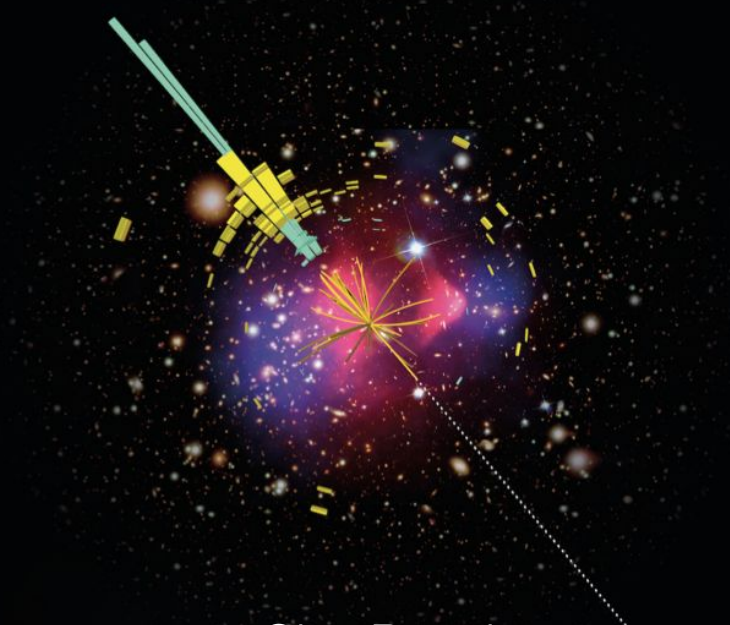
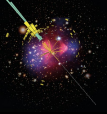


# t-channel models: activities and goals

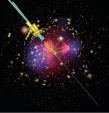


Oleg Brandt  
for the LHC DM WG organisers





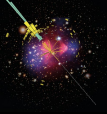
- Raison d'être & rôle:
  - Coordinate discussion about DM searches at the LHC between theory and experiment
  - Provide advice about searches & parameter spaces of simplified models
  - Defining benchmark models and interpretations for DM searches
  - Facilitate collaboration across the LHC experiments and theory
  - Open and topical meetings, with  $O(100)$  interested physicists participating
  - Facilitate development of higher-precision calculations for backgrounds
  - Interface to direct and indirect detection communities



- Logistics:
  - [Website](#)
  - [Indico agenda space](#), [t-channel rolling agenda](#)
  - Mailing list for discussion/questions (everyone subscribed can post):
    - [lhc-dmwg-contributors@cern.ch](mailto:lhc-dmwg-contributors@cern.ch), [subscribe](#)
  - Mailing list for t-channel studies (everyone subscribed can post)
    - [lhc-dmwg-contributors-tchannel@cern.ch](mailto:lhc-dmwg-contributors-tchannel@cern.ch), [subscribe](#)
  - Mailing list for announcements (restricted posting, write to organisers)
    - [lhc-dmwg@cern.ch](mailto:lhc-dmwg@cern.ch), [subscribe](#)
  - Mailing list DM WG organisers:
    - [lhc-dmwg-admin@cern.ch](mailto:lhc-dmwg-admin@cern.ch)

Open to newcomers!  
Easy to contribute!

- LHC DM WG organisers ([email us](#)):
  - ATLAS: Oleg Brandt, Priscilla Pani
  - CMS: Phil Harris
  - LHCb: Xabier Cid Vidal
  - Theory: Uli Haisch, Tim Tait



# Navigating (DM) theory space

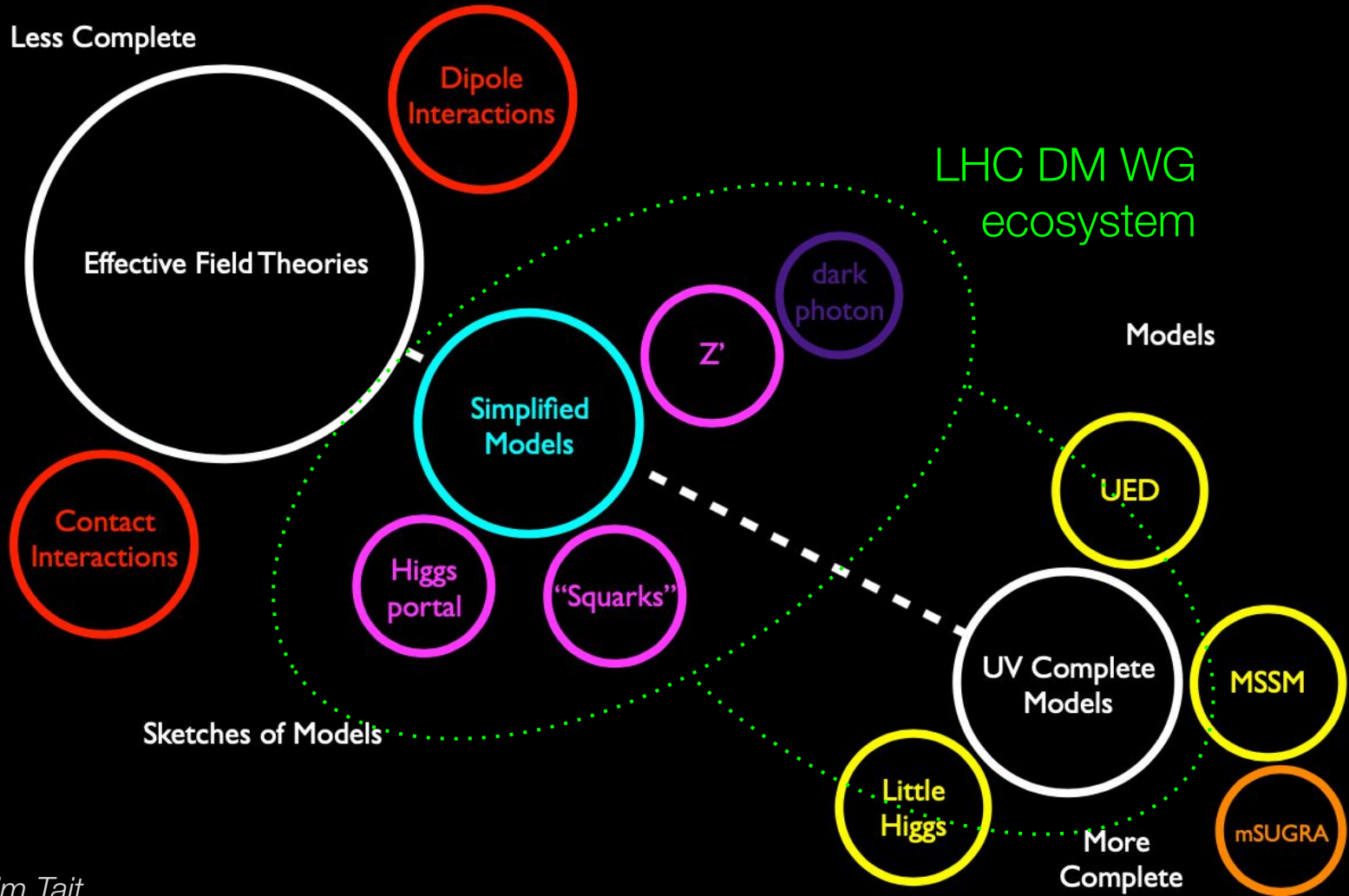
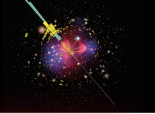
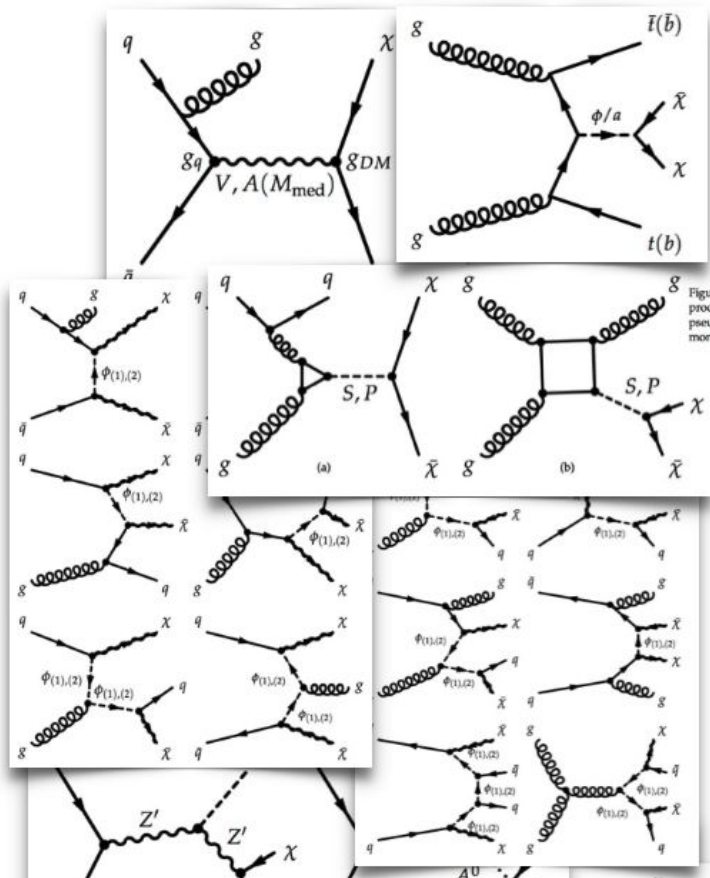


Figure: Tim Tait



# LHC DM WG: past activities

- Series of White Papers published in Phys. Dark Univ.



Dark Matter Benchmark Models for Early LHC Run-2 Searches: Report of the ATLAS/CMS Dark Matter Forum

August 8, 2016

*Phys. Dark Univ. 26 (2020) 100371*

5.62

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**Recommendations on presenting LHC searches for missing transverse energy signals using simplified s-channel models of dark matter**

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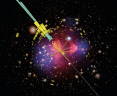
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**LHC Dark Matter Working Group:**

