Dark Matter characterisation and interpretation of the MET signature at the LHC

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Dec 13, 2016

(Re) interpretation workshop

CERN

What do we know about Dark Matter?

Spin ?

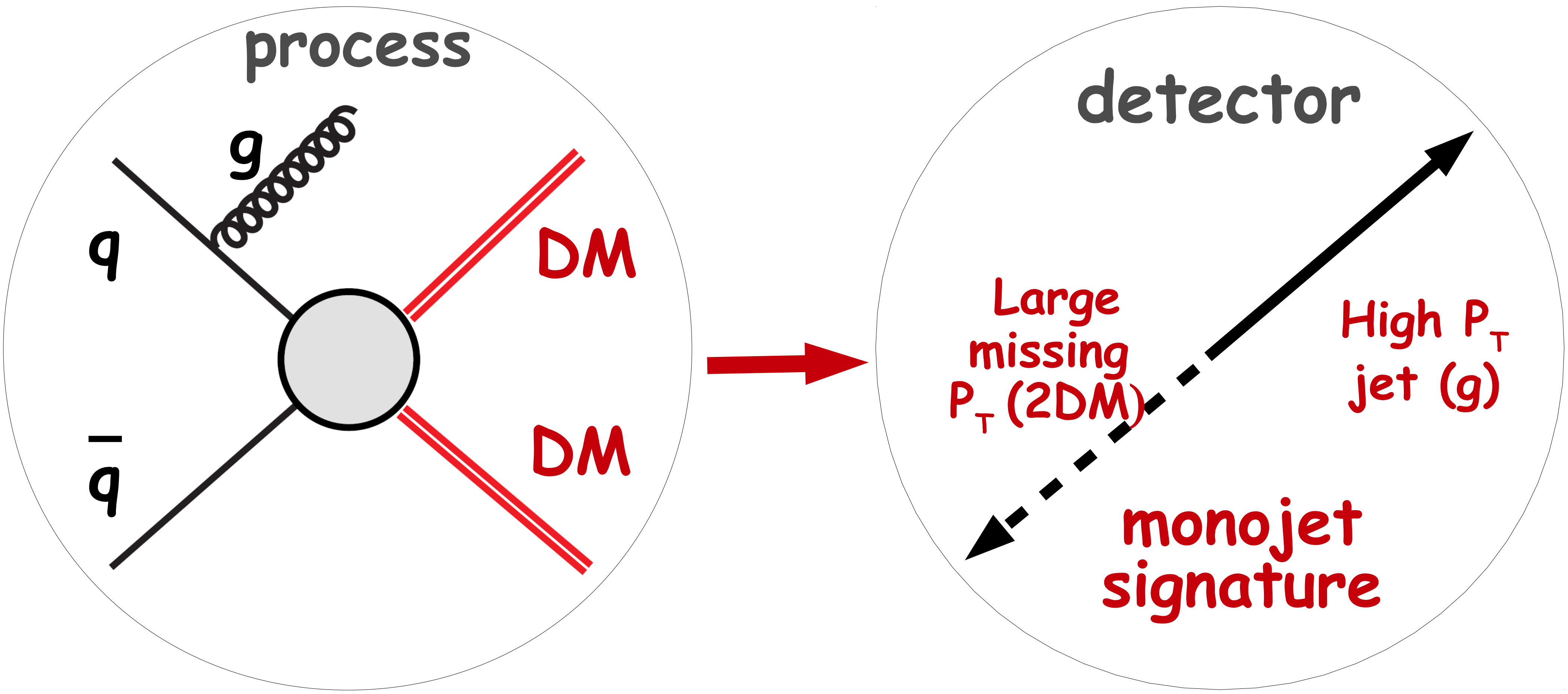
Mass ?

Stable
- Yes ? No ?
- symmetry behind stability ?

Couplings
- gravity V
- Weak ?
- Higgs ?
- Quarks/gluons ?
- Leptons ?
- New sector ?

Thermal relic
- Yes ? No ?

Hunting for DM at Colliders



Motivation for DM Characterisation

- **If DM is produced at the LHC:**
  - **We need to be able to identify the underlying model.**
    - SUSY? Extra Dimensions? Inert Two Higgs Doublet Model?
  - **We need to know: Mass, Spin, Mediator properties**
- **Also:** From LHC DM forum (arXiv:1507.00966)
  - "Different spins of Dark Matter particles will typically give similar results..... Thus the choice of Dirac fermion Dark Matter should be sufficient as benchmarks for the upcoming Run-2 searches."

    Is this true? Important for future studies on exclusion/discovery of DM

This study

- **The effects of DM spin on observables at the LHC for Spin=0,1/2,1 for events with a mono-jet signature**
- **Consider contact interactions first: simplest case.**
  - Complete set of DIM5/DIM6 operators involving two SM quarks (gluons) and two DM particles.
- **Explore LHC discovery potential for scenarios with different DM spins and potential to distinguish these scenarios**

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]*

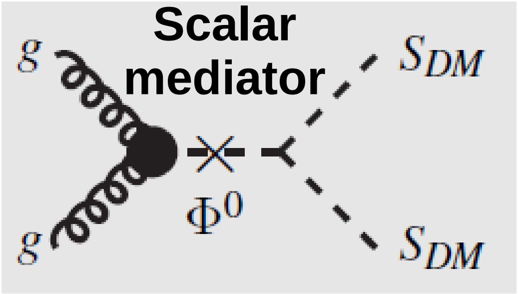
Complex vector DM‡	
$\frac{\tilde{m}}{\Lambda^2}V_\mu^\dagger V^\mu\bar{q}q$	[V1]*
$\frac{\tilde{m}}{\Lambda^2}V_\mu^\dagger V^\mu\bar{q}i\gamma^5 q$	[V2]*
$\frac{1}{2\Lambda^2}(V_\nu^\dagger\partial_\mu V^\nu - V^\nu\partial_\mu V_\nu^\dagger)\bar{q}\gamma^\mu q$	[V3]
$\frac{1}{2\Lambda^2}(V_\nu^\dagger\partial_\mu V^\nu - V^\nu\partial_\mu V_\nu^\dagger)\bar{q}i\gamma^\mu\gamma^5 q$	[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]*

$\frac{1}{\Lambda^2}\bar{\chi}q\bar{q}\chi$	[D1T]
$\frac{i}{2\Lambda^2}(\bar{\chi}\gamma^5 q\bar{q}\chi + \bar{\chi}q\bar{q}\gamma^5\chi)$	[D2T]
$\frac{1}{2\Lambda^2}(\bar{\chi}\gamma^5 q\bar{q}\chi - \bar{\chi}q\bar{q}\gamma^5\chi)$	[D3T]
$\frac{1}{\Lambda^2}\bar{\chi}\gamma^5 q\bar{q}\gamma^5\chi$	[D4T]

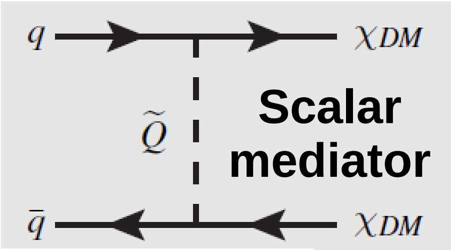
additional, not-independent operators can be written

Mapping EFT operators to simplified models

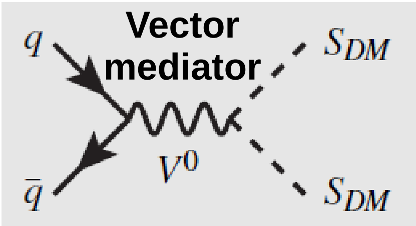
C5,C5A $\frac{1}{\Lambda^2}\phi^*\phi G^{\mu\nu}G^{\mu\nu}$, $\frac{1}{\Lambda^2}\phi^*\phi \tilde{G}^{\mu\nu}G^{\mu\nu}$ $\longrightarrow$



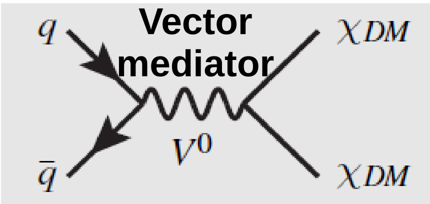
D1T-D4T $\frac{1}{\Lambda^2}\bar{\chi}q\bar{q}\chi$ $\longrightarrow$

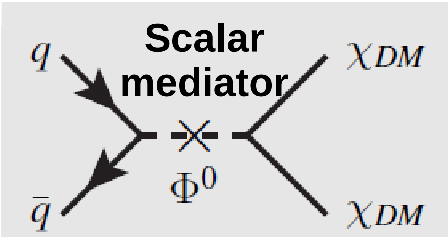


C3 $\frac{i}{\Lambda^2}[\phi^*(\partial_\mu\phi - (\partial_\mu\phi^*)\phi]\bar{q}\gamma^\mu q$ $\longrightarrow$

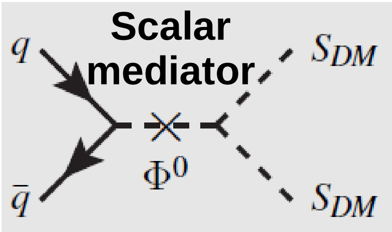


D1-D4, D5-D8 $\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$ $\frac{1}{\Lambda^2}\bar{\chi}\chi\bar{q}q$ $\longrightarrow$



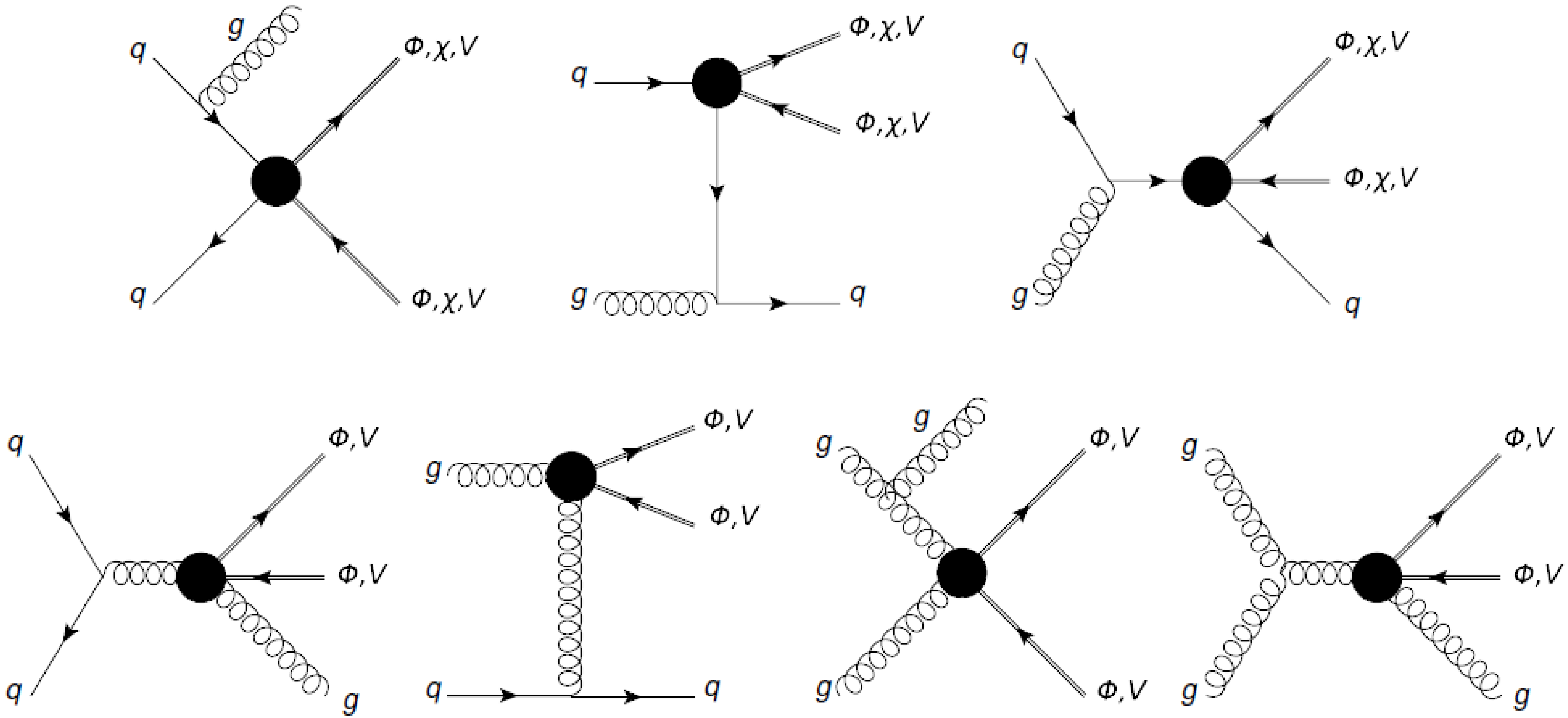


C1 $\frac{1}{\Lambda^2}\phi^*\phi\bar{q}q\Phi \Longrightarrow \frac{v}{\Lambda^2}\phi^*\phi\bar{q}q$ $\longrightarrow$

