Towards Decoding the Nature of Dark Matter at the LHC

Alexander Belyaev

Southampton University & Rutherford Appleton LAB

LPC forum
FNAL
17 August 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**
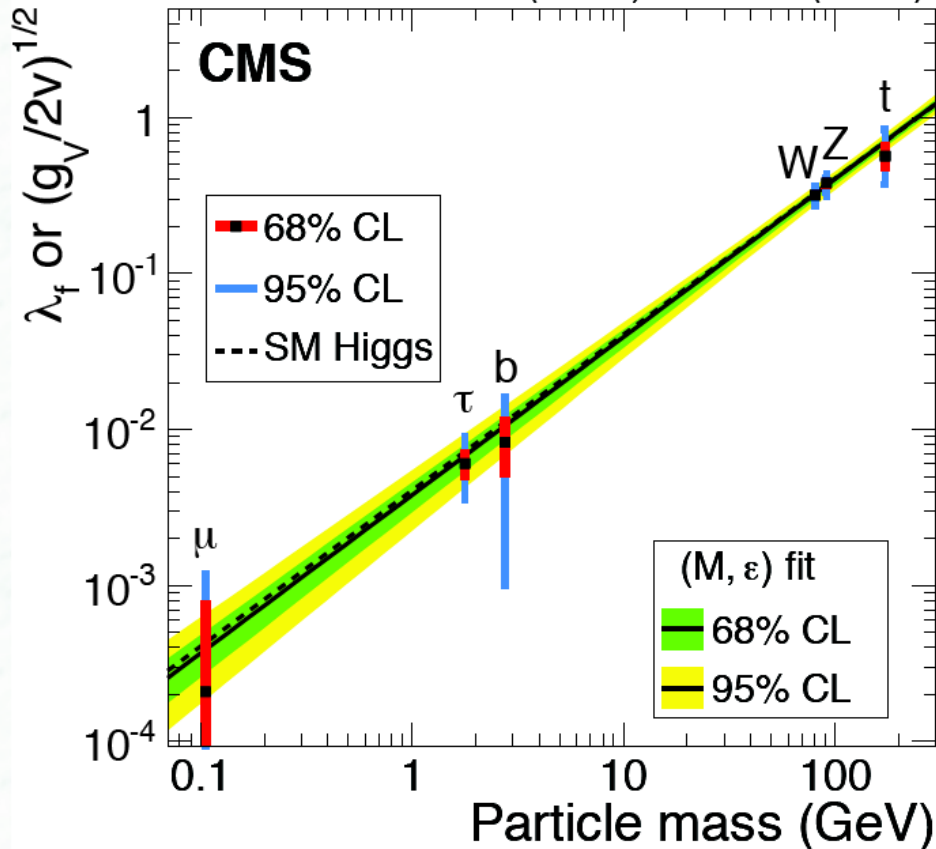- I. Ginzburg, D.Locke, A. Freegard, T. Hosken, AB – distinguishing DM spin at the ILC

The the Standard Model is very successful at the LHC

λ = Yukawa coupling for fermions
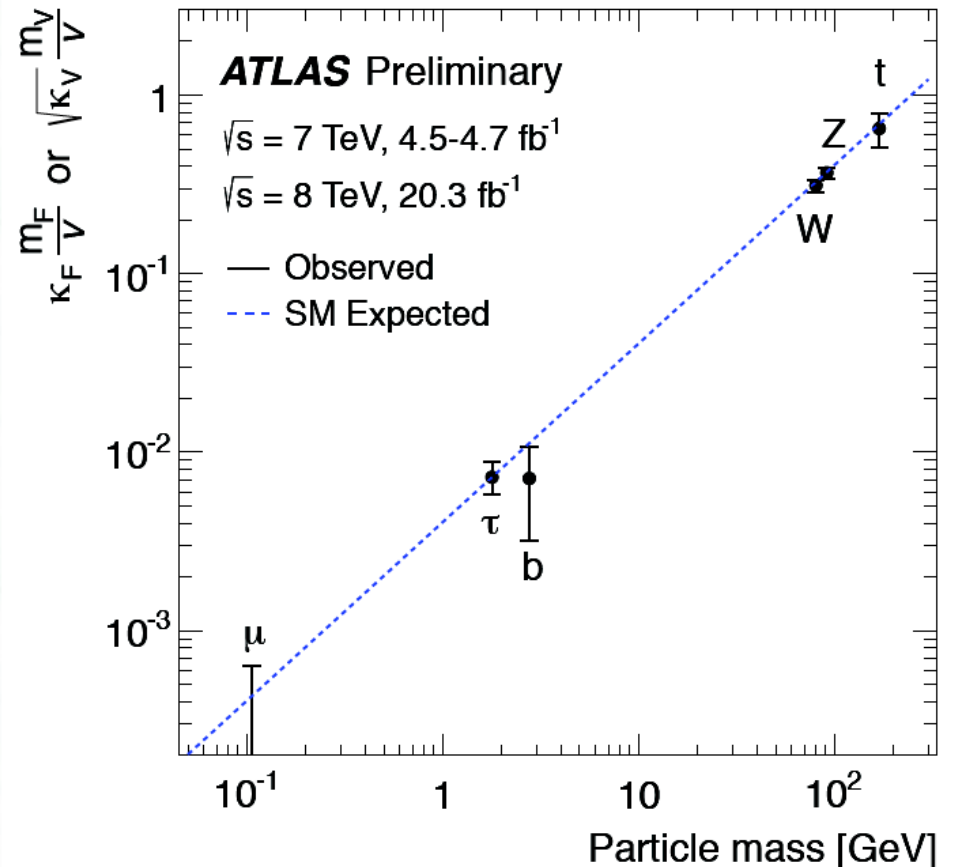√g/2v = couplings for W/Z bosons

EPJ C75 (2015) 5, 212

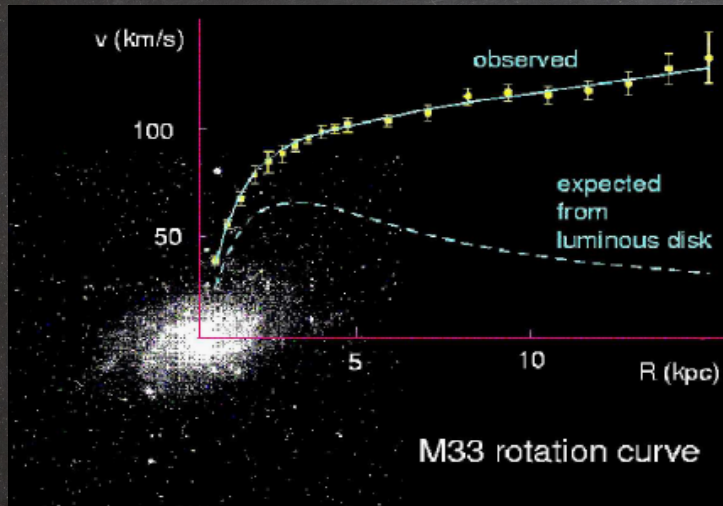**For the first time, non-universal, mass-dependent couplings observed**

ATLAS-CONF-2015-007

But at a bigger scale SM is empirically incomplete!

the presence of non-baryonic, cold dark matter: DM is **neutral, stable, colourless, non-baryonic** and **massive** (cold or warm). Neutrinos are too light, make instead hot DM

Galactic rotation curves

CMB: WMAP and PLANCK

Large Scale Structures
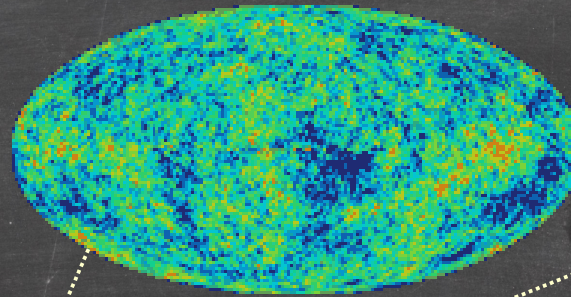

Gravitational lensing

Bullet cluster

But at a bigger scale SM is empirically incomplete!

- the presence of non-baryonic, cold dark matter: DM is **neutral, stable, colourless, non-baryonic** and **massive** (cold or warm). Neutrinos are too light, make instead hot DM
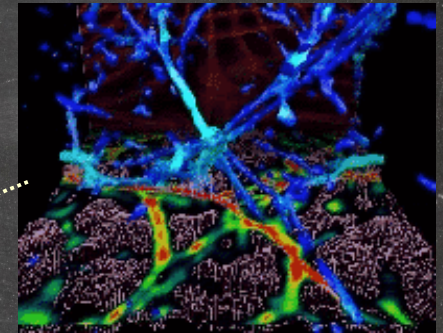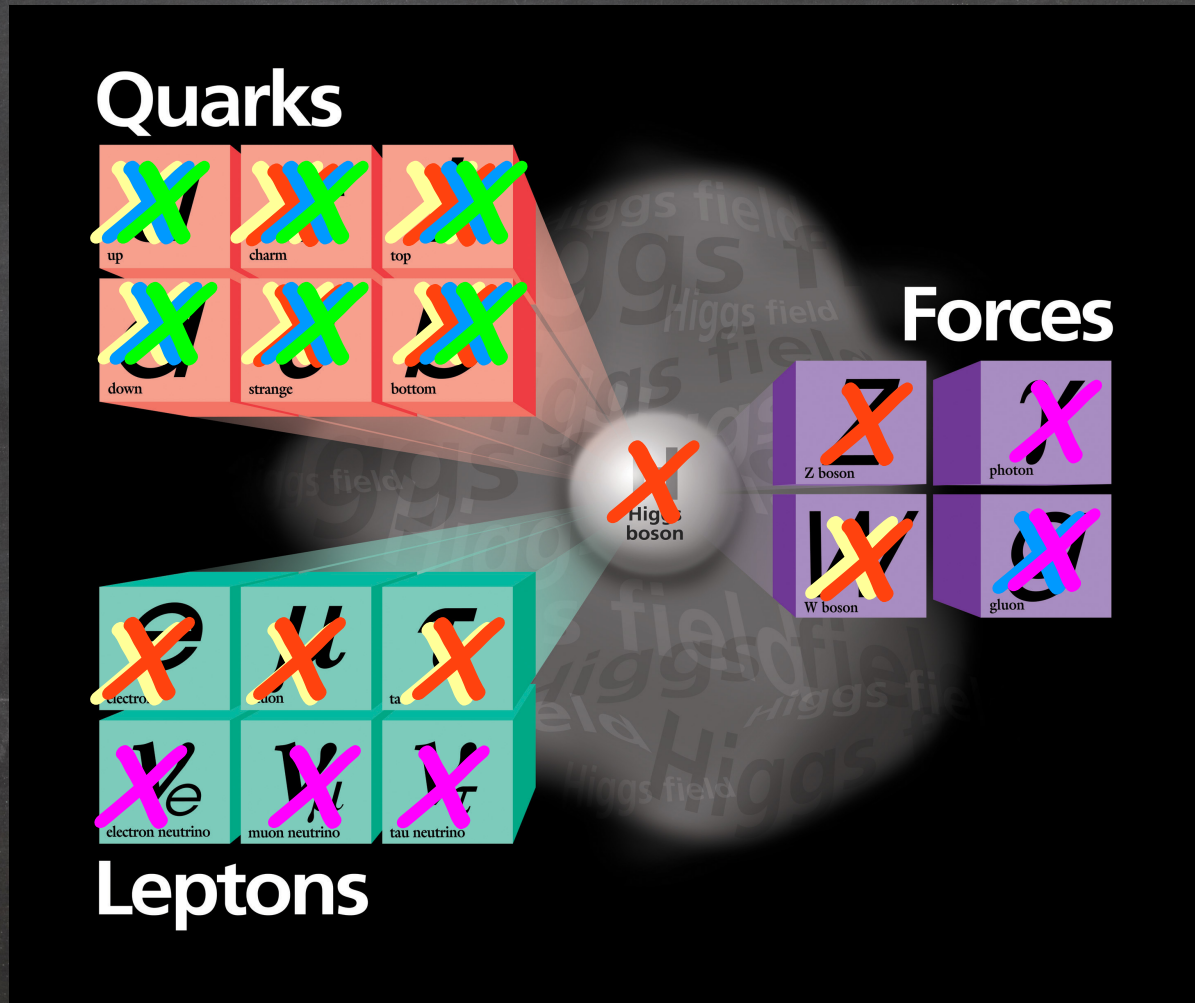
While Higgs Boson Discovery has completed the SM puzzle ...

While Higgs Boson Discovery has completed the SM puzzle ... the SM itself can be viewed itself as a piece of a bigger puzzle – the BSM one !

The Nature of Higgs Boson

Fine-tuning problem

The origin of matter/anti-matter asymmetry

Dark Matter problem

Connection to GUT & couplings unification
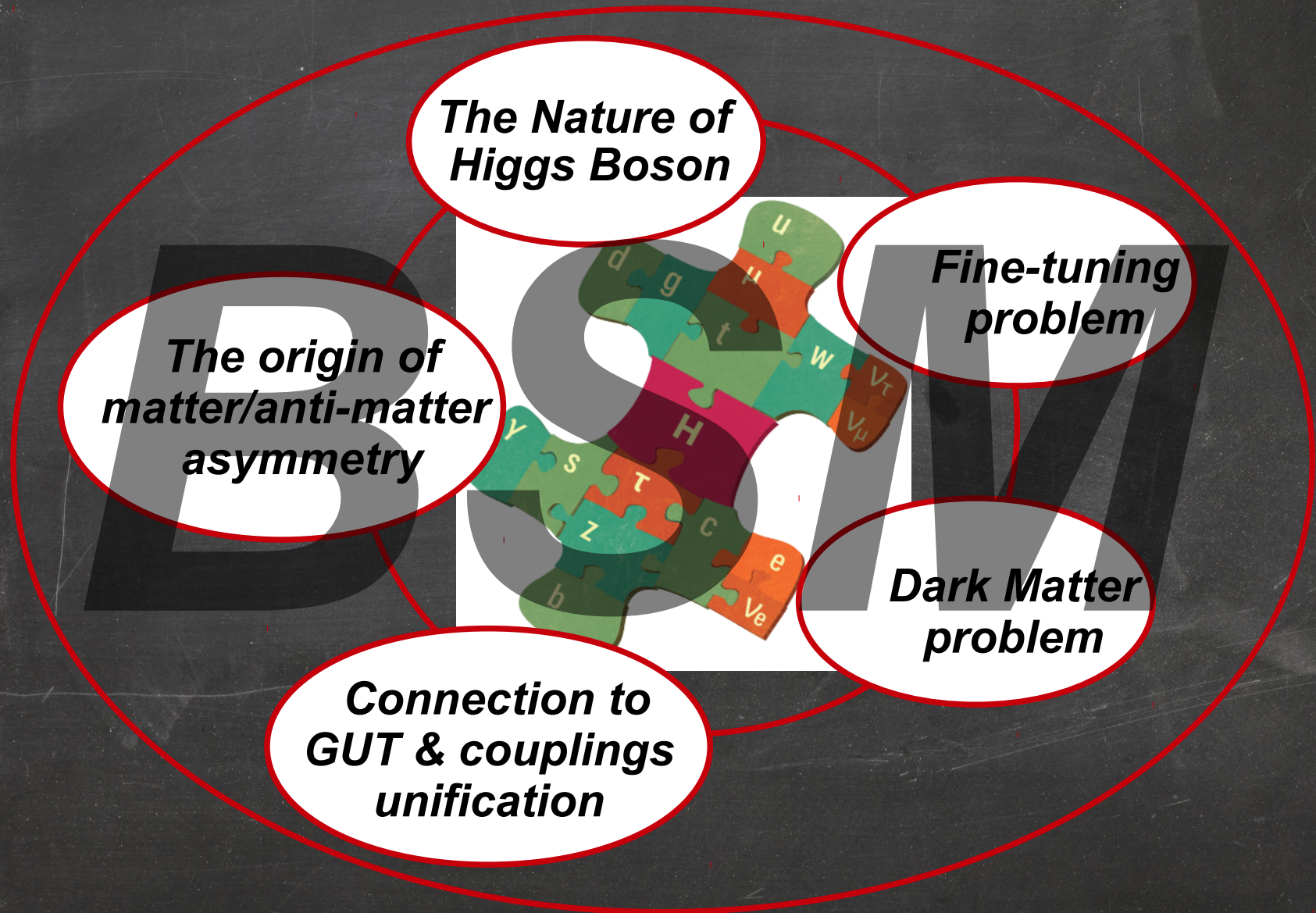
Why we are so keen to study DM?
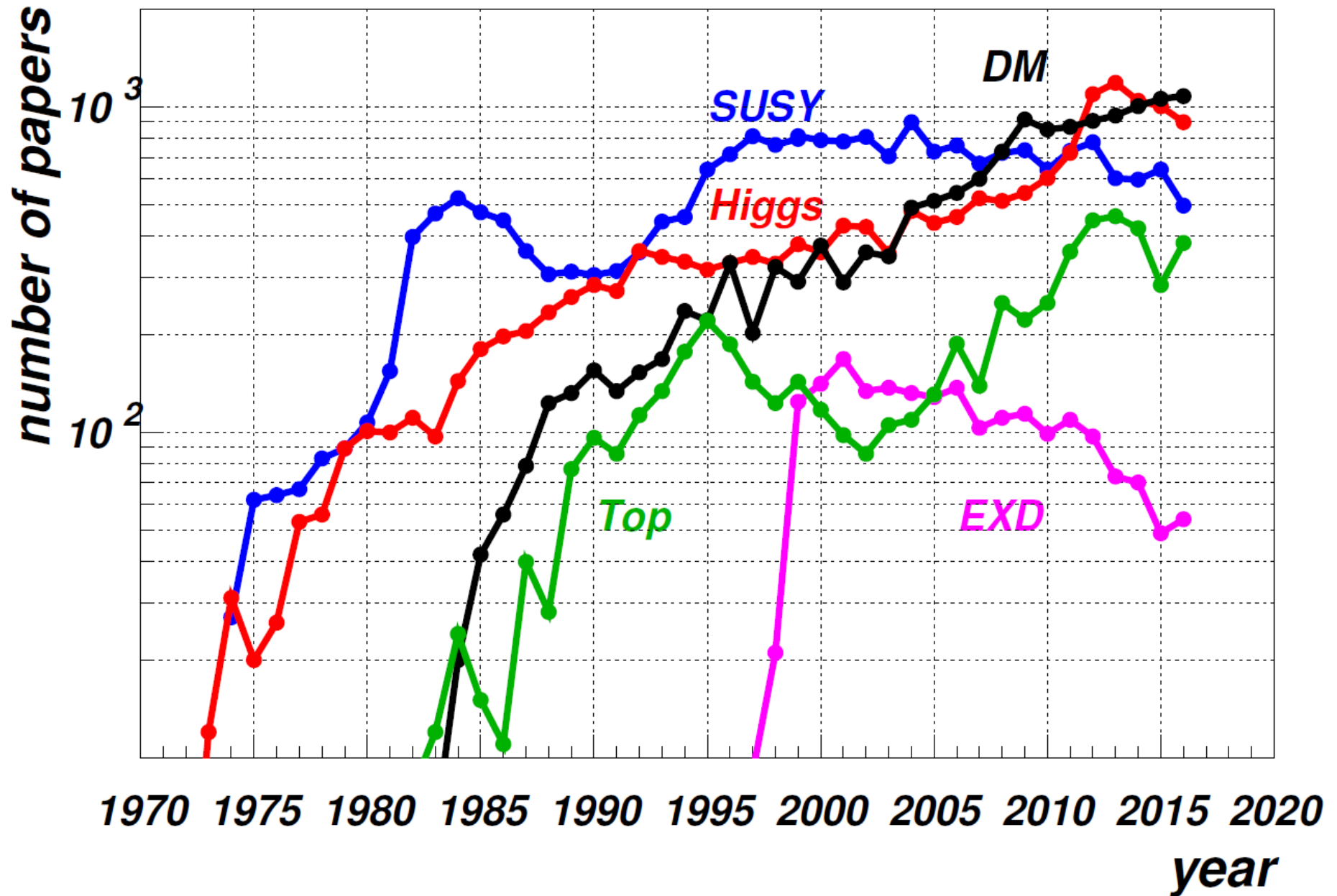
Why we are so keen to study DM?
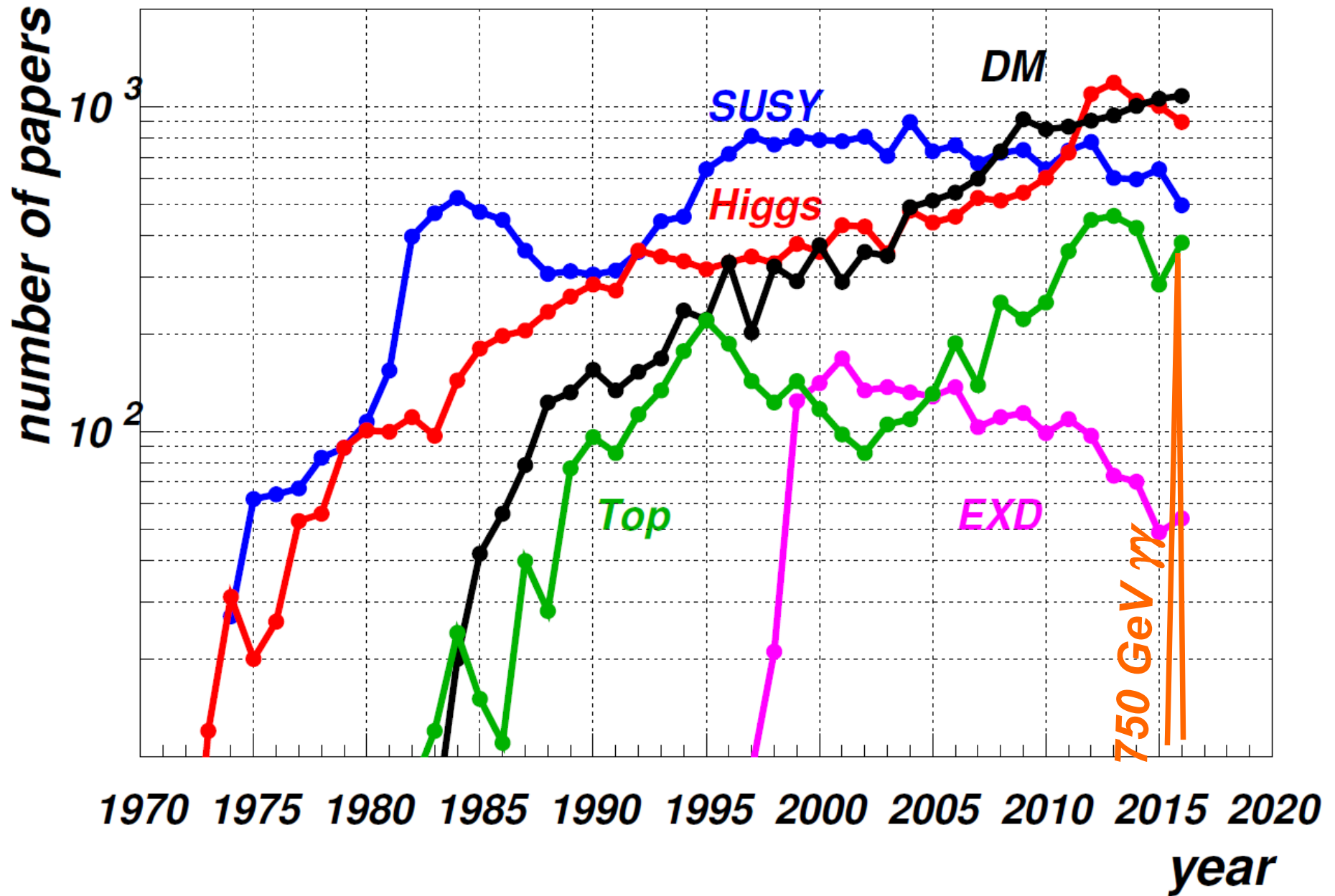
Because the existence of DM is the strongest evidence for BSM, even though we know almost nothing about it!

