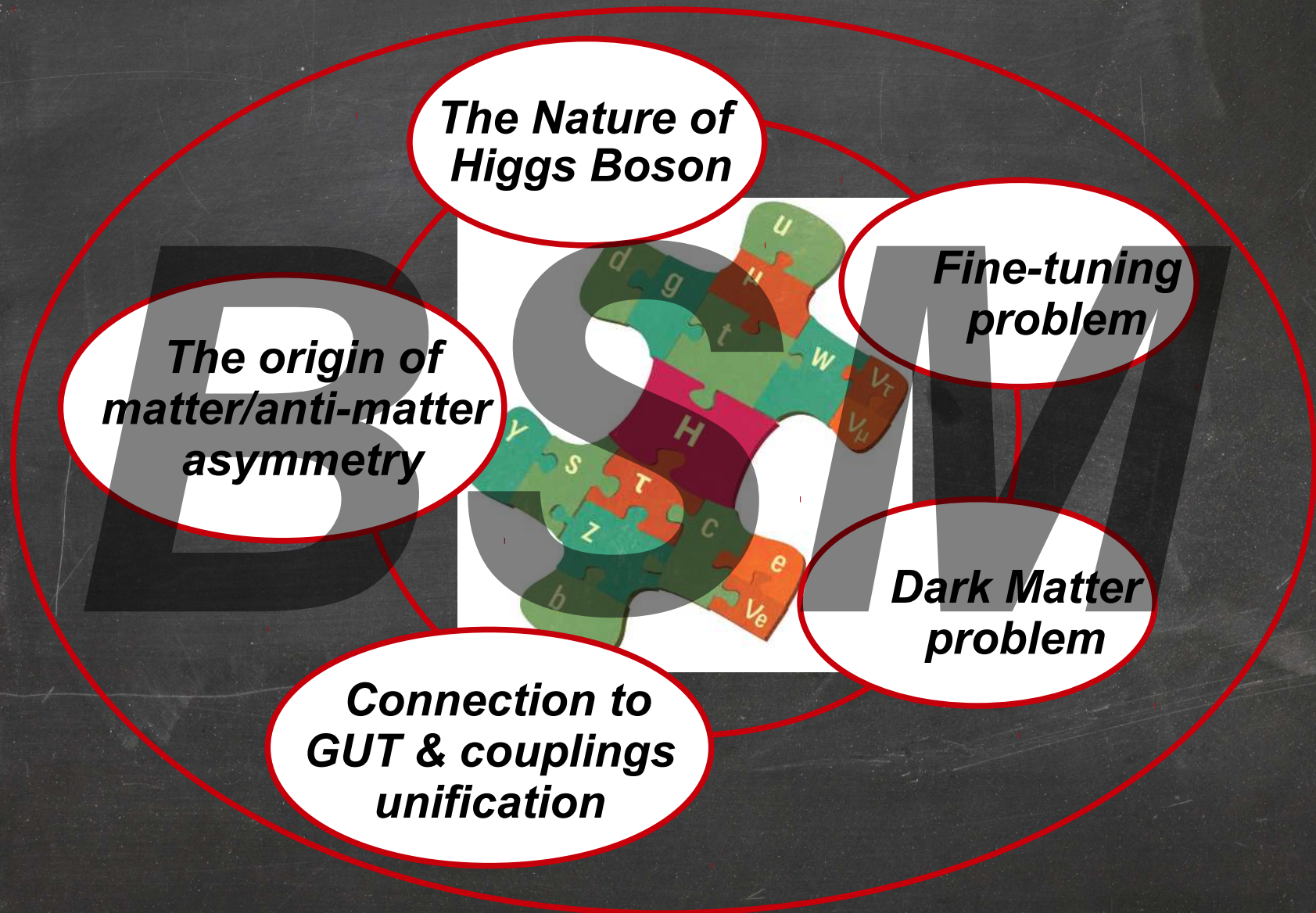
**Helmholtz International School  
"Modern Colliders - Theory and Experiment 2018" and Workshop  
"Calculations for Modern and Future Colliders (CALC2018)"**

# Higgs Boson Discovery has finished the SM puzzle

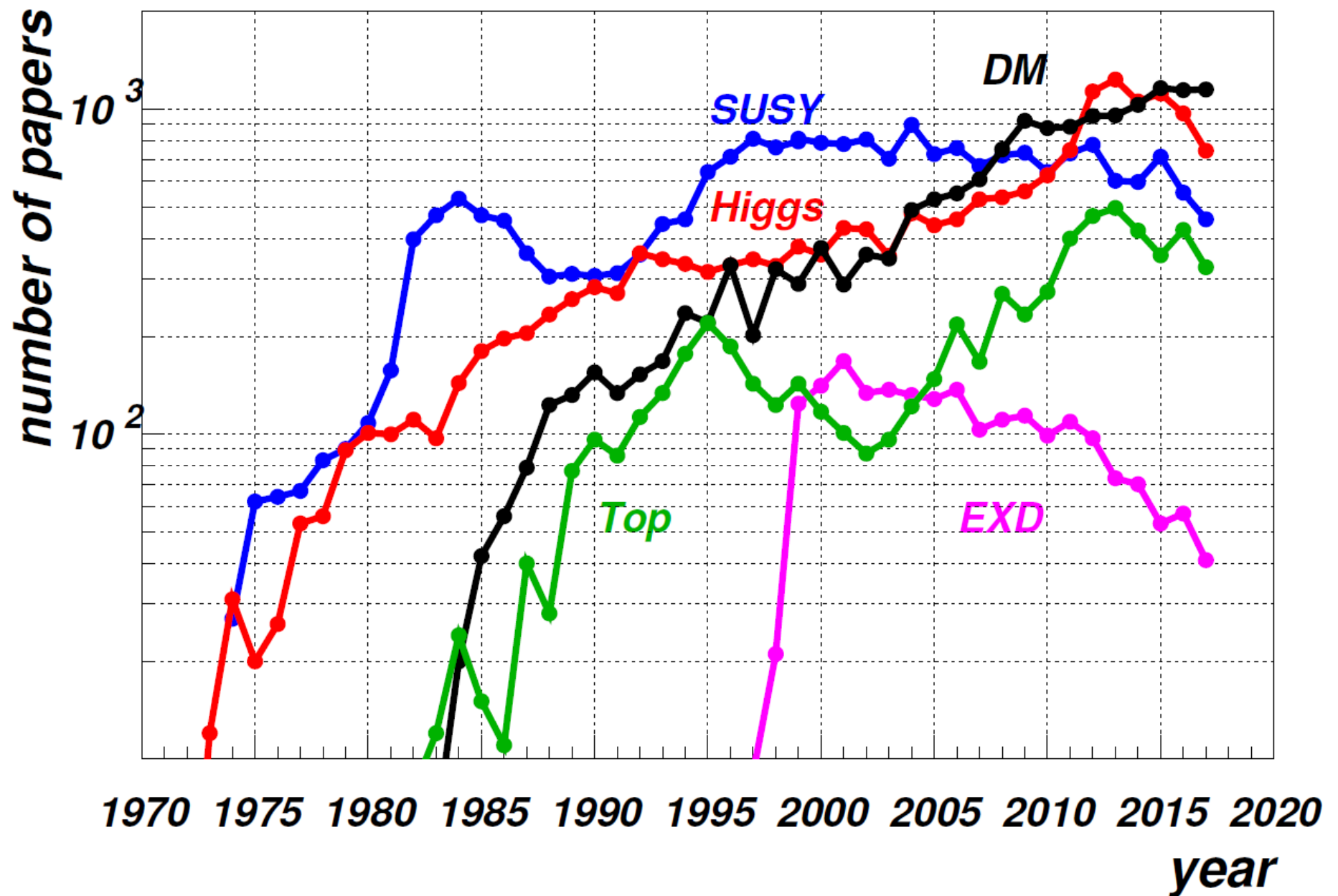




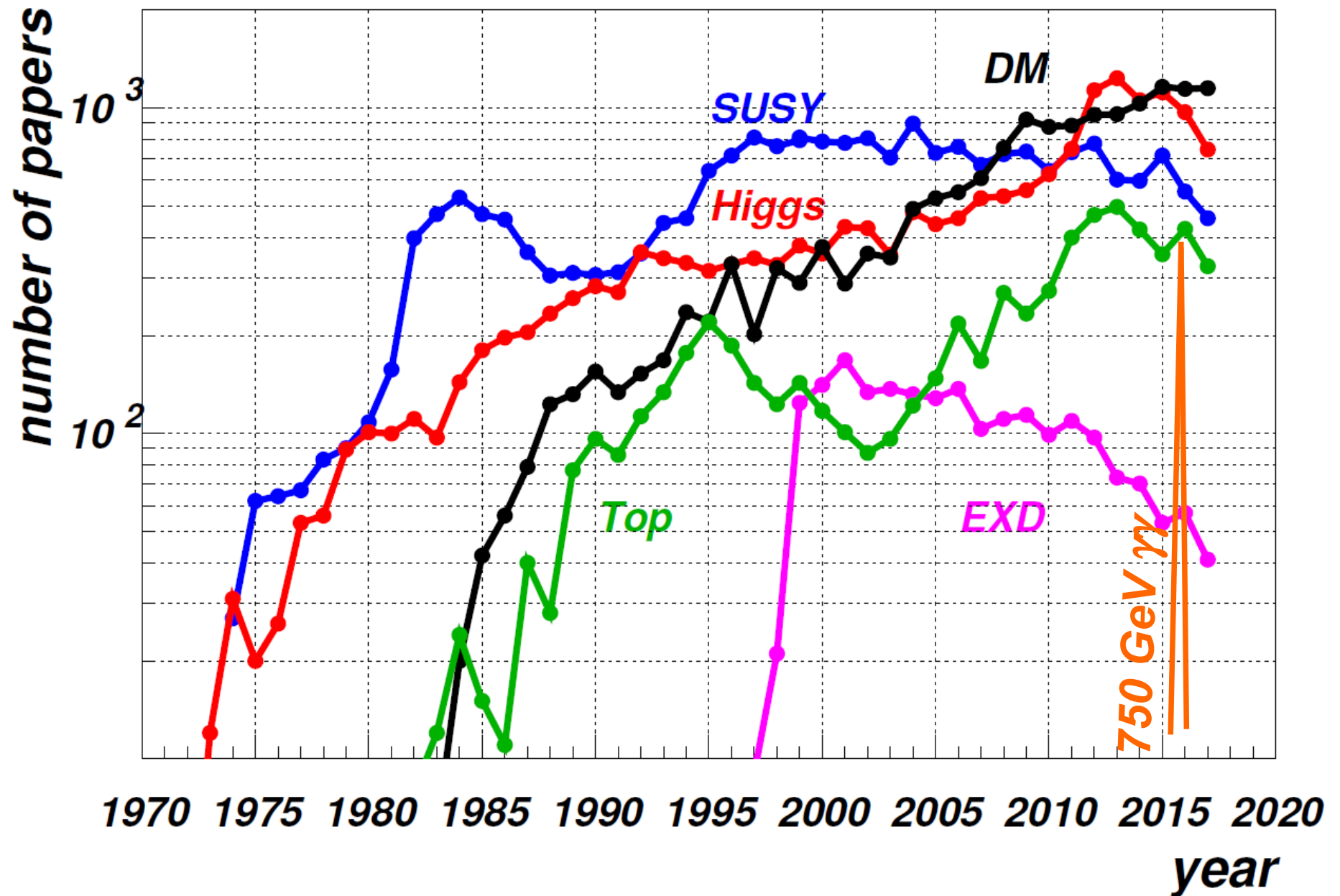
**Higgs Boson Discovery has finished the SM puzzle, but it is just a piece of some (more) complete and consistent one!**



# Why we are so keen to study DM?

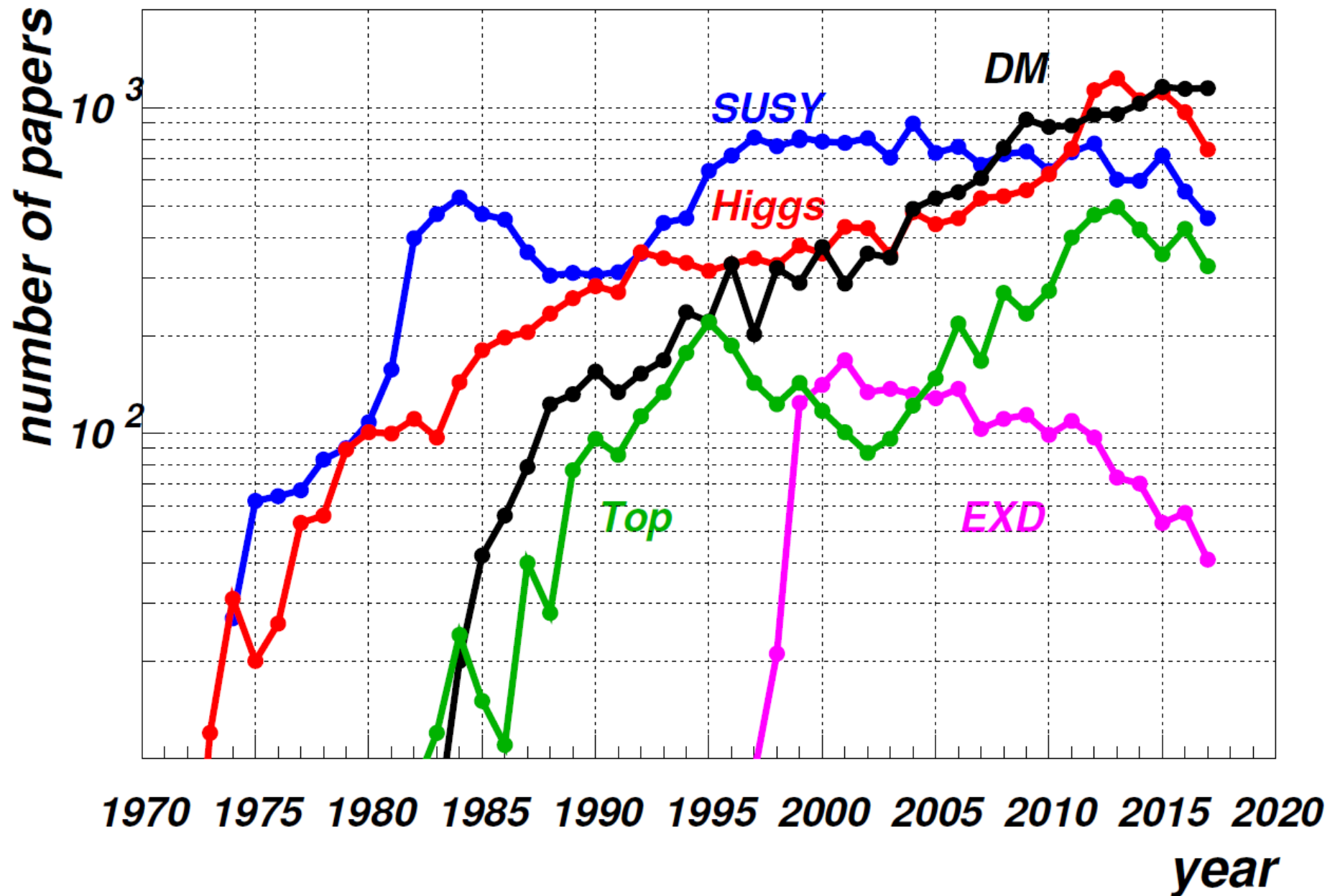


# Why we are so keen to study DM?



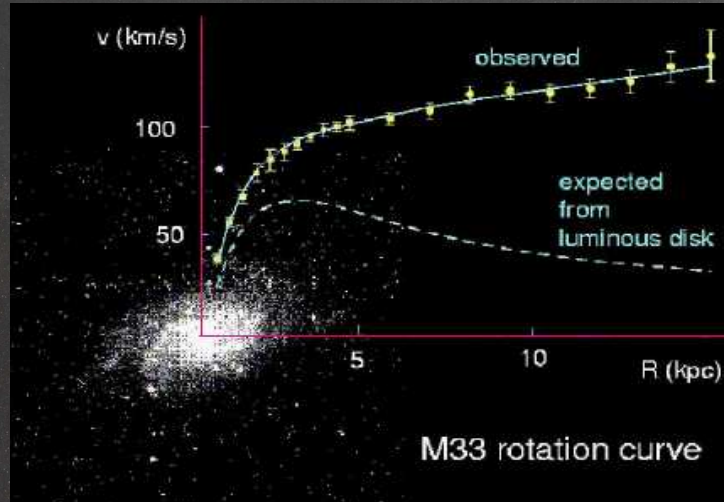


# Why we are so keen to study DM?

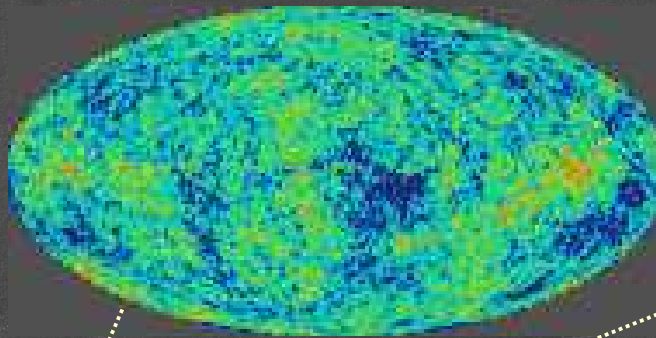


# Because the existence of DM is the strongest evidence for BSM!

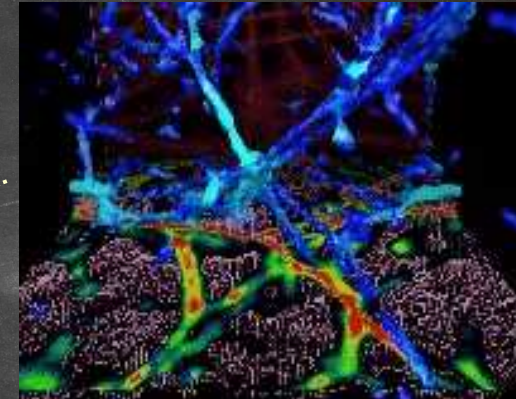
## Galactic rotation curves



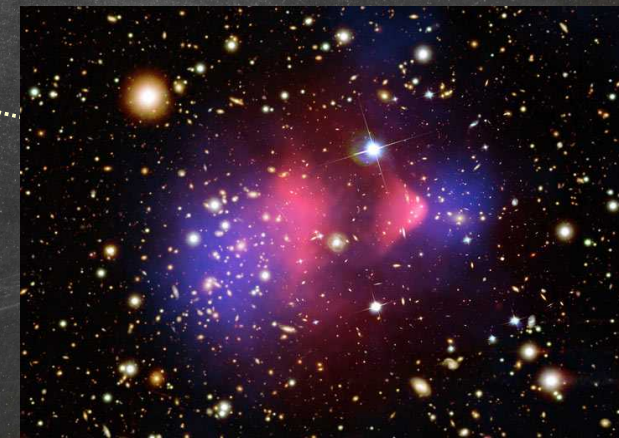
## CMB: WMAP and PLANCK



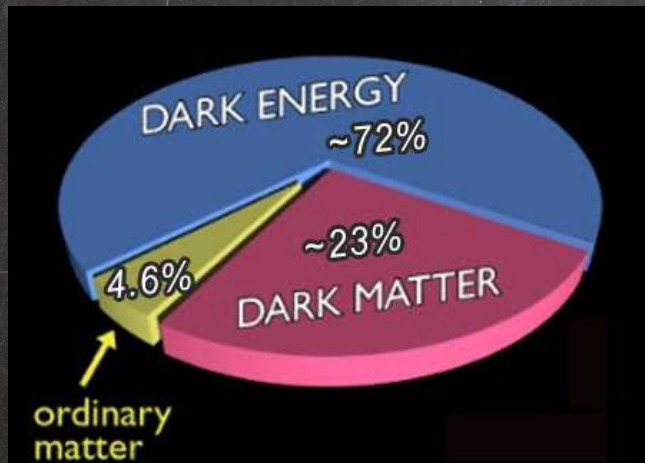
## Large Scale Structures



## Bullet cluster



## Gravitational lensing





Even though we know almost nothing about it!

*Spin* ☐

*Mass* ☐

*Stable*

*Yes* ☐

*No* ☐

*symmetry*

*behind stability* ☐

*Couplings*  
*gravity*

☒

*Weak*

☐

*Higgs*

☐

*Quarks/gluons*

☐

*Leptons*

☐

*New mediators*

☐

*Thermal relic*

*Yes* ☐

*No* ☐



# How we can decode the fundamental nature of Dark Matter?



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## We need a DM signal first!



# How we can decode the fundamental nature of Dark Matter?

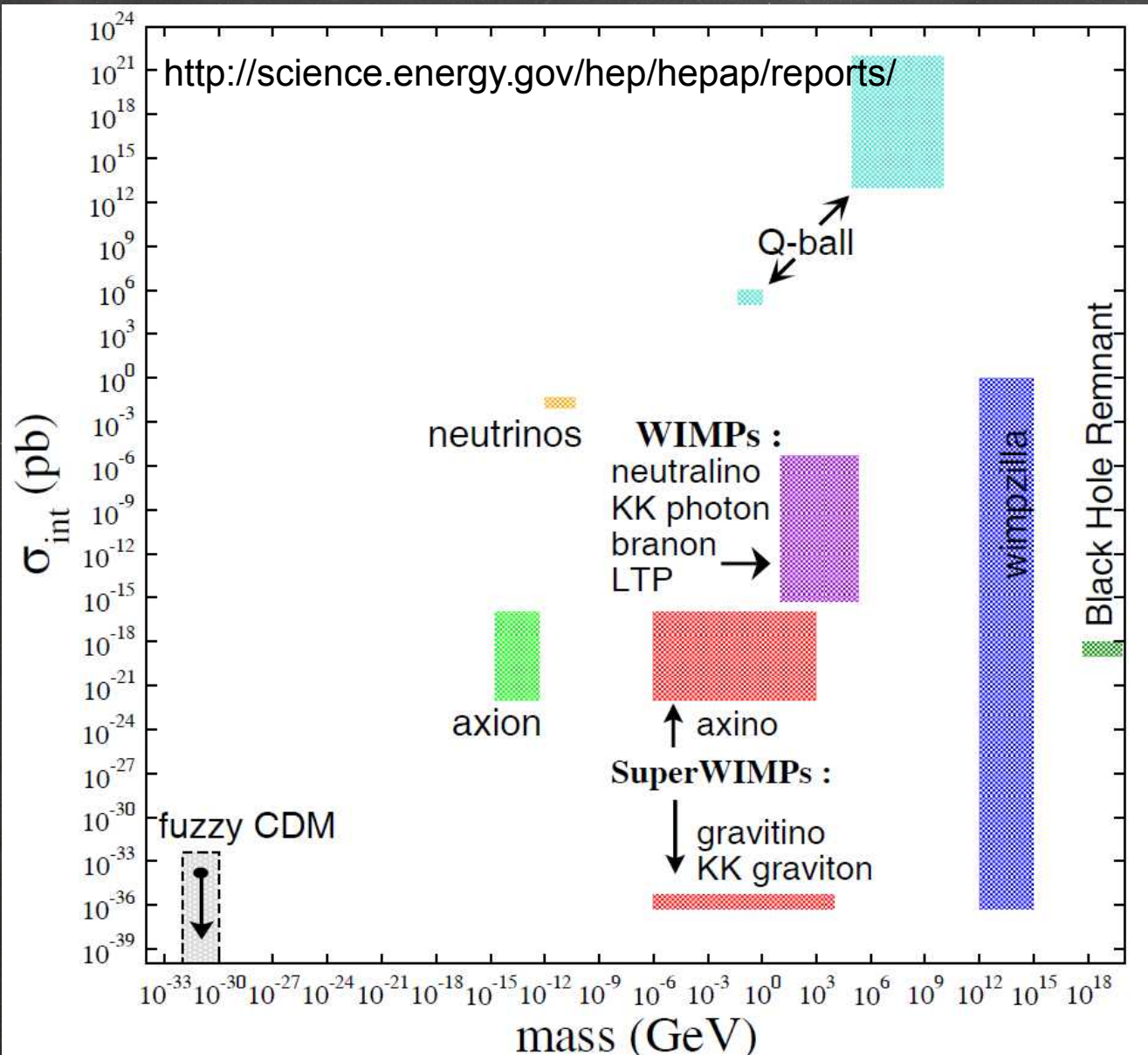
**We need a DM signal first!**

**But at the moment we can:**

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



# DM candidates: interaction vs mass



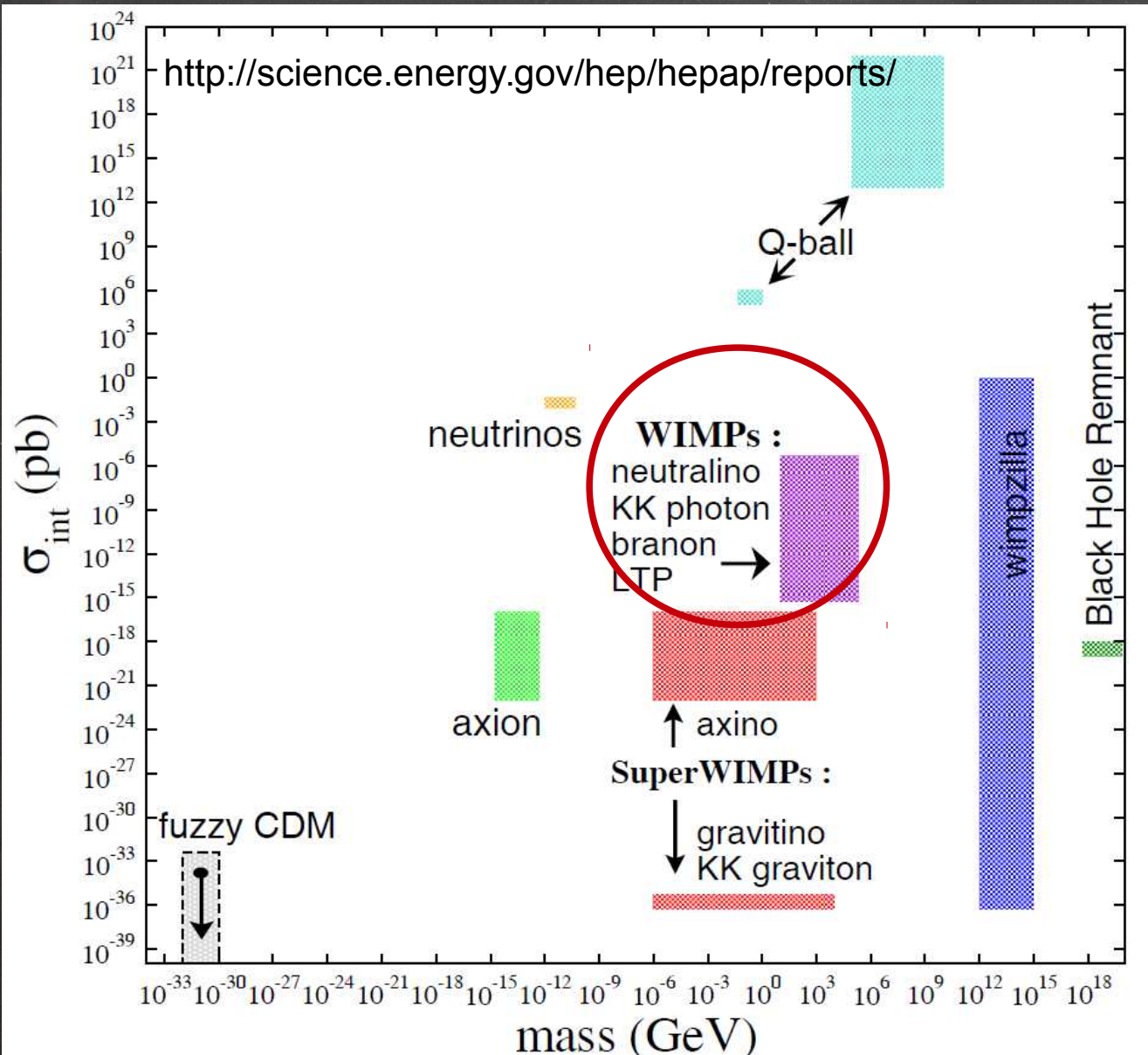
- Planck mass BH remnants: tiny black holes protected by gravity effects [Chen '04] from decay via Hawking radiation
- Wimpzillas: very massive non-thermal WIMPs [Kolb, Chung, Riotto '98]
- Q-balls: topological solitons that occur in QFT [Coleman '86]
- EW scale WIMPs, protected by parity – LSP, LKP, 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:

