Towards Decoding the Nature of Dark Matter at the LHC

Alexander Belyaev

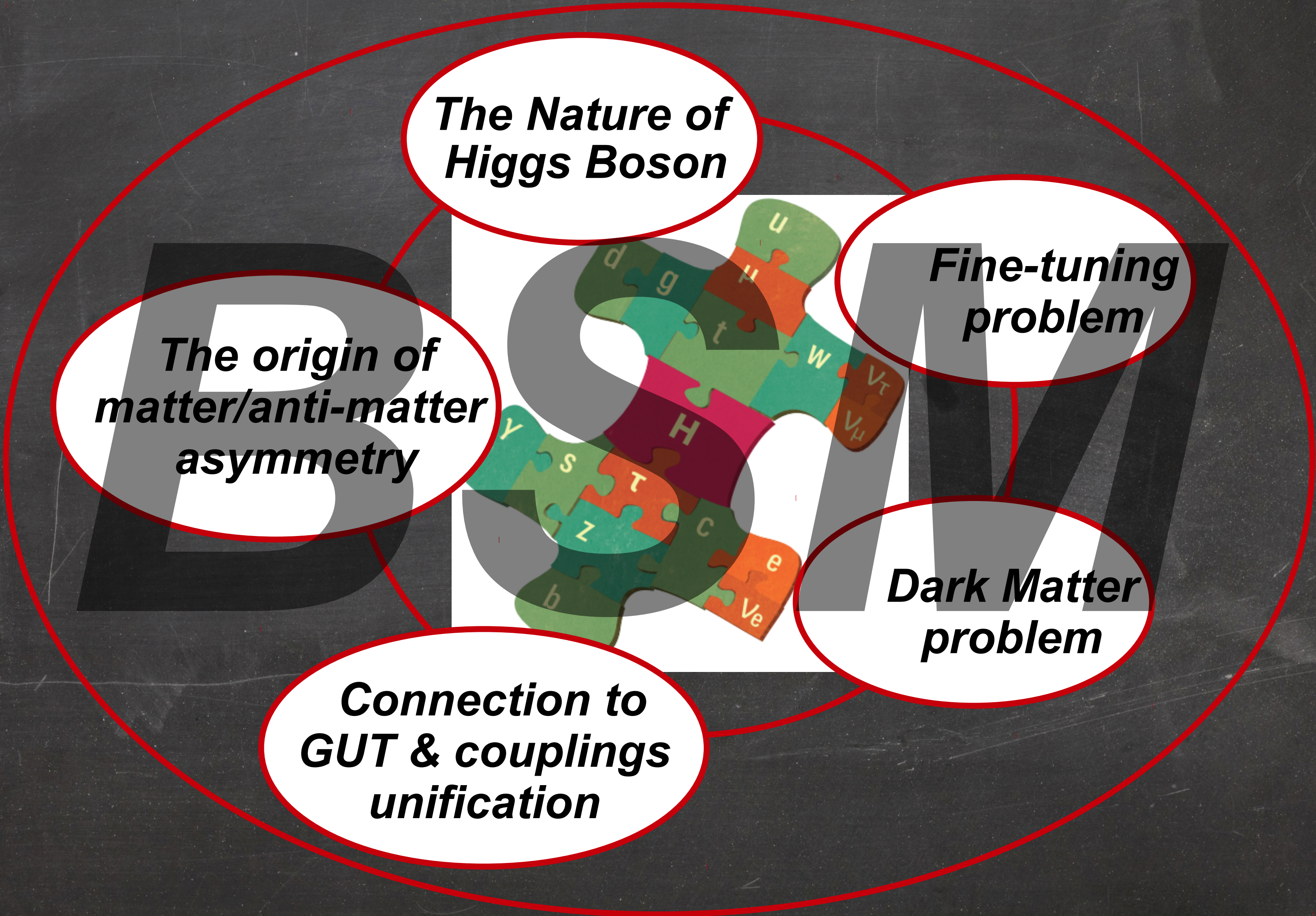
Southampton University & Rutherford Appleton Laboratory

NExT Physics meeting
RHUL
1st of November 2017

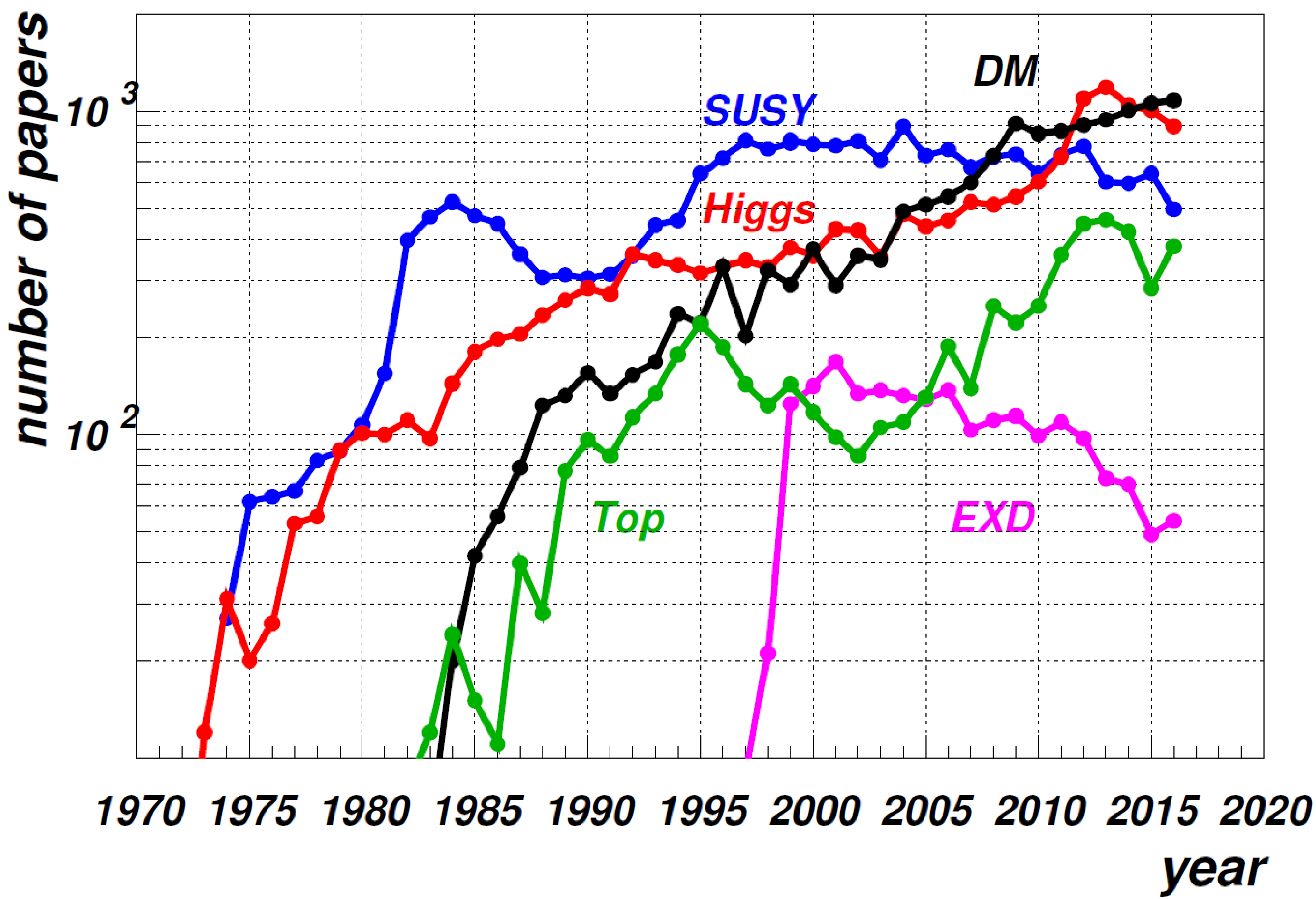
Collaborators & Projects

- L. Panizzi, A. Pukhov, M.Thomas, AB – arXiv:**1610.07545**
- D. Barducci, A.Bharucha, W. Porod, V. Sanz, AB – arXiv:**1504.02472**
- 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) – follow up arXiv:1612.00511
- M.Brede, D. Locke, L.Panizzi, M.Thomas, AB – follow up 1610.07545
- E.Bertuzzo, C.Caniu, O.Eboli, G. di Cortona, AB – follow up1610.07545
- T. Flacke, B. Jain, P. Schaefers, AB – DM from Z' and Top partners, arXiv:**1707.07000**
- I. Shapiro, M. Thomas, AB – Torsion DM, arXiv:**1611.03651**
- I. Ginzburg, D.Locke, A. Freegard, T. Hosken, AB – distinguishing DM spin at the ILC

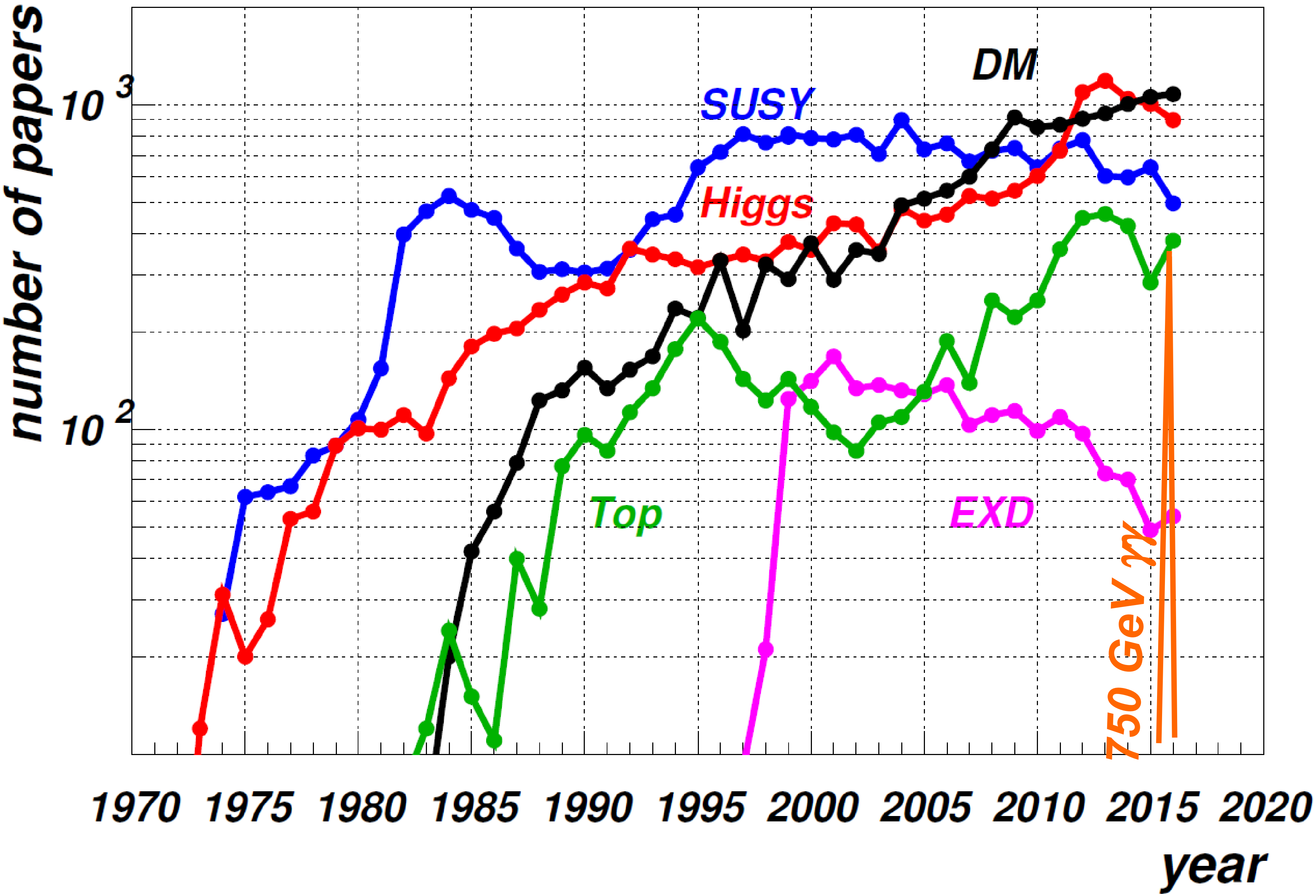
While Higgs Boson Discovery has completed the SM, the SM itself can be viewed itself as a piece of a bigger puzzle since SM is theoretically and empirically incomplete



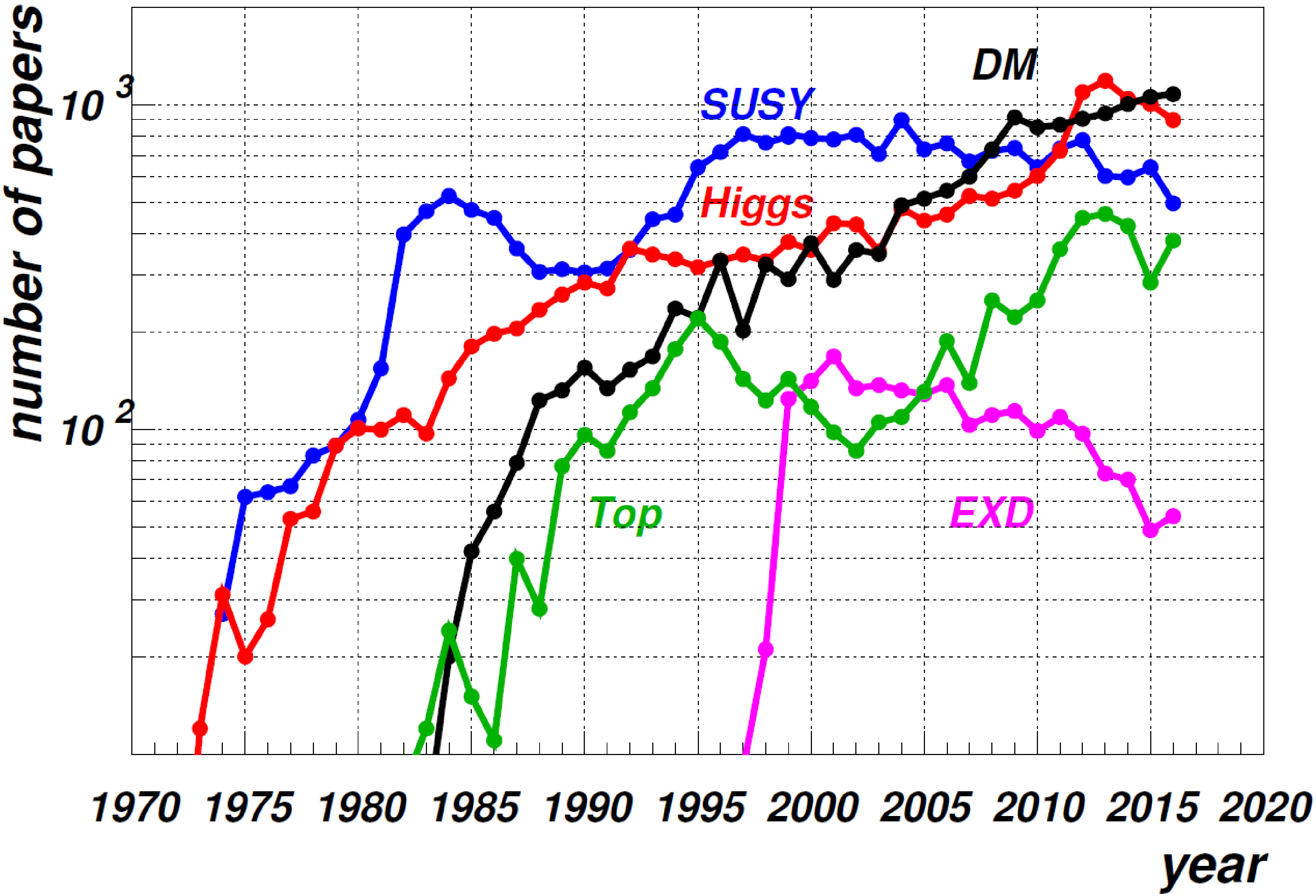
Why we are so keen to study DM?



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, even though we know almost nothing about it!

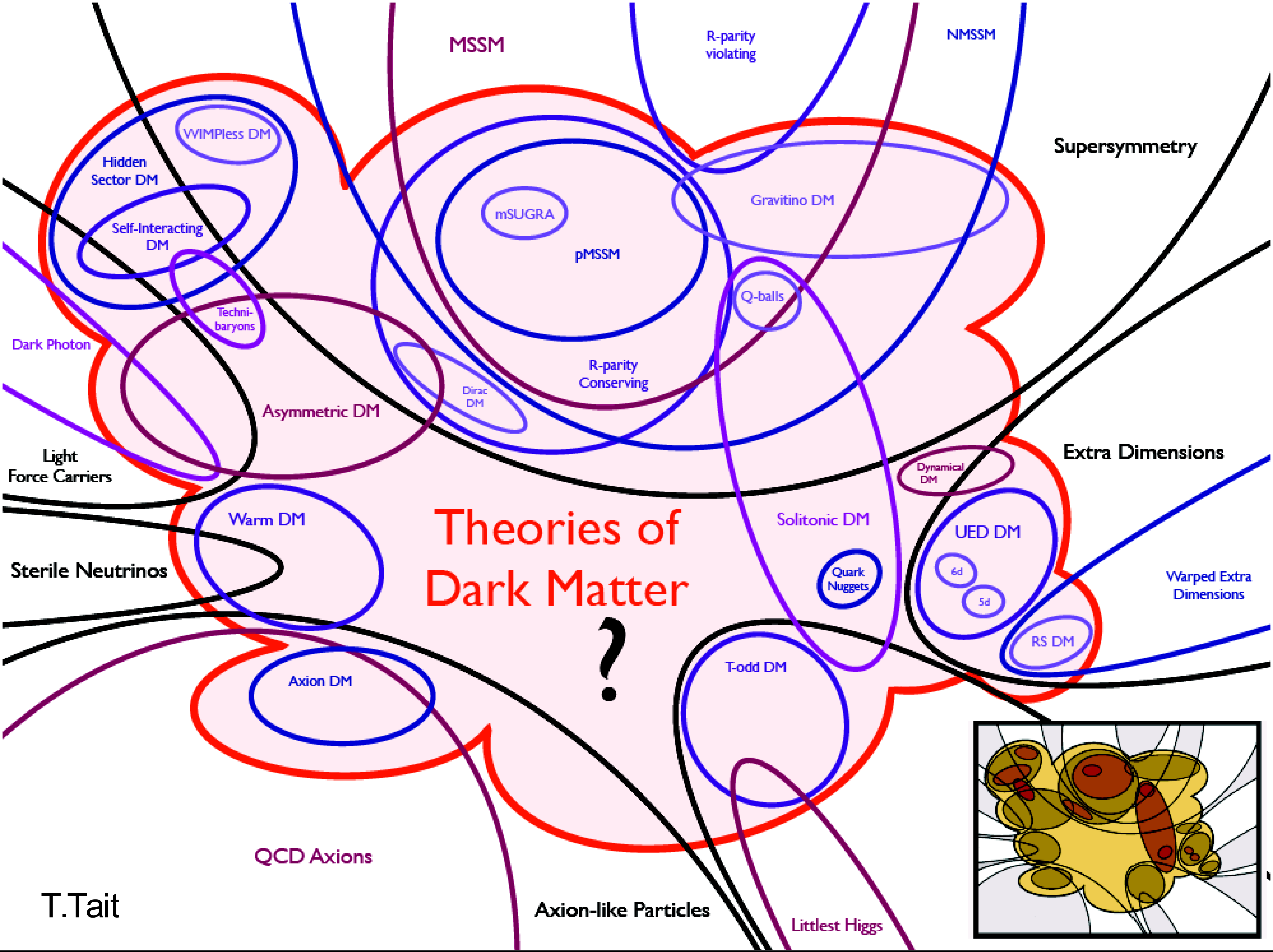
Spin ?