**Next-generation spin-0 dark matter models**

*Phys. Dark Univ. 27 (2020) 100351*

**Next White Paper**  
t-channel mediator models



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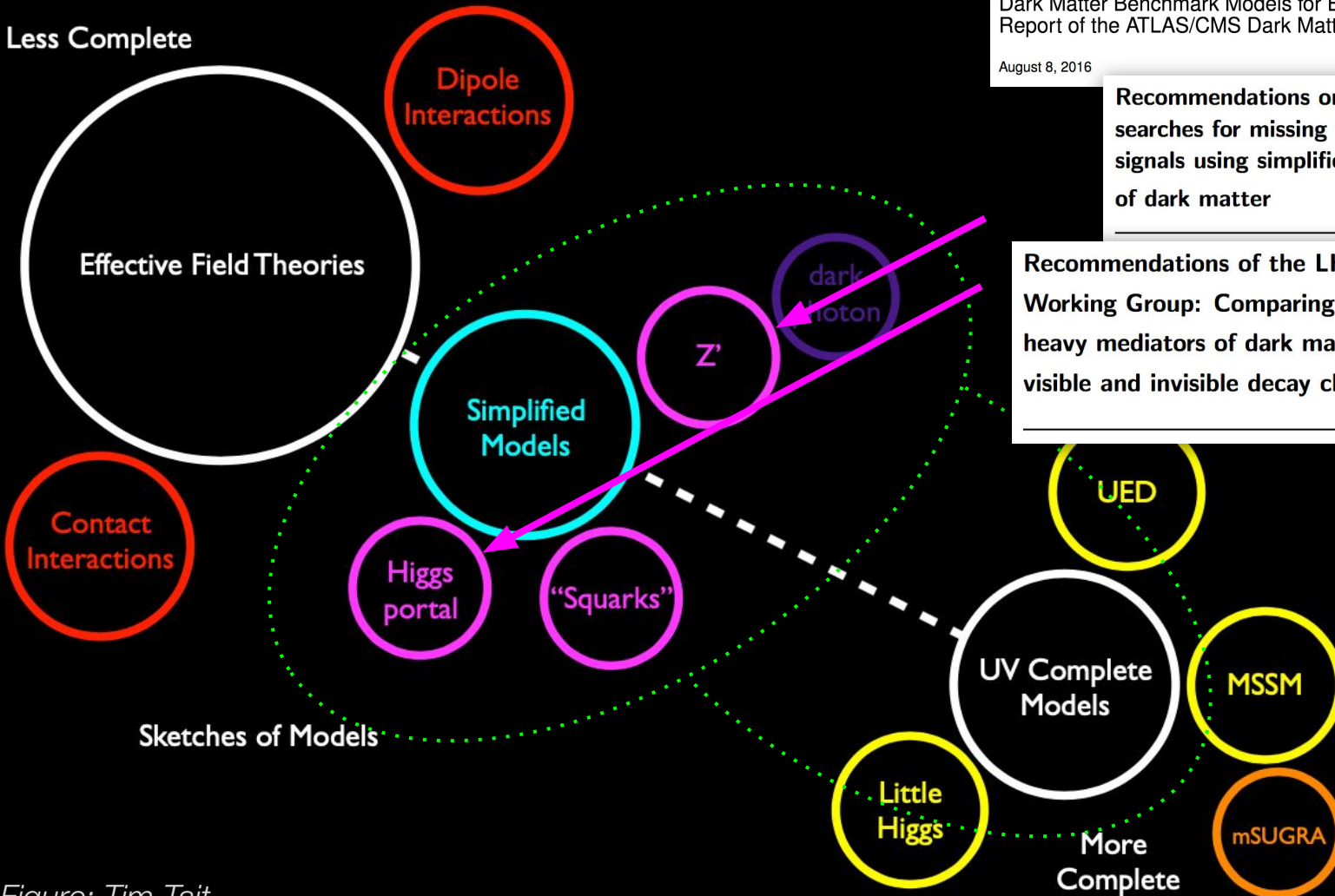
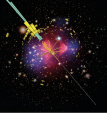
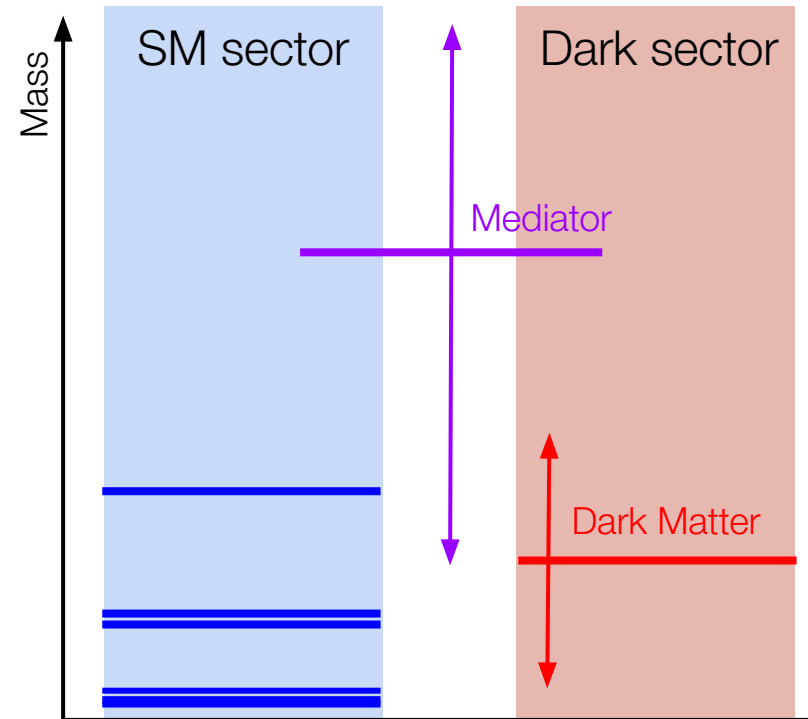
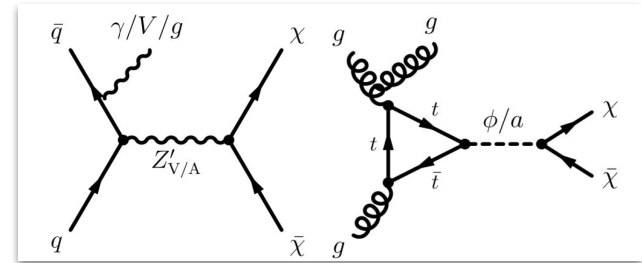


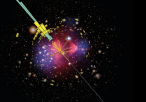
Figure: Tim Tait



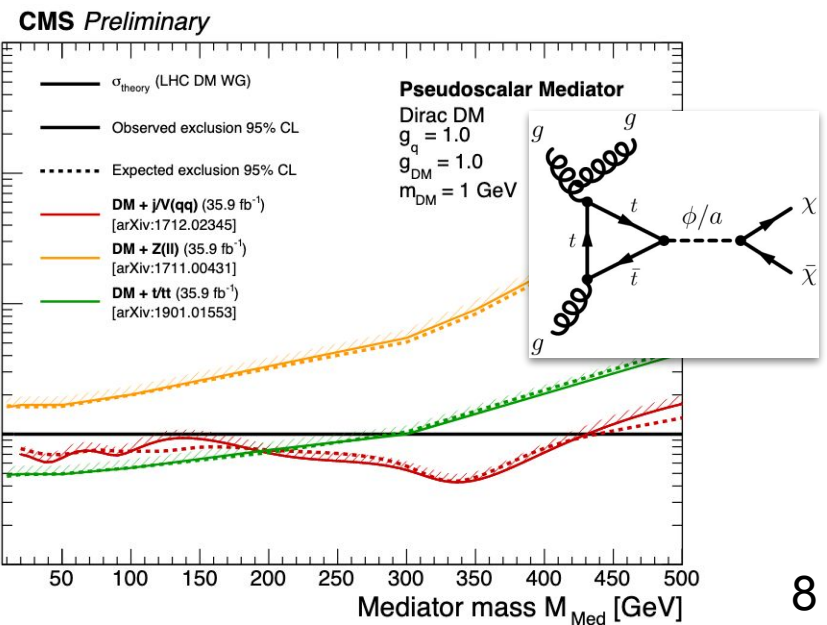
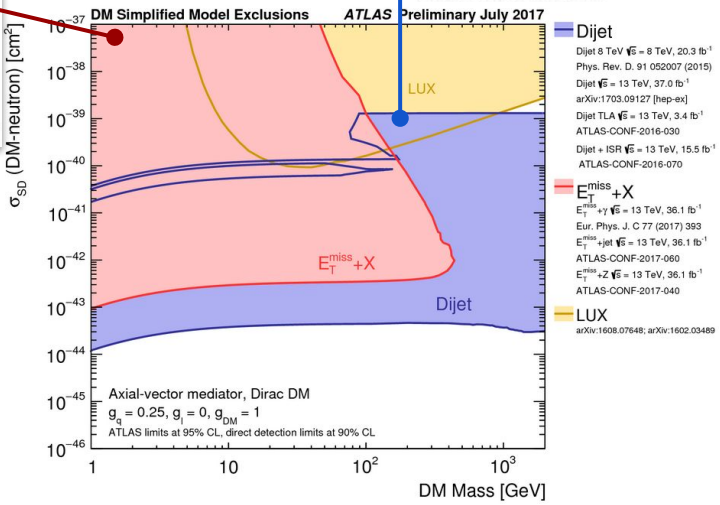
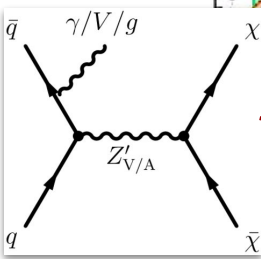
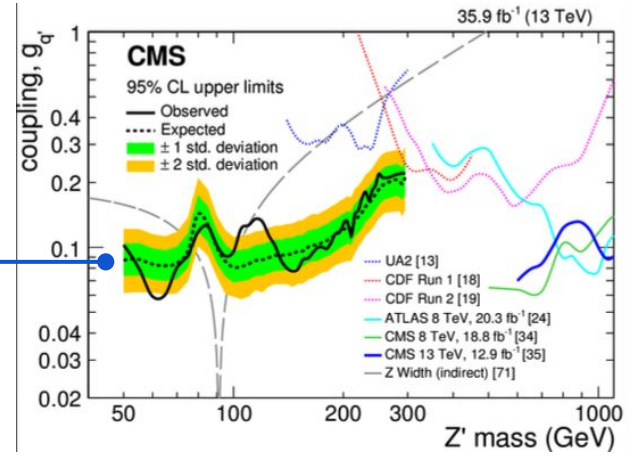
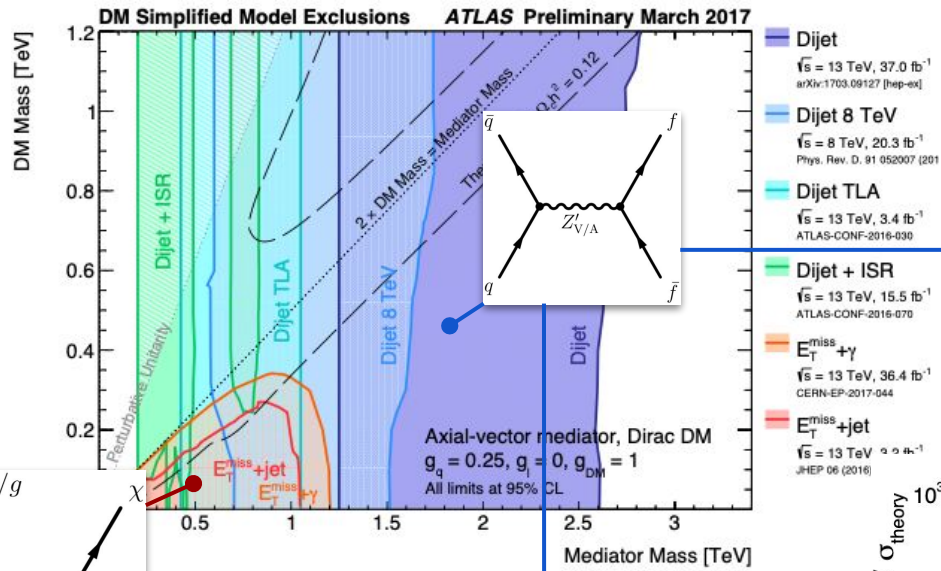
# s-channel mediator models

- Strong motivation (as strong as t-channel)
- Ansatz:
  - DM-mediator interaction
  - SM fermions-mediator interaction
- Mediator can be a vector vs scalar
  - (gauge vs Yukawa type of couplings)
  - Chiral structure (LH, RH) for SM fermions can be important
- Complementary signatures:
  - X+MET final states, X from ISR
  - resonance searches

