Inert two Higgs Doublet Model (i2HDM) as a consistent scalar DM model

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collaborators:

- G. Cacciapaglia, I. Ivanov, F. Rojas, M. Thomas, AB arXiv:1612.00511
- S.Novaes, M. Gregores, P.Mercadante, S. Quazi, S. Moon, S.Santos,T.Tomei, S. Moretti, M.Tomas, L. Panizzi, AB (pheno-exp/CMS) – final stage

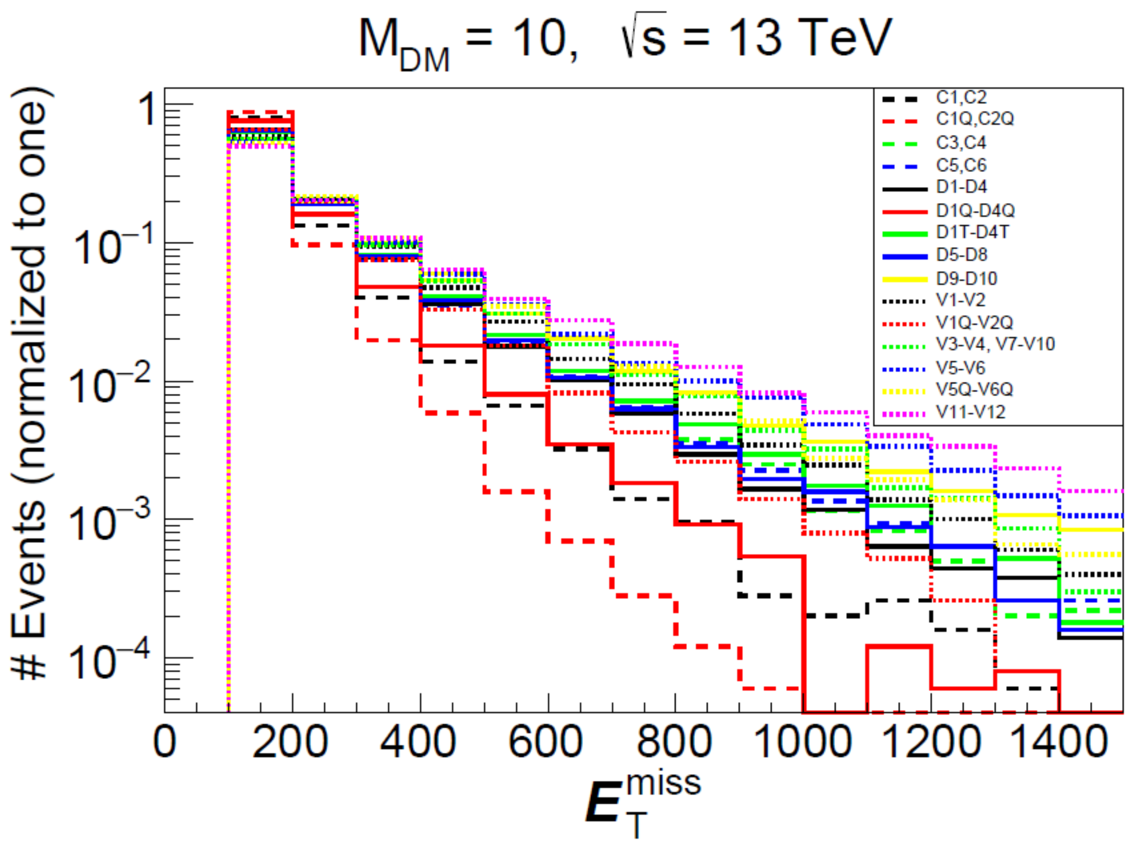
Dec 15, 2016
LHC DM WG Meeting
CERN

Outline

- The i2HDM and it its motivation
- LHC prospects and interplay with non-LHC Dark Matter Searches
- Prospects for the improvement of the high-lumi projections

- Will try also (given 10 mins slot!) to discuss points asked by organisers:
  - "what variants of 2HDMs (or other models) would provide a reasonably generic benchmark model for ATLAS and CMS to use?"
  - "are there urgent reasons to consider other generic, consistent model for the present set of ATLAS and CMS searches?"
  - "what previous work has been done on the above (implementation etc)?"
  - do the above models strongly motivate searches that are not being done
  - what is the collider phenomenology, in particular if a given model provides a mechanism to connect the various DM search channels at the LHC, how general is the mechanism?

The motivation to consider models with different DM spins



L. Panizzi, A. Pukhov, M.Thomas, AB - arXiv:1610.07545

- Different DM spin → different energy dependence of the DM operator, different M_{DMDM} distributions → different slopes of MET
  - potential to characterize DM spin, very 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 some operators from each other; all models are public at HEPMDB, https://hepmdb.soton.ac.uk/ (has got a permanent server status at SOTON)

i2HDM as a well-motivated consistent model

- History:
  - inert two Higgs Doublet Model (IDM, or i2HDM) was introduced at by Deshpande and Ma (1978), about same time as 2HDM
  - resurrected in 2006 by several groups, inspired by DM searches, a lot of papers since then
- **The model**
  - **Scalar lagrangian** $\mathcal{L} = |D_\mu \phi_1|^2 + |D_\mu \phi_2|^2 - V(\phi_1, \phi_2)$

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

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

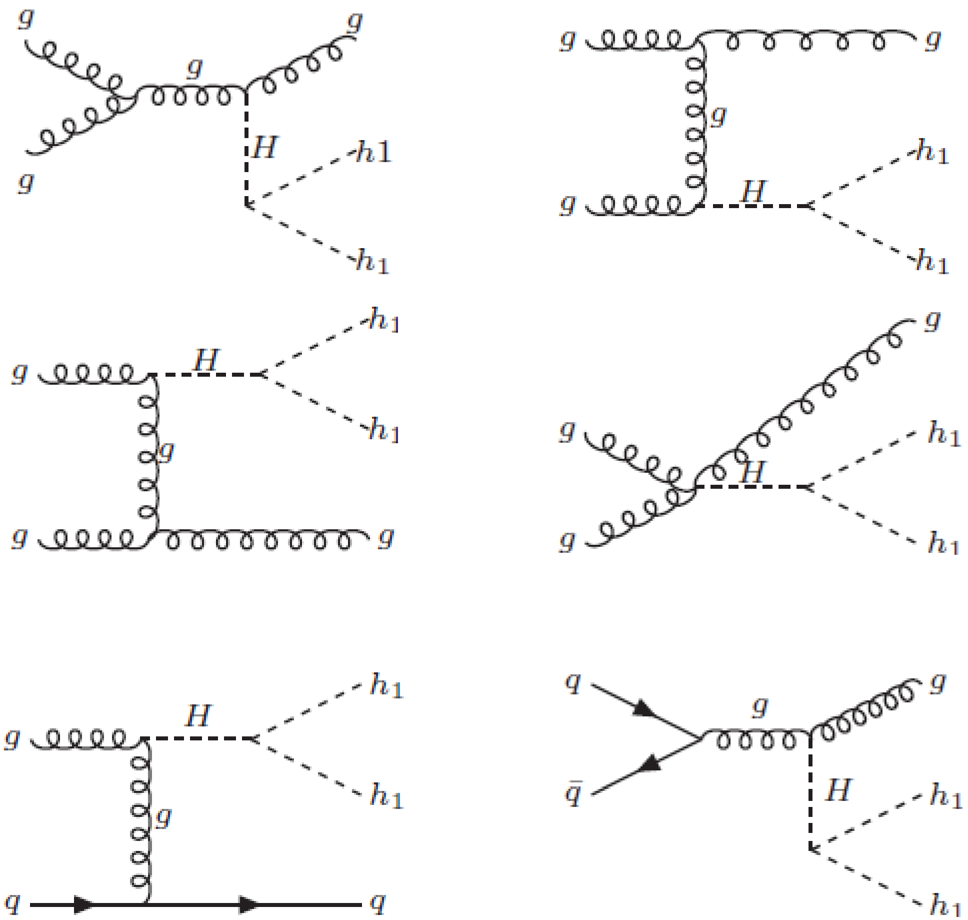
$\langle\phi_i^0\rangle = v_i/\sqrt{2}$: $v_1 = v$ **and** $v_2 = 0$ → **Z_2 symmetry**

  - **New scalars** h_1 , h_2 , h^+ :CP-odd and CP-even neutral Higgses - assignment which is which is ambiguous [involved only in gauge interactions and do not interact with fermions]
  - **5 new parameters:**

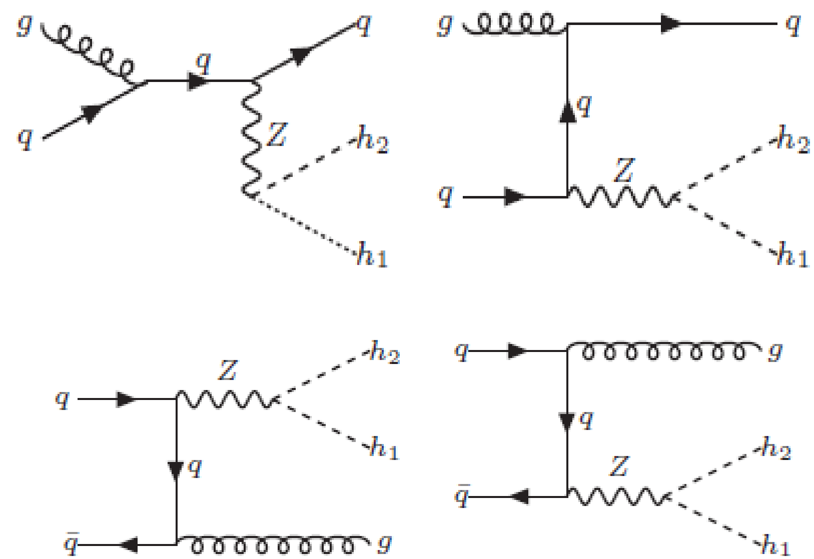
$$M_{h_1}\,, \quad M_{h_2} > M_{h_1}\,, \quad M_{h+} > M_{h_1}\,, \quad \lambda_2 > 0\,, \quad \lambda_{345} > -2\sqrt{\lambda_1\lambda_2}$$