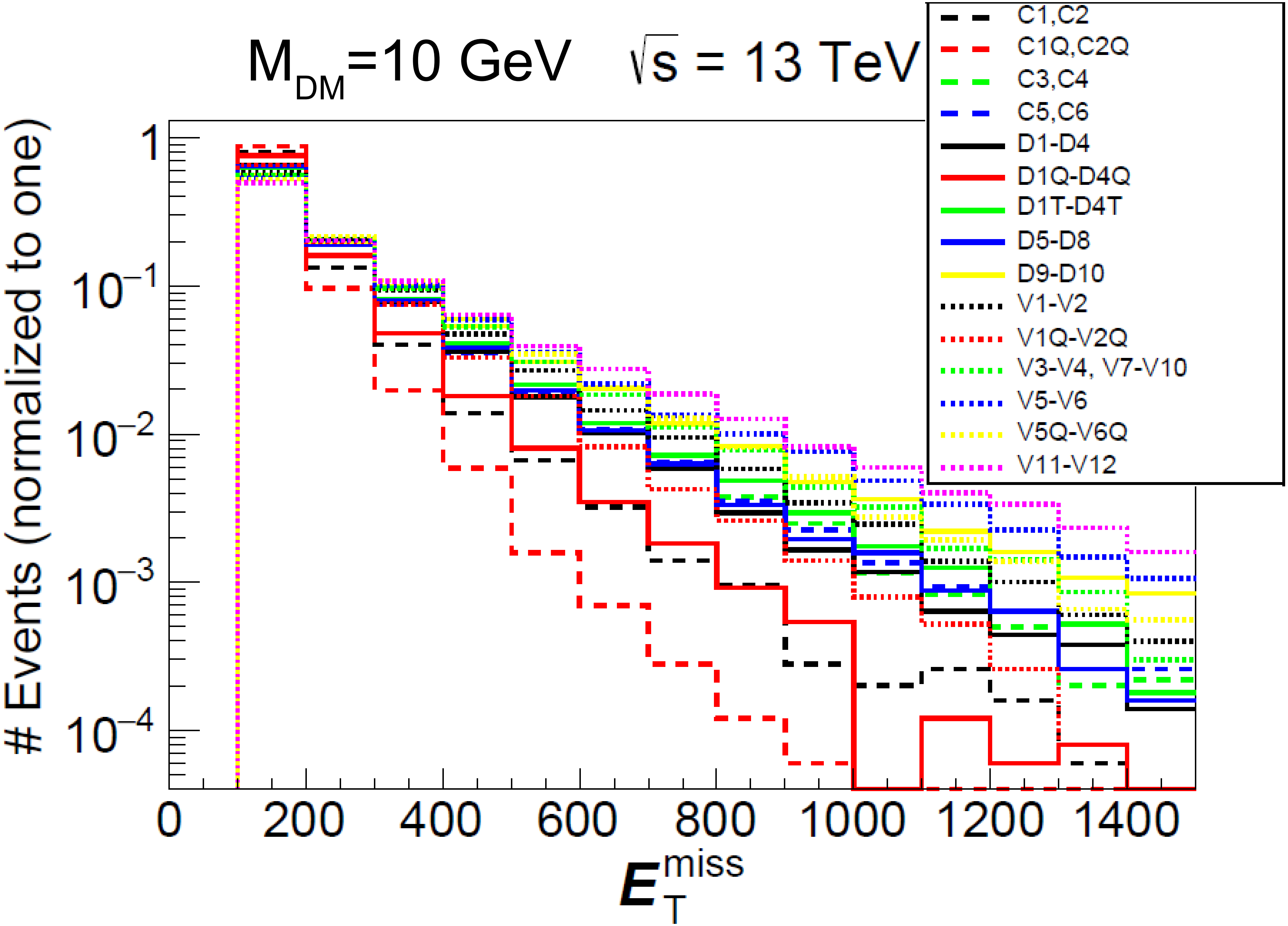


D9,D10 $\frac{1}{\Lambda^2}\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q \longrightarrow \frac{1}{\Lambda^2}$ [2 $\bar{\chi}q\bar{q}\chi$ - $\frac{1}{2}\big(\bar{\chi}\chi\bar{q}q + \bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q + \bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q + \bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5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

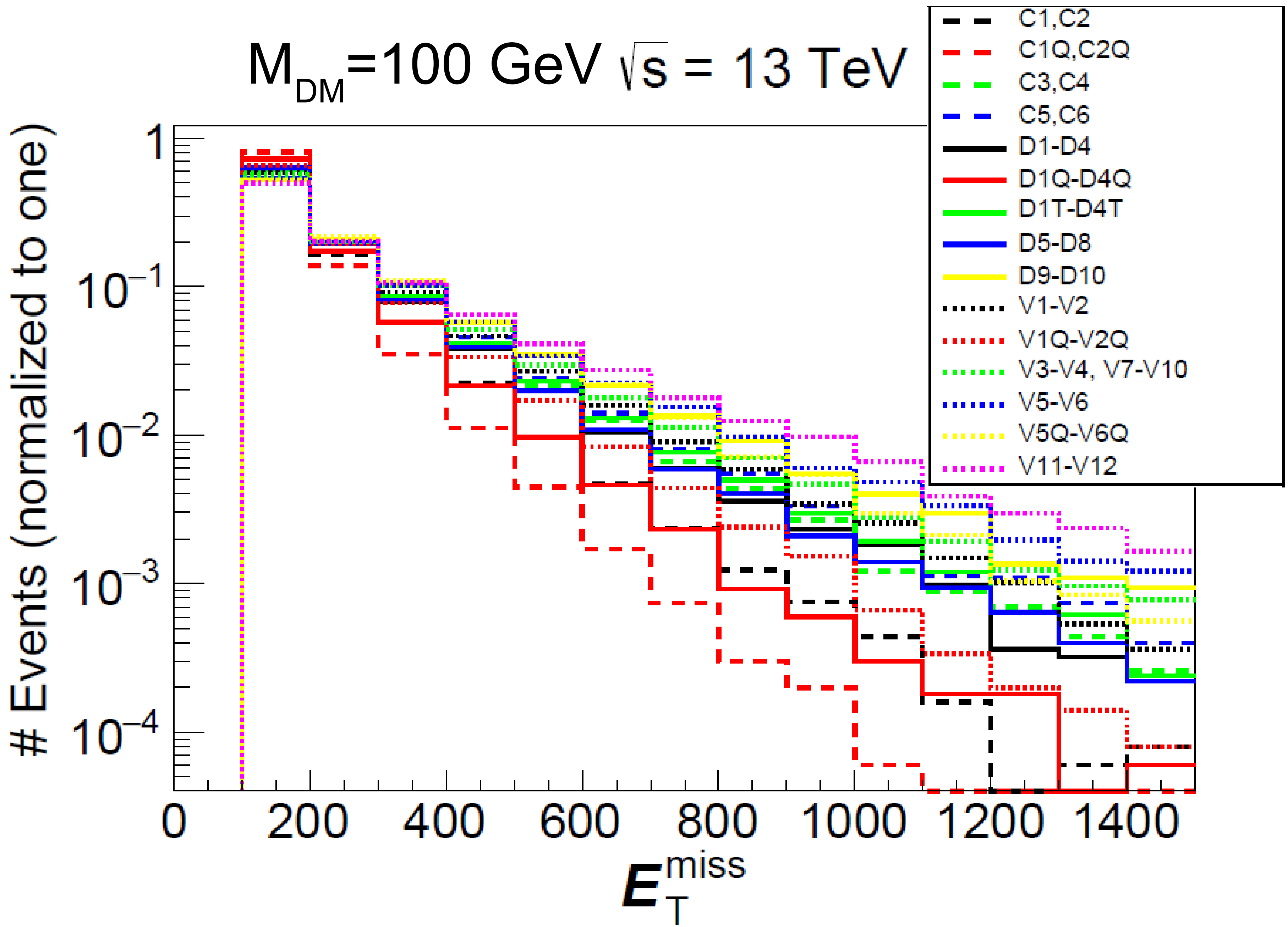
Mono-jet diagrams from EFT operators



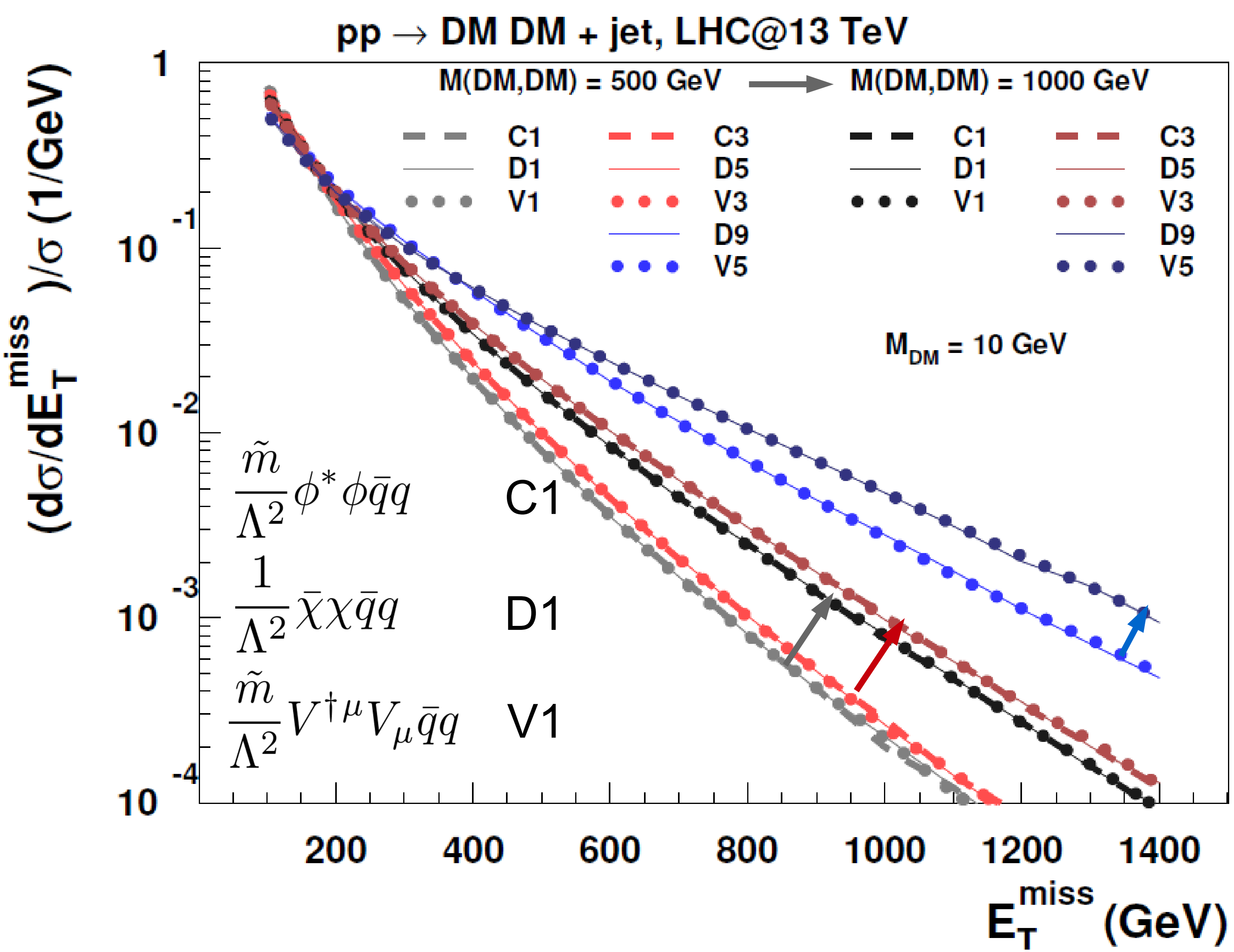
Missing E_T (MET) distributions: the large range of slopes



