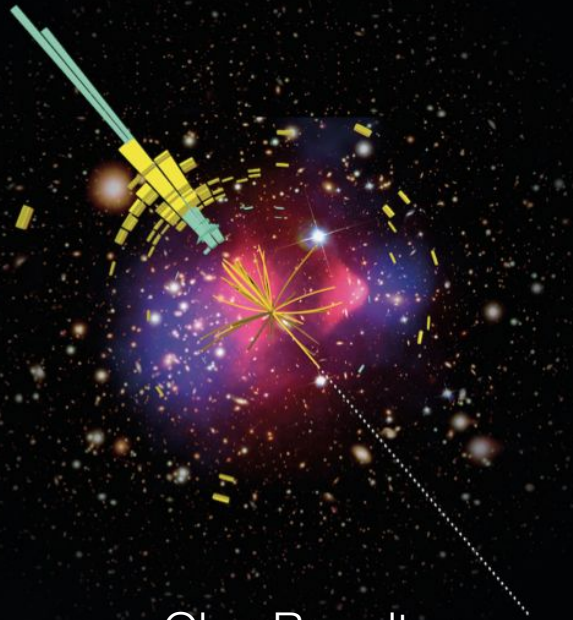
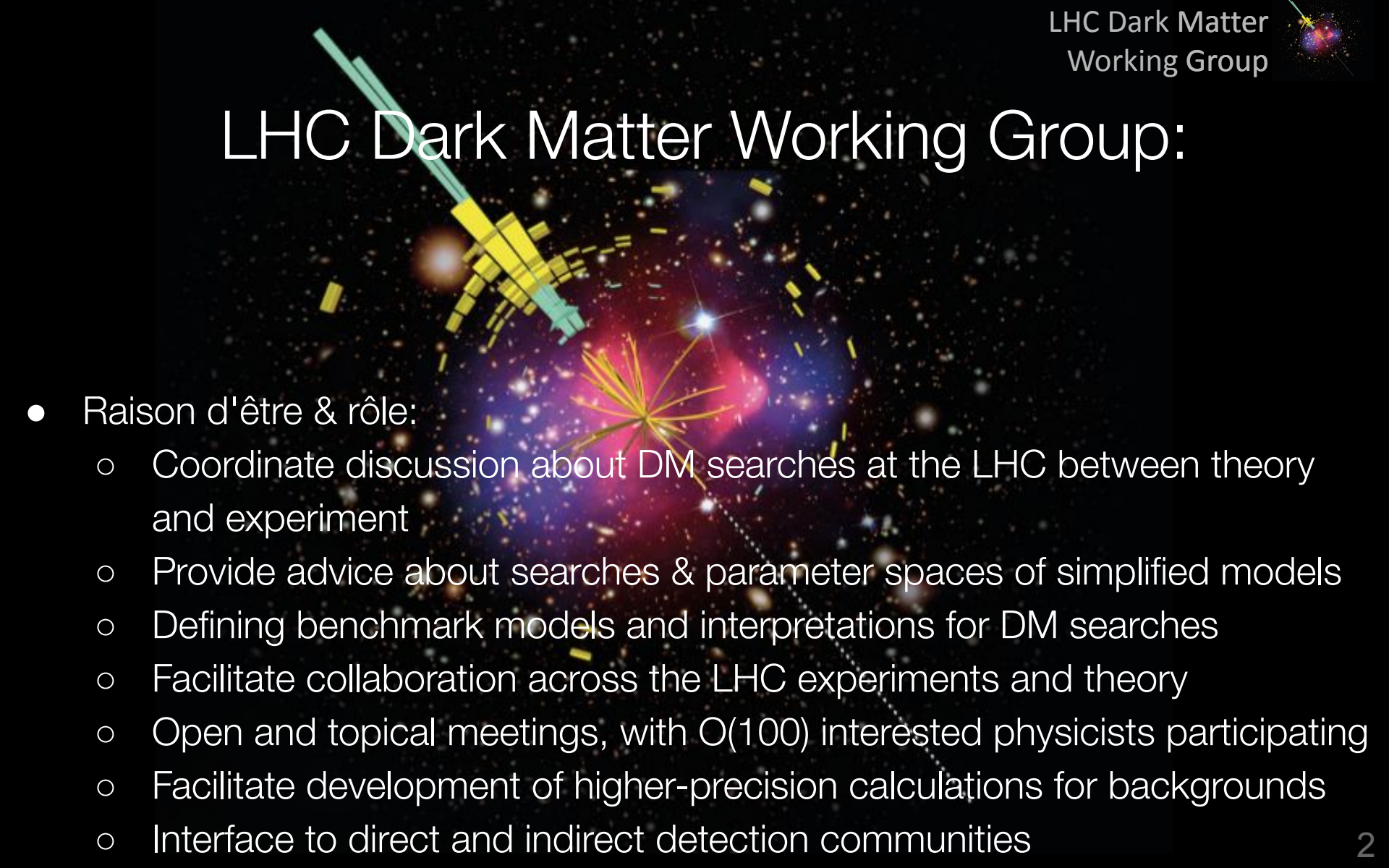
LHC Dark Matter Working Group: activities, challenges, connections



Oleg Brandt
for the LHC DM WG organisers

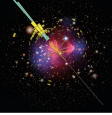
UNIVERSITY OF CAMBRIDGE

LHC Dark Matter Working Group:



- 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

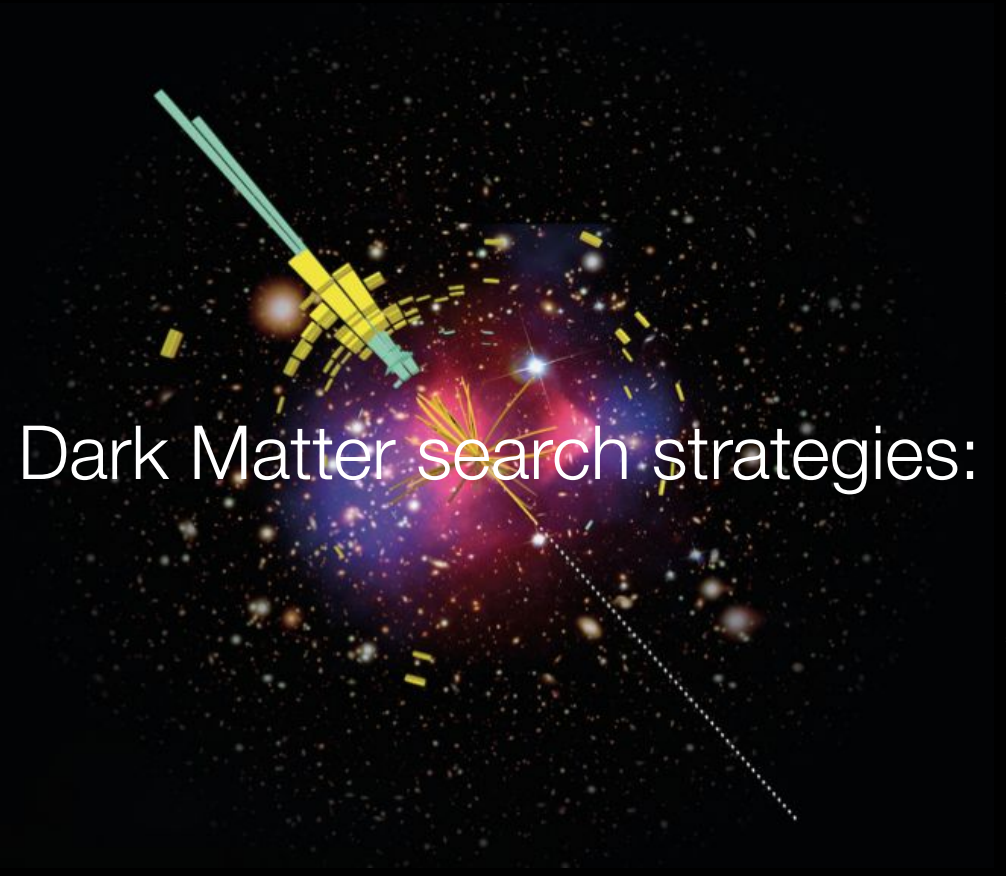
LHC DM WG context



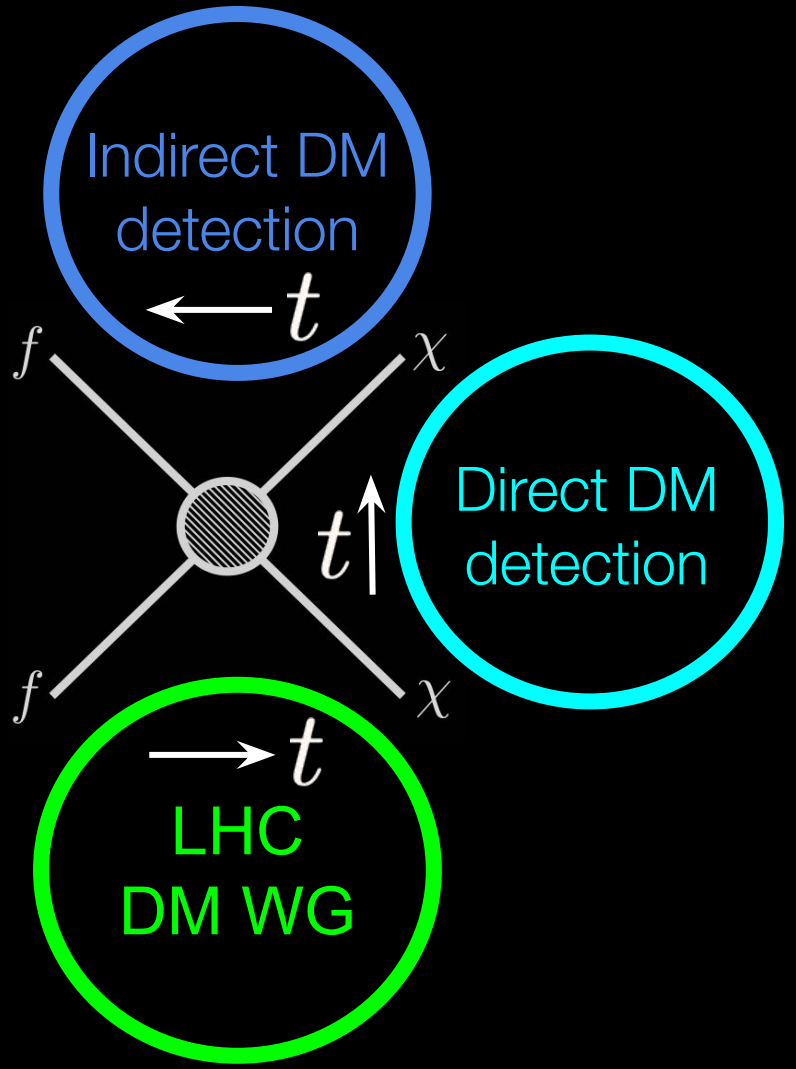
Open to newcomers!
Easy to contribute!