i2HDM as a well-motivated consistent model

- mono-jet signatures
  - $h_1 h_1$ j production



  - $h_1 h_2$ j production

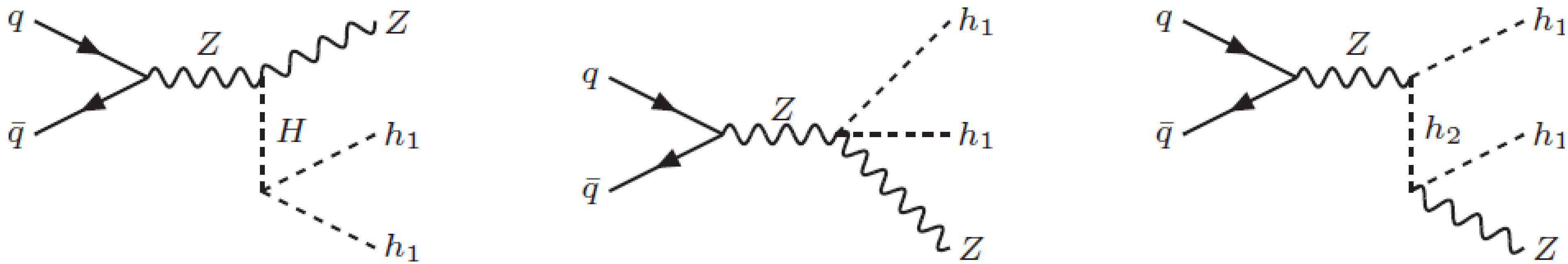


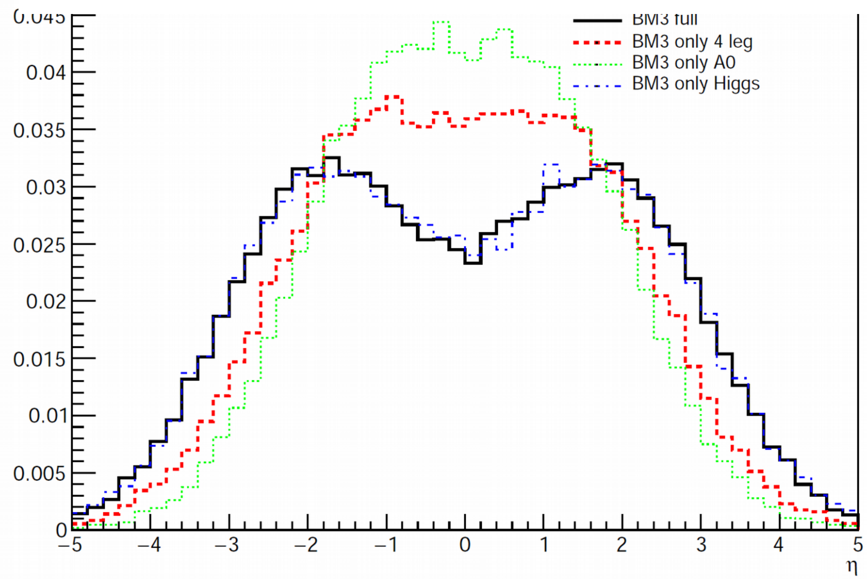
There is no interference between mediators for mono-jet signature: simplified model can be used, BUT

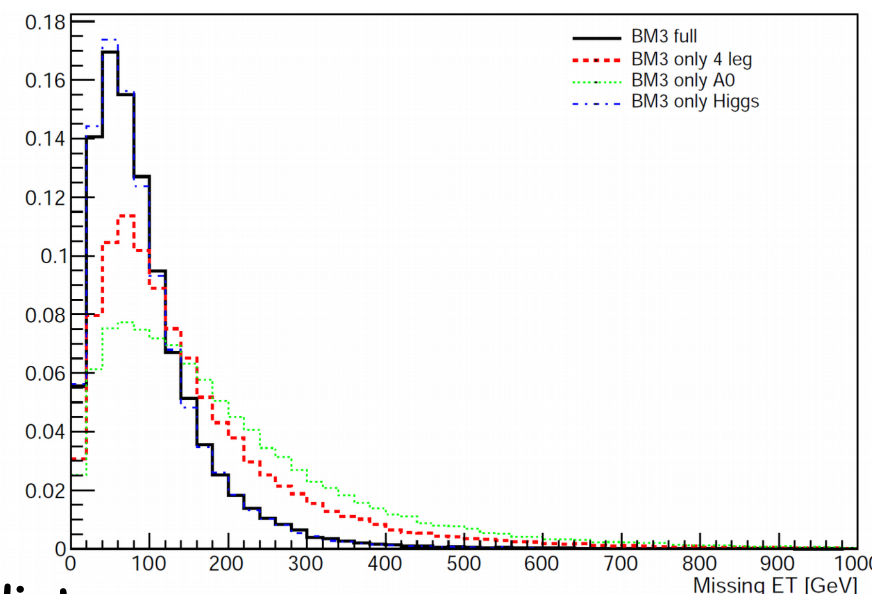
- **Simplified models with spin ½ DM will not describe mono-jet MET shape correctly when mediators are off-shell: scalar DM model should be used!**

i2HDM as a well-motivated consistent model

- mono-Z signature [or leptons+MET, Belanger,Dumont,Goudelis,Herrmann,Kraml,Sengupta; also, Datta, Ganguly,Khan,Rakshit]



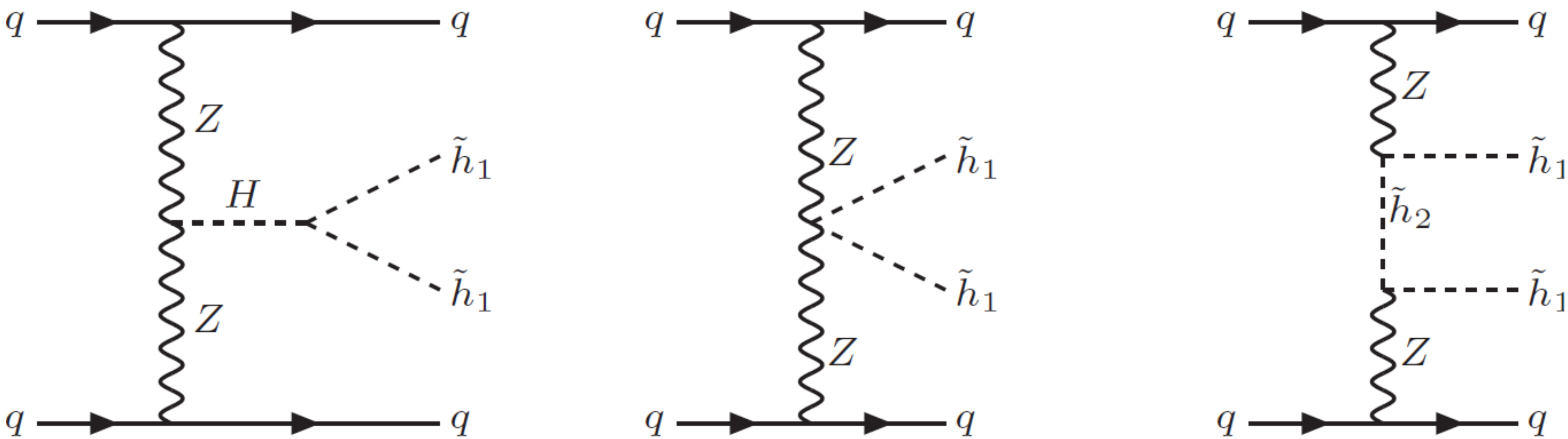




- **non-negligible interference between mediators**
- **quartic ZZh_1h_1 coupling – is not in simplified model**
- **can be a discovery channel (when λ_{345}~0)** [work in progress with P. Schaefers]
- signature is more model-independent and robust then for the models with S-singlet
- **Can not be described by simplified models!**

i2HDM as a well-motivated consistent model

- VBF signature



- **non-negligible interference between mediators**
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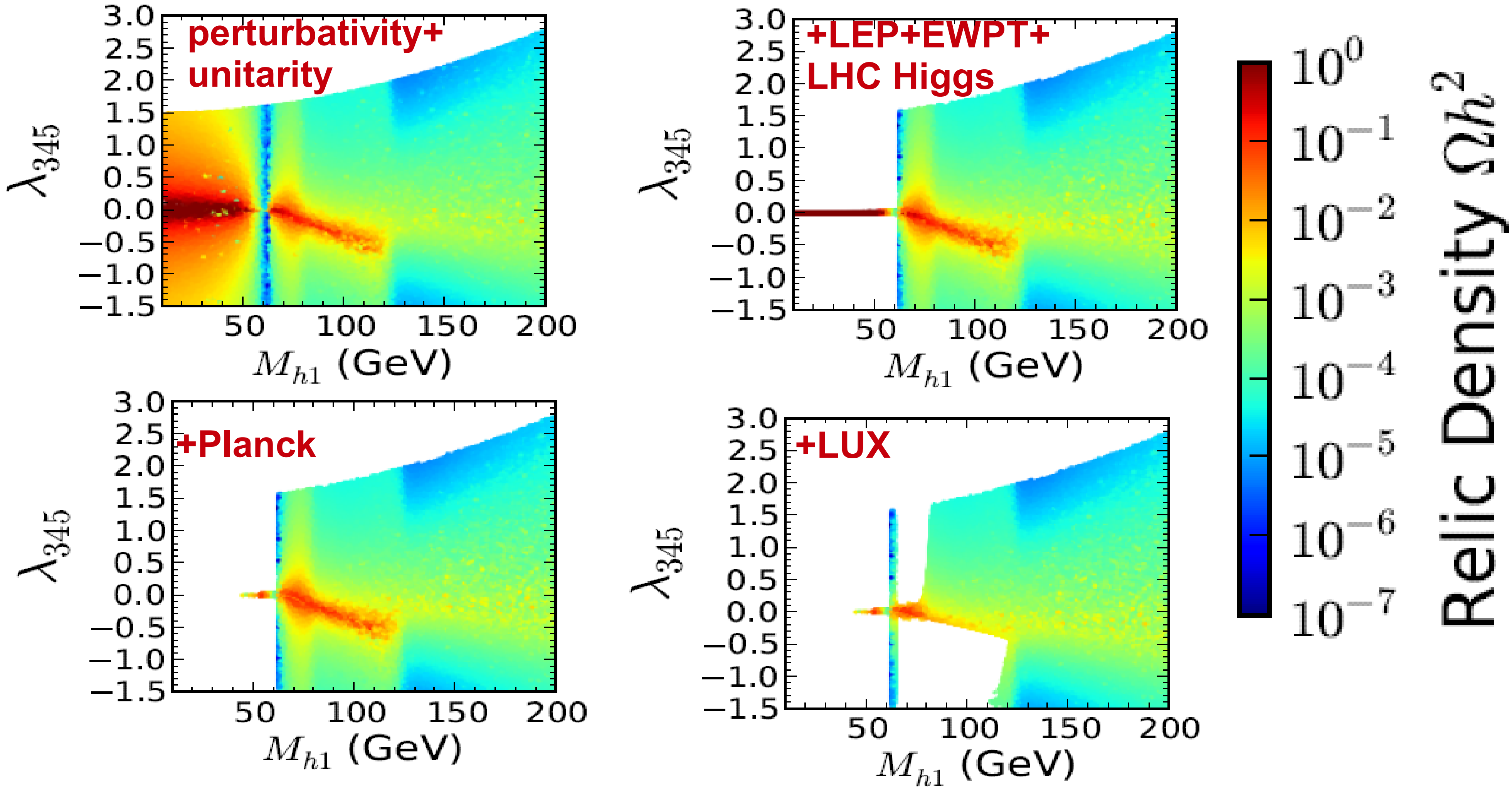
- **can be a discovery channel (when λ_{345}~0)**
- **Can not be described by simplified models!**

i2HDM as a well-motivated consistent model

- **In arXiv:1612.00511 we add**
  - **detailed combined analysis of the i2HDM model in its full 5D parameter space** taking into account perturbativity and unitarity, LEP and EWPT, Higgs data from the LHC, DM relic density, direct/indirect DM detection **complemented by Delphes level LHC mono-jet analysis at the LHC**
  - quantitative exploration of the surviving regions of parameters, including very fine details and qualitatively **new region not seen in previous studies ($h_1 h_2$ co-annihilation, λ_{345}~0)**
  - **A combination of $h_1 h_1$ and $h_1 h_2$ and processes** giving the LHC mono-jet signatures: those with direct DM pair production and those with production of DM and another scalar with a close mass from the inert multiplet
  - **implication of experimental LHC studies on disappearing charged tracks** relevant to high (~ 500 GeV) DM mass region
  - separate, **equally detailed analyses for the assumptions of the DM relic density being fitted to the Planck results or under-abundant**