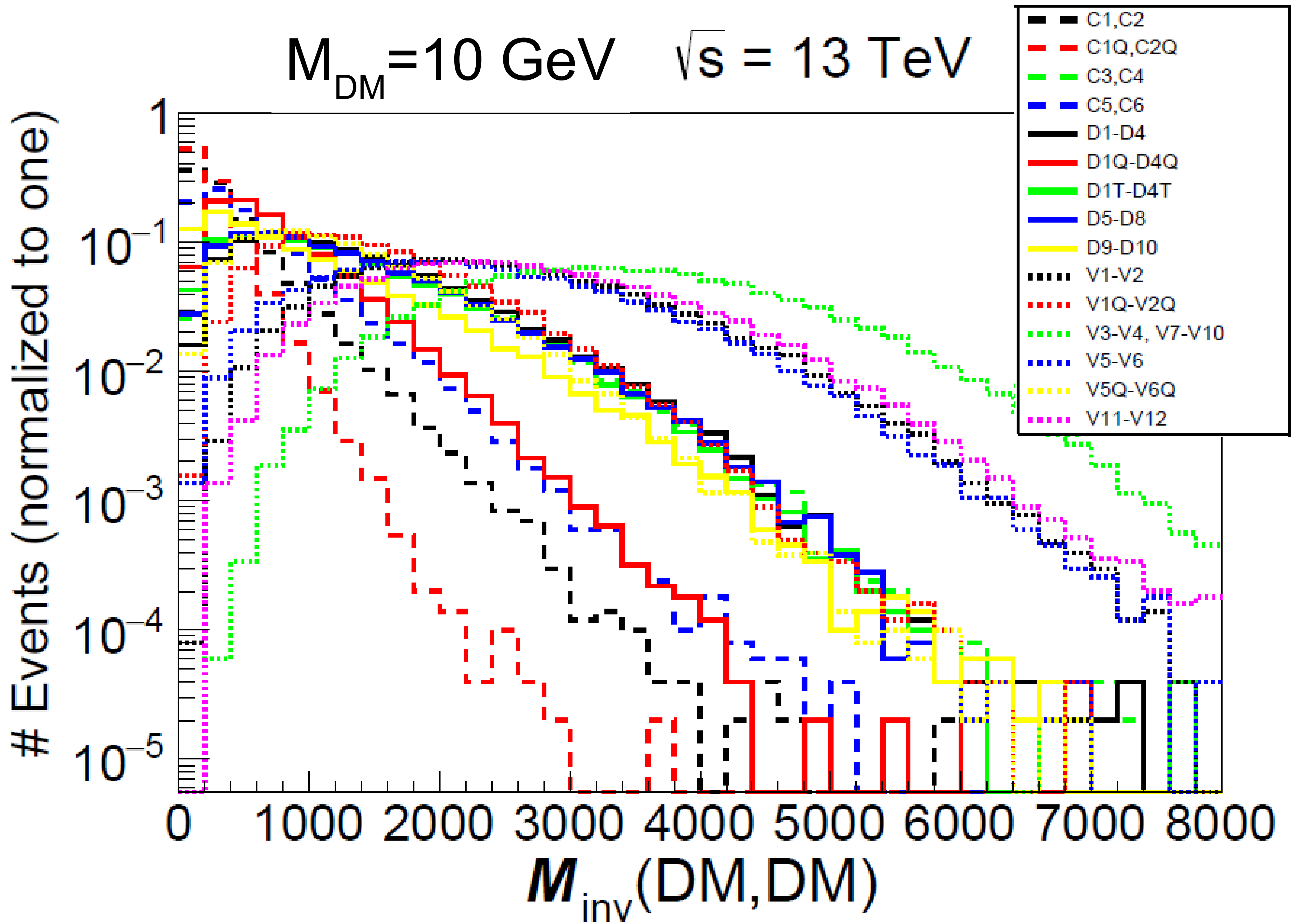
M_{DM} dependence is weak for 10-100 GeV range



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



M(DM,DM) distributions are defined by energy behaviour of DM operator and are different for different DM spins



On the BG uncertainty

- **The BG is statistically driven, e.g. pp-> Zj → ννj 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

On the BG uncertainty

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CMS-PAS-EXO-16-013

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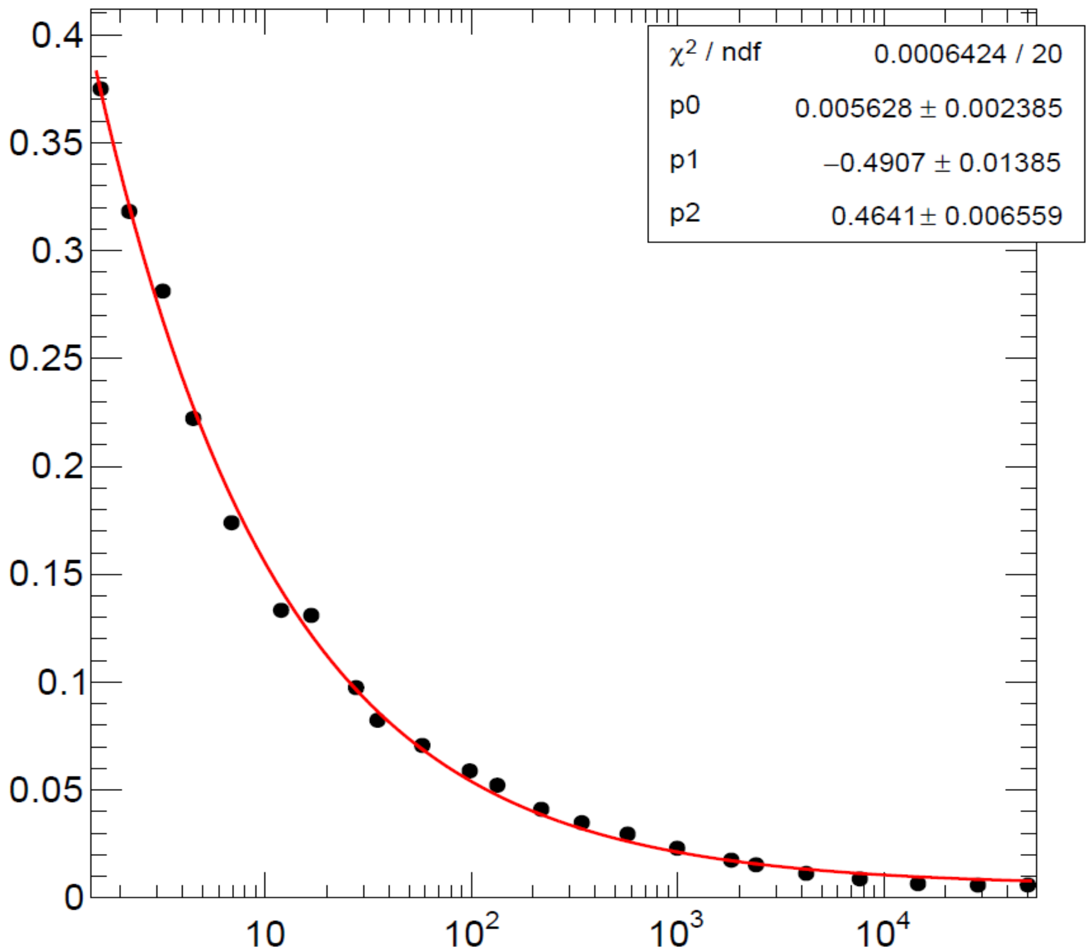
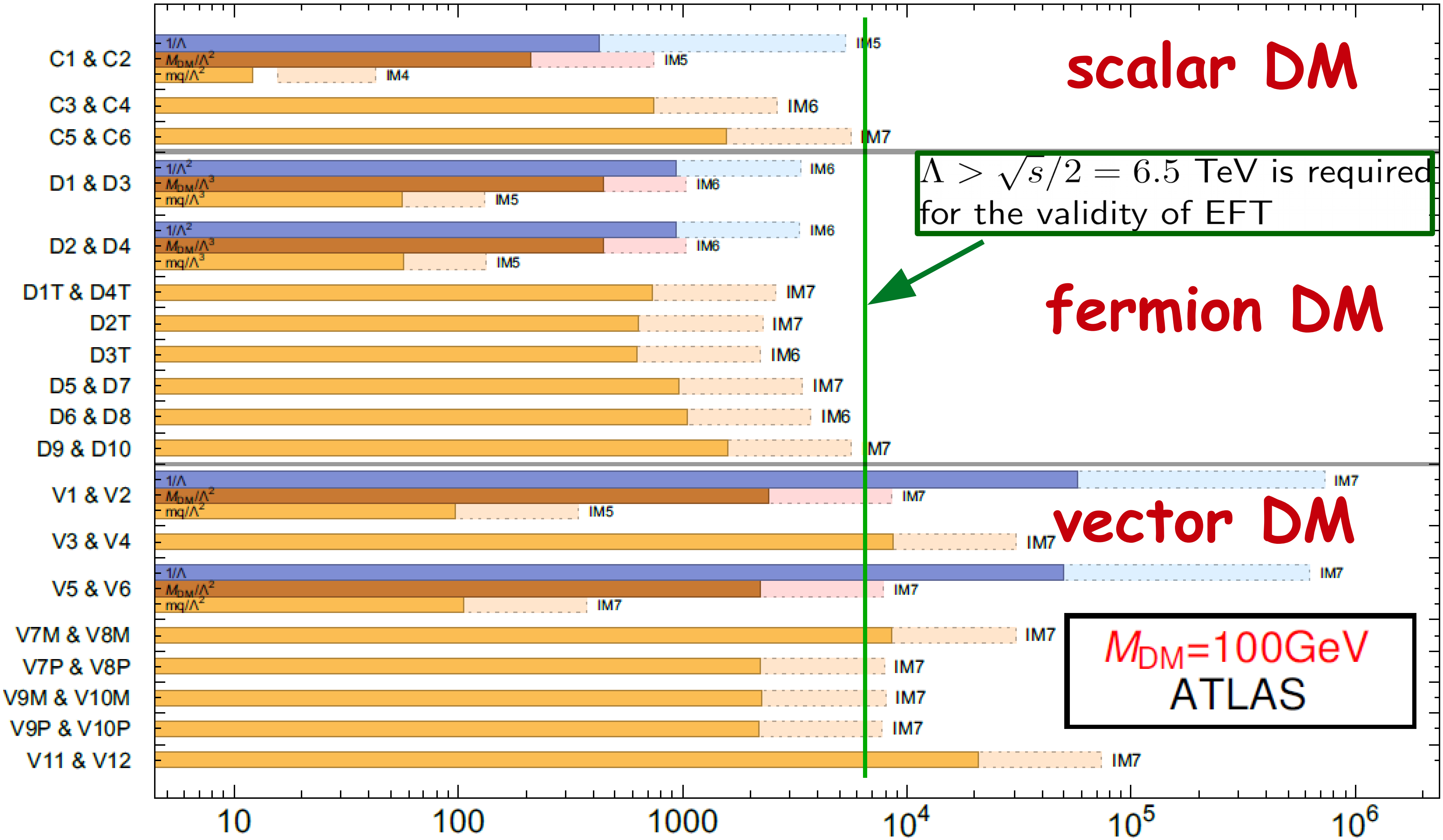
840 – 900	9.5 ± 1.4	2.0 ± 0.3	12.2 ± 0.6	12.0 ± 1.6	13
900 – 960	5.4 ± 1.0	1.1 ± 0.2	7.6 ± 0.3	6.9 ± 1.2	7
960 – 1020	3.3 ± 0.8	0.77 ± 0.21	5.2 ± 0.3	4.5 ± 1.0	3
1020 – 1160	2.5 ± 0.8	0.52 ± 0.16	3.6 ± 0.2	3.2 ± 0.9	1
1160 – 1250	1.7 ± 0.6	0.3 ± 0.11	2.3 ± 0.1	2.2 ± 0.7	2
> 1250	1.4 ± 0.5	0.19 ± 0.08	1.6 ± 0.1	1.6 ± 0.6	3