Spin ?

Mass ?

Stable
Yes ?   No ?
symmetry
behind stability ?

Couplings
gravity ✓
Weak ?
Higgs ?
Quarks/gluons ?
Leptons ?
New mediators ?

Thermal relic
Yes ?   No ?

Theories of Dark Matter

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

T.Tait

Spectrum of Theory Space

Less Complete

Dipole Interactions

Effective Field Theories

dark photon

Z'

Models

Simplified Models

Contact Interactions

Higgs portal

"Squarks"

UED

UV Complete Models

MSSM

Sketches of Models

Little Higgs

More Complete

mSUGRA
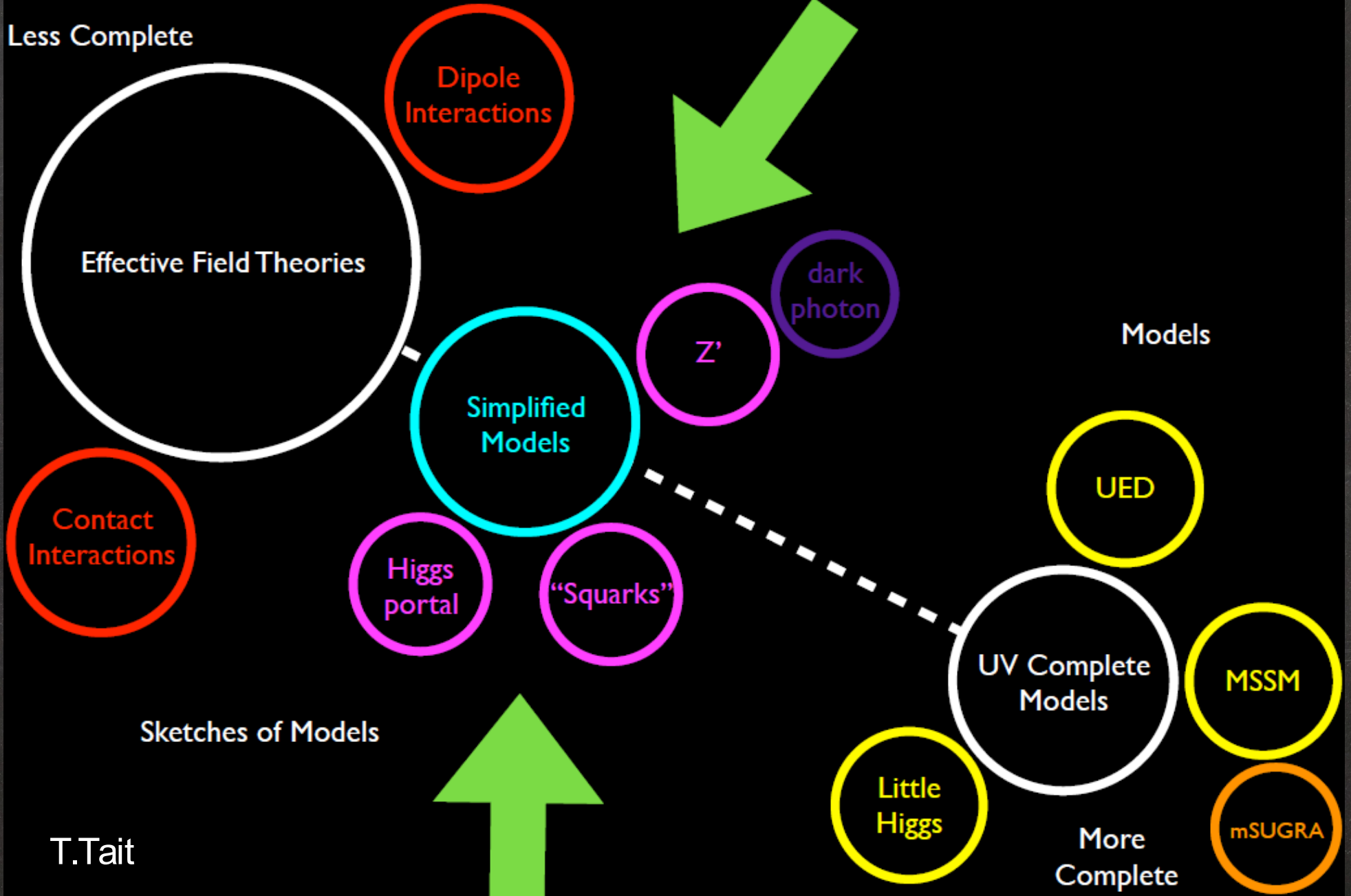
T.Tait

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**

Efficient annihilation now: Indirect (ID) DM Detection

(——) **DM**   (——) **DM**

SM   **SM**

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

$(\overline{\text{DM}})$ DM $(\overline{\text{DM}})$ DM

SM SM

Efficient annihilation now: Indirect (ID) DM Detection

Efficient scattering off nuclei: DM Direct Detection (DD)

Signature from energy deposition from nuclei recoil: LUX, XENON, WARP,
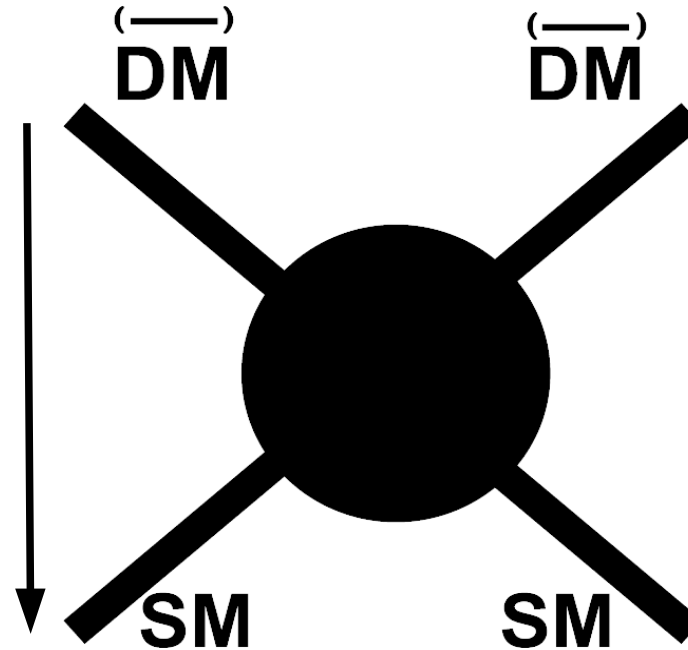
DM Observables: the power of WIMP

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

(——)   (——)
DM   **DM**

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

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

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

Efficient annihilation now: Indirect (ID) DM Detection

Efficient production at colliders

LHC signatures

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

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

SM   **SM**

Efficient scattering off nuclei: DM Direct Detection (DD)

Signature from energy deposition from nuclei recoil: LUX, XENON, WARP,
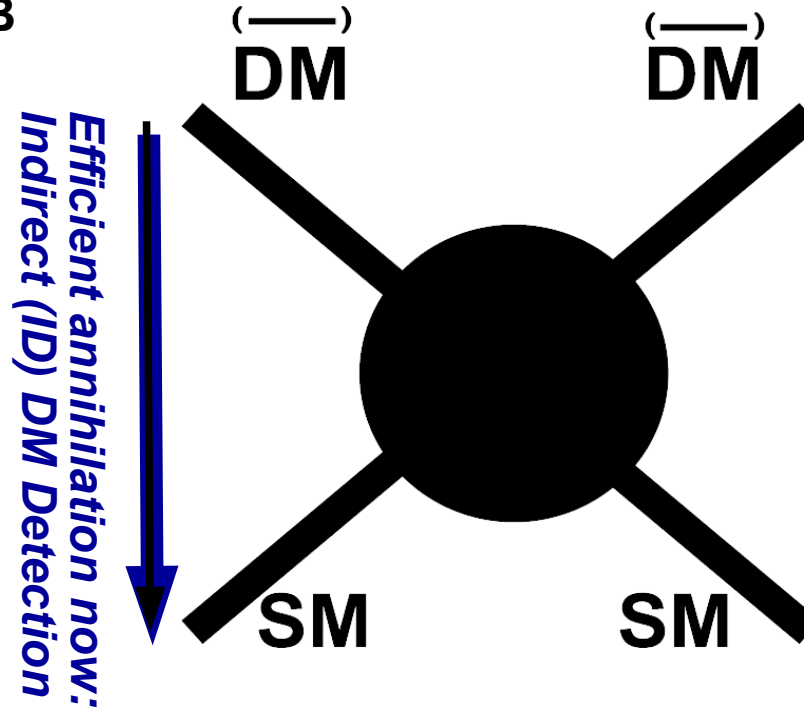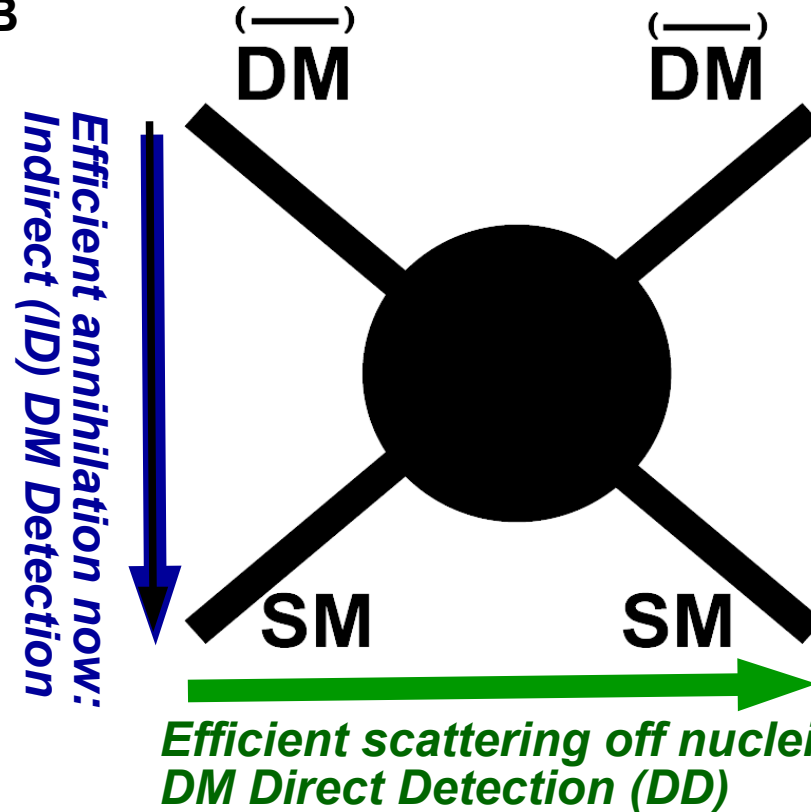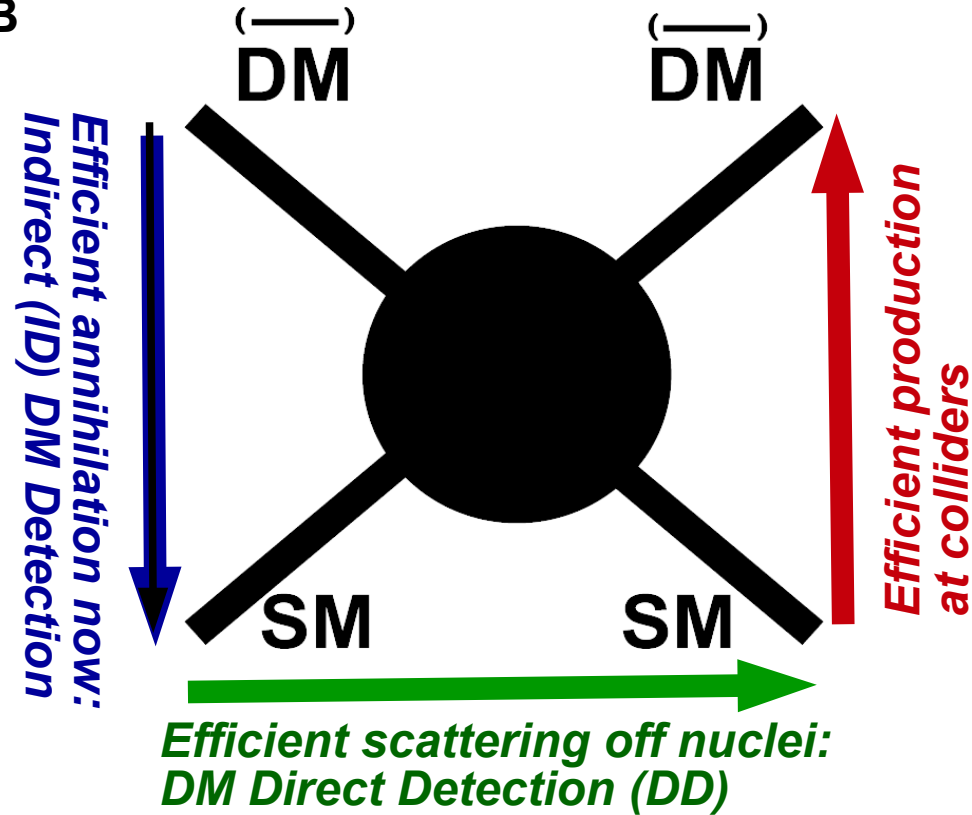
DM Observables: the power of WIMP

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

(——) **DM**   (——) **DM**

SM   **SM**

Efficient annihilation now: Indirect (ID) DM Detection

Efficient production at colliders

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
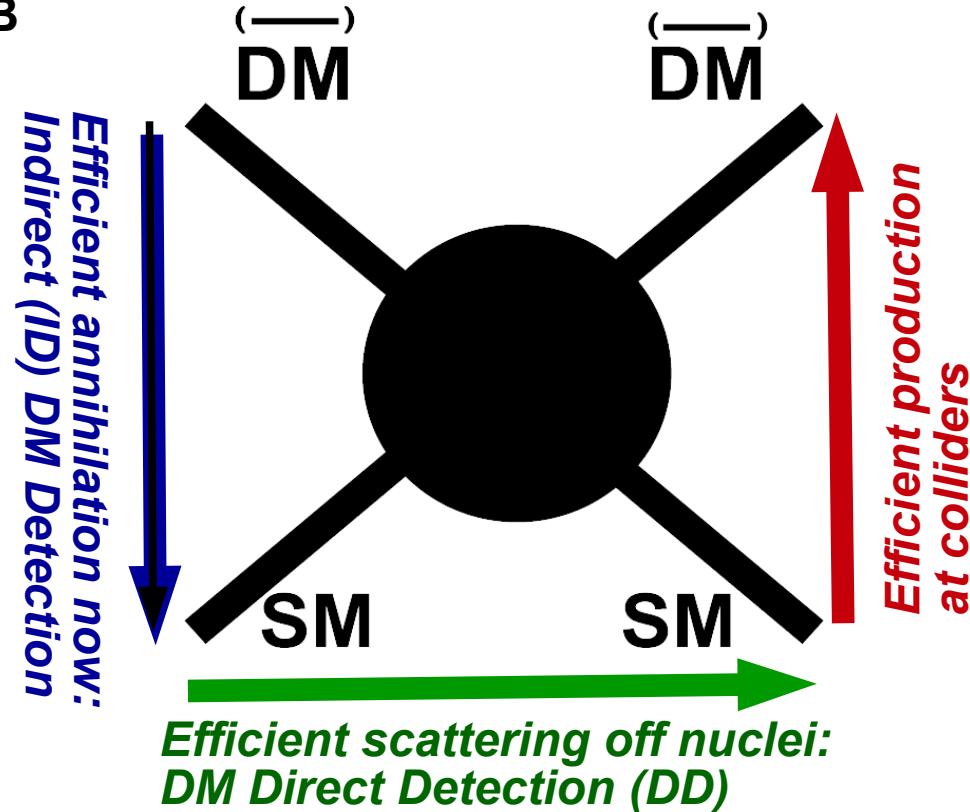
- VBF+MET
- soft leptons+MET
- ....