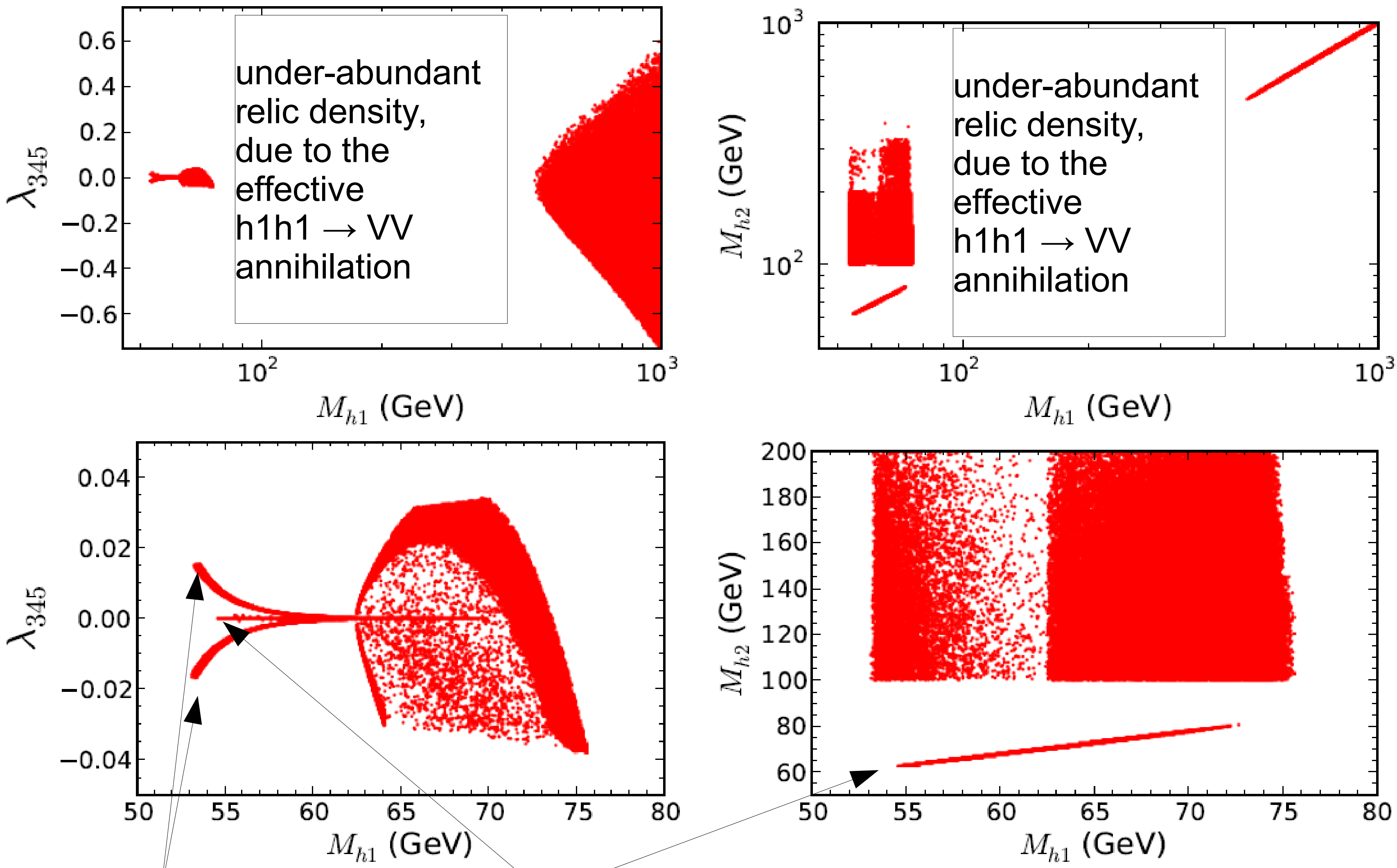
Limiting i2HDM parameter space



M_{h1}<45 GeV is generically excluded,

results agree with those of **Ilnicka,Krawczyk,Robens,1508.01671**

i2HDM space with h_1 contributing 100% to DM budget



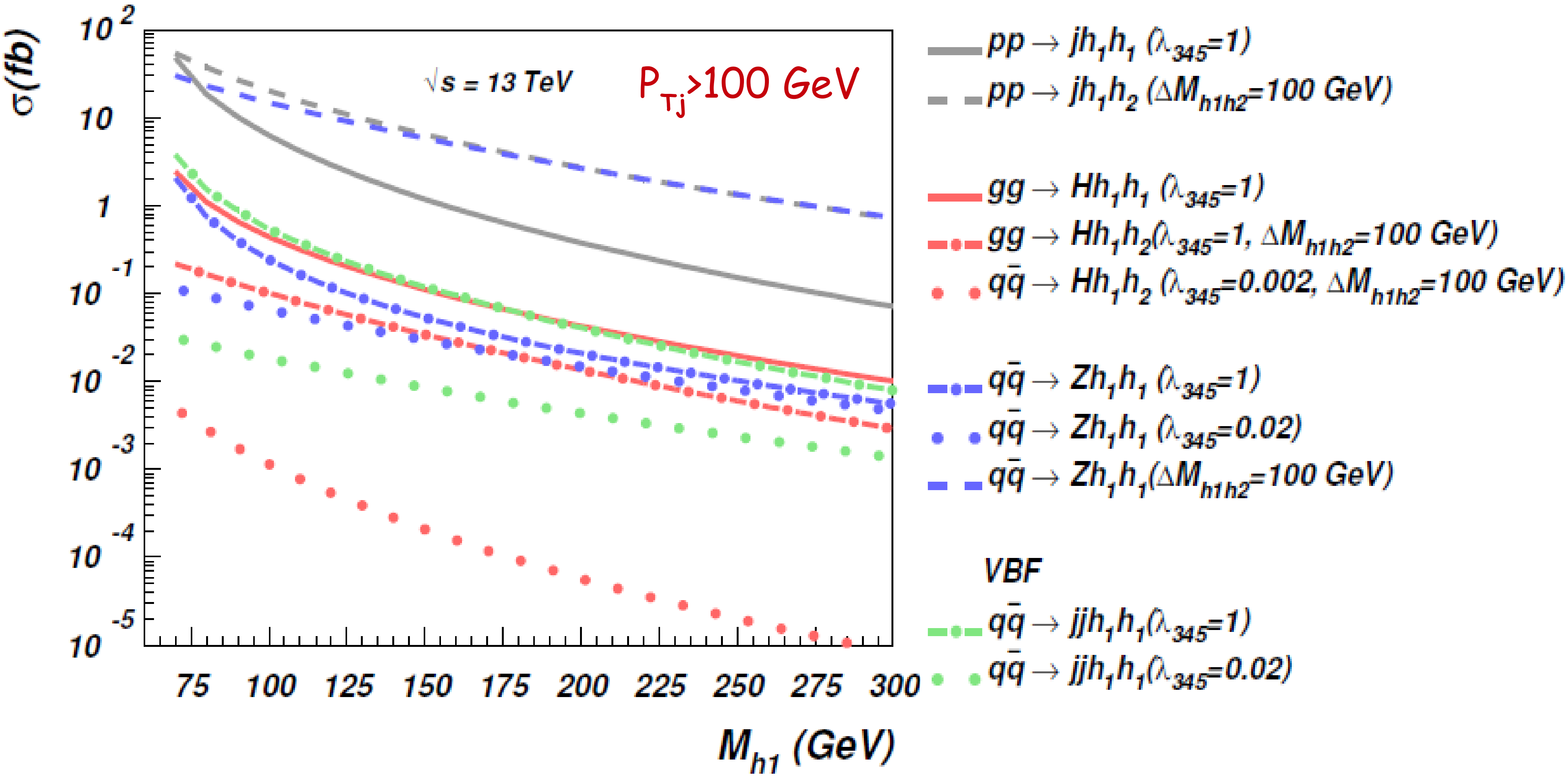
h_1h_1 annihilation enhanced by λ_{345}

h_1h_2 co-annihilation effective even when $\lambda_{345}\sim 0$

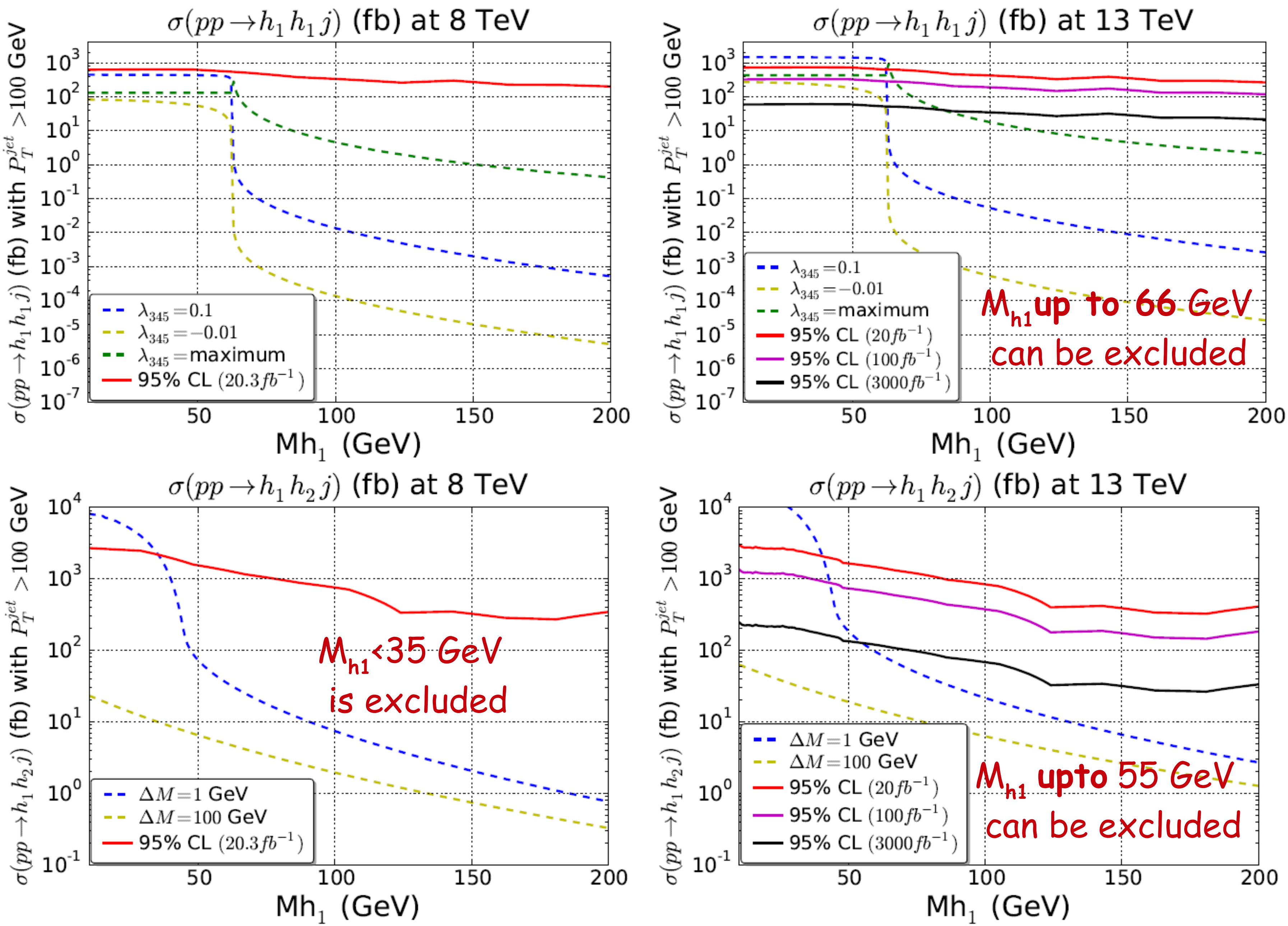
M_{h1}<52 GeV is excluded

Probing i2HDM at the LHC

- Setup: CalcHEP3->PYTHIA8->Delphes3->CheckMATE1,2
- mono-jet signatures

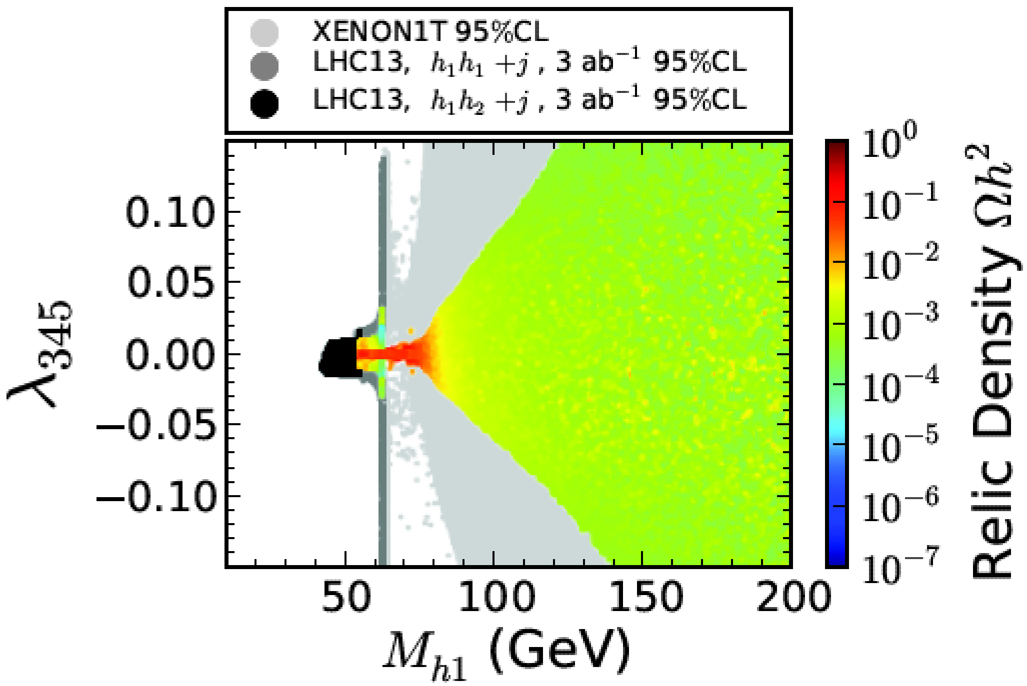


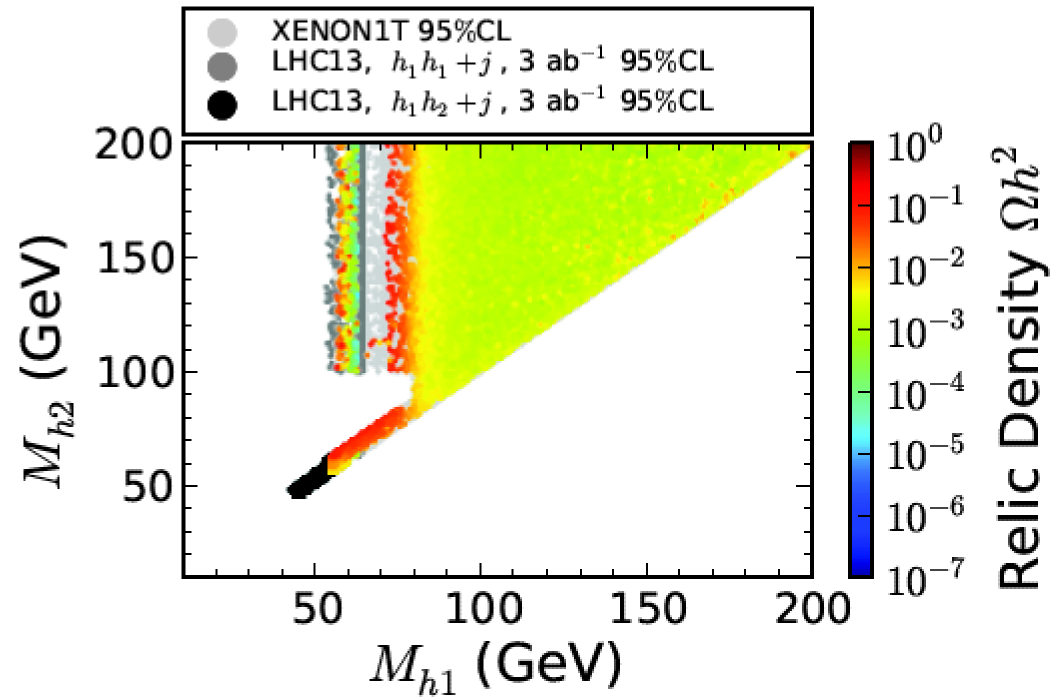
Probing i2HDM at the LHC



No sensitivity at the LHC@8TeV, limited sensitivity at LHC@13TeV

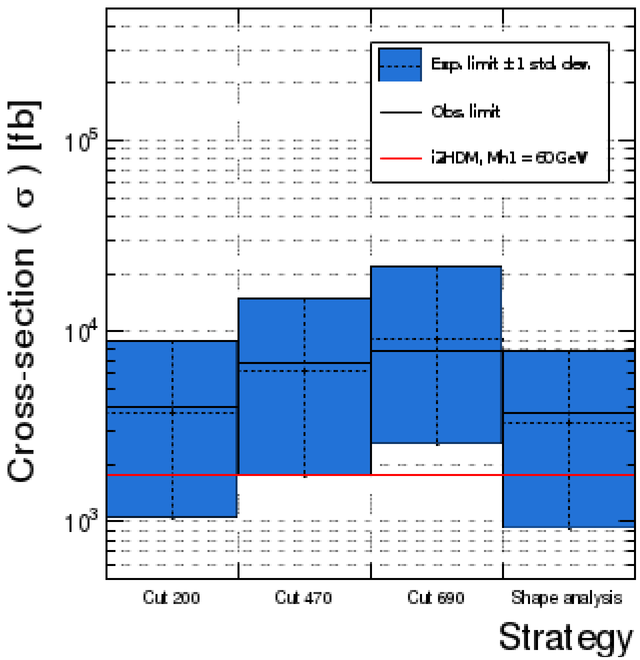
Combining projected limits