On the BG uncertainty



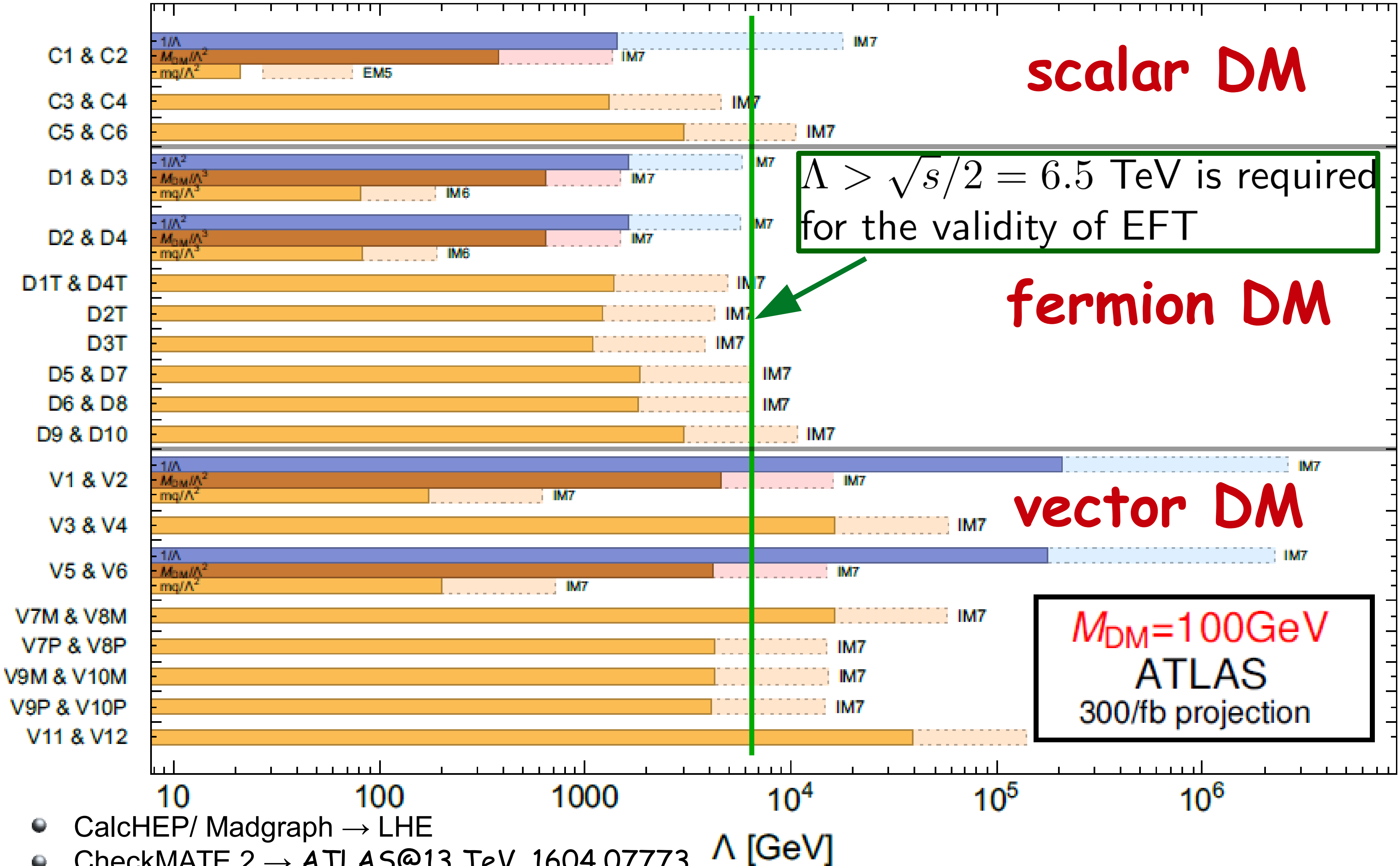
- The BG is statistically driven, e.g. pp-> Zj → ννj BG is defined from the pp → Zj → l^+l^-j one
- For the high enough statistics the BG error can be as low as 1%, but not much lower than this!
- Once ~ 1% δBG is reached (we assume as a floor), the increase of luminosity does not improve LHC sensitivity: the BG uncertainty linearly grows with luminosity together with signal
- at about 300 fb^{-1} such saturation is reached for all operators for current LHC cuts

LHC@13TeV reach at 3.2 fb^{-1}



- CalcHEP/ Madgraph → LHE
- CheckMATE 2 → ATLAS@13 TeV, 1604.07773

LHC@13TeV reach at 300 fb^{-1}



- CalcHEP/ Madgraph → LHE
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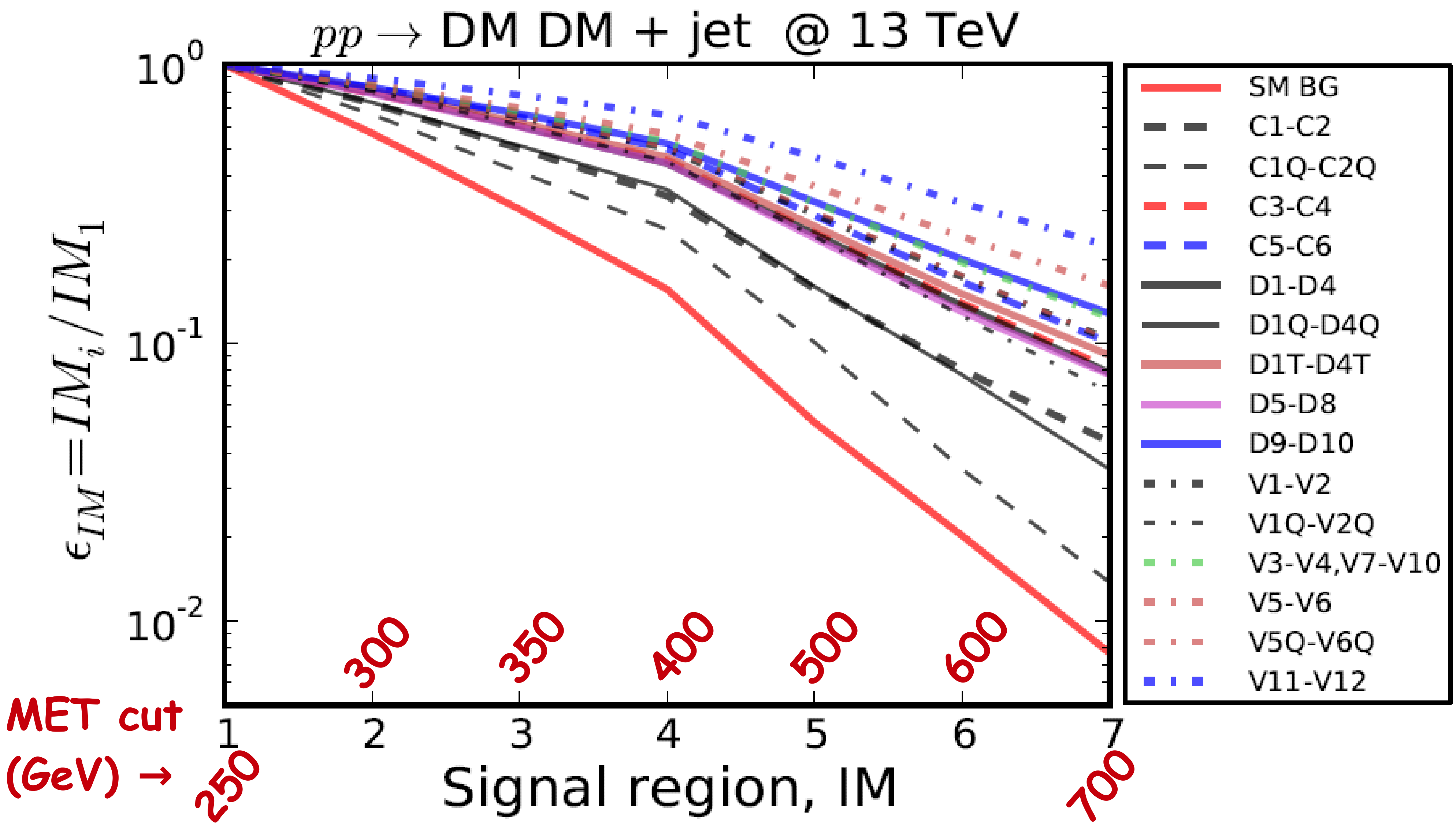
Distinguishing DM operators: different efficiencies (MET slopes) – about factor of 50 spread (in IM7) for different operators and the SM BG



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

$$\chi^2 = \sum_{i=EM3,EM4,EM5,EM6,IM7} [(N1_i - \kappa \times N2_i)/\delta BG_i]^2$$

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

- N1 signal is assumed at 1σ
- N2 signal is tested against it at high luminosity

			Complex Scalar DM				Dirac Fermion DM	
			10 GeV		100 GeV		10 GeV	100 GeV
			C1	C5	C1	C5	D9	D9
Complex Scalar DM	10 GeV	C1	0.0	**33.68**	1.35	**36.36**	**51.38**	**63.44**
		C5	**25.26**	0.0	**17.84**	0.07	1.8	4.56
	100 GeV	C1	1.29	**22.62**	0.0	**24.69**	**37.85**	**48.21**
		C5	**27.1**	0.07	**19.36**	0.0	1.51	4.0
Dirac Fermion DM	10 GeV	D9	**36.37**	1.7	**28.17**	1.43	0.0	0.86
	100 GeV	D9	**43.14**	4.13	**34.48**	3.64	0.82	0.0

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

$$\chi^2 = \sum_{i=EM3,EM4,EM5,EM6,IM7} [(N1_i - \kappa \times N2_i)/\delta BG_i]^2$$

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

			Complex Scalar DM				Dirac Fermion DM		Complex Vector DM			
			10 GeV		100 GeV		10 GeV	100 GeV	10 GeV			
			C1	C5	C1	C5	D9	D9	V1	V3	V5	V11
Complex Scalar DM	10 GeV	C1	0.0	**33.68**	1.35	**36.36**	**51.38**	**63.44**	**37.57**	**50.0**	**73.55**	**96.47**
		C5	**25.26**	0.0	**17.84**	0.07	1.8	4.56	0.41	1.4	7.29	**15.09**
	100 GeV	C1	1.29	**22.62**	0.0	**24.69**	**37.85**	**48.21**	**26.33**	**36.4**	**57.02**	**77.7**
		C5	**27.1**	0.07	**19.36**	0.0	1.51	4.0	0.38	1.04	6.52	**13.97**
Dirac Fermion DM	10 GeV	D9	**36.37**	1.7	**28.17**	1.43	0.0	0.86	1.08	0.12	2.1	6.4
	100 GeV	D9	**43.14**	4.13	**34.48**	3.64	0.82	0.0	3.4	1.03	0.3	2.91
Complex Vector DM	10 GeV	V1	**27.87**	0.41	**20.54**	0.37	1.13	3.71	0.0	0.92	6.13	**12.87**
		V3	**35.62**	1.33	**27.27**	0.99	0.12	1.08	0.89	0.0	2.44	7.22
		V5	**48.96**	6.47	**39.92**	5.82	1.98	0.3	5.5	2.28	0.0	1.38
		V11	**61.93**	**12.92**	**52.45**	**12.03**	5.81	2.75	**11.14**	6.51	1.33	0.0