$$\frac{\theta_{QCD}}{32\pi^2} F^{\mu\nu} \tilde{F}_{\mu\nu}$$

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



# DM candidates: interaction vs mass

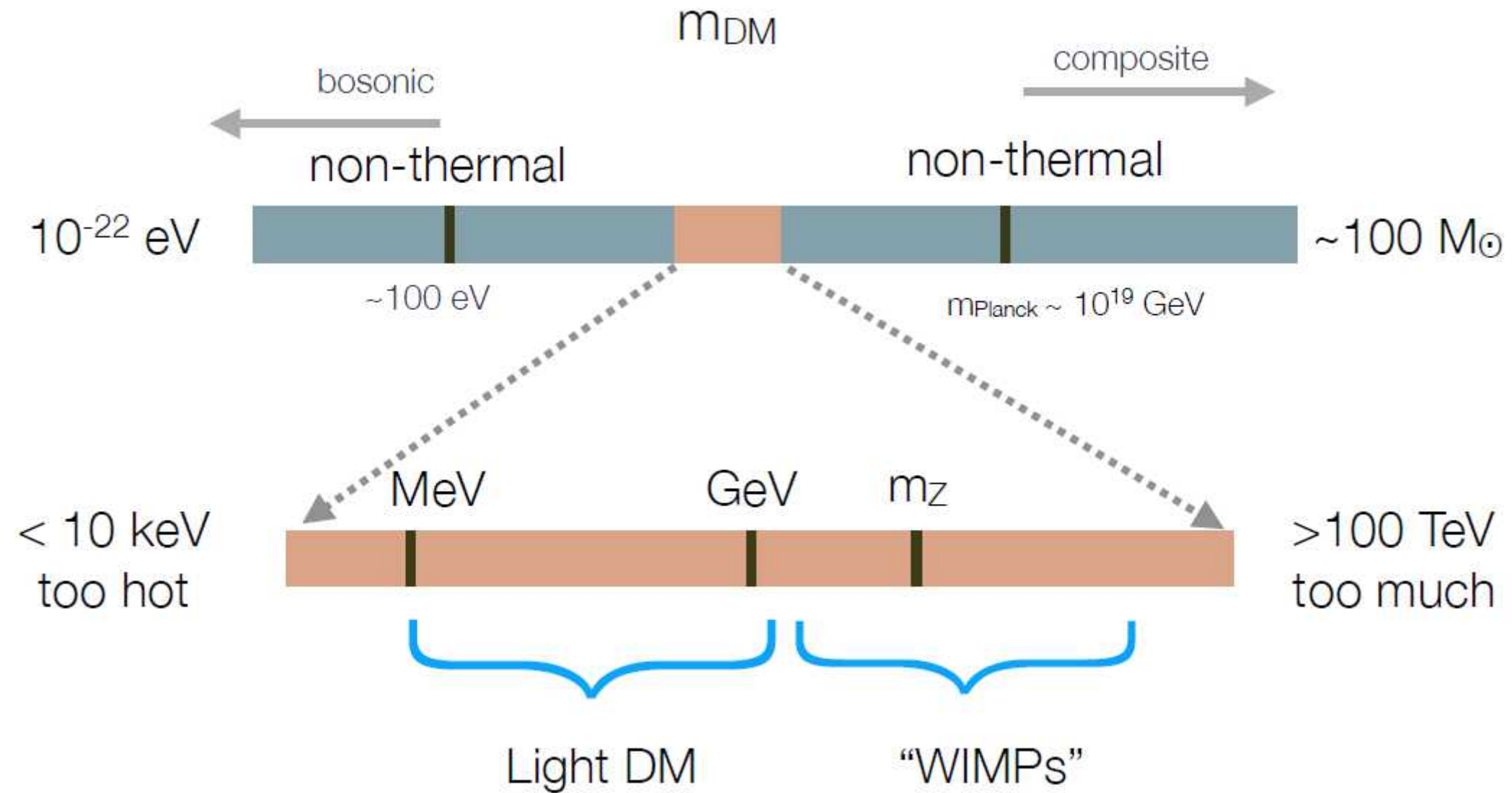


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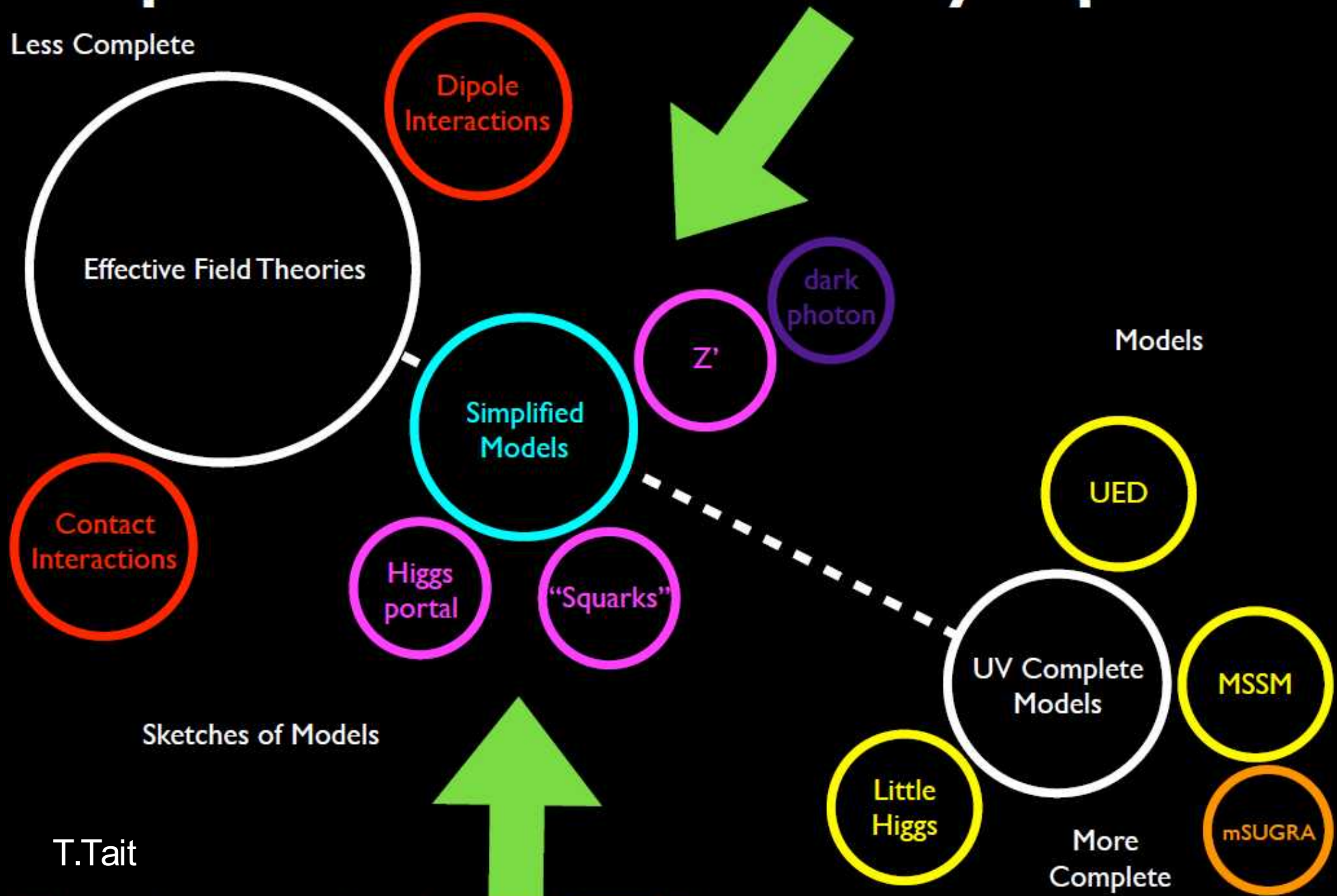
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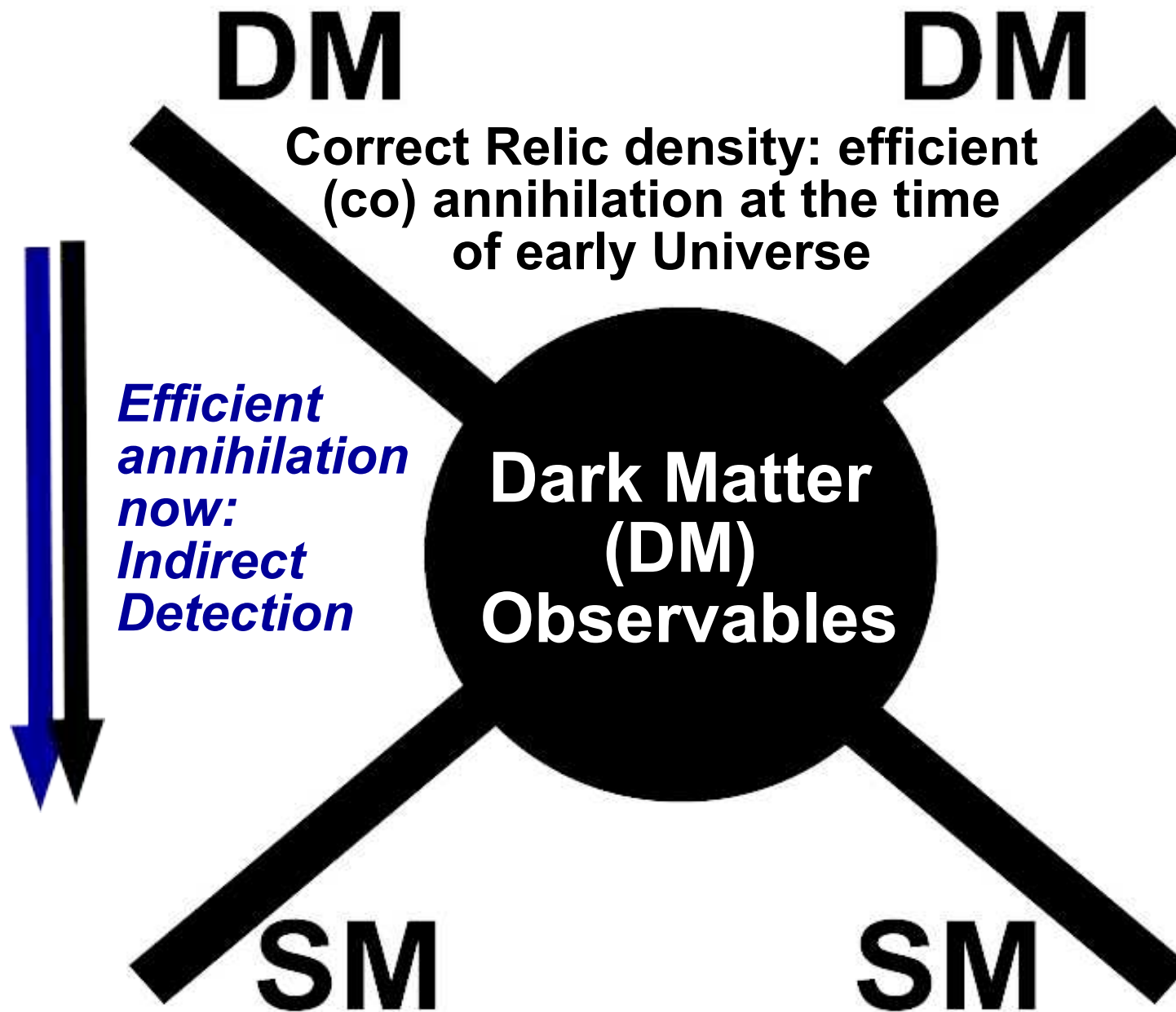
# Mass range for thermal DM





# Spectrum of Theory Space







**DM**

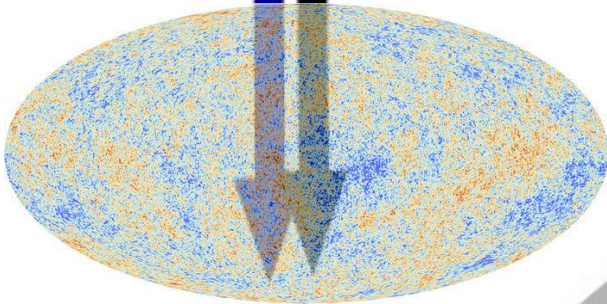
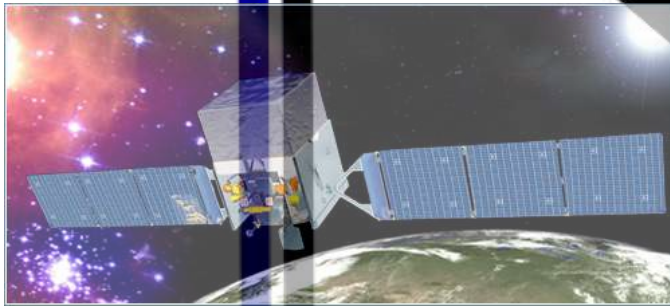
**DM**

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

**Dark Matter  
(DM)  
Observables**

**SM**

**SM**



**DM**

**DM**

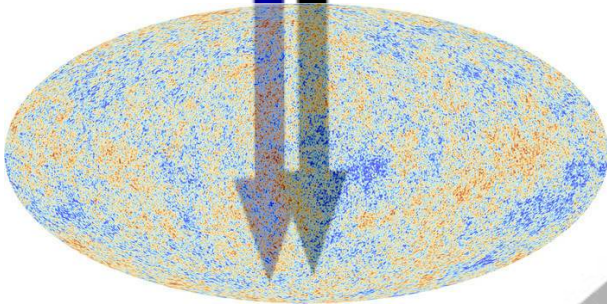
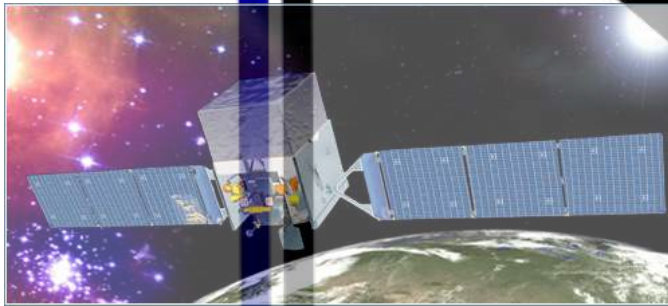
**Correct Relic density: efficient  
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**Dark Matter  
(DM)  
Observables**

***Efficient scattering  
off nuclei: Direct  
Detection***

**SM**

**SM**



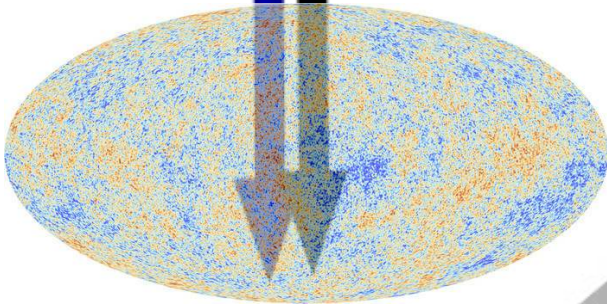
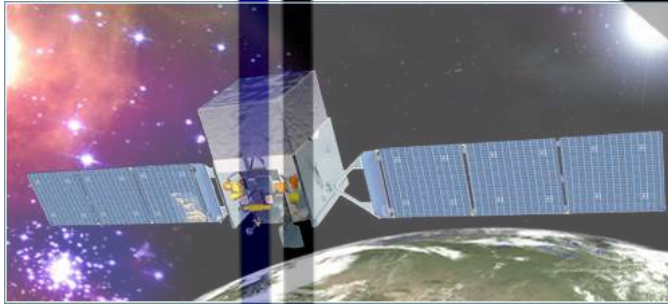


**DM**

**DM**

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**Dark Matter  
(DM)  
Observables**



**SM**



**SM**

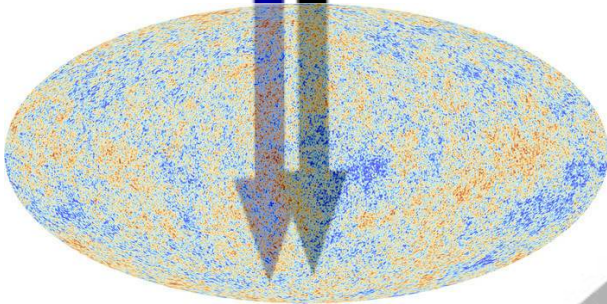
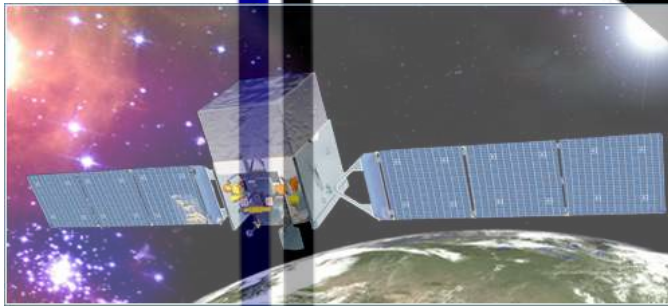
**DM**

**DM**

**Correct Relic density: efficient  
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**Dark Matter  
(DM)  
Observables**

*Efficient  
production  
at colliders*



**SM**



**SM**



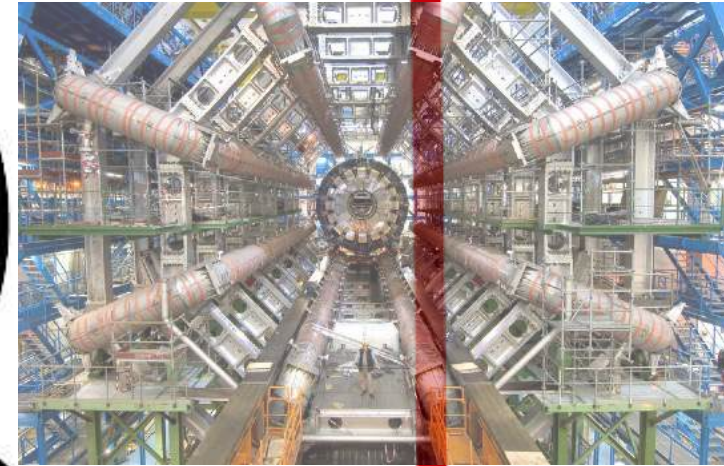
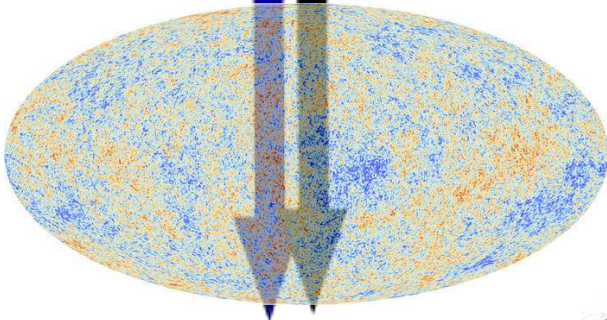
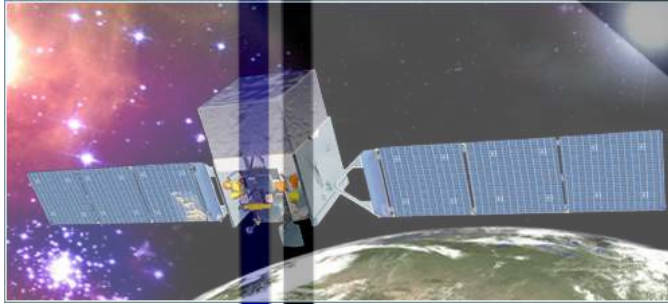


# DM

# DM

Correct Relic density: efficient  
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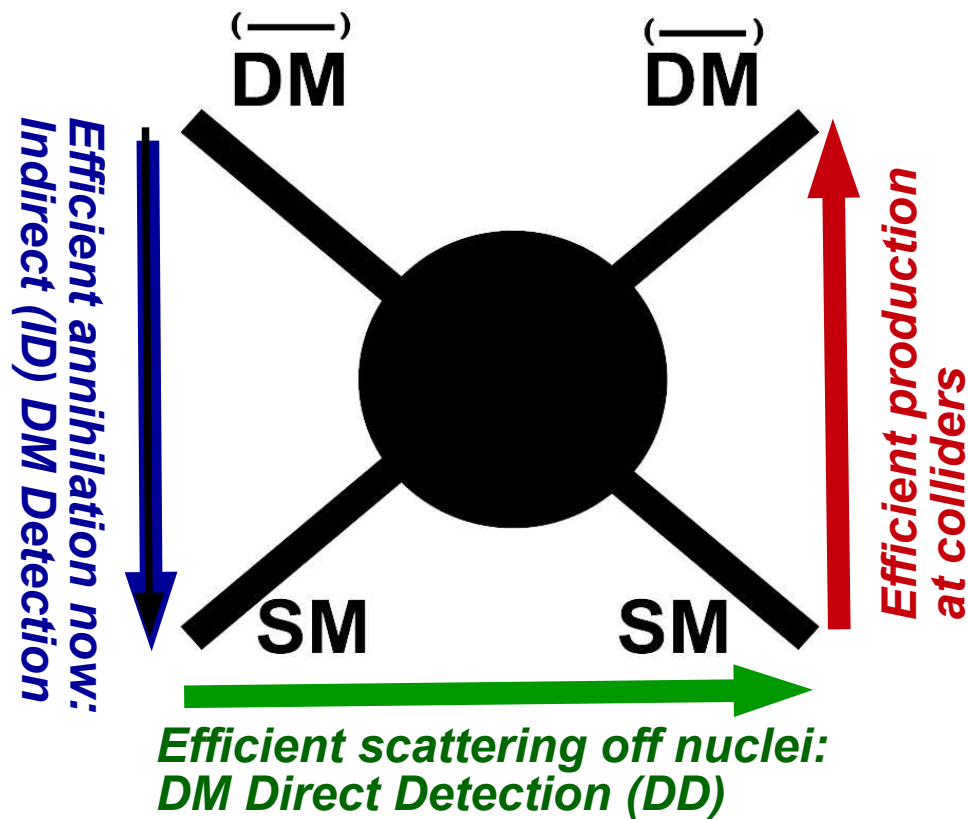
**Dark Matter  
(DM)  
Observables**