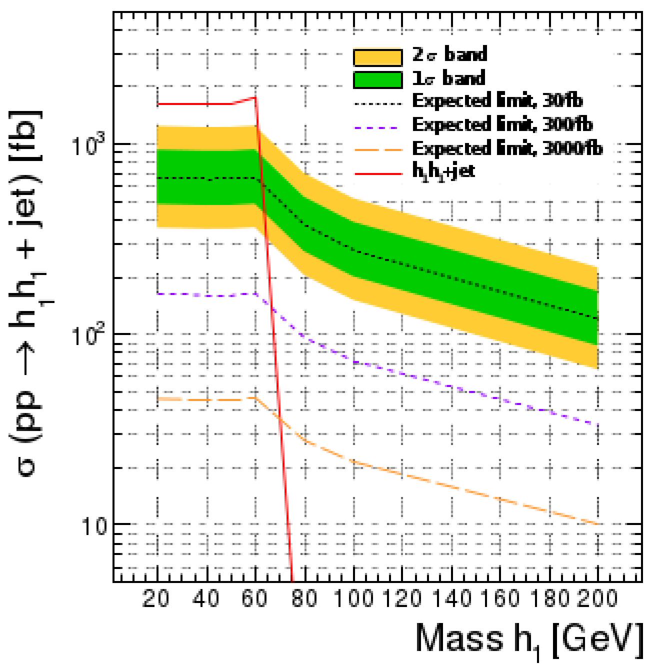




LHC@13TeV will able to cover partly $\mathbf{h_1h_2}$ co-annihilation region at λ_{345}=0, which DM DD experiments will be not able to probe

Prospects for the improvement of the LHC projections





S.Novaes, M. Gregores, P.Mercadante, S. Quazi, S. Moon,
S.Santos,T.Tomei, S. Moretti, M.Tomas, L. Panizzi, AB

- we use the theta package [T. Müller, J. Ott, J. Wagner-Kuhr], to perform the shape-based analysis using CLS method to estimate upper limits on the signal template strength which is then converted to limits in the i2HDM process cross-section.
- Full-fledged shape analysis is shown to be superior to cut-and-count approach, **improving the cut-based limit by about factor of two**
- We extrapolate limit to 30/fb (2016 data!), 300 and 3000/fb
- Work in progress