Summary/Discussion

- Different DM spin → different energy dependence of the DM operator, different M_{DMDM} distributions → different slopes of MET
  - potential to characterize DM spin, different efficiencies, should be explored by ATLAS/CMS

- Application beyond EFT
  - when the DM mediator **is not produced on-the-mass-shell** - M_{DMDM} is not fixed: t-channel mediator or mediators with mass below $2M_{DM}$
  - On the contrary, when DM comes from the resonance decay, MET shape will be the same for different DM spins (given that SM operator is fixed)

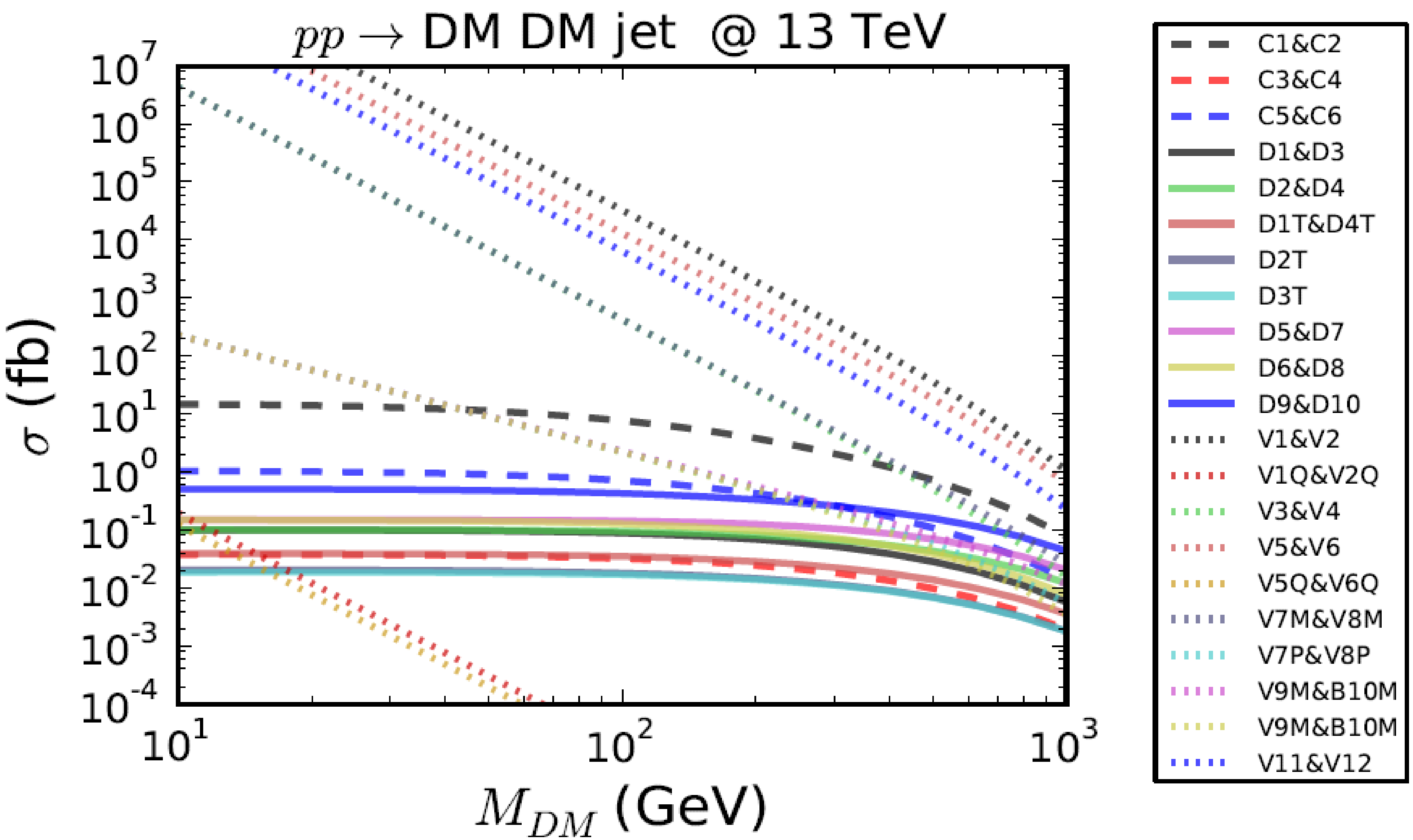
- Projection for 300 fb^{-1}: it is possible to distinguish C1-C2,C5-C6,D9-D10,V1-V2,V3-V4,V5-V6 and V11-12 from each other; all models are public at HEPMDB, https://hepmdb.soton.ac.uk/ has got a permanent server status at SOTON!

- Re-interpretation at high-luminosity is limited by present searches
  - Low MET cuts → low S/B ratio, hits 1% floor at 300 fb^{-1}, is this a limit?
  - the study on improving of the LHC sensitivity within the CheckMATE is on the way: will add a "projected" analysis to CM

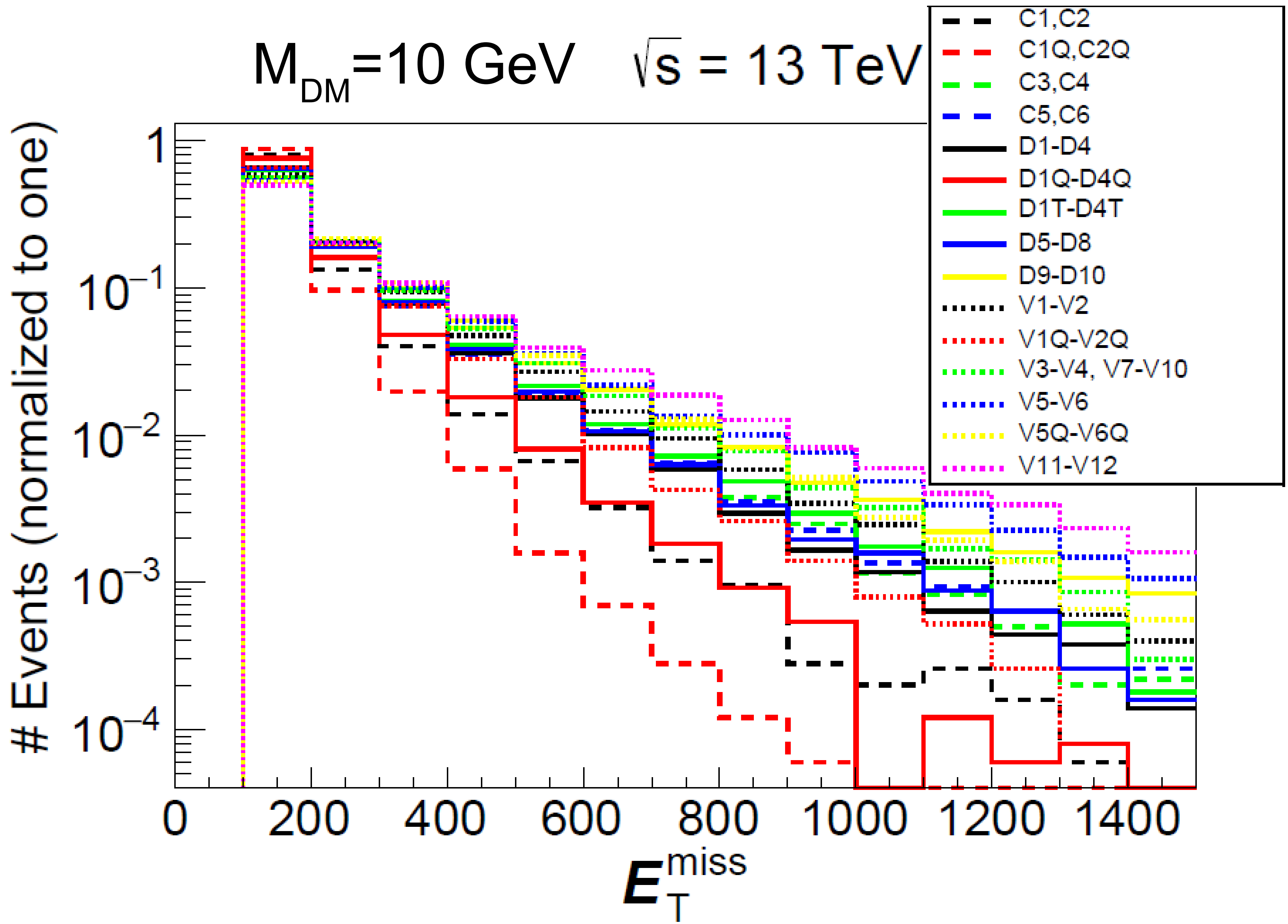
Thank you!

Backup Slides

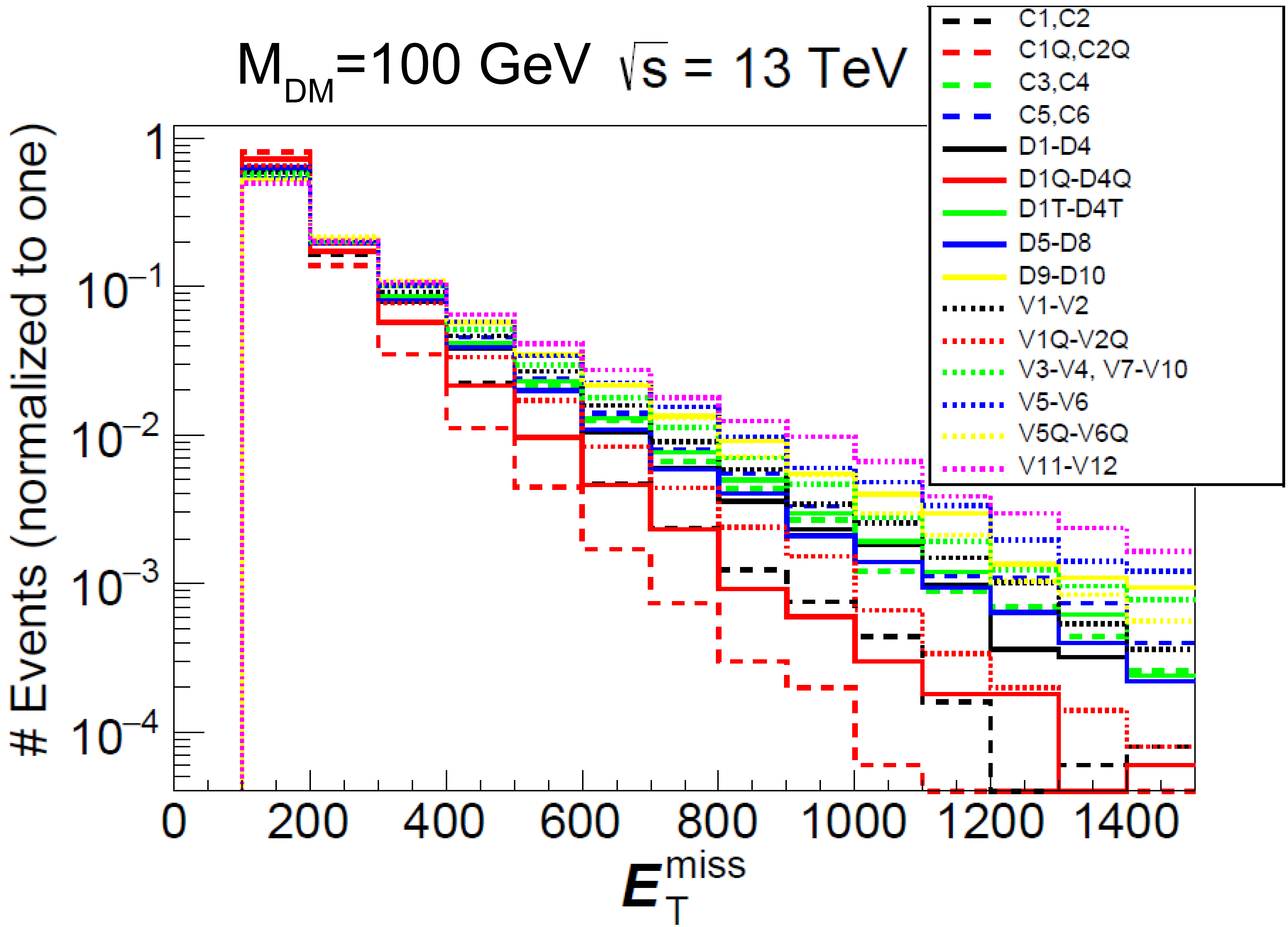
Absolute values of the cross sections provide an additional information to distinguish EFT operators