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

process

q

$\bar{q}$

DM

DM

→

detector

?

Hunting for DM at Colliders

process

q

q̄

DM

DM

→

detector

Nothing!

Hunting for DM at Colliders

process

g

q

q̄

DM

DM

detector

Large missing P_T (2DM)

High P_T jet

monojet signature
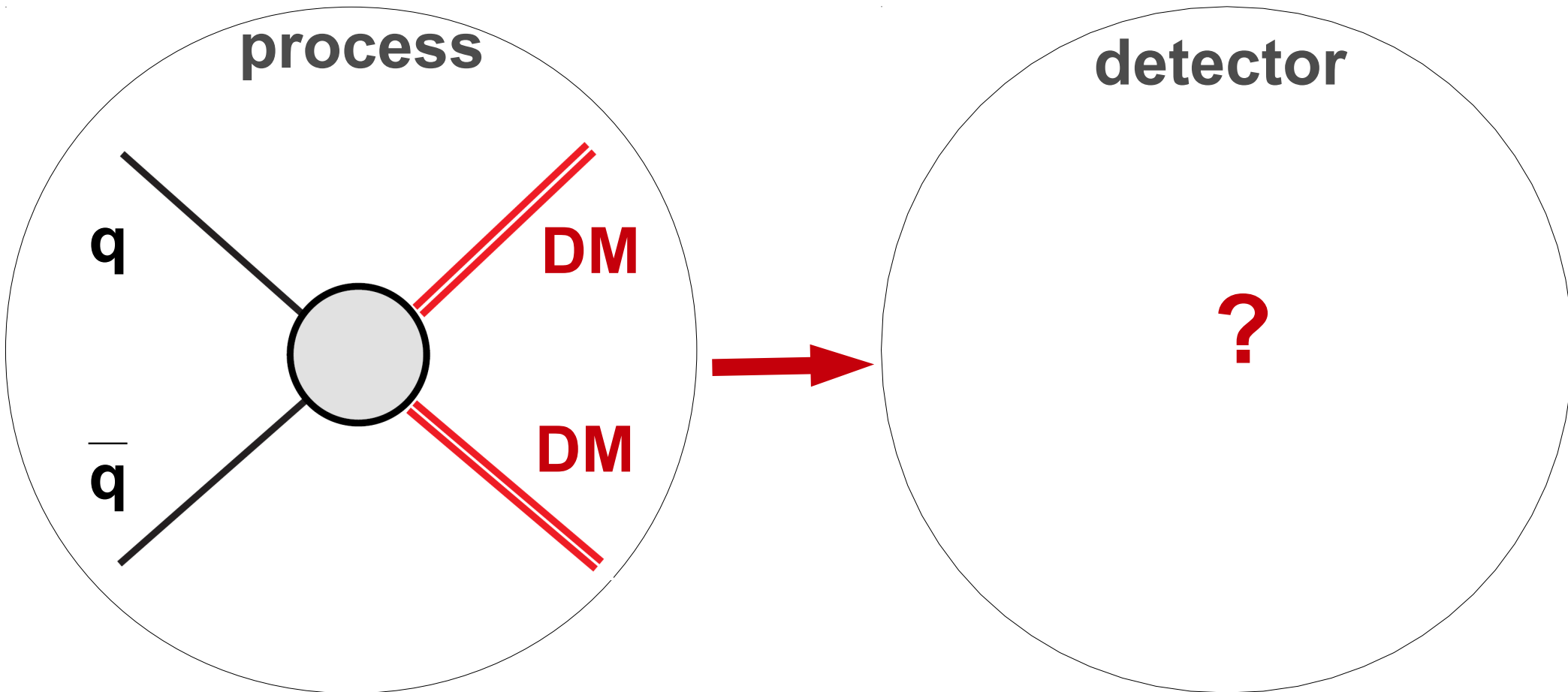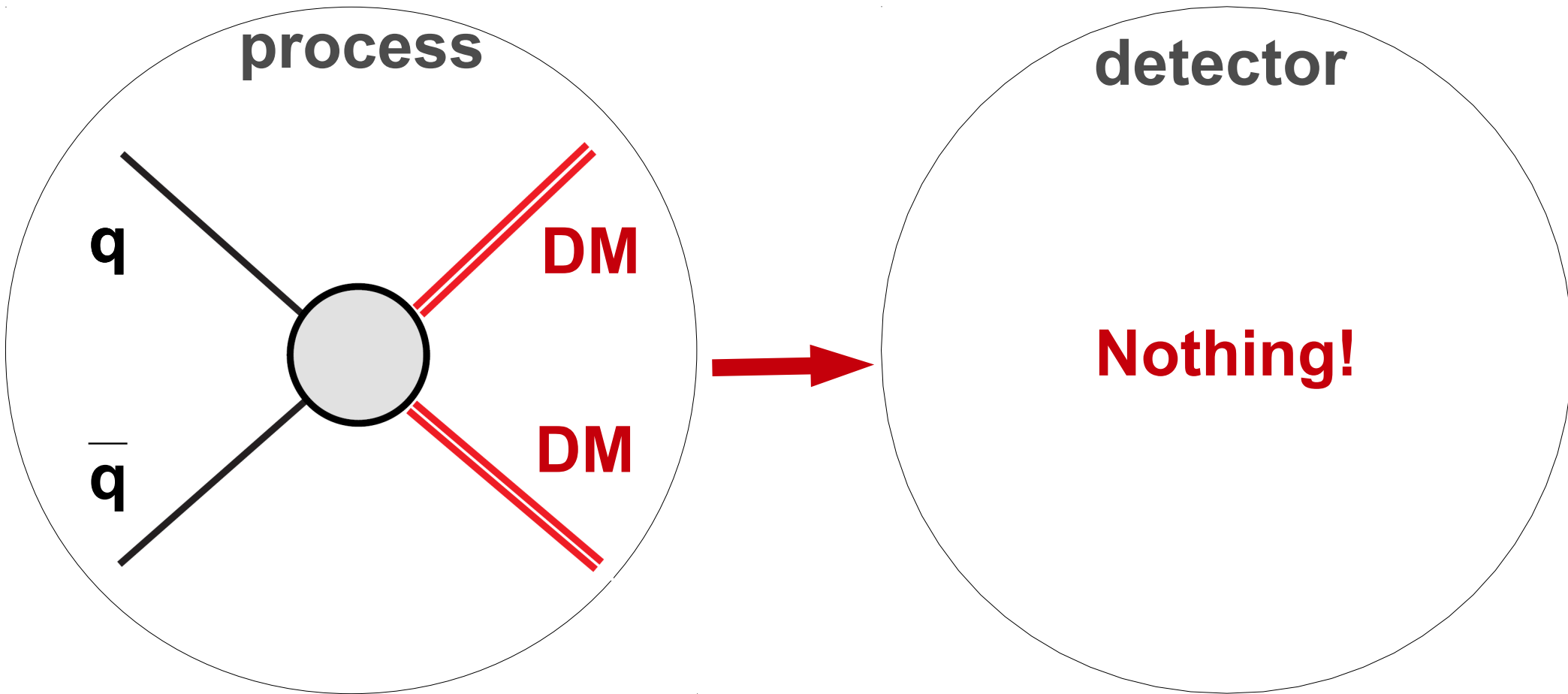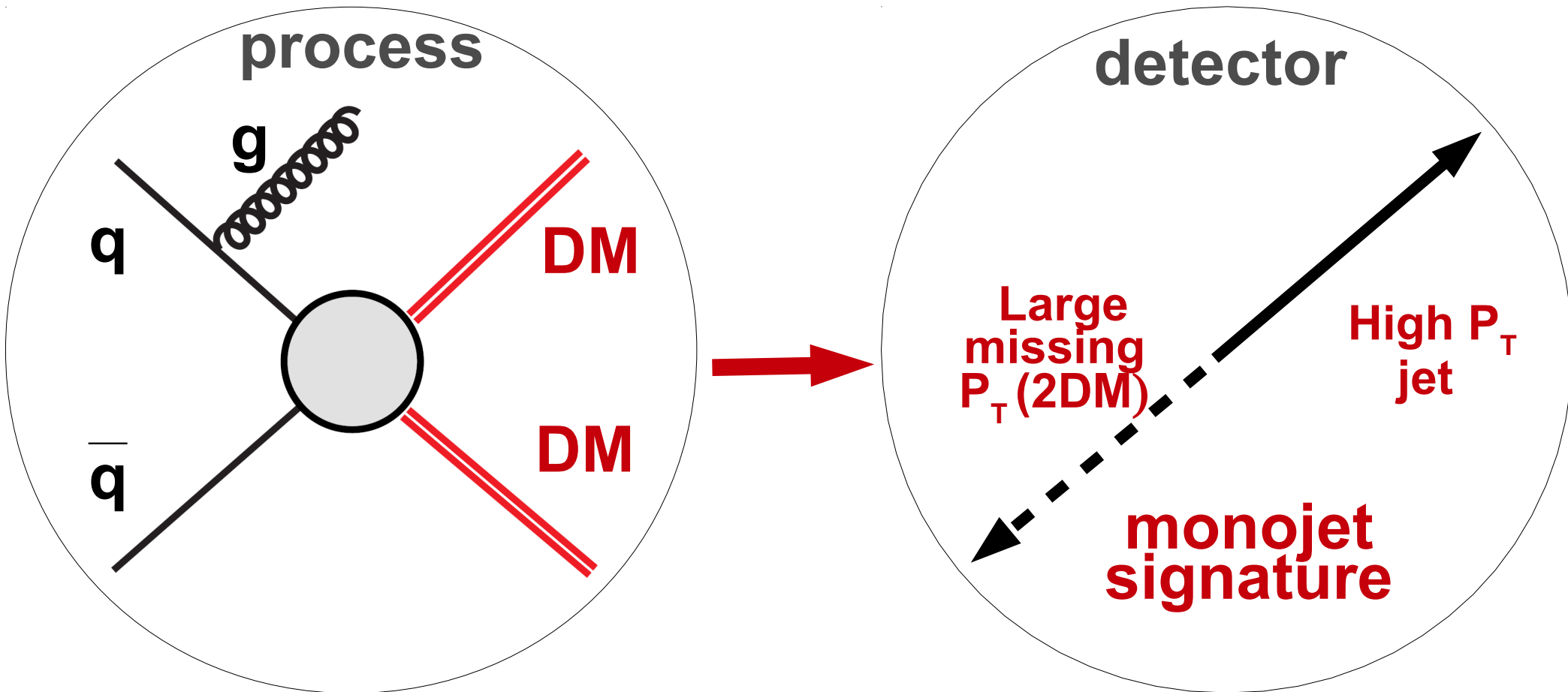
Can we test DM properties at the LHC?

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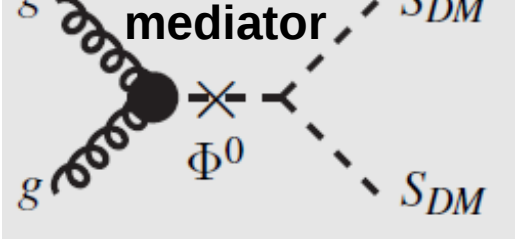
DIM5/6 operators (spin 0,1/2,1)

Complex scalar DM[†]

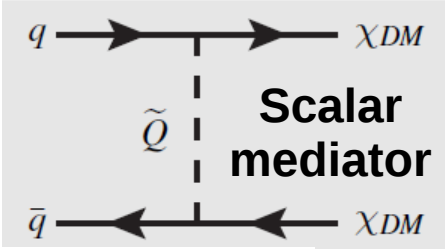|	
$\frac{\tilde{m}}{\Lambda^2}\phi^\dagger\phi\,\bar{q}q$	[C1]*
$\frac{\tilde{m}}{\Lambda^2}\phi^\dagger\phi\,\bar{q}i\gamma^5 q$	[C2]*
$\frac{1}{\Lambda^2}\phi^\dagger i\overleftrightarrow{\partial}_\mu\phi\,\bar{q}\gamma^\mu q$	[C3]
$\frac{1}{\Lambda^2}\phi^\dagger i\overleftrightarrow{\partial}_\mu\phi\,\bar{q}\gamma^\mu\gamma^5 q$	[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[†]

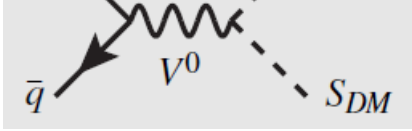|	
$\frac{1}{\Lambda^2}\bar{\chi}\chi\,\bar{q}q$	[D1]*
$\frac{1}{\Lambda^2}\bar{\chi}i\gamma^5\chi\,\bar{q}q$	[D2]*
$\frac{1}{\Lambda^2}\bar{\chi}\chi\,\bar{q}i\gamma^5 q$	[D3]*
$\frac{1}{\Lambda^2}\bar{\chi}\gamma^5\chi\,\bar{q}\gamma^5 q$	[D4]*
$\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\chi\,\bar{q}\gamma_\mu q$	[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]	*additional,*
$\frac{i}{2\Lambda^2}(\bar{\chi}\gamma^5 q\bar{q}\chi + \bar{\chi}q\bar{q}\gamma^5\chi)$	[D2T]	*not-independent*
$\frac{1}{2\Lambda^2}(\bar{\chi}\gamma^5 q\bar{q}\chi - \bar{\chi}q\bar{q}\gamma^5\chi)$	[D3T]	*operators can be written*
$\frac{1}{\Lambda^2}\bar{\chi}\gamma^5 q\bar{q}\gamma^5\chi$	[D4T]	
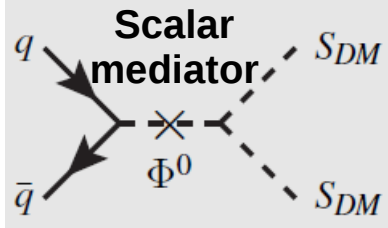
Mapping EFT operators to simplified models

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

Scalar mediator: g, g → Φ^0 → S_{DM}, S_{DM}

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

$q \to \chi_{DM}$; $\tilde{Q}$ Scalar mediator; $\bar{q} \to \chi_{DM}$

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

Vector mediator: q, $\bar{q}$ → V^0 → S_{DM}, S_{DM}

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

Vector mediator: q, $\bar{q}$ → V^0 → χ_{DM}, χ_{DM}

Scalar mediator: q, $\bar{q}$ → Φ^0 → χ_{DM}, χ_{DM}

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

Scalar mediator: q, $\bar{q}$ → Φ^0 → S_{DM}, S_{DM}

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

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: $\sigma_{2\to2} \propto \dfrac{1}{\Lambda^2} \times \left(\dfrac{E}{\Lambda}\right)^{\Delta_\sigma}$

- On the other hand, from EFT operator we have: $\sigma_{2\to2} \propto \dfrac{1}{E^2} \times \left(\dfrac{E^{D-4}}{\Lambda^{D-4}}\right)^2$

  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: $\dfrac{1}{2\Lambda^2}\left(V_\nu^\dagger \partial^\nu V_\mu + V^\nu \partial^\nu V_\mu^\dagger\right)\bar{q}\gamma^\mu q$

  ➡ 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	$\Delta_\sigma(\sigma_{2\to2} \propto E^{\Delta_\sigma})$	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$_{DM}$/Λ** 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 Λ in different parametrisations:

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

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

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

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

Legend:
- C1,C2
- C1Q,C2Q
- C3,C4
- C5,C6

scalar DM

- D1-D4
- D1Q-D4Q
- D1T-D4T
- D5-D8
- D9-D10

fermion DM

- V1-V2
- V1Q-V2Q
- V3-V4, V7-V10
- V5-V6
- V5Q-V6Q
- V11-V12

vector DM

Y-axis: # Events (normalized to one)