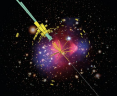




# s-channel mediator models

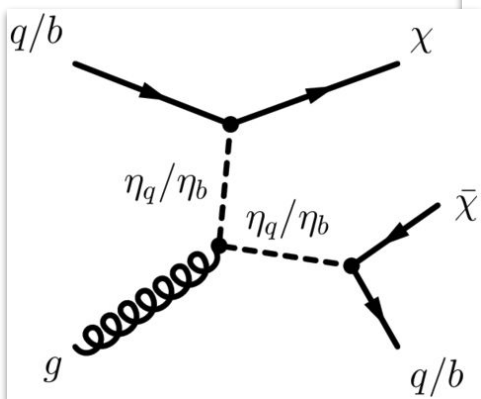
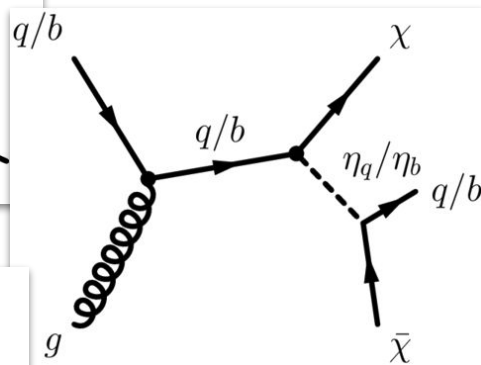
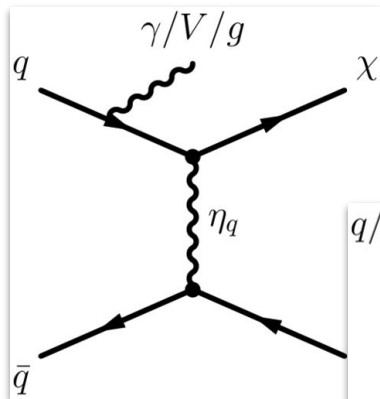






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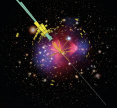
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**Next White Paper**  
t-channel mediator models



# Navigating (DM) theory space

**Next White Paper**  
t-channel mediator models

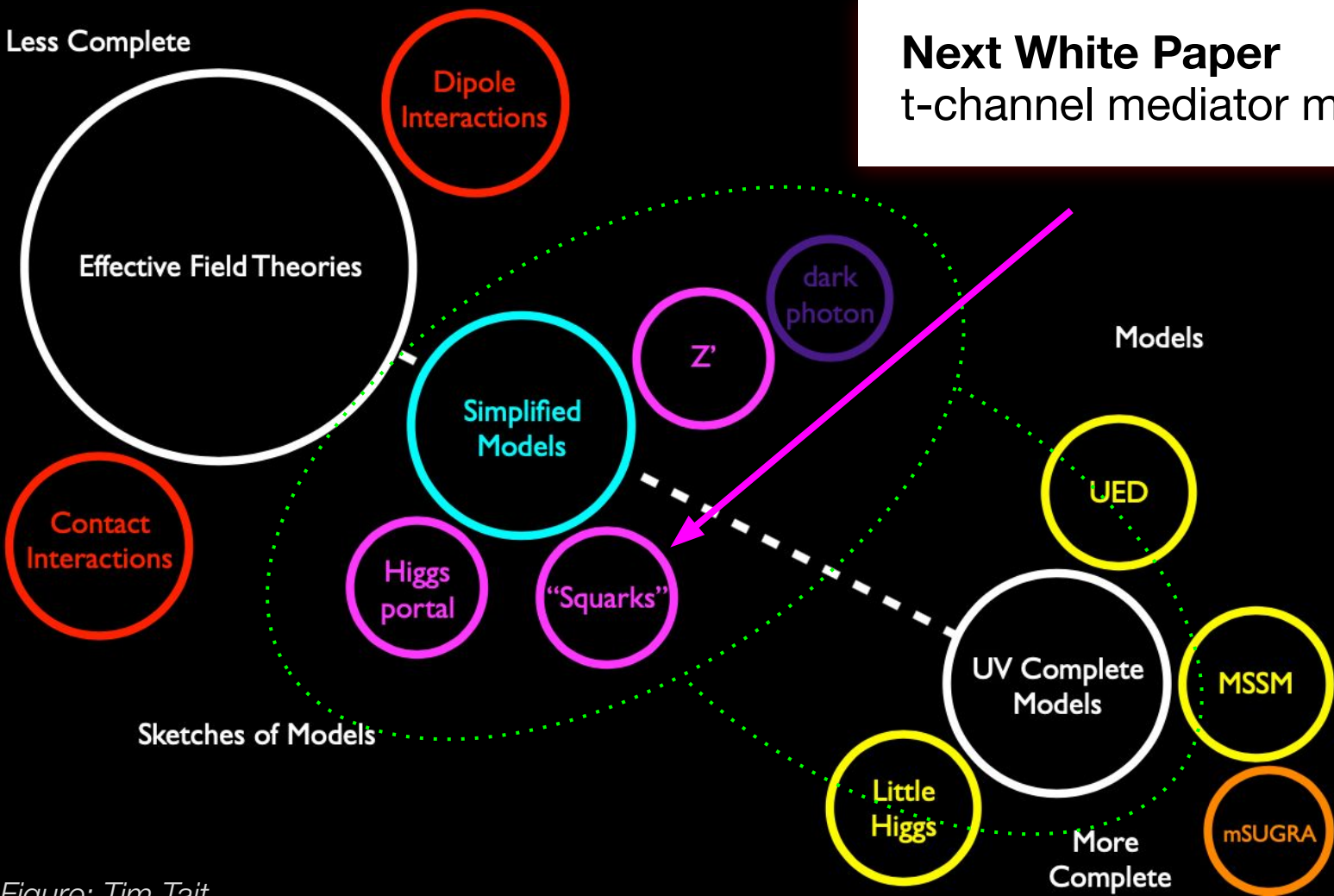
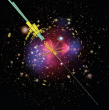
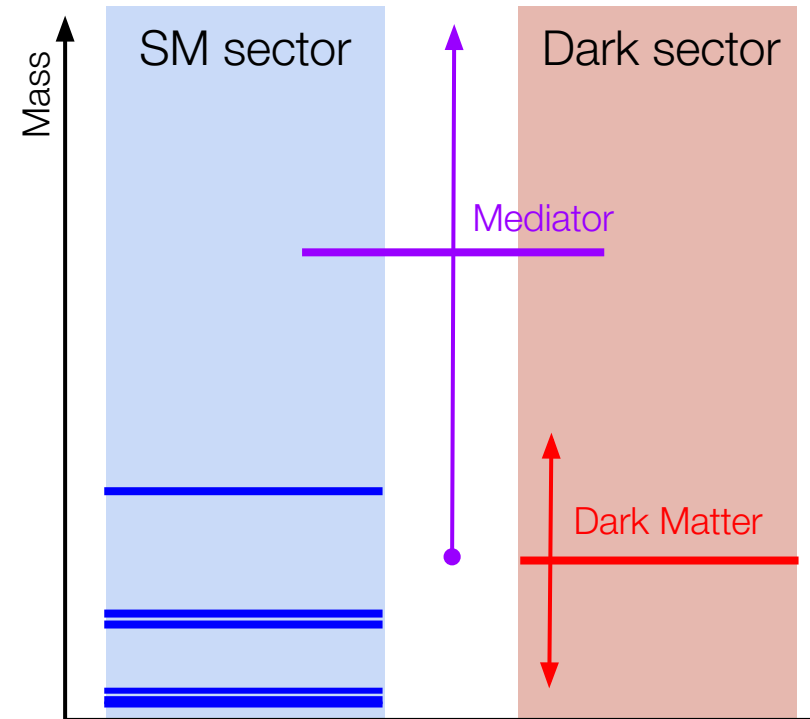
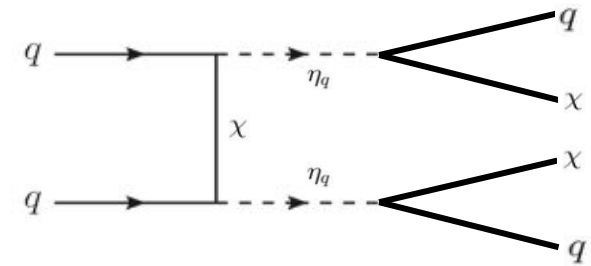


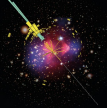
Figure: Tim Tait



# t-channel mediator models

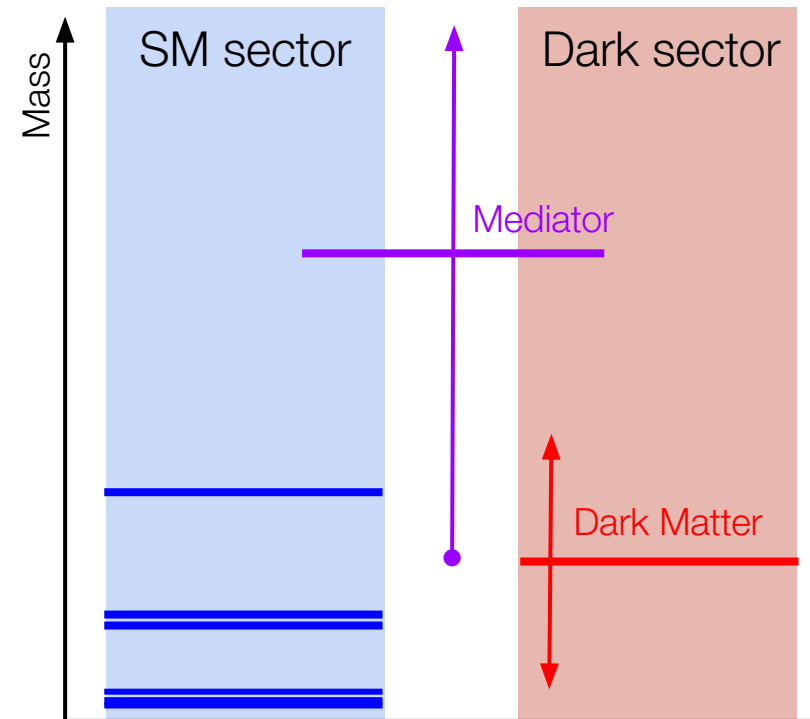
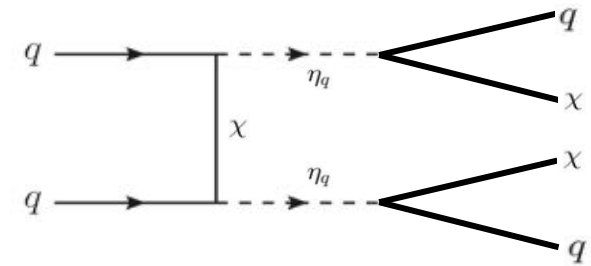
- Strong motivation (as strong as s-channel)
- Ansatz:
  - DM interacting with SM fermions and a mediator
- Corollary:
  - SM mediators must carry charge (since SM particles carry charge)
  - mediator shares the symmetry that stabilises DM
  - $\rightarrow m_{\text{Mediator}} > m_{\text{DM}}$
  - Different possibilities for DM and mediator spin QN, but one must be a fermion, and the other a boson