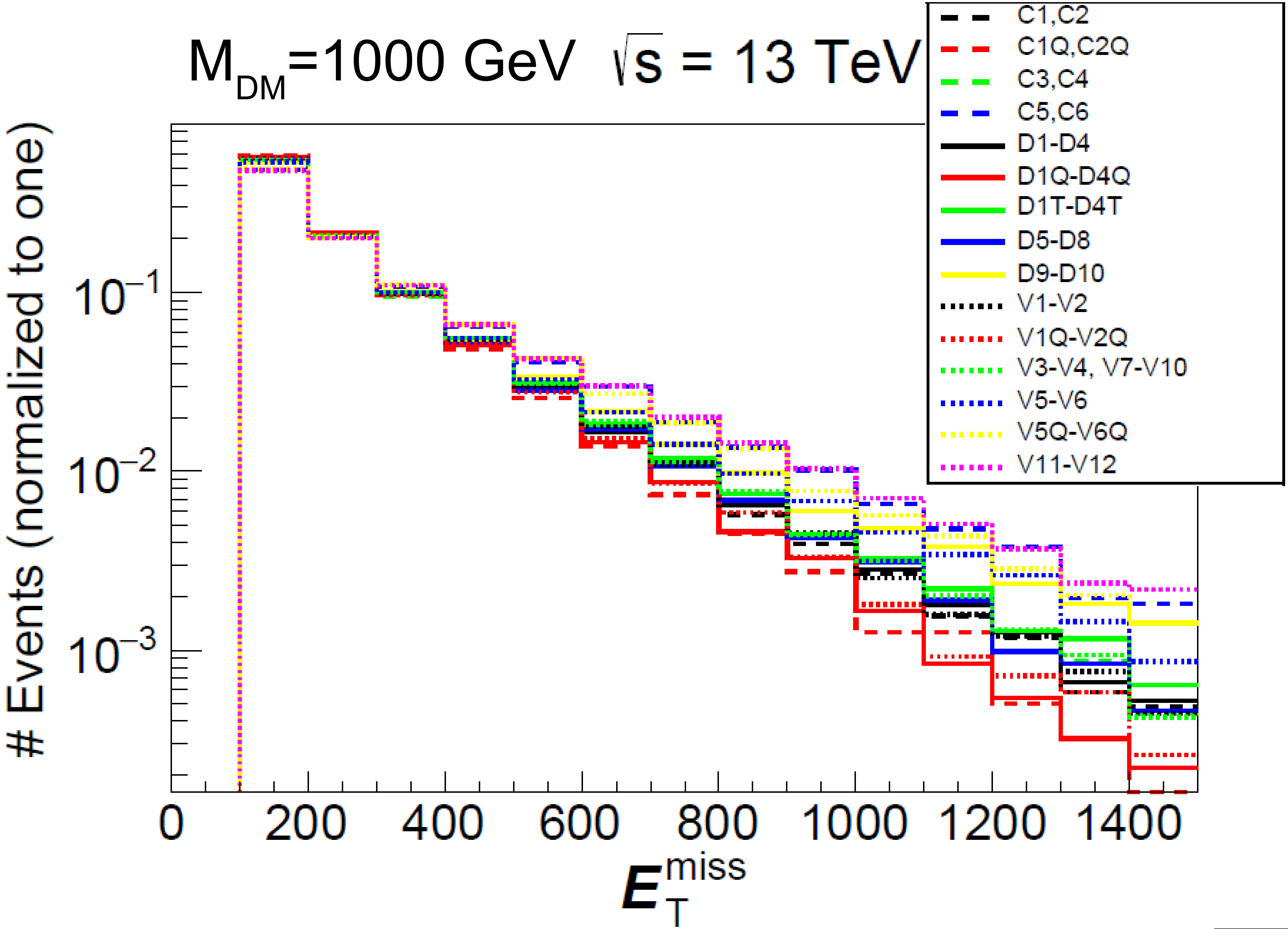
Missing E_T (MET) distributions: the large range of slopes



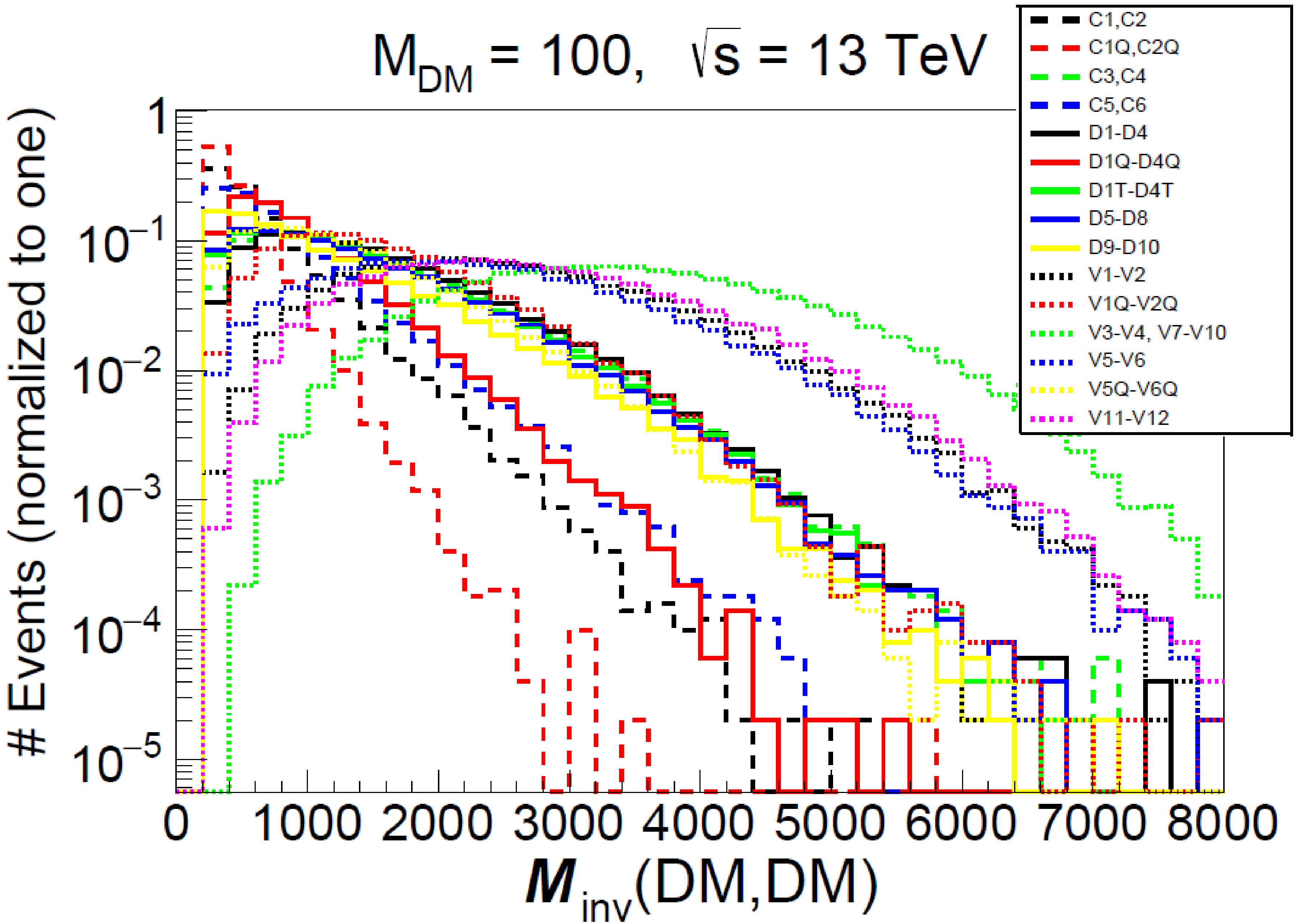
M_{DM} dependence is weak for 10-100 GeV range



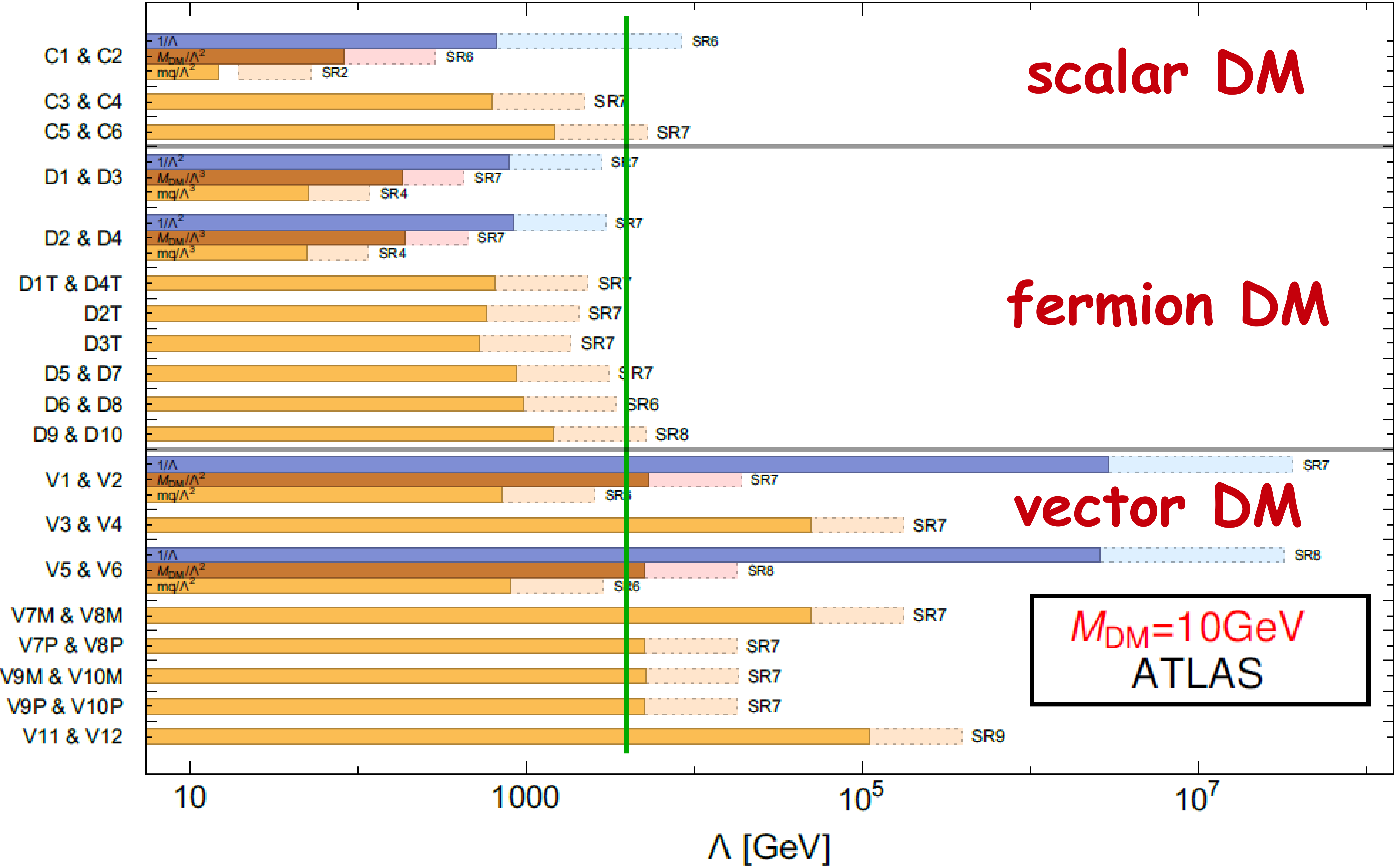
MET shape visibly changes for heavy DM case