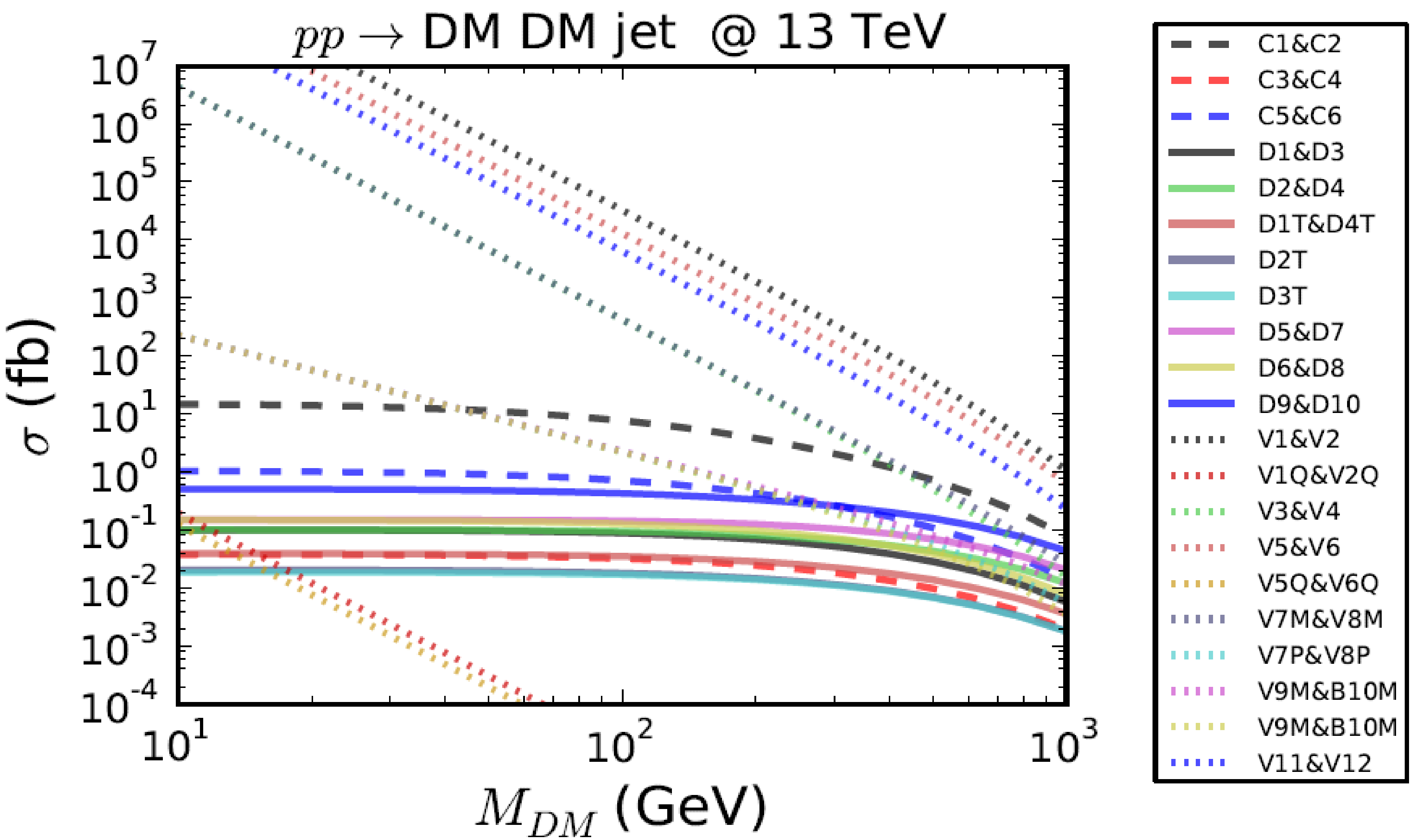
Summary/Discussion

- The i2HDM is well-motivated consistent model
  - can be used to build (or be a part of) a bigger theory
  - Z-boson and H-boson are mediators generic for the whole class of analogous models
  - Very simple → Very predictive: dimension of the parameter space is 5, however for the specific LHC signatures 2-3 parameters are relevant i.e. M_{h1} and λ_{345} (and Mh2)
- The model can not be explored using samples with fermion DM - there is a generic dependence on the spin if mediator is off-shell
- In general, can not be approximated by simplified models
  - mono-Z or VBF signatures ; h1h1VV coupling, interference between
- Mono-jet signature has a limited sensitivity [generic for these class of models] – up to about 70 GeV for M_{h1} even with the improved shape-based analysis
- Disappearing charged tracks probe mass scale up to 500 GeV even with 8TeV
- Mono-Z (or leptons+MET) signatures [quite generic for these class of models] can be a discovery channels (when Hh1h1 coupling is small) (work in progress)
- The model was implemented into CalcHEP & micrOMEGAs
- and is available at HEPMDB (https://hepmdb.soton.ac.uk/ - has got a permanent status at SOTON

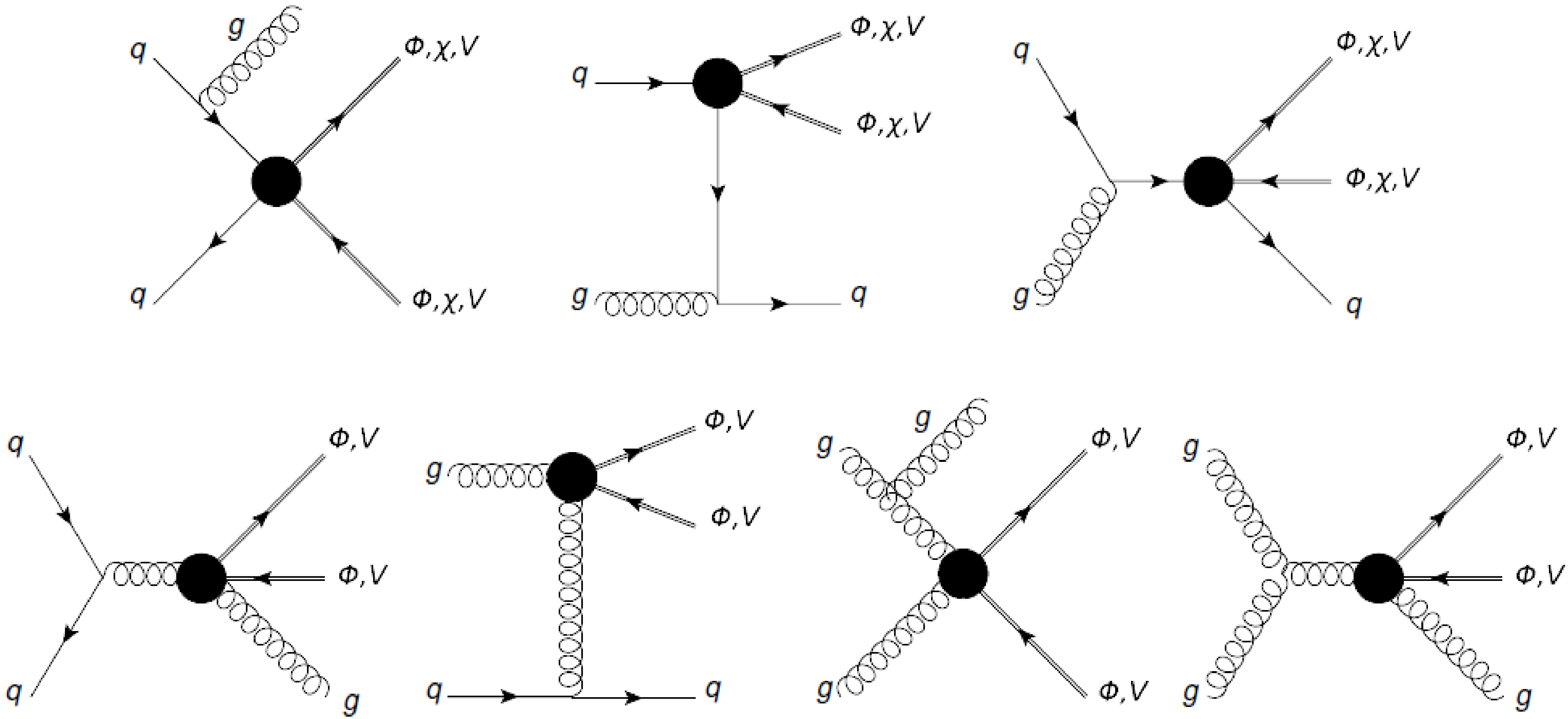
Thank you!

Backup Slides

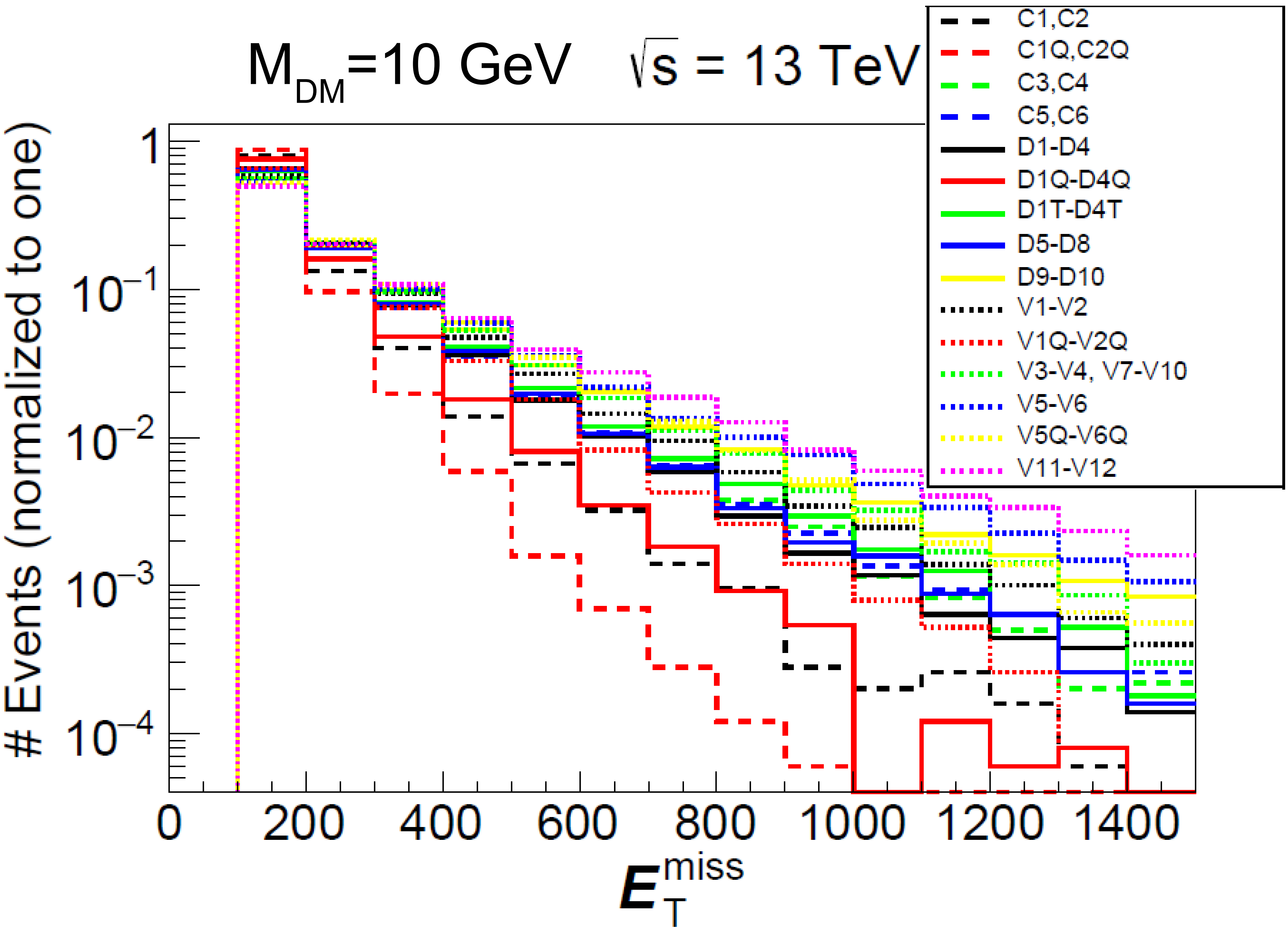
Absolute values of the cross sections provide an additional information to distinguish EFT operators