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

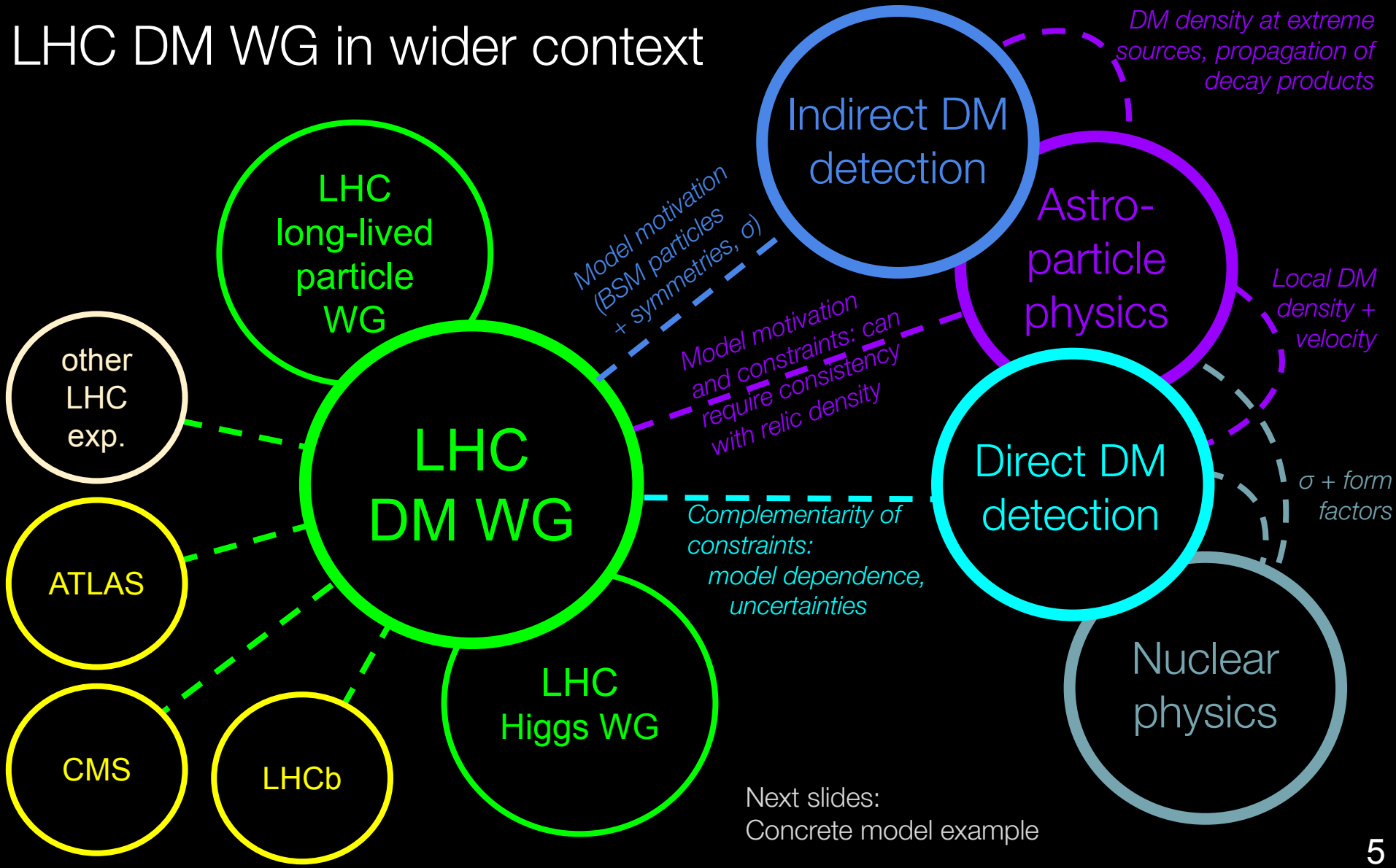
- LHC DM WG organisers (email us):
  - ATLAS: James Frost, Priscilla Pani
  - CMS: Phil Harris
  - LHCb: Xabier Cid Vidal
  - Theory: Uli Haisch, Tim Tait



Dark Matter search strategies:

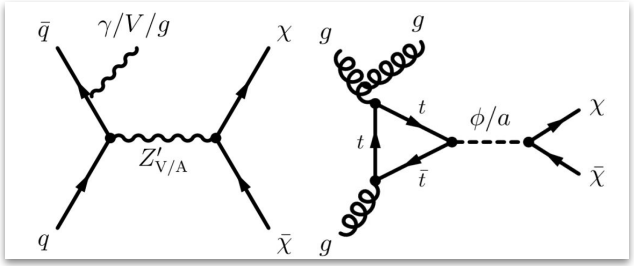


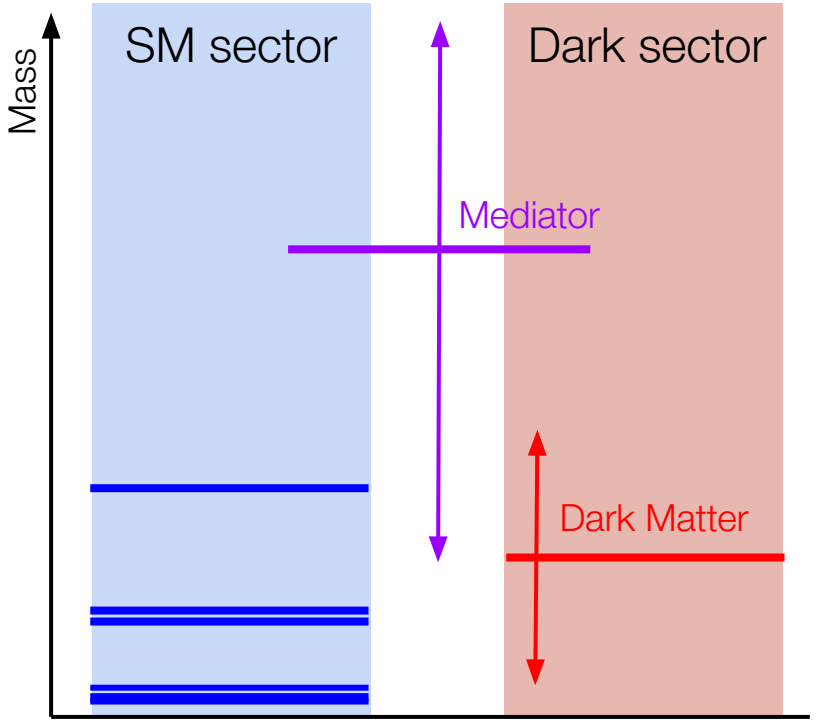
LHC DM WG in wider context



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+ISR
  - resonance searches





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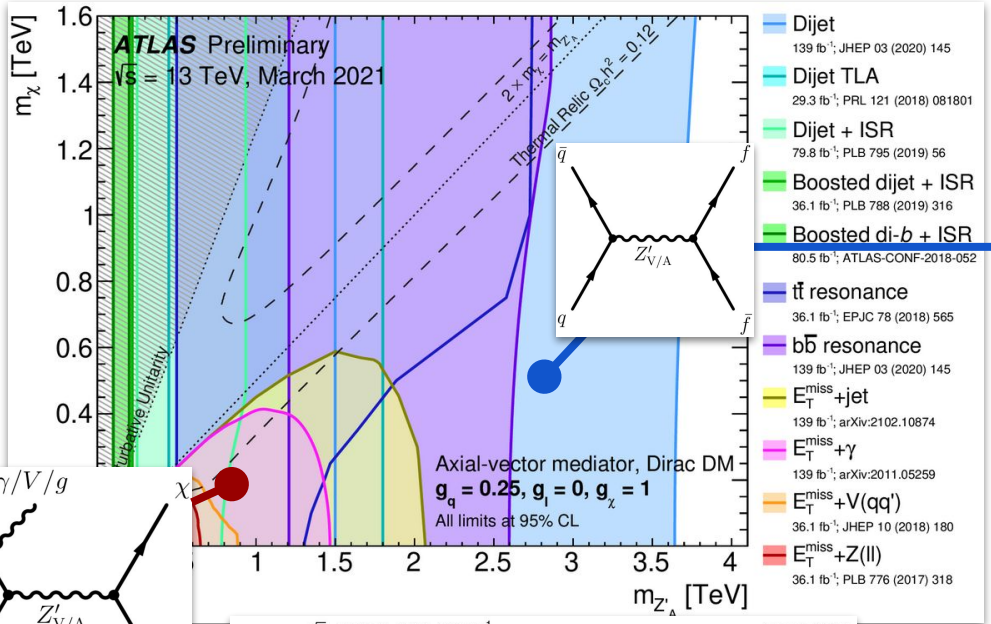
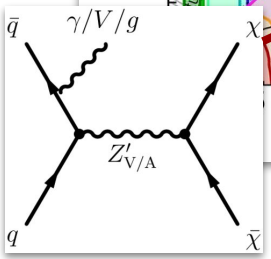
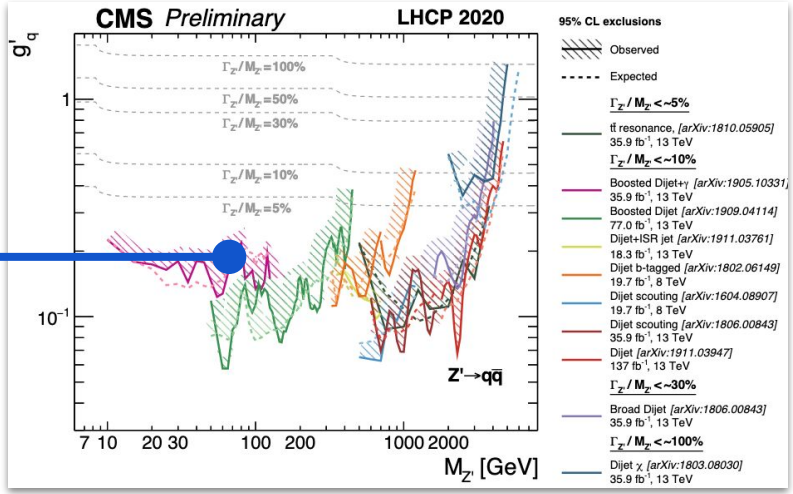
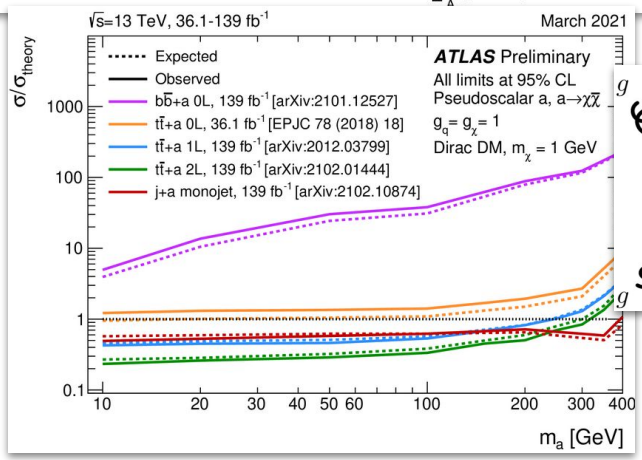
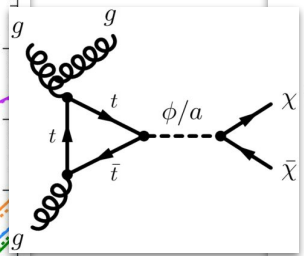
s-channel mediator models