Mass ?

Stable
Yes ? No ?
symmetry behind stability ?

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

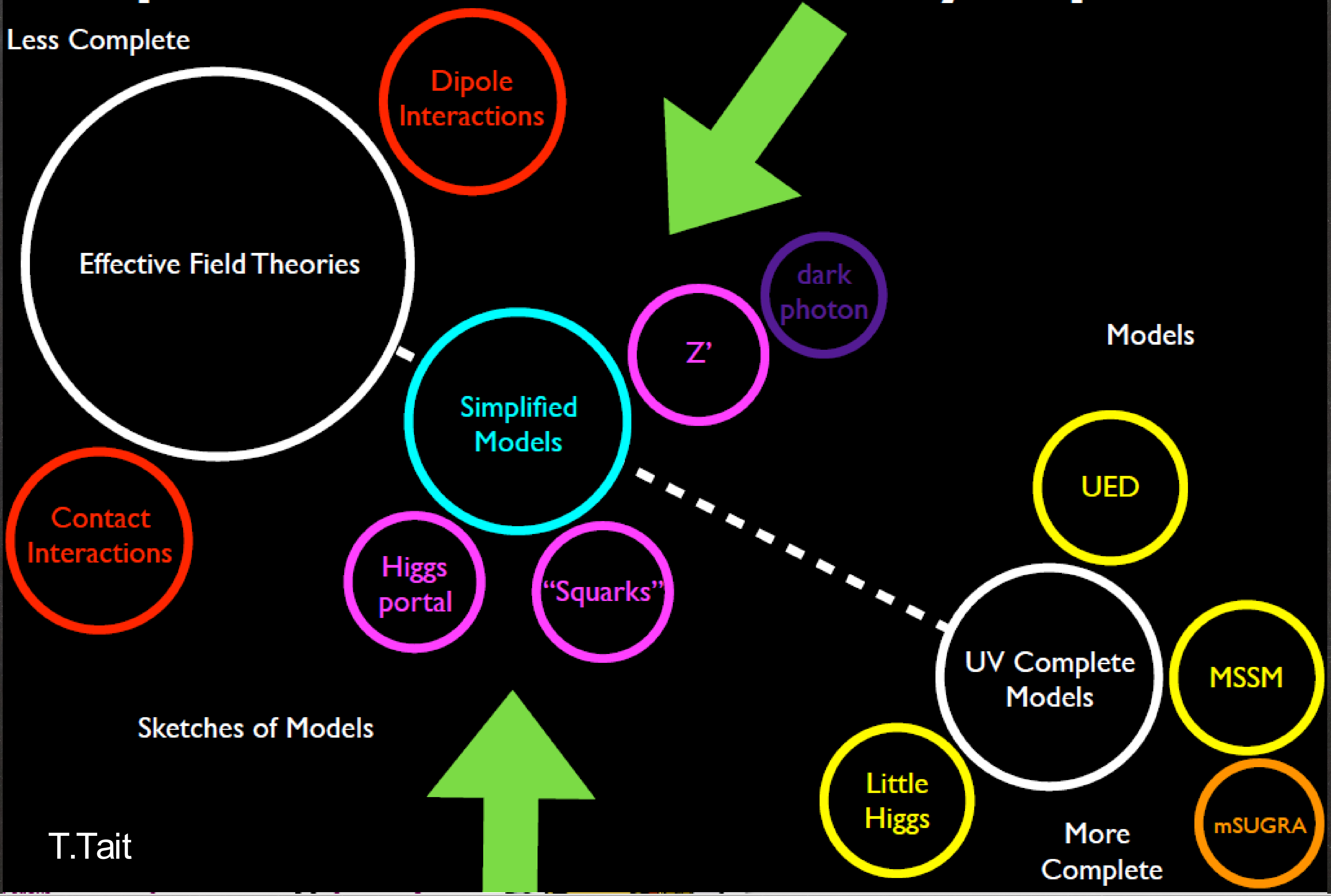
Thermal relic
Yes ? No ?



MSSM
R-parity violating
NMSSM
Supersymmetry
WIMPless DM
Hidden Sector DM
Self-Interacting DM
Techni-baryons
mSUGRA
pMSSM
Gravitino DM
Q-balls
Dark Photon
Asymmetric DM
Dirac DM
R-parity Conserving
Light Force Carriers
Extra Dimensions
Dynamical DM
Warm DM
Theories of Dark Matter
?
Solitonic DM
UED DM
Sterile Neutrinos
Quark Nuggets
6d
5d
Warped Extra Dimensions
RS DM
Axion DM
T-odd DM
QCD Axions
Axion-like Particles
Littlest Higgs

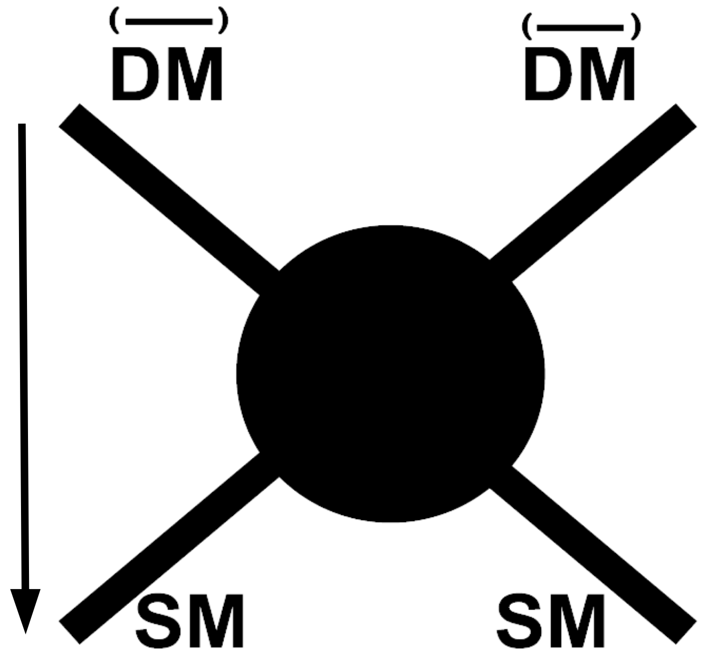
T.Tait

Spectrum of Theory Space



DM Observables: the power of WIMP

Correct Relic density: efficient (co) annihilation
WMAP, Planck ; annihilation to photons can affect CMB



DM Observables: the power of WIMP

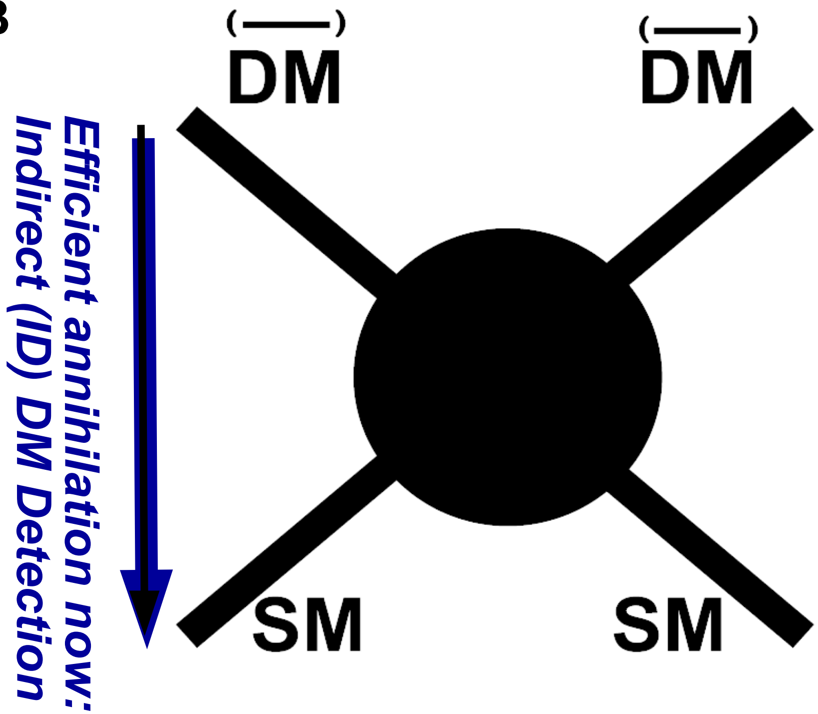
Correct Relic density: efficient (co) annihilation WMAP, Planck ; annihilation to photons can affect CMB

Signatures from neutralino annihilation in halo, core of the Earth and Sun

- **photons,**
- **Anti-protons**
- **positrons,**
- **Neutrinos**

Neutrino telescopes:

- **Amanda**
- **Icecube**
- **Antares**



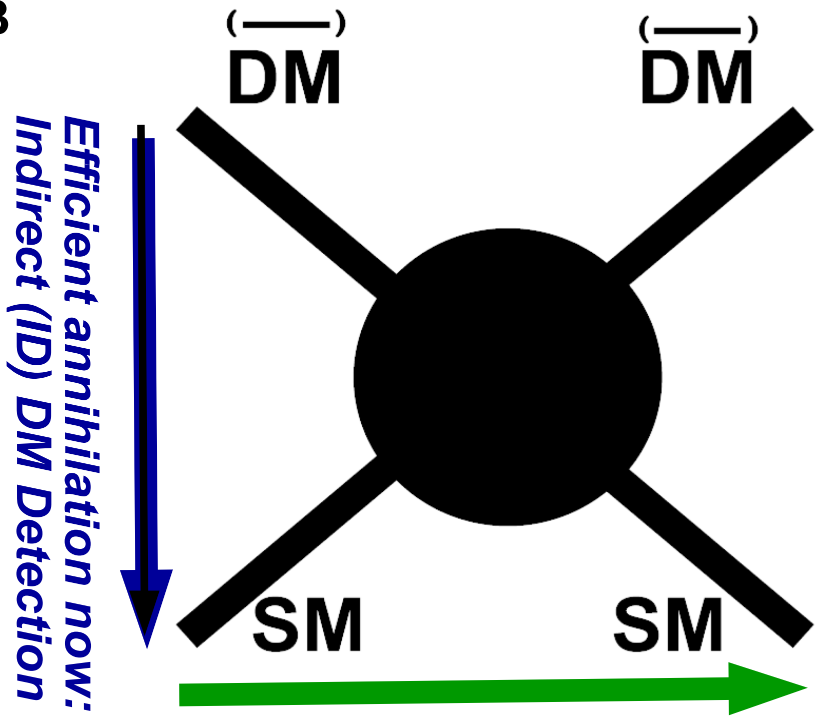
DM Observables: the power of WIMP

Correct Relic density: efficient (co) annihilation
WMAP, Planck ; annihilation to photons can affect CMB

Signatures from neutralino annihilation in halo, core of the Earth and Sun

- **photons,**
- **Anti-protons**
- **positrons,**
- **Neutrinos**

Neutrino telescopes:
- **Amanda**
- **Icecube**
- **Antares**



Efficient scattering off nuclei:
DM Direct Detection (DD)

Signature from energy deposition from nuclei recoil: LUX, XENON, WARP,

DM Observables: the power of WIMP

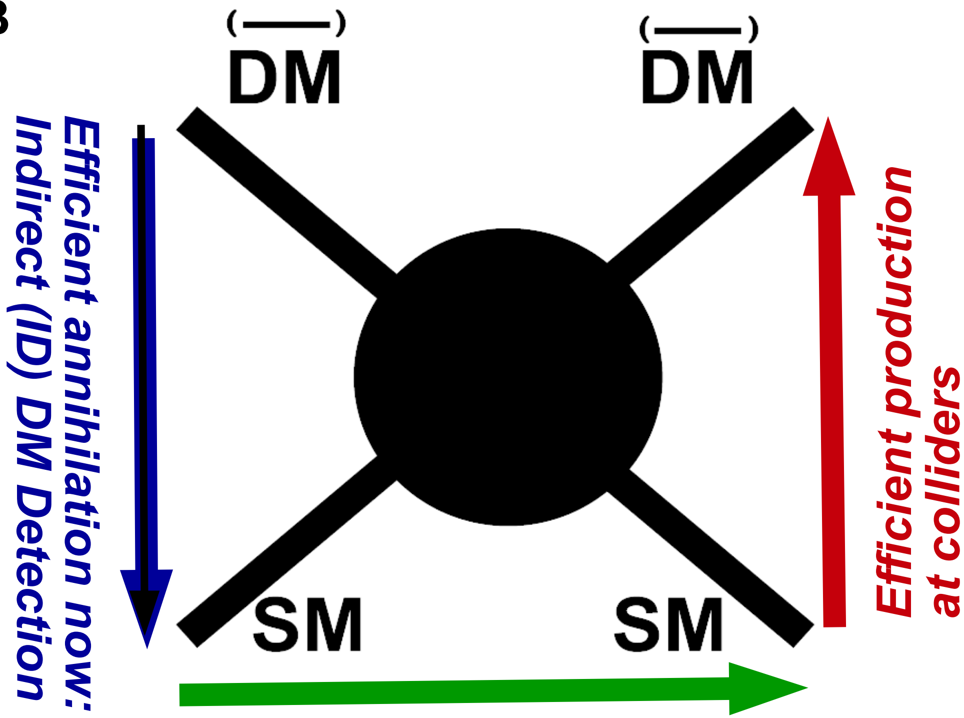
Correct Relic density: efficient (co) annihilation WMAP, Planck ; annihilation to photons can affect CMB

Signatures from neutralino annihilation in halo, core of the Earth and Sun

- photons,
- Anti-protons
- positrons,
- Neutrinos

Neutrino telescopes:

- Amanda
- Icecube
- Antares



Efficient scattering off nuclei:
DM Direct Detection (DD)

Signature from energy deposition from nuclei recoil: LUX, XENON, WARP,

LHC signatures

- mono-jet
- mono-photon
- mono-Z
- mono Higgs
- VBF+MET
- soft leptons+MET
- ….

DM Observables: the power of WIMP

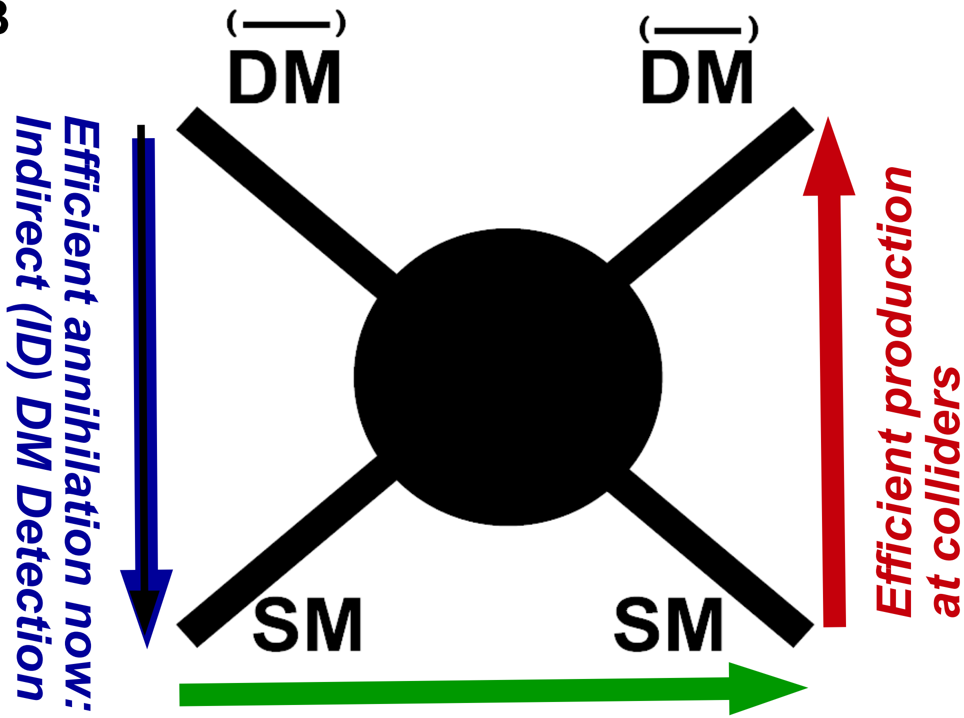
Correct Relic density: efficient (co) annihilation WMAP, Planck ; annihilation to photons can affect CMB

Signatures from neutralino annihilation in halo, core of the Earth and Sun

- **photons,**
- **Anti-protons**
- **positrons,**
- **Neutrinos**

Neutrino telescopes:

- **Amanda**
- **Icecube**
- **Antares**



Efficient scattering off nuclei: DM Direct Detection (DD)

Signature from energy deposition from nuclei recoil: LUX, XENON, WARP,

LHC signatures

- **mono-jet**
- **mono-photon**
- **mono-Z**
- **mono Higgs**

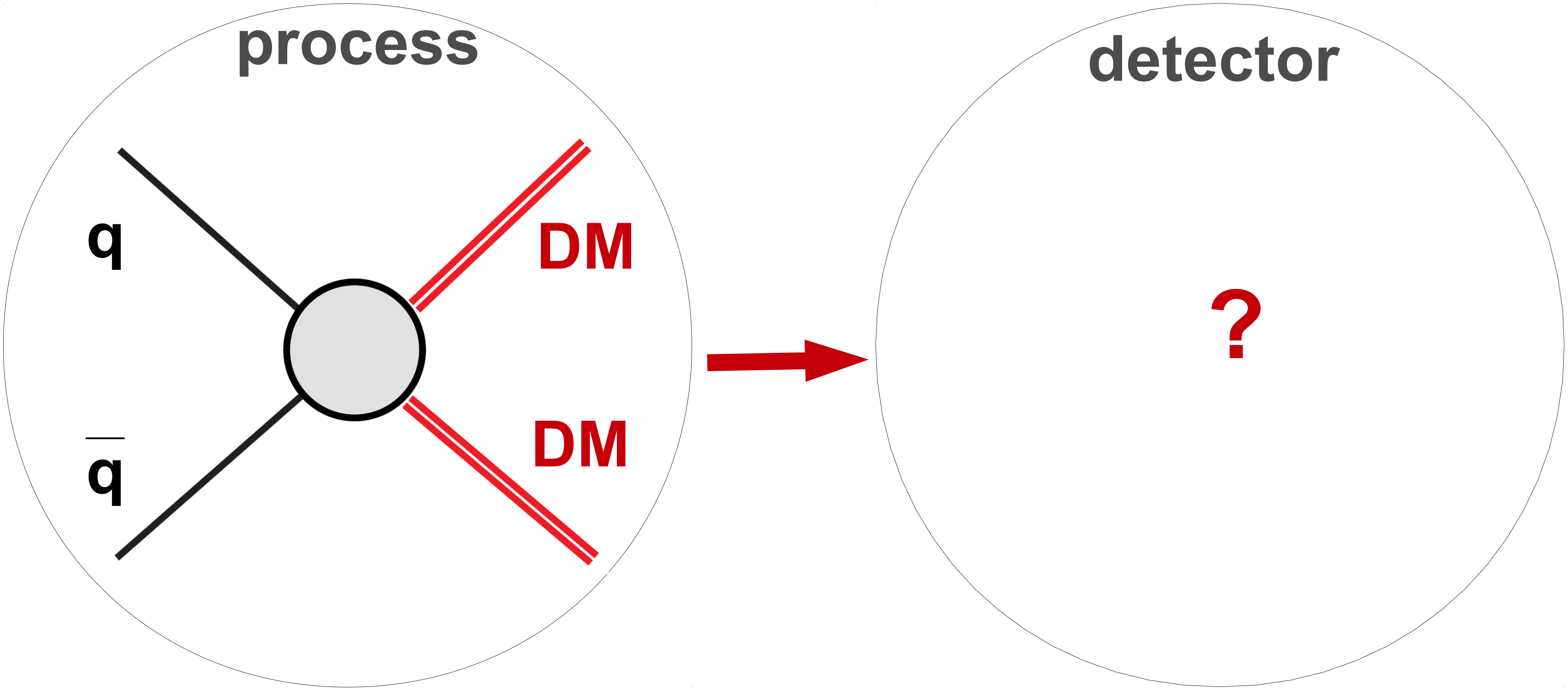
- **VBF+MET**
- **soft leptons+MET**
- **….**