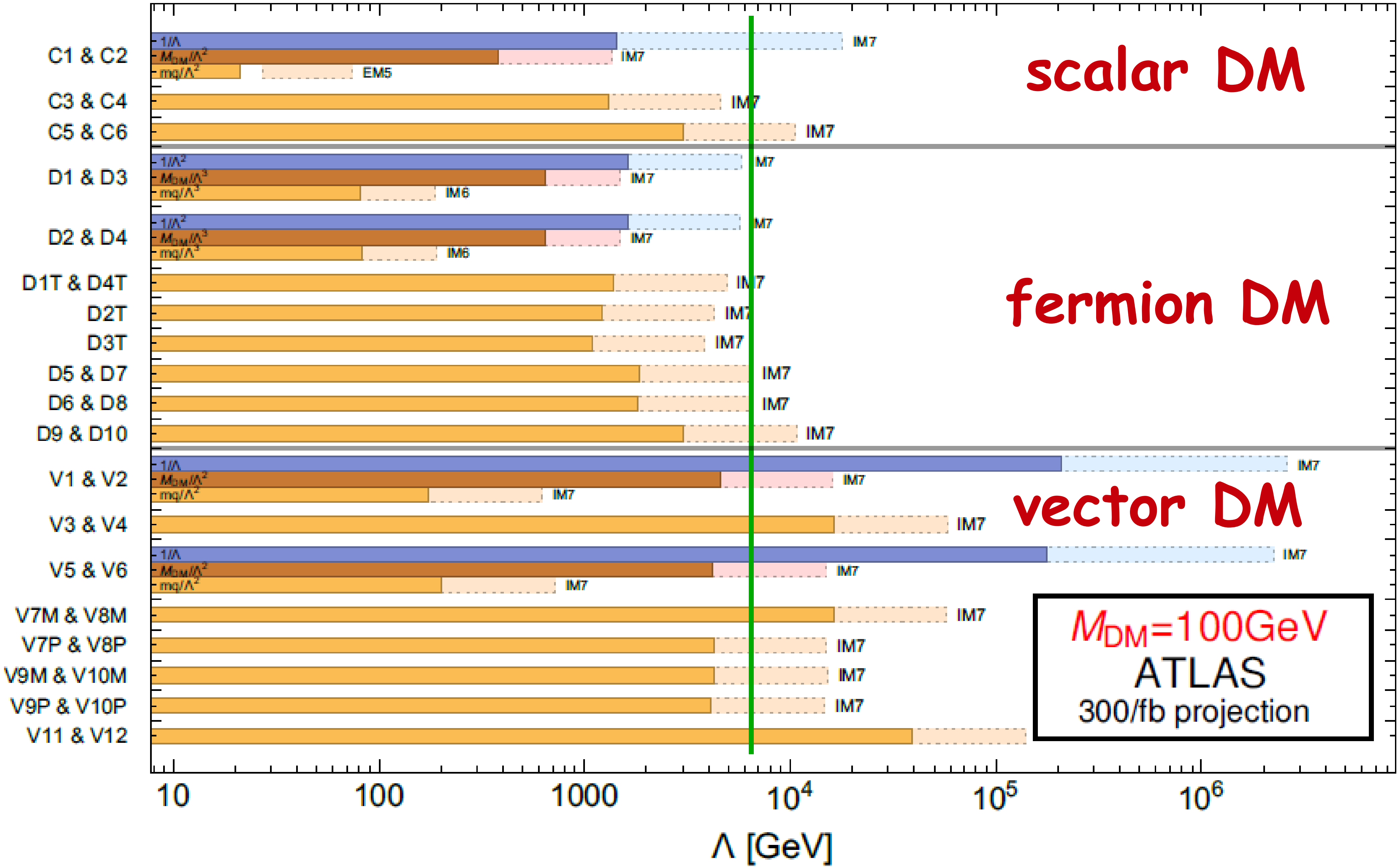
While M(DM,DM) distributions are defined by spin of DM!