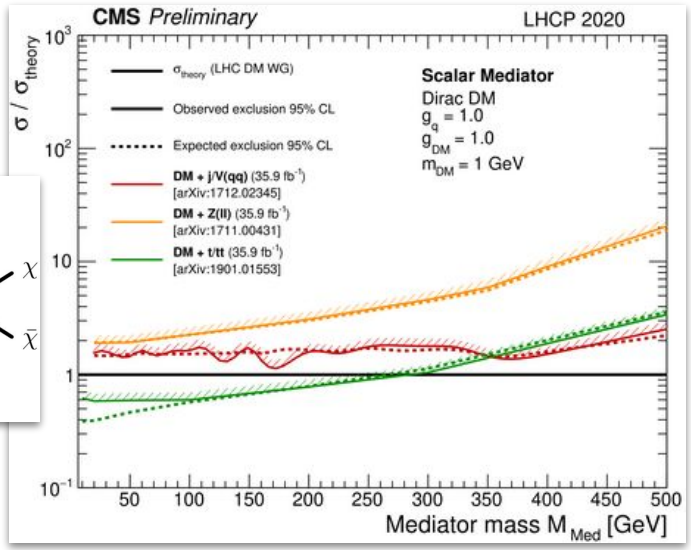




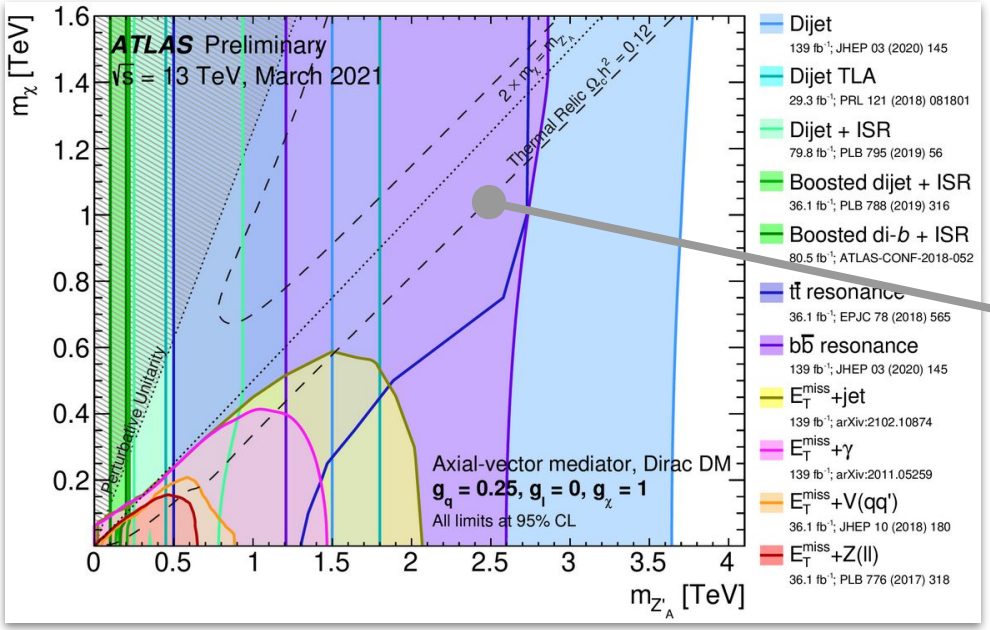








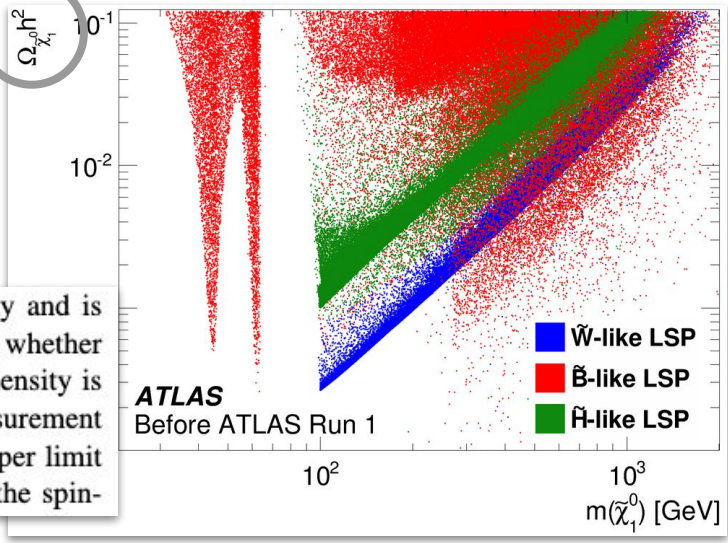
s-channel connections: relic density



Relic density input:

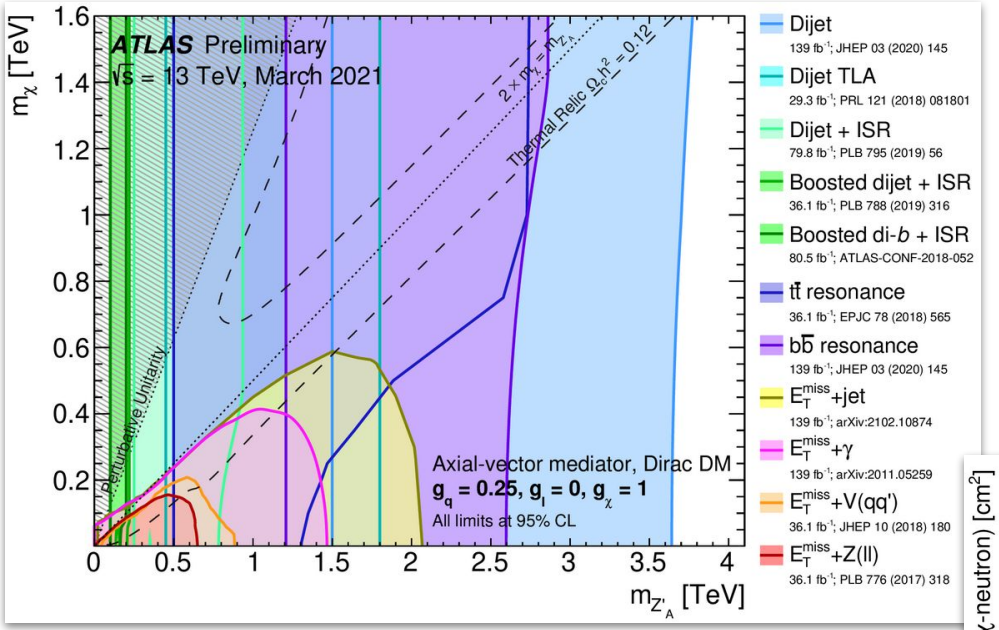
- from astroparticle physics (Planck / WMAP)
- In simplified models, use relic density to *guide* searches
  - No constraint: simplified model incomplete

- In complete models (e.g. SUSY), use relic density to *constrain* searches



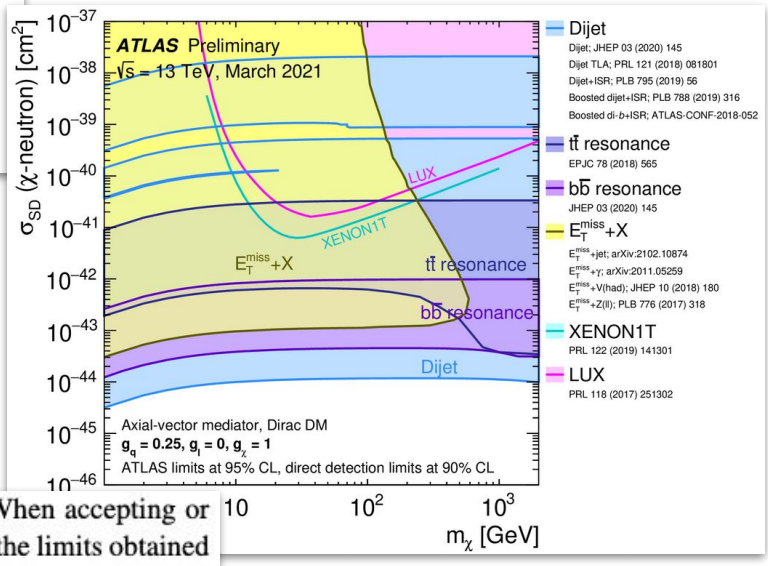
zero cosmological abundance. It is assumed that the LSP abundance is determined thermally and is not diluted by other processes e.g. late-time entropy addition. No assumption is made about whether the LSP is the sole constituent of dark matter. As a result, the total cold dark matter energy density is used as an upper limit on the LSP abundance. The limit is based on the latest combined measurement from the Planck Collaboration of $\Omega_{\mathrm{CDM}}h^2 = 0.1188 \pm 0.0010$ (Table 4 of Ref. [97]).[2] The upper limit is set to the observed central value plus double the experimental uncertainty. The limit on the spin-

s-channel connections: direct detection



Direct detection input:

- *WIMP assumption* + *local DM density* + type of interaction
- In simplified models, highlight complementarity between colliders and direct detection



- Challenges:
  - uncertainties on direct det.?
    (so far: 4x, 10x)
    → constrain complete models:

the remaining non-LSP dark matter is invisible to the direct detection experiments. When accepting or rejecting models, the calculated value is allowed to be up to a factor of four higher than the limits obtained by the experiments, to account for nucleon form-factor uncertainties [33].

s-channel connections: direct detection

Direct detection input:

- *WIMP assumption* + *local DM density* + type of interaction
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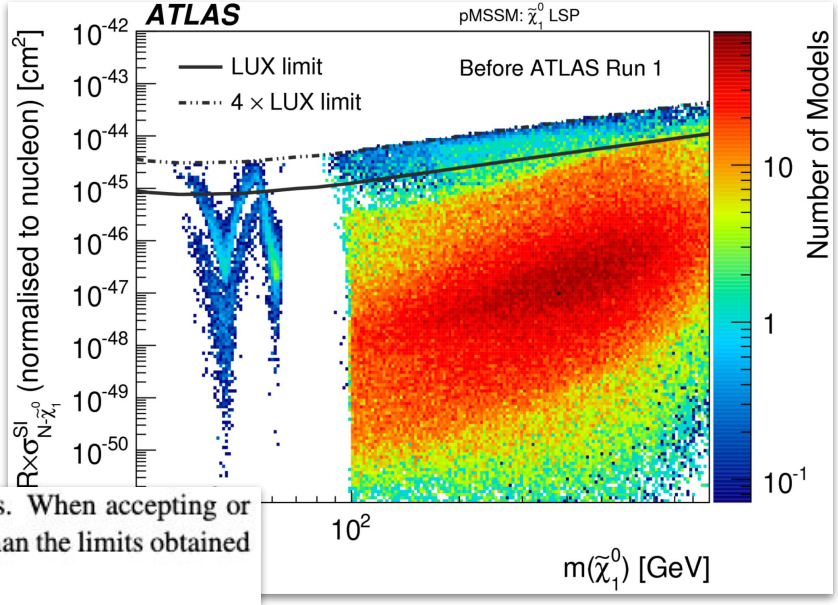