Note: **there is no 100%correlation between signatures above. For example, the high rate of annihilation does not always guarantee high rate for DD!**

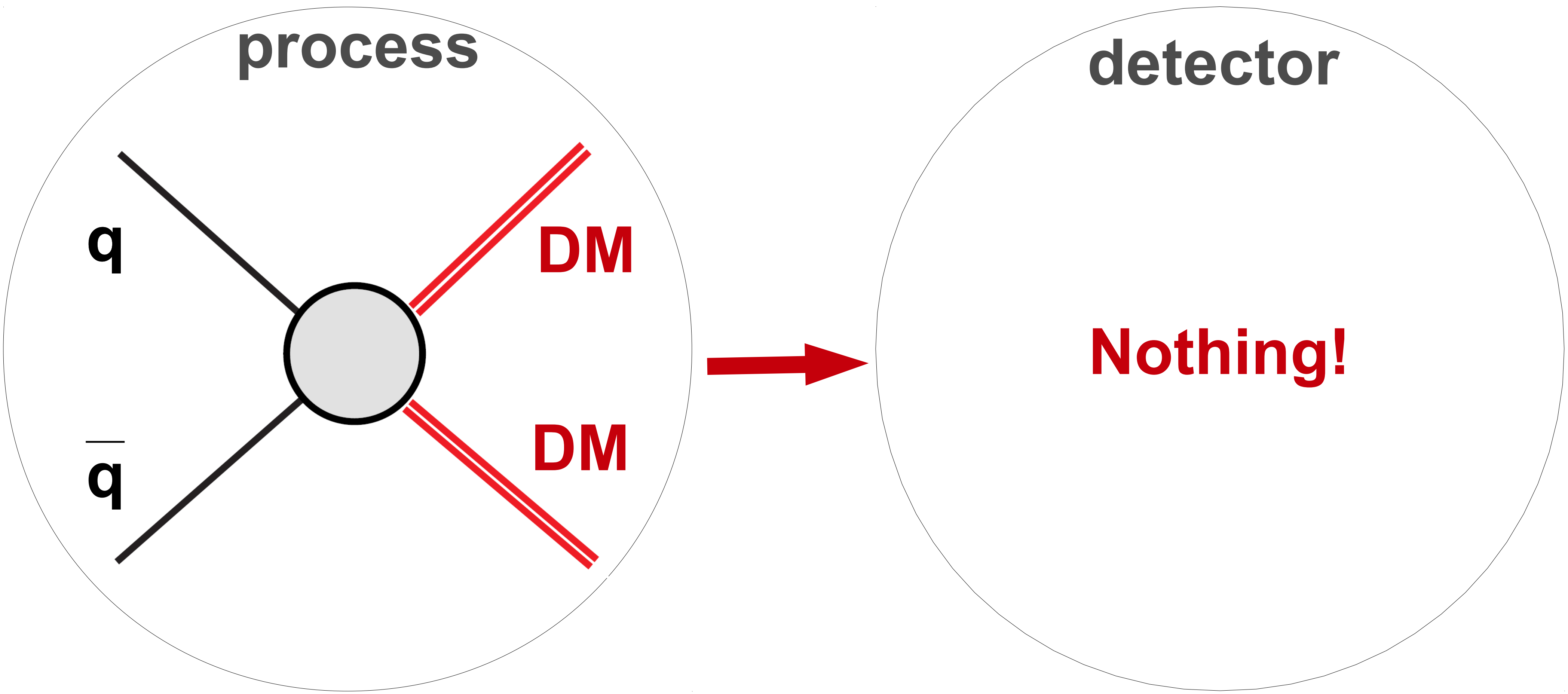
Actually there is a great complementarity in this:

- **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**

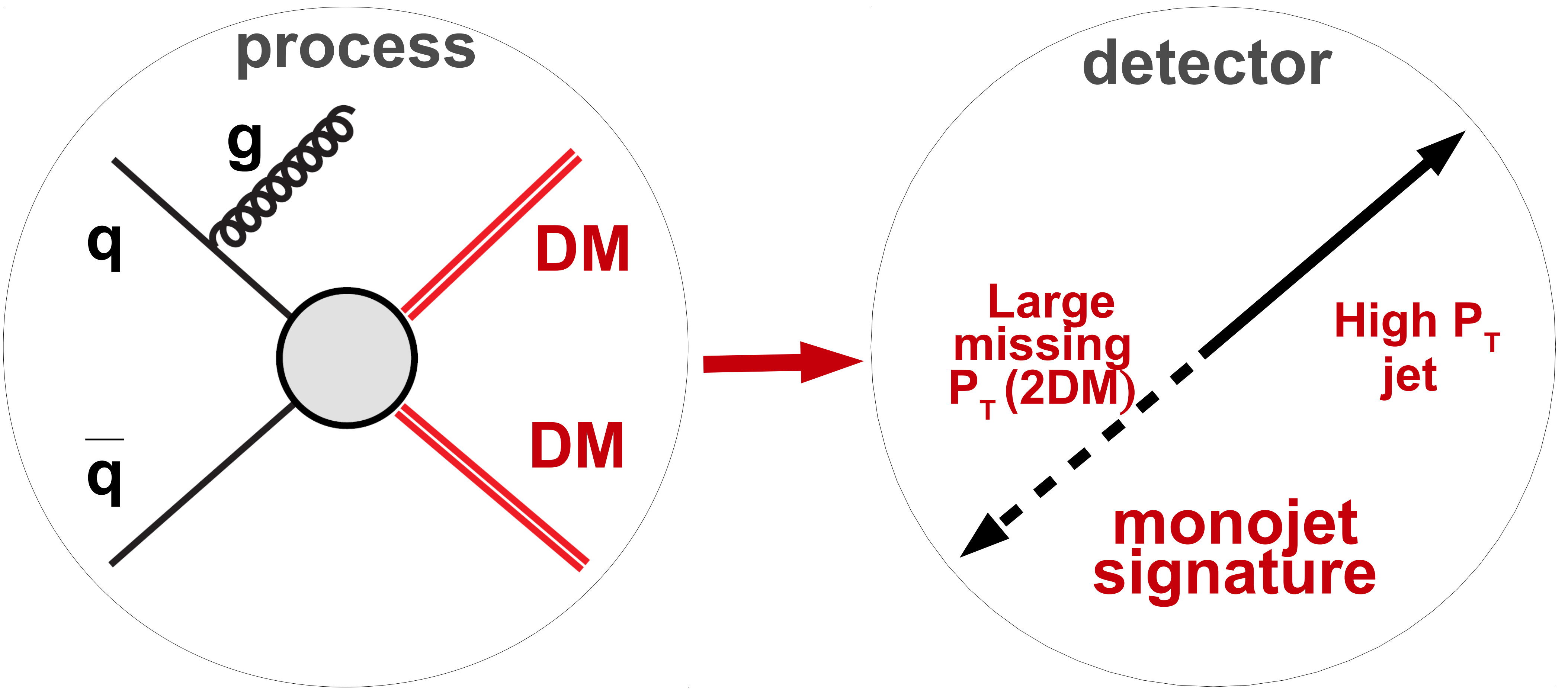
Hunting for DM at Colliders



Hunting for DM at Colliders



Hunting for DM at Colliders

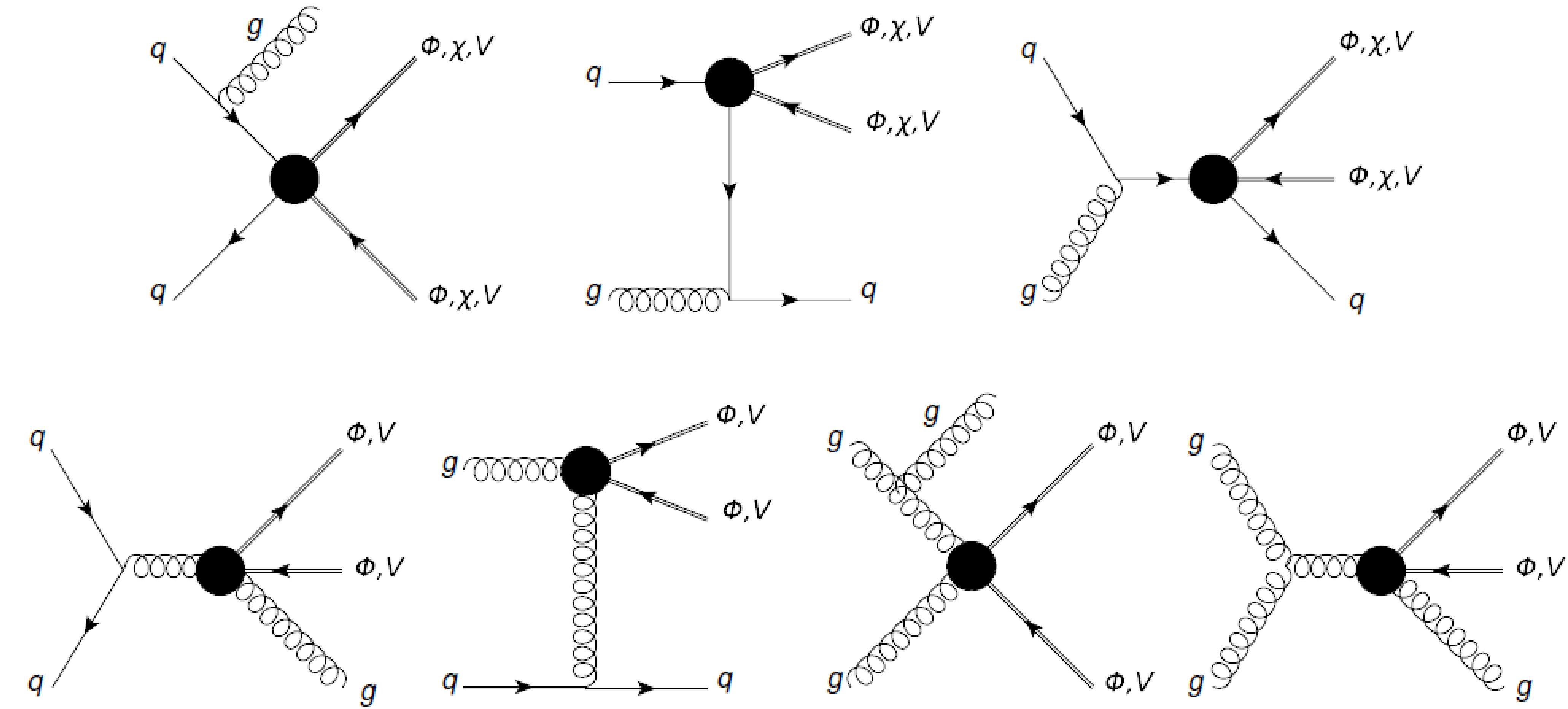


Can we test DM properties at the LHC?

- 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."

- Let us check the effects of DM spin on Missing transverse momentum **(MET)** distributions at the LHC:
  - let us start with EFT approach first – the simplest model-independent approach:
  - Complete set of DIM5/DIM6 operators involving two SM quarks (gluons) and two DM particles
  - consider spin=0, 1/2, 1 DM
  - mono-jet signature
  - explore 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†	
$\frac{\tilde{m}}{\Lambda^2}\phi^\dagger\phi\bar{q}q$	$[C1]^*$
$\frac{\tilde{m}}{\Lambda^2}\phi^\dagger\phi\bar{q}i\gamma^5 q$	$[C2]^*$
$\frac{1}{\Lambda^2}\phi^\dagger i\overleftrightarrow{\partial_\mu}\phi\bar{q}\gamma^\mu q$	$[C3]$
$\frac{1}{\Lambda^2}\phi^\dagger i\overleftrightarrow{\partial_\mu}\phi\bar{q}\gamma^\mu\gamma^5 q$	$[C4]$
$\frac{1}{\Lambda^2}\phi^\dagger\phi G^{\mu\nu}G_{\mu\nu}$	$[C5]^*$
$\frac{1}{\Lambda^2}\phi^\dagger\phi\tilde{G}^{\mu\nu}G_{\mu\nu}$	$[C6]^*$

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

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

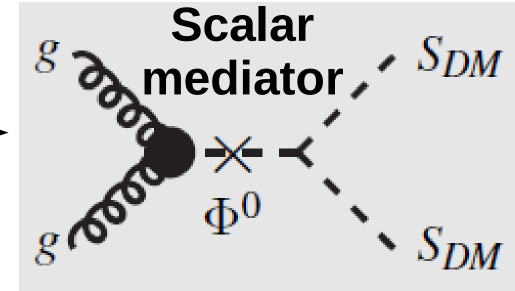
* operators applicable to real DM fields, modulo a factor $1/2$

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

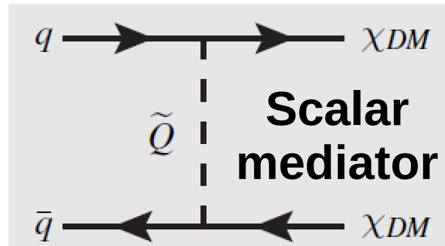
‡ All but V11 and V12 listed in Kumar *et al.*, *Vector dark matter at the LHC*, Phys. Rev. **D92** (2015) 095027, [arXiv:1508.04466]

Mapping EFT operators to simplified models

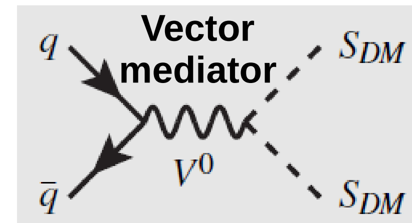
C5,C5A $\frac{1}{\Lambda^2}\phi^*\phi G^{\mu\nu}G^{\mu\nu}$, $\frac{1}{\Lambda^2}\phi^*\phi \tilde{G}^{\mu\nu}G^{\mu\nu}$ $\longrightarrow$



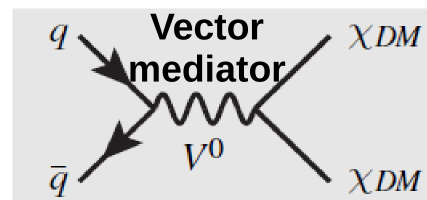
D1T-D4T $\frac{1}{\Lambda^2}\bar{\chi}q\bar{q}\chi$ $\longrightarrow$

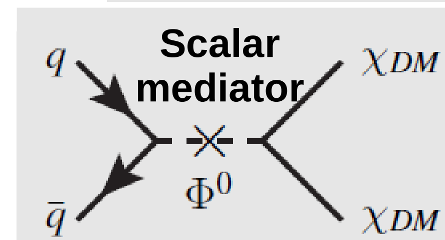


C3 $\frac{i}{\Lambda^2}[\phi^*(\partial_\mu\phi - (\partial_\mu\phi^*)\phi]\bar{q}\gamma^\mu q$ $\longrightarrow$

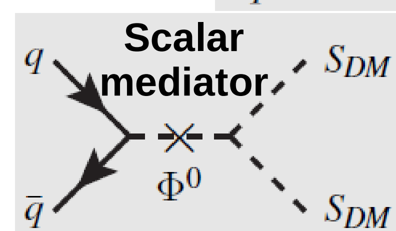


D1-D4, D5-D8 $\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$ $\frac{1}{\Lambda^2}\bar{\chi}\chi\bar{q}q$ $\longrightarrow$



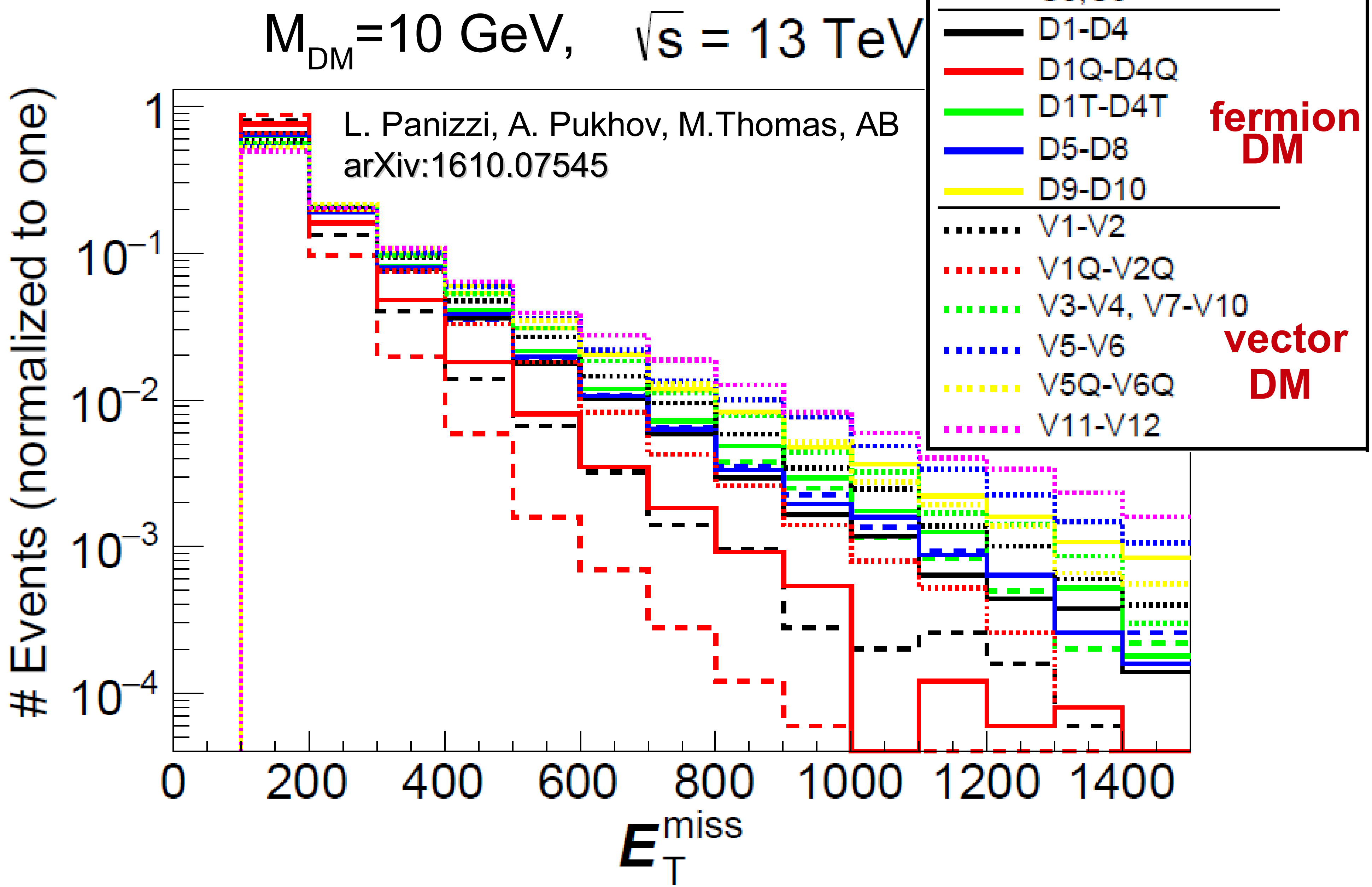


C1 $\frac{1}{\Lambda^2}\phi^*\phi\bar{q}q\Phi \Longrightarrow \frac{v}{\Lambda^2}\phi^*\phi\bar{q}q$ $\longrightarrow$