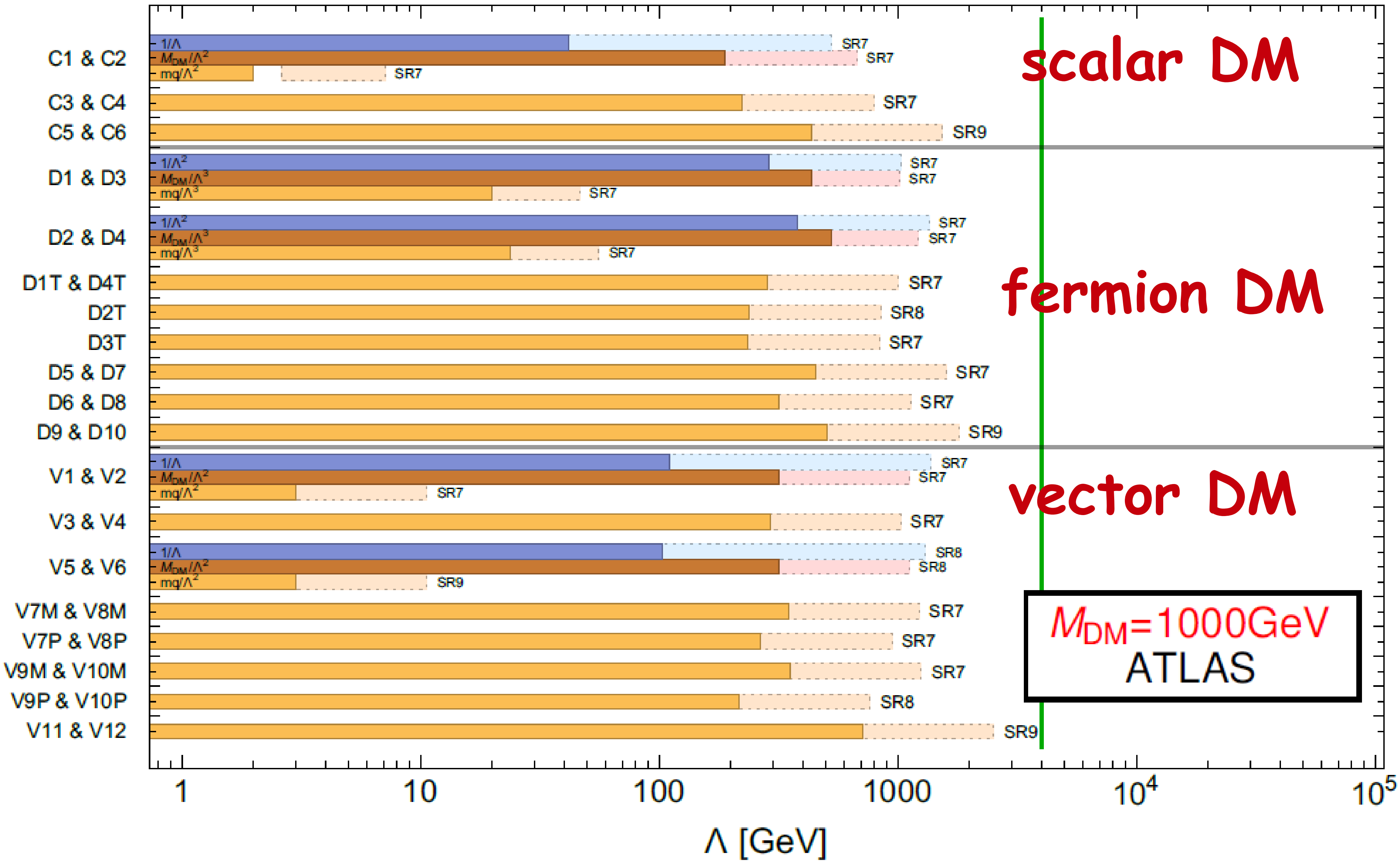
LHC@13TeV reach at 300 fb^{-1}



LHC@13TeV reach at 300 fb^{-1}



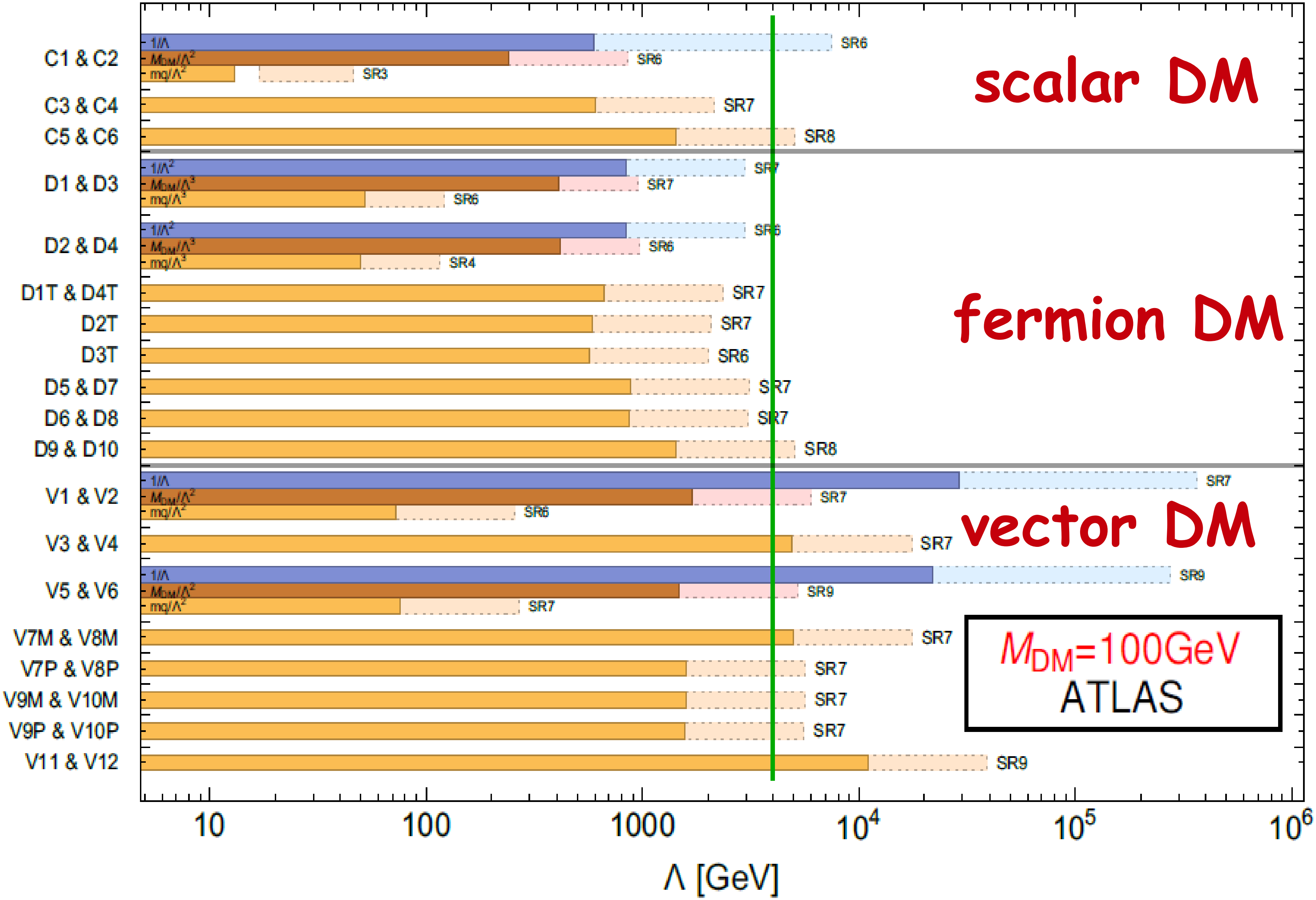
LHC@13TeV reach at 300 fb^{-1}



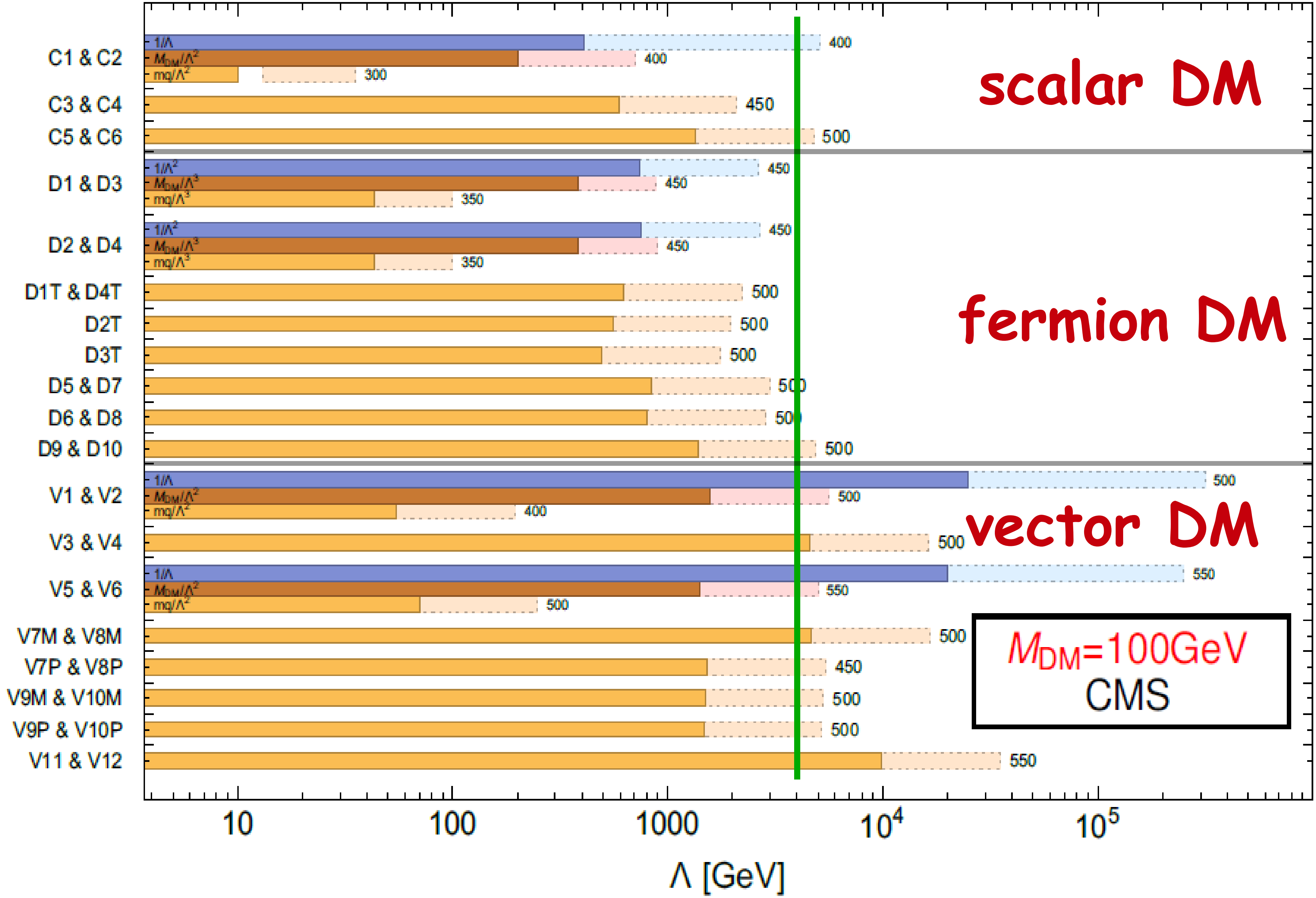
	Operators	Coefficient	Excluded Λ (GeV) at 100 fb^{-1} DM Mass 10 GeV	100 GeV	1000 GeV
Complex Scalar DM	C1 & C2	$1/\Lambda$ m_q/Λ^2	1168 21	1115 20	267 6
	C3 & C4	$1/\Lambda^2$	1134	1131	662
	C5 & C6	$1/\Lambda^2$	2656	2611	1398
Dirac Fermion DM	D1 & D3	$1/\Lambda^2$ m_q/Λ^3	1386 78	1405 77	861 45
	D2 & D4	$1/\Lambda^2$ m_q/Λ^3	1426 78	1399 78	1022 53
	D1T & D4T	$1/\Lambda^2$	1217	1199	780
	D2T	$1/\Lambda^2$	1053	1052	670
	D3T	$1/\Lambda^2$	969	938	644
	D5 & D7	$1/\Lambda^2$	1580	1591	1190
	D6 & D8	$1/\Lambda^2$	1608	1585	955
	D9 & D10	$1/\Lambda^2$	2613	2619	1580
Complex Vector DM	V1 & V2	$1/\Lambda$ m_q/Λ^2	1.57×10^7 1581	156383 156	992 11
	V3 & V4	$1/\Lambda^2$	1.4×10^5	14240	1144
	V5 & V6	$1/\Lambda$ m_q/Λ^2	1.31×10^7 1778	1.34×10^5 176	980 13
	V7M & V8M	$1/\Lambda^2$	1.43×10^5	14223	1276
	V7P & V8P	$1/\Lambda^2$	11734	3660	870
	V9M & V10M	$1/\Lambda^2$	11684	3716	1041
	V9P & V10P	$1/\Lambda^2$	11690	3594	784
	V11 & V11A	$1/\Lambda^2$	3.40×10^5	34210	2833

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

LHC@8TeV


scalar DM
fermion DM
vector DM
C1 & C2
C3 & C4
C5 & C6
D1 & D3
D2 & D4
D1T & D4T
D2T
D3T
D5 & D7
D6 & D8
D9 & D10
V1 & V2
V3 & V4
V5 & V6
V7M & V8M
V7P & V8P
V9M & V10M
V9P & V10P
V11 & V12
SR3
SR4
SR6
SR7
SR8
SR9
M_{DM}=100GeV
ATLAS
10
100
1000
10^4
10^5
10^6
Λ [GeV]

LHC@8TeV



C1 & C2
C3 & C4
C5 & C6
D1 & D3
D2 & D4
D1T & D4T
D2T
D3T
D5 & D7
D6 & D8
D9 & D10
V1 & V2
V3 & V4
V5 & V6
V7M & V8M
V7P & V8P
V9M & V10M
V9P & V10P
V11 & V12
1/Λ
M_{DM}/Λ^2
mq/Λ^2
$1/\Lambda^2$
M_{DM}/Λ^3
mq/Λ^3
400
300
450
500
350
550
scalar DM
fermion DM
vector DM
M_{DM}=100GeV
CMS
10
100
1000
10^4
10^5
Λ [GeV]

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

$$\chi^2 = \sum_{i=EM3,EM4,EM5,EM6,IM7} [(N1_i - \kappa \times N2_i)/\delta BG_i]^2$$

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

			Complex Scalar DM				Dirac Fermion DM		Complex Vector DM										
			10 GeV		100 GeV		10 GeV	100 GeV	10 GeV				100 GeV				1000 GeV		
			C1	C5	C1	C5	D9	D9	V1	V3	V5	V11	V1	V3	V5	V11	V1	V5	V11
Complex Scalar DM	10 GeV	C1	0.0	**33.68**	1.35	**36.36**	**51.38**	**63.44**	**37.57**	**50.0**	**73.55**	**96.47**	**40.08**	**53.15**	**78.9**	**102.08**	**43.68**	**76.83**	**110.91**
		C5	**25.26**	0.0	**17.84**	0.07	1.8	4.56	0.41	1.4	7.29	**15.09**	0.3	1.98	9.25	**17.49**	0.68	8.28	**21.11**
	100 GeV	C1	1.29	**22.62**	0.0	**24.69**	**37.85**	**48.21**	**26.33**	**36.4**	**57.02**	**77.7**	**28.09**	**39.16**	**62.03**	**82.79**	**31.16**	**60.21**	**90.71**
		C5	**27.1**	0.07	**19.36**	0.0	1.51	4.0	0.38	1.04	6.52	**13.97**	0.18	1.59	8.42	**16.3**	0.47	7.5	**19.79**
Dirac Fermion DM	10 GeV	D9	**36.37**	1.7	**28.17**	1.43	0.0	0.86	1.08	0.12	2.1	6.4	0.68	0.05	3.08	8.03	0.46	2.36	**10.54**
	100 GeV	D9	**43.14**	4.13	**34.48**	3.64	0.82	0.0	3.4	1.03	0.3	2.91	2.54	0.63	0.77	3.92	2.32	0.62	5.64
Complex Vector DM	10 GeV	V1	**27.87**	0.41	**20.54**	0.37	1.13	3.71	0.0	0.92	6.13	**12.87**	0.18	1.37	7.72	**15.16**	0.25	6.63	**18.64**
		V3	**35.62**	1.33	**27.27**	0.99	0.12	1.08	0.89	0.0	2.44	7.22	0.45	0.07	3.6	8.94	0.3	2.9	**11.57**
		V5	**48.96**	6.47	**39.92**	5.82	1.98	0.3	5.5	2.28	0.0	1.38	4.44	1.66	0.14	2.06	4.05	0.18	3.32
		V11	**61.93**	**12.92**	**52.45**	**12.03**	5.81	2.75	**11.14**	6.51	1.33	0.0	**9.91**	5.41	0.72	0.1	9.04	0.91	0.5
	100 GeV	V1	**29.4**	0.29	**21.66**	0.17	0.7	2.74	0.17	0.46	4.89	**11.32**	0.0	0.81	6.45	**13.44**	0.13	5.58	**16.66**
		V3	**37.46**	1.86	**29.02**	1.5	0.05	0.65	1.3	0.07	1.76	5.94	0.78	0.0	2.73	7.5	0.57	2.11	**9.91**
		V5	**51.87**	8.11	**42.88**	7.43	2.86	0.74	6.84	3.32	0.14	0.73	5.79	2.55	0.0	1.21	5.31	0.14	2.23
		V11	**64.82**	**14.81**	**55.29**	**13.88**	7.21	3.66	**12.98**	7.97	1.97	0.1	**11.63**	6.76	1.17	0.0	**10.77**	1.54	0.16
	1000 GeV	V1	**31.93**	0.67	**23.95**	0.46	0.48	2.49	0.25	0.3	4.45	**10.3**	0.13	0.59	5.91	**12.4**	0.0	4.87	**15.52**
		V5	**51.03**	7.34	**42.05**	6.68	2.22	0.6	5.94	2.71	0.18	0.94	5.05	1.99	0.14	1.61	4.43	0.0	2.81
		V11	**69.57**	**17.65**	**59.83**	**16.65**	9.34	5.2	**15.75**	**10.18**	3.13	0.49	**14.24**	8.82	2.13	0.16	**13.32**	2.65	0.0