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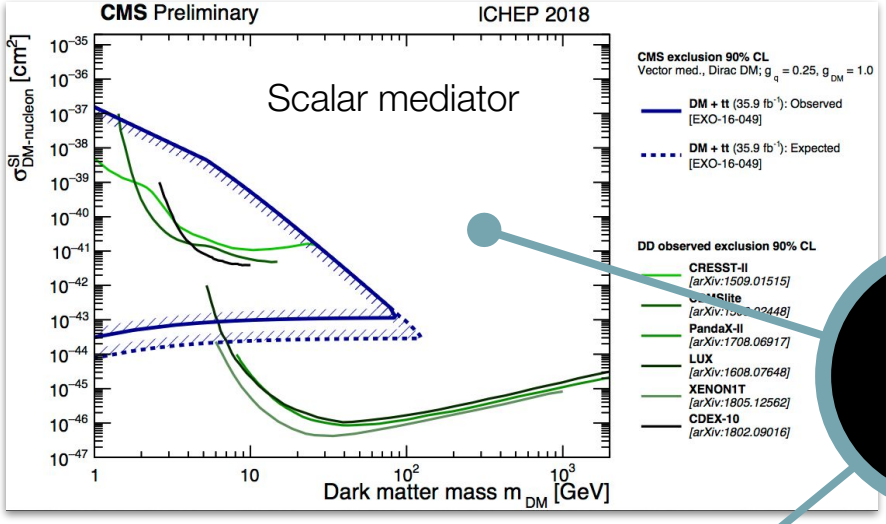
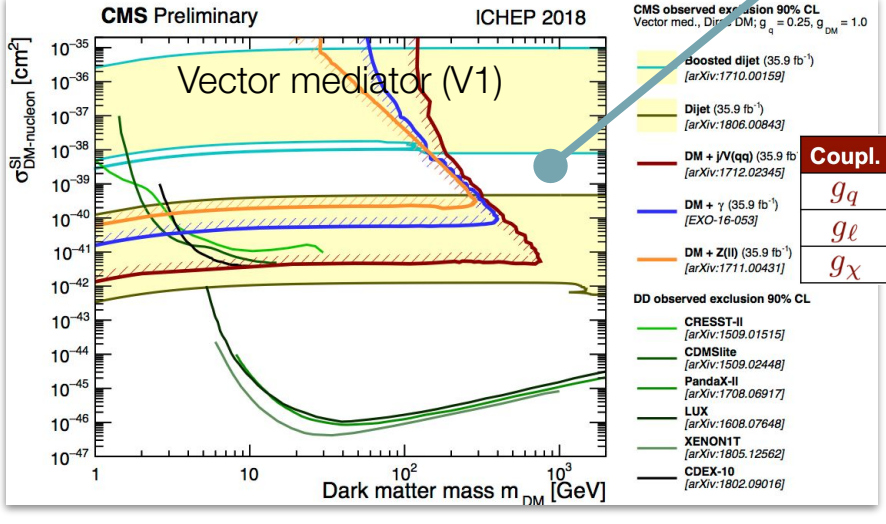
s-channel connections: direct detection



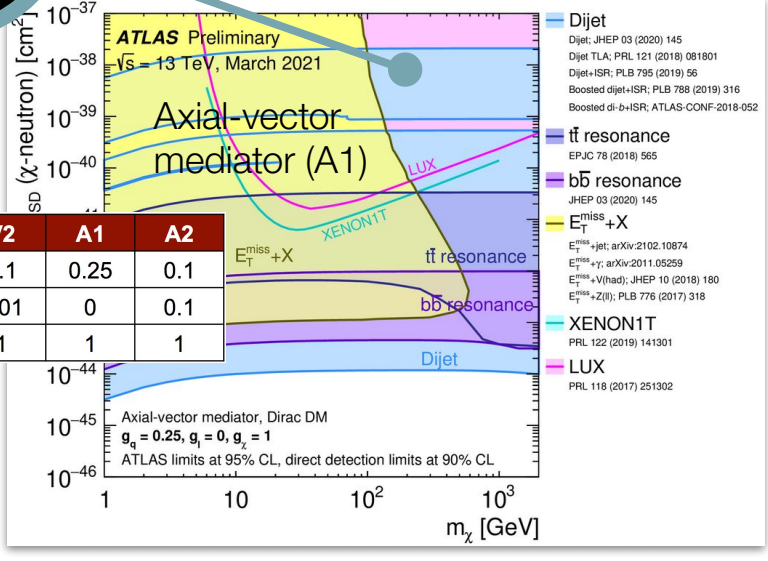


Nuclear physics: Form Factor

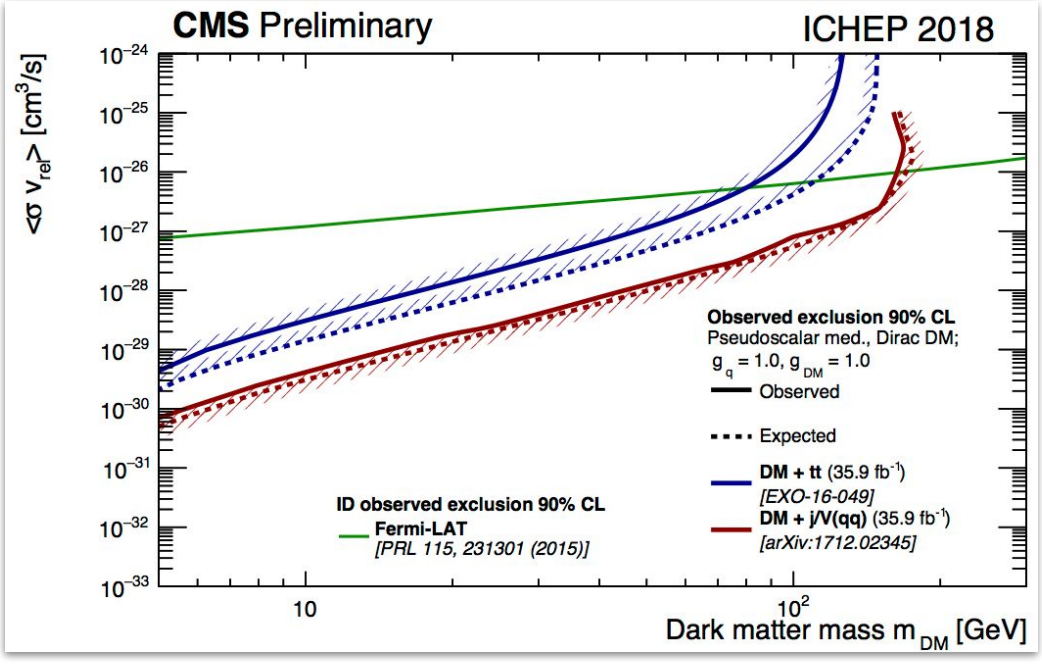
Coupl.	V1	V2	A1	A2
g_q	0.25	0.1	0.25	0.1
g_ℓ	0	0.01	0	0.1
g_χ	1	1	1	1

Direct detection input:

- WIMP assumption + local DM density + *type of interaction*
- Study impact of mediator + coupling assumptions (even within the same model)



s-channel connections: direct detection



- Challenges:
  - uncertainties on indirect detection?

Indirect detection input:

- WIMP assumption + DM density at extreme sources + type of interaction + (inter-)galactic propagation
- Use constraints to *guide* searches

LHC DM WG ecosystem in theory space

LHC Dark Matter Working Group

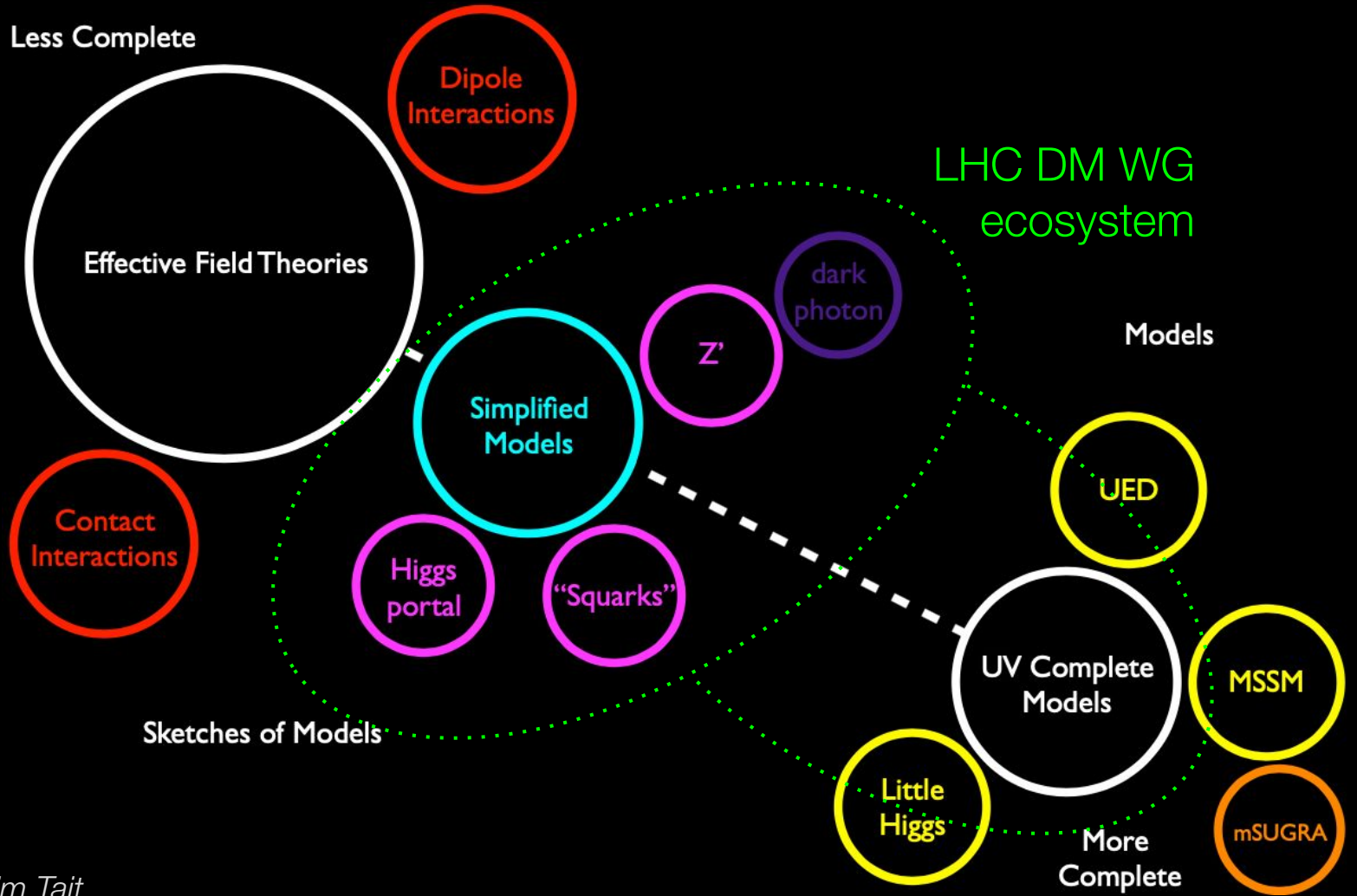
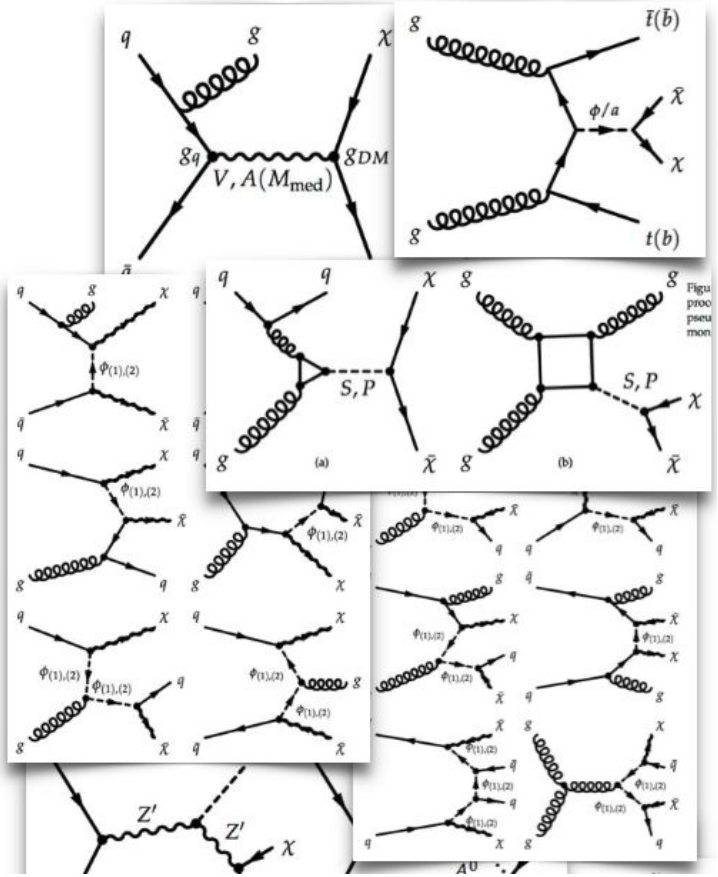
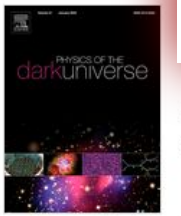