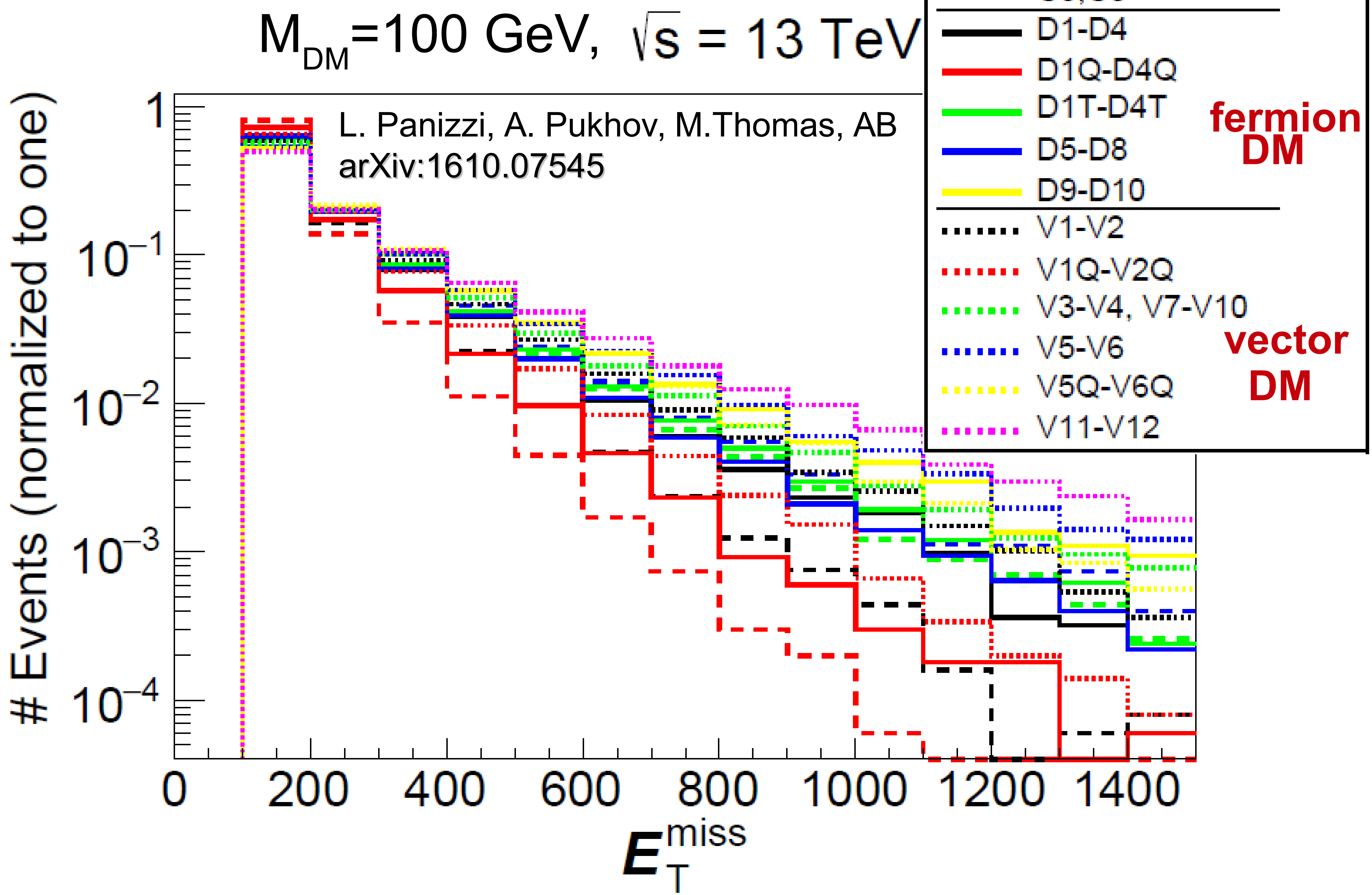


D9,D10 $\frac{1}{\Lambda^2}\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q \longrightarrow$ $\frac{8}{\Lambda^2}$[$\bar{\chi}q\bar{q}\chi$ - $\frac{1}{4}\left(\bar{\chi}\chi\bar{q}q + \bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q + \bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q - \bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5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

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

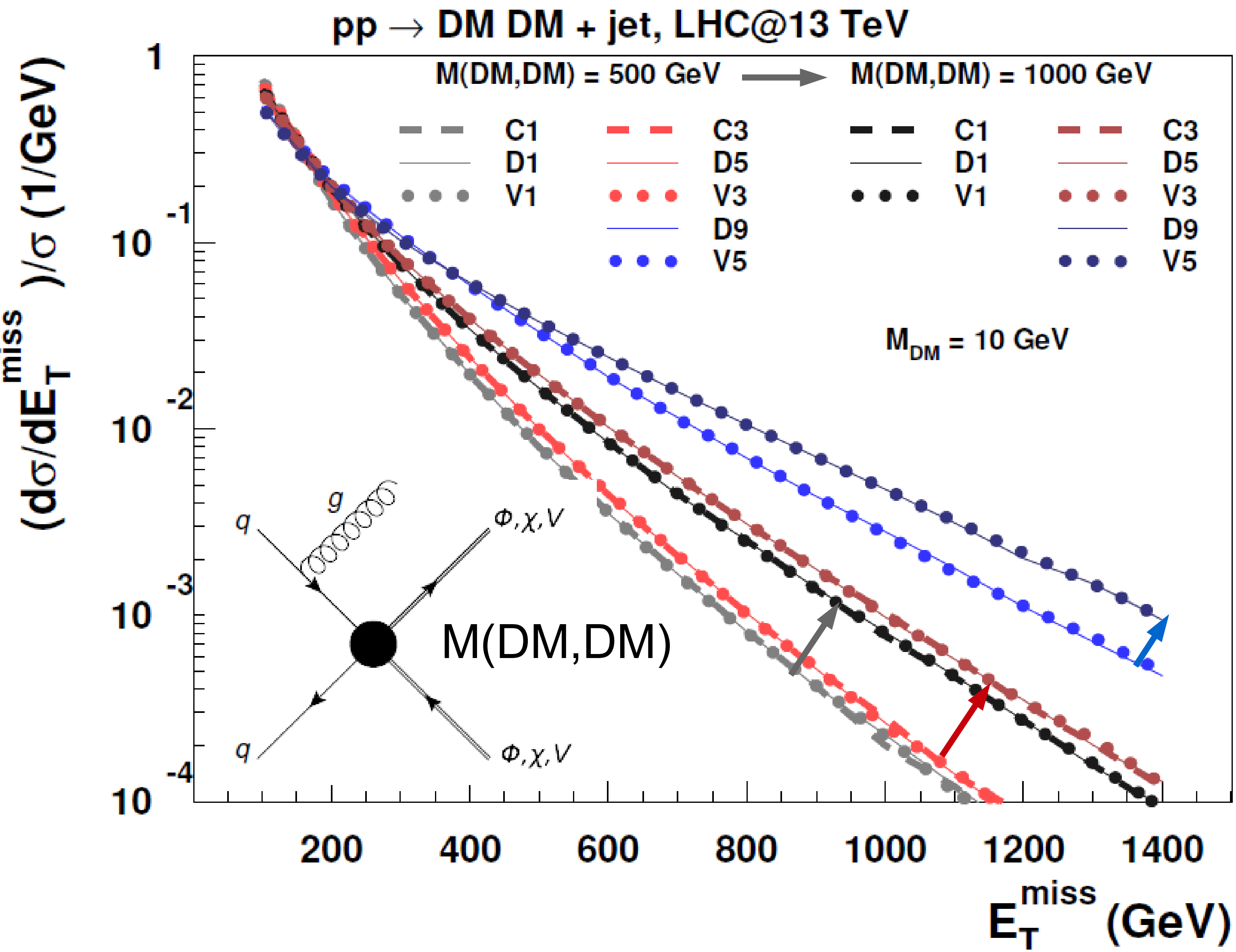


M_{DM} dependence is weak for 10-100 GeV range



Properties of MET distributions:

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



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

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

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

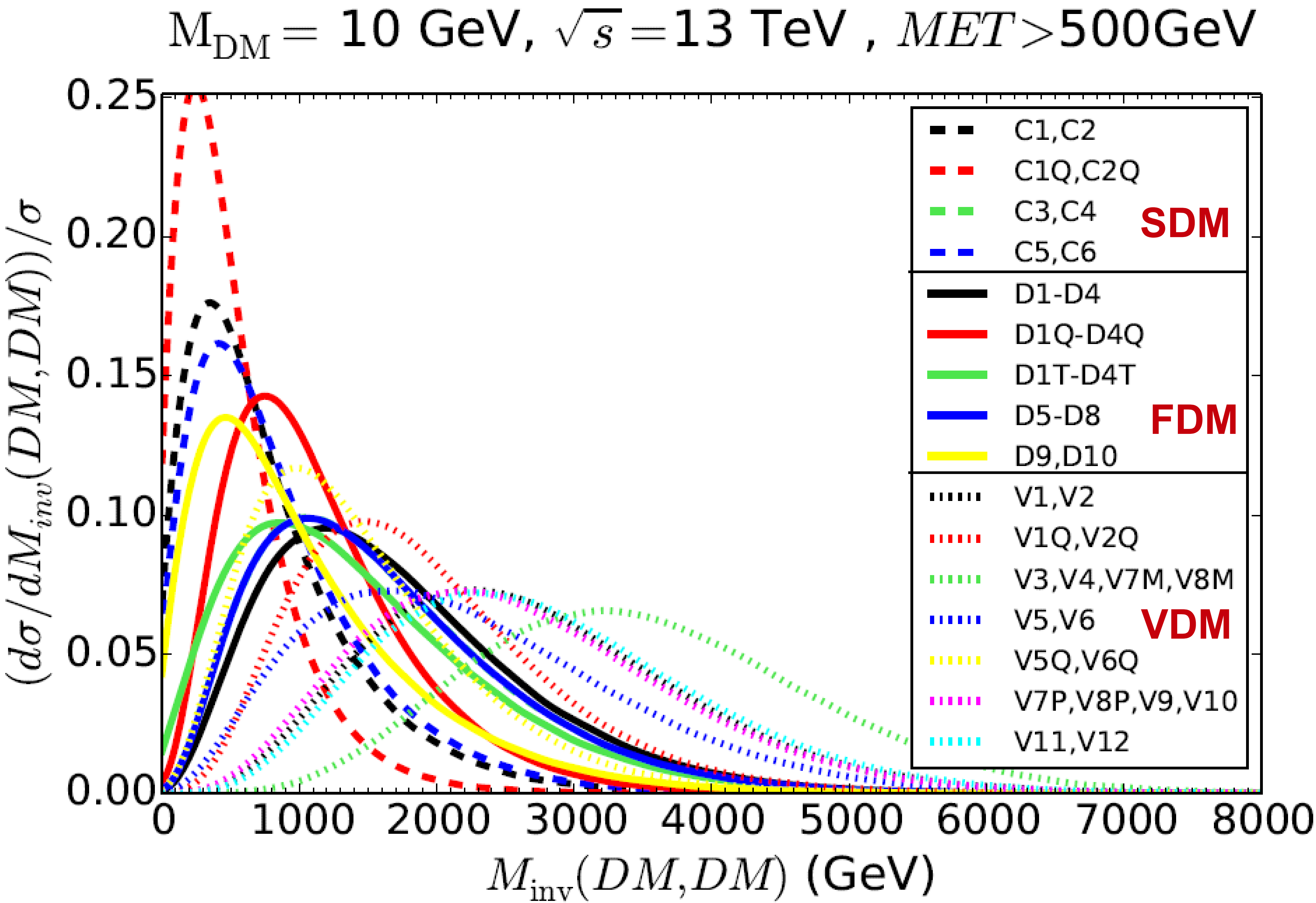
$$\frac{1}{\Lambda^2}\phi^\dagger i\overleftrightarrow{\partial_\mu}\phi\bar{q}\gamma^\mu q \quad [C1]$$

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

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

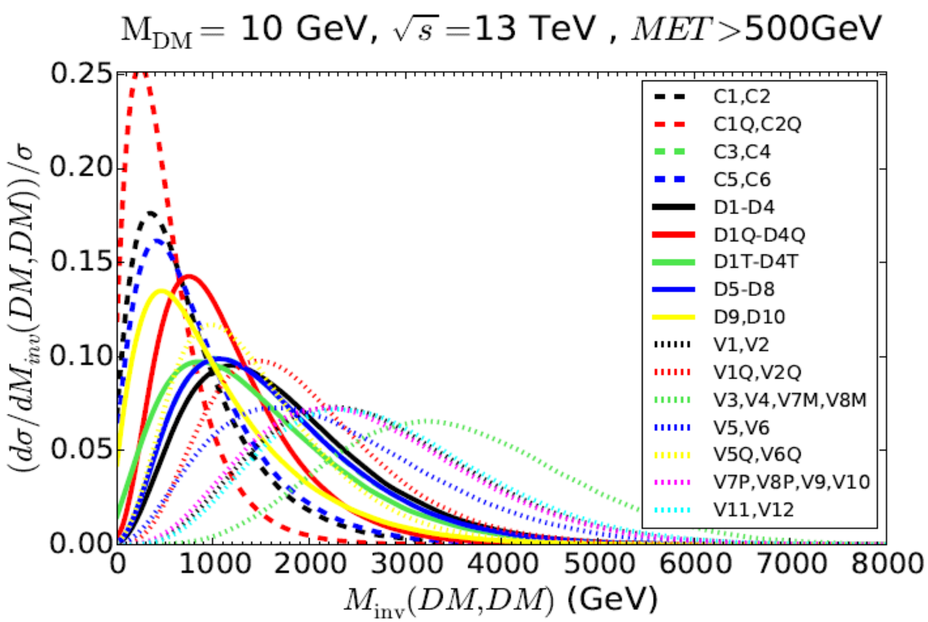
$$\frac{\tilde{m}}{\Lambda^2}V_\mu^\dagger V_\nu\bar{q}i\sigma^{\mu\nu}q \quad [V5]$$

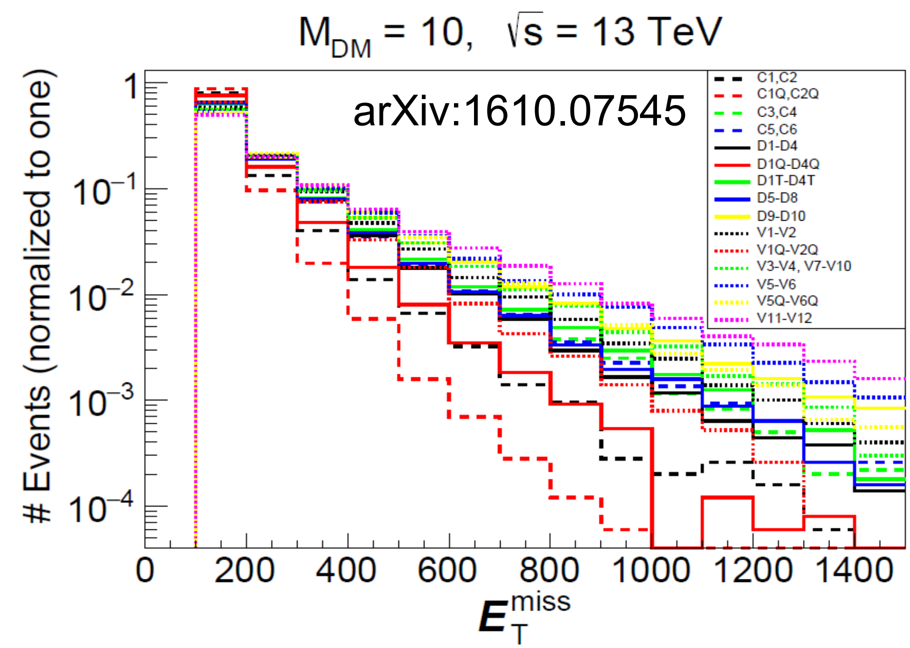
On the other hand, M(DM,DM) distributions, defined by the EFT operators are different!



Distinguishing DM operators/theories

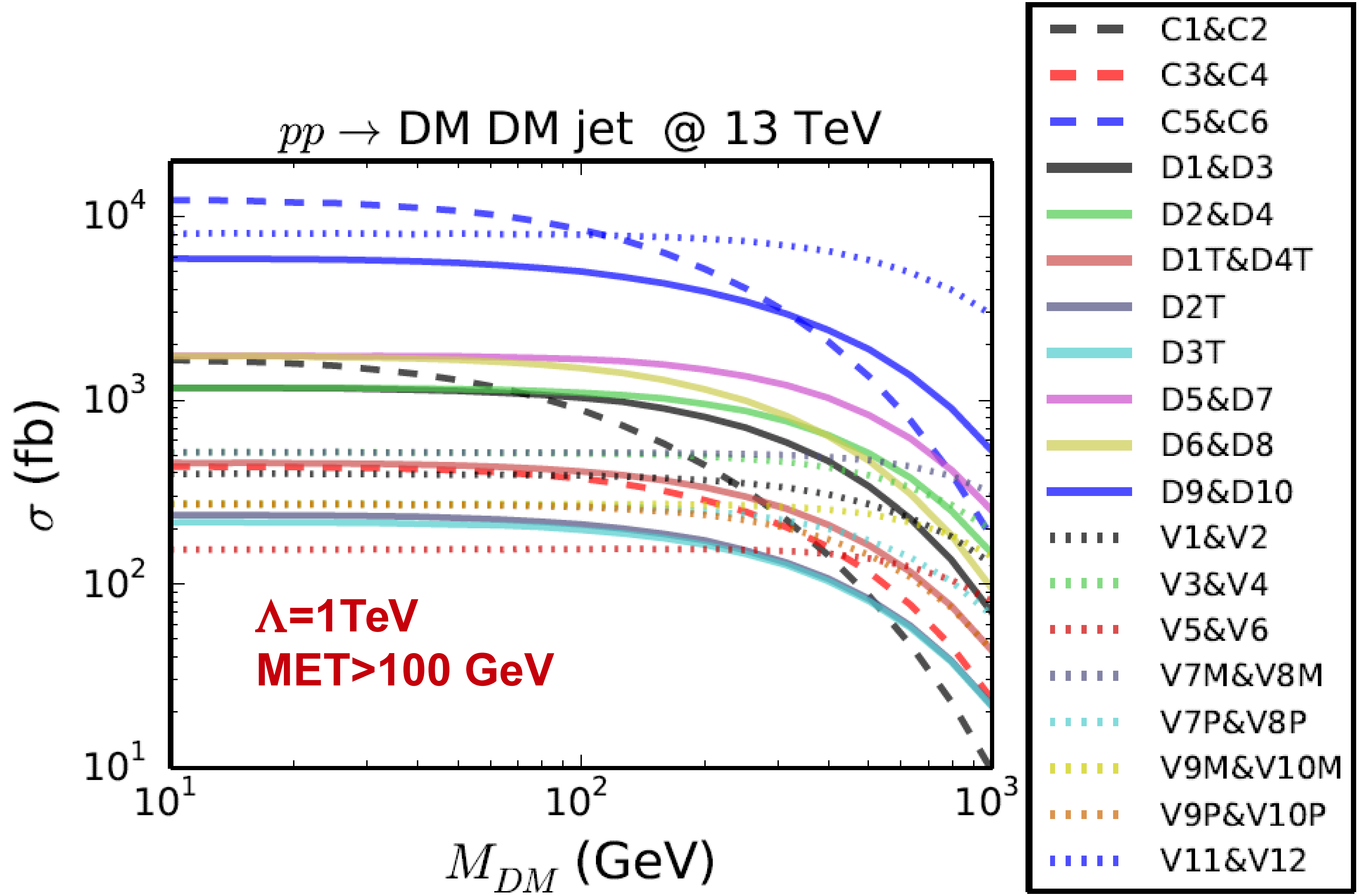
M(DM,DM) distributions ⟷ are correlated with Different MET shapes