# SM

# SM

# Complementarity of DM searches



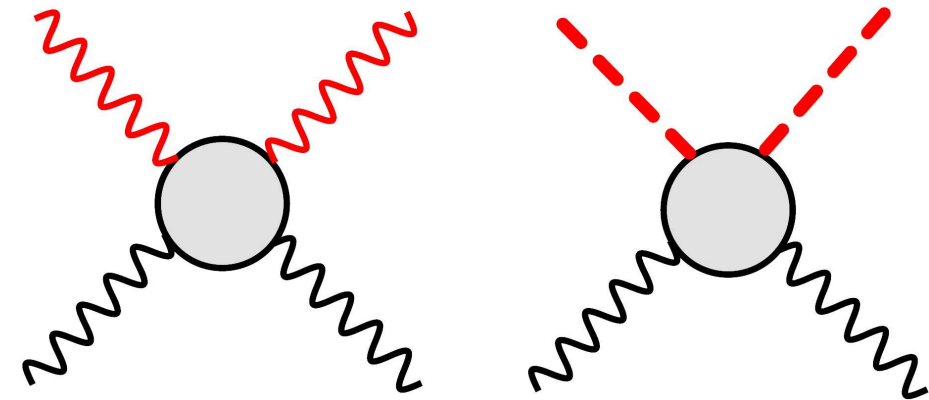
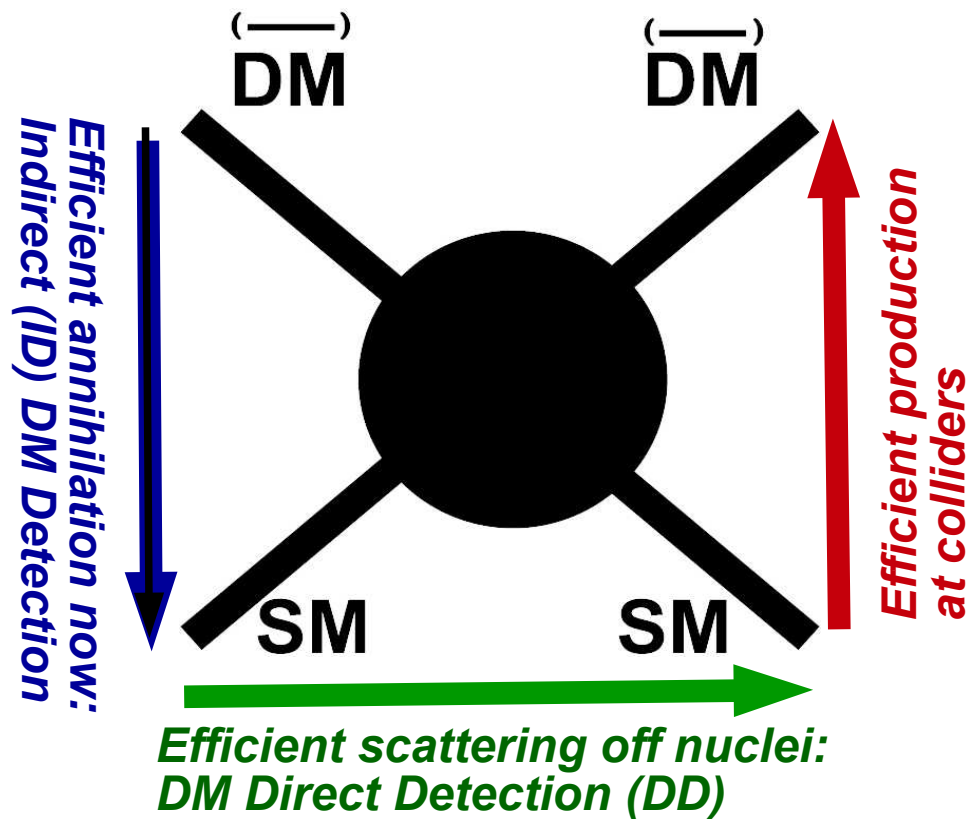
**Important:** there is no 100% correlation between signatures above. E.g. the high rate of annihilation does not always guarantee high rate for DD!

**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 can efficiently determine the nature of DM



# Complementarity of DM searches



*Example of DM interactions with negligible/suppressed DD rates*

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# Direct Dark Matter Detection

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

- Elastic recoil energy

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

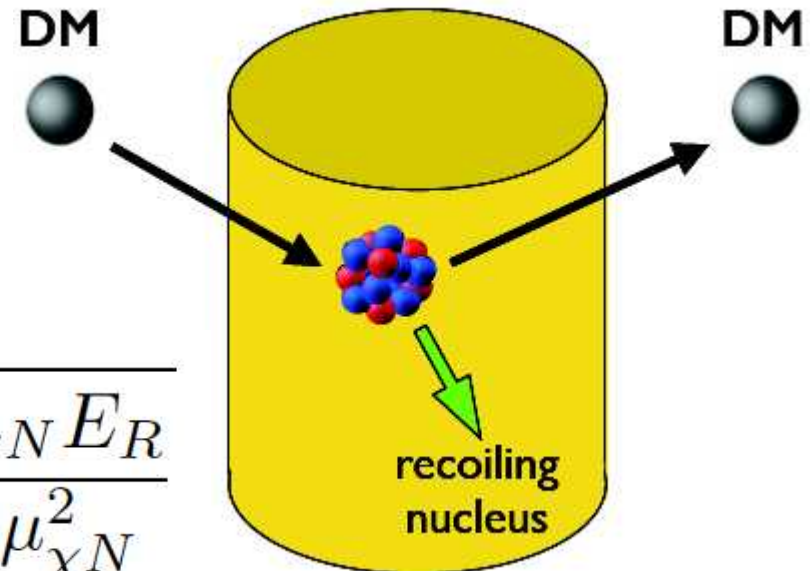
- Minimum WIMP speed required to produce a recoil energy

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

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

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

astrophysics





# Direct Dark Matter Detection

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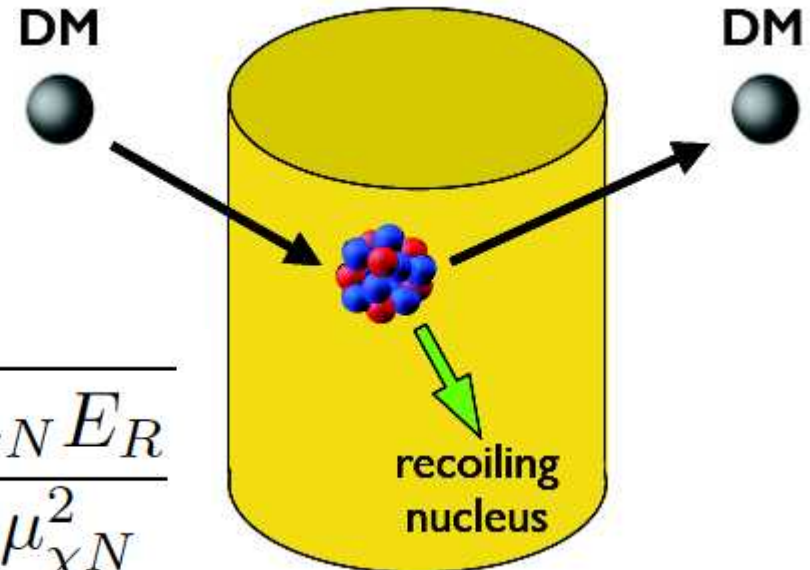
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$$\frac{dR}{dE_R} = \underbrace{\frac{\sigma_0 F^2(E_R)}{2m_\chi \mu_{\chi N}^2}}_{\text{particle physics}} \underbrace{\rho_\chi \eta(v_{\min}, t)}_{\text{halo integral}}^{\text{astrophysics}}$$



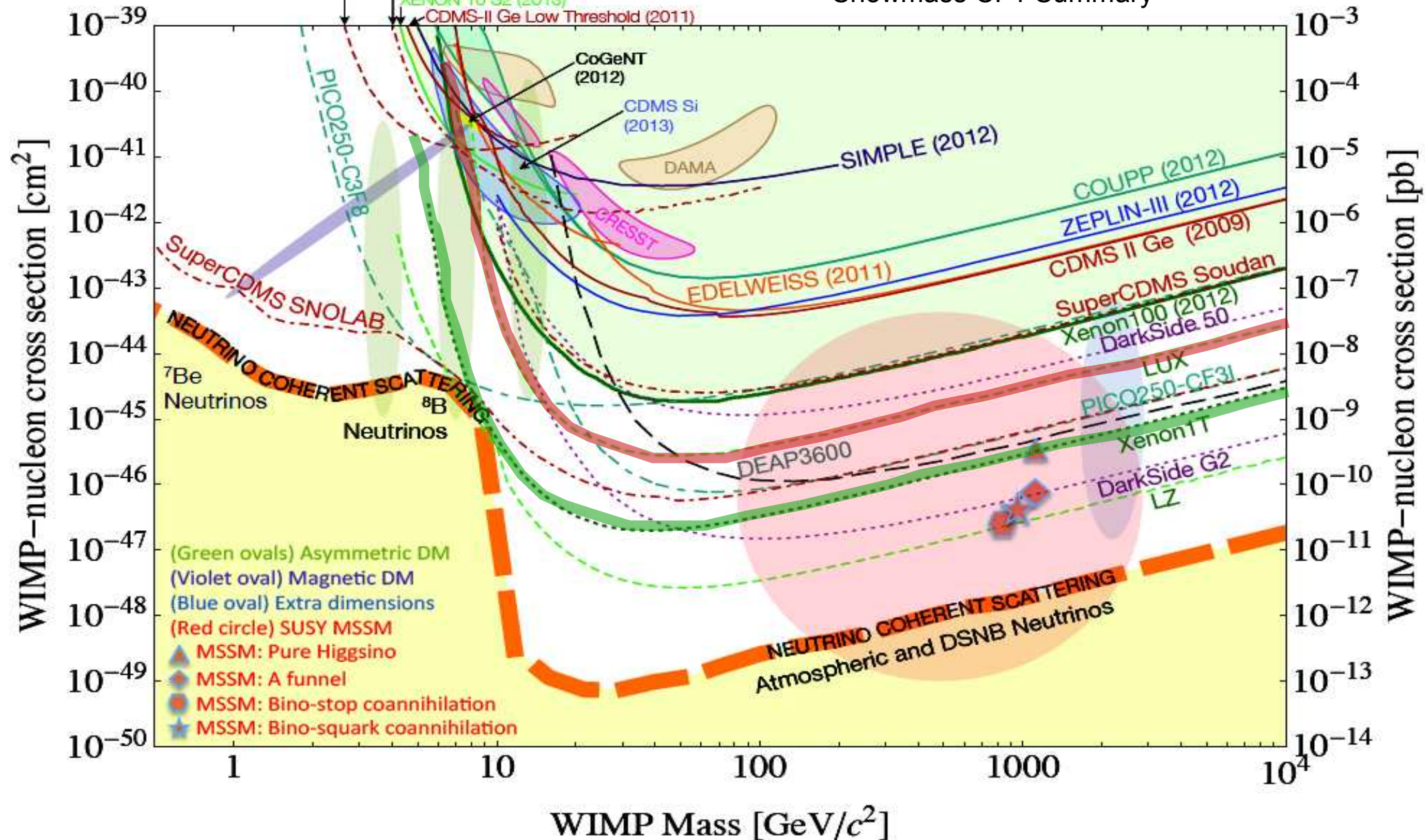
# DM DD experiments





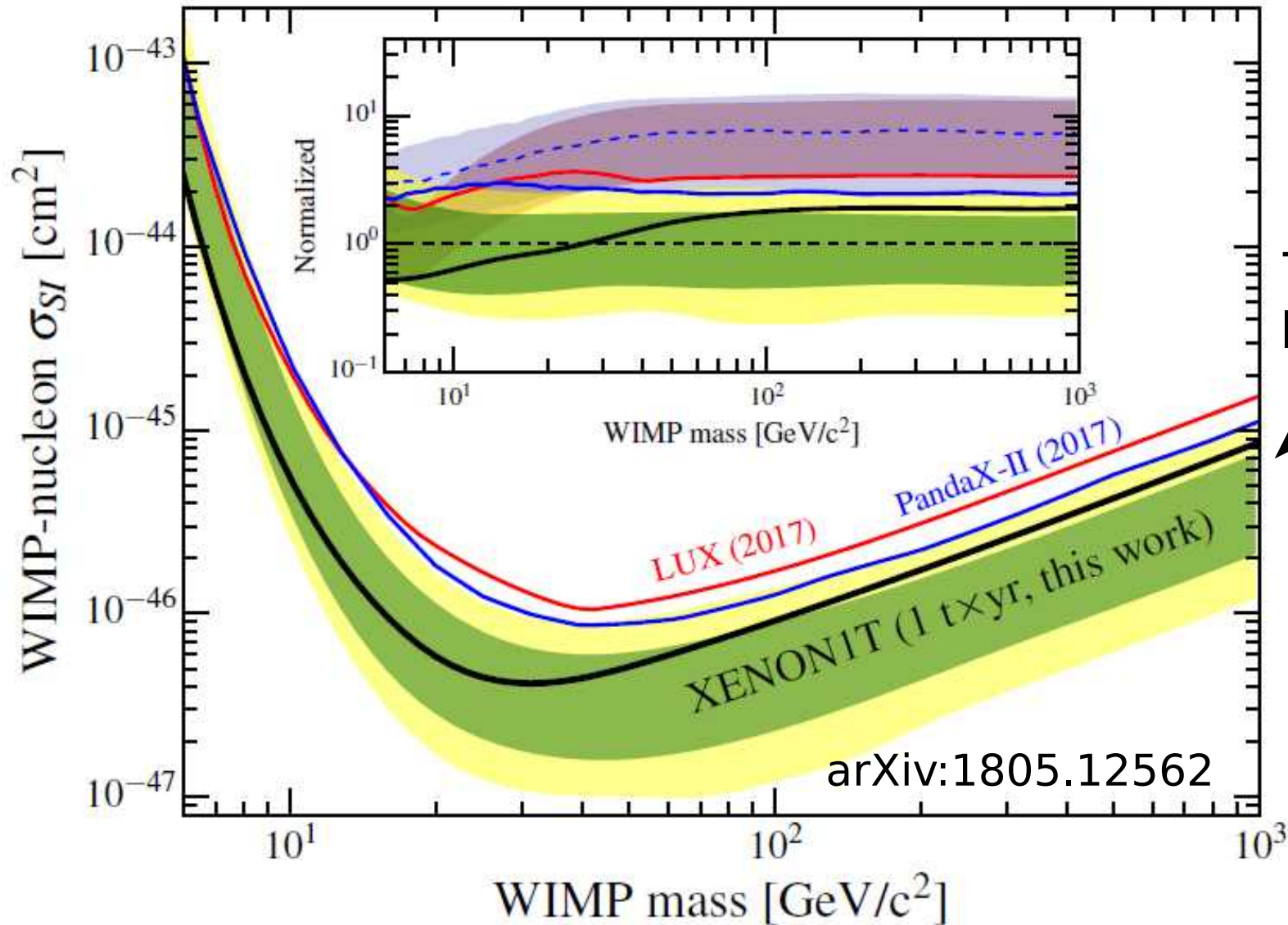
# Power of DM DD to rule out theory space

ArXiv:1310.8327  
Snowmass CF1 Summary



# Latest XENON 1T results

$$10^{-46} \text{ cm}^2 = 10^{-10} \text{ pb}$$



The limit scales linearly with  $M_{\text{DM}}$

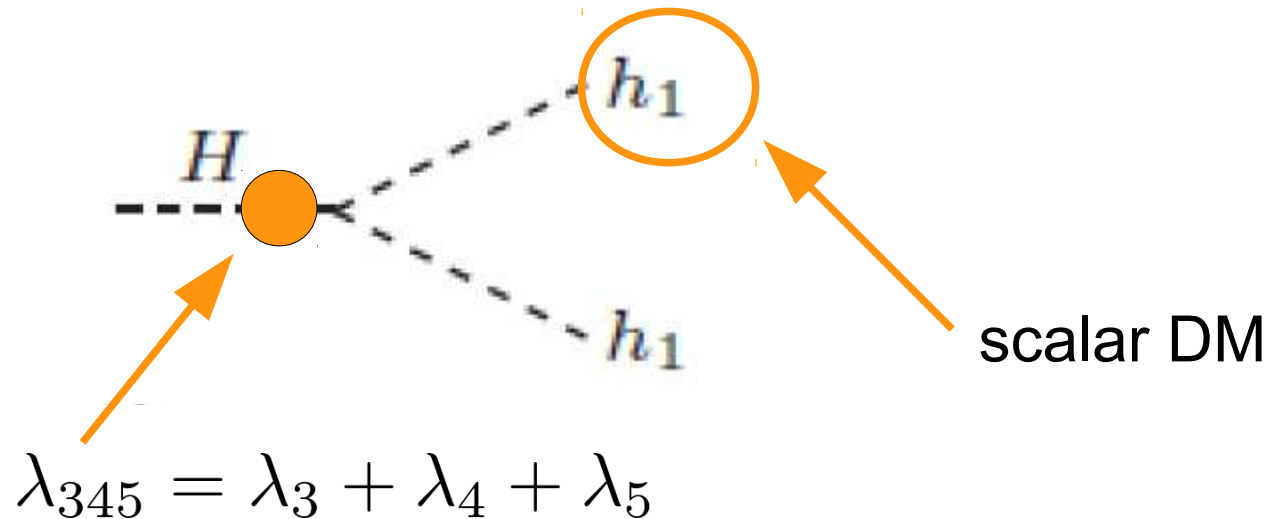


# Power of DM DD to rule out theory space

## Inert 2 Higgs Doublet Model

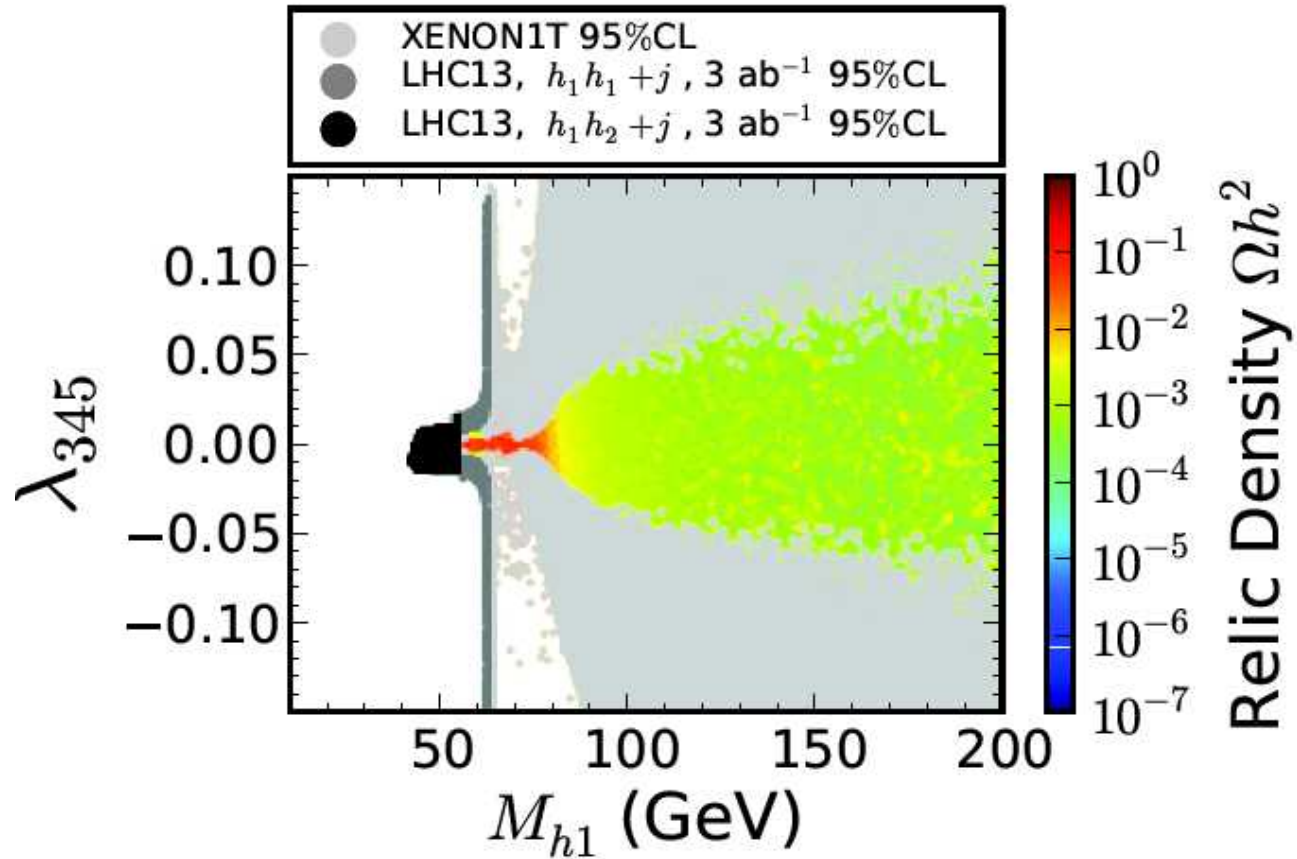
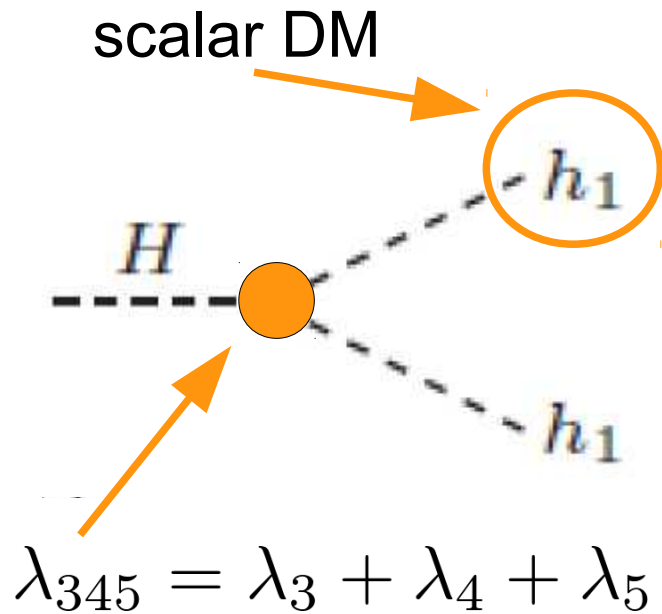
$$\phi_1 = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H \end{pmatrix} \quad \phi_2 = \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2}h^+ \\ h_1 + ih_2 \end{pmatrix}$$

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



# Power of DM DD to rule out theory space

## Inert 2 Higgs Doublet Model



AB, G. Cacciapaglia, I. Ivanov, F. Rojas, M. Thomas, 2017



# Power of DM DD to rule out theory space

## Vector DM Model

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

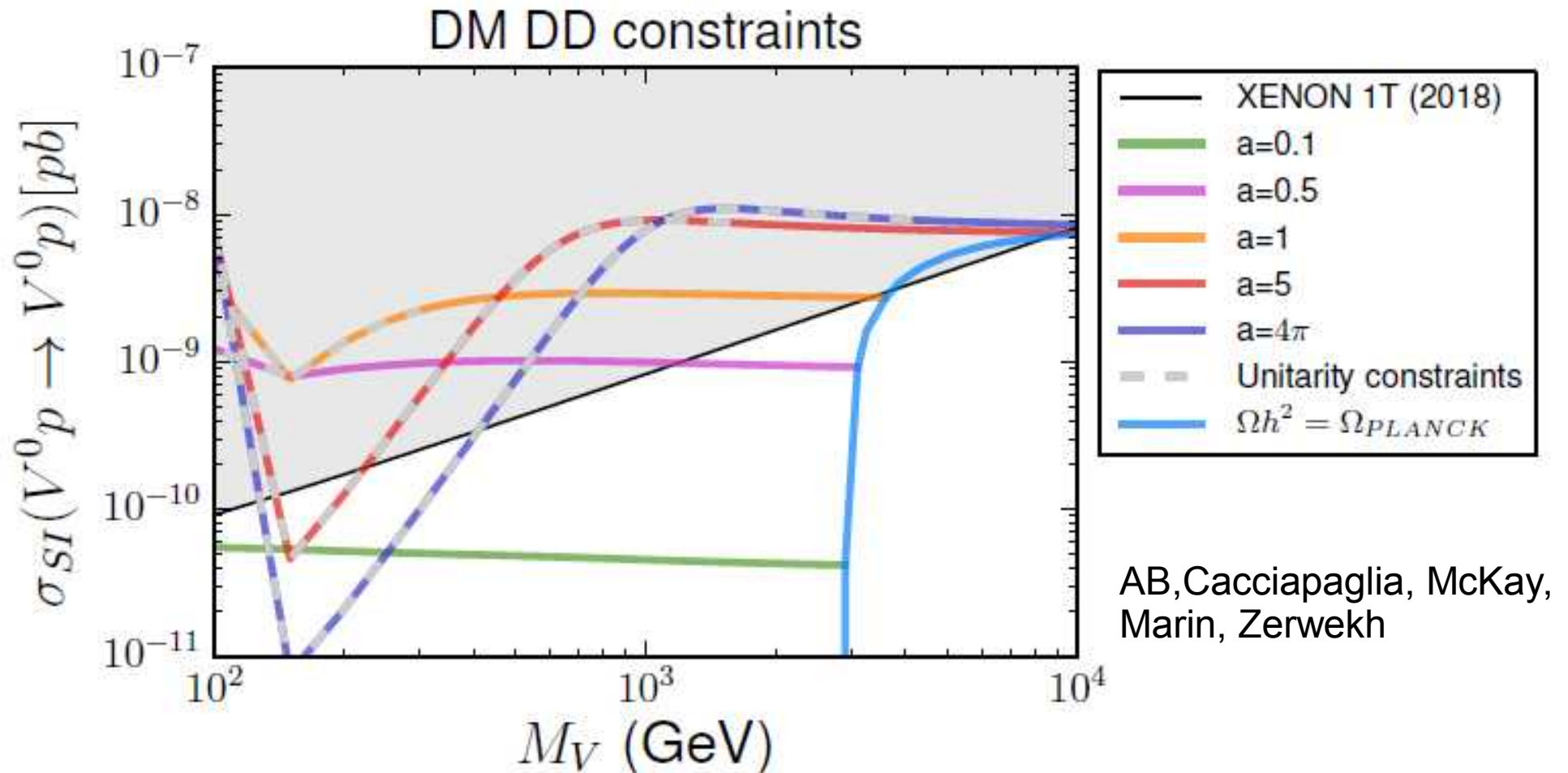
- DM from vector triplet
- SM gauge coupling
- $V_{DM} V_{DM} H$  coupling is the only free parameter