X-axis: E_T^{miss}
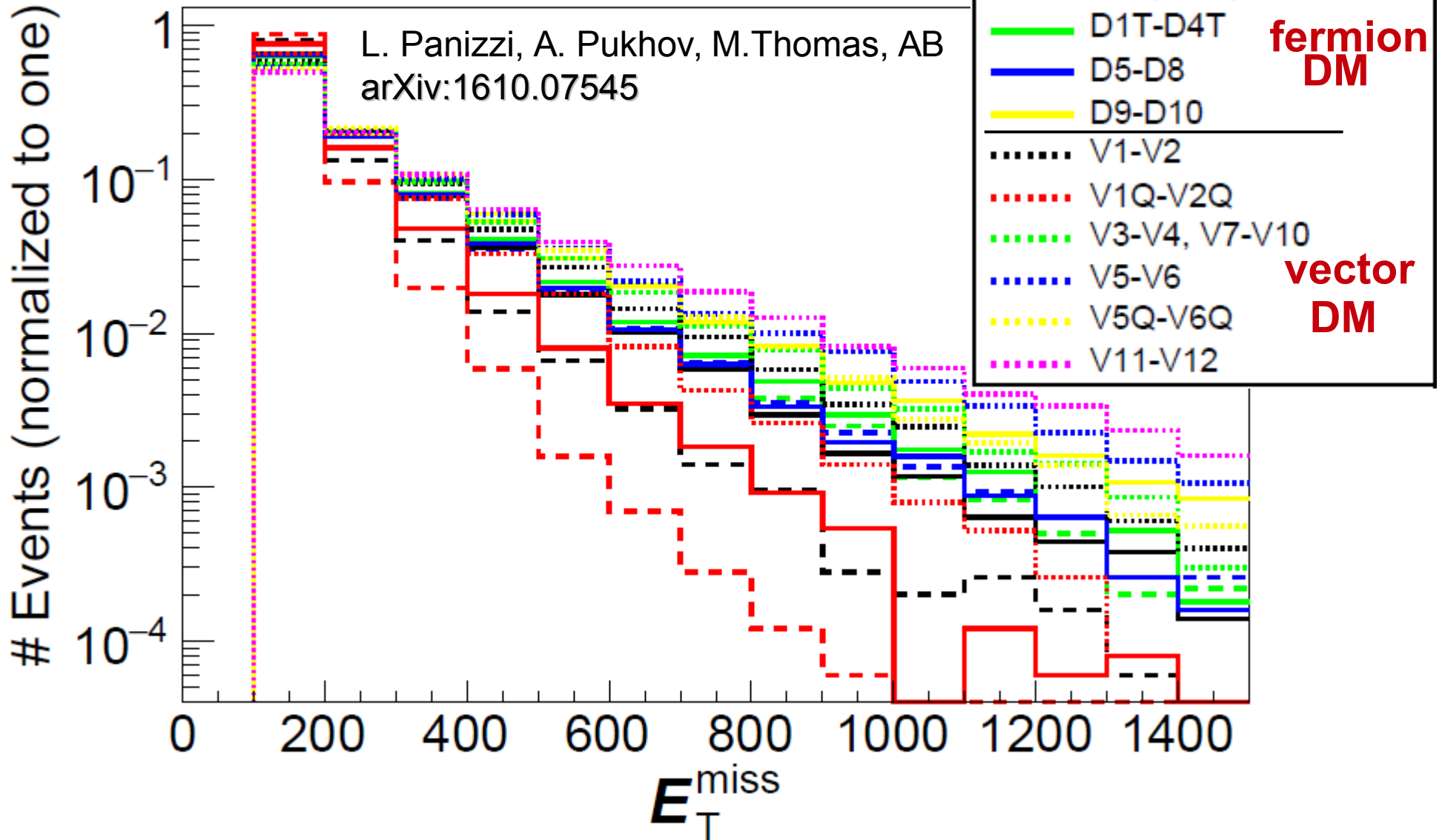
M_{DM} dependence is weak for 10-100 GeV range

M_{DM}=100 GeV, $\sqrt{s}$ = 13 TeV

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

Legend:

scalar DM
- C1,C2
- C1Q,C2Q
- C3,C4
- C5,C6

fermion DM
- D1-D4
- D1Q-D4Q
- D1T-D4T
- D5-D8
- D9-D10

vector DM
- V1-V2
- V1Q-V2Q
- V3-V4, V7-V10
- V5-V6
- V5Q-V6Q
- V11-V12

Y-axis: # Events (normalized to one)

X-axis: E_T^{miss}
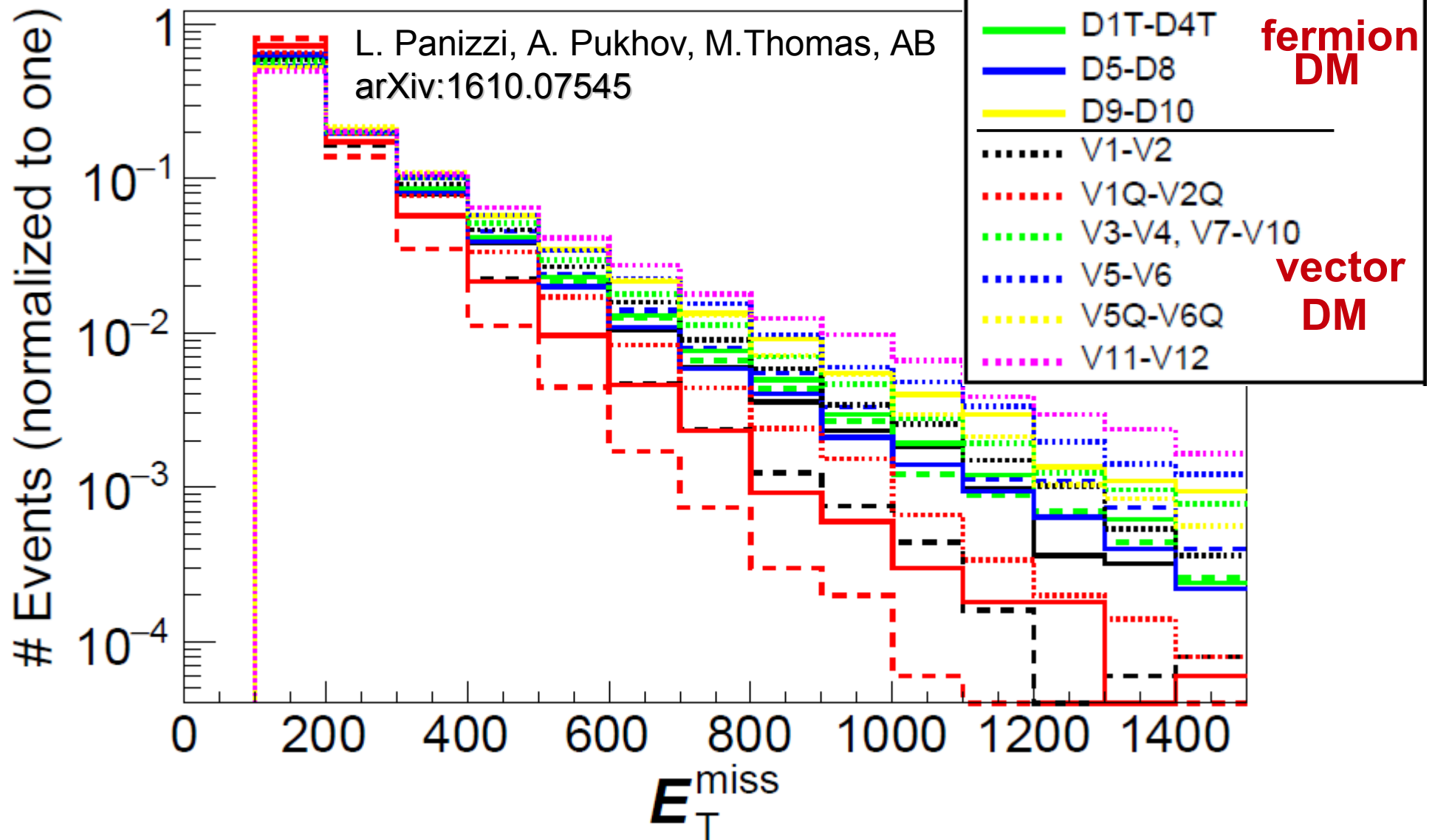
Properties of MET distributions:

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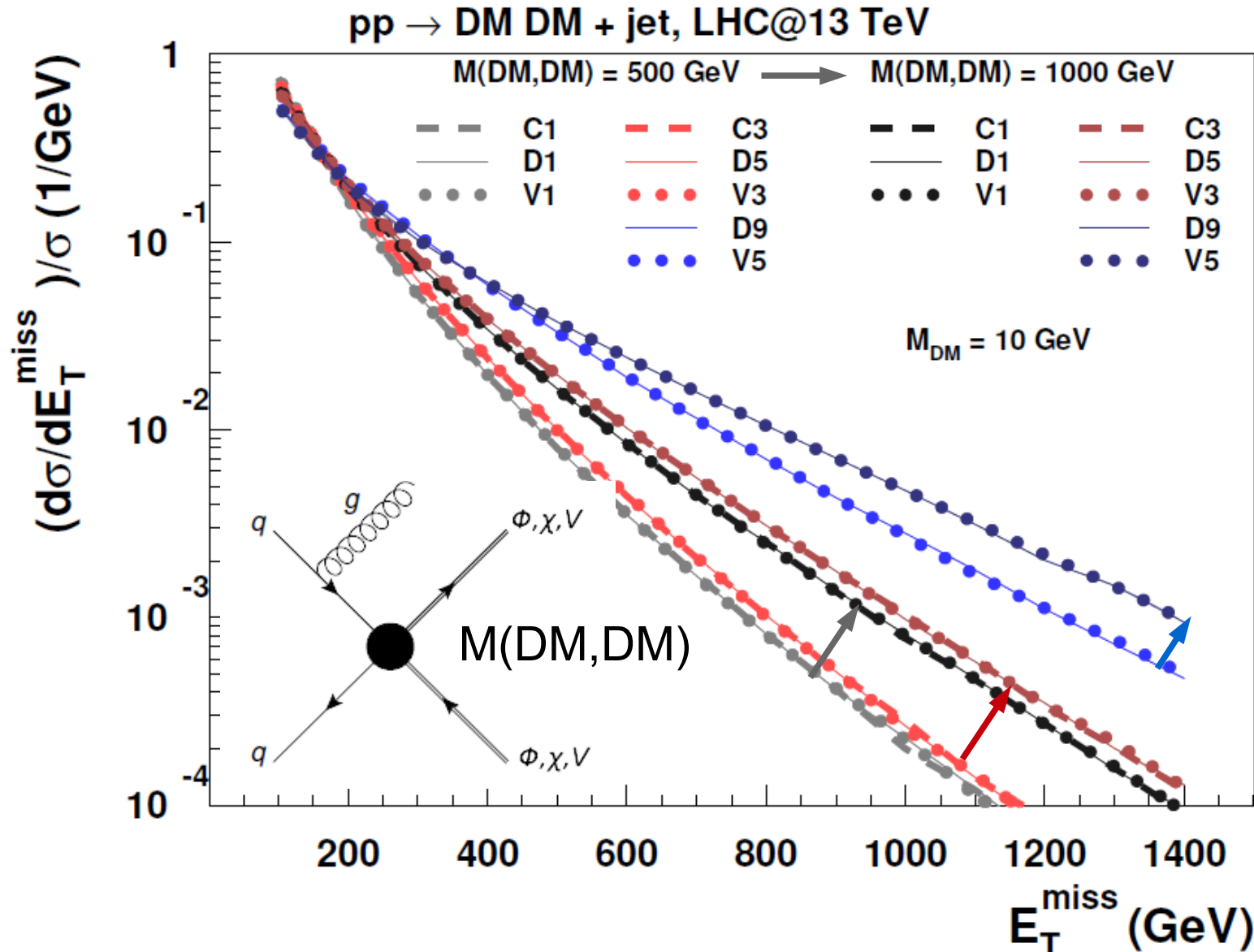
$$\frac{\tilde{m}}{\Lambda^2}\phi^*\phi\bar{q}q \qquad [C1]$$

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

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

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

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

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

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

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

$M_{DM} = 10$ GeV, $\sqrt{s} = 13$ TeV , $MET > 500$ GeV
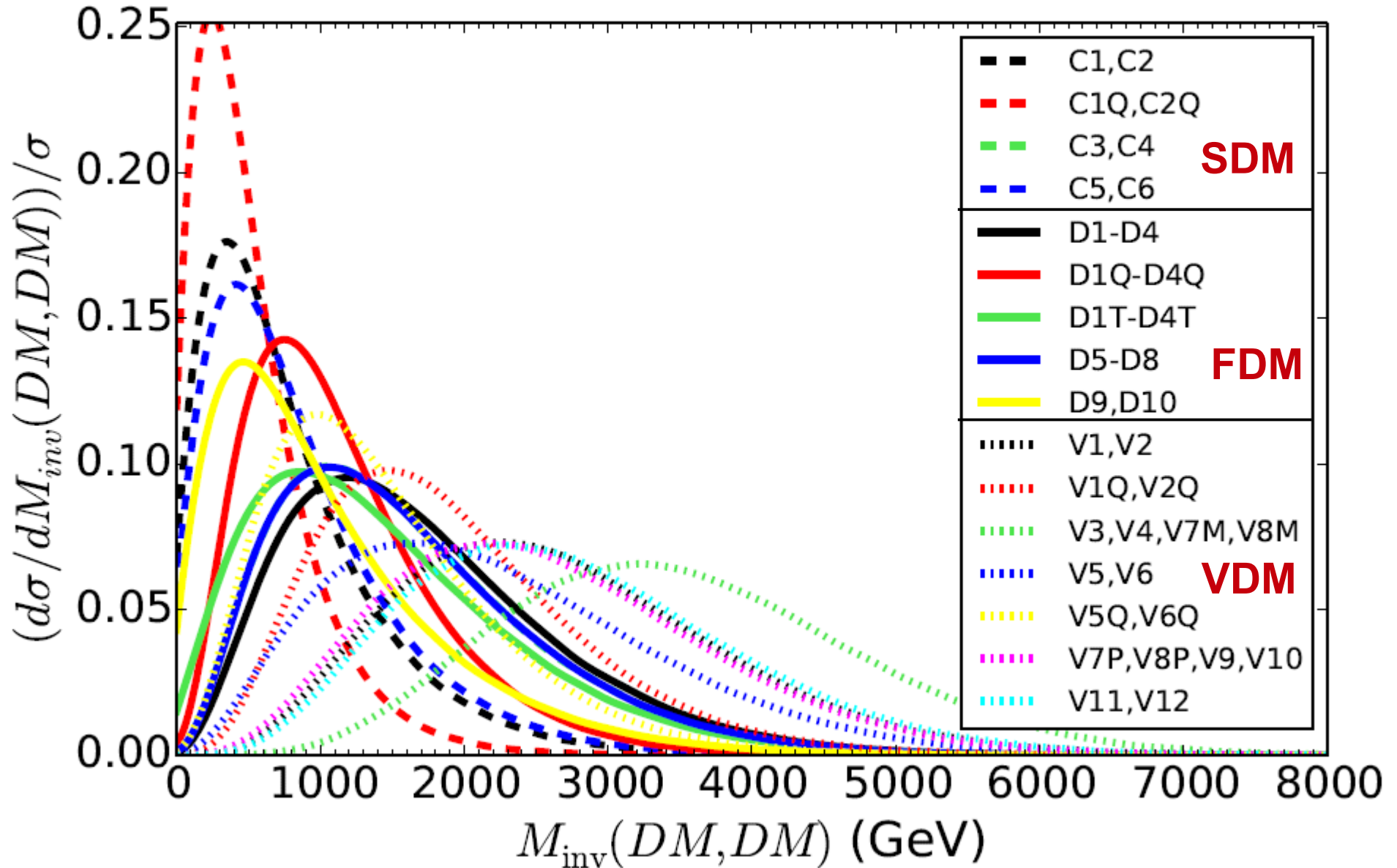
Distinguishing DM operators/theories

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

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

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

arXiv:1610.07545
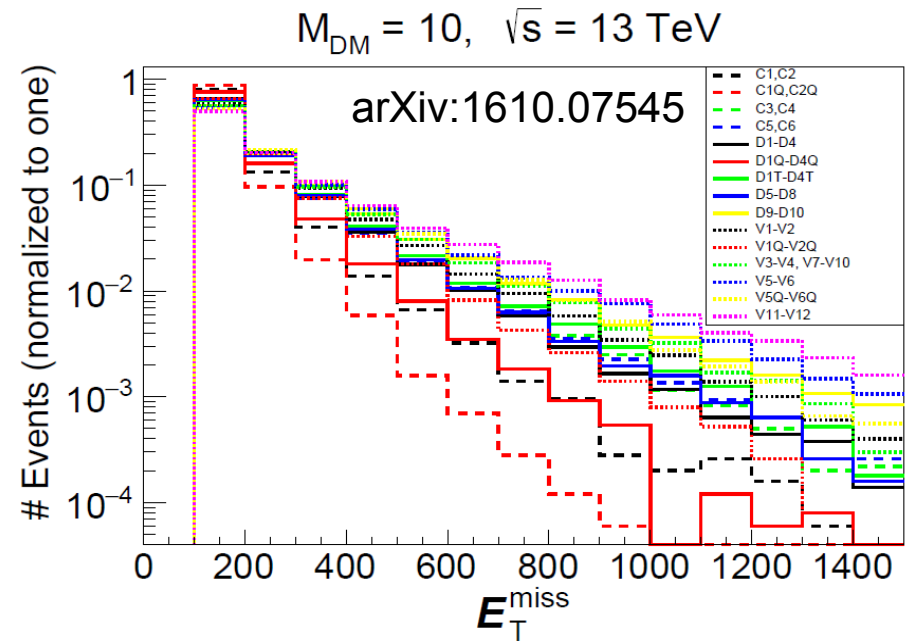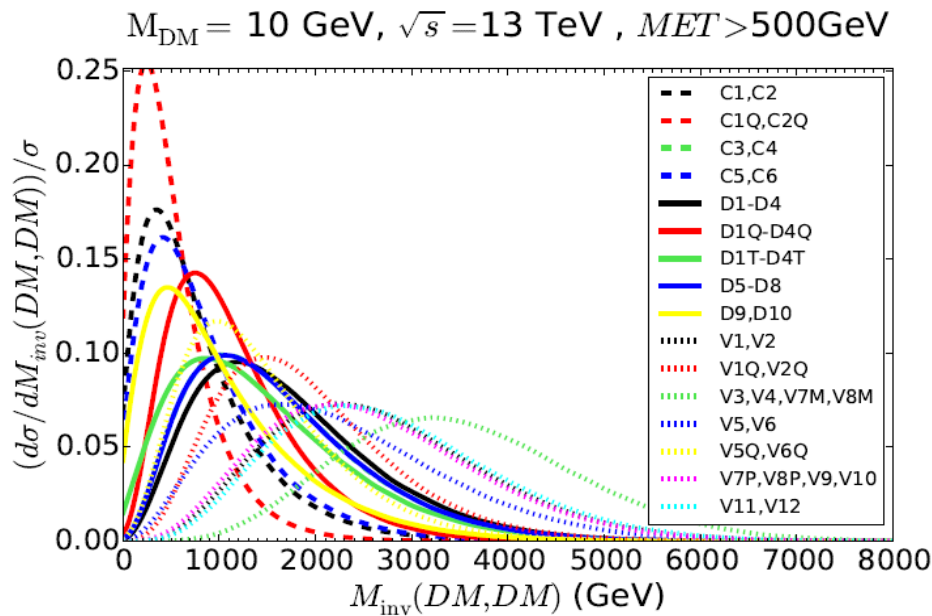
- energy dependence of the DM operator → M_{DMDM} distributions → slopes of MET
- projection for 300 fb⁻¹: some operators C1-C2,C5-C6,D9-D10,V1-V2,V3-V4,V5-V6 and V11-12 can be distinguished from each other
- Application beyond EFT: when the DM mediator is not produced on-the-mass-shell and M_{DMDM} is not fixed: t-channel mediator or mediators with mass below $2M_{DM}$