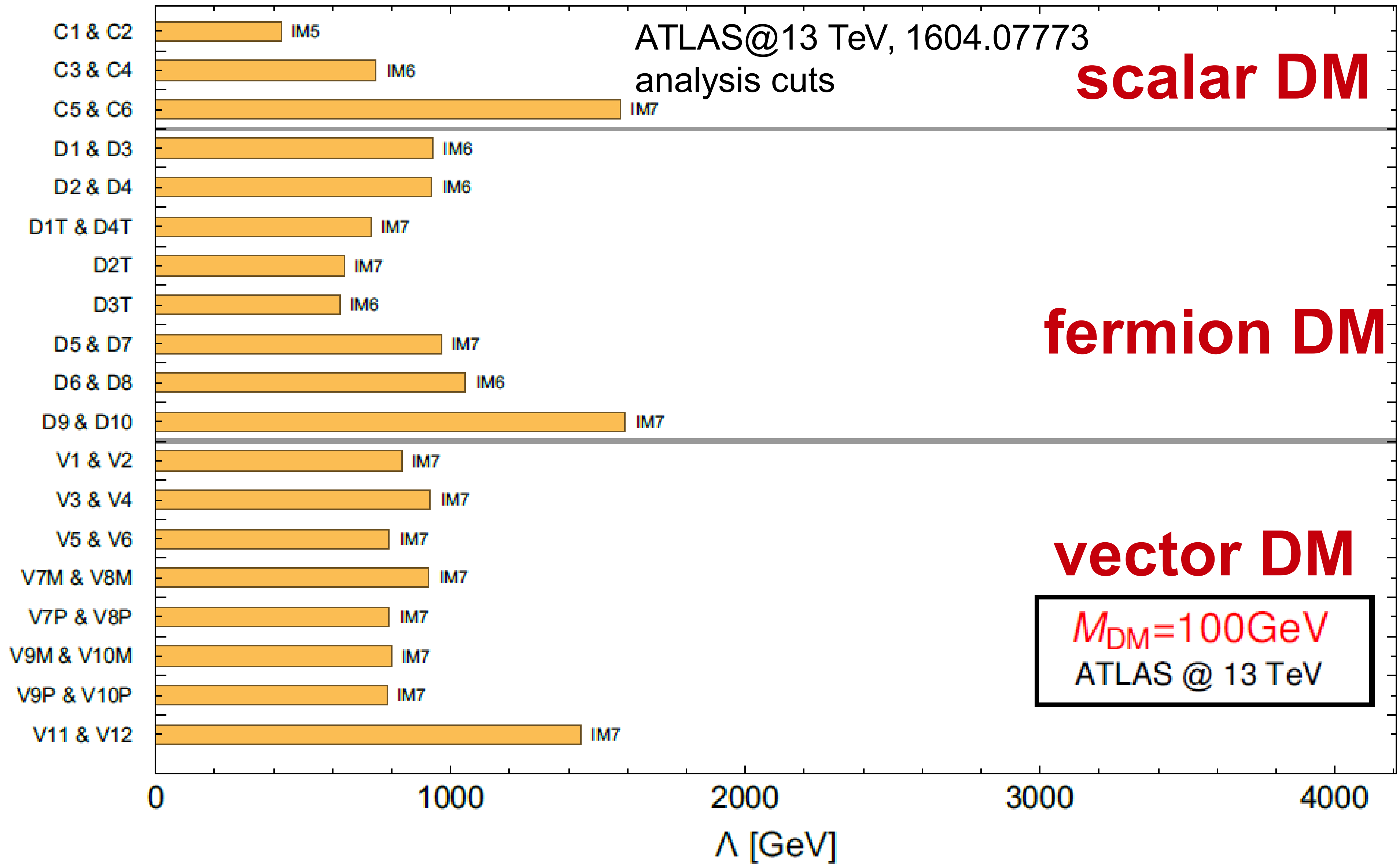
- energy dependence of the DM operator → M_{DMDM} distributions → slopes of MET
- projection for 300 fb^{-1}: some operators C1-C2,C5-C6,D9-D10,V1-V2,V3-V4,V5-V6 and V11-12 can be distinguished from each other
- Application beyond EFT: when the DM mediator is not produced on-the-mass-shell and M_{DMDM} is not fixed: t-channel mediator or mediators with mass below $2M_{DM}$

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



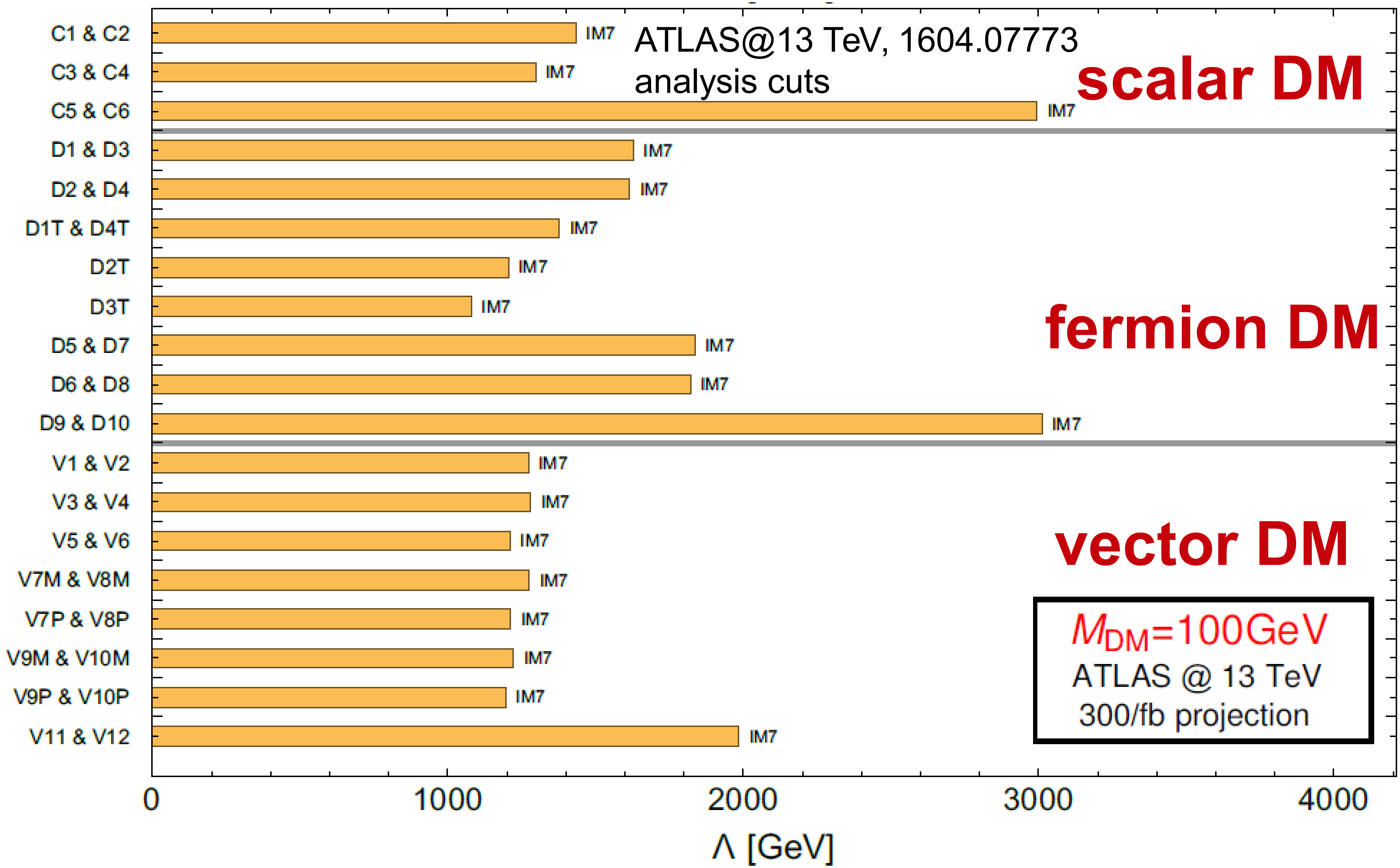
LHC@13TeV reach at 3.2 fb^{-1}

LanHEP→ CalcHEP/ Madgraph → LHE→ CheckMATE 2 chain



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

LanHEP→ CalcHEP/ Madgraph → LHE→ CheckMATE 2 chain



LHC@13TeV Reach for spin 0 and ½ DM

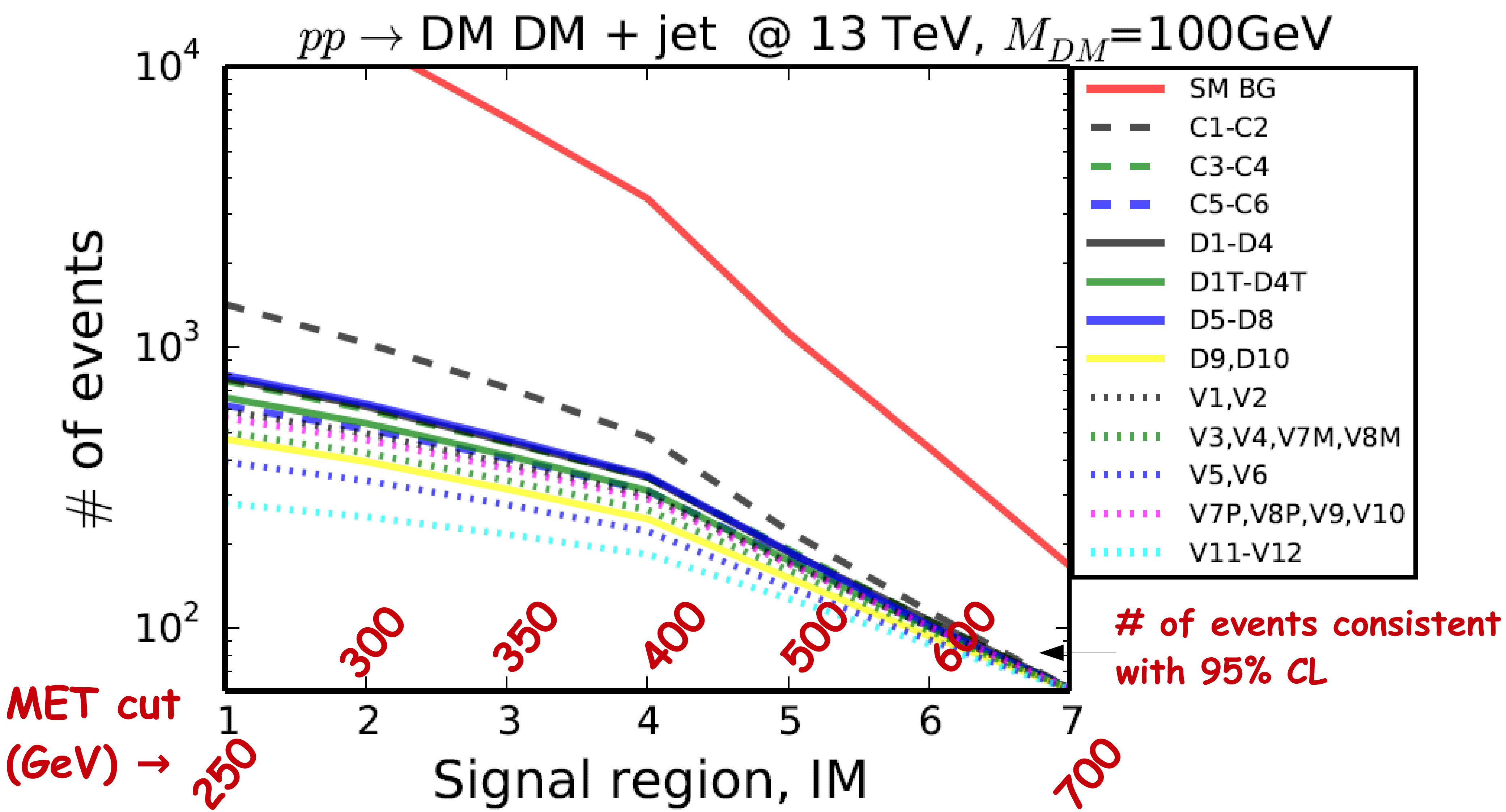
	Operators	Coefficient	Excluded Λ (GeV) at 3.2 fb^{-1}			Excluded Λ (GeV) at 100 fb^{-1}		
			DM Mass			DM Mass		
			10 GeV	100 GeV	1000 GeV	10 GeV	100 GeV	1000 GeV
Complex Scalar DM	C1 & C2	$1/\Lambda$	456	424	98	1168	1115	267
	C3 & C4	$1/\Lambda^2$	750	746	400	1134	1131	662
	C5 & C6	$1/\Lambda^2$	1621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

LHC@13TeV Reach for spin 1 DM

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

Distinguishing DM operators

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



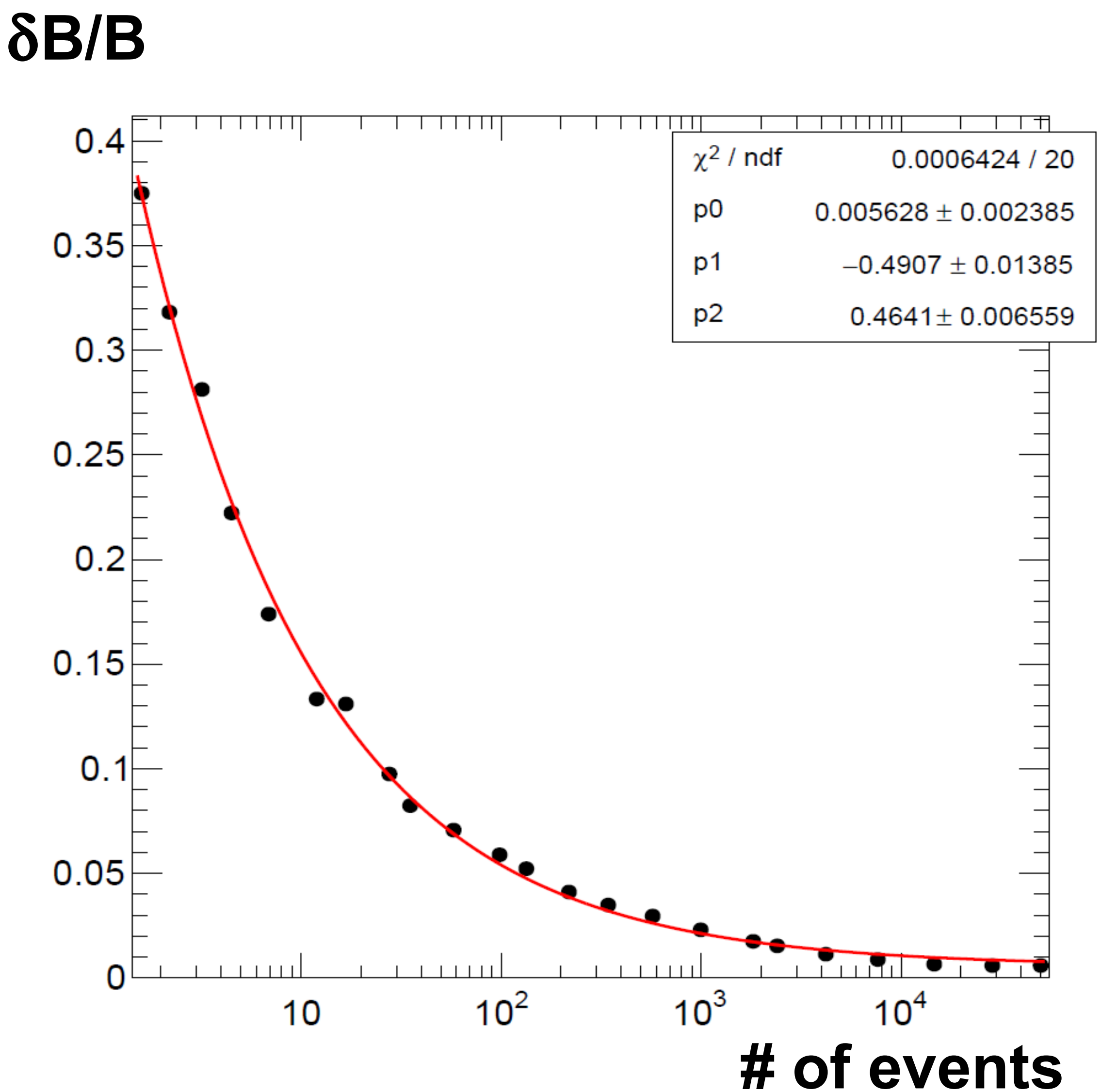
On the BG uncertainty

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

CMS-PAS-EXO-16-013

E_T^{miss} Range (GeV)	$Z(\nu\nu)$+jets	$W(\ell\nu)$+jets	Total (Pre-fit)	Total (Post-fit)	Data
200 – 230	14919 ± 221	11976 ± 196	27761 ± 1464	28654 ± 171	28601
230 – 260	7974 ± 116	5776 ± 101	14114 ± 757	14675 ± 97	14756
260 – 290	4467 ± 70	2867 ± 50	7193 ± 351	7666 ± 68	7770
290 – 320	2518 ± 46	1520 ± 34	4083 ± 204	4215 ± 48	4195
320 – 350	1496 ± 35	818 ± 20	2385 ± 118	2407 ± 37	2364
350 – 390	1204 ± 31	555 ± 15	1817 ± 87	1826 ± 32	1875
390 – 430	684 ± 20	275 ± 9	978 ± 45	998 ± 23	1006
430 – 470	382 ± 14	155 ± 6	589 ± 30	574 ± 17	543
470 – 510	248 ± 11	87.3 ± 3.8	337 ± 15	344 ± 12	349
510 – 550	160 ± 8	52.2 ± 2.7	211 ± 9	219 ± 9	216
550 – 590	99.5 ± 6.0	29.2 ± 1.9	134 ± 6	134 ± 7	142
590 – 640	77.3 ± 4.9	18.9 ± 1.4	100 ± 4	98.5 ± 5.8	111
640 – 690	44.8 ± 3.5	11.2 ± 0.9	59.6 ± 2.6	58.0 ± 4.1	61
690 – 740	27.8 ± 2.5	6.1 ± 0.6	36.6 ± 1.5	35.2 ± 2.9	32
740 – 790	21.8 ± 2.3	5.3 ± 0.6	23.8 ± 1.0	27.7 ± 2.7	28
790 – 840	13.5 ± 1.9	2.8 ± 0.4	15.3 ± 0.7	16.8 ± 2.2	14
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 → nnj 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% dBG 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

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

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

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

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

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

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

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

			Complex Scalar DM				Dirac Fermion DM				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 ↔ Collider interplay

- the connection between physics at high and low energy is crucial to properly explore complementarity collider and non-collider DM experiments
- RGEs for the EFT introduce the mixing between different operators

Kopp,Niro,Schwetz,Zupan(2009); Hill, Solon(2012); Frandsen, Haisch, Kahlhoefer, Mertsch, Schmidt-Hoberg (2012); Kopp,Michaels, Smirnov(2014); Crivellin,D'Eramo,Procura(2014);Crivellin, Haisch(2014); Berlin, Robertson,Solon,Zurek(2016); D'Eramo, de Vries, Panci(2016); D'Eramo,Kavanagh, Panci(2016)

$$\mathcal{L} \supset -\frac{J^{\mu}_{DM} J_{SM,\mu}}{\Lambda^2}, \qquad J^{SM}_{\mu} = \sum_{i=1}^{3}\left[c^{(i)}_{Vq}(\Lambda)\,\overline{q^{(i)}}\gamma_\mu q^{(i)} + c^{(i)}_{Aq}(\Lambda)\,\overline{u^{(i)}}\gamma_\mu\gamma_5 u^{(i)} + \ldots\right]$$

let us take, for example, $J^{\mu}_{DM} = c_{V\chi}\,\overline{\chi}\gamma^\mu\chi + c_{A\chi}\,\overline{\chi}\gamma^\mu\gamma_5\chi$

Once the wilson coefficient are evolved at the low scale, we need to match the low energy parton-level lagrangian with the low energy nucleon one

$$\mathcal{L} \supset -\frac{J^{\mu}_{DM}}{\Lambda^2}\left(c^{(N)}_V\overline{N}\gamma_\mu N + c^{(N)}_A\overline{N}\gamma_\mu\gamma_5 N\right)$$

and

$$\sigma^N_{SI} = \frac{\mu_N^2}{\pi}\frac{(c_{V\chi}c^{(N)}_V)^2}{\Lambda^4}$$

where $\mu_N = m_\chi m_N/(m_\chi + m_N)$

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

- In case of axial operators, e.g

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

  couplings $\mathbf{c_V^{(q)}}$ arise due to the running of the wilson coeffcient $\mathbf{c_A^{(q)}}$ leading to sizable constraints on the DM DD constraints