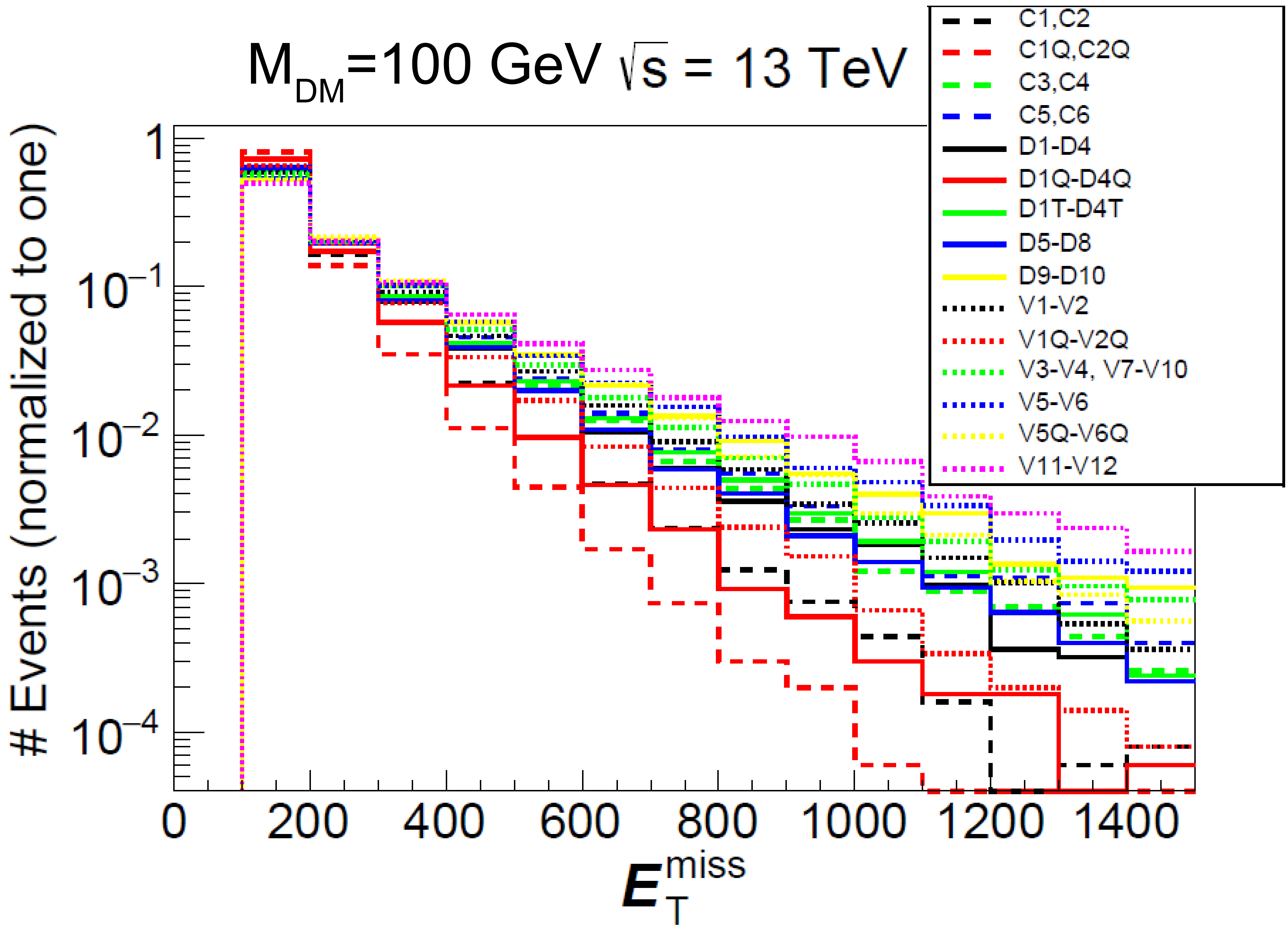
Mono-jet diagrams from EFT operators



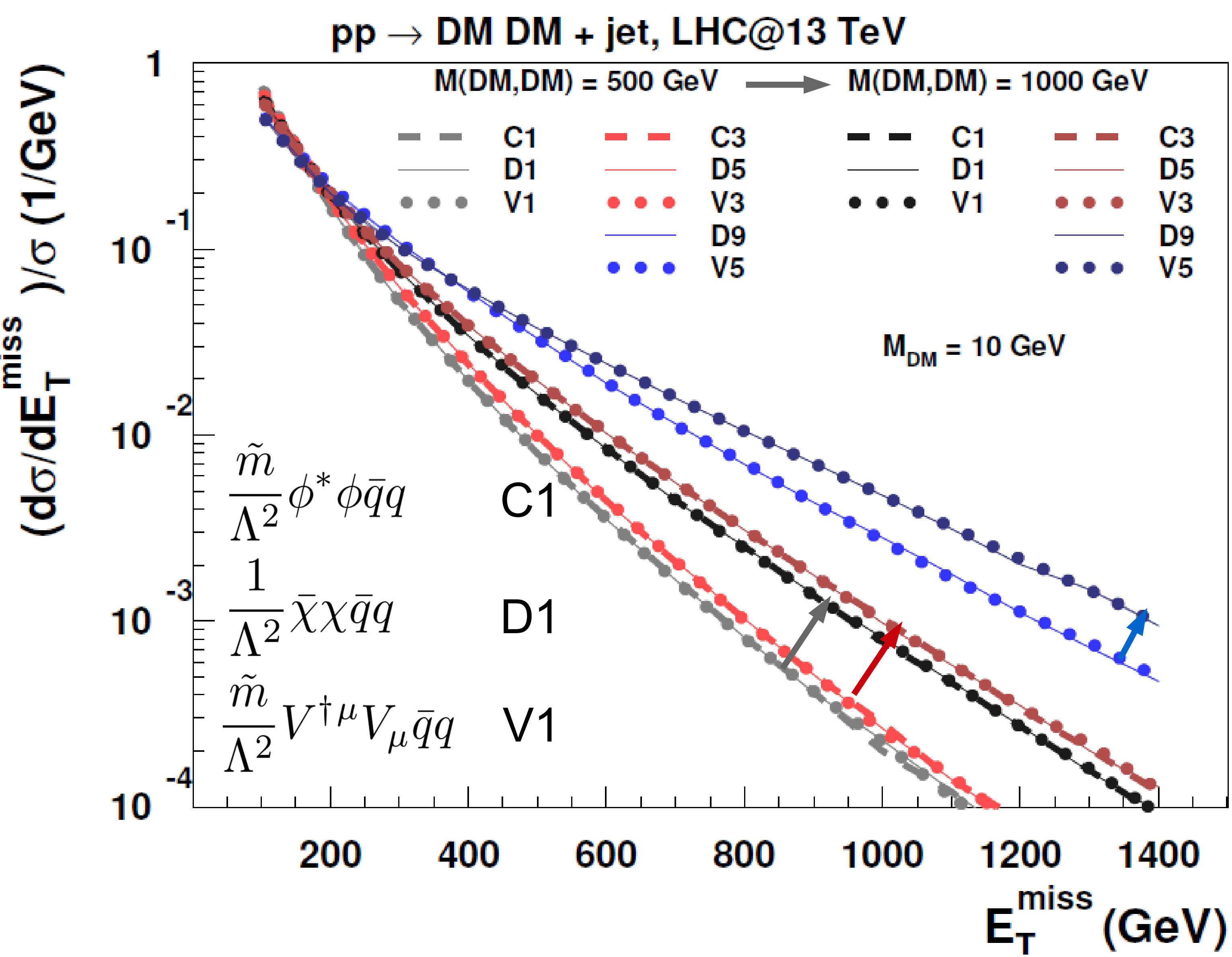
Missing E_T (MET) distributions: the large range of slopes