$pp \rightarrow$ DM DM jet @ 13 TeV

Λ=1TeV
MET>100 GeV

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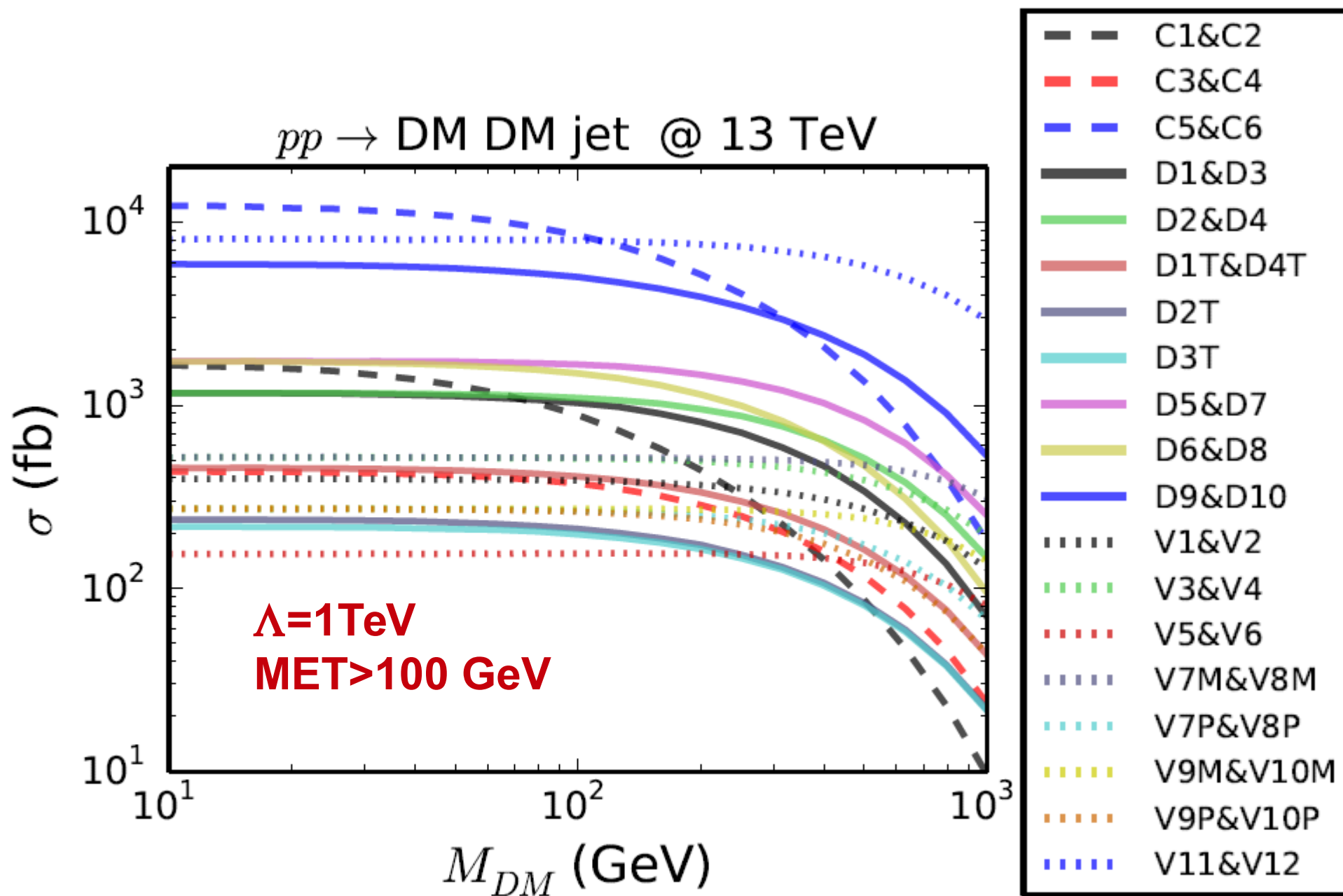
LHC@13TeV reach at 3.2 fb^{-1}

LanHEP→ CalcHEP/ Madgraph → LHE→ CheckMATE 2 chain
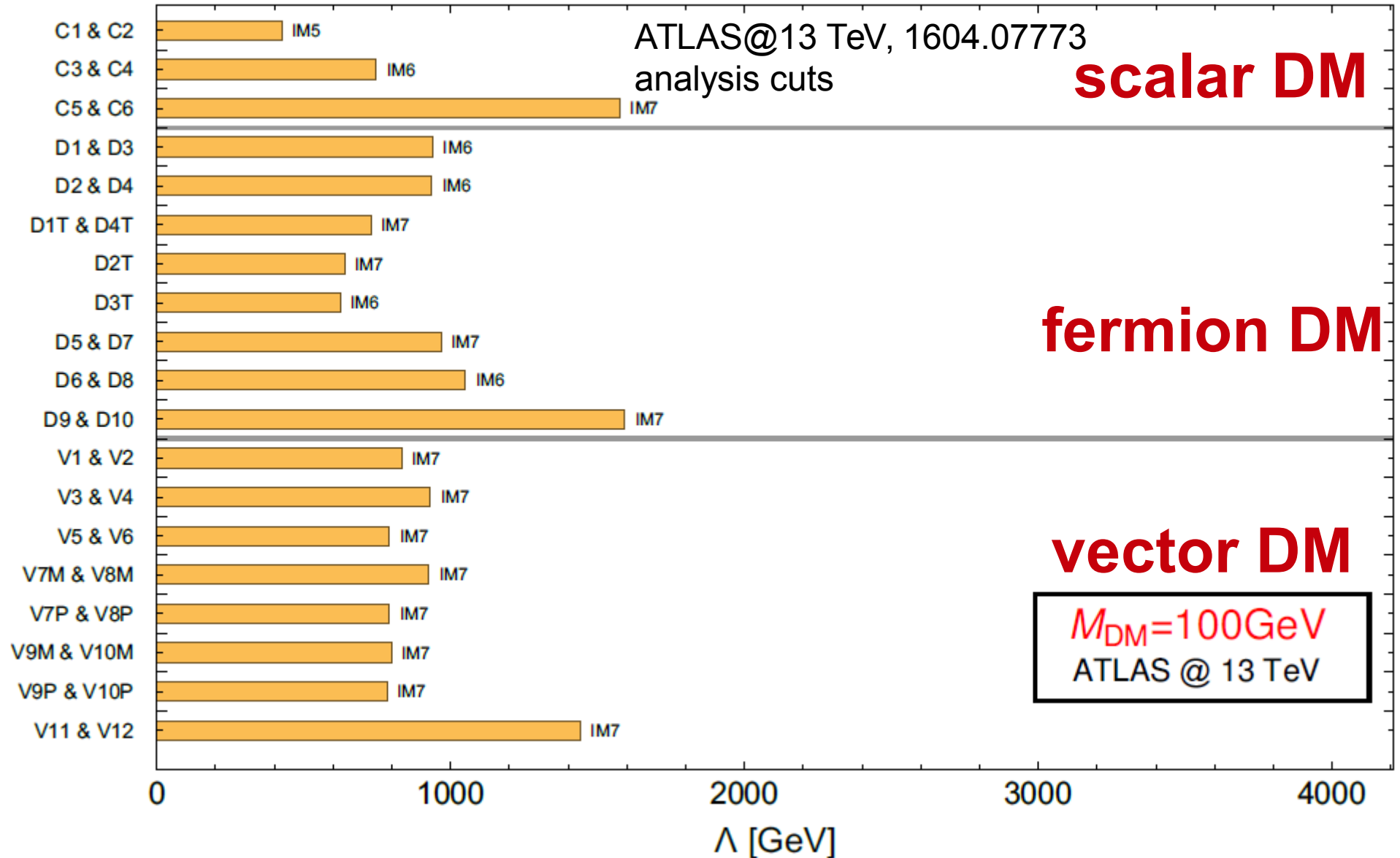
LHC@13TeV reach projected 100 fb^{-1}

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
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

Complex Vector DM

Distinguishing DM operators

energy dependence of the operator → M_DMDM shape → MET shape
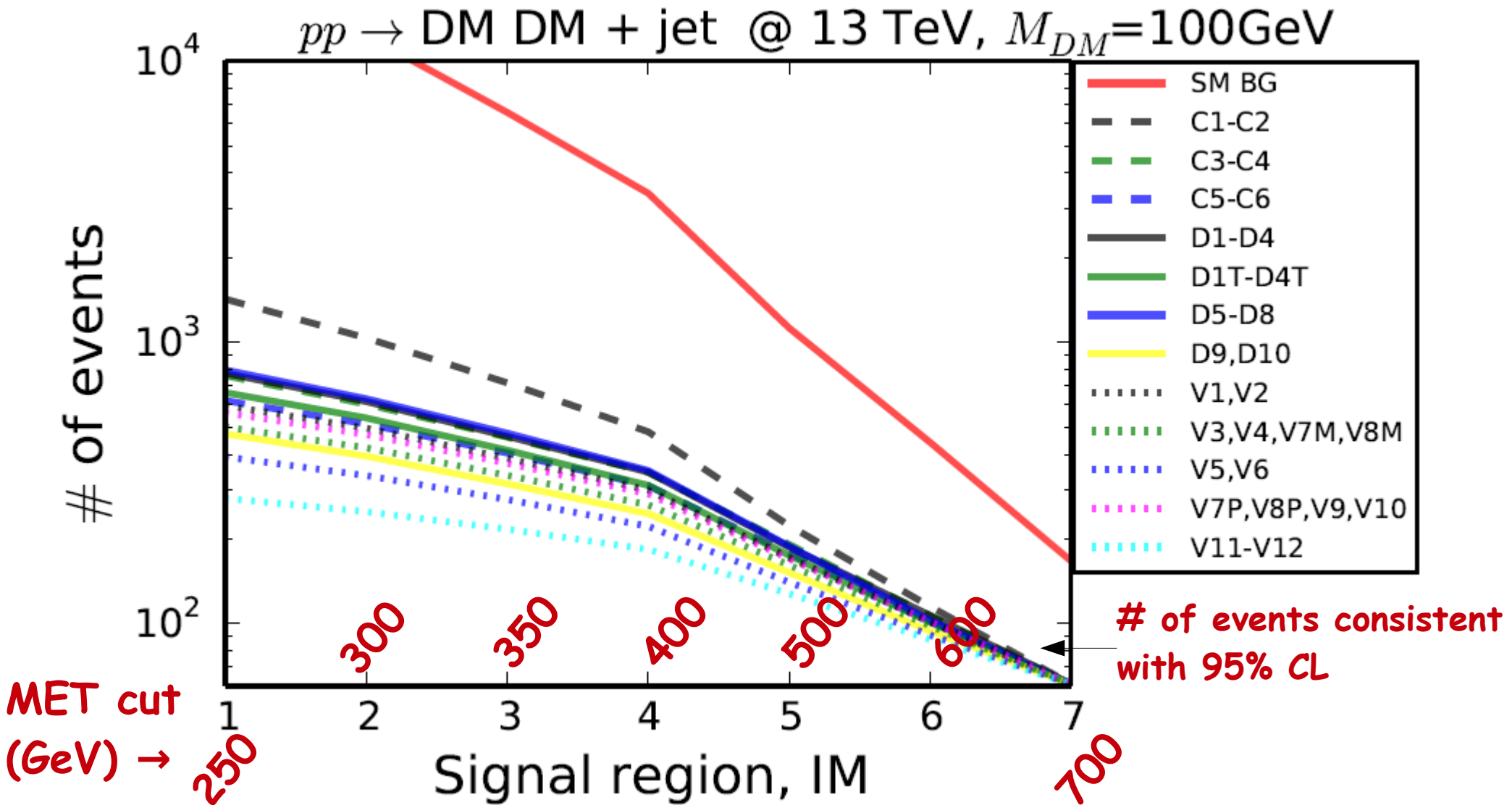
$pp \to$ DM DM + jet @ 13 TeV, M_{DM}=100GeV

Legend:
- SM BG
- C1-C2
- C3-C4
- C5-C6
- D1-D4
- D1T-D4T
- D5-D8
- D9,D10
- V1,V2
- V3,V4,V7M,V8M
- V5,V6
- V7P,V8P,V9,V10
- V11-V12

# of events (y-axis)

Signal region, IM (x-axis)

MET cut (GeV) → 250, 300, 350, 400, 500, 600, 700

# of events consistent with 95% CL

On the BG uncertainty

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

CMS-PAS-EXO-16-013

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

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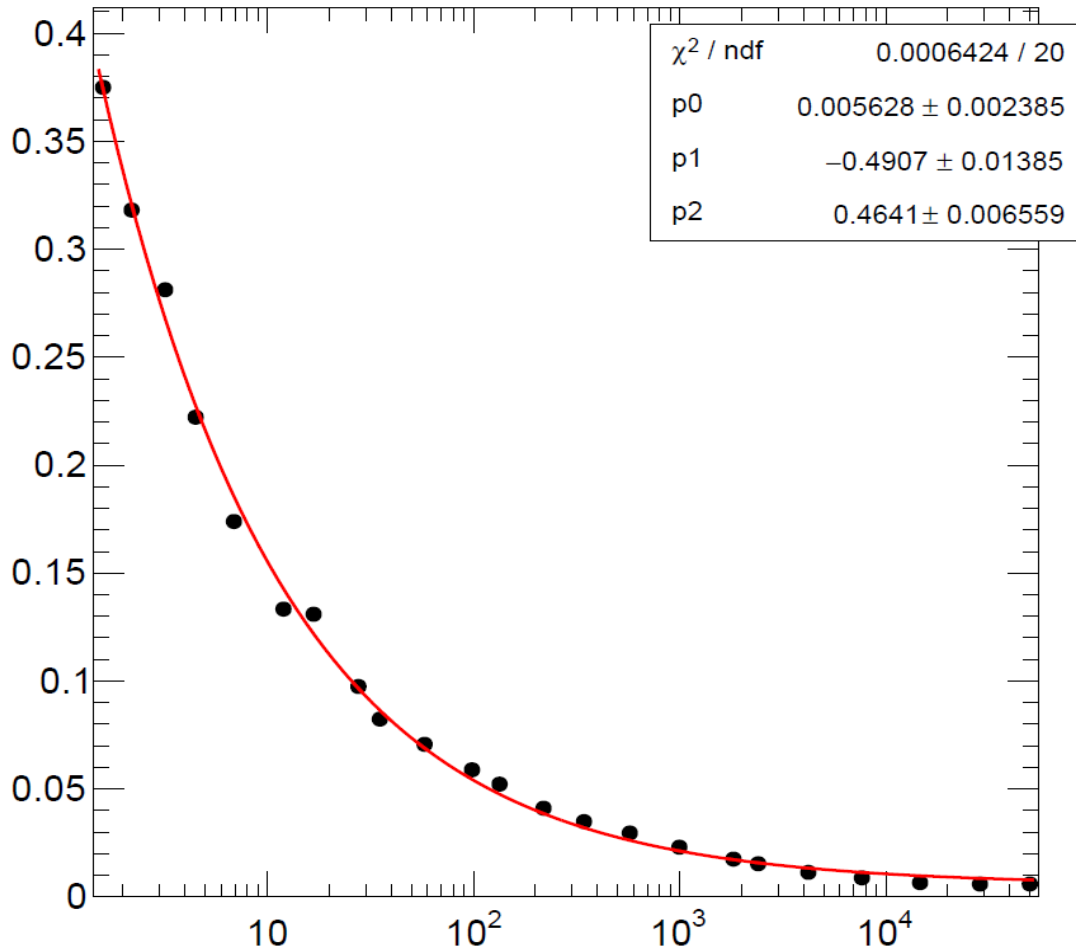
On the BG uncertainty

- **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 $\chi^2 > 9.48$ (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	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: χ² for pairs of DM operators

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

: if χ²>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)

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

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

$$\mathcal{L} \supset -\frac{J^\mu_{DM}}{\Lambda^2}\left(c^{(N)}_V \overline{N}\gamma_\mu N + c^{(N)}_A \overline{N}\gamma_\mu\gamma_5 N \right) \qquad \text{and} \qquad \sigma^N_{SI} = \frac{\mu_N^2}{\pi}\frac{(c_{V\chi}c^{(N)}_V)^2}{\Lambda^4}$$

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

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

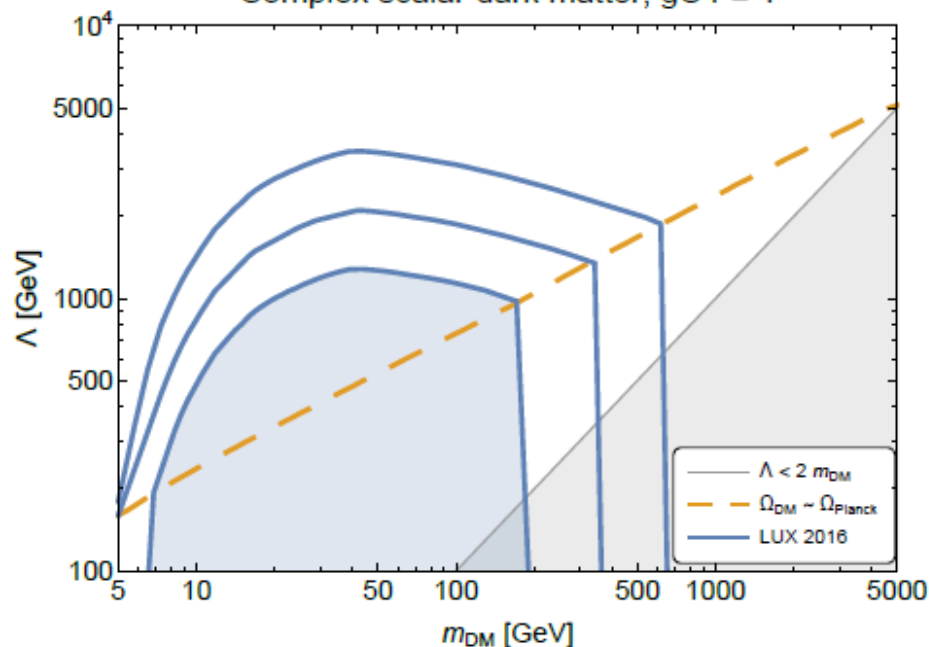- In case of axial operators, e.g

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

  couplings $c_V^{(q)}$ arise due to the running of the wilson coeffcient $c_A^{(q)}$ 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

  $c_A^{(u)}, c_A^{(d)}, c_V^{(u)}, c_V^{(d)}$=**(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

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

  couplings $c_V^{(q)}$ arise due to the running of the wilson coeffcient $c_A^{(q)}$ 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