Figure: Tim Tait

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

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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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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

LHC Dark Matter Working Group

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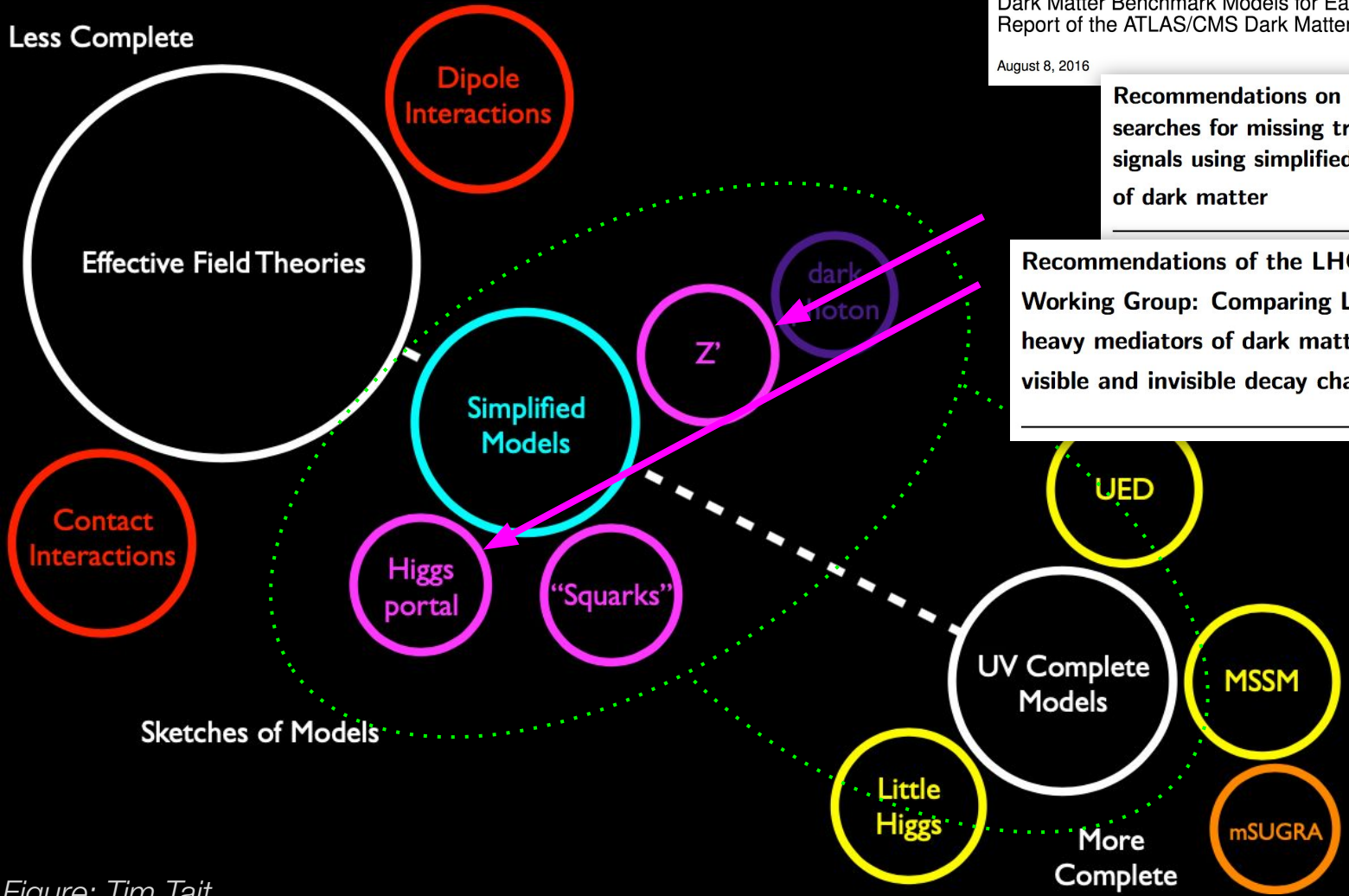
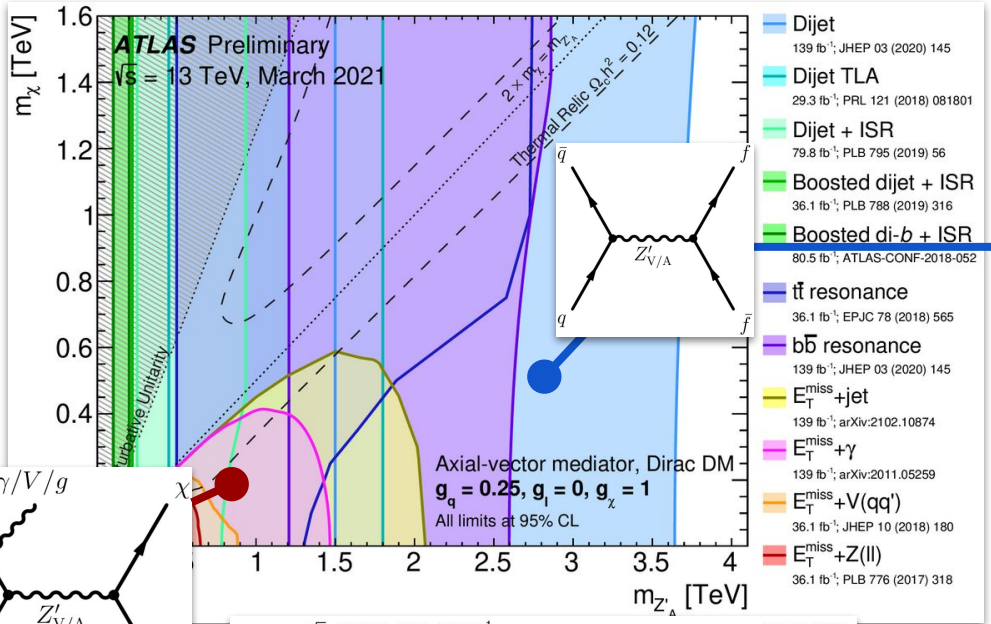
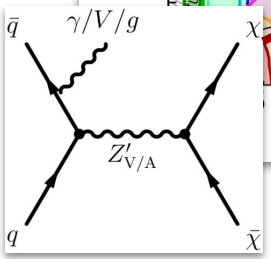
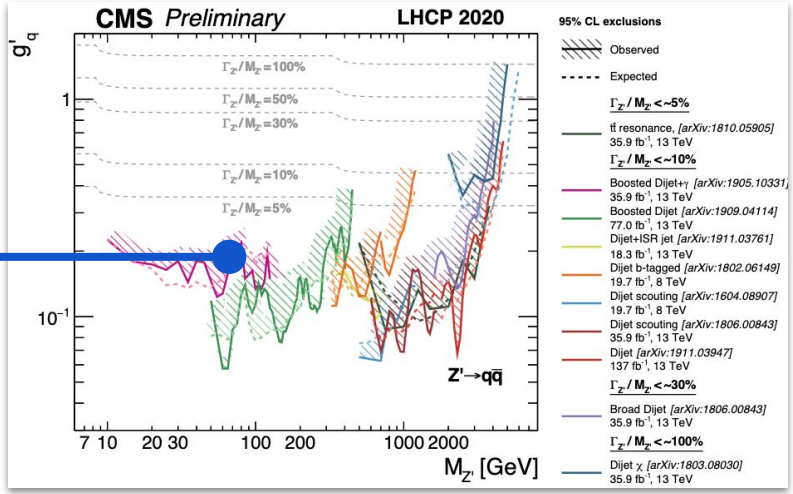