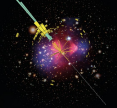




# t-channel mediator models

- Self-consistent mediator-SM pairing:
  - LH quarks
  - RH up-type quarks
  - RH down-type quarks
  - leptons
- Signatures:
  - No restriction across families
    - can have interesting flavour dependence beyond MFV
  - No resonant mediator searches!
    - MET ubiquitous!
  - Possible long-lived particle signatures

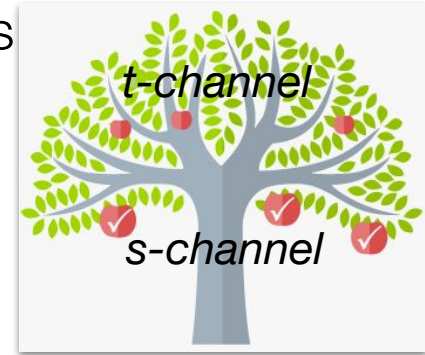
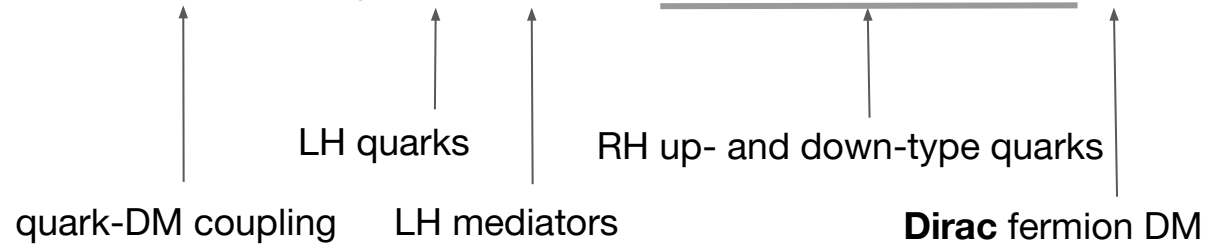




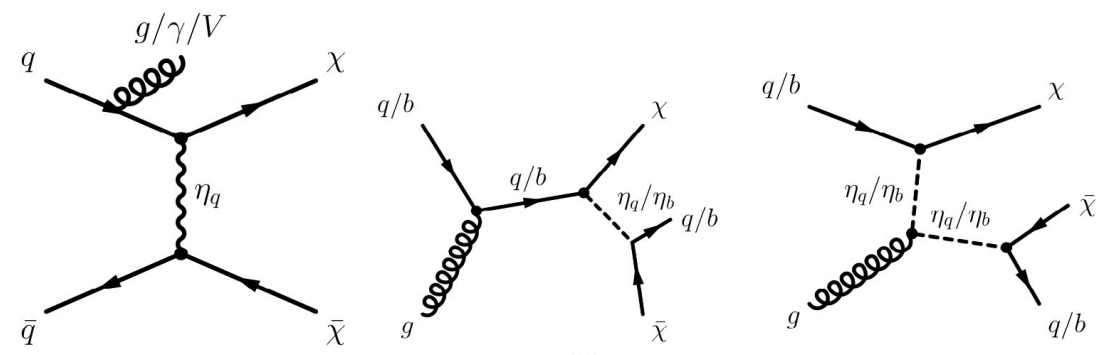
# Basic signatures

- Example Lagrangian for Dirac DM coupling to 1&2<sup>nd</sup> families

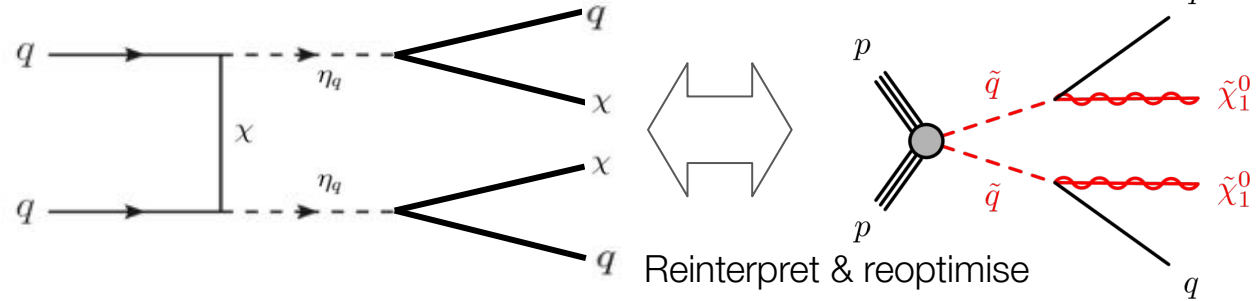
$$\mathcal{L} \supset g_{q\chi} \sum_{i=1,2} (\bar{Q}_{L,i} \eta_{L,q_i} + \bar{u}_{R,i} \eta_{R,u_i} + \bar{d}_{R,i} \eta_{R,d_i}) \chi + \text{h.c.}$$

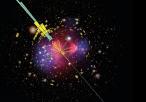


Jet + MET:



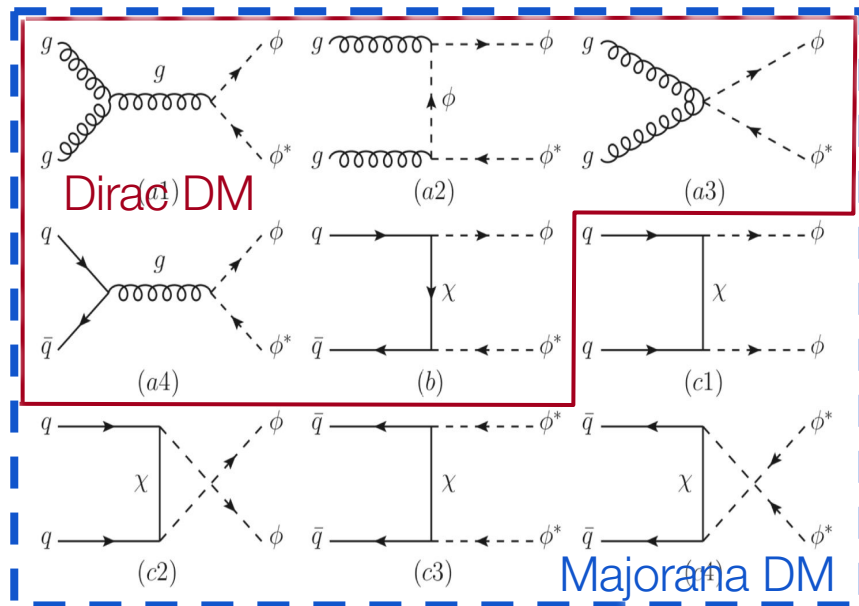
Di-jet + MET:





# Going beyond

- Study impact of spin of DM particles
  - Majorana DM has more diagrams
  - Quantify effect on which phase-space regions are relevant?
- Try out DM properties [1,2,3,4,5]:
  - Dirac/Majorana fermion
  - Scalar
  - Vector



◆ 18 restrictions with 3 parameters each

Name	DM	Mediators	Parameters
S3M.uni	$\tilde{\chi}$	$\varphi_{Q_f}, \varphi_{u_f}, \varphi_{d_f}$	
S3D.uni	$\chi$		
S3M.3rd	$\tilde{\chi}$	$\varphi_{Q_3}, \varphi_{u_3}, \varphi_{d_3}$	$M_\varphi, M_\chi, \lambda_\varphi$
S3D.3rd	$\chi$		
S3M.uR	$\tilde{\chi}$	$\varphi_{u_1}$	
S3D.uR	$\chi$		
F3S.uni	$\tilde{S}$	$\psi_{Q_f}, \psi_{u_f}, \psi_{d_f}$	
F3C.uni	$S$		
F3S.3rd	$\tilde{S}$	$\psi_{Q_3}, \psi_{u_3}, \psi_{d_3}$	$M_S, M_\psi, \lambda_\psi$
F3C.3rd	$S$		
F3S.uR	$\tilde{S}$	$\psi_{u_1}$	
F3C.uR	$S$		
F3V.uni	$\tilde{V}_\mu$	$\psi_{Q_f}, \psi_{u_f}, \psi_{d_f}$	
F3W.uni	$V_\mu$		
F3V.3rd	$\tilde{V}_\mu$	$\psi_{Q_3}, \psi_{u_3}, \psi_{d_3}$	$M_V, M_\psi, \lambda_\psi$
F3W.3rd	$V_\mu$		
F3V.uR	$\tilde{V}_\mu$	$\psi_{u_1}$	
F3W.uR	$V_\mu$		

♣ Universal models (uni):

- ★ 1 dark matter particle
- ★ 12 mass-degenerate mediators
- ★ 1 flavour-conserving coupling

$$\mathcal{L}_{X,\text{uni}}(X) = \sum_{F=Q,u,d} \sum_{f=1}^3 [\lambda_\varphi \bar{X} F_f \varphi_f^\dagger + \text{h.c.}]$$

♣ 3rd generation models (3rd):

- ★ 1 dark matter particle
- ★ 4 mass-degenerate mediators
- ★ 1 flavour-conserving coupling

$$\mathcal{L}_{X,3\text{rd}}(X) = \sum_{F=Q,u,d} [\lambda_\varphi \bar{X} F_3 \varphi_3^\dagger + \text{h.c.}]$$

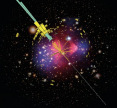
♣ uR models (uR):

- ★ 1 dark matter particle
- ★ 1 mediator
- ★ Coupling to the right-handed up-quark

$$\mathcal{L}_{X,\text{uR}}(X) = [\lambda_\varphi \bar{X} u_1 \varphi_{u_1}^\dagger + \text{h.c.}]$$

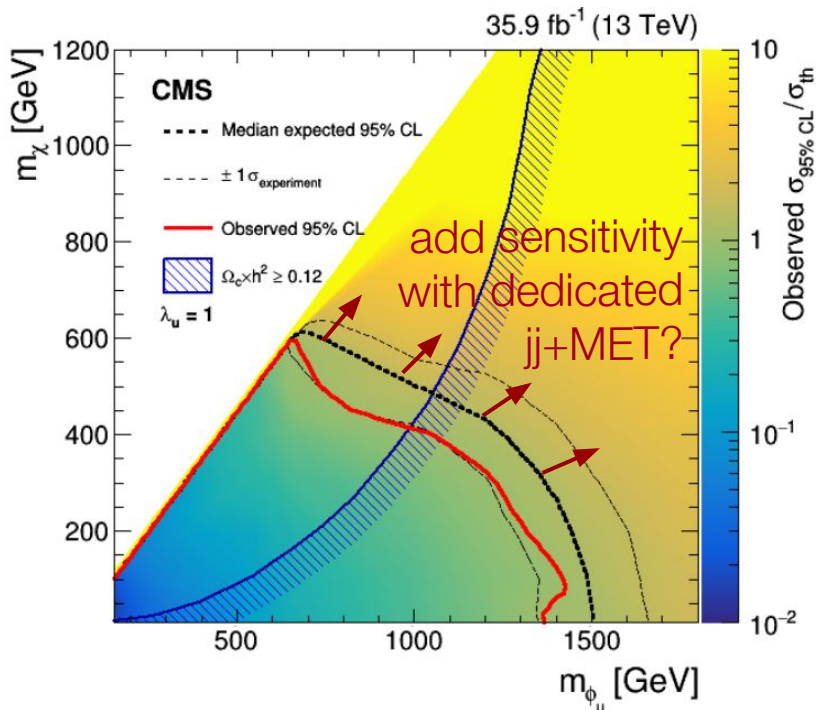
→ cf. Chiara's talk for details

- Important step forward:
  - New Über-UFO [1,2,3] available
    - can do all DM spin hypotheses
  - über-UFO validated against few existing implementations