AB, Cacciapaglia, McKay,  
Marin, Zerwekh

# Power of DM DD to rule out theory space

## Vector DM Model



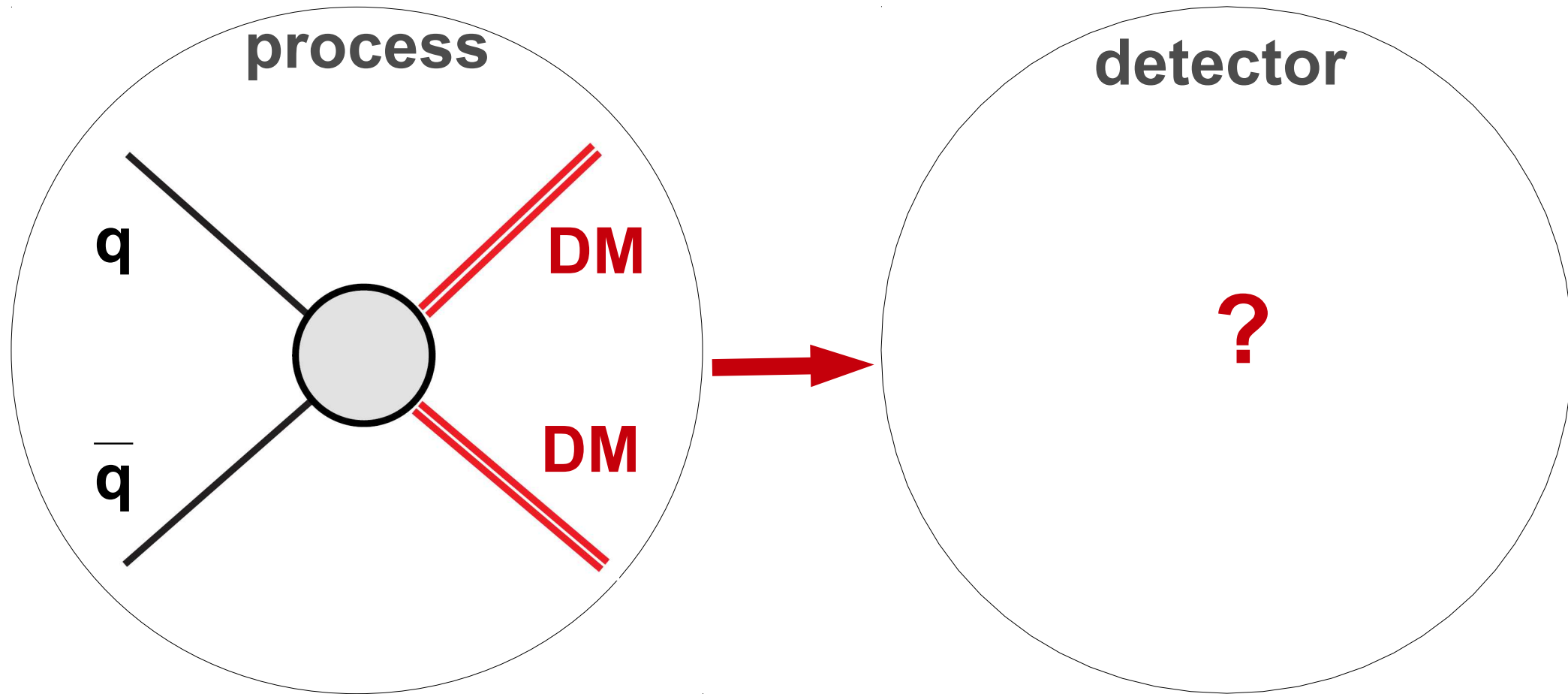
- ZENON 1T excludes **both** large  $HV_{DM}V_{DM}$  couplings and large  $M_{DM}$
- The **rest** of the parameter space can be covered at future colliders



# Power of DM DD to rule out theory space

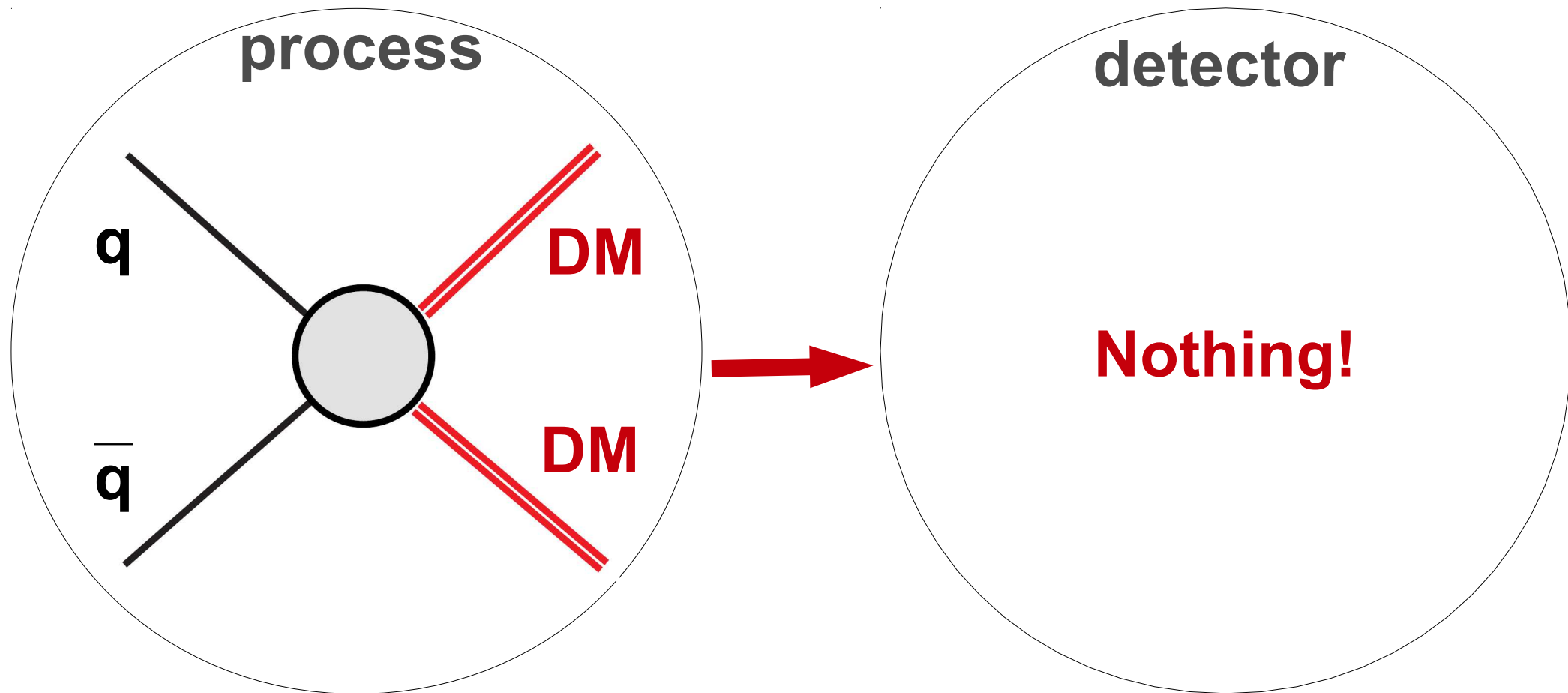
- DM Interaction with SM particles is very limited
- E.g. coupling of Dirac Fermion DM interaction with Z-boson is excluded above  $10^{-3}$  level with DM DD searches
- Majorana Fermion DM does not have this problem, the limit comes from Higgs interactions, the coupling above  $0.1$  is excluded

# DM DD interplay with Collider Searches

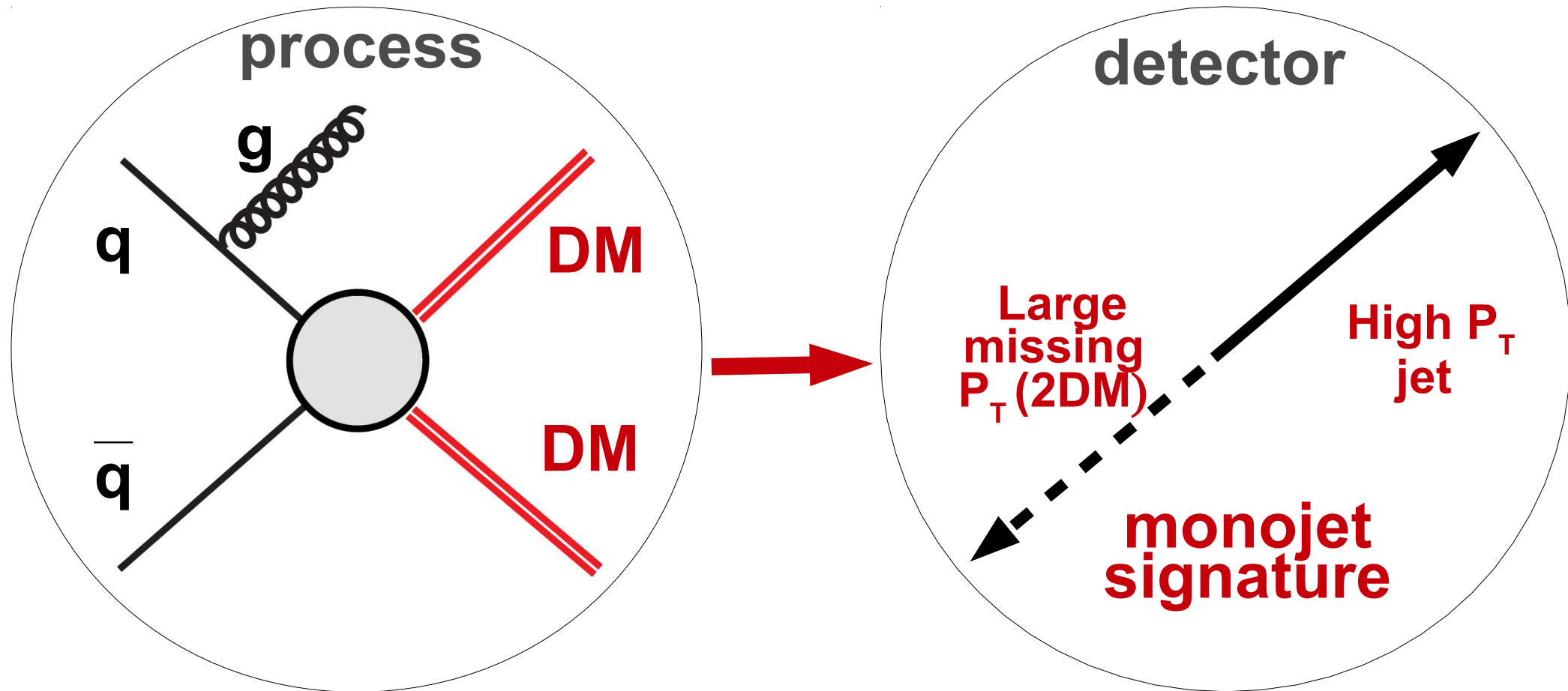




# Hunting for DM at Colliders



# Hunting for DM at Colliders





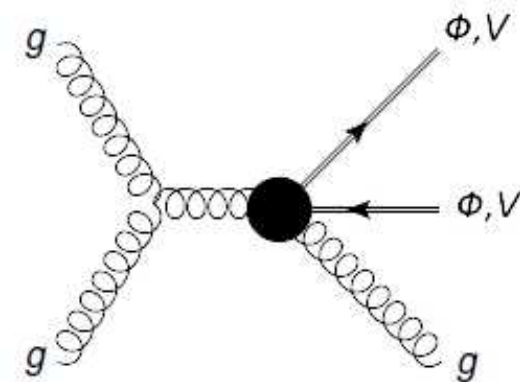
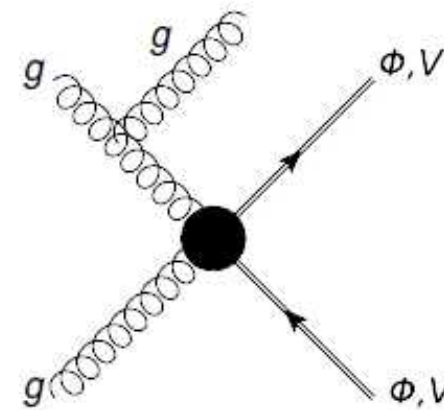
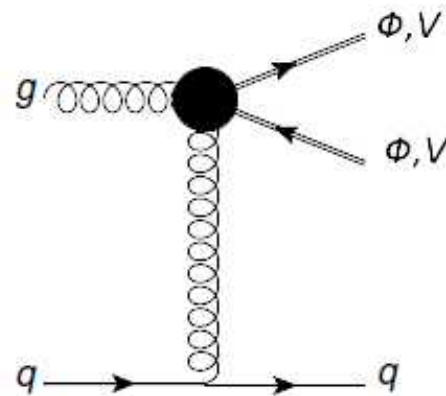
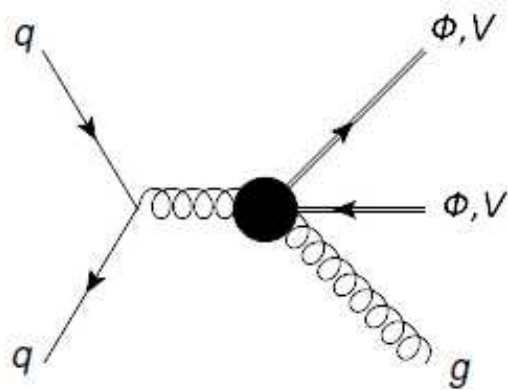
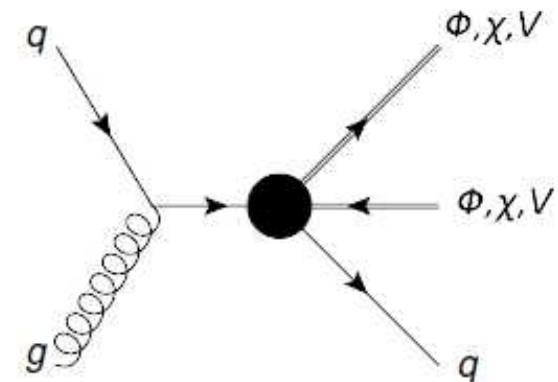
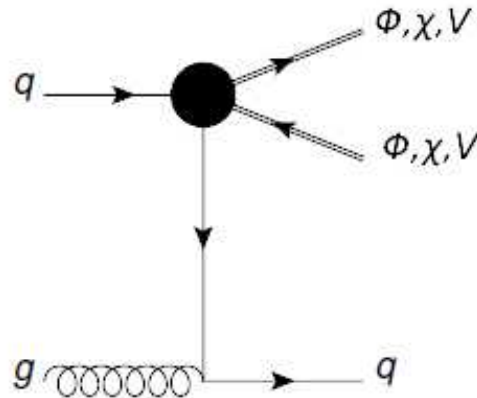
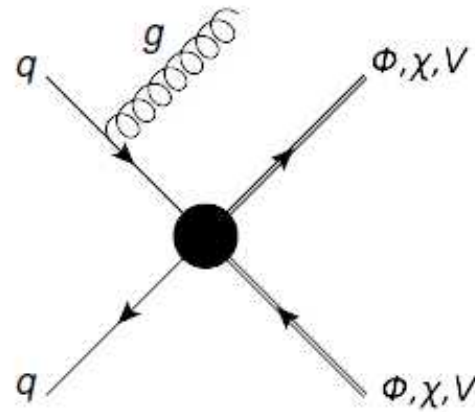
# Can we test DM properties at the LHC?

Let us check the effects of DM spin on Missing transverse momentum (**MET**) distributions at the LHC:

- 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

**The aim: to find LHC discovery potential for scenarios with different DM spins and potential to distinguish these scenarios**

# Mono-jet diagrams from EFT operators





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

Complex scalar DM <sup>†</sup>	
$\frac{\bar{m}}{\Lambda^2} \phi^\dagger \phi \bar{q} q$	[C1]*
$\frac{\bar{m}}{\Lambda^2} \phi^\dagger \phi \bar{q} i \gamma^5 q$	[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 <sup>†</sup>	
$\frac{1}{\Lambda^2} \bar{\chi} \chi \bar{q} q$	[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 <sup>‡</sup>	
$\frac{\bar{m}}{\Lambda^2} V_\mu^\dagger V^\mu \bar{q} q$	[V1]*
$\frac{\bar{m}}{\Lambda^2} V_\mu^\dagger V^\mu \bar{q} i \gamma^5 q$	[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]
$\frac{\bar{m}}{\Lambda^2} V_\mu^\dagger V_\nu \bar{q} i \sigma^{\mu\nu} q$	[V5]
$\frac{\bar{m}}{\Lambda^2} V_\mu^\dagger V_\nu \bar{q} \sigma^{\mu\nu} \gamma^5 q$	[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]
$\frac{1}{2\Lambda^2} \epsilon^{\mu\nu\rho\sigma} (V_\nu^\dagger \partial_\rho V_\mu - V^\nu \partial_\rho V_\mu^\dagger) \bar{q} i \gamma_\mu q$	[V9M]
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$\frac{1}{2\Lambda^2} \epsilon^{\mu\nu\rho\sigma} (V_\nu^\dagger \partial_\rho V_\mu - V^\nu \partial_\rho V_\mu^\dagger) \bar{q} i \gamma_\mu \gamma^5 q$	[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]*

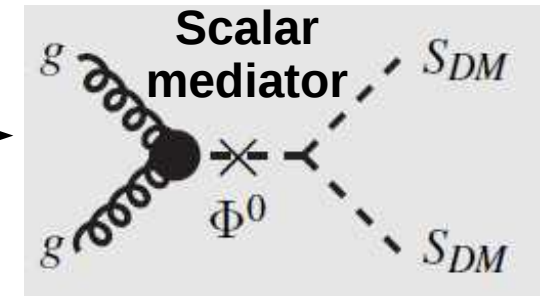
\* operators applicable to real DM fields, modulo a factor 1/2

† 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

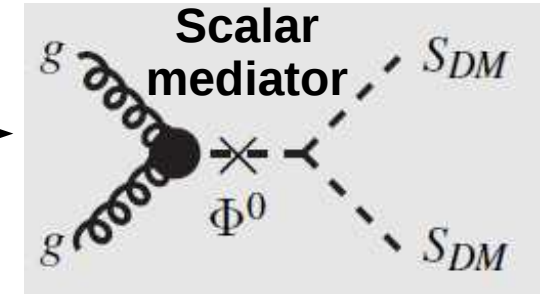
**C5,C5A**  $\frac{1}{\Lambda^2} \phi^* \phi G^{\mu\nu} G^{\mu\nu}$  ,  $\frac{1}{\Lambda^2} \phi^* \phi \tilde{G}^{\mu\nu} G^{\mu\nu}$   $\longrightarrow$





# Mapping EFT operators to simplified models

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

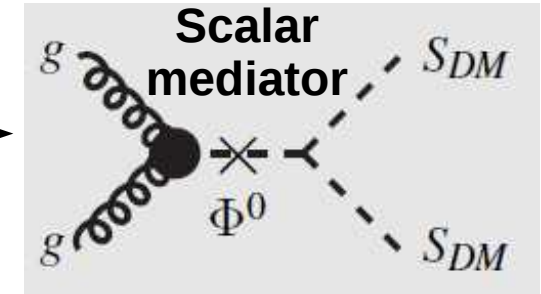


**D1T-D4T**  $\frac{1}{\Lambda^2} \bar{\chi} q \bar{q} \chi$   $\longrightarrow$

A Feynman diagram illustrating the mapping of the D1T-D4T operators. It shows a quark line (labeled 'q') and an anti-quark line (labeled 'q̄') meeting at a vertex, which then splits into two outgoing scalar mediator lines (labeled 'χ<sub>DM</sub>'). The mediator lines are represented by dashed lines. A central cross symbol is labeled 'Q̃'.

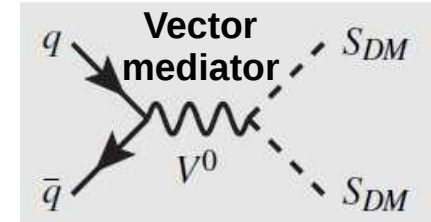
# Mapping EFT operators to simplified models

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



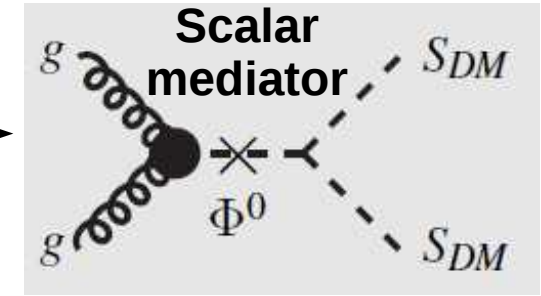
**D1T-D4T**  $\frac{1}{\Lambda^2} \bar{\chi} q \bar{q} \chi \longrightarrow$

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



# Mapping EFT operators to simplified models

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



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

Scalar mediator

$\tilde{Q}$

$\chi_{DM}$

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

Vector mediator

$V^0$

$S_{DM}$

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

Vector mediator

$V^0$

$\chi_{DM}$

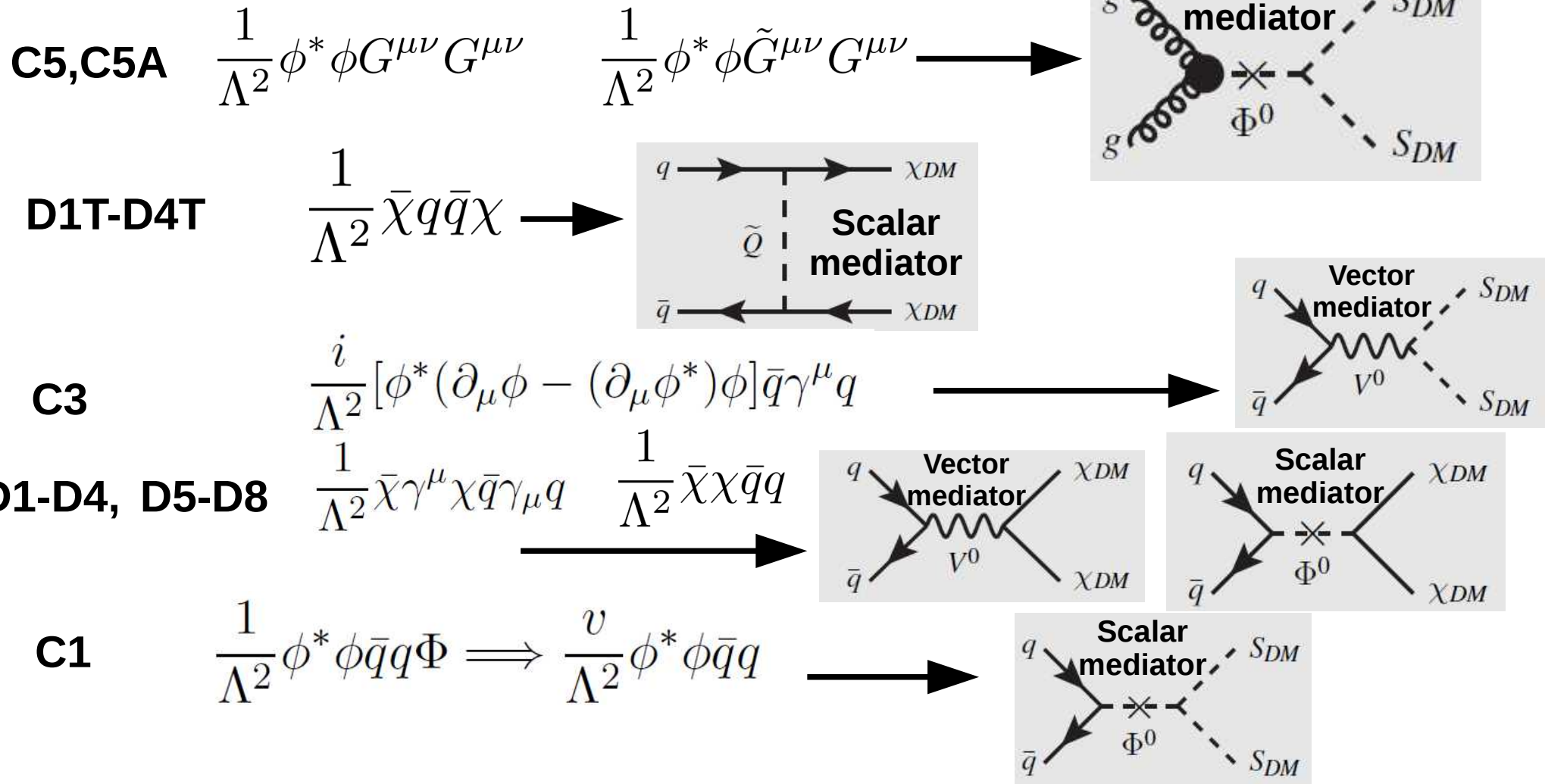
Scalar mediator

$\Phi^0$

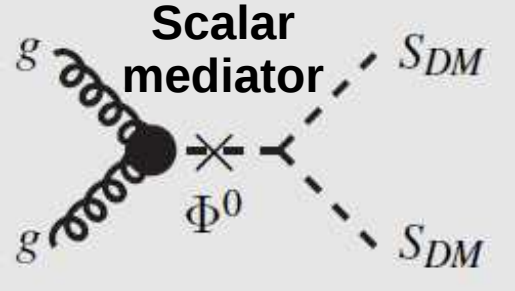
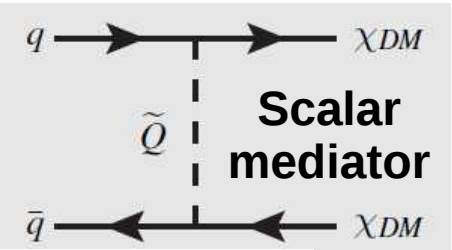
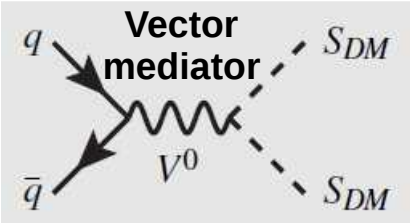
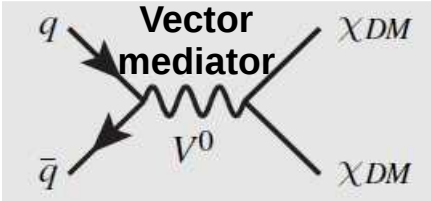
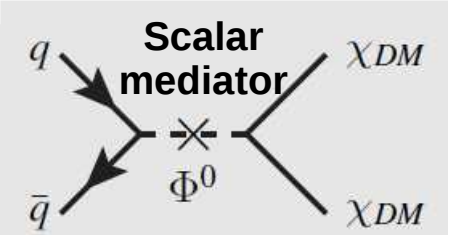
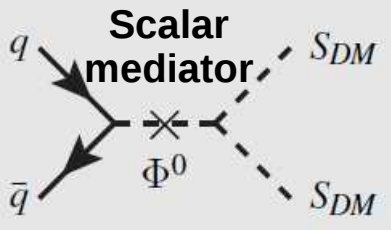
$\chi_{DM}$