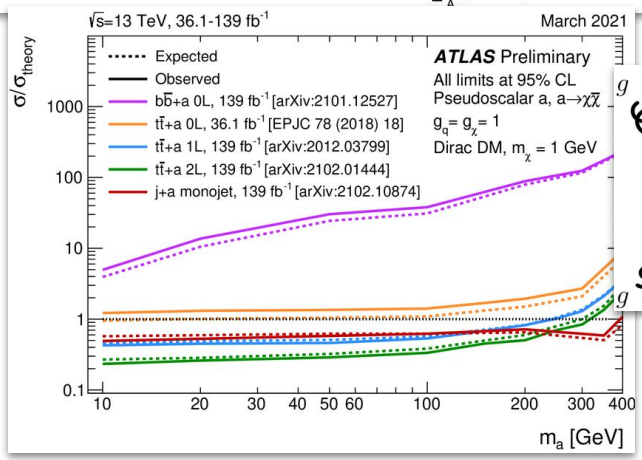
Figure: Tim Tait

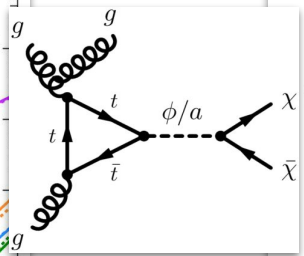
s-channel mediator models

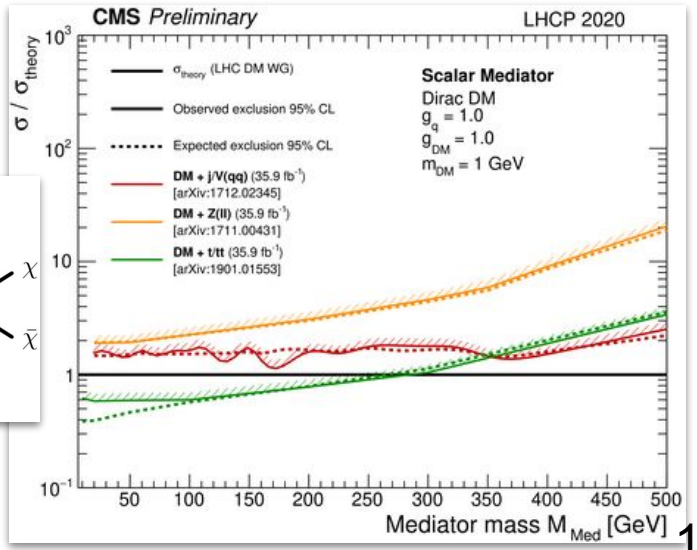




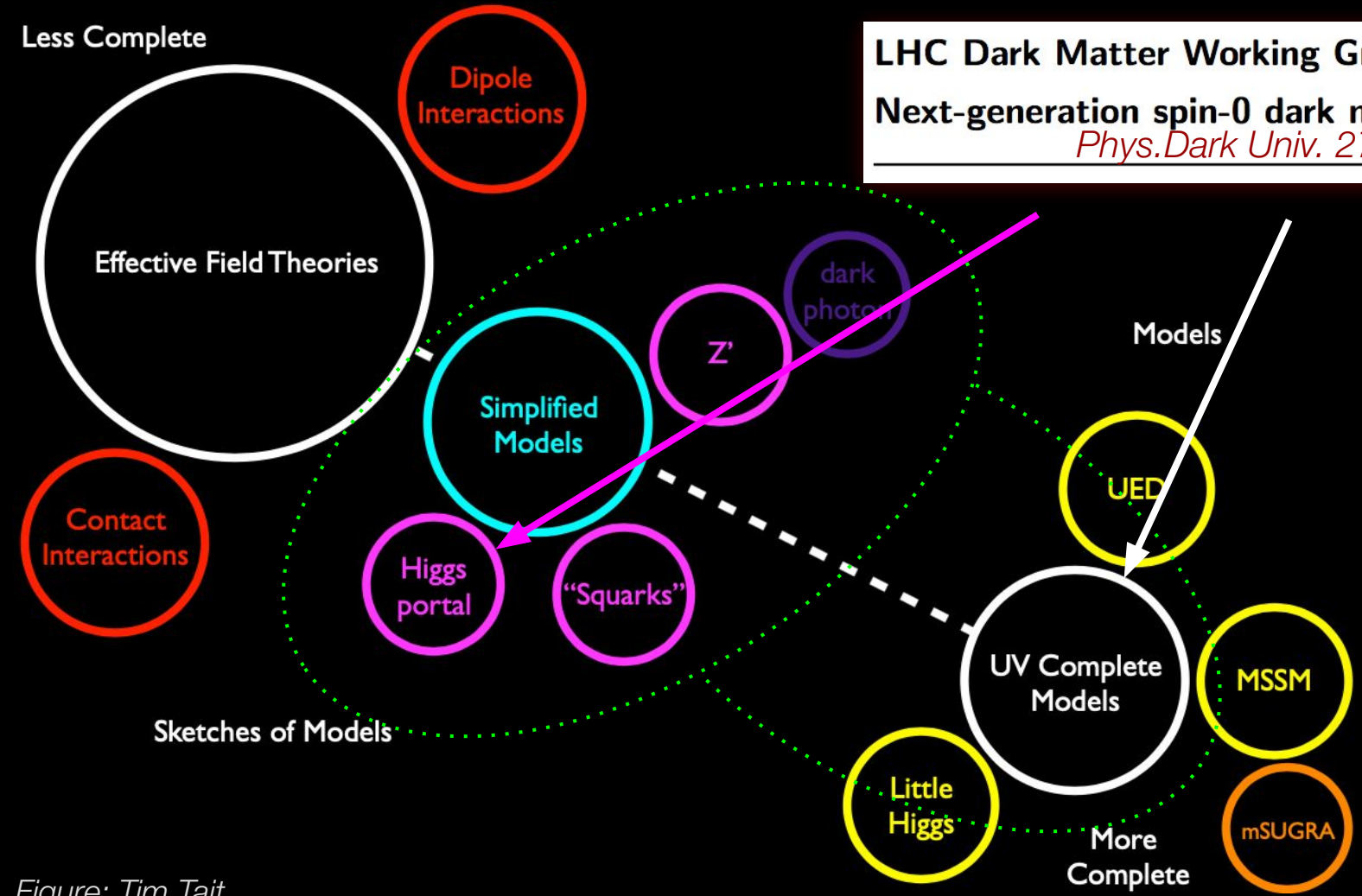








Navigating (DM) theory space



LHC Dark Matter Working Group:

Next-generation spin-0 dark matter models

Phys.Dark Univ. 27 (2020) 100351

Figure: Tim Tait

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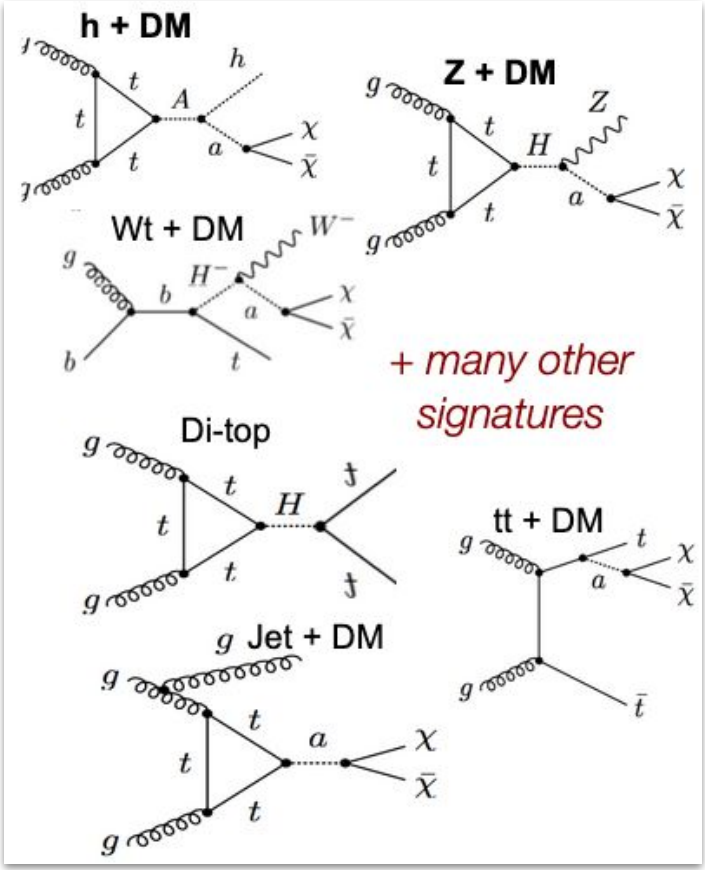

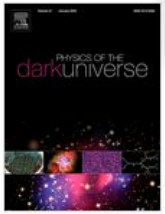

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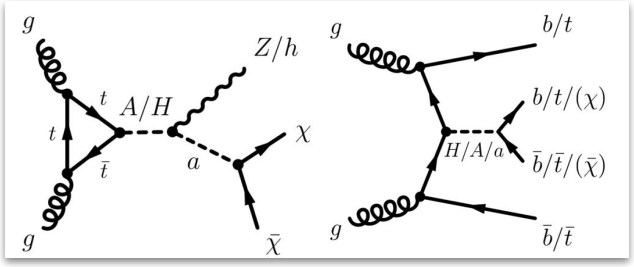
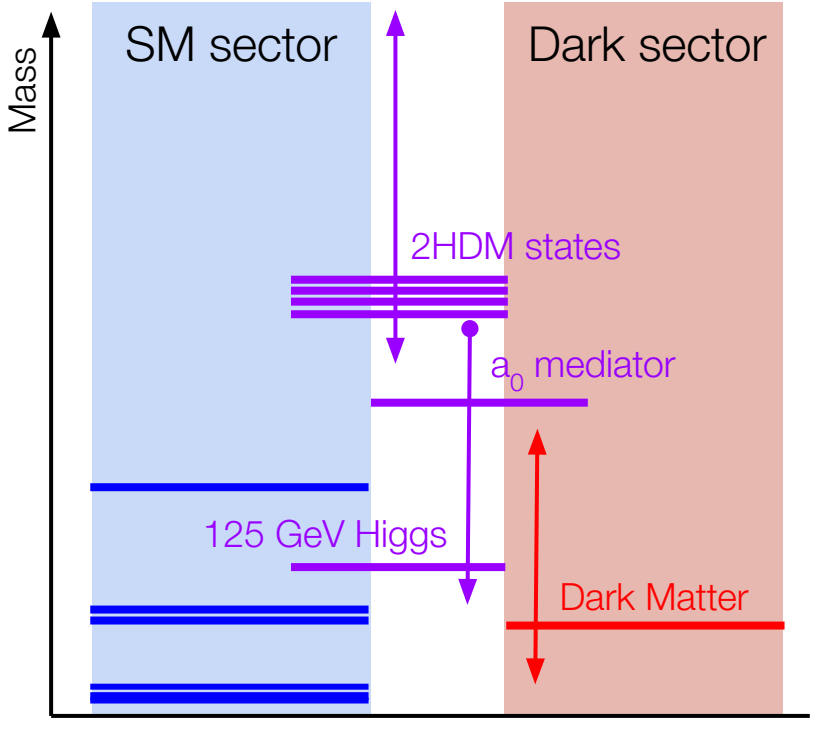
Next White Paper
t-channel mediator models

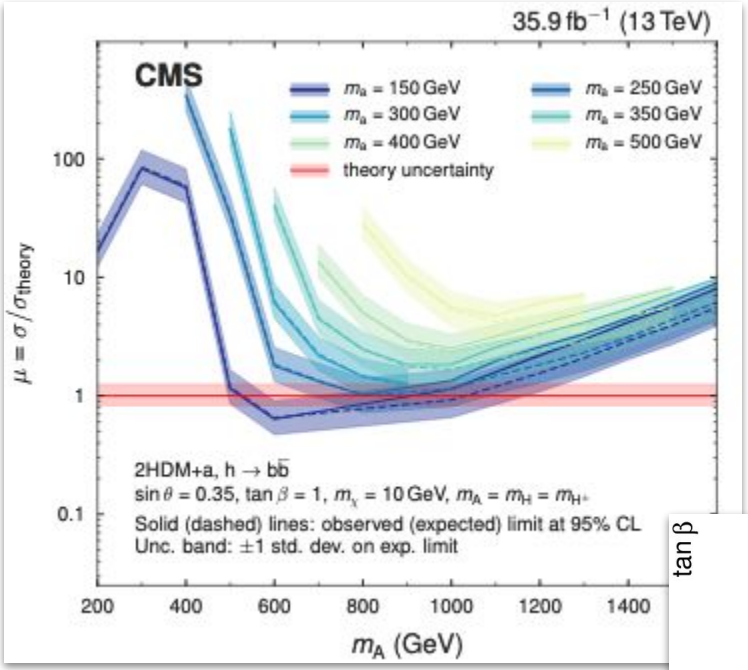
Extended Higgs sectors: 2HDM+a

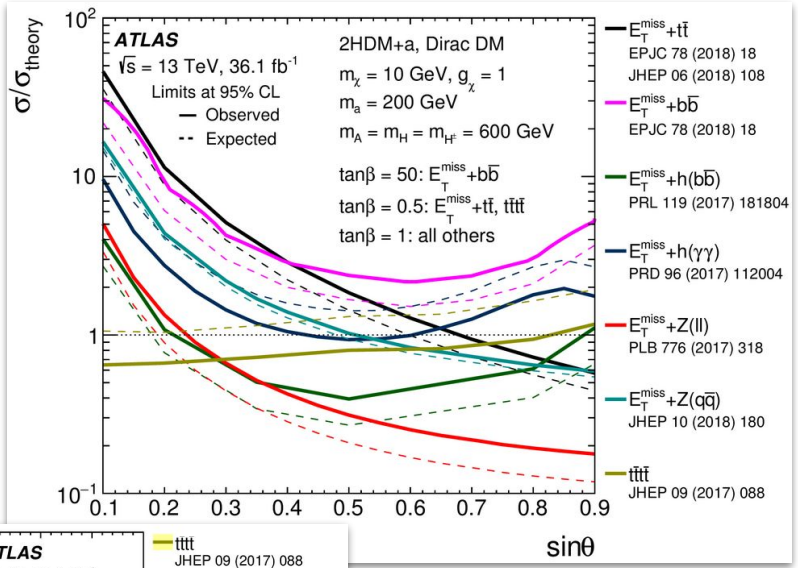
- Compelling: Higgs sector “special”
- Ansatz:
  - Extended Higgs sector:
    - 2HDM as simple UV-complete Higgs sector extension
    - a_0: portal to DM
    - interesting physics from A_0 - a_0 mixing → A, a
- Complementary signatures:
  - Prominence of h+MET, Z+MET, Wt+MET (not in other models)
  -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