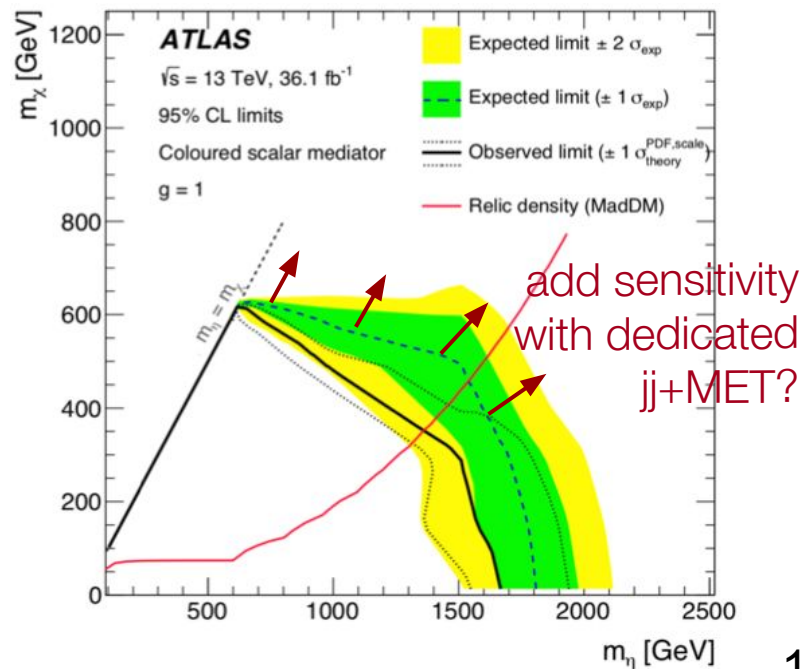


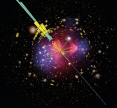
# Previous work

- Fermion portal DM [1,2]
  - [CMS monojet](#)
  - Coincides with S3D\_uR restriction for Über-UFO
  - Previous results reproduced [1]



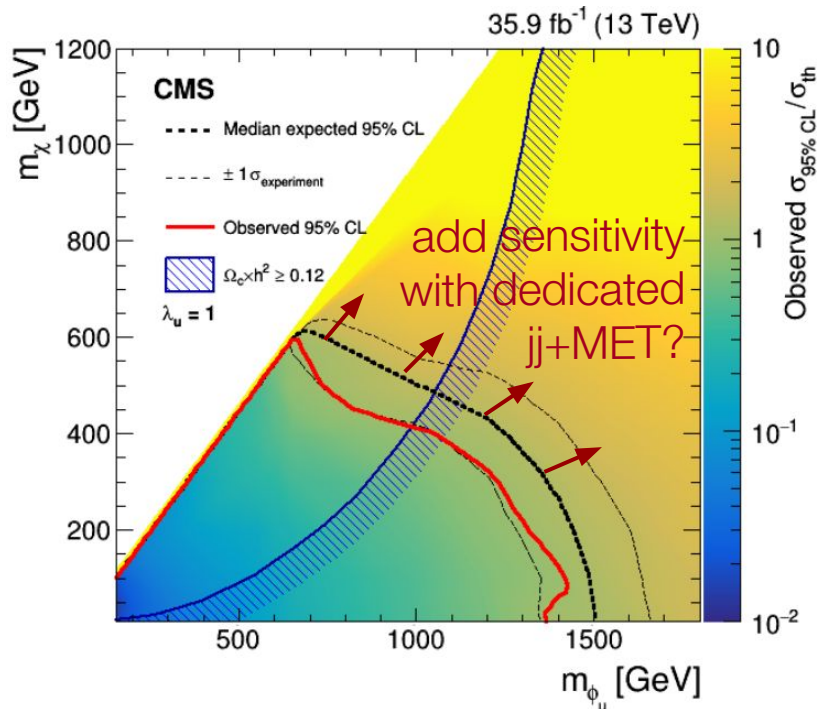
- Scalar color-charged model [1,2]
  - [ATLAS monojet](#)
  - LH coupling 1<sup>st</sup> gen. restriction for Über-UFO worked out [1]
  - Previous results reproduced



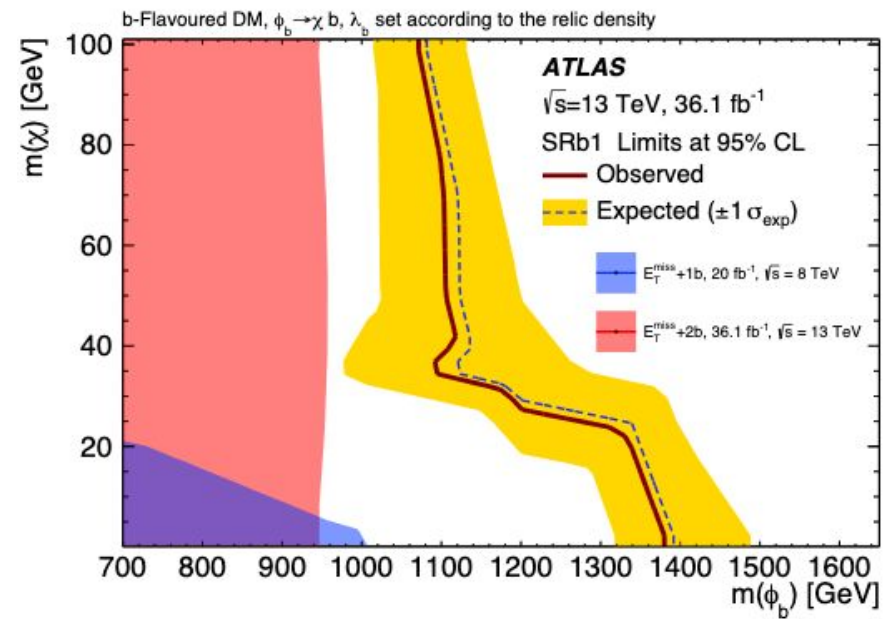


# Previous work

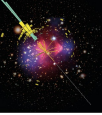
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  - Previous results reproduced [1]



- Scalar color-charged b model [2,3]
  - [ATLAS mono-b-jet](#)
  - RH coupling 3<sup>rd</sup> generation
  - qualitatively similar kinematic behaviour to 1<sup>st</sup> gen case [1]

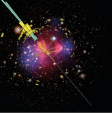






- Über-UFO ready and validated
  - matched to previous results & confirmed
- Next steps:
  - Converging on first 1st generation scans soon
  - Study impact of NLO vs LO:
    - flat k-factor or non-trivial dependency on e.g. MET?
  - Impact of DM spin assumptions: Dirac/Majorana, scalar, vector
  - Study connection to flavour-sector observables
    - go beyond minimal flavour violation
  - Study connection to long-lived particle signatures
    - Easy to get in t-channel models
      - Almost “generic” feature



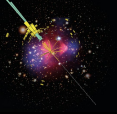


- Past LHC DM WG White Papers:
  - instrumental in guiding LHC DM searches
- Current focus: next white paper on t-channel models
  - Series of dedicated meetings organised to share results
  - Über-UFO ready to study different spin and coupling assumptions
    - Previous ATLAS & CMS models mapped
    - Basic sensitivity laid out for 1<sup>st</sup> generation searches
    - Converging on first 1<sup>st</sup> generation recommendations
  - Great range in pheno+experimental space to explore & contribute:
    - Impact of spin & coupling assumptions, 3<sup>rd</sup> generation couplings
    - Connection to LLP signatures
    - Constraints from flavour sector
  - → If interested, please get involved!
    - [Topics & sign up](#), [discuss findings](#), [rolling agenda](#)

[Email LHC DM WG organisers](#)

[Discuss your DM question](#)

[Discuss t-channel models](#)

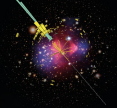


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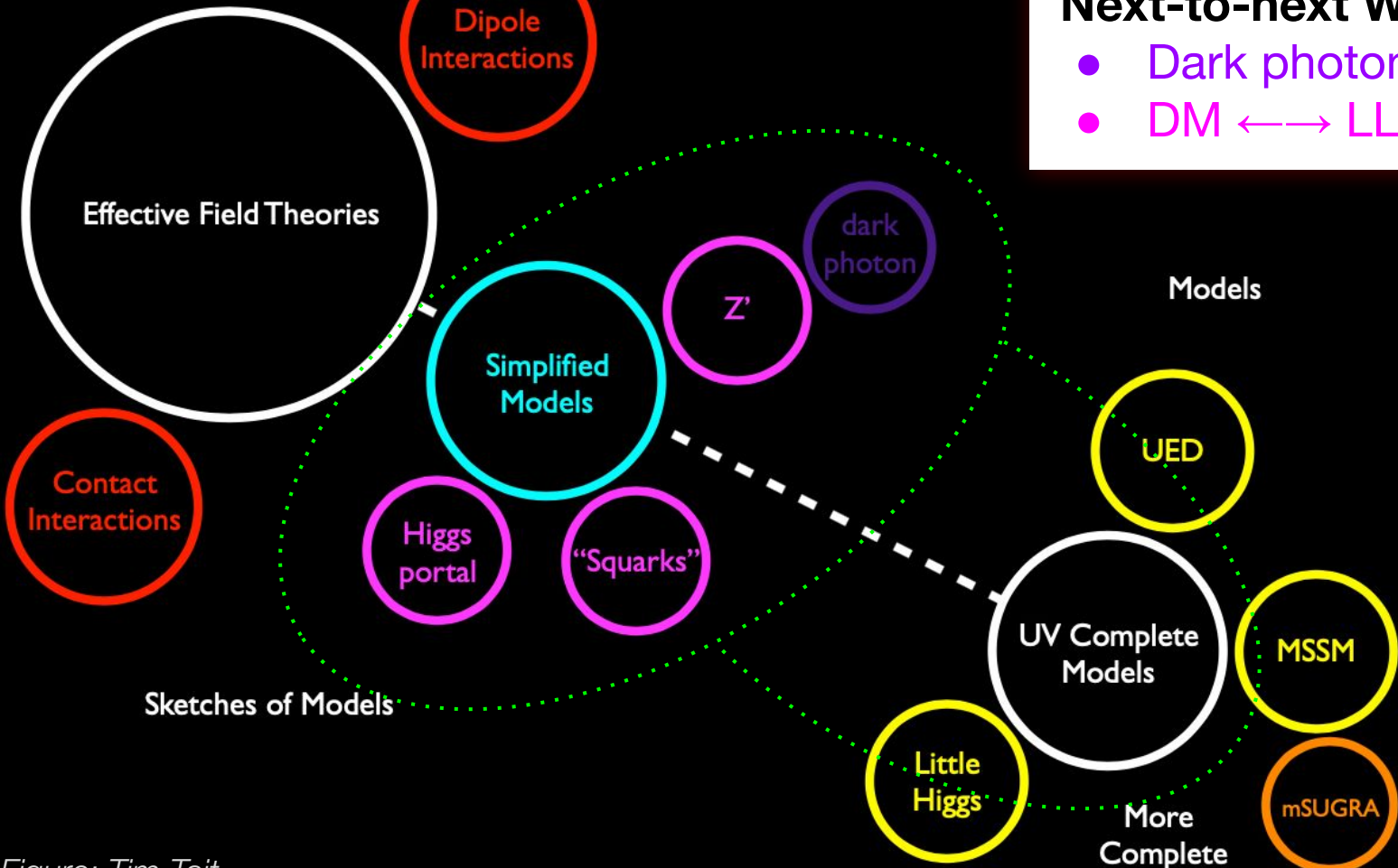
[Discuss t-channel models](#)

Thank you!