# Mapping EFT operators to simplified models

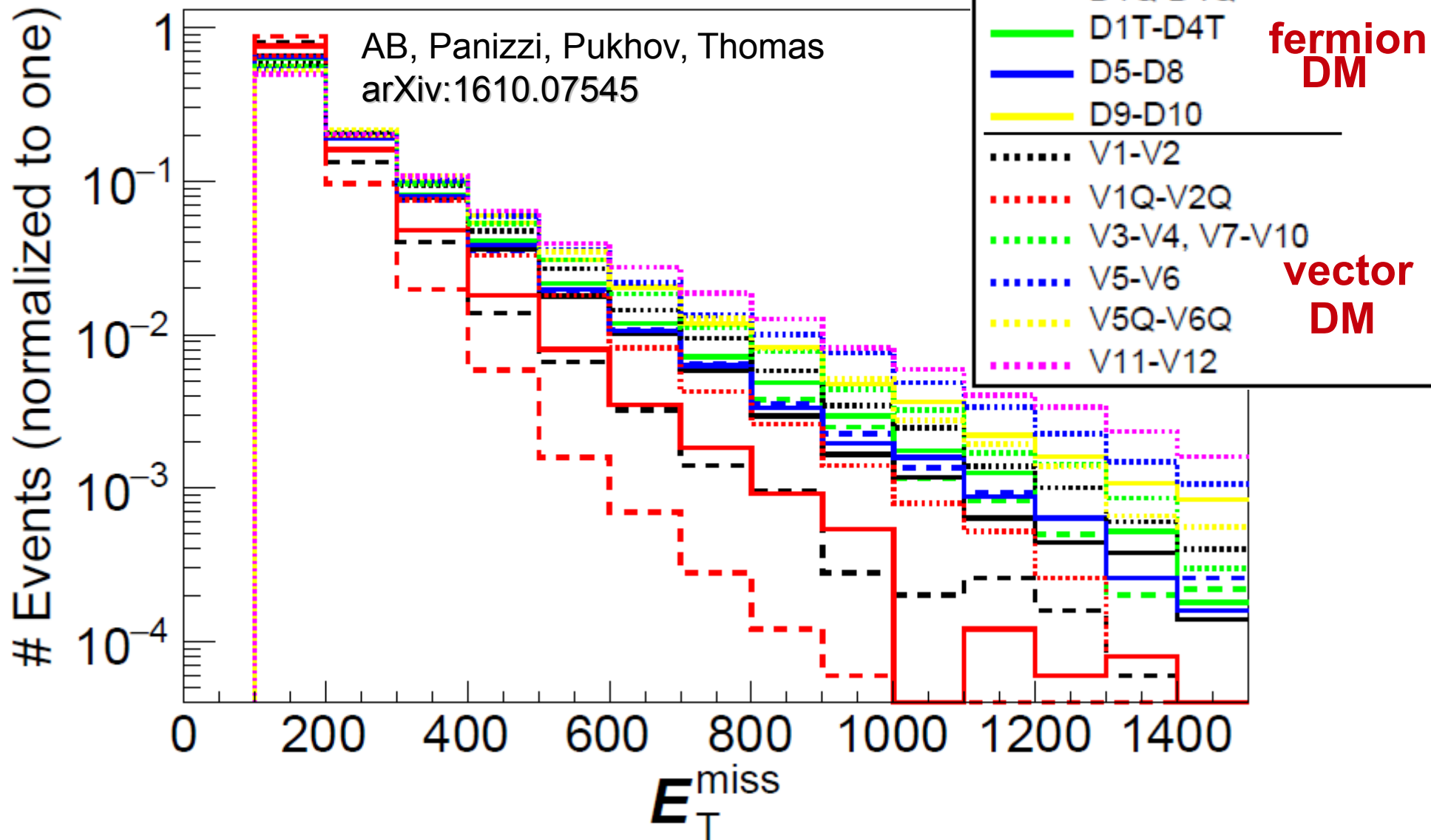


# Mapping EFT operators to simplified models

<b>C5,C5A</b>	$\frac{1}{\Lambda^2} \phi^* \phi G^{\mu\nu} G^{\mu\nu} \rightarrow \frac{1}{\Lambda^2} \phi^* \phi \tilde{G}^{\mu\nu} G^{\mu\nu}$	
<b>D1T-D4T</b>	$\frac{1}{\Lambda^2} \bar{\chi} q \bar{q} \chi$	
<b>C3</b>	$\frac{i}{\Lambda^2} [\phi^* (\partial_\mu \phi - (\partial_\mu \phi^*) \phi)] \bar{q} \gamma^\mu q$	
<b>D1-D4, D5-D8</b>	$\frac{1}{\Lambda^2} \bar{\chi} \gamma^\mu \chi \bar{q} \gamma_\mu q \rightarrow \frac{1}{\Lambda^2} \bar{\chi} \chi \bar{q} q$	 
<b>C1</b>	$\frac{1}{\Lambda^2} \phi^* \phi \bar{q} q \Phi \Rightarrow \frac{v}{\Lambda^2} \phi^* \phi \bar{q} q$	
<b>D9,D10</b>	$\frac{1}{\Lambda^2} \bar{\chi} \sigma^{\mu\nu} \chi \bar{q} \sigma_{\mu\nu} q \rightarrow \frac{8}{\Lambda^2} [ \bar{\chi} q \bar{q} \chi - \frac{1}{4} ( \bar{\chi} \chi \bar{q} q + \bar{\chi} \gamma^5 \chi \bar{q} \gamma^5 q + \bar{\chi} \gamma^\mu \chi \bar{q} \gamma_\mu q - \bar{\chi} \gamma^\mu \gamma^5 \chi \bar{q} \gamma_\mu \gamma^5 q ) ]$	

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

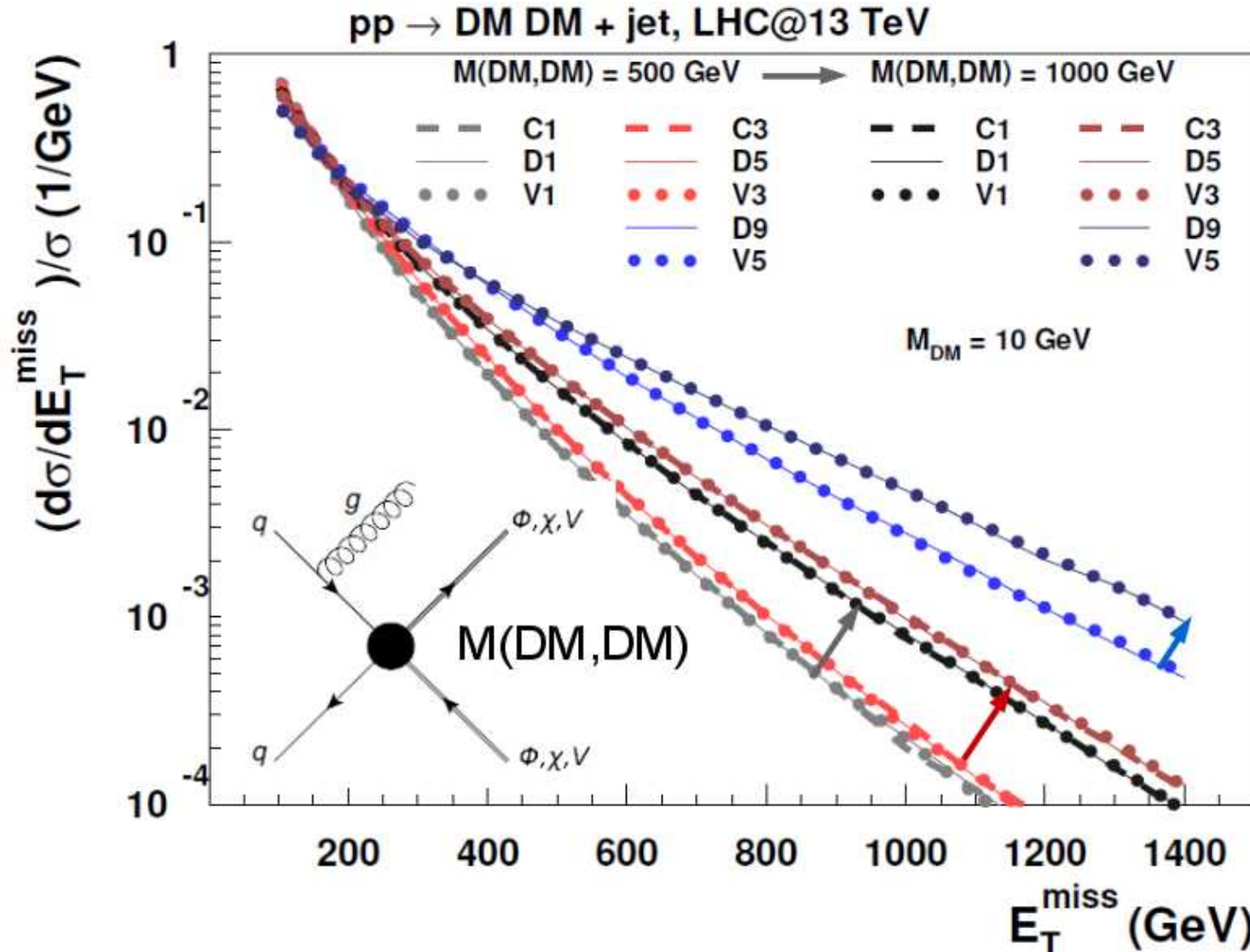
$M_{DM} = 10$  GeV,  $\sqrt{s} = 13$  TeV





# Properties of MET distributions:

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



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

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

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

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

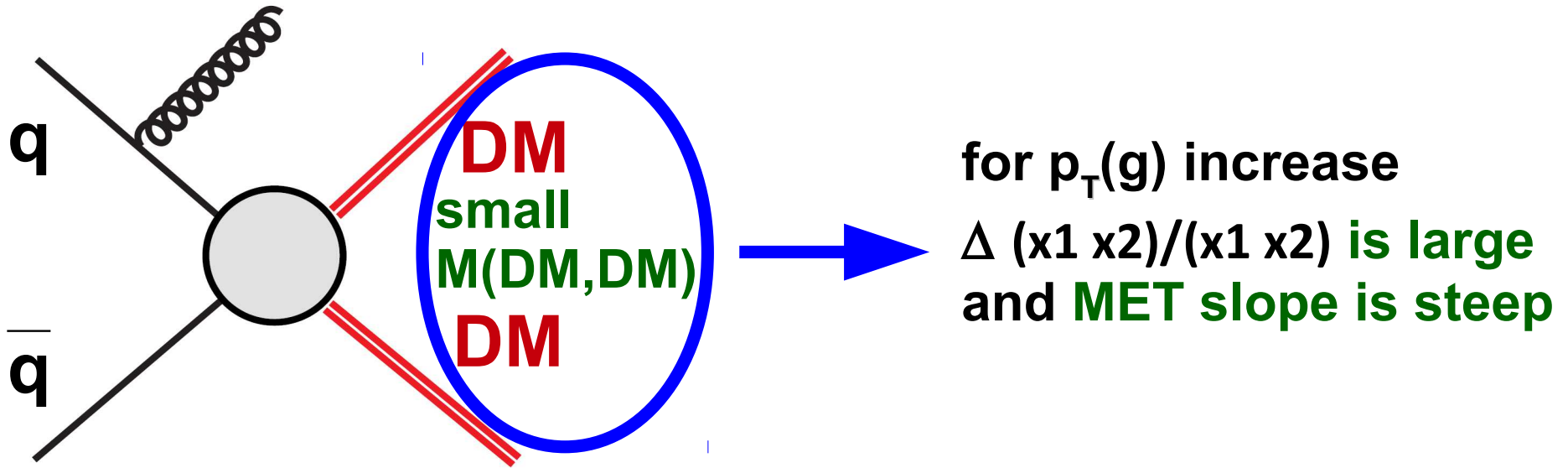
$$\frac{1}{\Lambda^2} \bar{\chi} \gamma^{\mu} \chi \bar{q} \gamma_{\mu} q \quad [\text{D5}]$$

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

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

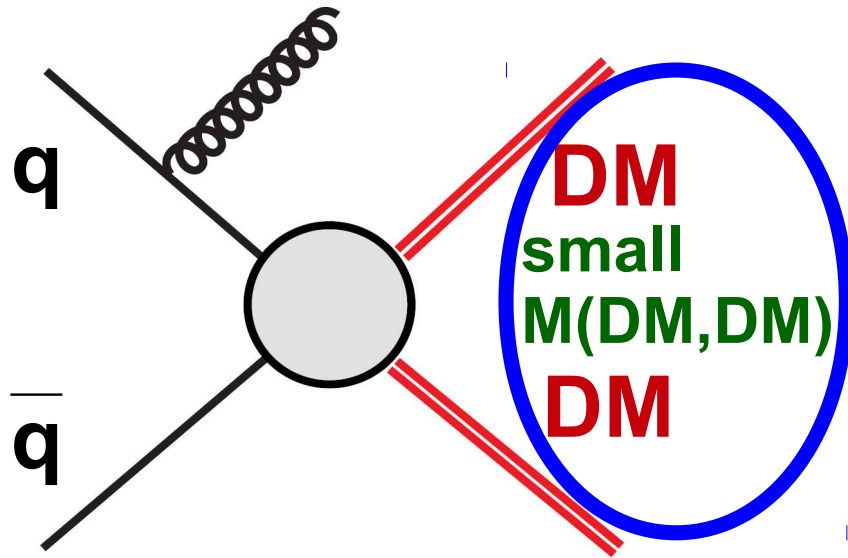
# Properties of MET distributions for small and large $M(\text{DM}, \text{DM})$

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



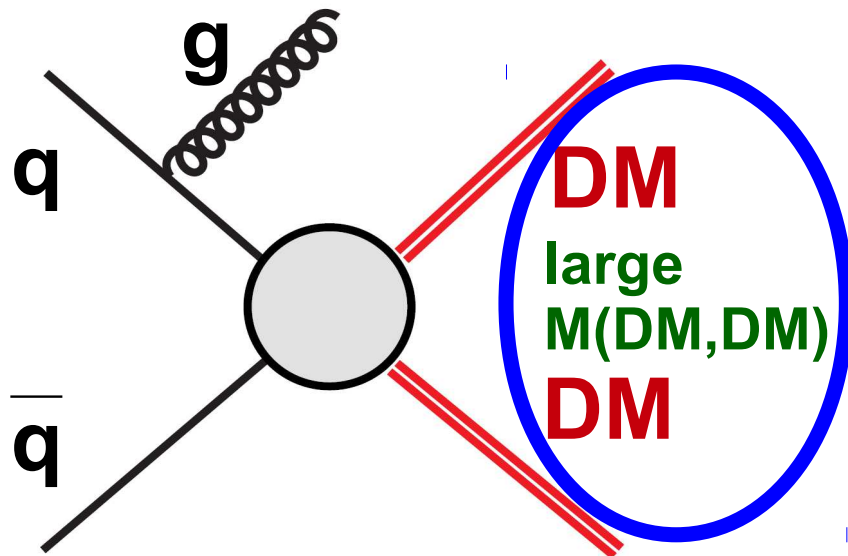
# Properties of MET distributions for small and large $M(\text{DM}, \text{DM})$

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



for  $p_T(g)$  increase

$\Delta (x_1 x_2)/(x_1 x_2)$  is **large**  
and **MET slope is steep**



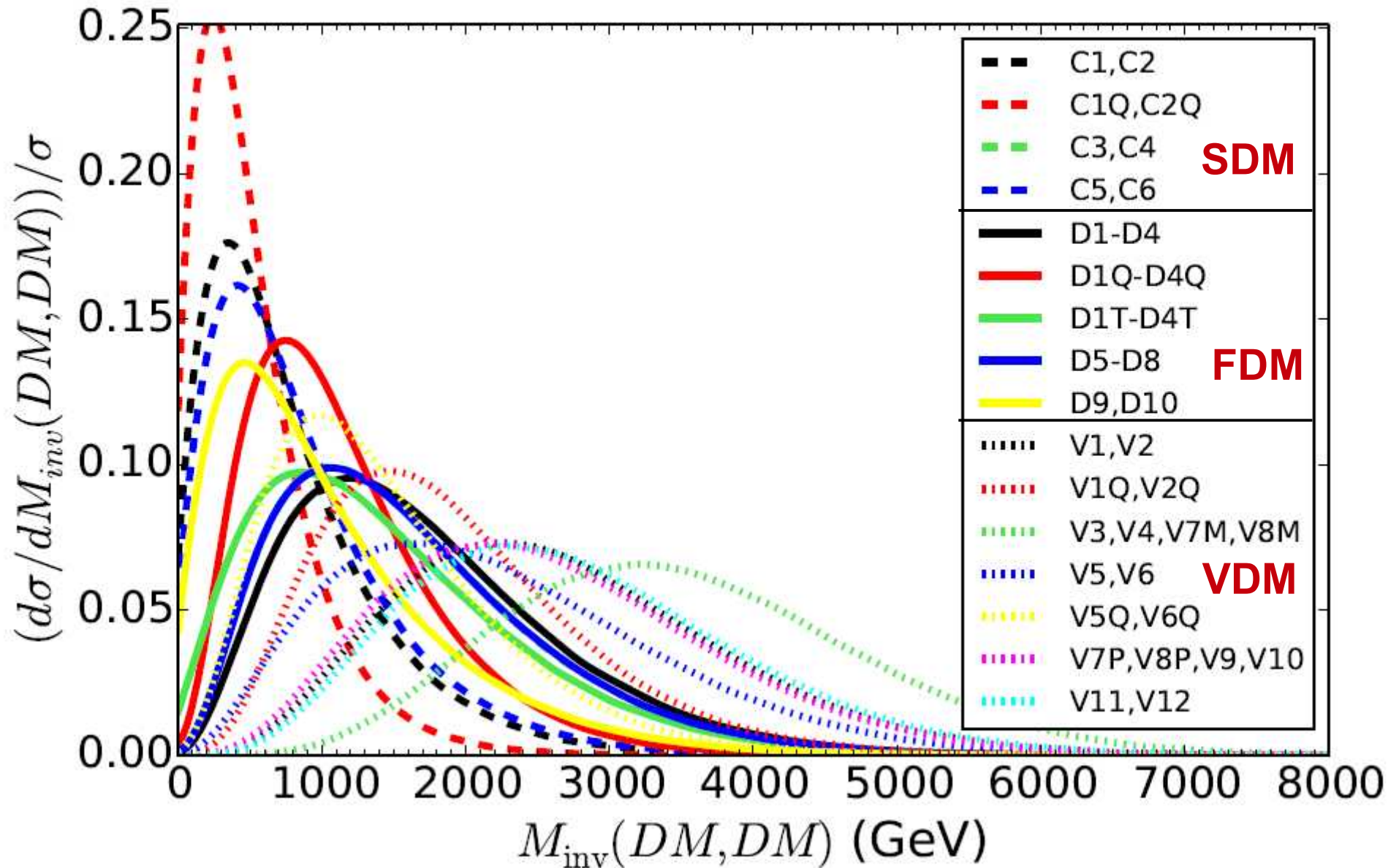
for  $p_T(g)$  increase

$\Delta (x_1 x_2)/(x_1 x_2)$  is **small**  
and **MET slope is gradual**



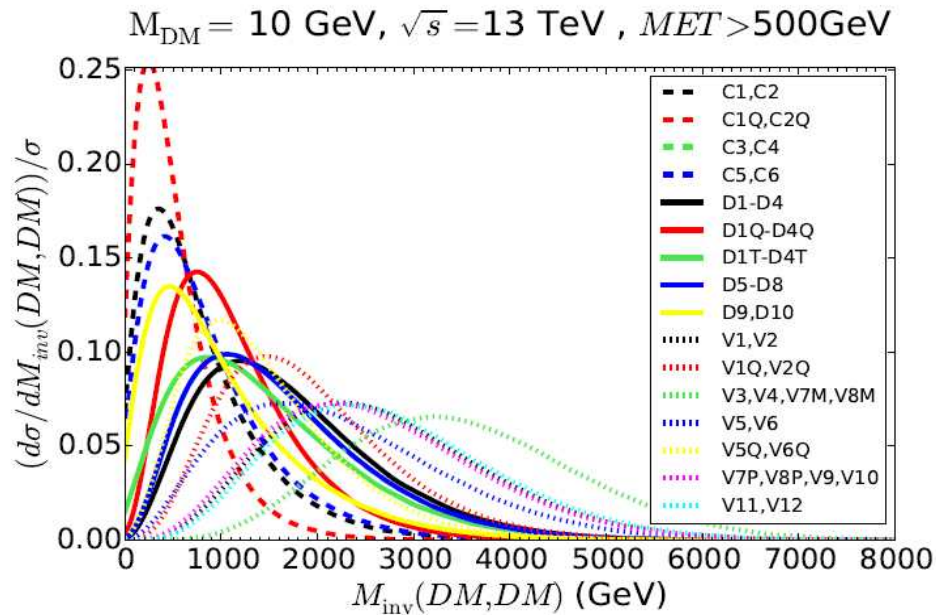
On the other hand,  $M(\text{DM},\text{DM})$  distributions, defined by the EFT operators are different!

$$M_{\text{DM}} = 10 \text{ GeV}, \sqrt{s} = 13 \text{ TeV}, MET > 500 \text{ GeV}$$