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

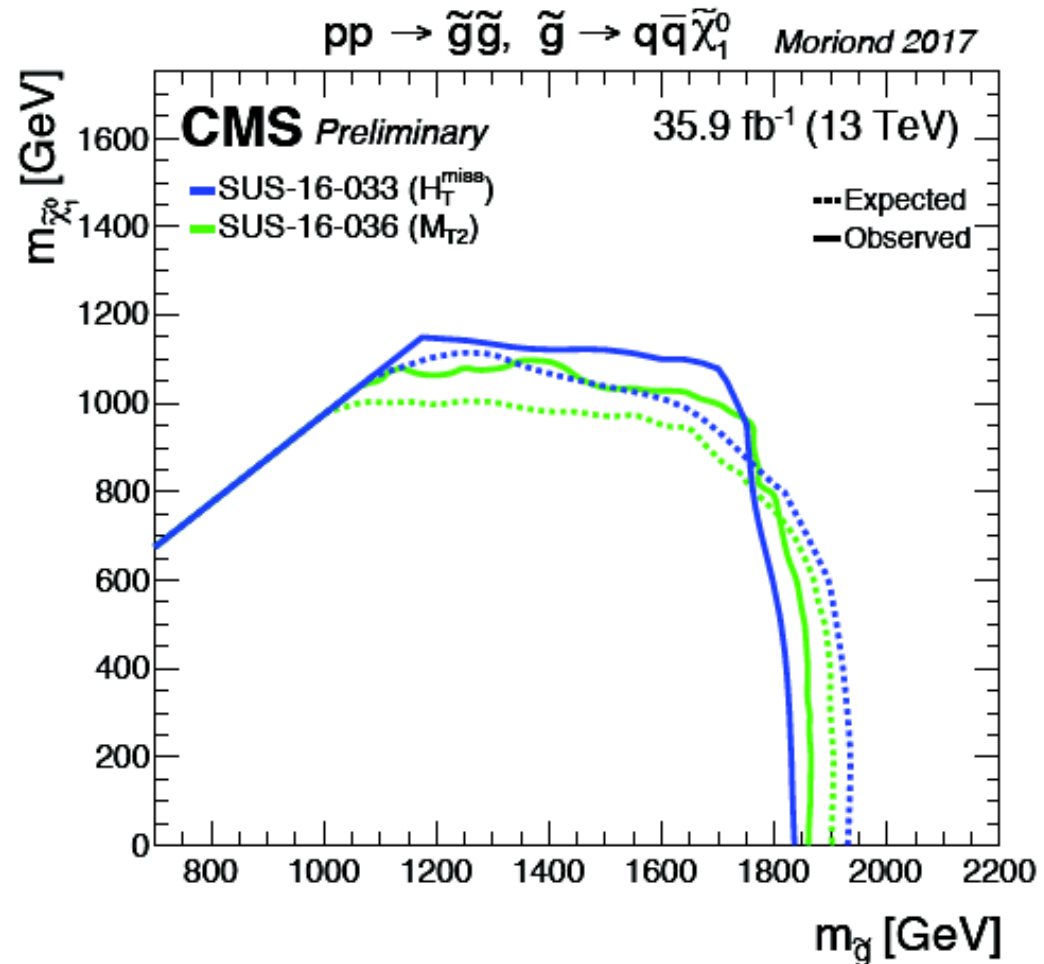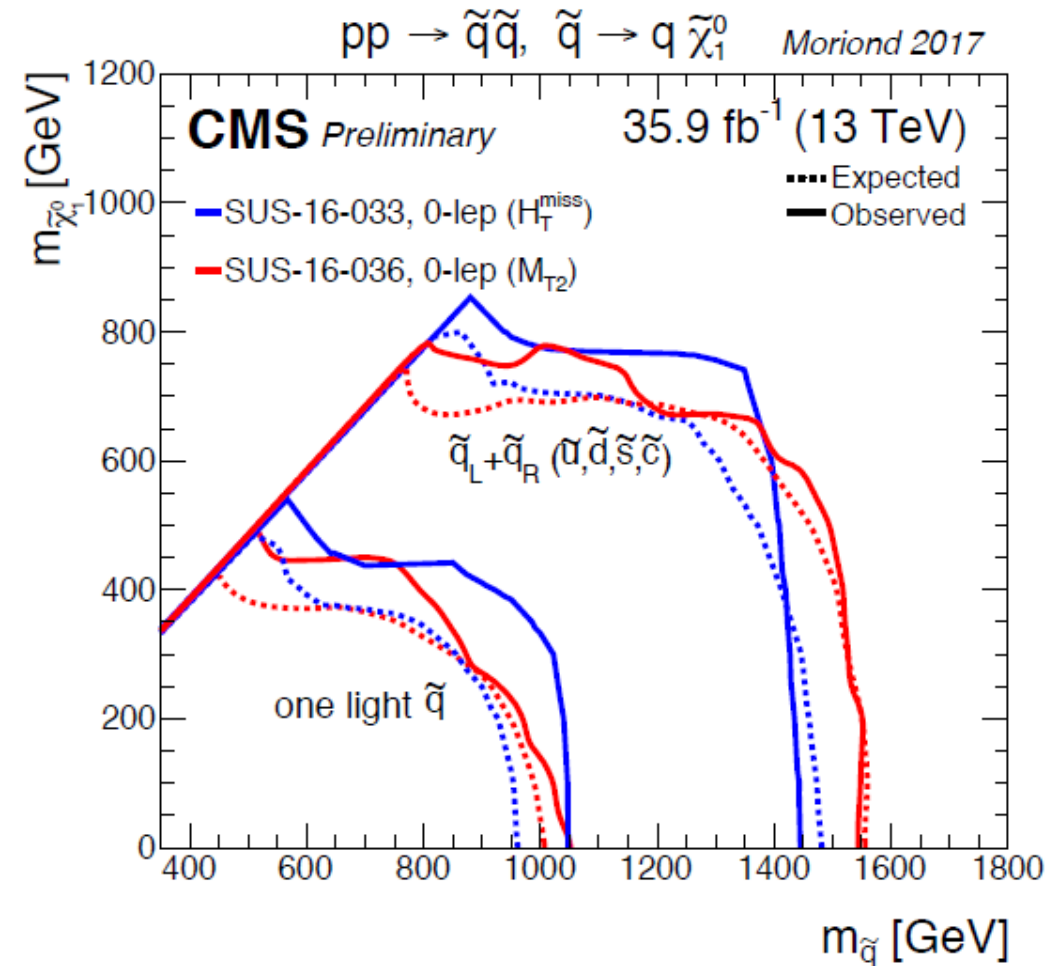Complex scalar dark matter, gC4 = 1   Dirac fermion dark matter, gD7 = 1
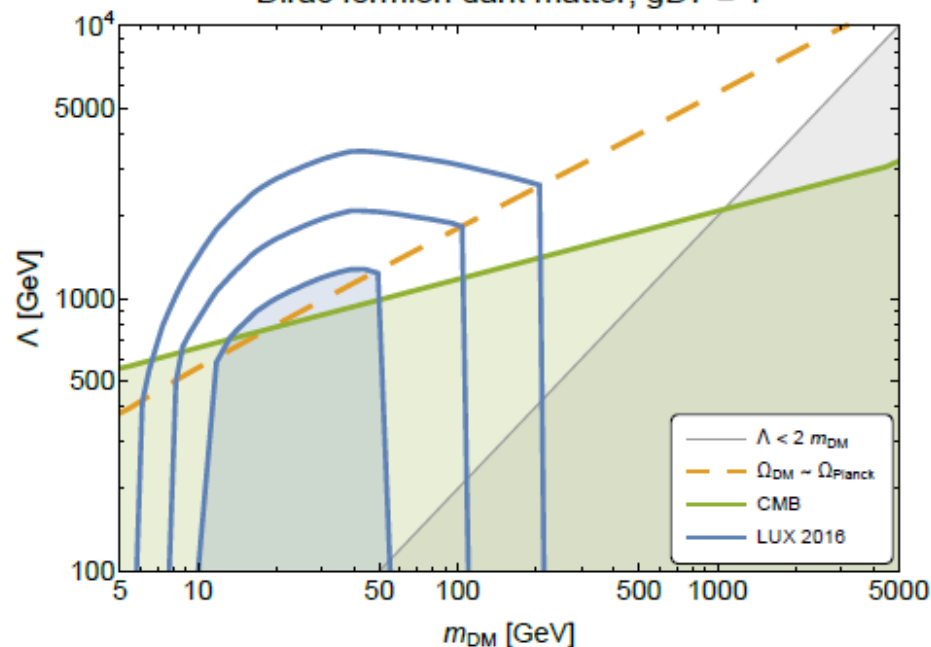
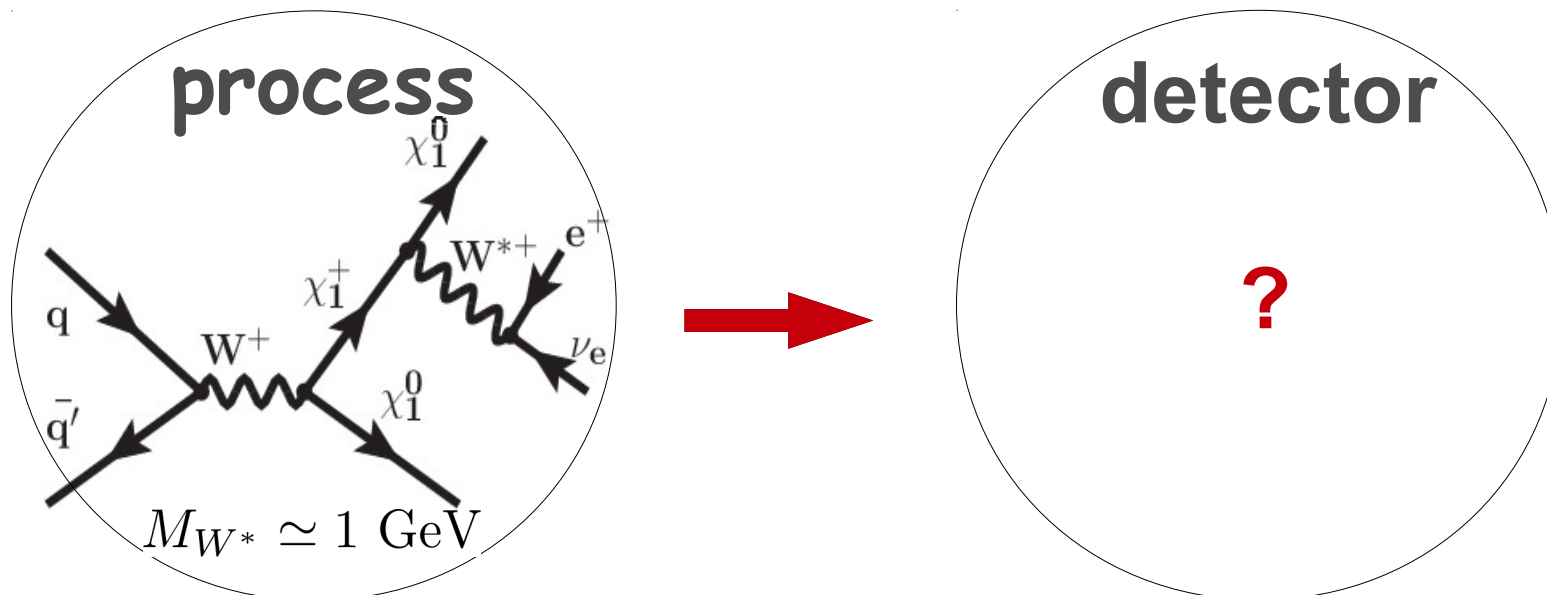AB, Bertuzzo, Caniu, Eboli, di Cortona (preliminary)

Application for the case beyond EFT: SUSY

There is no limit on the LSP mass if the mass of strongly interacting SUSY particles above ~ 1.9 TeV
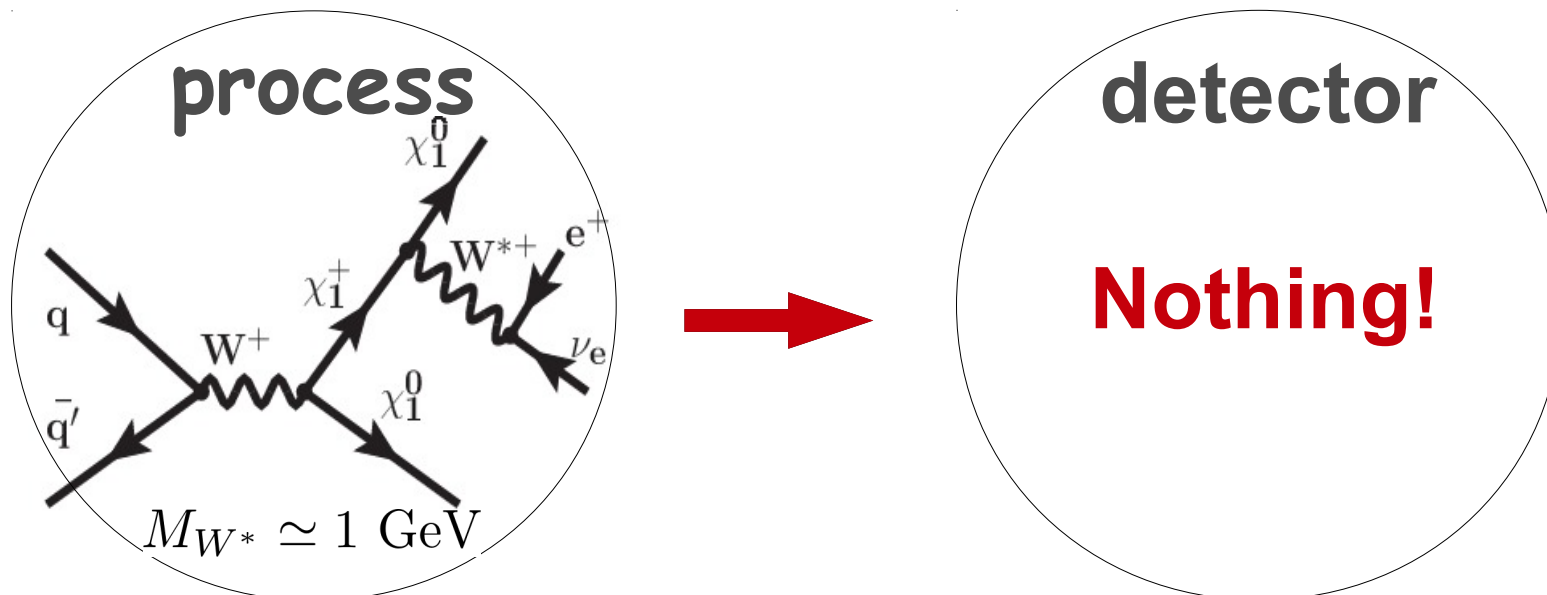
Susy Compressed Mass Spectrum scenario

- 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;
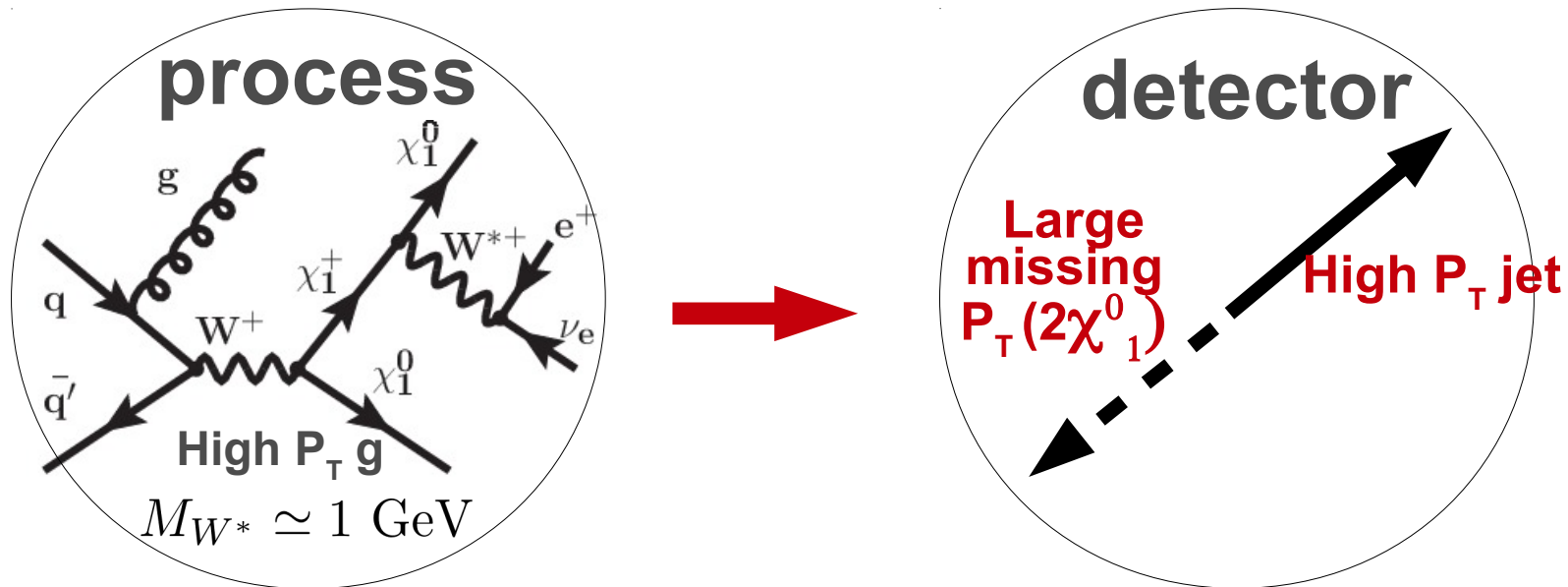 Han,Kribs,Martin,Menon '14

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;
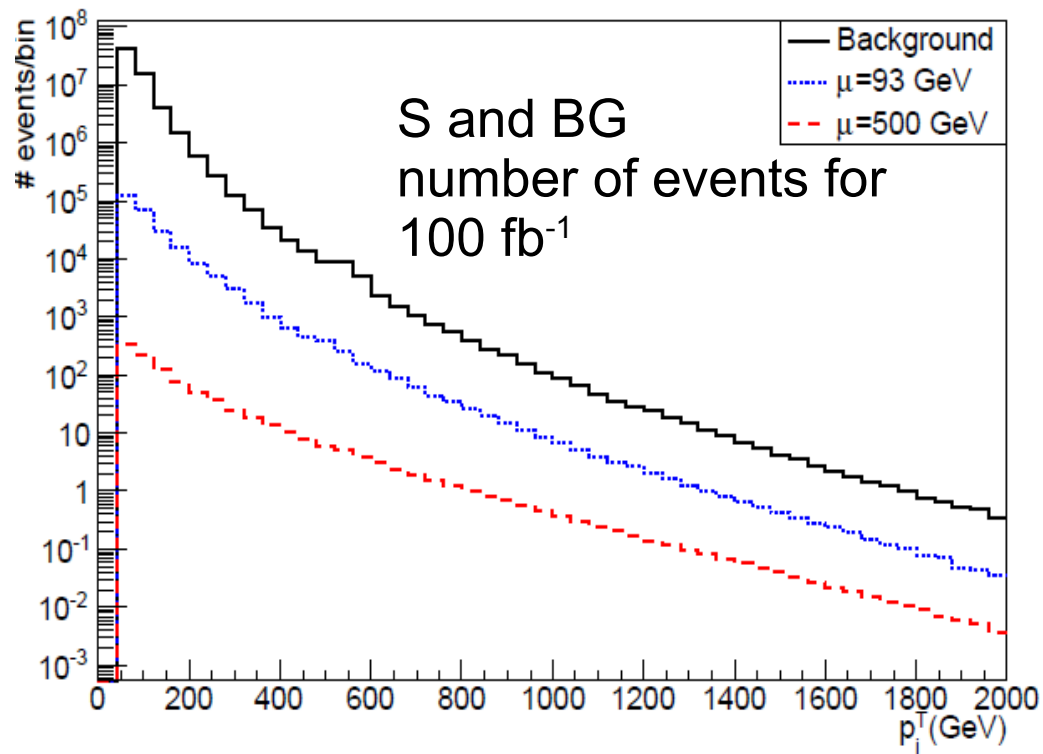 Han, Kribs, Martin, Menon '14