# Future LHC DM WG projects

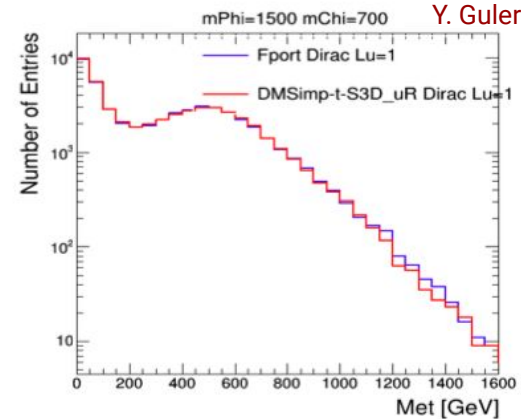
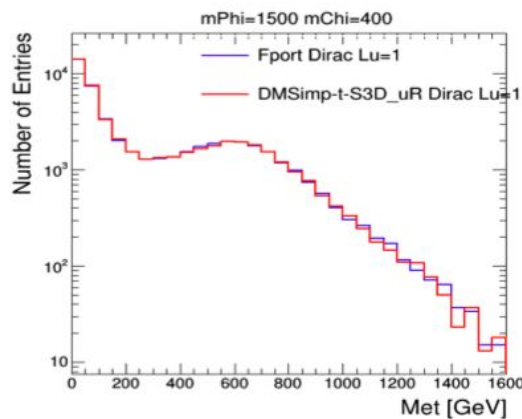
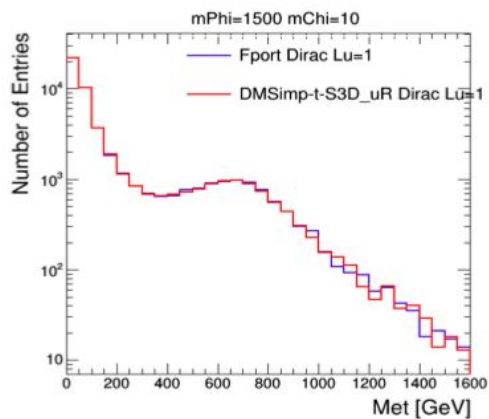
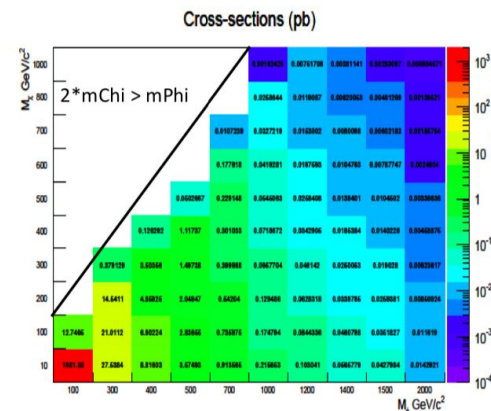
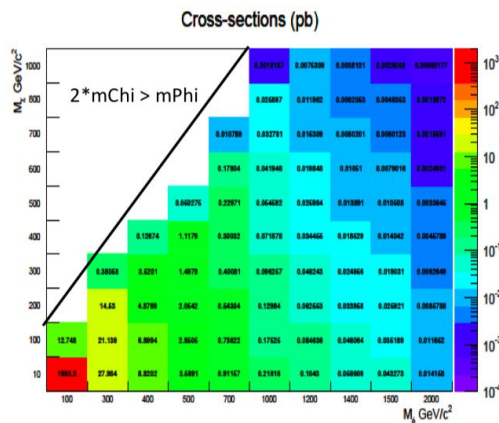
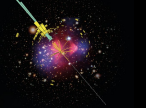
Less Complete



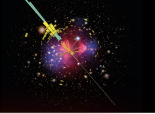
## Next-to-next White Paper

- Dark photon?
- $DM \leftrightarrow LLP$ ?

Figure: Tim Tait

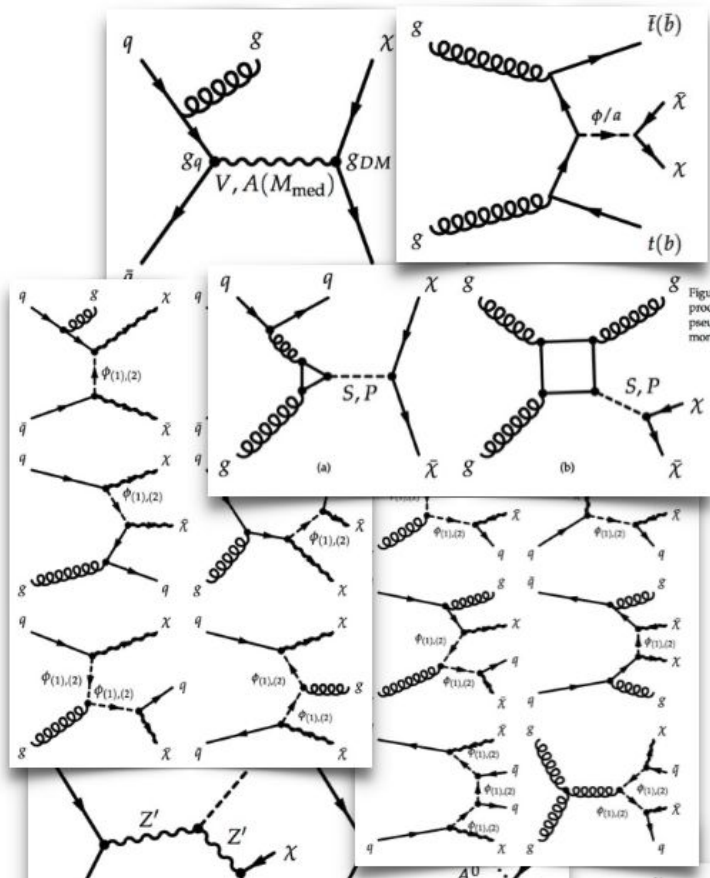


Y. Guler



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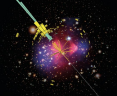
*Phys. Dark Univ. 26 (2019) 100377*

**LHC Dark Matter Working Group:**

**Next-generation spin-0 dark matter models**

*Phys. Dark Univ. 27 (2020) 100351*

**Next White Paper**  
t-channel mediator models



# Navigating (DM) theory space

Dark Matter Benchmark Models for Early LHC Run-2 Searches:  
Report of the ATLAS/CMS Dark Matter Forum

August 8, 2016

Recommendations on presenting LHC searches for missing transverse energy signals using simplified  $s$ -channel models of dark matter

Recommendations of the LHC Dark Matter Working Group: Comparing LHC searches for heavy mediators of dark matter production in visible and invisible decay channels

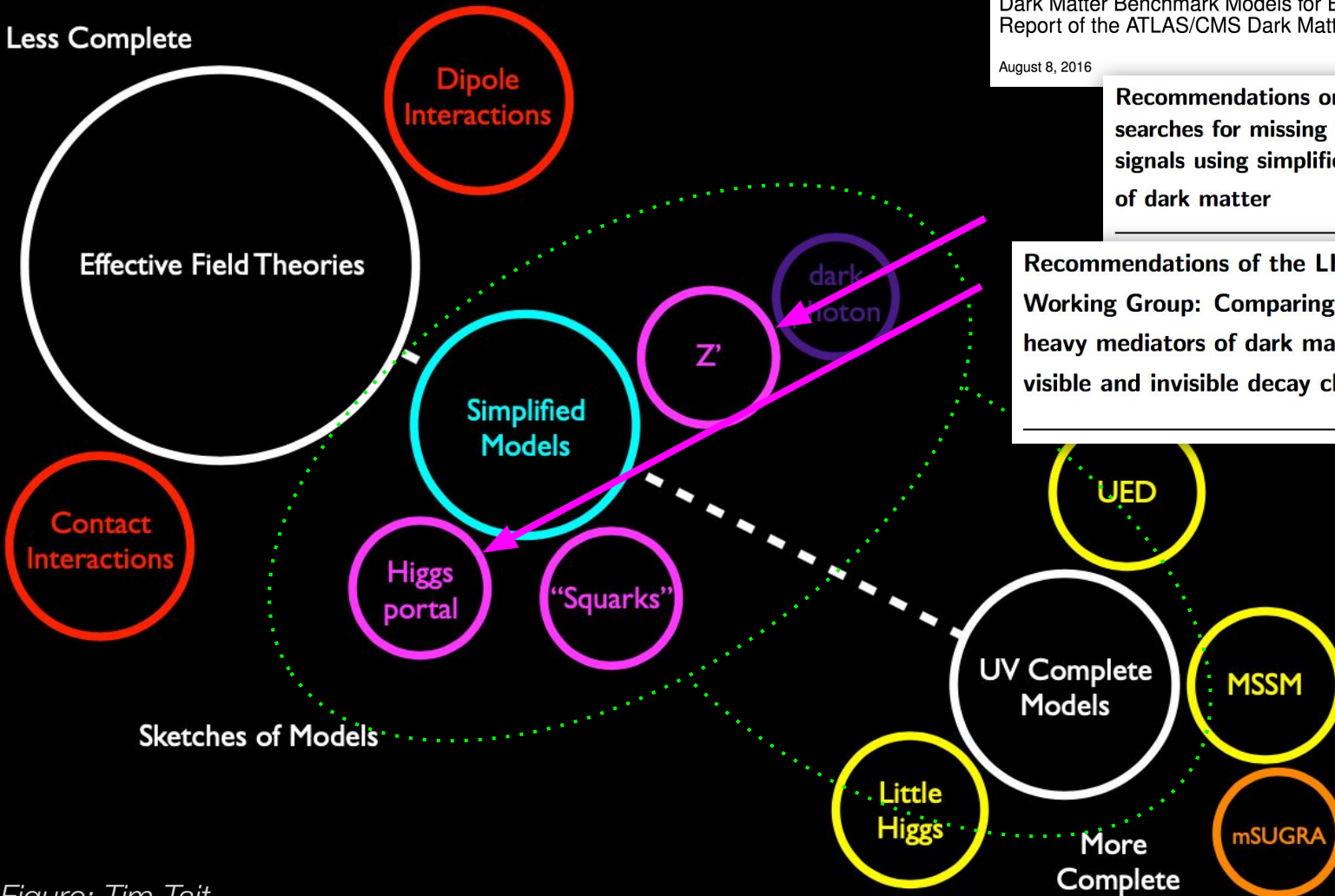
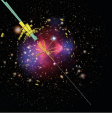
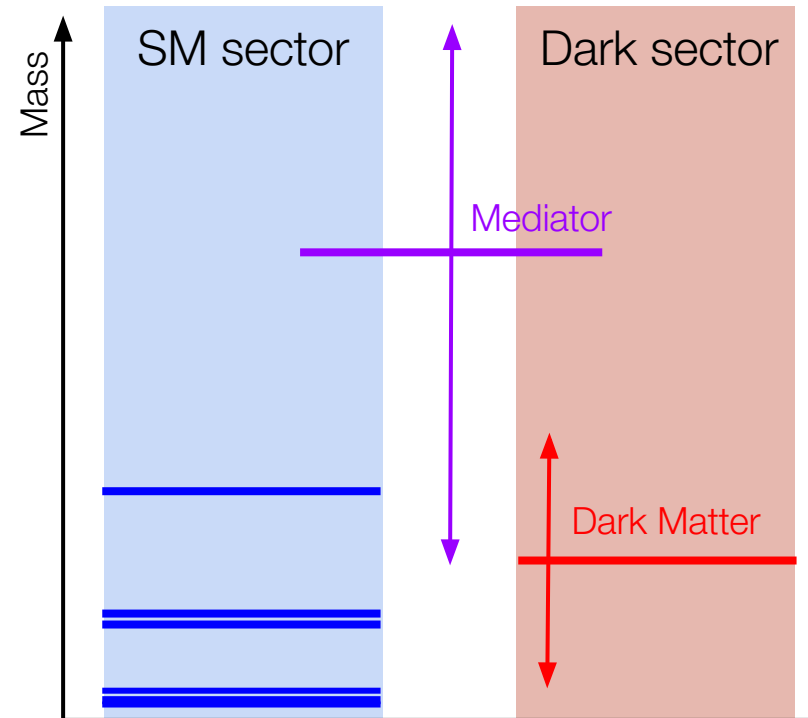
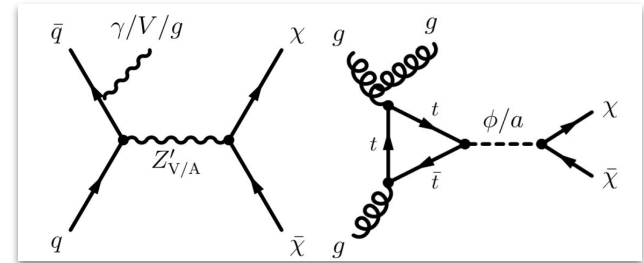