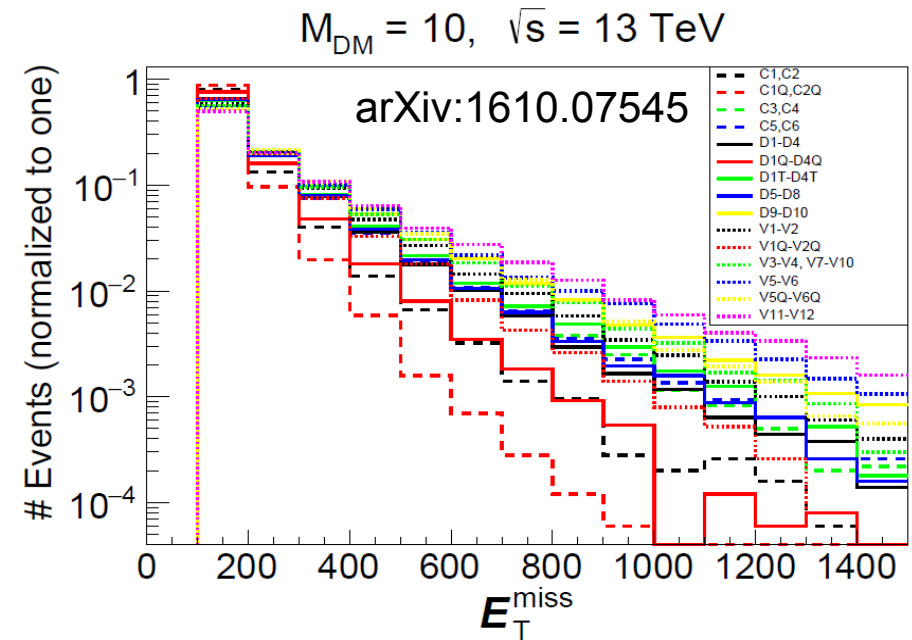


# Distinguishing DM operators/theories

The harder  $M(\text{DM}, \text{DM})$  distributions



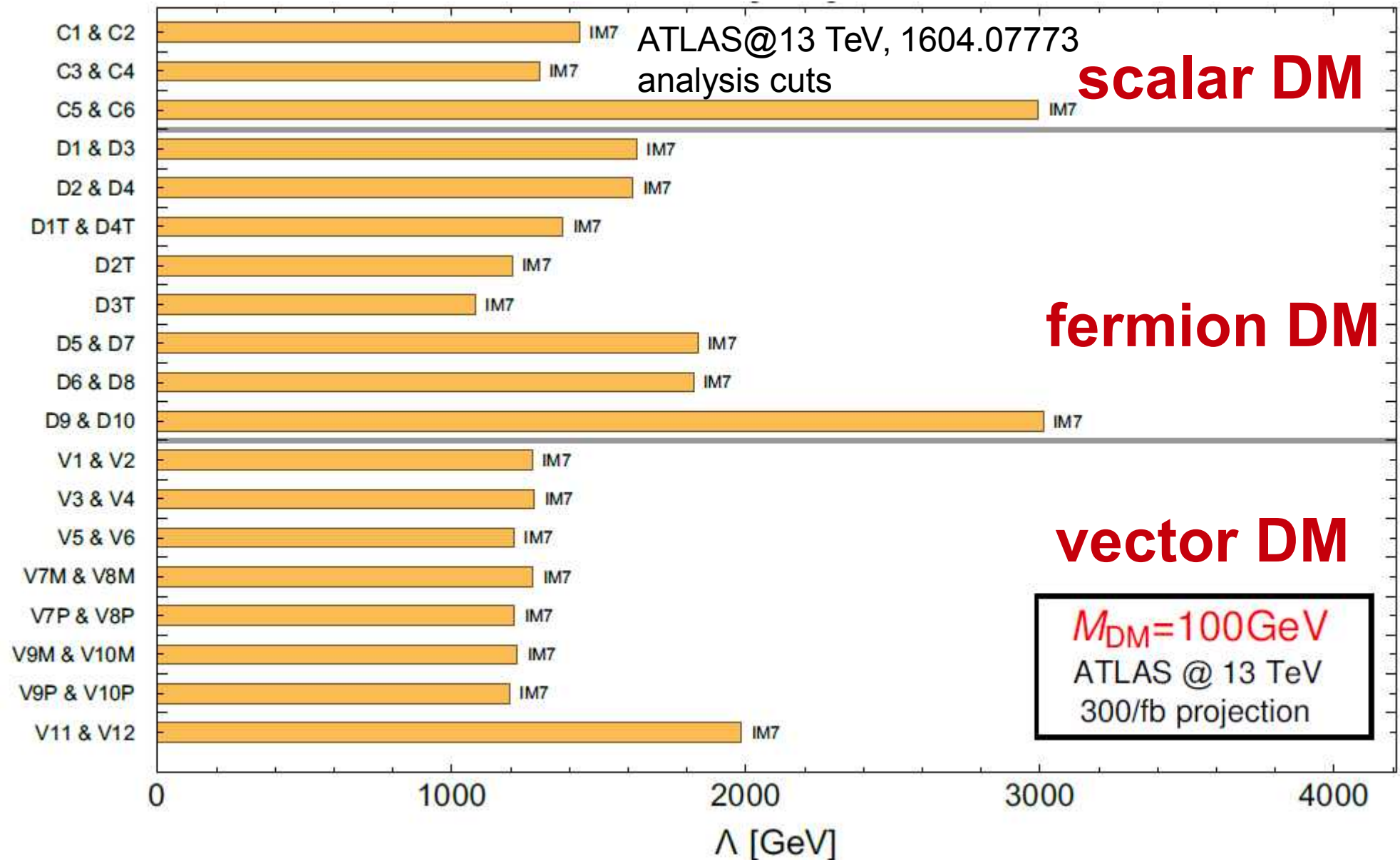
The flatter MET shapes



- ⇒ energy dependence of the DM operator →  $M_{\text{DMDM}}$  distributions → slopes of MET
- ⇒ projection for  $300 \text{ fb}^{-1}$ : 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  $M_{\text{DMDM}}$  is not fixed: t-channel mediator or mediators with mass below  $2M_{\text{DM}}$

# LHC@13TeV reach projected 100 fb<sup>-1</sup>

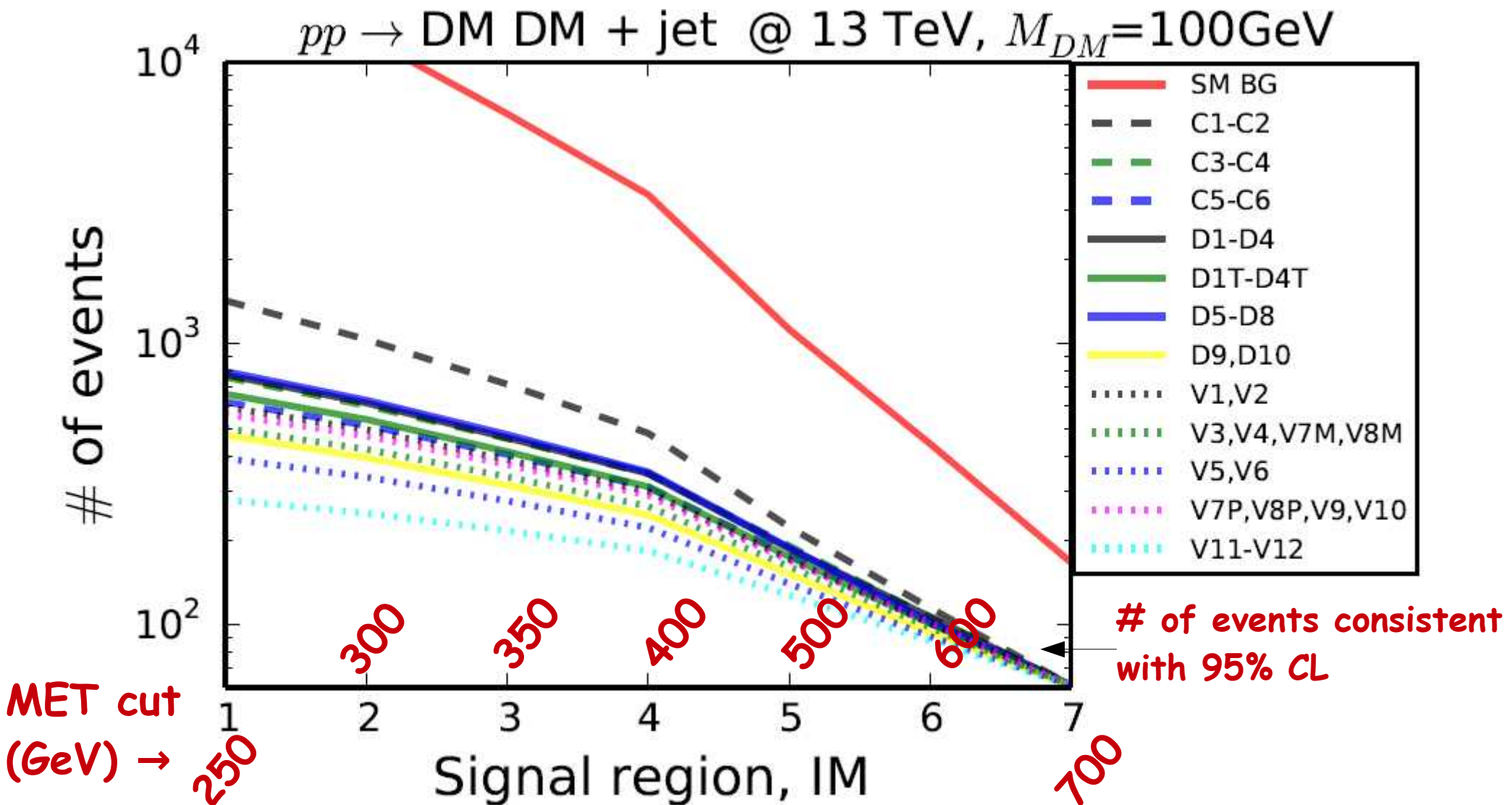
LanHEP → CalcHEP/ Madgraph → LHE → CheckMATE 2 chain





# Distinguishing DM operators

energy dependence of the operator  $\rightarrow M_{\text{DMDM}}$  shape  $\rightarrow$  MET shape



# Distinguishing the DM operators: $\chi^2$ for pairs of DM operators

$$\chi_{k,l}^2 = \min_{\kappa} \sum_{i=3}^7 \left[ \left( \frac{1}{2} N_i^k - \kappa \cdot N_i^l \right) / (10^{-2} B G_i) \right]^2$$

: if  $\chi^2 > 9.48$  (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	<b>19.7</b>	<b>25.54</b>	<b>74.63</b>	<b>11.73</b>	<b>41.79</b>	<b>25.78</b>	<b>52.58</b>
		C5	<b>15.74</b>	0.0	0.37	<b>16.25</b>	1.11	3.93	0.74	7.35
	1000 GeV	C1	<b>19.89</b>	0.36	0.0	<b>11.82</b>	2.33	2.09	0.27	4.58
		C5	<b>50.86</b>	<b>13.86</b>	<b>10.34</b>	0.0	<b>21.03</b>	3.7	<b>11.18</b>	1.53
Dirac Fermion DM	100 GeV	D1	<b>9.88</b>	1.17	2.52	<b>25.99</b>	0.0	9.23	2.4	<b>14.17</b>
		D9	<b>30.49</b>	3.59	1.96	3.96	7.99	0.0	2.71	0.52
	1000 GeV	D1	<b>20.31</b>	0.73	0.27	<b>12.92</b>	2.25	2.93	0.0	5.42
		D9	<b>37.38</b>	6.54	4.18	1.6	<b>11.96</b>	0.5	4.89	0.0

# Distinguishing the DM operators: $\chi^2$ for pairs of DM operators

$$\chi_{k,l}^2 = \min_{\kappa} \sum_{i=3}^7 \left[ \left( \frac{1}{2} N_i^k - \kappa \cdot N_i^l \right) / (10^{-2} B G_i) \right]^2$$

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

			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



# Importance of the operator running in the DM DD $\leftrightarrow$ Collider interplay

- In case of axial operators, e.g

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

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

# Importance of the operator running in the DM DD $\leftrightarrow$ Collider interplay

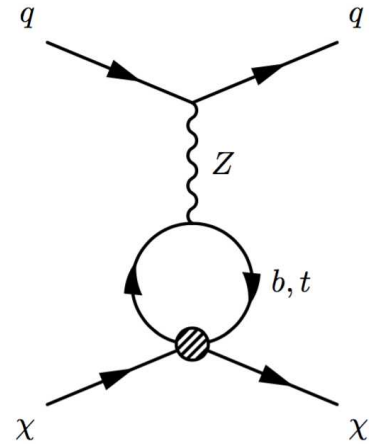
- In case of axial operators. e.g

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

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

- One can use **runDM** program ([github.com/bradkav/runDM](https://github.com/bradkav/runDM)) by  
F. D'Eramo, B. J. Kavanagh & P. Panci

$$\mathbf{c}_A^{(u)}, \mathbf{c}_A^{(d)}, \mathbf{c}_V^{(u)}, \mathbf{c}_V^{(d)} = (1, 1, 0, 0)[5\text{TeV}] \rightarrow (1.1, 1.1, 0.04, -0.07)[1\text{GeV}]$$



# Importance of the operator running in the DM DD $\leftrightarrow$ Collider interplay

- In case of axial operators. e.g

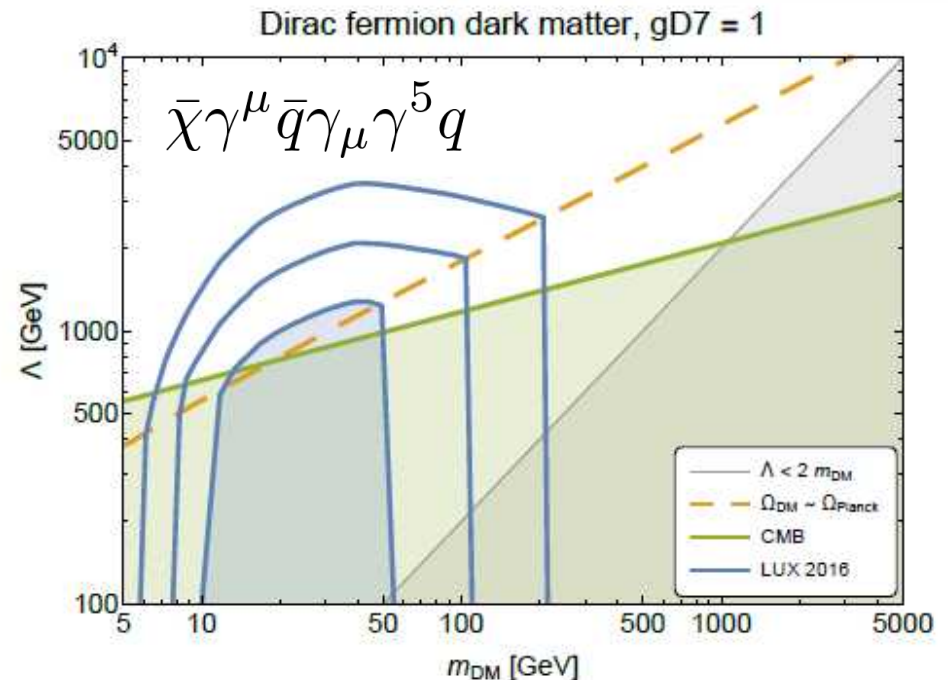
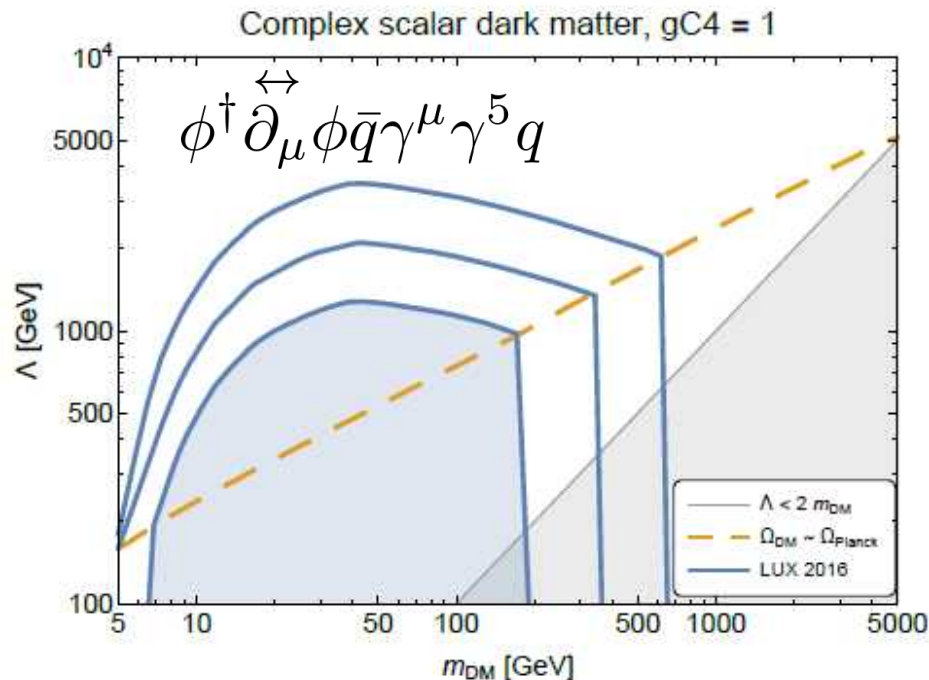
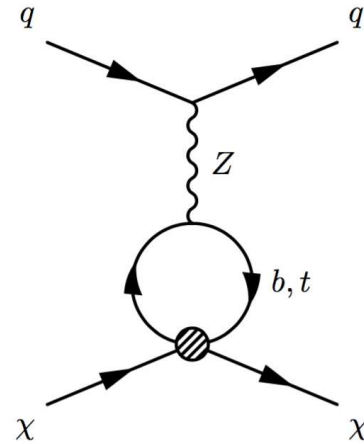
$$c_A^{(q)} c_\chi \bar{\chi} \gamma^\mu \chi \bar{q} \gamma_\mu \gamma_5 q \quad (D7)$$

$$\text{or} \quad c_A^{(q)} c_\phi \phi^\dagger \overleftrightarrow{\partial}_\mu \phi \bar{q} \gamma^\mu \gamma_5 q \quad (C4)$$

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

- One can use **runDM** program ([github.com/bradkav/runDM](https://github.com/bradkav/runDM)) by F. D'Eramo, B. J. Kavanagh & P. Panci

$$\mathbf{c}_A^{(u)}, \mathbf{c}_A^{(d)}, \mathbf{c}_V^{(u)}, \mathbf{c}_V^{(d)} = (1, 1, 0, 0)[5\text{TeV}] \rightarrow (1.1, 1.1, 0.04, -0.07)[1\text{GeV}]$$

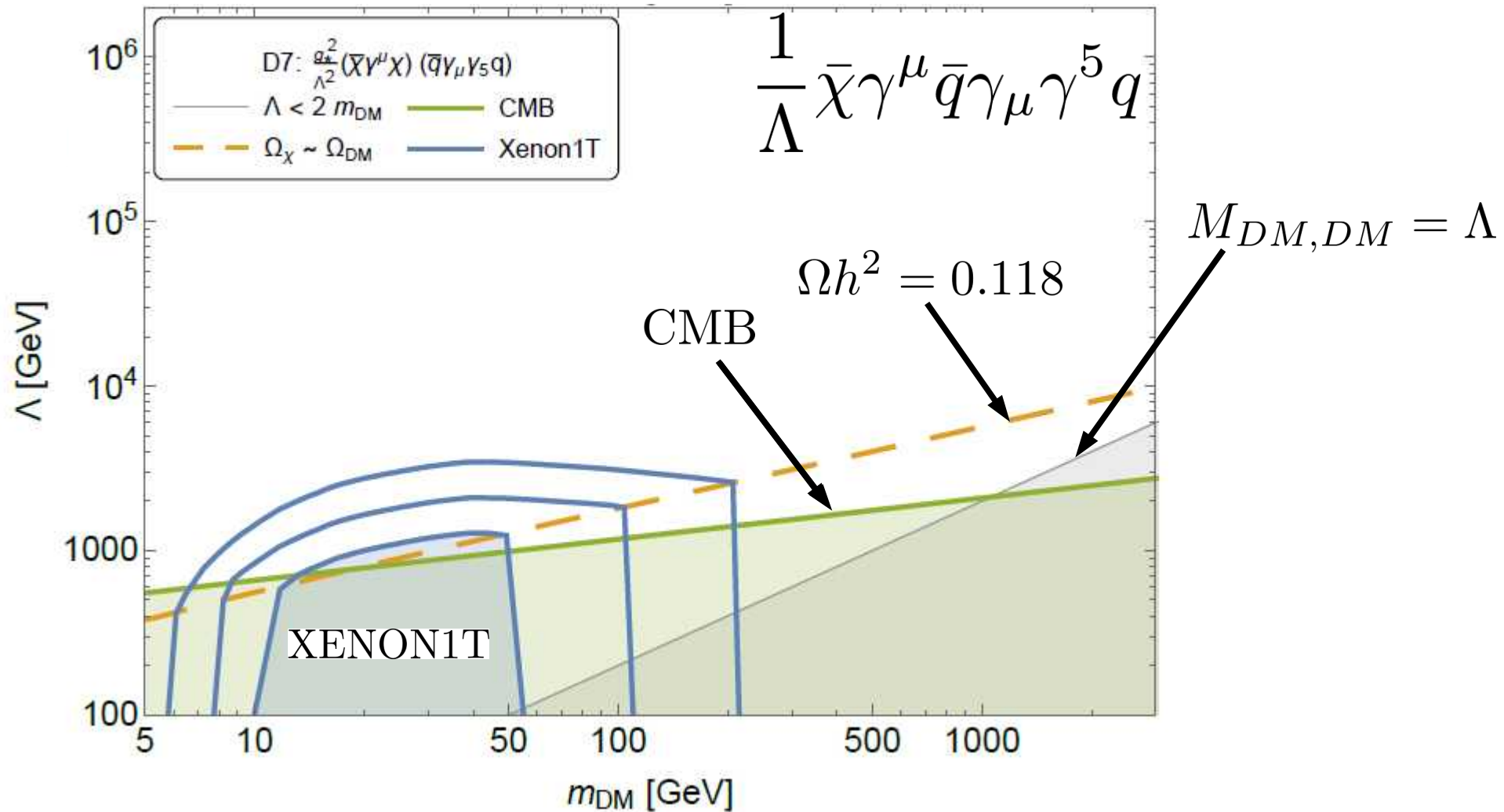


AB, Bertuzzo, Caniu, di Cortona, Eboli, Pukhov 2018



# DM DD $\leftrightarrow$ Collider interplay

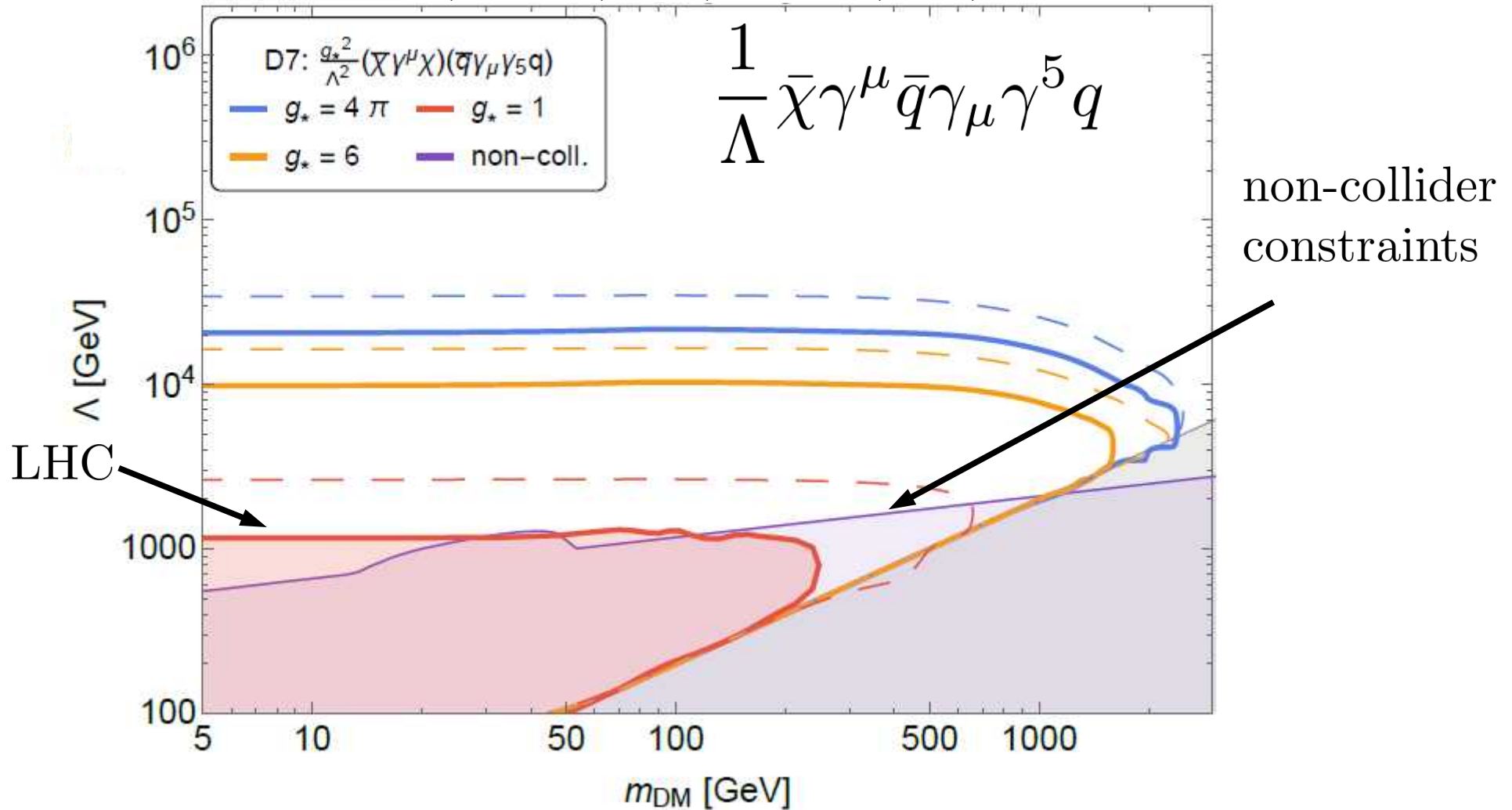
AB, Bertuzzo, Caniu, di Cortona, Eboli, Pukhov 2018