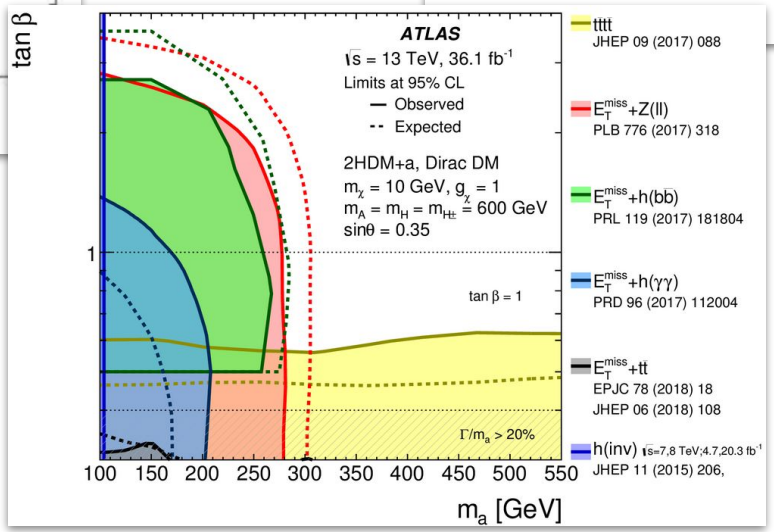




Extended Higgs sectors: 2HDM+a







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

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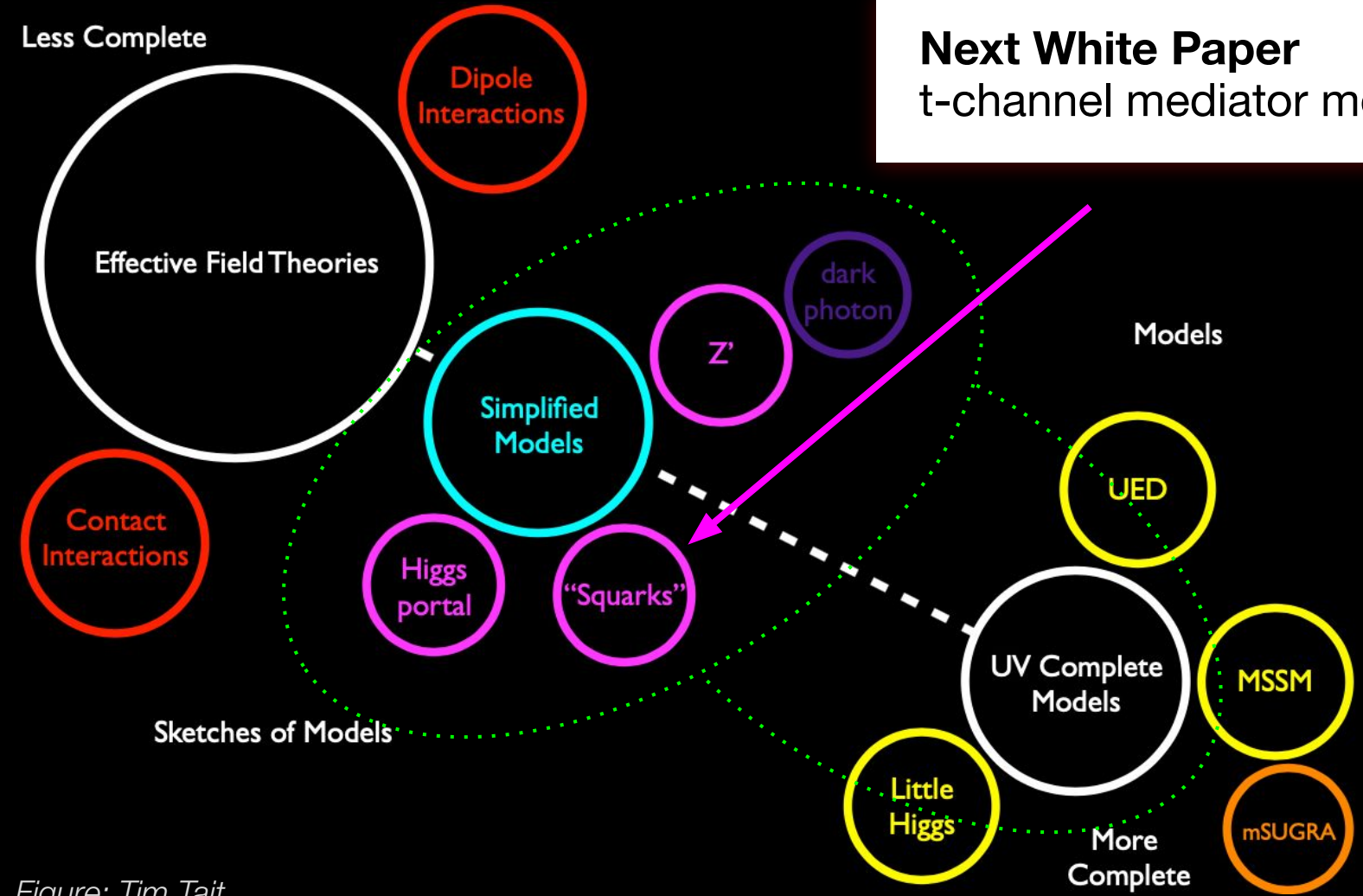
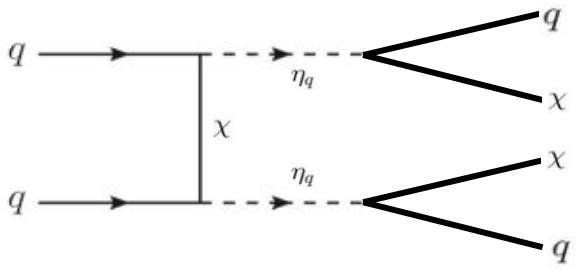


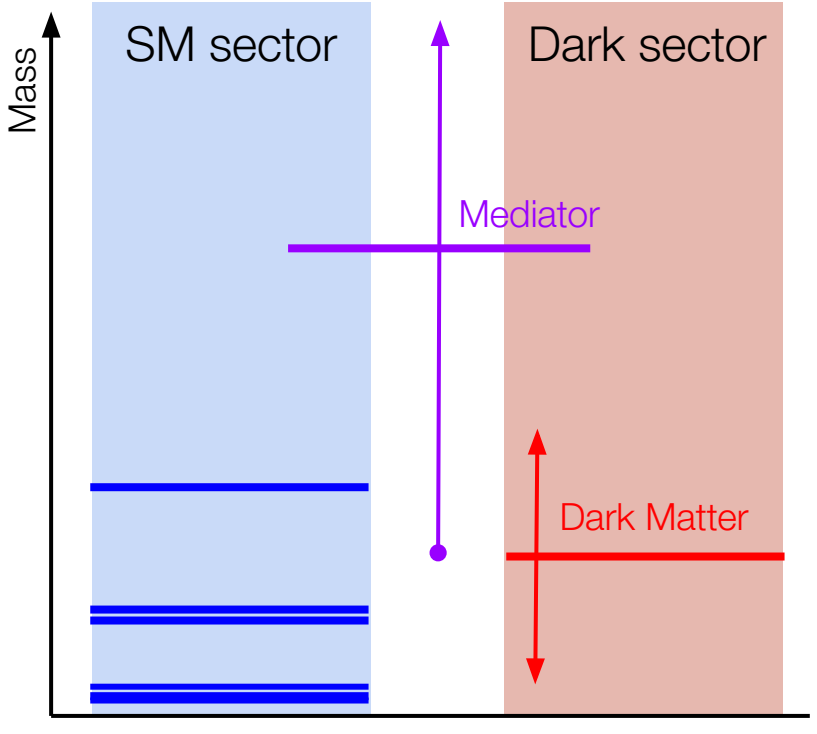
Next White Paper
t-channel mediator models

Figure: Tim Tait

t-channel mediator models

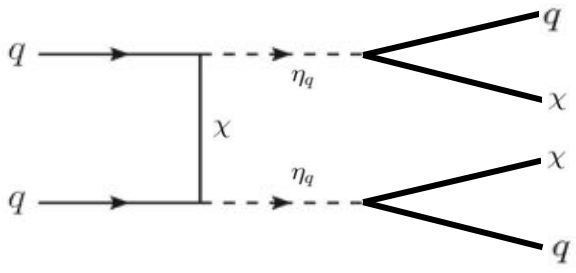
- Strong motivation (as strong as s-channel)
- Ansatz:
  - DM interacting with SM fermions and a mediator
- Corollary:
  - SM mediators must carry charge (since SM particles carry charge)
  - mediator shares the symmetry that stabilises DM
    → $m_{Mediator} > m_{DM}$
  - Different possibilities for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