Figure: Tim Tait

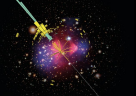


# s-channel mediator models

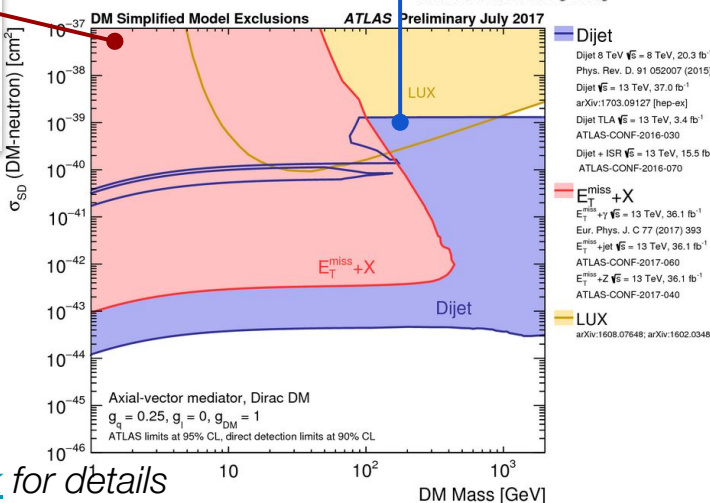
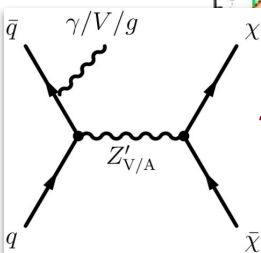
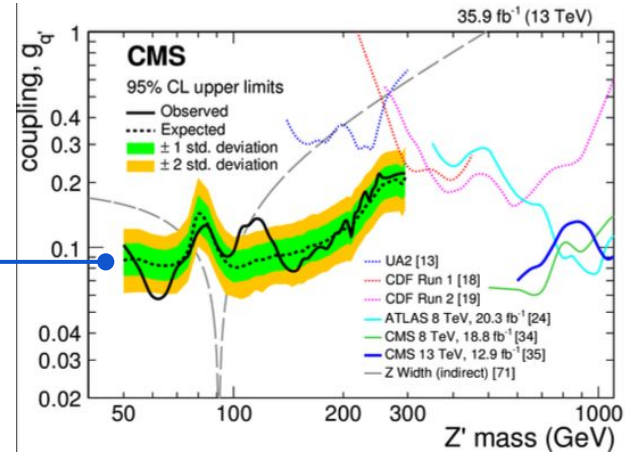
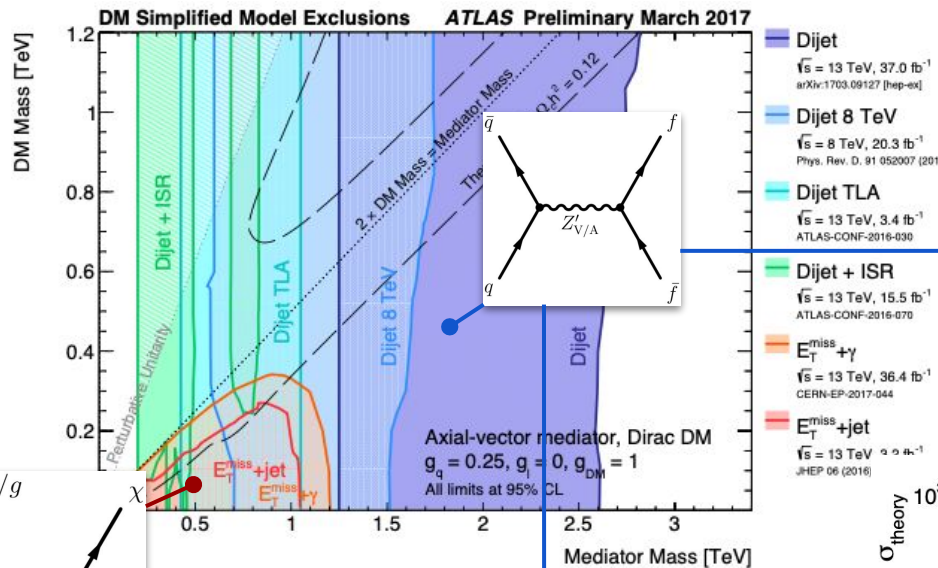
- Strong motivation (as strong as t-channel)
- Ansatz:
  - DM-mediator interaction
  - SM fermions-mediator interaction
- Mediator can be a vector vs scalar
  - (gauge vs Yukawa type of couplings)
  - Chiral structure (LH, RH) for SM fermions can be important
- Complementary signatures:
  - X+MET final states, X from ISR
  - resonance searches



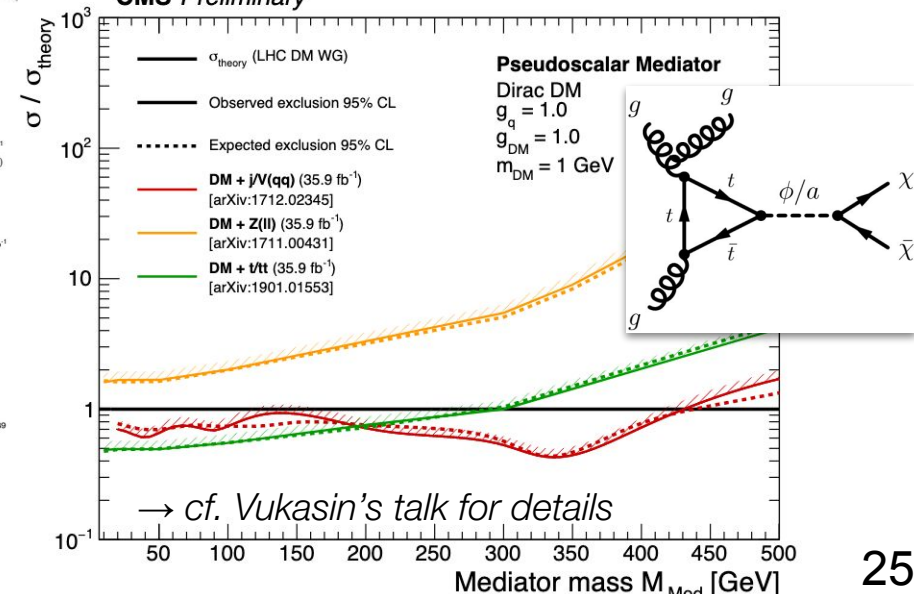




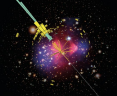
# s-channel mediator models



**CMS Preliminary**

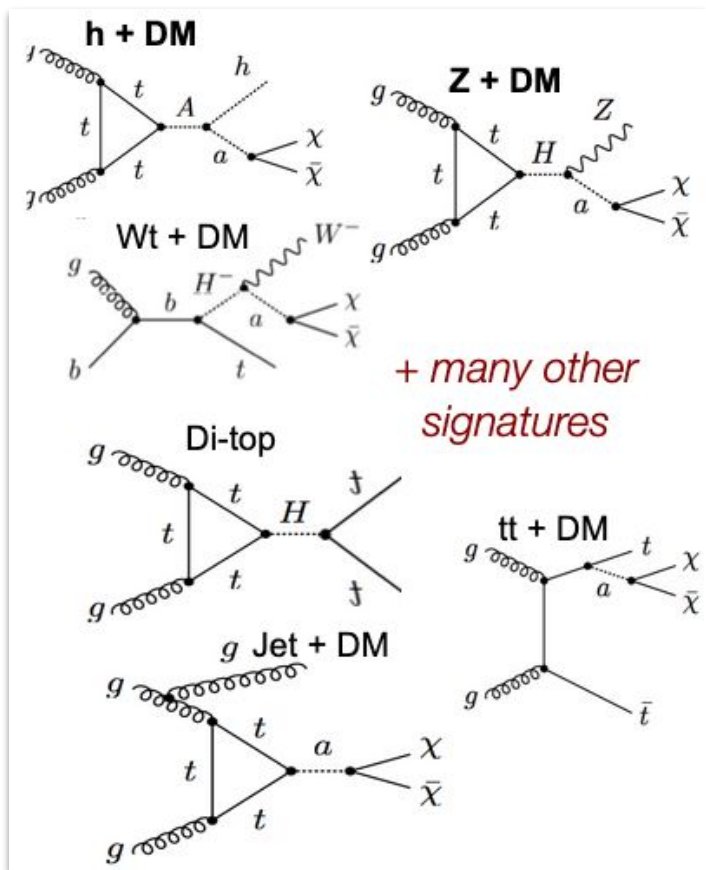


→ cf. [Chad's talk](#) for details



# LHC DM WG: past activities

- Series of White Papers published in Phys. Dark Univ.