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

$\mathbf{c_A^{(u)}, c_A^{(d)}, c_V^{(u)}, c_V^{(d)}=(1,1,0,0)}$[5TeV] → (**1.1, 1.1, 0.04, -0.07**)[1GeV]

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

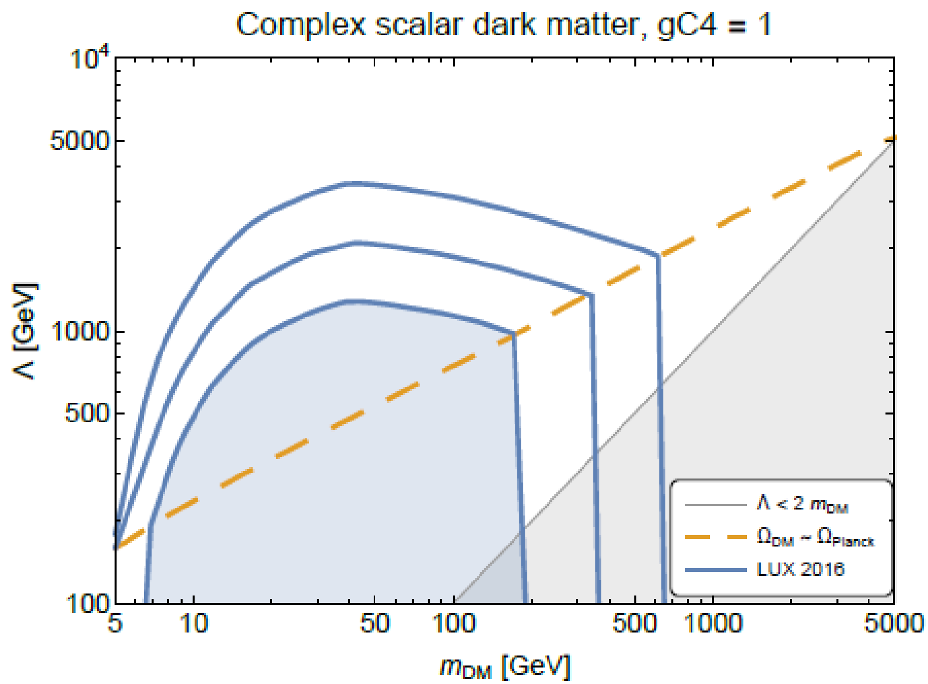
- In case of axial operators, e.g

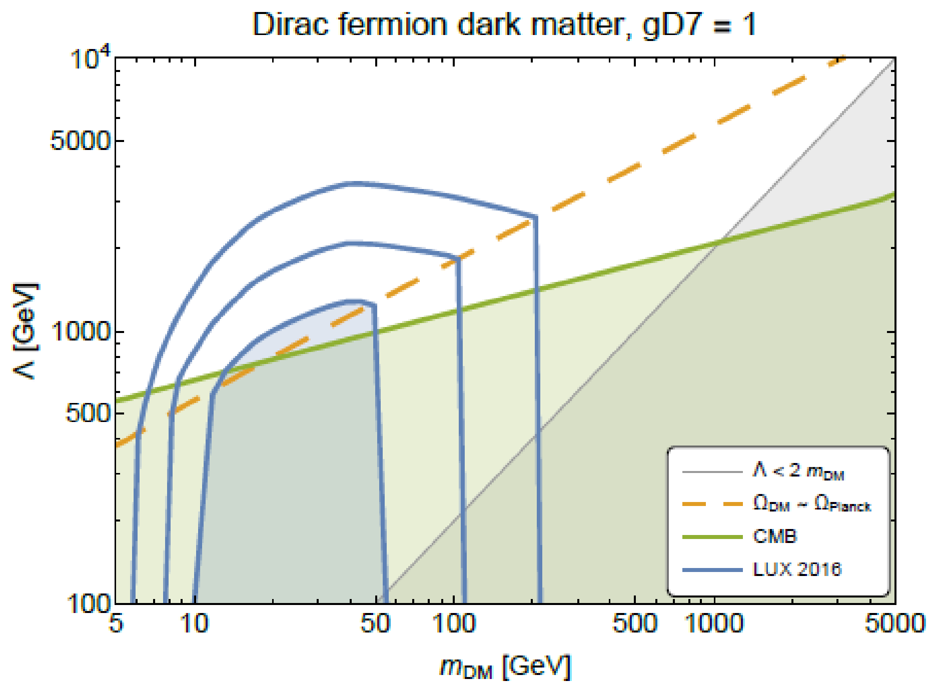
$$c_A^{(q)} c_\chi \overline{\chi}\gamma^\mu \chi \overline{q}\gamma_\mu\gamma_5 q \qquad (D7) \qquad \text{or} \qquad c_A^{(q)} c_\phi \phi^\dagger \overleftrightarrow{\partial}_\mu \phi \overline{q}\gamma^\mu\gamma_5 q \qquad (C4)$$

  couplings $\mathbf{c_V^{(q)}}$ arise due to the running of the wilson coeffcient $\mathbf{c_A^{(q)}}$ leading to sizable constraints on the DM DD constraints

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

$\mathbf{c_A^{(u)}, c_A^{(d)}, c_V^{(u)}, c_V^{(d)}=(1,1,0,0)}$[5TeV] → (1.1, 1.1, 0.04, -0.07)[1GeV]

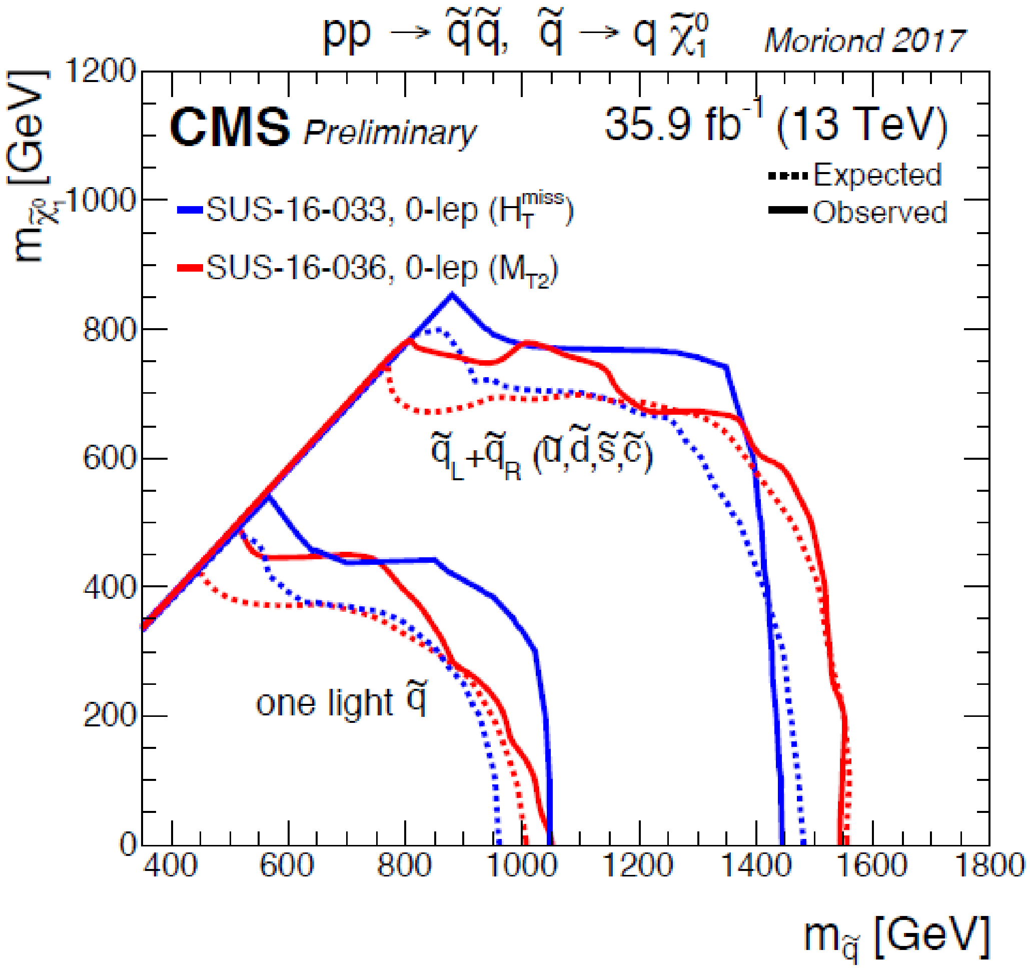


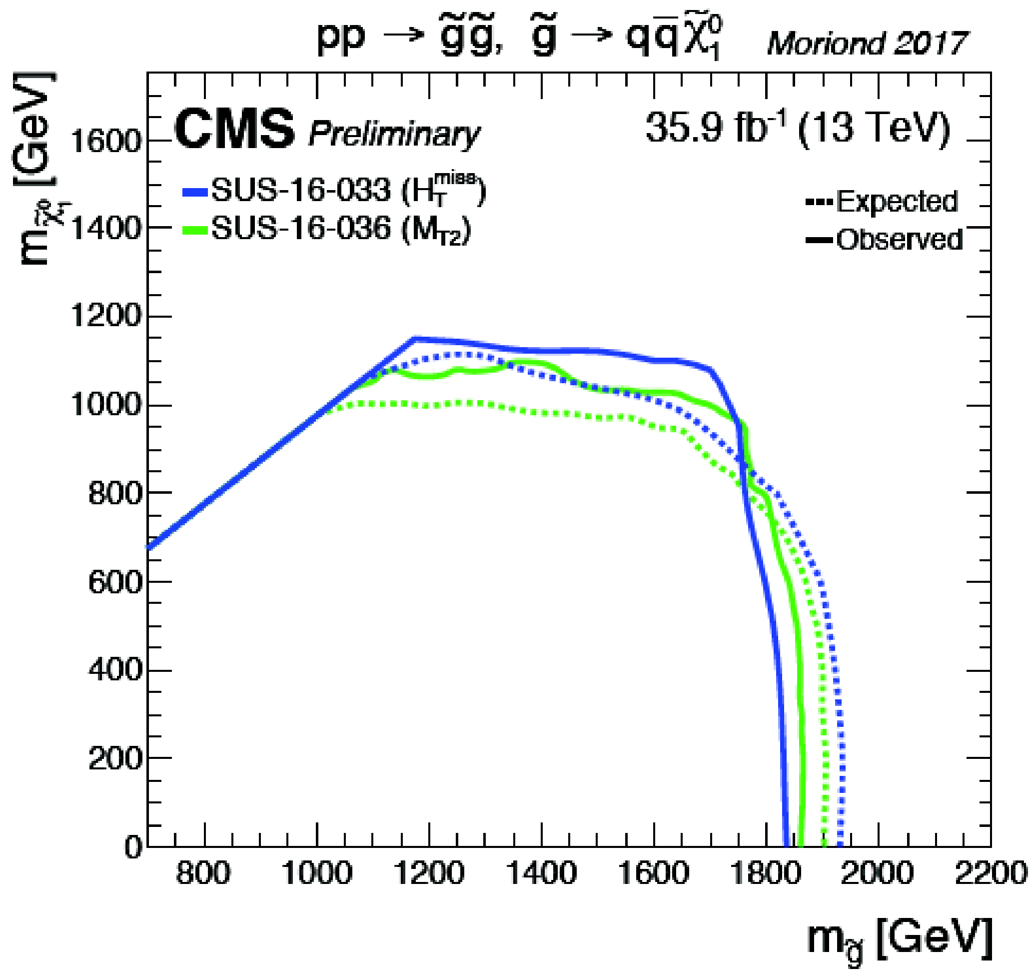


AB, Bertuzzo, Caniu, Eboli, di Cortona (preliminary)

Beyond EFT: SUSY

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

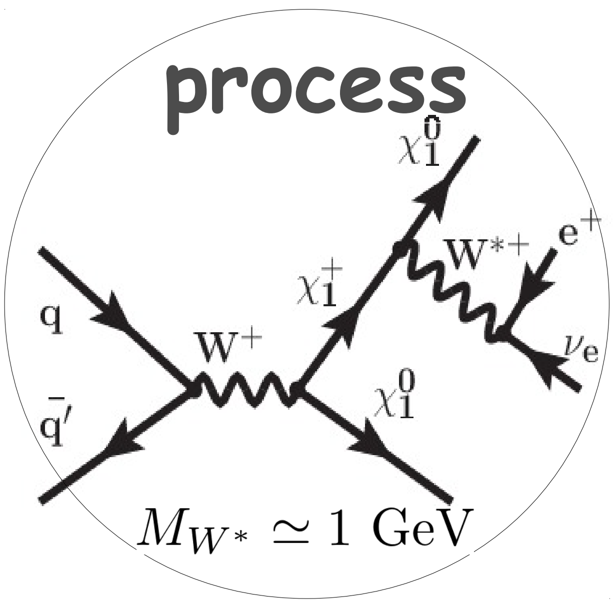


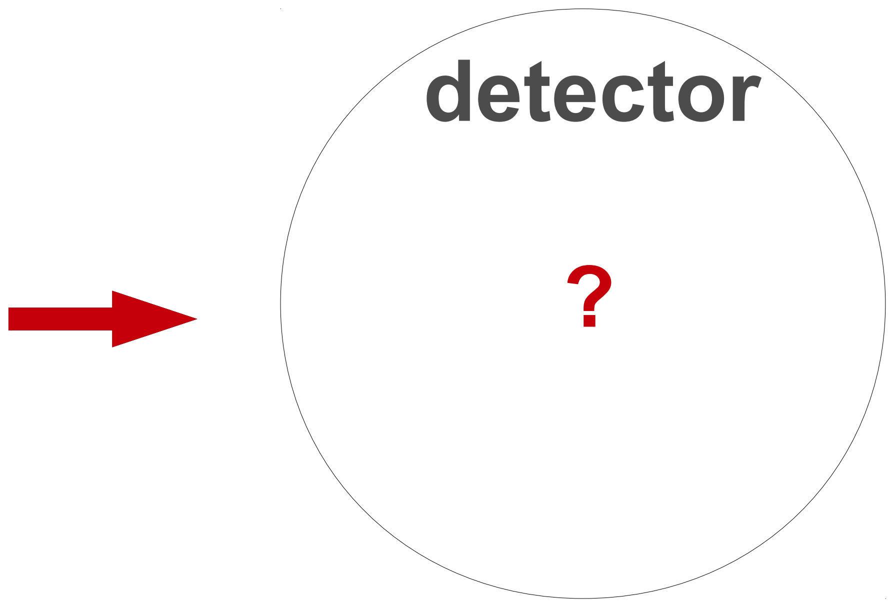


Susy Compressed Mass Spectrum scenario

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

- 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

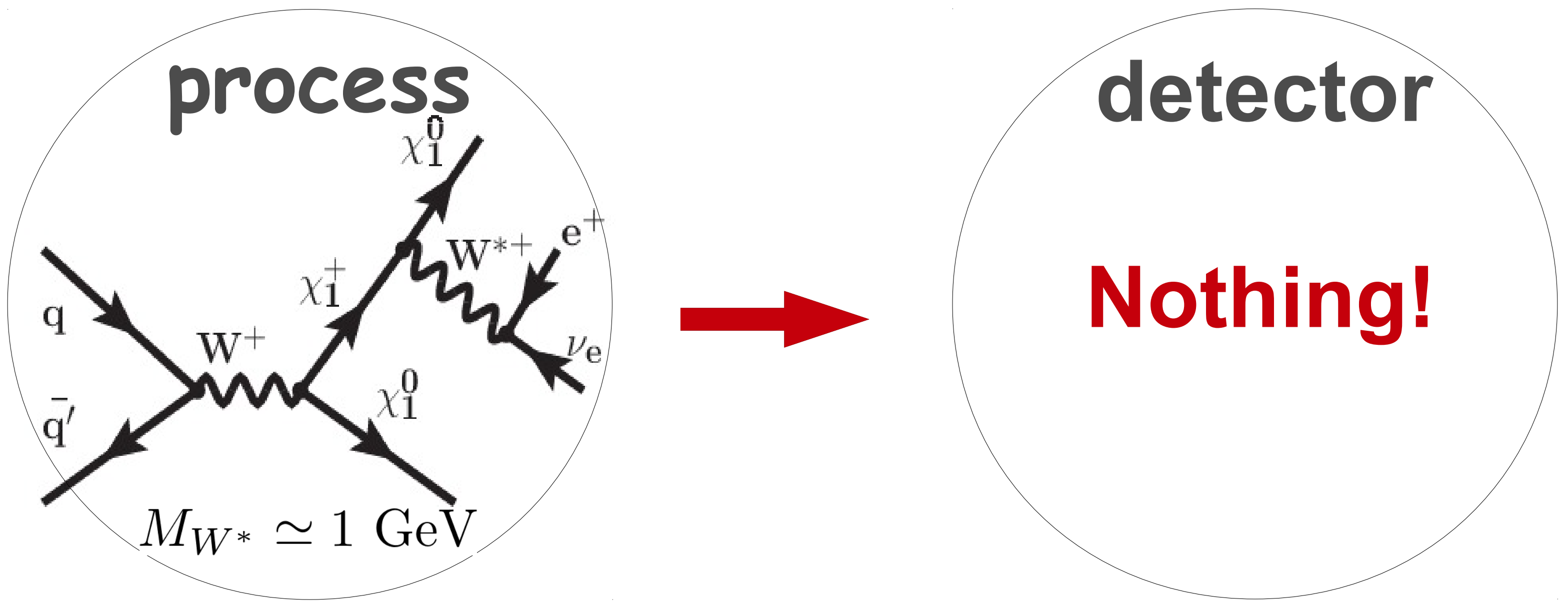




Susy Compressed Mass Spectrum scenario

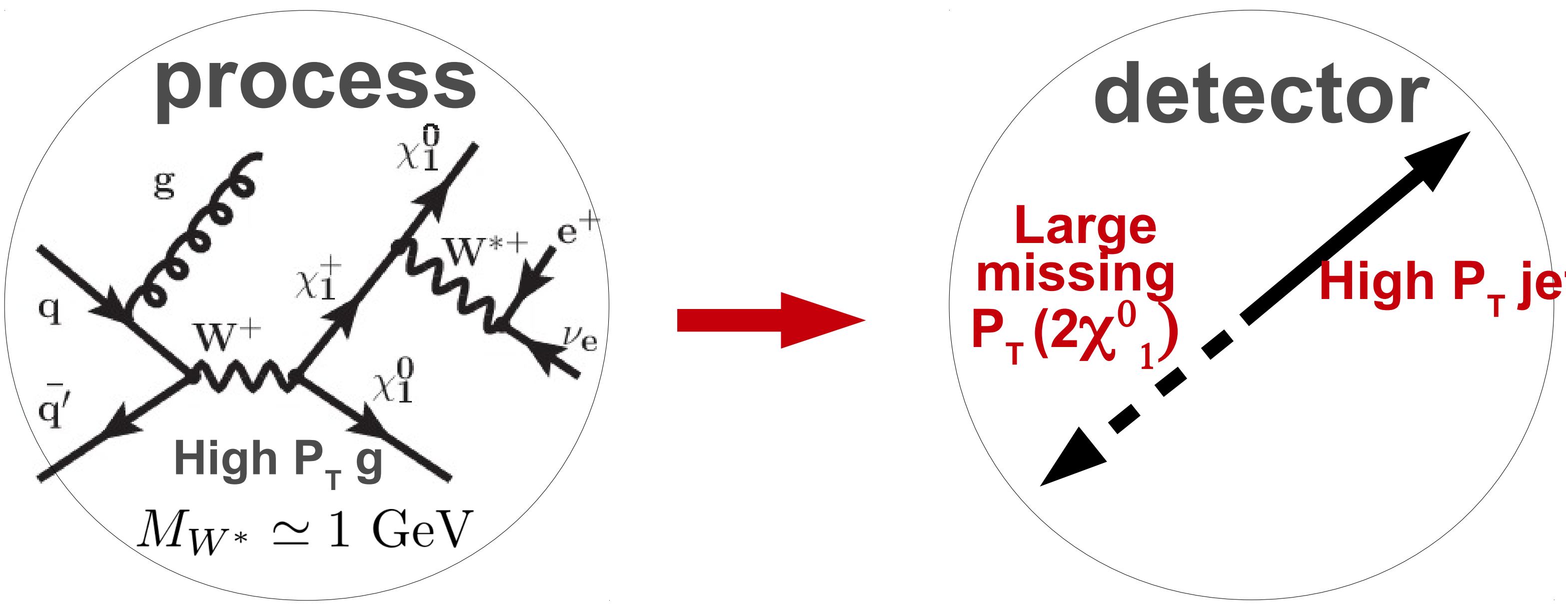
- The most challenging case takes place when only $\chi^0_{1,2}$ and $\chi^\pm$ are accessible at the LHC, and the mass gap between them is not enough for any leptonic signature