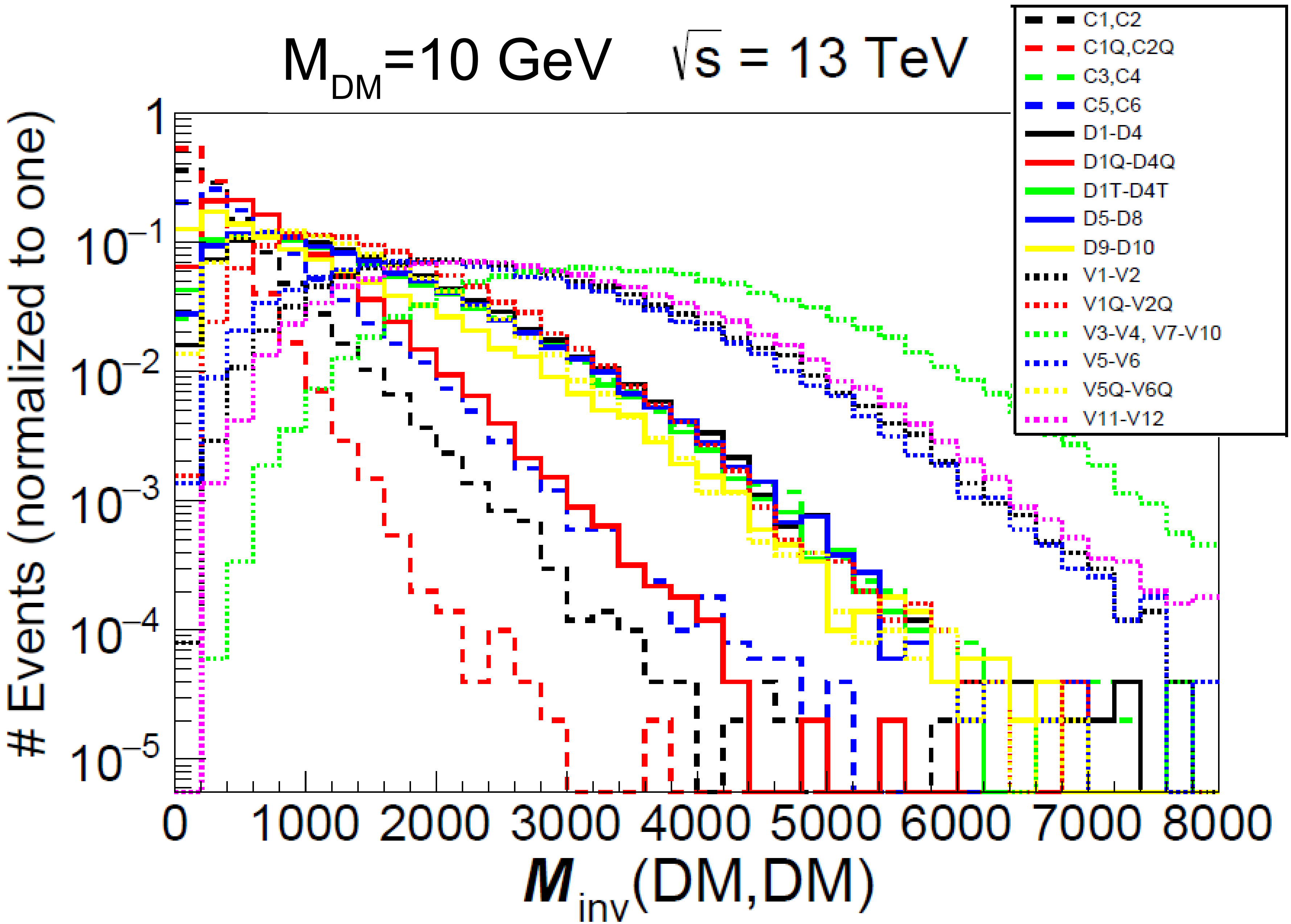
M_{DM} dependence is weak for 10-100 GeV range



- 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

- **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

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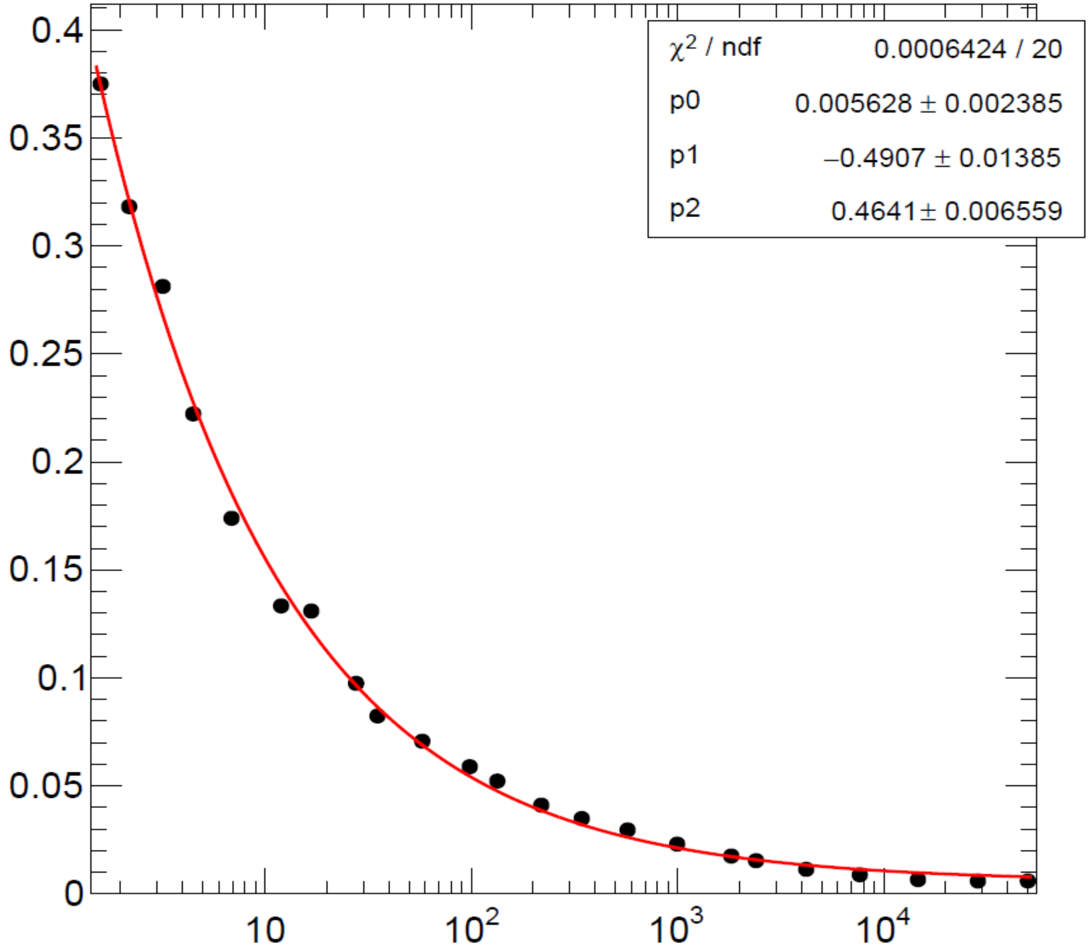
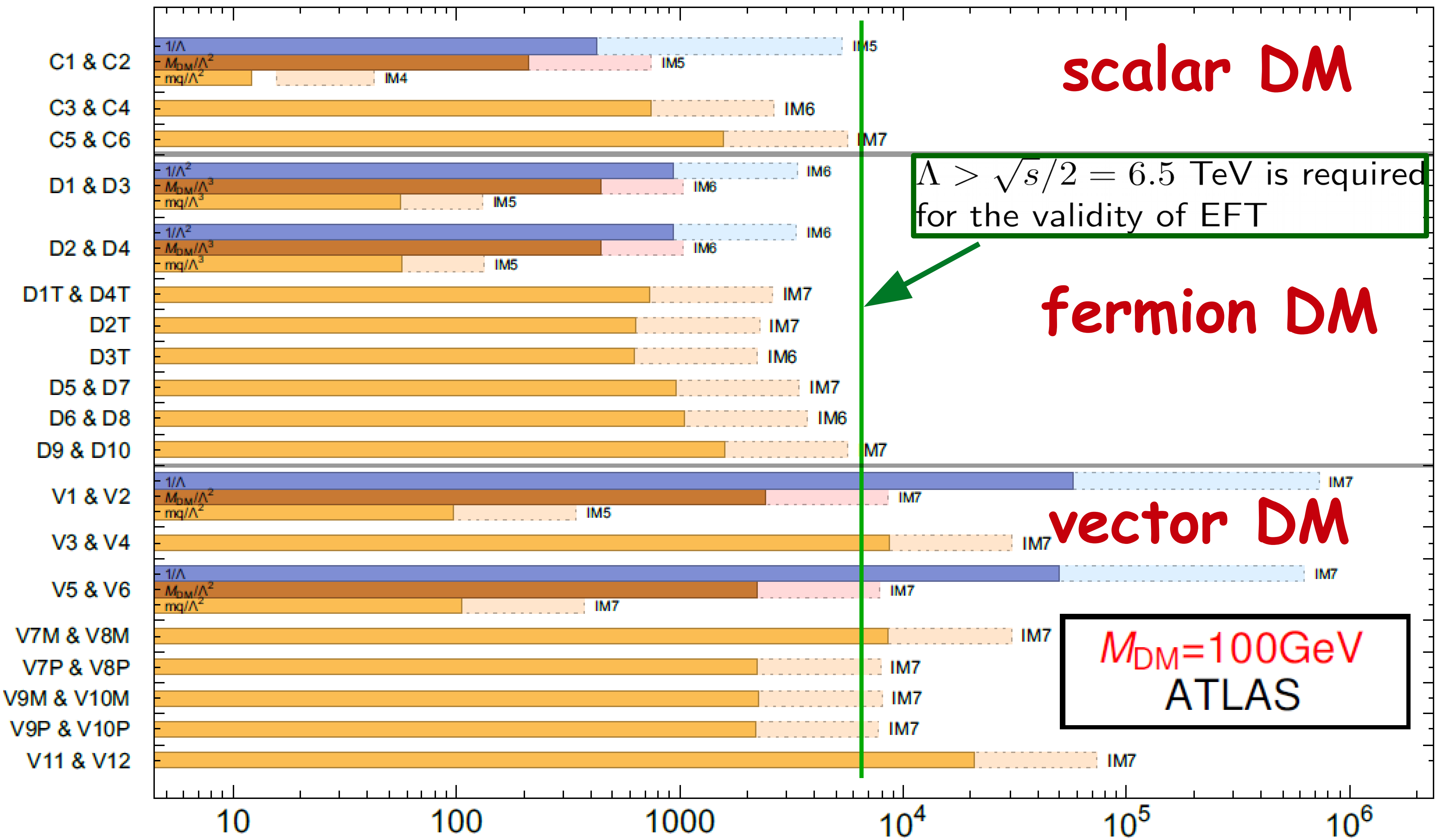
840 – 900	9.5 ± 1.4	2.0 ± 0.3	12.2 ± 0.6	12.0 ± 1.6	13
900 – 960	5.4 ± 1.0	1.1 ± 0.2	7.6 ± 0.3	6.9 ± 1.2	7
960 – 1020	3.3 ± 0.8	0.77 ± 0.21	5.2 ± 0.3	4.5 ± 1.0	3
1020 – 1160	2.5 ± 0.8	0.52 ± 0.16	3.6 ± 0.2	3.2 ± 0.9	1
1160 – 1250	1.7 ± 0.6	0.3 ± 0.11	2.3 ± 0.1	2.2 ± 0.7	2
> 1250	1.4 ± 0.5	0.19 ± 0.08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