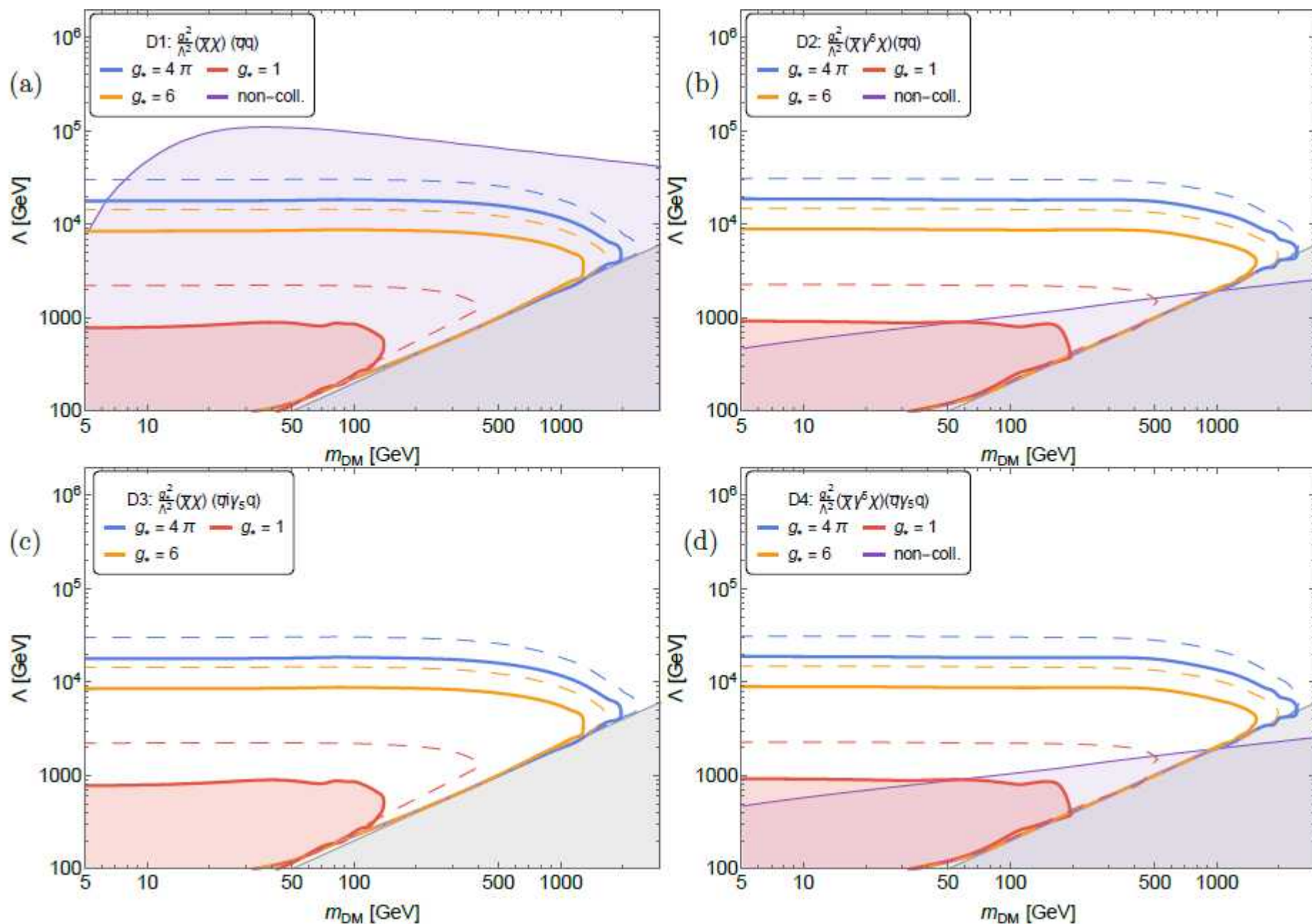
CMB:  $p_{\text{ann}} < 4.1 \times 10^{-28} \frac{\text{cm}^3}{\text{s GeV}}$  at 95% C.L. , where  $p_{\text{ann}} = \sum_j f_j(600, m_{\text{DM}}) \frac{\langle \sigma v \rangle_j(600)}{m_{\text{DM}}}$

# DM DD $\leftrightarrow$ Collider interplay

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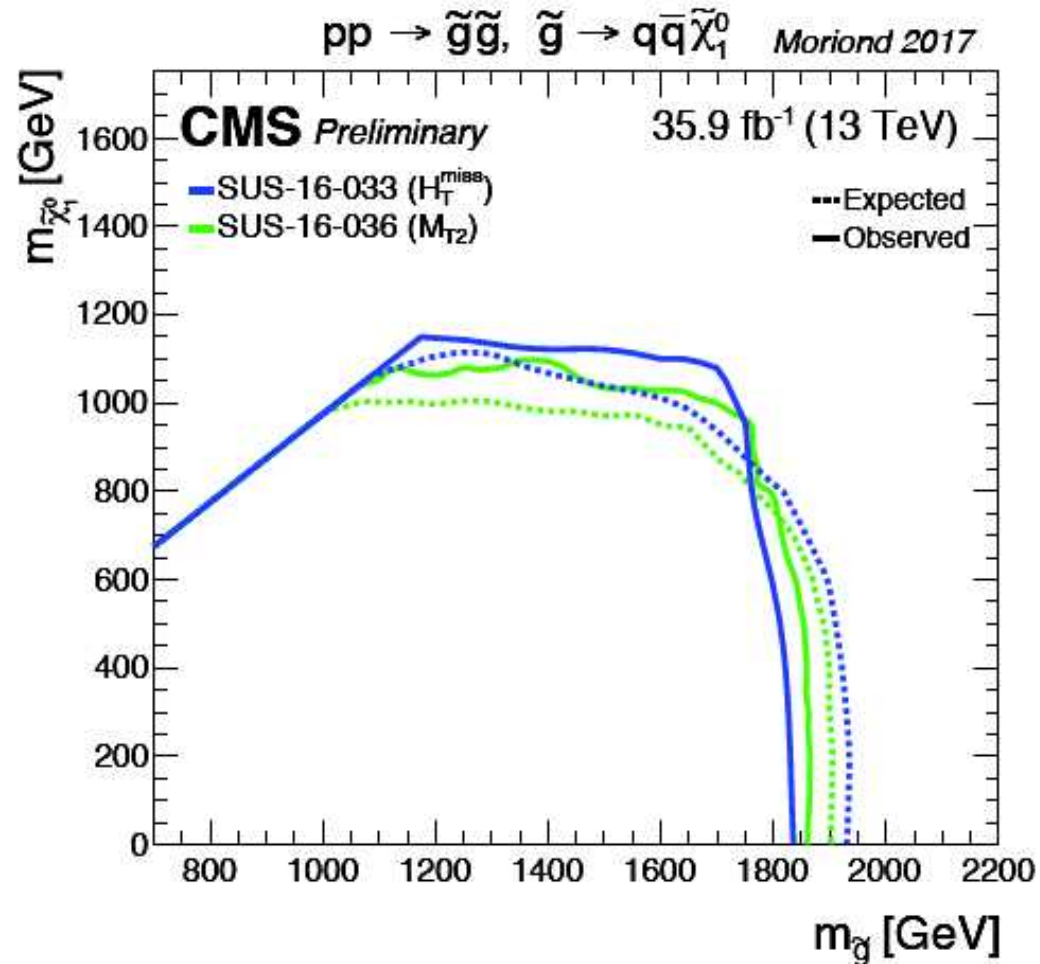
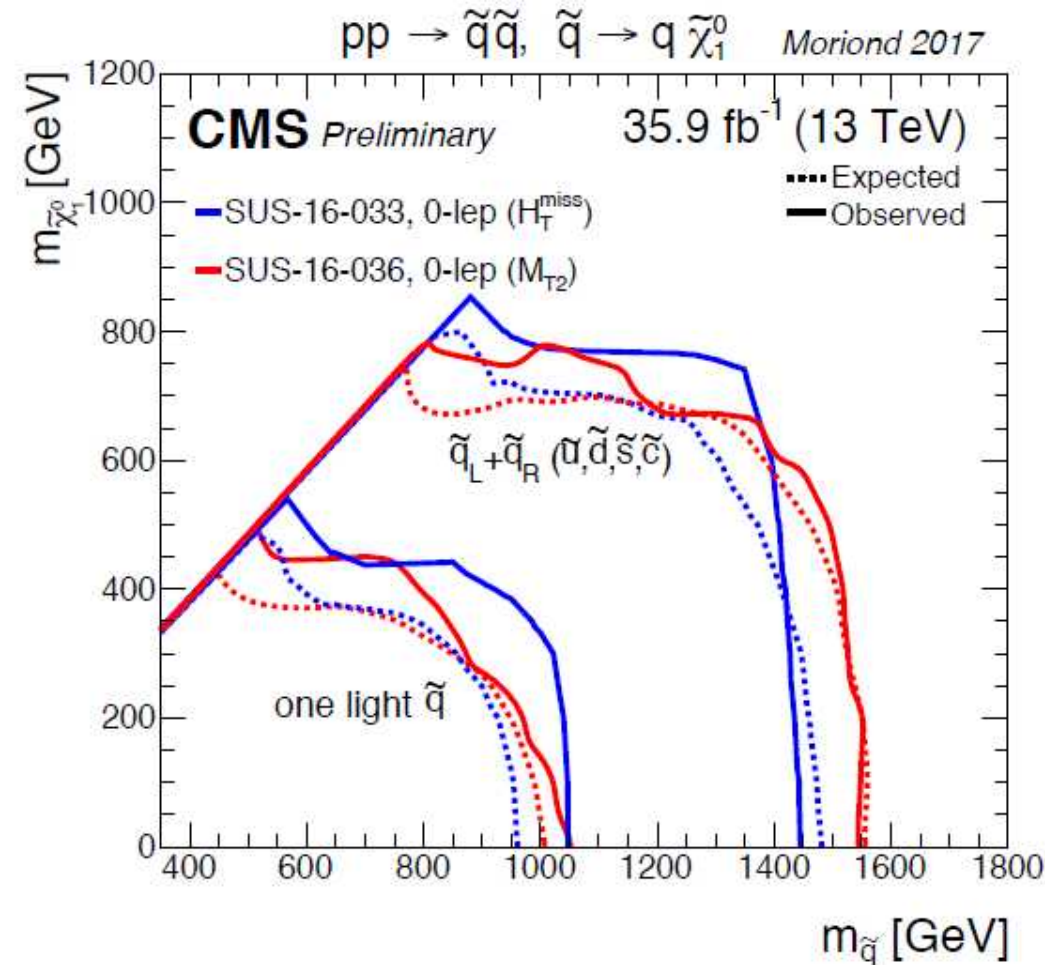
# DM DD $\leftrightarrow$ Collider interplay





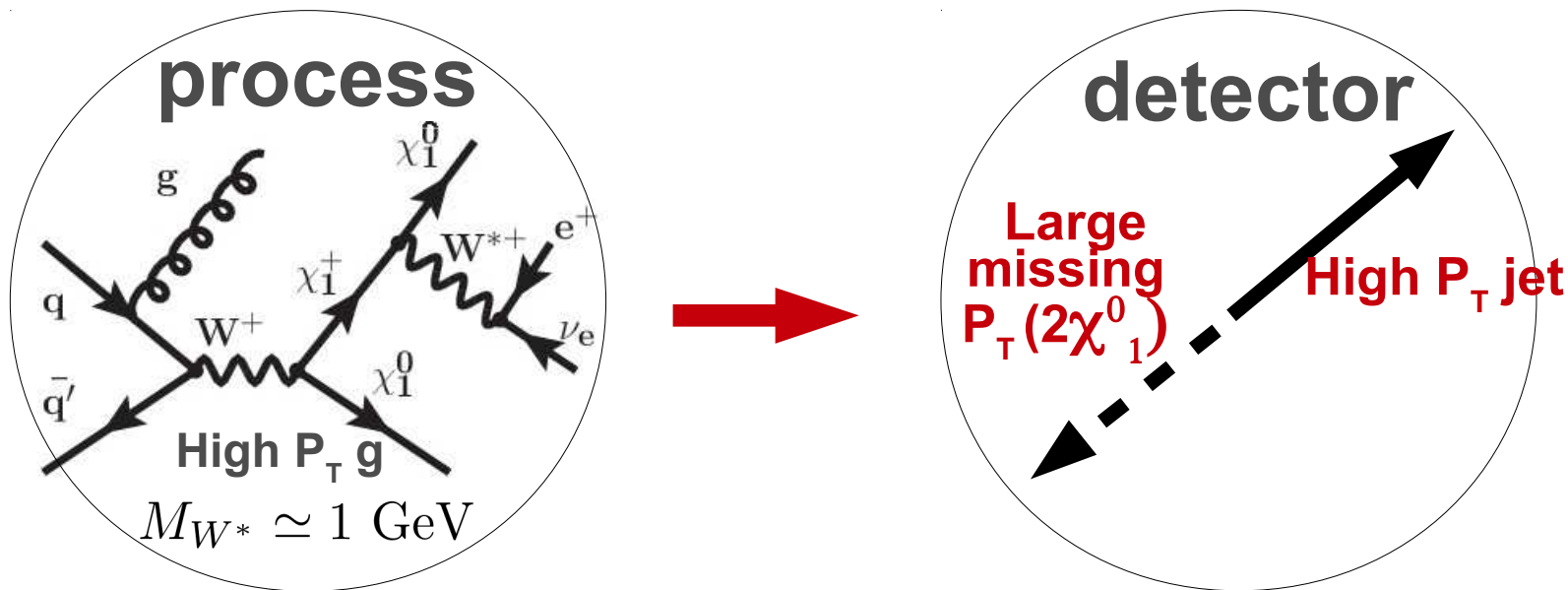
# Application beyond the EFT: SUSY

# There is no limit on the LSP mass if the mass of strongly interacting SUSY particles above $\sim 1.9$ TeV



# SUSY Compressed Mass Spectrum scenario

- The most challenging case takes place when only  $\chi_{1,2}^0$  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

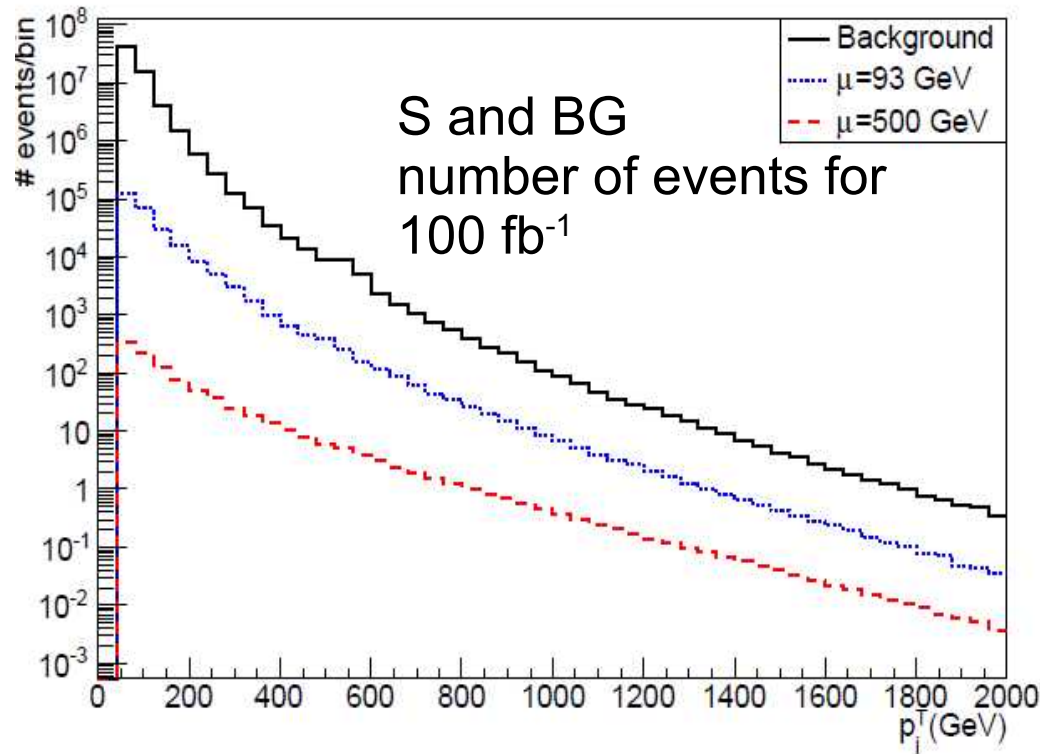




# Signal vs Background

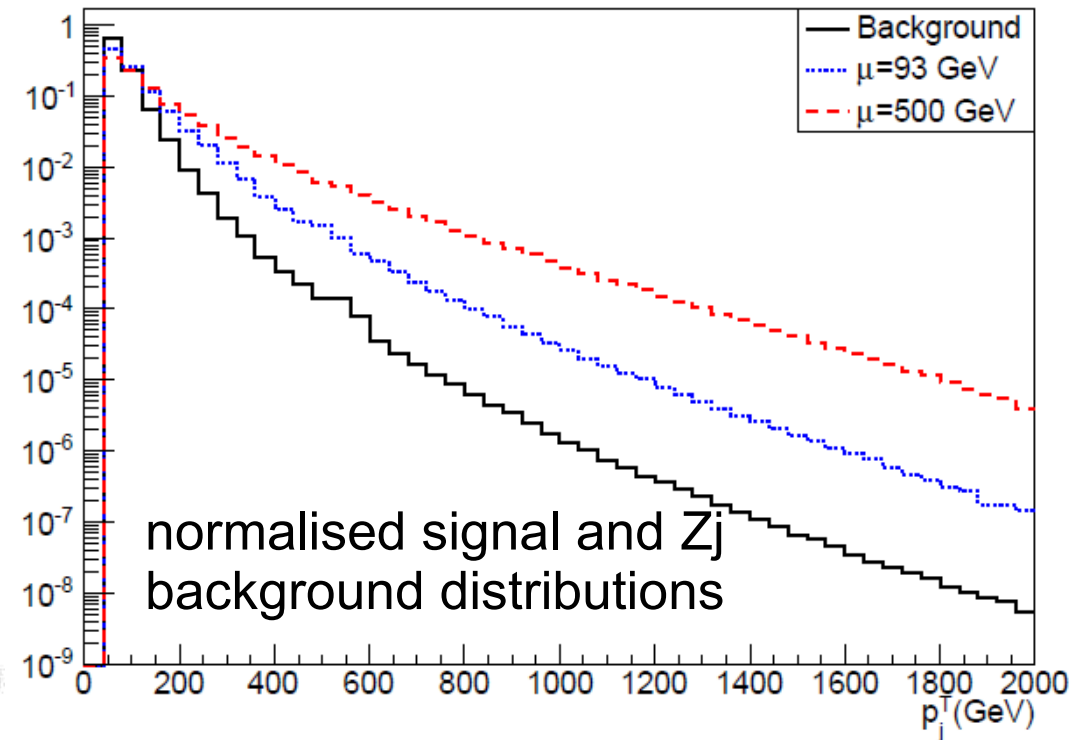
- *difference in rates is pessimistic ...*

pp→vvj vs. pp→χχj



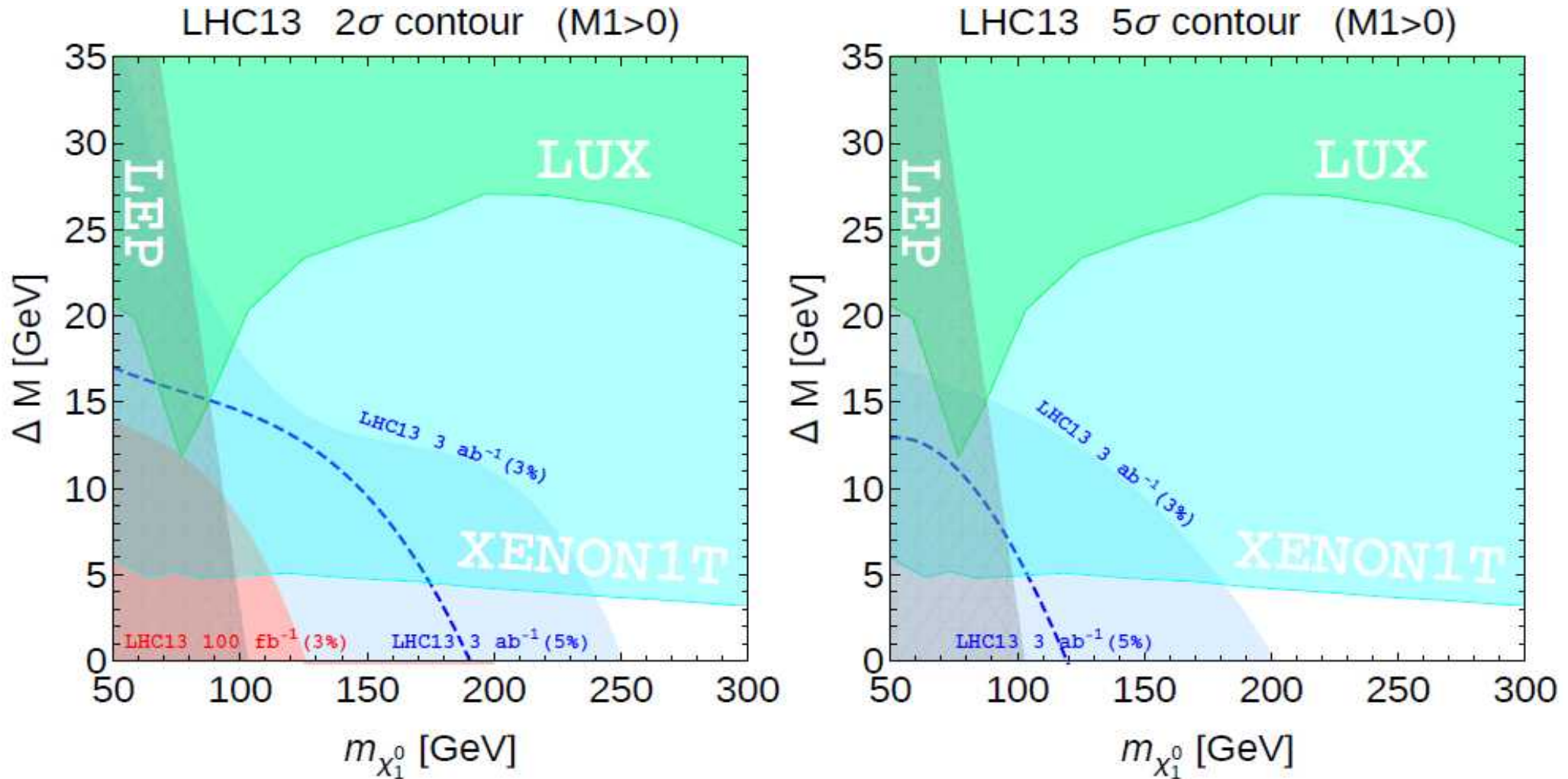
- *but the difference in shapes is encouraging, especially for large DM mass → bigger  $M(\text{DM}, \text{DM})$  → flatter MET*

pp→vvj vs. pp→χχj



Signal and Zj background p<sub>T</sub><sup>j</sup> distributions for the 13 TeV LHC