Signal vs Background
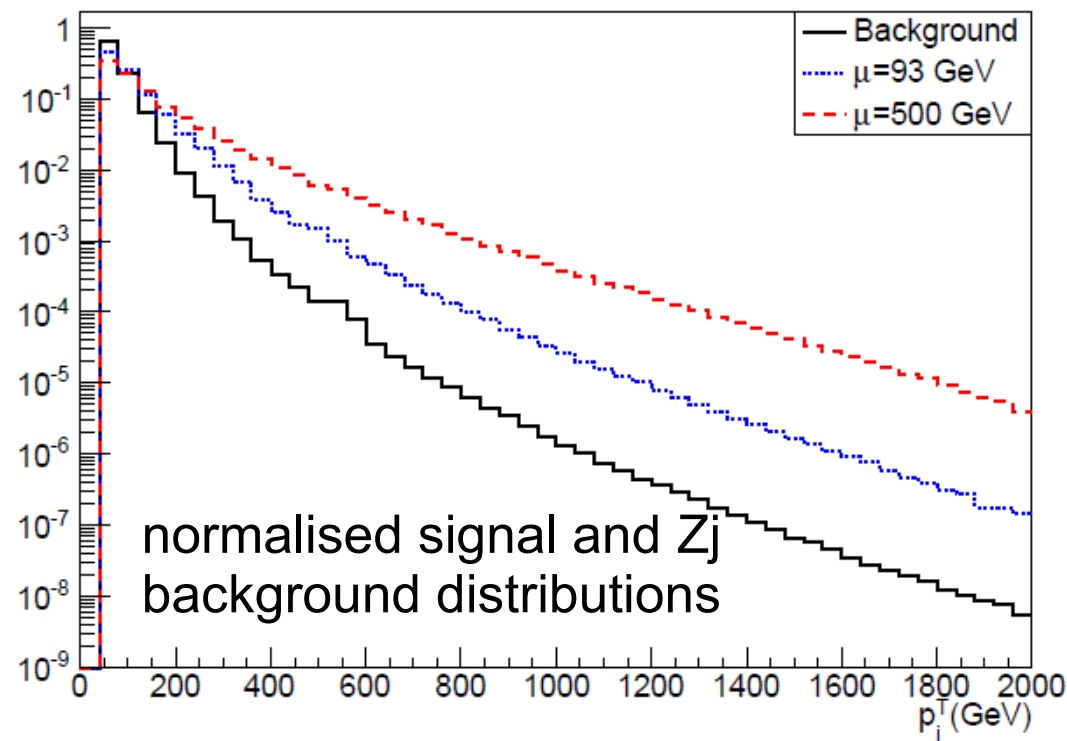
- difference in rates is pessimistic ...

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

pp→ννj vs. pp→χχj

S and BG number of events for 100 fb^{-1}

pp->ννj vs. pp->χχj

normalised signal and Zj background distributions

Signal and Zj background parton-level p_T^j distributions for the 13 TeV LHC
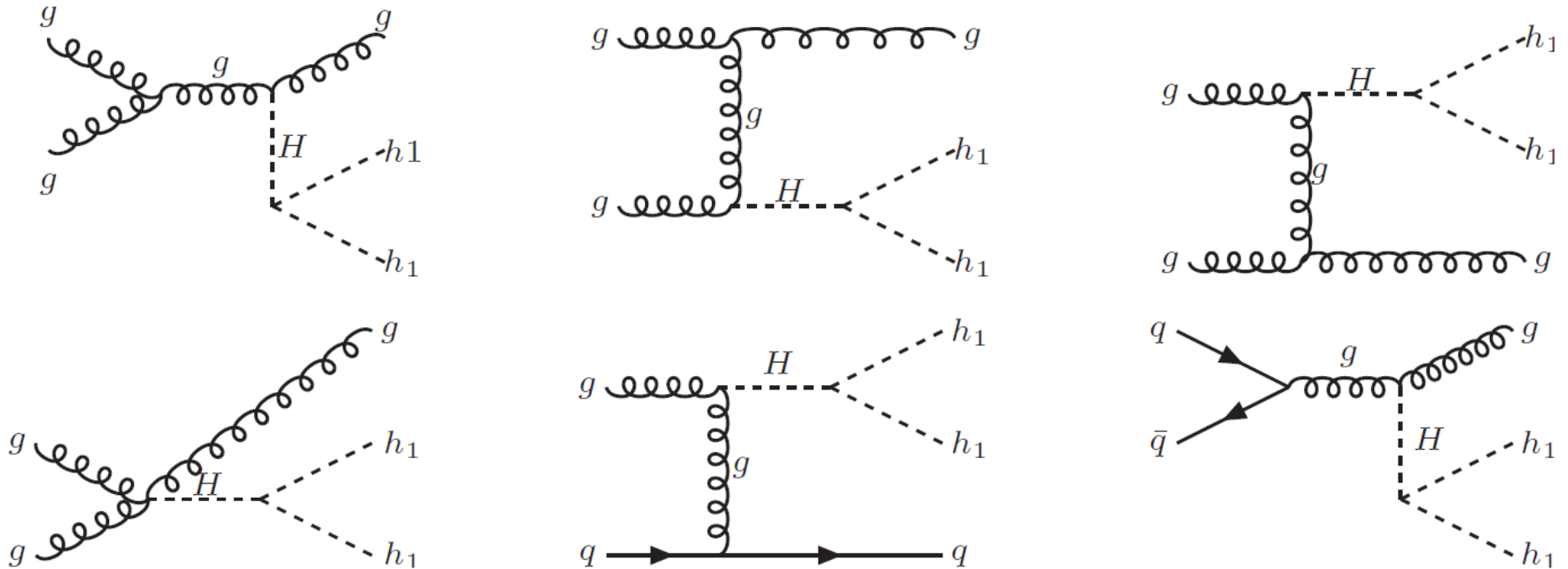
LHC/DM direct detection sensitivity
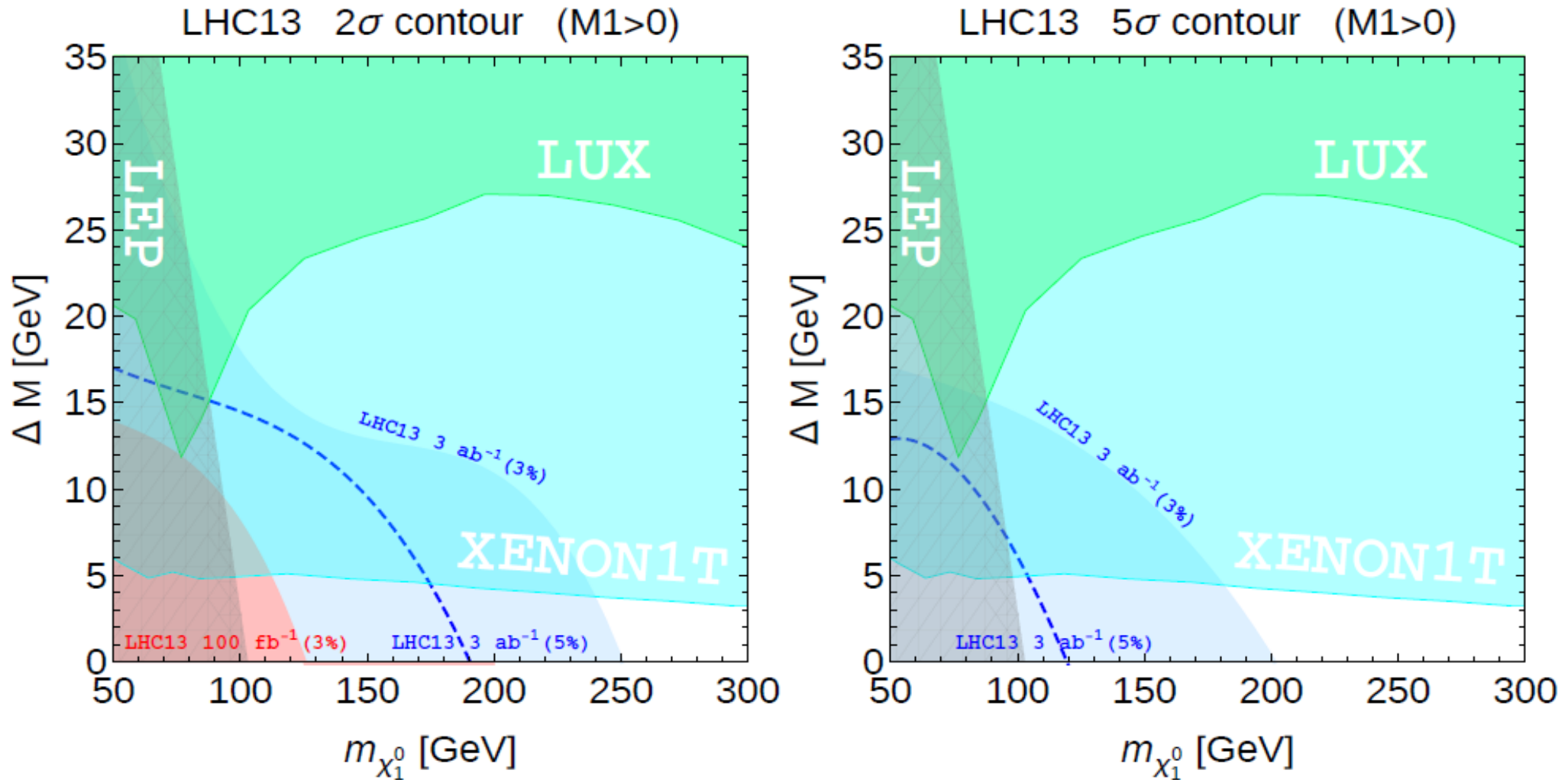
Barducci,Bharucha,Porod,Sanz,AB JHEP 1507 (2015) 066, arXiv:1504.02472

- 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

$$\phi_1 = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H \end{pmatrix} \qquad \phi_2 = \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2}h^+ \\ h_1 + ih_2 \end{pmatrix}$$
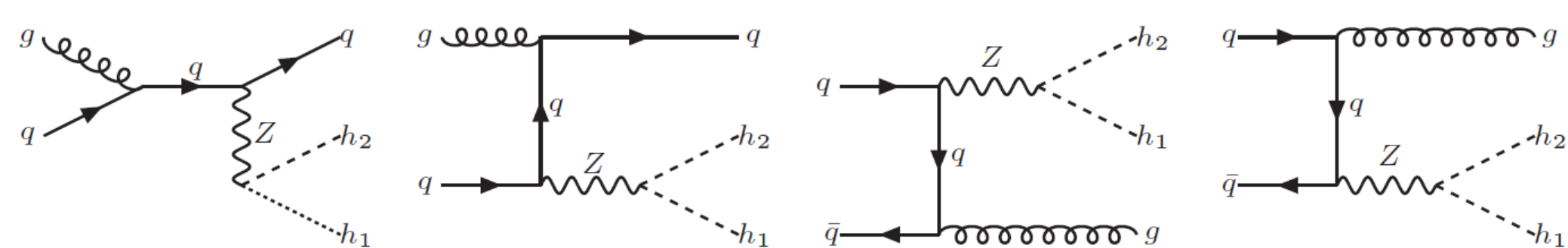
$$\begin{aligned} V \;=\; & -m_1^2(\phi_1^\dagger \phi_1) - m_2^2(\phi_2^\dagger \phi_2) + \lambda_1(\phi_1^\dagger \phi_1)^2 + \lambda_2(\phi_2^\dagger \phi_2)^2 \\ + \;& \lambda_3(\phi_1^\dagger \phi_1)(\phi_2^\dagger \phi_2) + \lambda_4(\phi_2^\dagger \phi_1)(\phi_1^\dagger \phi_2) + \frac{\lambda_5}{2}\left[(\phi_1^\dagger \phi_2)^2 + (\phi_2^\dagger \phi_1)^2\right] \end{aligned}$$

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

$\sigma(pp \to h_1 h_1 j)$ (fb) at 13 TeV

Legend:
- $\lambda_{345} = 0.1$ (blue dashed)
- $\lambda_{345} = -0.01$ (yellow dashed)
- $\lambda_{345} = $ maximum (green dashed)
- 95% CL ($20\,fb^{-1}$) (red)
- 95% CL ($100\,fb^{-1}$) (magenta)
- 95% CL ($3000\,fb^{-1}$) (black)

G. Cacciapaglia, I. Ivanov, F. Rojas, M. Thomas, AB arXiv:1612.00511

y-axis: $\sigma(pp \to h_1 h_1 j)$ (fb) with $P_T^{jet} > 100$ GeV

x-axis: Mh_1 (GeV)
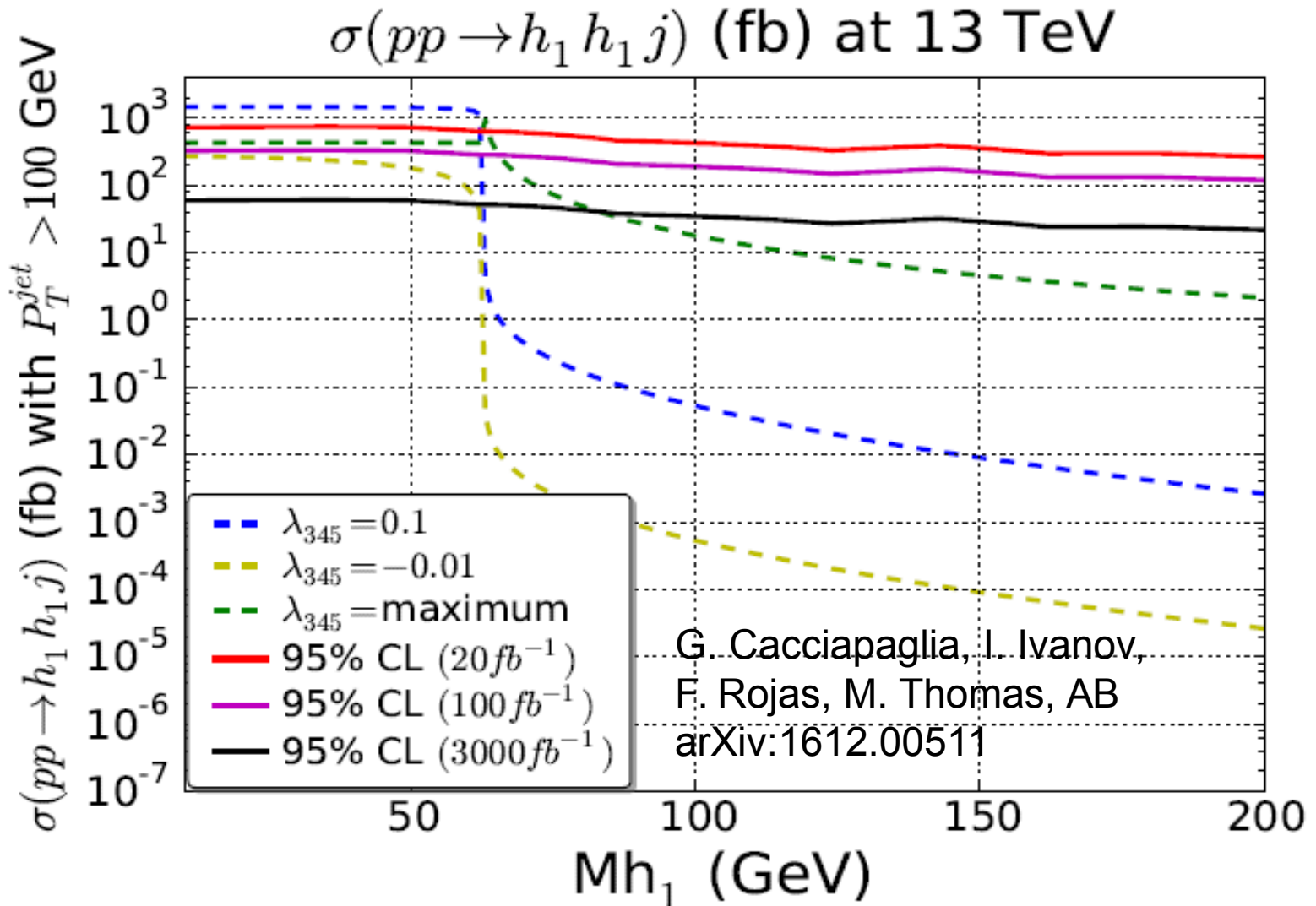
Beyond the mono-jet signature