On the BG uncertainty



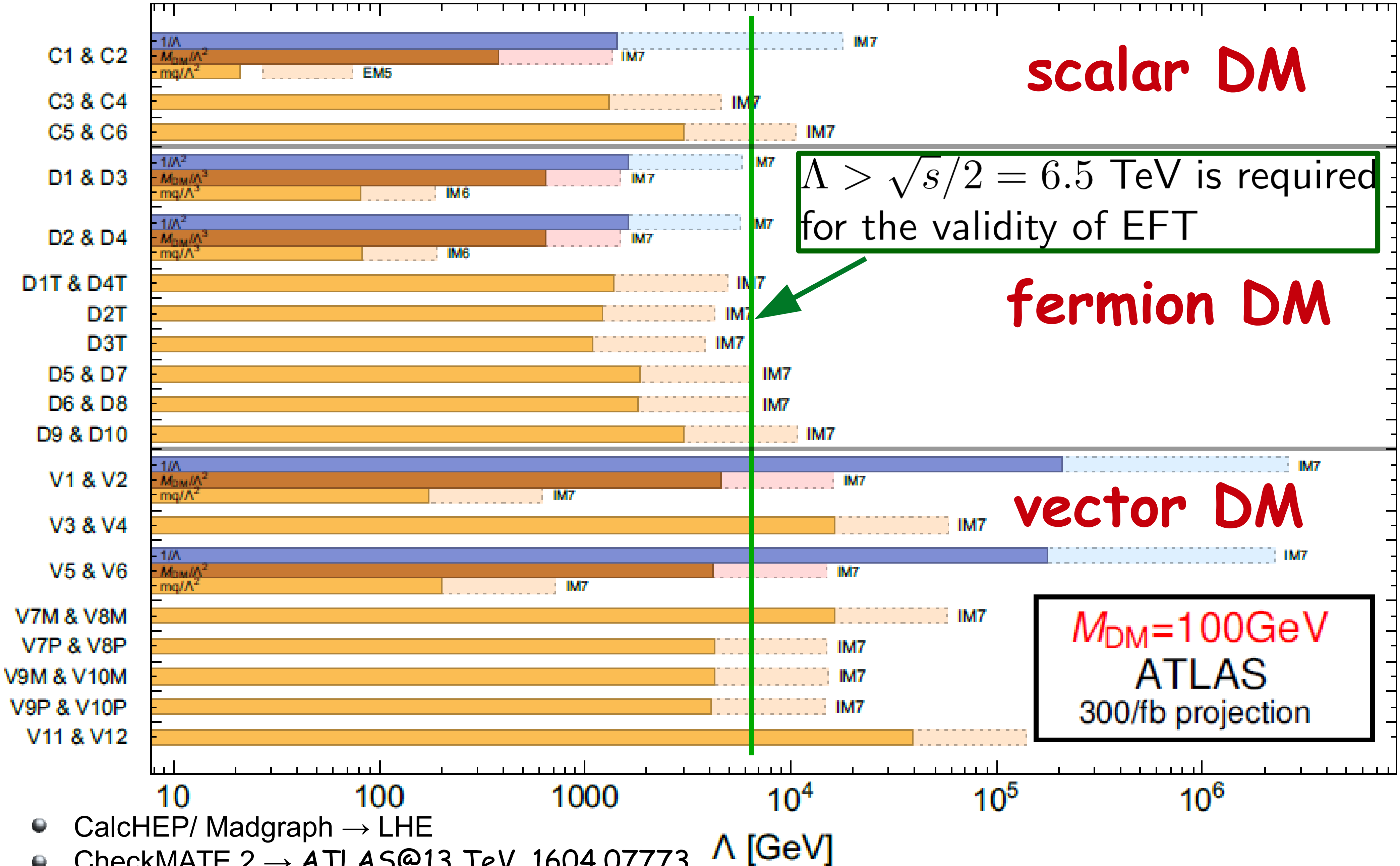
- The BG is statistically driven, e.g. pp-> Zj → ννj BG is defined from the pp → Zj → l^+l^-j one
- For the high enough statistics the BG error can be as low as 1%, but not much lower than this!
- Once ~ 1% δBG is reached (we assume as a floor), the increase of luminosity does not improve LHC sensitivity: 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}



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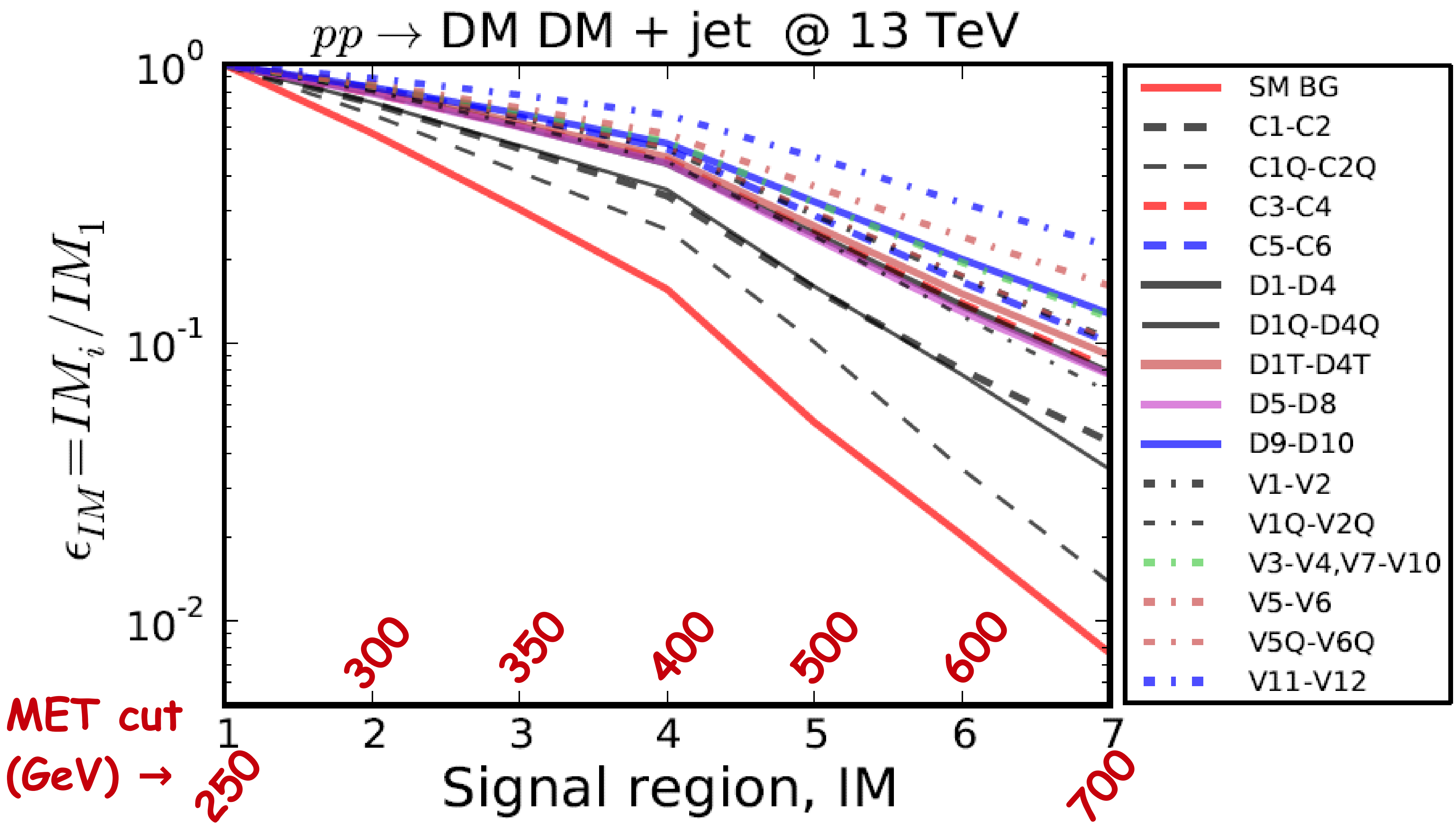
Distinguishing DM operators: different efficiencies (MET slopes) – about factor of 50 spread (in IM7) for different operators and the SM BG



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 10 GeV C1	Complex Scalar DM 10 GeV C5	Complex Scalar DM 100 GeV C1	Complex Scalar DM 100 GeV C5	Dirac Fermion DM 10 GeV D9	Dirac Fermion DM 100 GeV 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

i2HDM benchmarks

BM	1	2	3	4	5	6
M_{h_1} (GeV)	55	55	50	70	100	100
M_{h_2} (GeV)	63	63	150	170	105	105
M_{h_+} (GeV)	150	150	200	200	200	200
λ_{345}	1.0×10^{-4}	0.027	0.015	0.02	1.0	0.002
λ_2	1.0	1.0	1.0	1.0	1.0	1.0
Ωh^2	9.2×10^{-2}	1.5×10^{-2}	9.9×10^{-2}	9.7×10^{-2}	1.3×10^{-4}	1.7×10^{-3}
σ^p_{SI} (pb)	1.7×10^{-14}	1.3×10^{-9}	4.8×10^{-10}	4.3×10^{-10}	5.3×10^{-7}	2.1×10^{-12}
R^{LUX}_{SI}	1.6×10^{-5}	0.19	0.51	0.37	0.48	2.5×10^{-5}
$Br(H \to h_1 h_1)$	5.2×10^{-6}	0.27	0.13	0.0	0.0	0.0
σ_{LHC8} (fb)						
$h_1 h_1 j$	5.44×10^{-3}	288.	134.	6.05×10^{-3}	1.80	7.23×10^{-6}
$h_1 h_2 j$	36.7	36.7	6.48	3.90	6.93	6.93
$h_1 h_1 Z$	6.14×10^{-2}	21.4	30.7	12.2	0.101	2.52×10^{-2}
$h_1 h_1 H$	1.70×10^{-4}	8.98	4.21	2.19×10^{-4}	0.100	3.33×10^{-7}
$h_1 h_2 H$	5.35×10^{-3}	6.31×10^{-3}	9.80×10^{-3}	7.54×10^{-3}	3.86×10^{-2}	5.51×10^{-4}
$h_1 h_1 jj$	2.39×10^{-2}	17.2	8.11	4.44×10^{-2}	0.212	1.62×10^{-2}
σ_{LHC13} (fb)						
$h_1 h_1 j$	1.67×10^{-2}	878.	411.	1.93×10^{-2}	6.25	2.50×10^{-5}
$h_1 h_2 j$	92.4	92.4	17.8	11.1	19.1	19.1
$h_1 h_1 Z$	0.153	46.2	66.9	28.3	0.241	6.47×10^{-2}
$h_1 h_1 H$	6.69×10^{-4}	35.3	16.5	9.08×10^{-4}	0.441	1.51×10^{-6}
$h_1 h_2 H$	1.18×10^{-2}	1.40×10^{-2}	2.47×10^{-2}	1.99×10^{-2}	9.82×10^{-2}	1.34×10^{-3}
$h_1 h_1 jj$	0.101	62.7	29.6	0.189	0.904	7.49×10^{-2}