# LHC/DM direct detection sensitivity

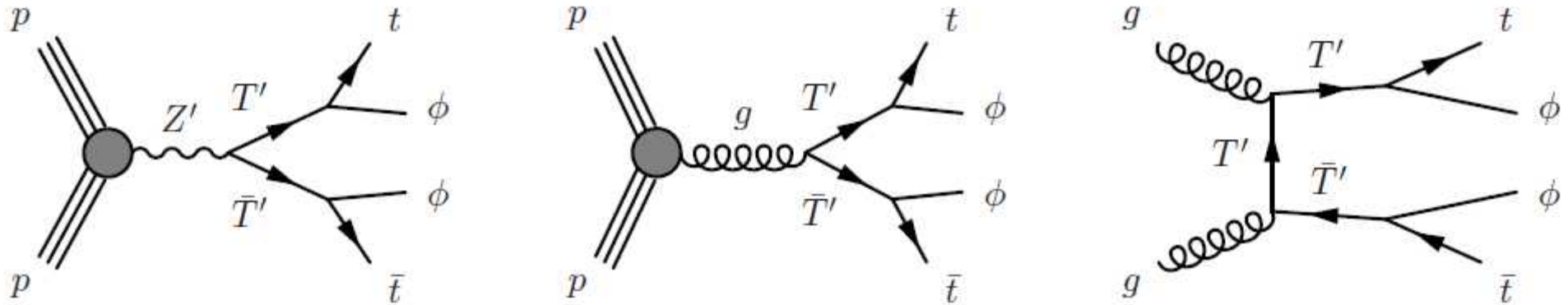


AB, Barducci, Bharucha, Porod, Sanz JHEP, 1504.02472

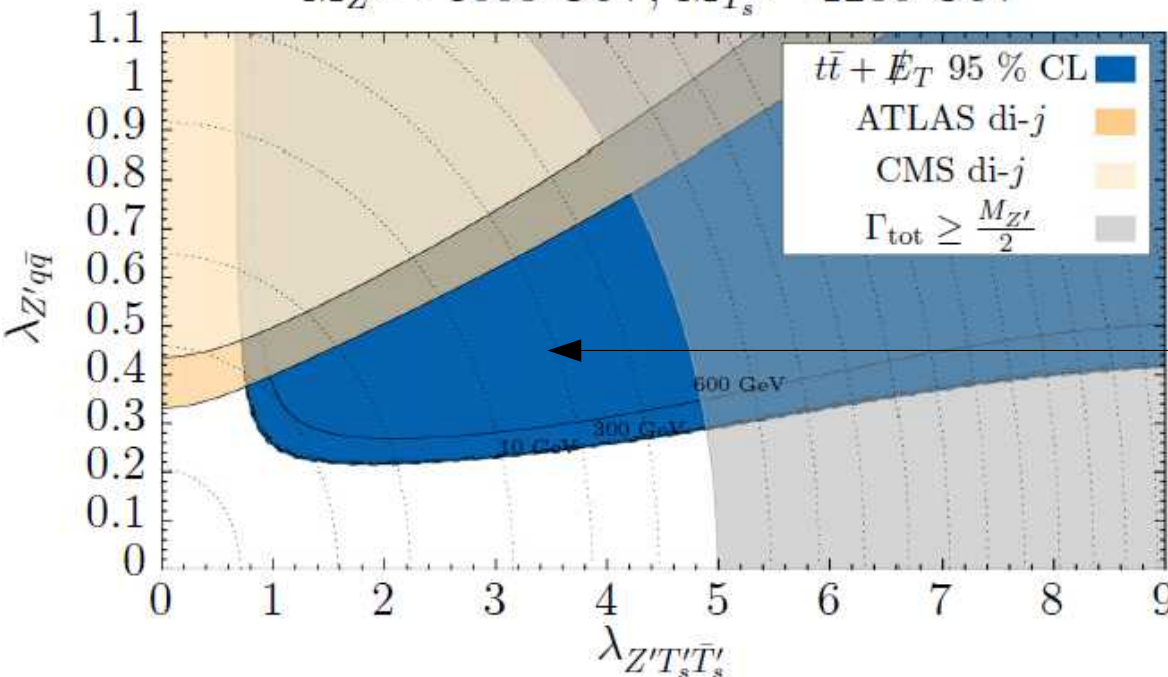
- SUSY DM, can be around the corner ( $\sim 100$  GeV), but it is hard to detect it!
- Great complementarity of DD and LHC for small DM (NSUSY) region

# Beyond the mono-jet signature

Example of the vector resonance in the Composite Higgs model:  
 $Z' \rightarrow T\bar{T} \rightarrow t\bar{t} \text{ DM DM}$  signature



$$M_{Z'} = 3000 \text{ GeV}, M_{T_s} = 1200 \text{ GeV}$$



Current LHC reach  
 with  $t\bar{t} + \cancel{E}_T$  signature  
 based on  
 ATLAS\_CONF\_2016\_050  
 results

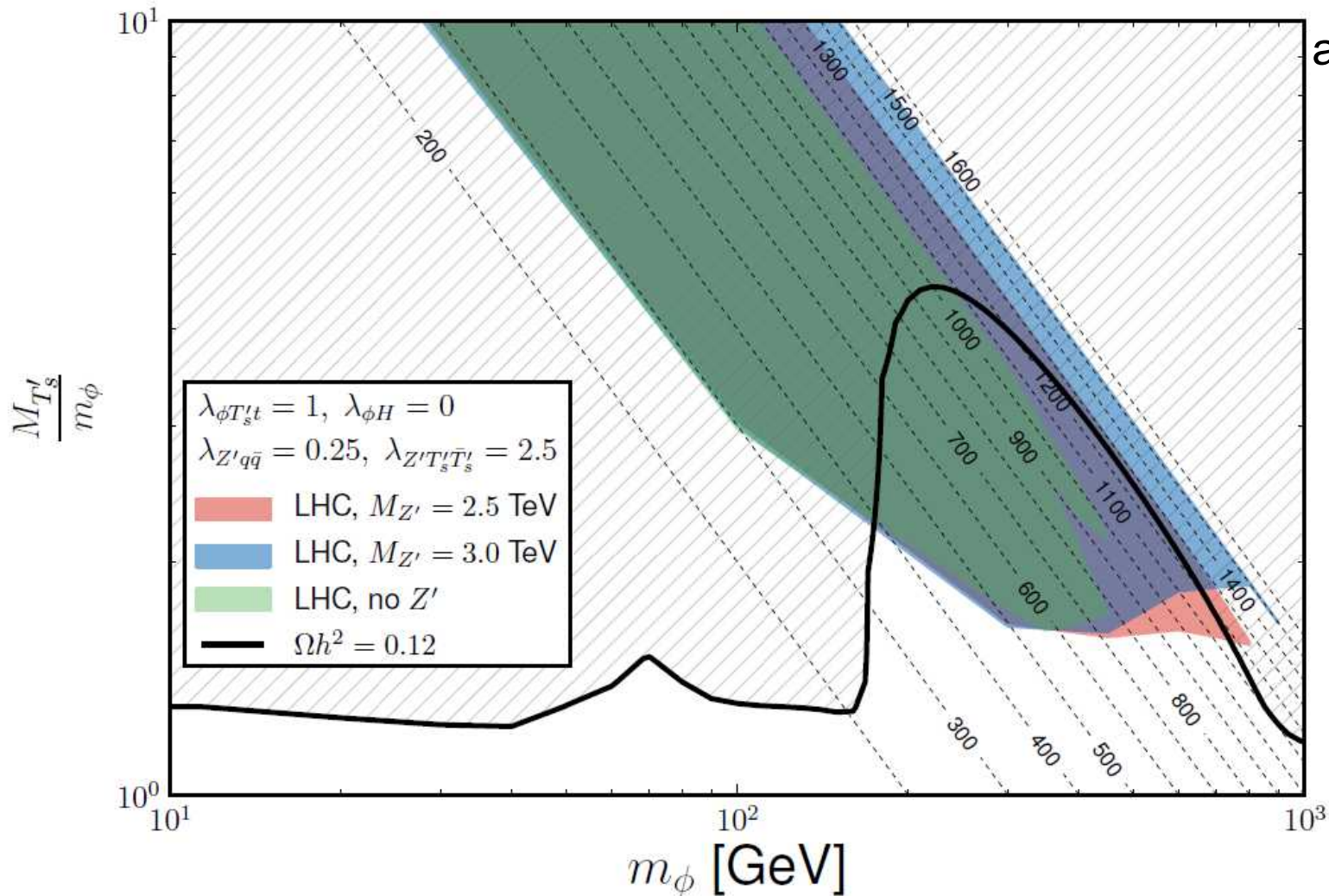
Flacke, Jaine, Schaefer, AB, 2017



# The role of $Z'$ vs QCD for $pp \rightarrow TT \rightarrow t t \text{ DM DM}$

arXiv: 1707.07000

$Z' + \text{QCD } TT$   
production



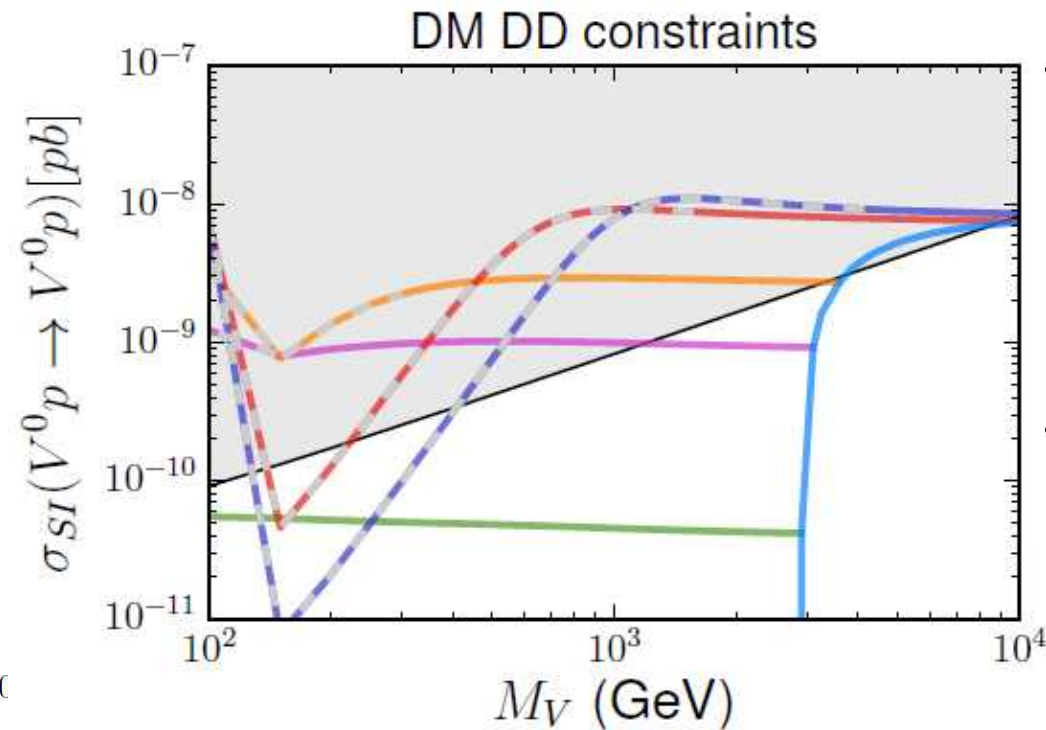
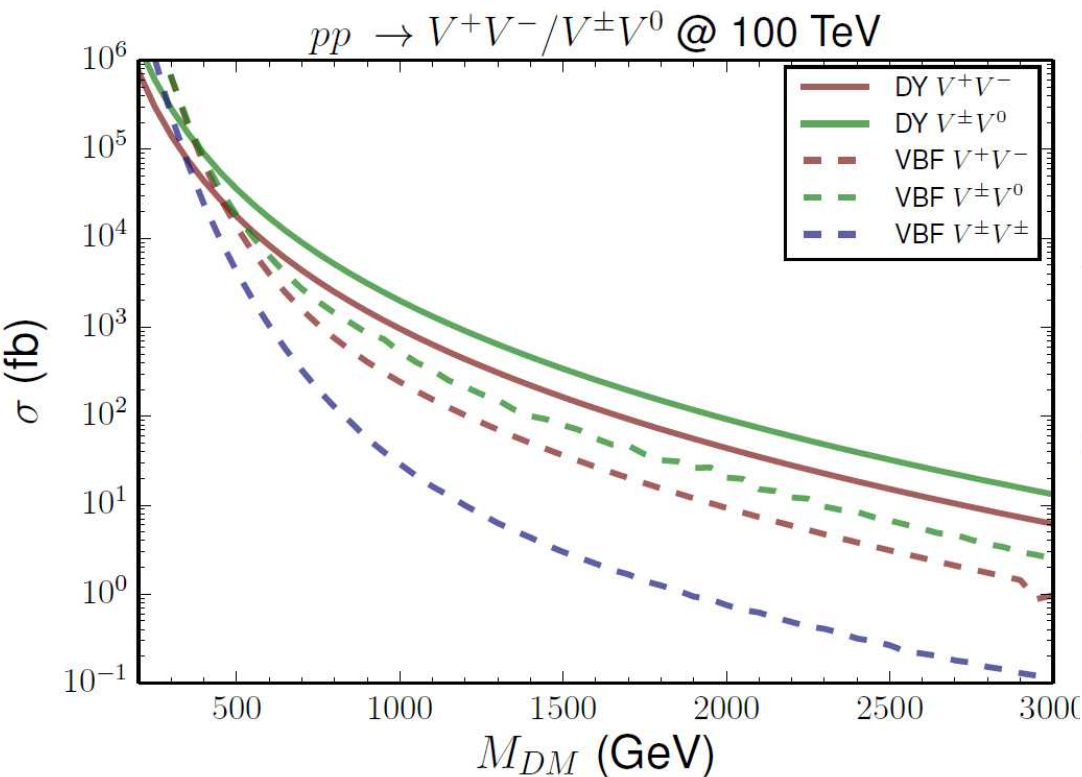
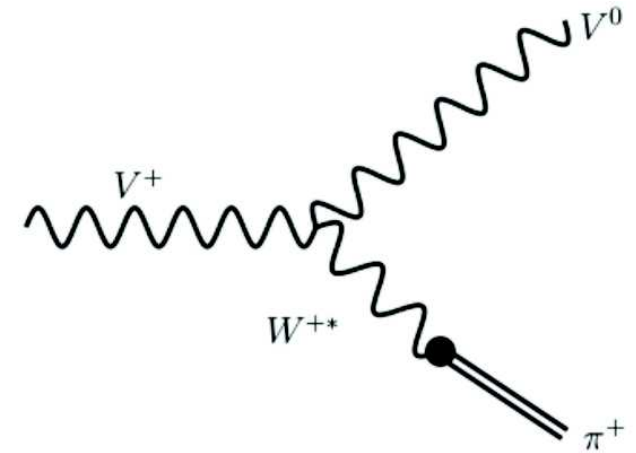
⇒ LHC is probing now DM and top partner masses up to about 0.9 and 1.5 TeV respectively: above bounds from QCD production alone by ~ factor of two

⇒ DM DD rates are loop-suppressed

# Disappearing Charged Tracks from DM

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

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

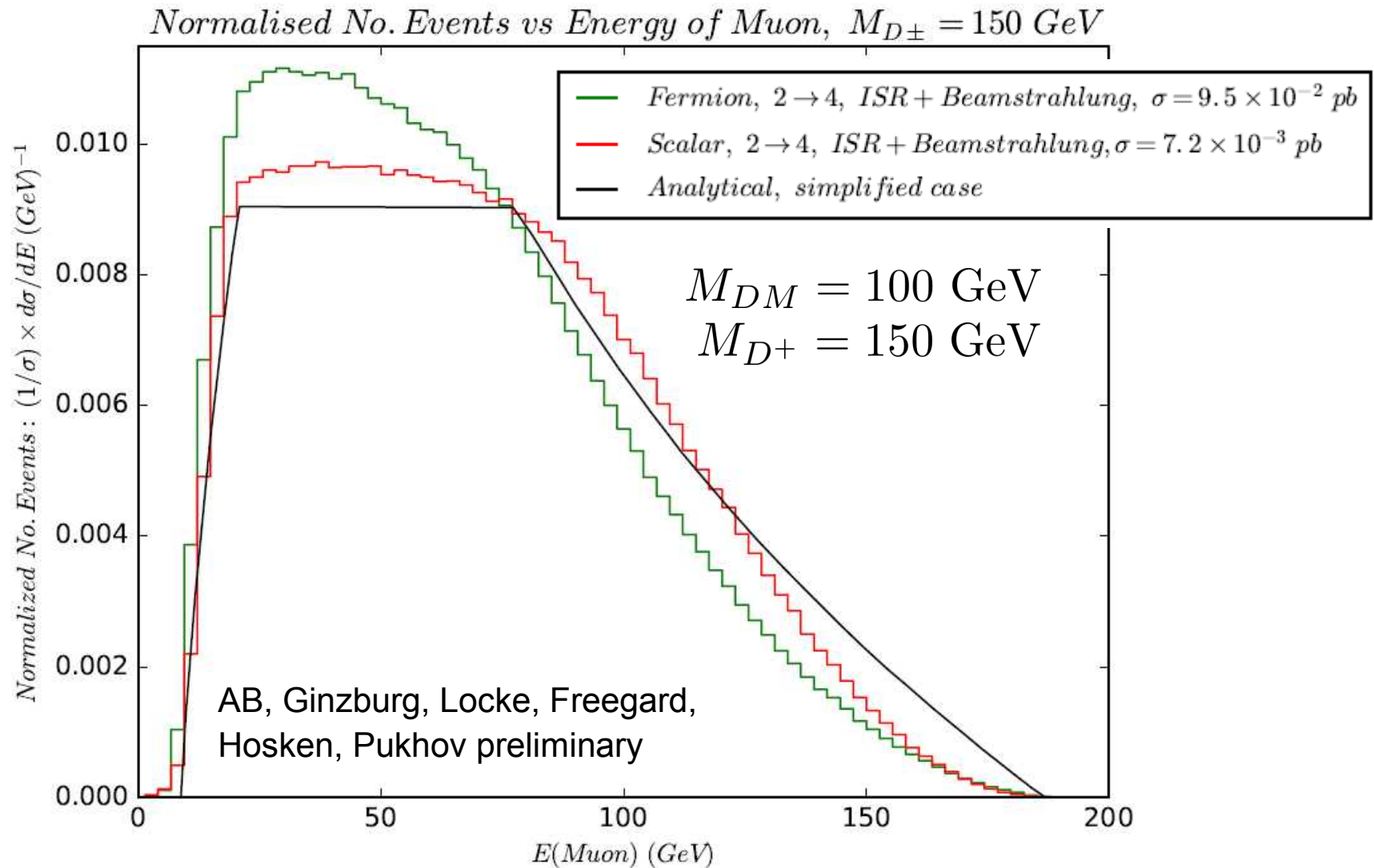


AB, Cacciapaglia, McKay, Marin, Zerwekh

# Decoding the nature of DM at the ILC

muon spectrum from the models with scalar and fermion DM

$e^+e^- \rightarrow D^+ D^- \rightarrow \text{DM DM } W^+ W^- \rightarrow \text{DM DM } jj \mu \nu$





# 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, long lived ...), new colliders (great potential of ILC and FCC)
- ⇒ Great synergy of collider and non-collider experiments (DD, CMB, relic density)

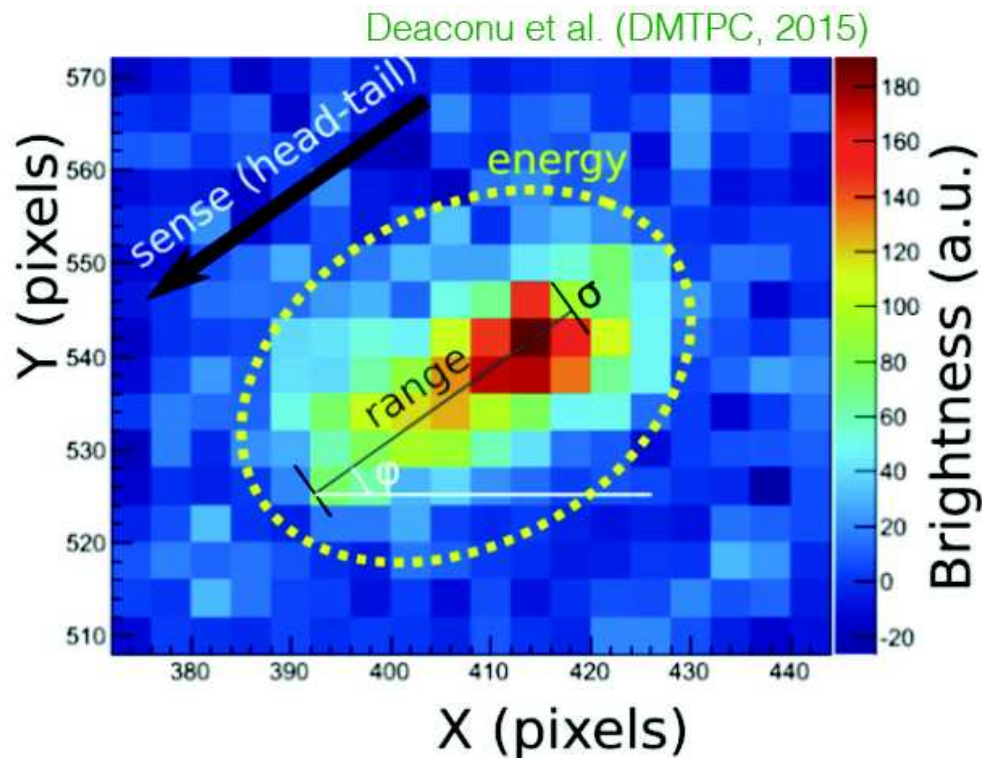
# Thank you!

# Backup Slides



# DM DD: directional detection – going beyond the neutrino floor

- The idea is to measure both the energy and the direction of the recoil
- Most mature technology is the gaseous Time Projection Chamber (TPC) : DRIFT, MIMAC, DMTPC, NEWAGE, D3



- Detecting recoil tracks in nuclear emulsion (e.g. NEWS experiment)  
Aleksandrov et al. [1604.04199]
- Directional detection is HARD,  
But it is also very POWERFUL.

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

$V_{DM}$ Operator	$\Lambda_d$	$d$	$\Lambda_D$	$D$	$\Delta_\sigma(\sigma_{2\rightarrow 2} \propto E^{\Delta_\sigma})$	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  $M_{DM}/\Lambda$  factor for each power of  $E/M_{DM}$  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  $\Lambda$  in different parametrisations:

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

# On the BG uncertainty

- The BG is statistically driven, e.g.  $pp \rightarrow Zj \rightarrow nnj$  BG is defined from the  $pp \rightarrow Zj \rightarrow l^+l^-j$  one

CMS-PAS-EXO-16-013

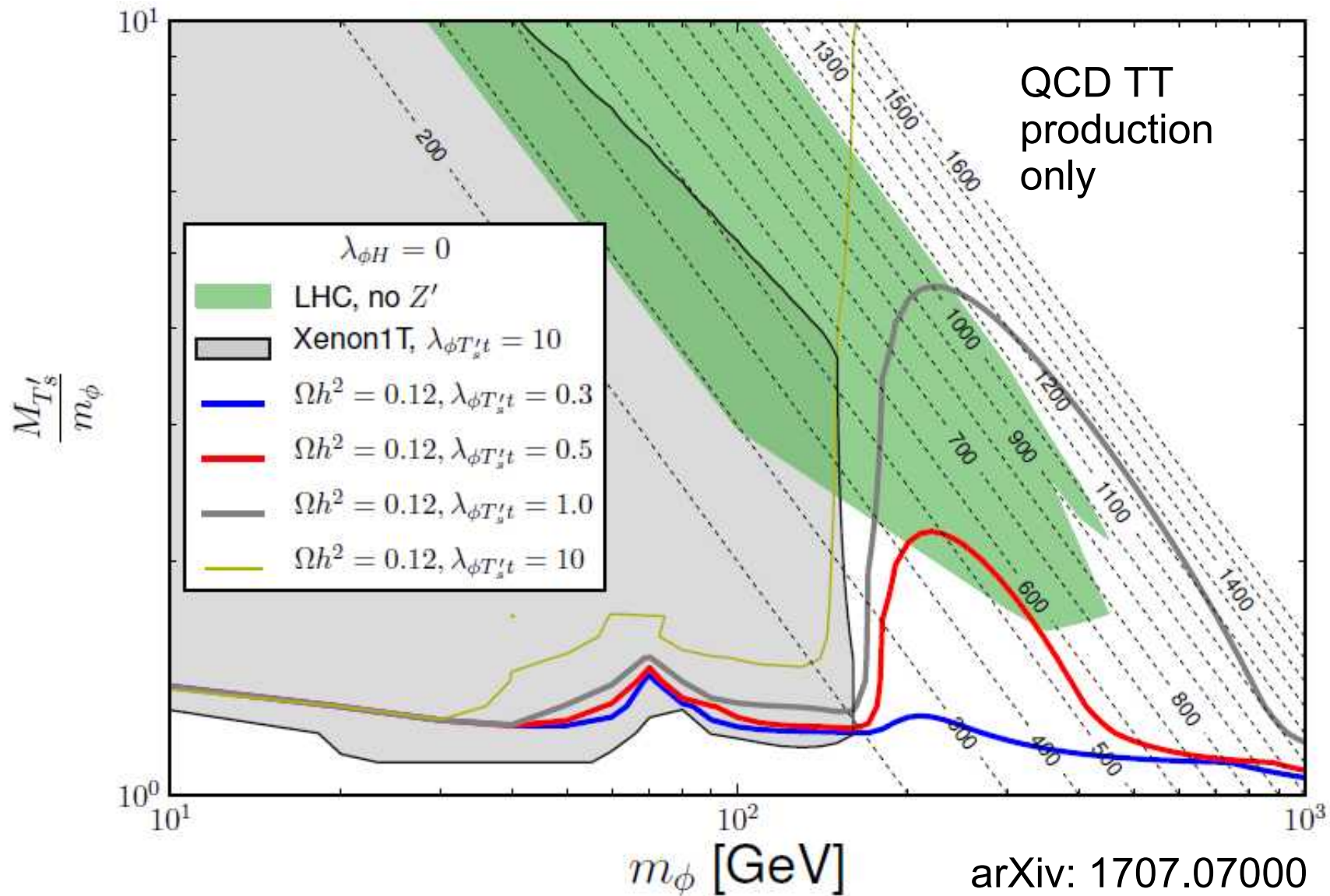
$E_T^{\text{miss}}$ Range (GeV)	$Z(\nu\nu)+\text{jets}$	$W(\ell\nu)+\text{jets}$	$Z(\ell\ell)+\text{jets}$	$\gamma+\text{jets}$	Top	Diboson	QCD	Total (Pre-fit)	Total (Post-fit)	Data
200 – 230	14919 ± 221	11976 ± 196	207 ± 13	230 ± 14	564 ± 55	251 ± 41	508 ± 171	27761 ± 1464	28654 ± 171	28601
230 – 260	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  
 $TT \rightarrow t t$  DM DM



# LHC@13TeV Reach for spin 0 and 1/2 DM

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



# Disappearing Charged Tracks from DM

The small mass gap between ( $\sim$  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**

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