Dark Matter Benchmark Models for Early LHC Run-2 Searches: Report of the ATLAS/CMS Dark Matter Forum

August 8, 2016

*Phys. Dark Univ. 26 (2020) 100371*

5.62

CiteScore

**Recommendations on presenting LHC searches for missing transverse energy signals using simplified s-channel models of dark matter**

5.66

Impact Factor

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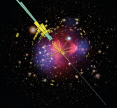
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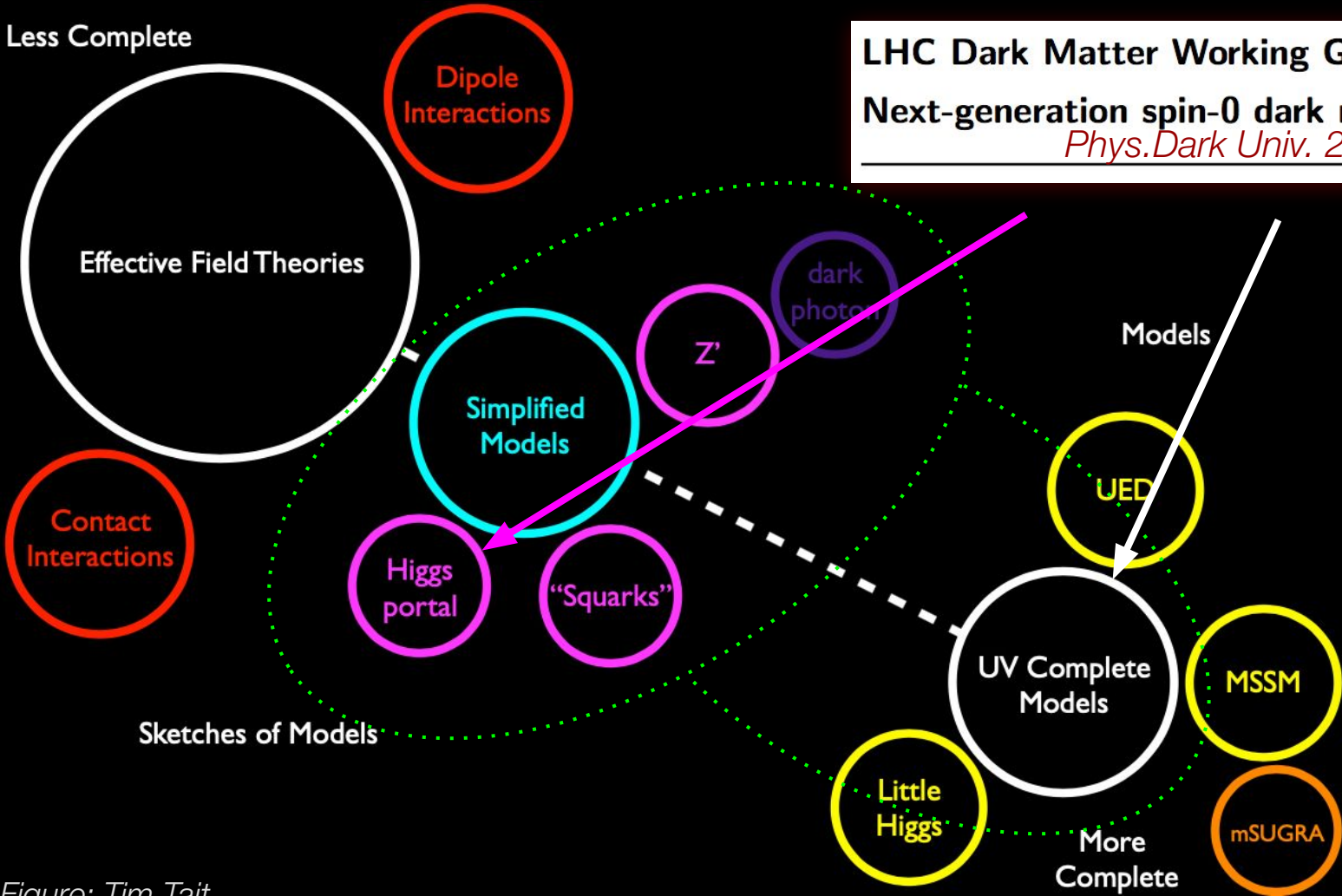
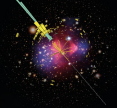
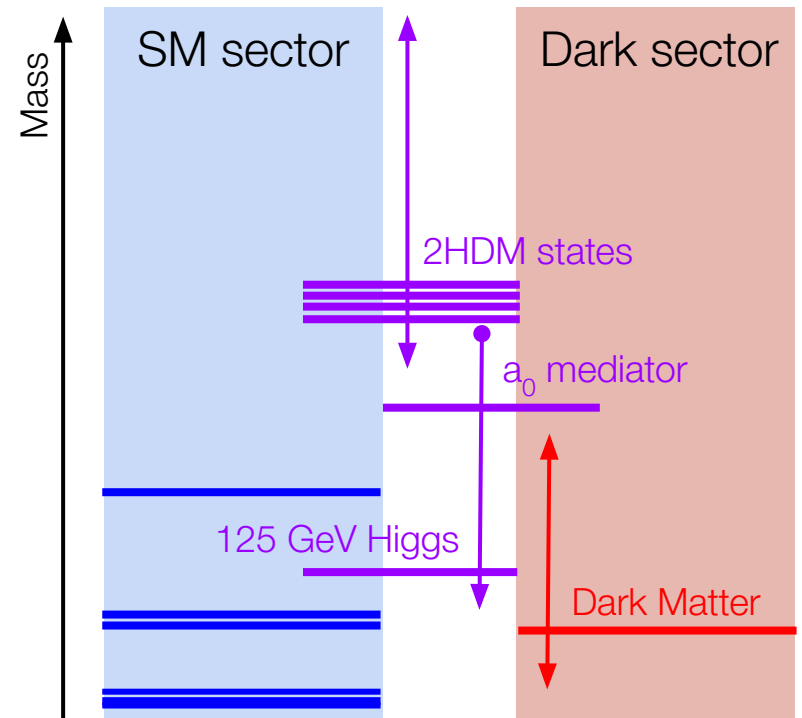
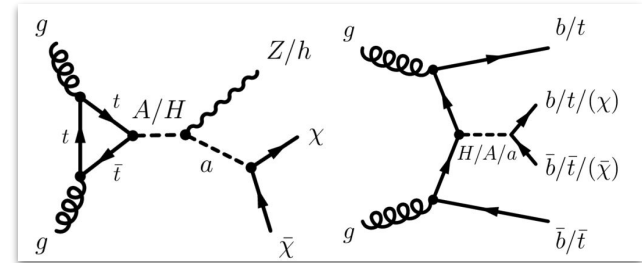


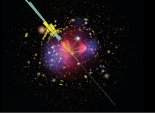
Figure: Tim Tait



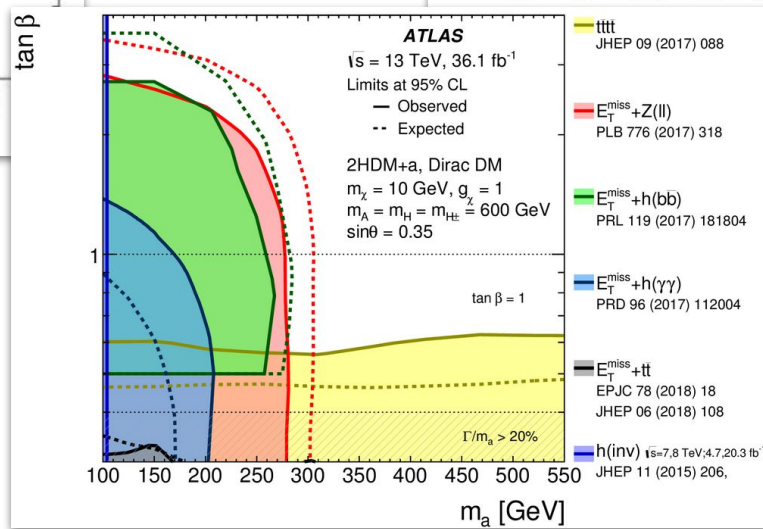
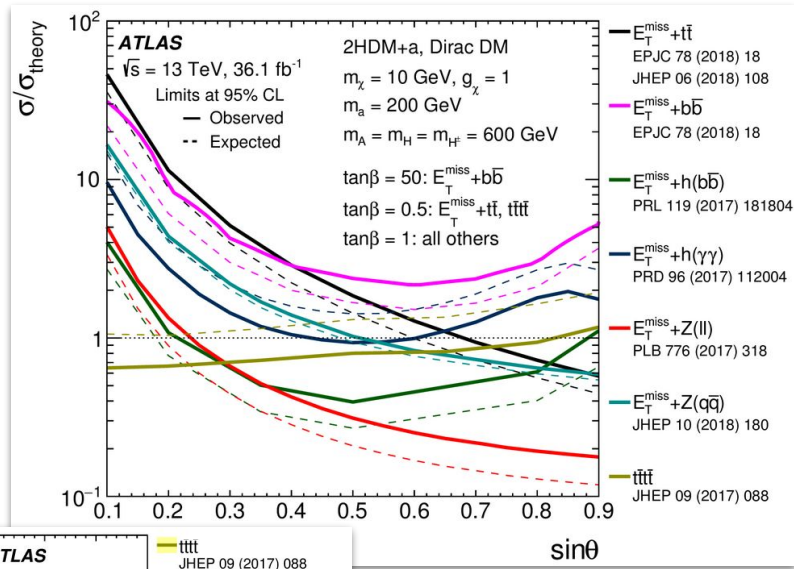
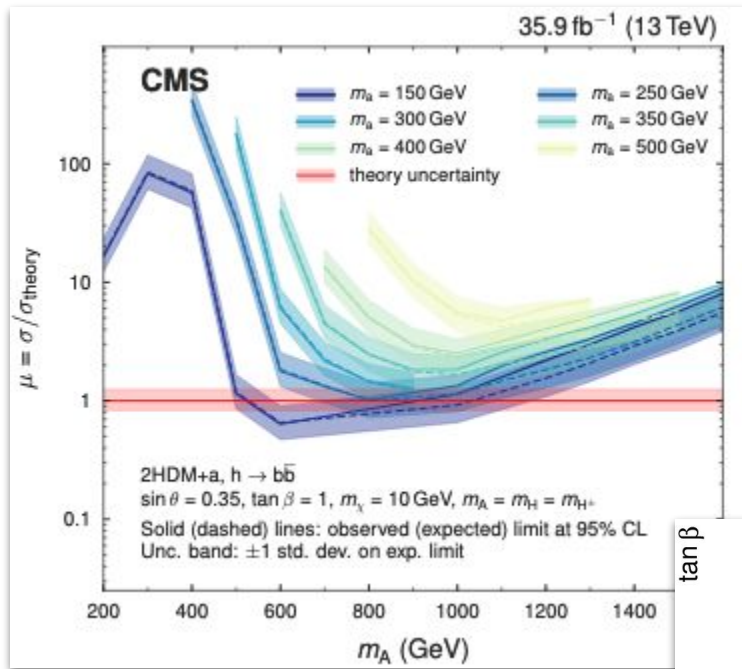
# Extended Higgs sectors: 2HDM+a

- Compelling: Higgs sector “special”
- Ansatz:
  - Extended Higgs sector:
    - 2HDM as simple UV-complete Higgs sector extension
    - $a_0$ : portal to DM
    - interesting physics from  $A_0 - a_0$  mixing  $\rightarrow A, a$
- Complementary signatures:
  - Prominence of mono-h, mono-Z, mono-Wt (not in other models)
  - non-resonant, e.g., jet+MET
  - resonant visible channels, e.g., tt





# Extended Higgs sectors: 2HDM+a



→ cf. [Kristian's talk](#) for details