- 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



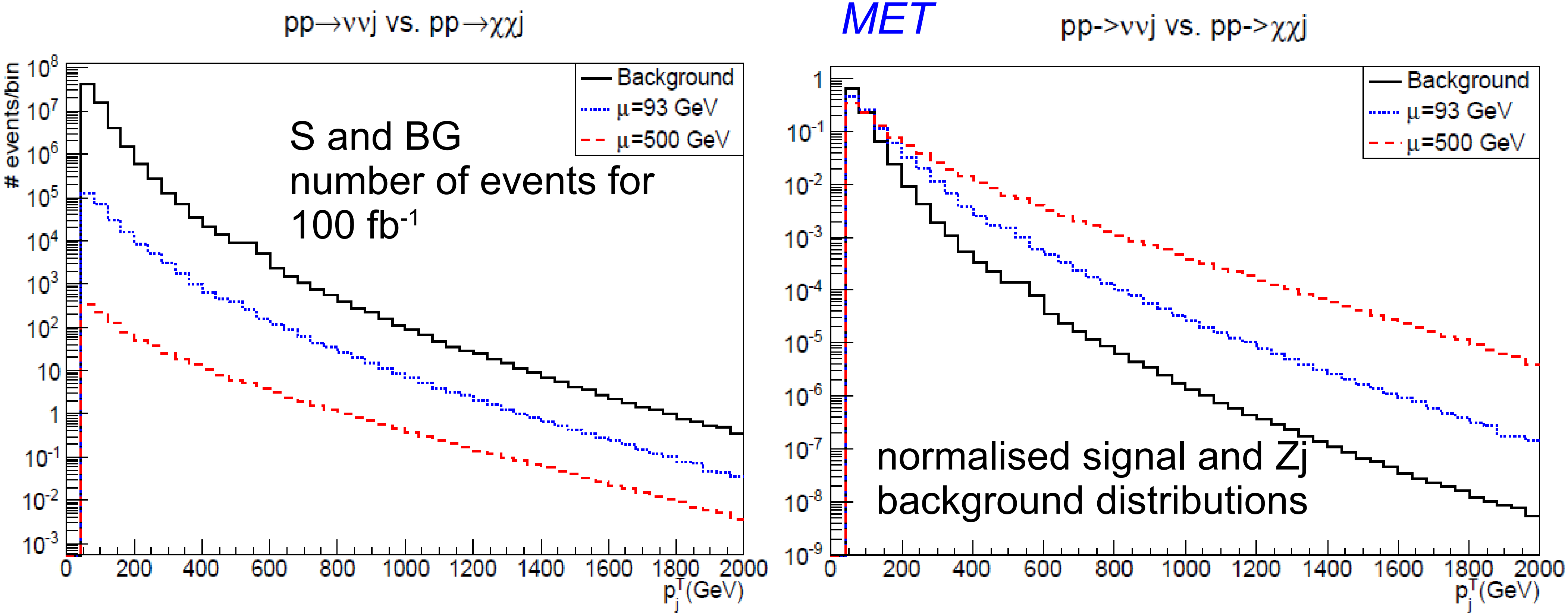
Susy Compressed Mass Spectrum scenario

- The most challenging case takes place when only $\chi^0_{1,2}$ and $\chi^{\pm}$ are accessible at the LHC, and the mass gap between them is not enough for any leptonic signature
- The only way to probe CHS is a mono-jet signature
["Where the Sidewalk Ends? ..." Alves, Izaguirre,Wacker '11] ,
which has been used in studies on compressed SUSY spectra, e.g. Dreiner,Kramer,Tattersall '12; Han,Kobakhidze,Liu,Saavedra,Wu'13; Han,Kribs,Martin,Menon '14



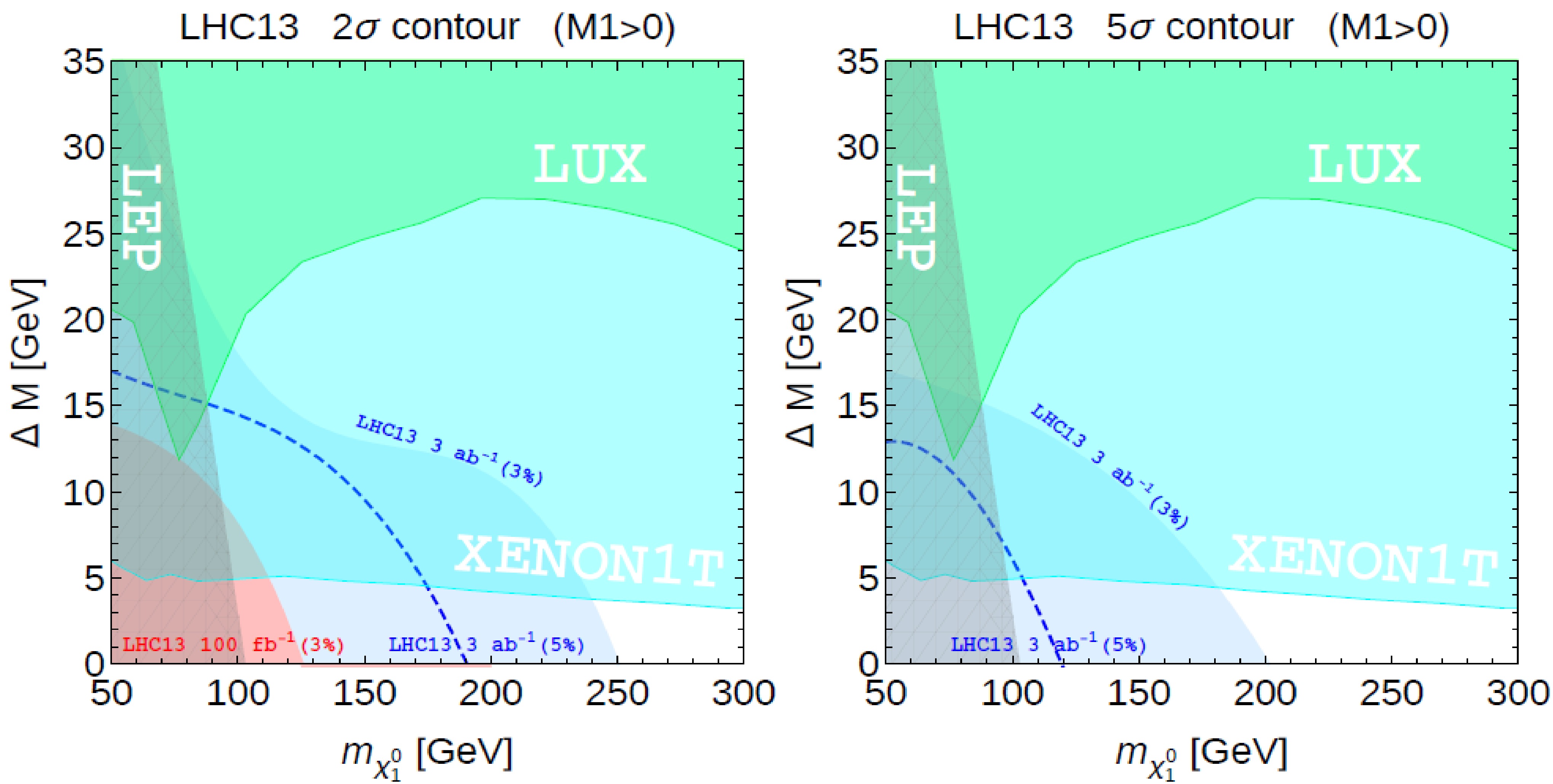
Signal vs Background

- *difference in rates is pessimistic ...*
- *but the difference in shapes is encouraging, especially for large DM mass → biger M(DM,DM) → flatter MET*



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

LHC/DM direct detection sensitivity



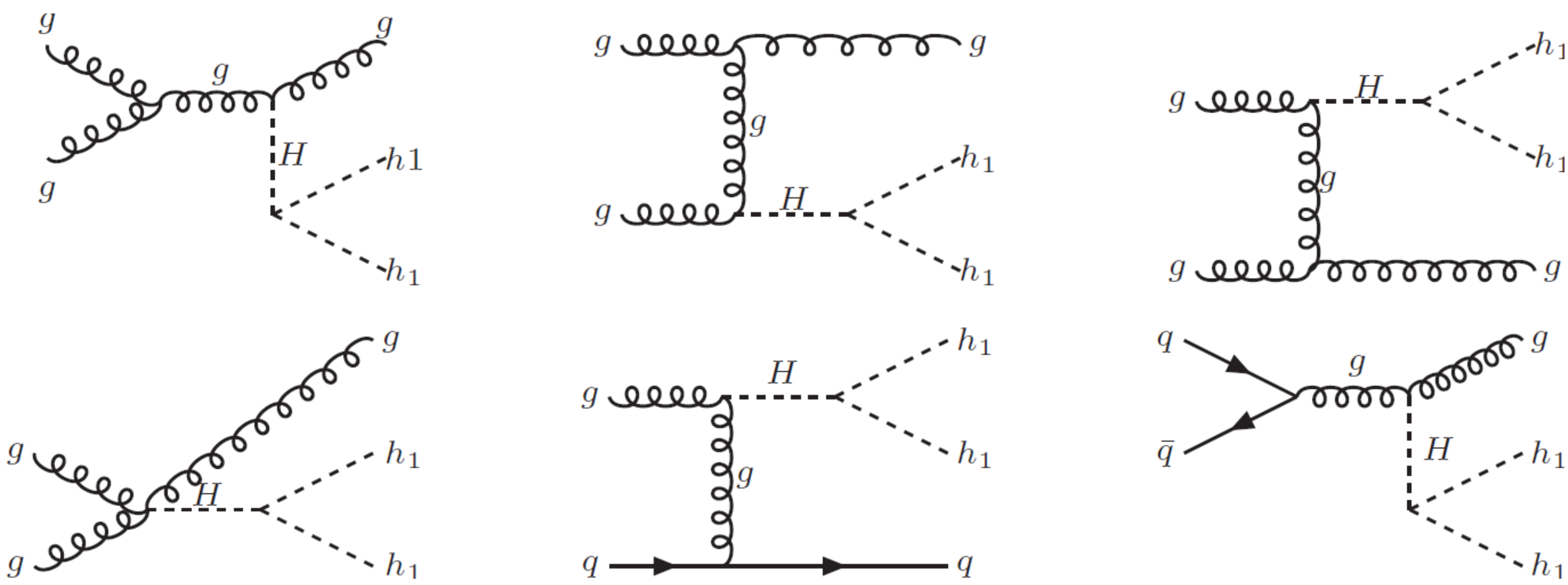
Barducci,Bharucha,Porod,Sanz,AB JHEP 1507 (2015) 066, arXiv:1504.02472

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

Case of inert 2 Higgs Doublet Model (i2HDM): consistent model with scalar DM

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

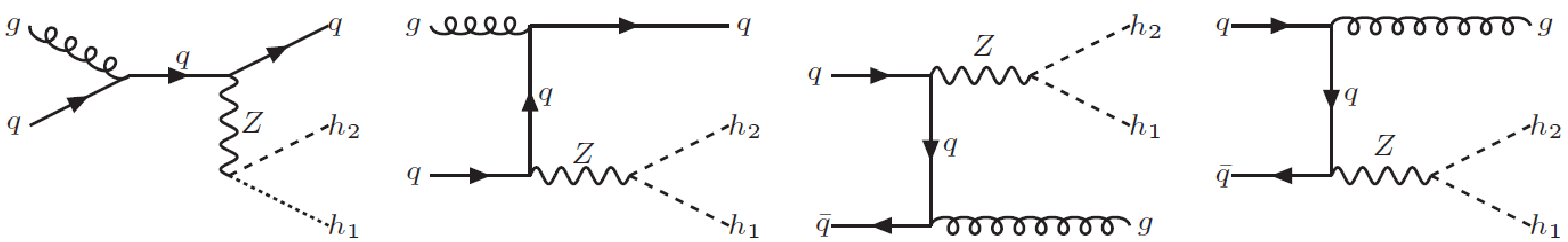
$$\begin{aligned} V &= -m_1^2(\phi_1^\dagger\phi_1) - m_2^2(\phi_2^\dagger\phi_2) + \lambda_1(\phi_1^\dagger\phi_1)^2 + \lambda_2(\phi_2^\dagger\phi_2)^2 \\ &+ \lambda_3(\phi_1^\dagger\phi_1)(\phi_2^\dagger\phi_2) + \lambda_4(\phi_2^\dagger\phi_1)(\phi_1^\dagger\phi_2) + \frac{\lambda_5}{2}\left[(\phi_1^\dagger\phi_2)^2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



Case of inert 2 Higgs Doublet Model (i2HDM): consistent model with scalar DM

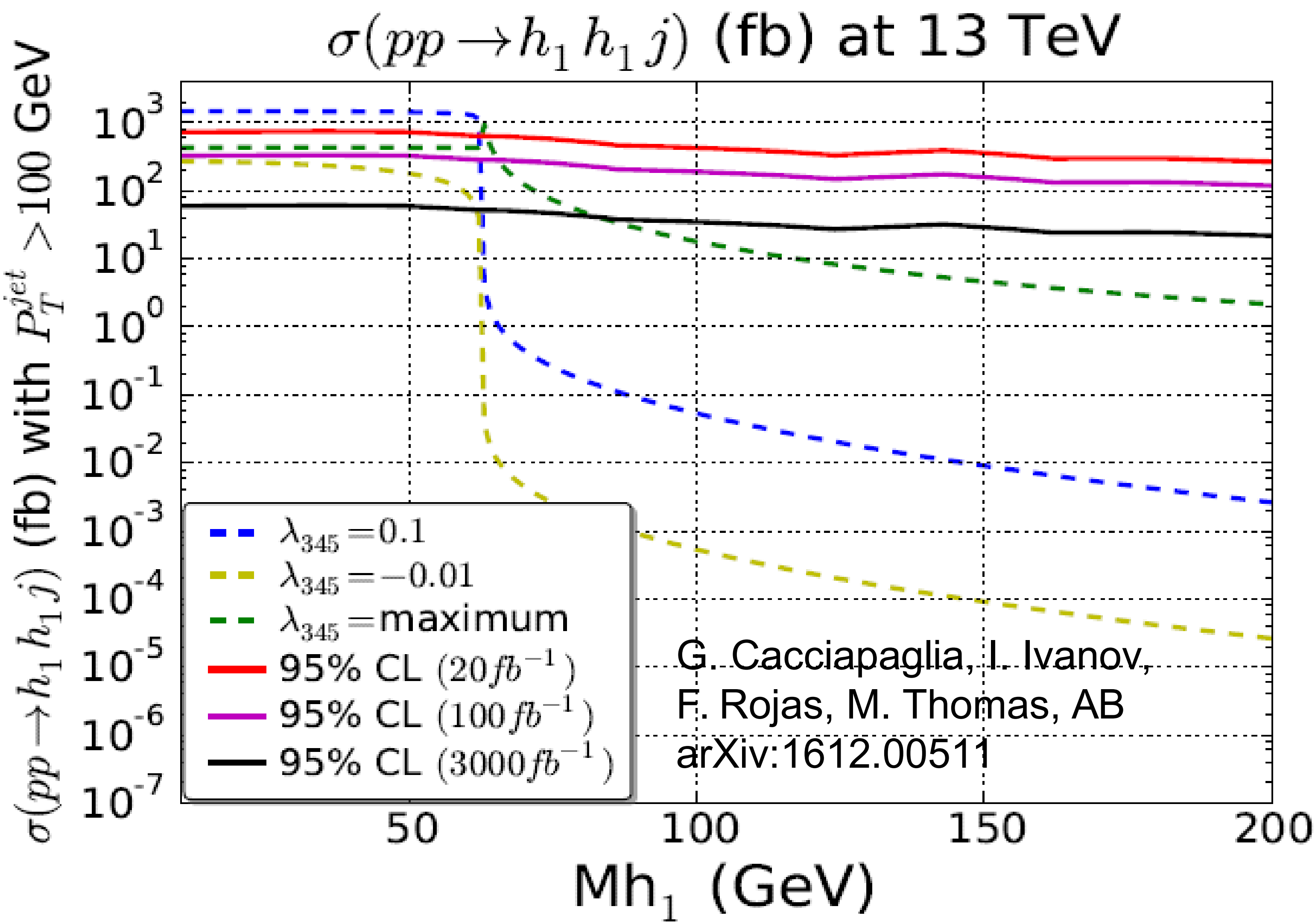
$$\phi_1 = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H \end{pmatrix} \qquad \phi_2 = \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2} h^+ \\ h_1 + i h_2 \end{pmatrix}$$

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



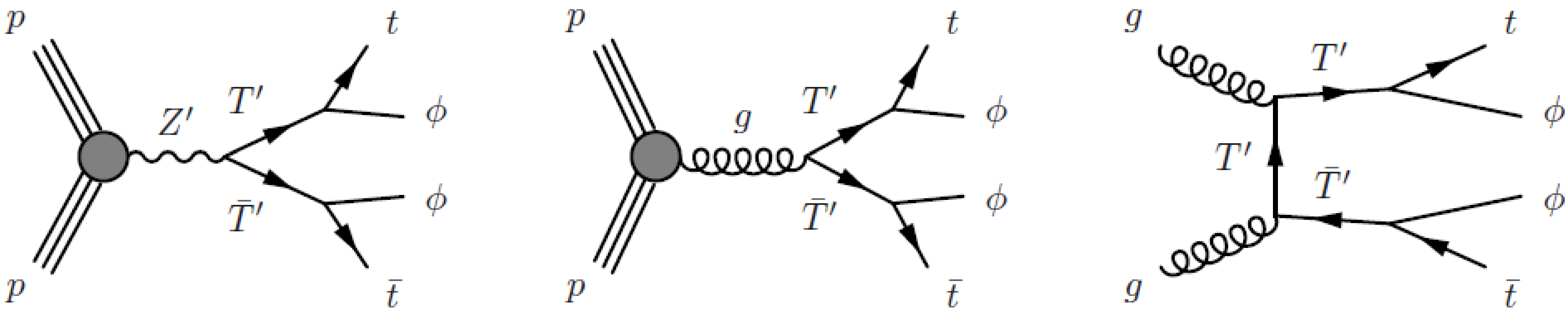
LHC reach for I2HDM with mono-jet signature