Example of the vector resonance in the Composite Higgs model:
Z'→ TT→ t t DM DM signature
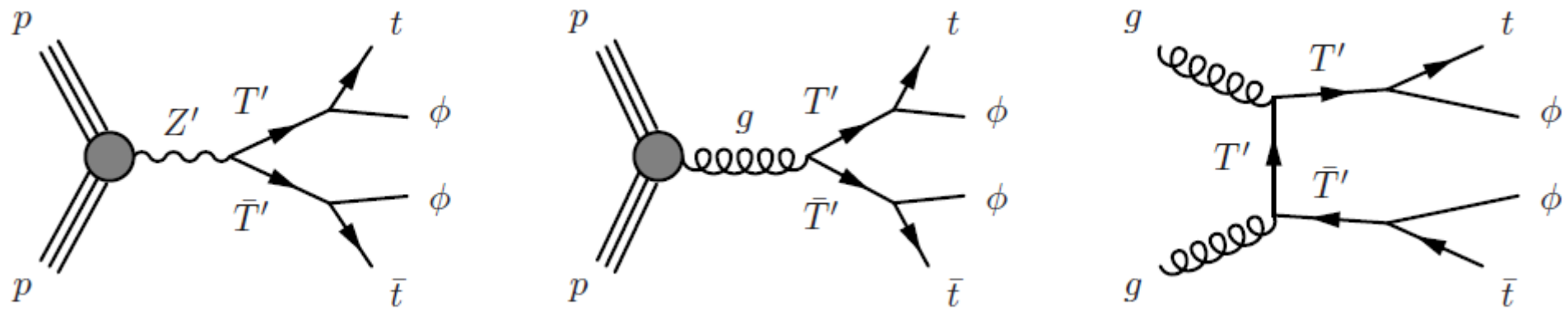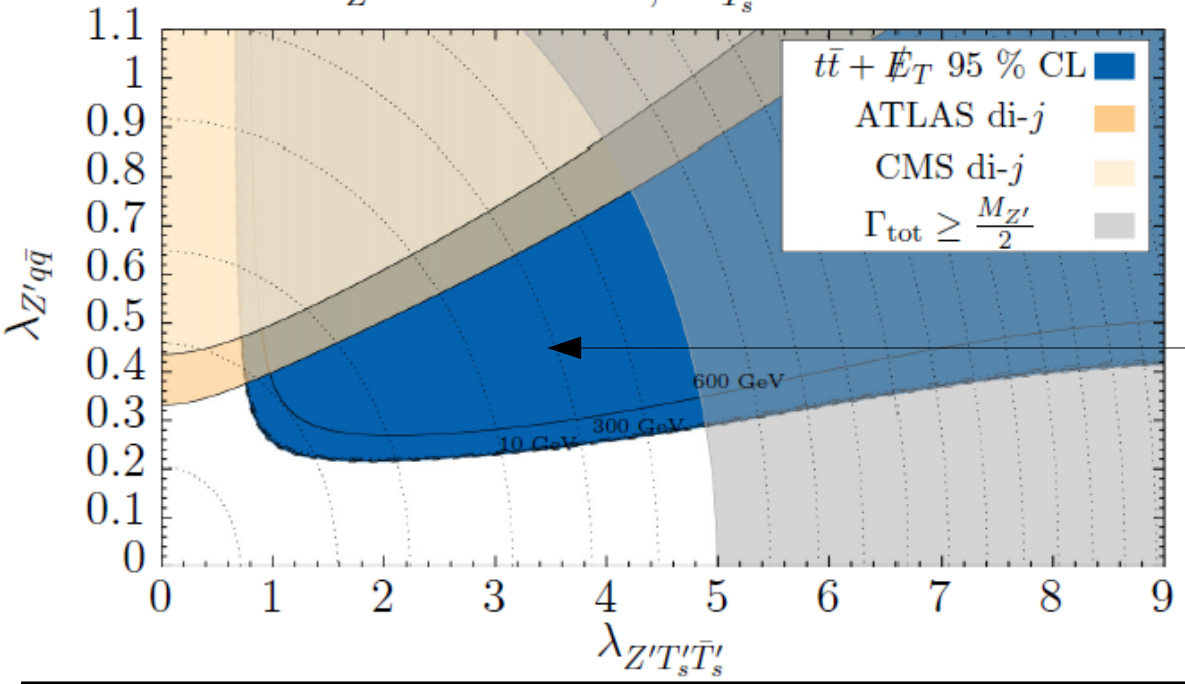
Current LHC reach
with tt+ MET signature
based on
ATLAS_CONF_2016_050
results

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
$TT \rightarrow t\, t\, DM\, DM$
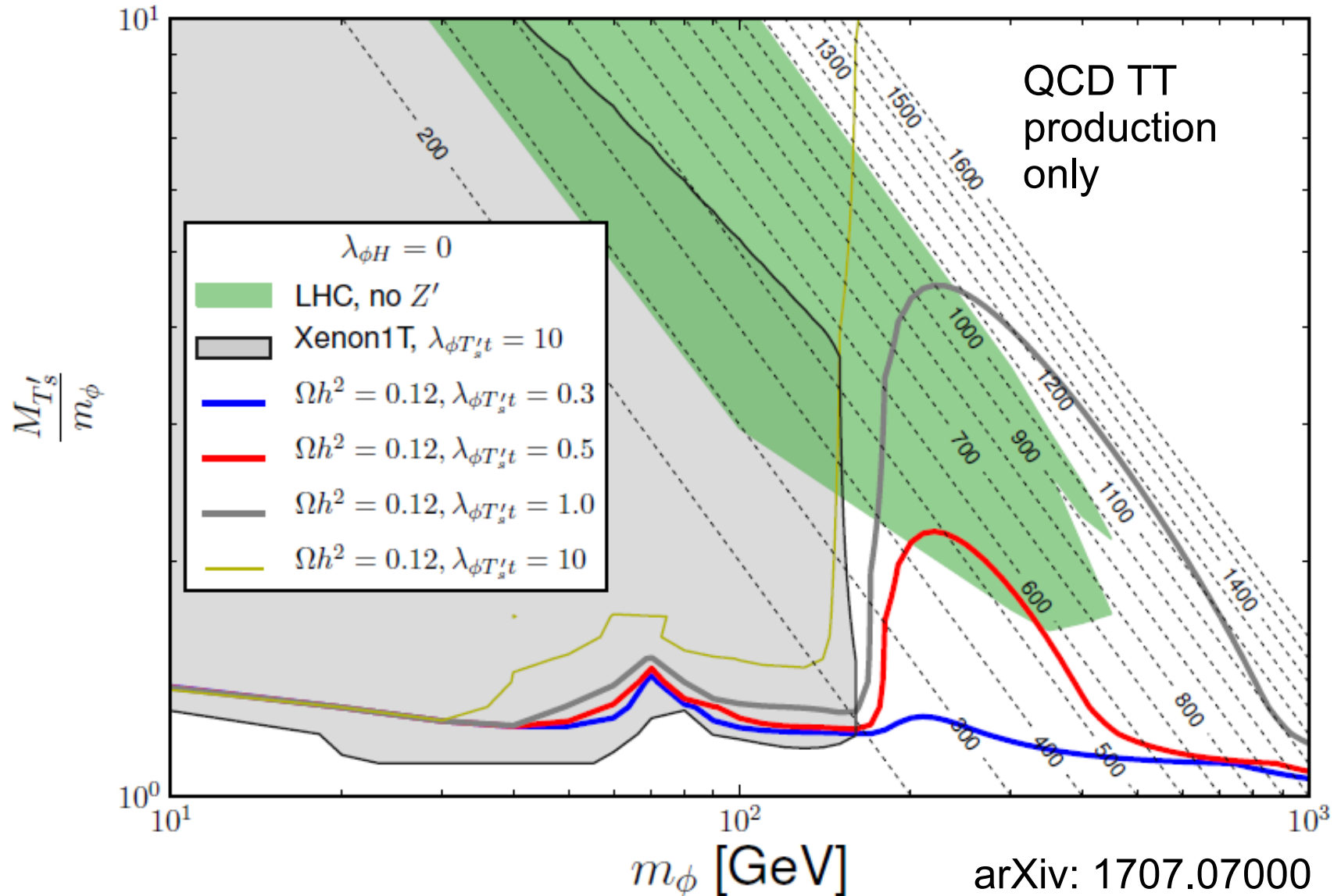
The role of Z' vs QCD for pp→ TT→ t t DM DM

arXiv: 1707.07000

Z' + QCD TT production

$\lambda_{\phi T'_s t} = 1$, $\lambda_{\phi H} = 0$
$\lambda_{Z' q\bar{q}} = 0.25$, $\lambda_{Z' T'_s \bar{T}'_s} = 2.5$

LHC, $M_{Z'} = 2.5$ TeV
LHC, $M_{Z'} = 3.0$ TeV
LHC, no Z'
$\Omega h^2 = 0.12$

$\frac{M_{T'_s}}{m_\phi}$

m_ϕ [GeV]
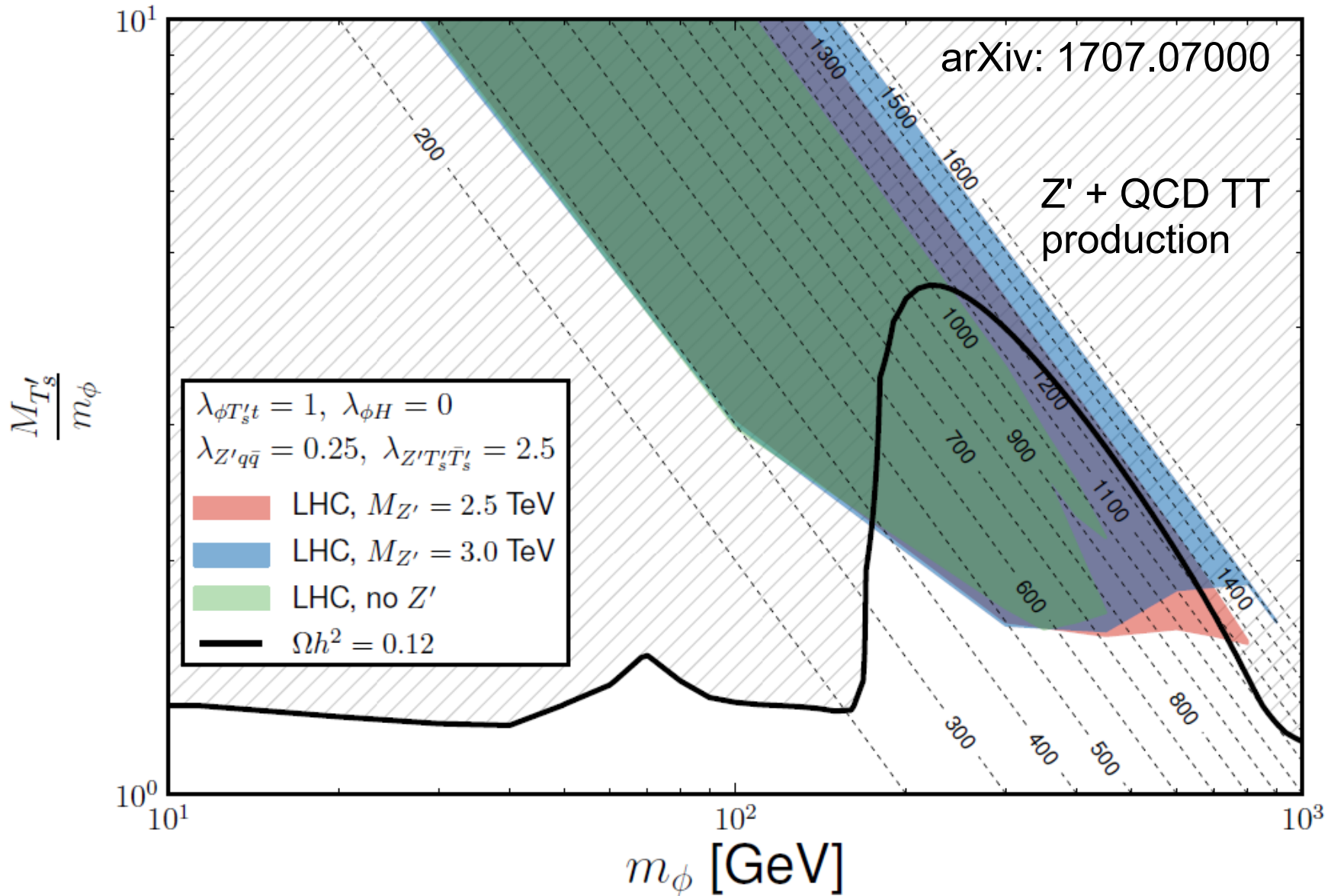
LHC is probing now DM and top patner masses up to about 0.9 and 1.5 TeV respectively: above bounds from QCD production alone by ~ factor of two

Decoding the nature of DM at the ILC

muon spectrum from the models with scalar and fermion DM

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

Normalised No. Events vs Energy of Muon, $M_{D\pm} = 150 \ GeV$

Legend:
- Fermion, $2 \to 4$, ISR + Beamstrahlung, $\sigma = 9.5 \times 10^{-2} \ pb$
- Scalar, $2 \to 4$, ISR + Beamstrahlung, $\sigma = 7.2 \times 10^{-3} \ pb$
- Analytical, simplified case

Y-axis: Normalized No. Events : $(1/\sigma) \times d\sigma/dE \ (GeV)^{-1}$

X-axis: $E(Muon) \ (GeV)$

I. Ginzburg, D.Locke, A. Freegard, T. Hosken, AB, preliminary
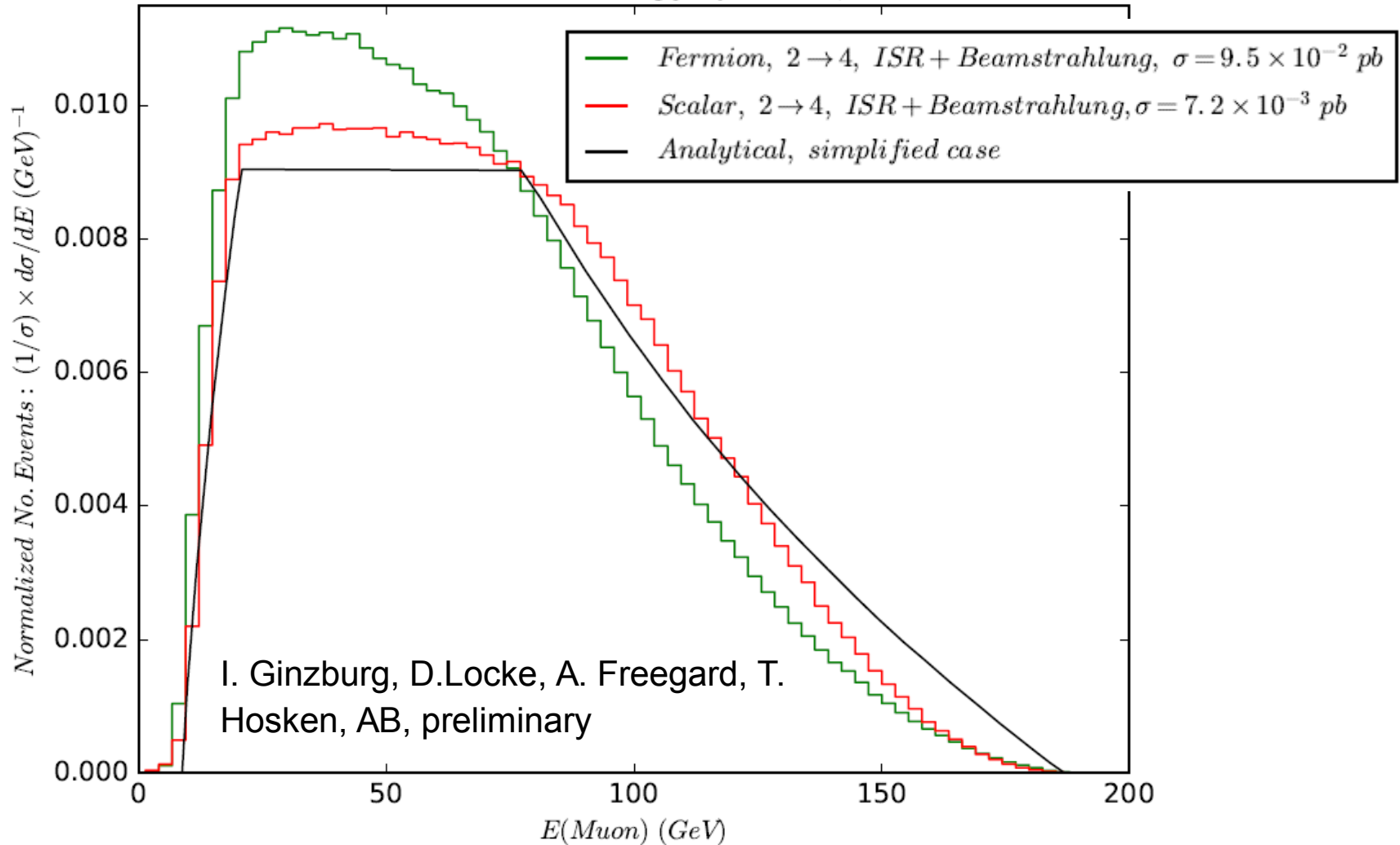
About Decoding Problem
in general

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

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

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

Login | Register

HEPMDB

High Energy Physics Models DataBase

Home News Calculate Tools Signatures Wiki Contact Us

Search in HEPMDB   🔍   Show All Models

Search Models :: Results for [MSSM]

1. **MSSM** [2011-06-21 10:54:07] hepmdb:0611.0028

   CalcHEP/MicrOMEGAs groups

   We present MSSM with SUGRA and AMSB scenario as well as MSSM with low energy input. Read file INSTALLATION for model installation and file CITE for references on scientific publications which pre...

2. **MSSM with bilinear R-Parity violation** [2011-11-17 20:00:51] hepmdb:1111.0036

   Florian Staub

   The MSSM with bilinear R-Parity violating terms in the superpotential and for the soft-breaking terms. Model files created by SARAH 3.1.0 Support of SLHA+ functionality to read spectrum files...

3. **TMSSM** [2011-11-17 20:06:23] hepmdb:1111.0037

   Florian Staub

   Triplet extended MSSM (including possibility of flavor violation) Model files created by SARAH 3.1.0 Support of

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**
  - 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 and respective 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

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_{SI}^{p} (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_{SI}^{LUX}	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

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{kin} + \mathcal{L}_{Z'q} + \mathcal{L}_{Z'\ell} + \mathcal{L}_{Z'Q'} + \mathcal{L}_{\phi Q'} - V_\phi$$

$$\mathcal{L}_{kin} = -\frac{1}{4}\left(\partial_\mu Z'_\nu - \partial_\nu Z'_\mu\right)\left(\partial^\mu Z'^\nu - \partial_\nu Z'^\mu\right) + \frac{M^2_{Z'}}{2} Z'_\mu Z'^\mu$$

$$+\frac{1}{2}\partial_\mu\phi\,\partial^\mu\phi - \frac{m^2_\phi}{2}\phi^2$$

$$+\overline{T'_s}\left(i\slashed{D} - M_{T'_s}\right)T'_s + \overline{Q'_d}\left(i\slashed{D} - M_{T'_d}\right)Q'_d\,,$$

$$\mathcal{L}_{Z'q} = \lambda_{Z'q\bar{q},L/R}\, Z'_\mu\left(\bar{q}_{L/R}\,\gamma^\mu\,q_{L/R}\right),$$

$$\mathcal{L}_{Z'\ell} = \lambda_{Z'\ell^+\ell^-,L/R}\, Z'_\mu\left(\bar{\ell}_{L/R}\,\gamma^\mu\,\ell_{L/R}\right),$$

$$\mathcal{L}_{Z'Q'} = \lambda_{Z'T'_s\overline{T'_s},L/R}\, Z'_\mu\left(\overline{T'}_{s,L/R}\,\gamma^\mu\,q_{L/R}\right)$$

$$+\lambda_{Z'T'_d\overline{T'_d},L/R}\, Z'_\mu\left(\overline{T'}_{d,L/R}\,\gamma^\mu\,T'_{d,L/R}\right)$$

$$+\lambda_{Z'T'_d\overline{T'_d},L/R}\, Z'_\mu\left(\overline{B'}_{d,L/R}\,\gamma^\mu\,B'_{d,L/R}\right),$$

$$\mathcal{L}_{\phi Q'} = \left(\lambda_{\phi T'_s t}\,\phi\,\bar{t}_R\,T'_{s,R} + \lambda_{\phi T'_d t}\,\phi\,\bar{t}_L\,T'_{d,L} + \lambda_{\phi T'_d t}\,\phi\,\bar{b}_L\,B'_{d,L}\right) + \text{h.c.},$$

$$V_\phi = \frac{\lambda_\phi}{4!}\phi^4 + \frac{\lambda_{\phi H}}{2}\phi^2\left(|H|^2 - \frac{v^2}{2}\right).$$