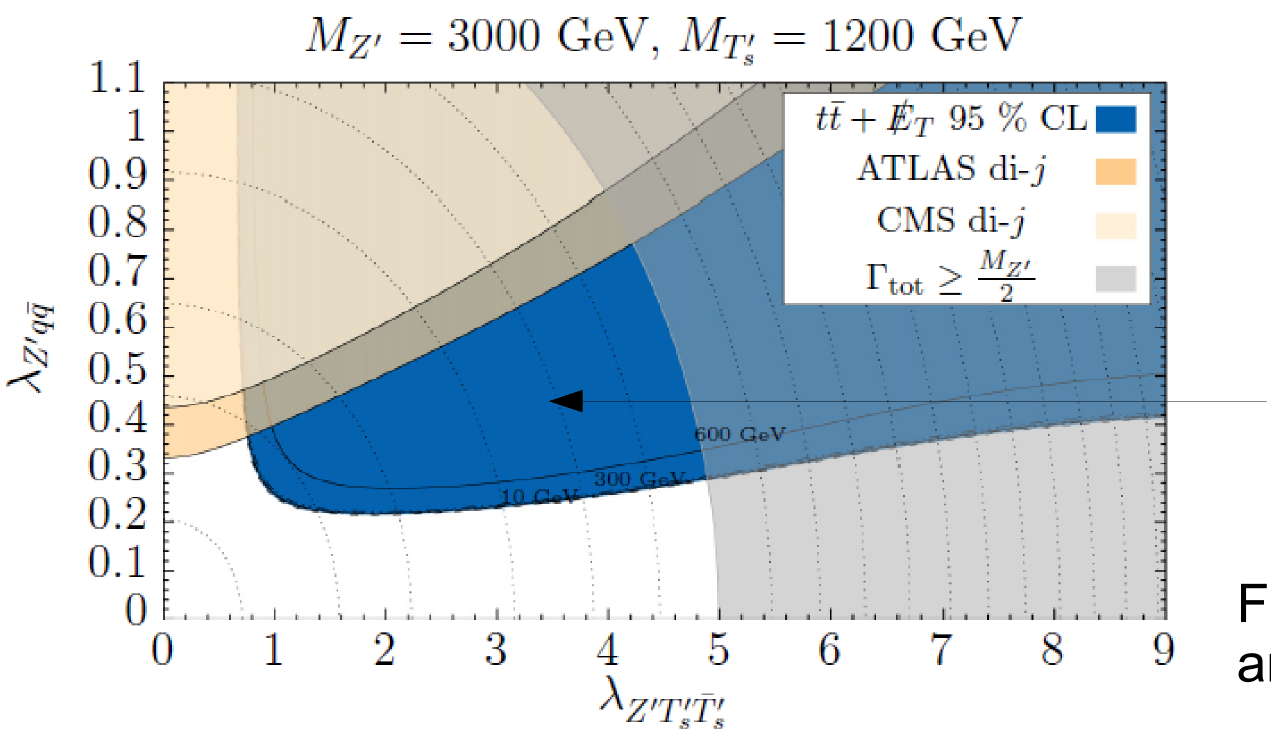
LHC is sensitive only to low DM masses – similar BG & signal shapes, poor improvement with luminosity increase



Beyond the mono-jet signature

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





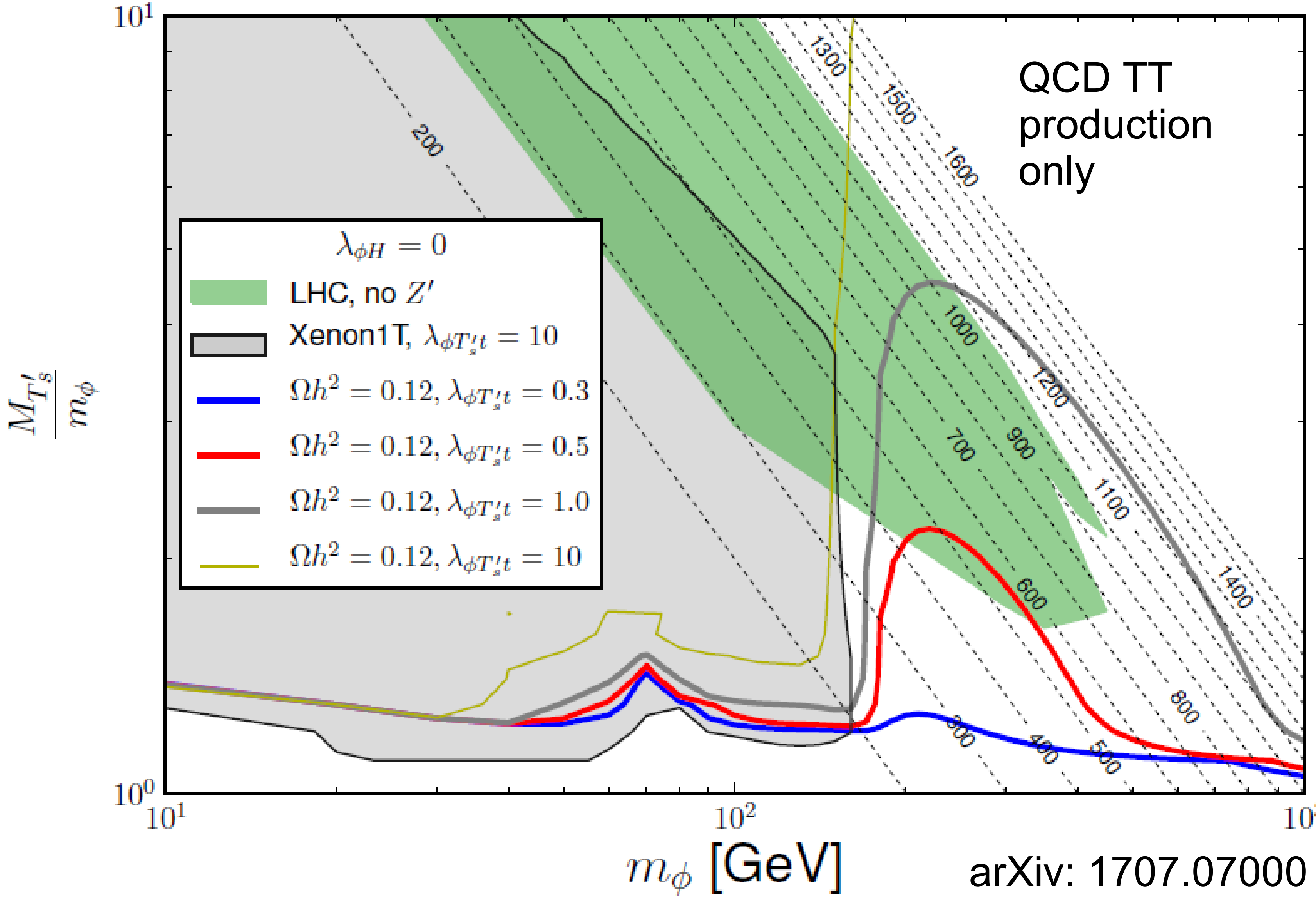
Current LHC reach with tt+ MET signature based on ATLAS_CONF_2016_050 results

Flacke, Jaine, Schaefers, AB
arXiv: 1707.07000

Complementarity of LHC and non-LHC DM searches

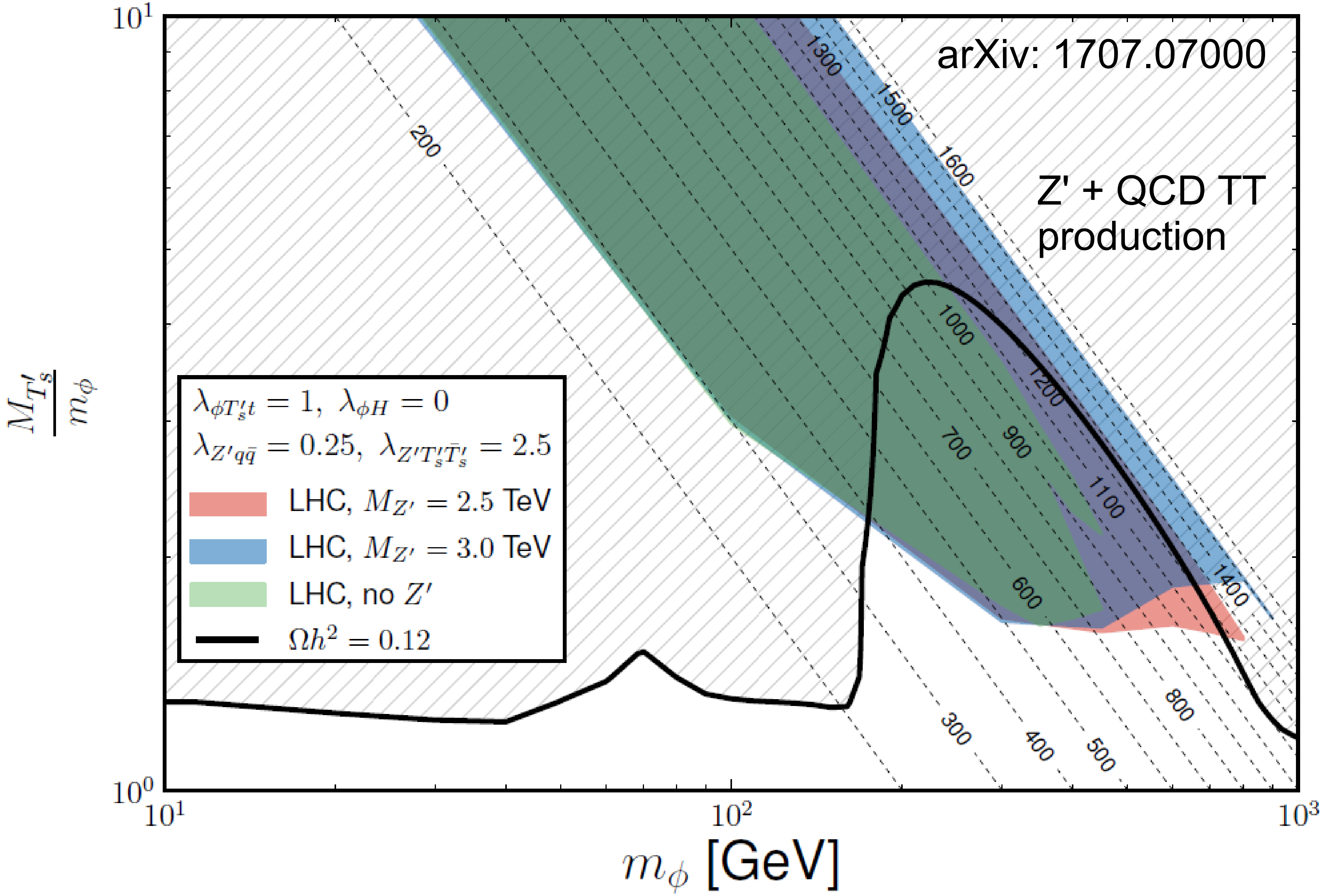
for the model with Vector Resonances, Top Partners and Scalar DM

TT→ t t DM DM



arXiv: 1707.07000

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

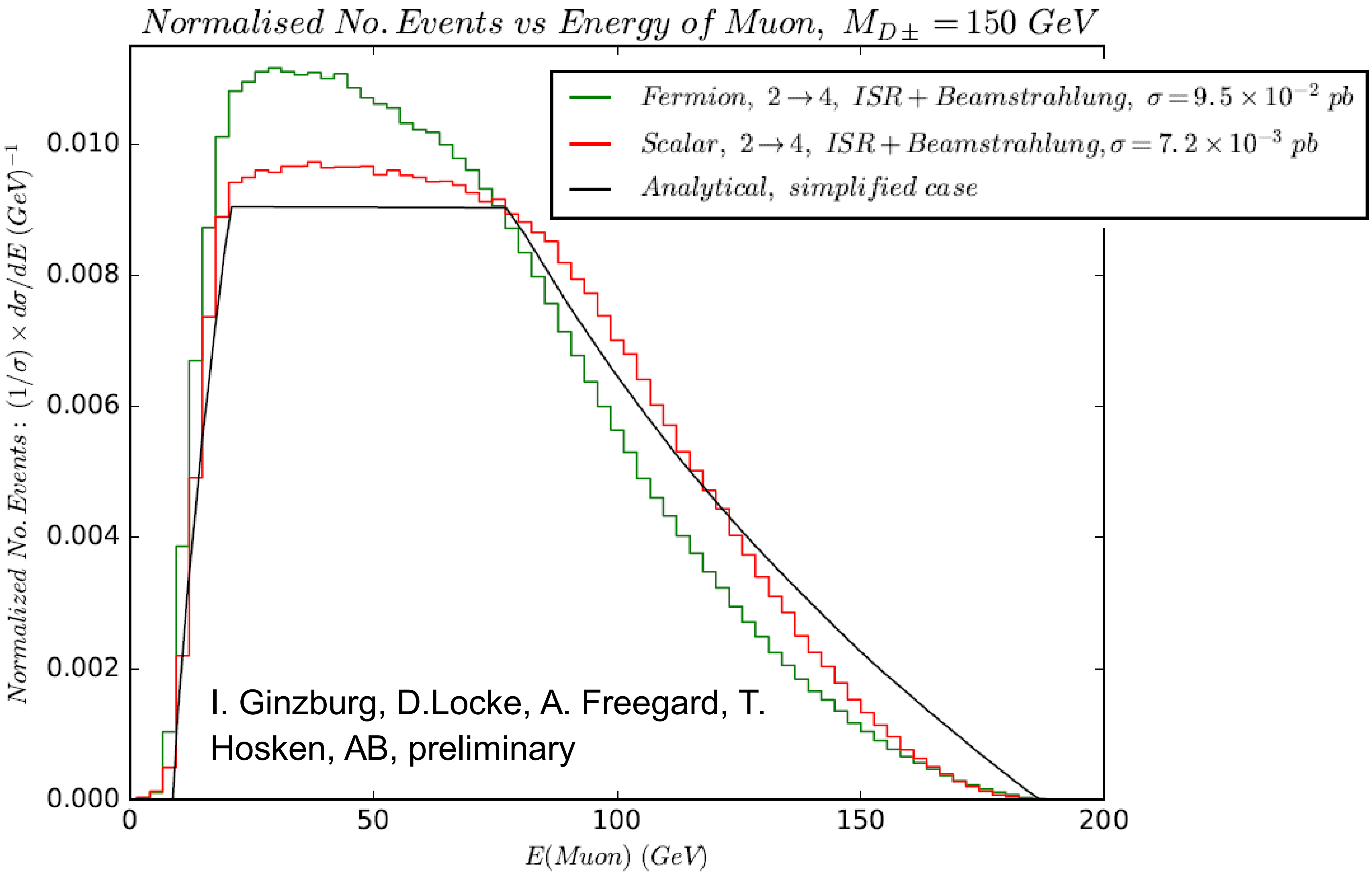


LHC is probing now DM and top partner masses up to about 0.9 and 1.5 TeV respectively: above bounds from QCD production alone by ~ factor of two!

Decoding the nature of DM at the ILC

muon spectrum from the models with scalar and fermion DM

$e^+e^- \to D^+ D^- \to DM\ DM\ W^+ W^- \to DM\ DM\ jj\ \mu\ \nu$



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
- **HEPMDB (High Energy Physics Model Database)** was created in 2011 to make the first step towards this: **hepmdb.soton.ac.uk/phenodata**
  - recently has got a status of the permanent server at Southampton
  - 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
  - users can upload their own model and perform simulation – became a very attractive feature for all range of researchers
  - **no database of signatures yet** (is under development) – you input could play and important role
- As a HEPMDB spin-off the **PhenoData** project was created **hepmdb.soton.ac.uk/phenodata** **(thanks to Dan Locke and James Blandford)**
  - stores data (digitized curves from figures, tables etc) from those HEP papers which did not provide data in arXiv or HEPData, and to avoid duplication of work of HEP researchers on digitizing plots.
  - has an easy search interface and paper identification via arXiv, DOI or preprint numbers. PhenoData is not intended to be a replication of any existing archive

Summary

- Different DM spin → different energy dependence of the DM component of the EFT operator, different M_{DMDM} distributions → different MET distributions: thus the MET is related to the DM spin andrespective operator and can characterise it
- At the LHC from 300 fb^{-1} it is possible to distinguish several classes of operators, all models are public at HEPMDB https://hepmdb.soton.ac.uk/
- The strategy on distinguishing EFT DM operators is generically applicable 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 $2M_{DM}$
- We should explore more signatures and models – to prepare more complete framework on decoding LHC signatures
- ILC is very complementary to the LHC in exploration of DM properties

Thank you!

Backup Slides

Parametrisation of the Vector DM operators

- The cross section for qq(gg) → DM DM process with a power of the energy asymptotic power, Δ_s takes a form: $$\sigma_{2\to 2} \propto \frac{1}{\Lambda^2} \times \left(\frac{E}{\Lambda}\right)^{\Delta_\sigma}$$
- On the other hand, from EFT operator we have: $$\sigma_{2\to 2} \propto \frac{1}{E^2} \times \left(\frac{E^{D-4}}{\Lambda^{D-4}}\right)^2$$ where ***D* is the actual energy** dimension of the EFT operator
- So, one finds: $$\Delta_\sigma = 2(D-5) \implies D = \Delta_\sigma/2 + 5$$
  - ***Note: D*** can be different from naive dimension ***d = 5 or 6***
  - consider V7P as an example: $$\frac{1}{2\Lambda^2}(V_\nu^\dagger \partial^\nu V_\mu + V^\nu \partial^\nu V_\mu^\dagger)\bar{q}\gamma^\mu q$$
  - with *d*=6, however for each (allowed) VDM longitudinal polarisation there is an additional **(E/M_{DM})** factor, so the actual energy scaling of VDM EFT operator, ***D*** is different!

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

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

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

- Dictionary between limits on Λ in different parametrisations:

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

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}

A Simplified Model with Vector Resonances, Top Partners and Scalar DM

$$
\begin{aligned}
\mathcal{L} &= \mathcal{L}_{SM} + \mathcal{L}_{kin} + \mathcal{L}_{Z'q} + \mathcal{L}_{Z'\ell} + \mathcal{L}_{Z'Q'} + \mathcal{L}_{\phi Q'} - V_\phi \\
\mathcal{L}_{kin} &= -\frac{1}{4}\left(\partial_\mu Z'_\nu - \partial_\nu Z'_\mu\right)\left(\partial^\mu Z'^\nu - \partial_\nu Z'^\mu\right) + \frac{M^2_{Z'}}{2} Z'_\mu Z'^\mu \\
&+ \frac{1}{2}\partial_\mu\phi\,\partial^\mu\phi - \frac{m^2_\phi}{2}\phi^2 \\
&+ \overline{T'_s}\left(i\not{D} - M_{T'_s}\right)T'_s + \overline{Q'_d}\left(i\not{D} - M_{T'_d}\right)Q'_d\,, \\
\mathcal{L}_{Z'q} &= \lambda_{Z'q\bar{q},L/R}\, Z'_\mu\left(\bar{q}_{L/R}\,\gamma^\mu\, q_{L/R}\right)\,, \\
\mathcal{L}_{Z'\ell} &= \lambda_{Z'\ell^+\ell^-,L/R}\, Z'_\mu\left(\bar{\ell}_{L/R}\,\gamma^\mu\, \ell_{L/R}\right)\,, \\
\mathcal{L}_{Z'Q'} &= \lambda_{Z'T'_s\overline{T'_s},L/R}\, Z'_\mu\left(\overline{T'}_{s,L/R}\,\gamma^\mu\, q_{L/R}\right) \\
&+ \lambda_{Z'T'_d\overline{T'_d},L/R}\, Z'_\mu\left(\overline{T'}_{d,L/R}\,\gamma^\mu\, T'_{d,L/R}\right) \\
&+ \lambda_{Z'T'_d\overline{T'_d},L/R}\, Z'_\mu\left(\overline{B'}_{d,L/R}\,\gamma^\mu\, B'_{d,L/R}\right)\,, \\
\mathcal{L}_{\phi Q'} &= \left(\lambda_{\phi T'_s t}\,\phi\,\bar{t}_R\,T'_{s,R} + \lambda_{\phi T'_d t}\,\phi\,\bar{t}_L\,T'_{d,L} + \lambda_{\phi T'_d t}\,\phi\,\bar{b}_L\,B'_{d,L}\right) + \text{h.c.}\,, \\
V_\phi &= \frac{\lambda_\phi}{4!}\phi^4 + \frac{\lambda_{\phi H}}{2}\phi^2\left(|H|^2 - \frac{v^2}{2}\right).
\end{aligned}
$$