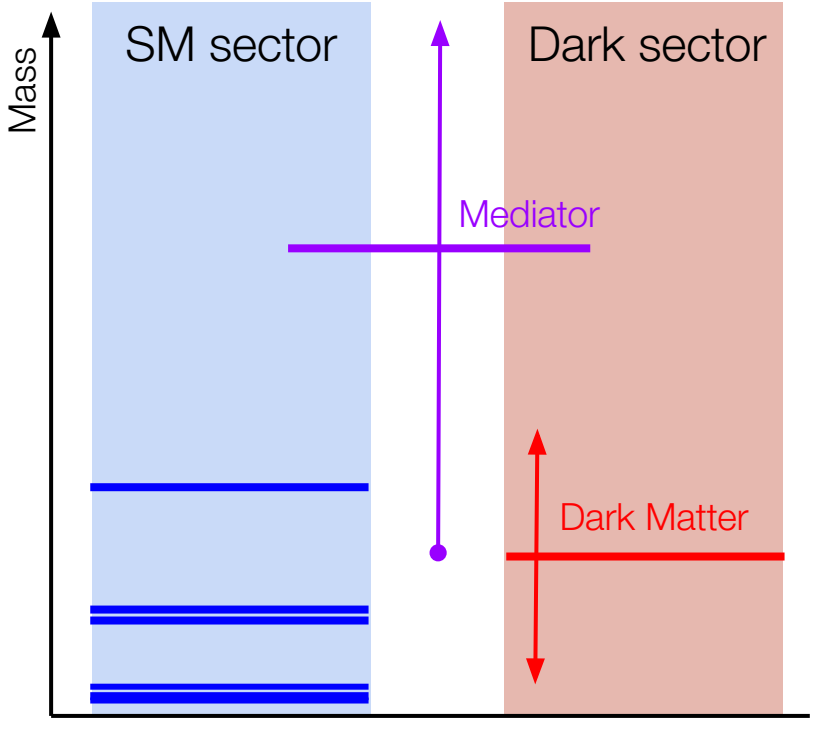




t-channel mediator models

- 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&2nd families

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

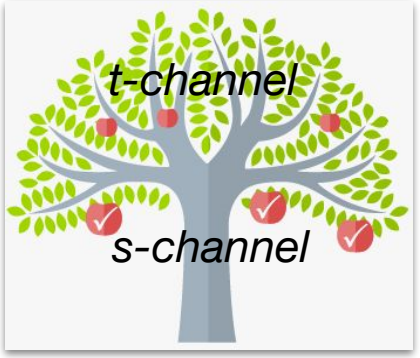
quark-DM coupling

LH mediators

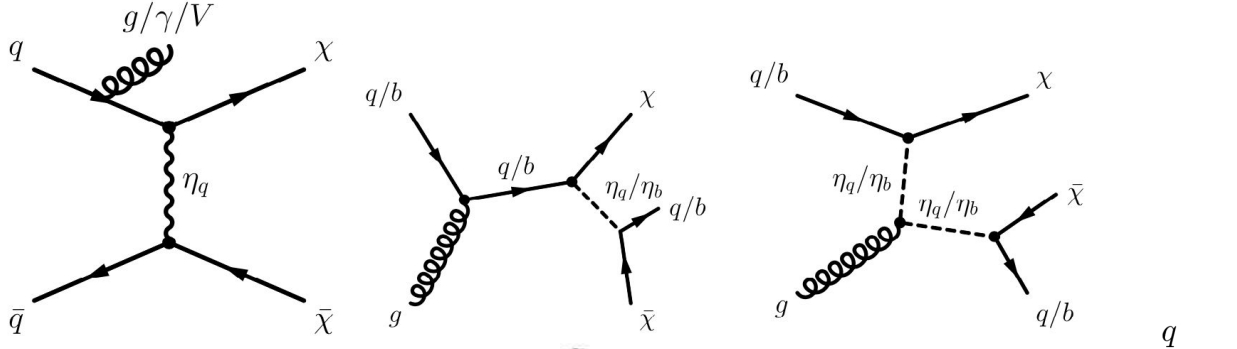
LH quarks

RH up- and down-type quarks

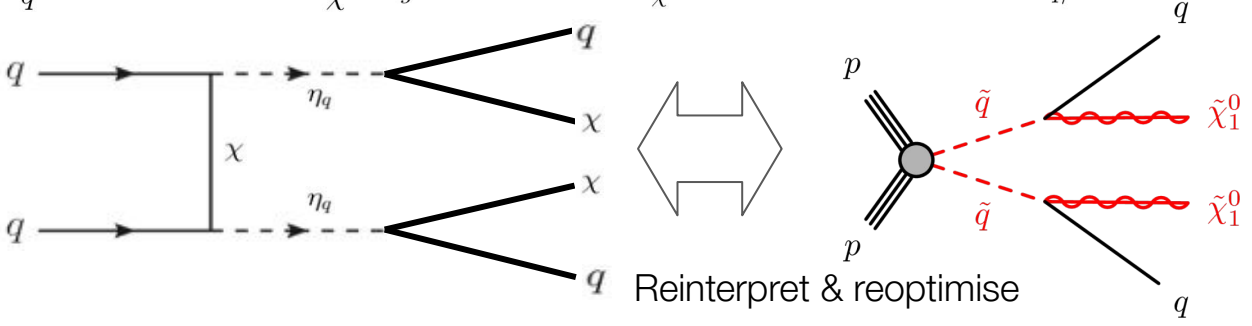
Dirac fermion DM



Jet + MET:



Di-jet + MET:



Reinterpret & reoptimise

LHC Dark Matter Working Group

[Email LHC DM WG organisers]

[Discuss your DM question]

[Discuss t-channel models]

Thank you!

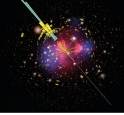
Few DM-related initiatives:

[https://snowmass21.org/]

[JENAS initiative]

ECFA NuPECC ApPEC

Summary



- 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 1st generation searches
    - Converging on first 1st generation recommendations
  - Great range in pheno+experimental space to explore & contribute:
    - Impact of spin & coupling assumptions, 3rd 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

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:
  - Dirac/Majorana fermion
  - Scalar
  - Vector

→ cf. Chiara's talk for details

✦ 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	χ		
S3M_3rd	$\tilde{\chi}$	$\varphi_{Q_3}, \varphi_{u_3}, \varphi_{d_3}$	$M_\varphi, M_\chi, \lambda_\varphi$
S3D_3rd	χ		
S3M_uR	$\tilde{\chi}$	φ_{u_1}	
S3D_uR	χ		
F3S_uni	$\tilde{S}$	$\psi_{Q_f}, \psi_{u_f}, \psi_{d_f}$	
F3C_uni	S		
F3S_3rd	$\tilde{S}$	$\psi_{Q_3}, \psi_{u_3}, \psi_{d_3}$	$M_S, M_\psi, \tilde{\lambda}_\psi$
F3C_3rd	S		
F3S_uR	$\tilde{S}$	ψ_{u_1}	
F3C_uR	S		
F3V_uni	$\tilde{V}_\mu$	$\psi_{Q_f}, \psi_{u_f}, \psi_{d_f}$	
F3W_uni	V_μ		
F3V_3rd	$\tilde{V}_\mu$	$\psi_{Q_3}, \psi_{u_3}, \psi_{d_3}$	$M_V, M_\psi, \tilde{\lambda}_\psi$
F3W_3rd	V_μ		
F3V_uR	$\tilde{V}_\mu$	ψ_{u_1}	
F3W_uR	V_μ		

✤Universal models (uni):
- ★ 1 dark matter particle
- ★ 12 mass-degenerate mediators
- ★ 1 flavour-conserving coupling

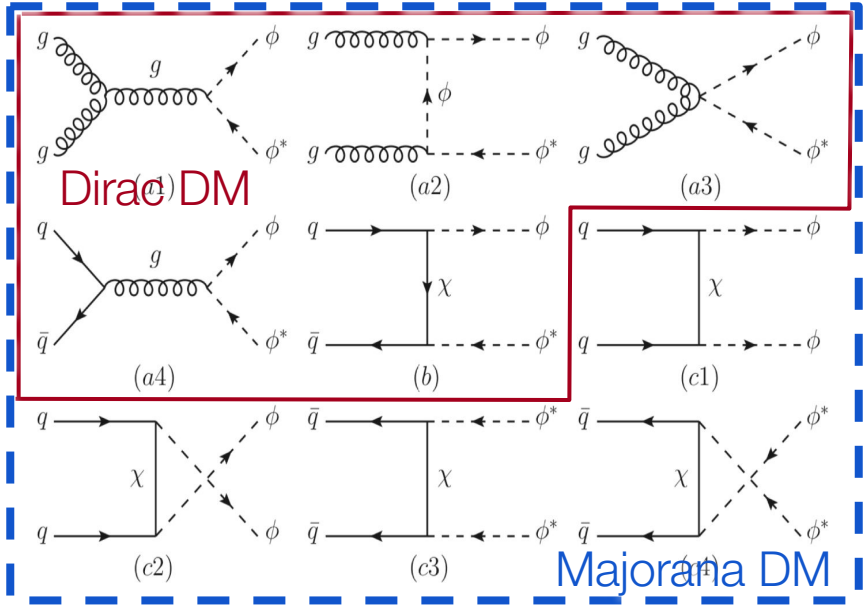
$$\mathcal{L}_{\text{X\_uni}}(X) = \sum_{F=Q,u,d} \sum_{f=1}^{3} \left[\lambda_\varphi \bar{X} F_f \varphi^\dagger_{F_f} + \text{h.c.}\right]$$

✤3rd generation models (3rd):
- ★ 1 dark matter particle
- ★ 4 mass-degenerate mediators
- ★ 1 flavour-conserving coupling

$$\mathcal{L}_{\text{X\_3rd}}(X) = \sum_{F=Q,u,d} \left[\lambda_\varphi \bar{X} F_3 \varphi^\dagger_{F_3} + \text{h.c.}\right]$$

✤uR models (uR):
- ★ 1 dark matter particle
- ★ 1 mediator
- ★ Coupling to the right-handed up-quark

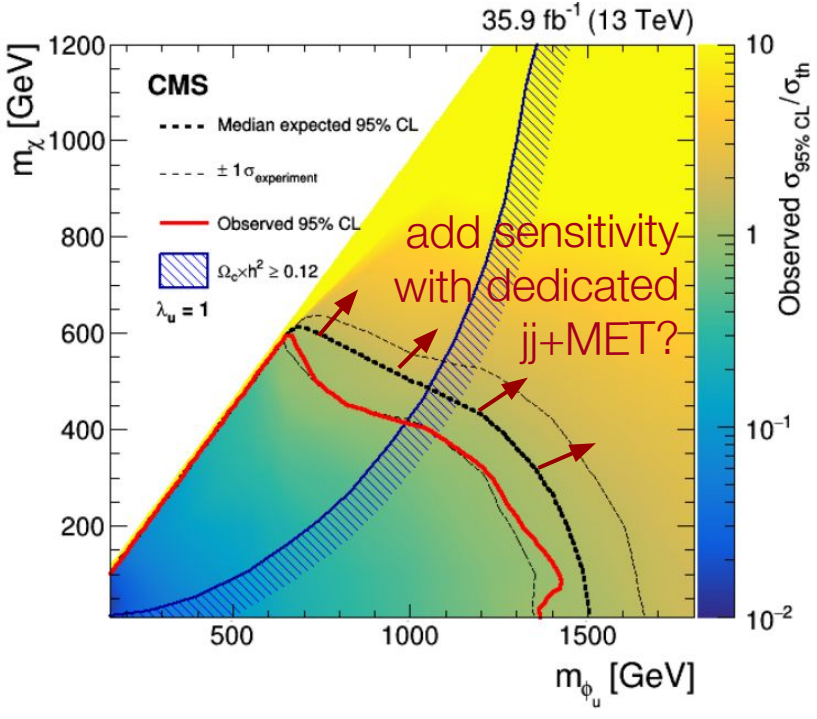
$$\mathcal{L}_{\text{X\_uR}}(X) = \left[\lambda_\varphi \bar{X} u_1 \varphi^\dagger_{u_1} + \text{h.c.}\right]$$



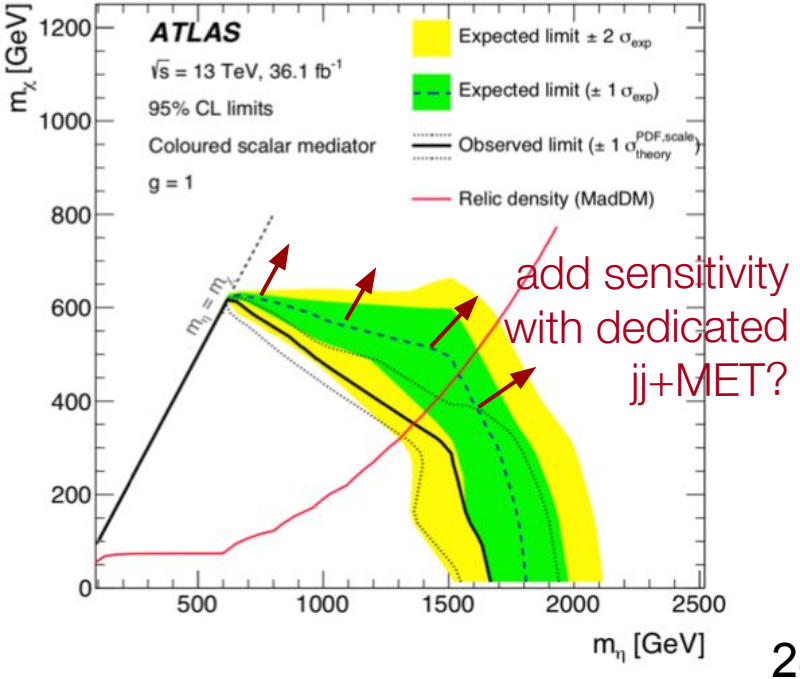
- Important step forward:
  - New Über-UFO [1,2,3] available
    - can do all DM spin hypotheses
  - über-UFO validated against few existing implementations

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 1st gen. restriction for Über-UFO worked out
  - Previous results reproduced



Previous work

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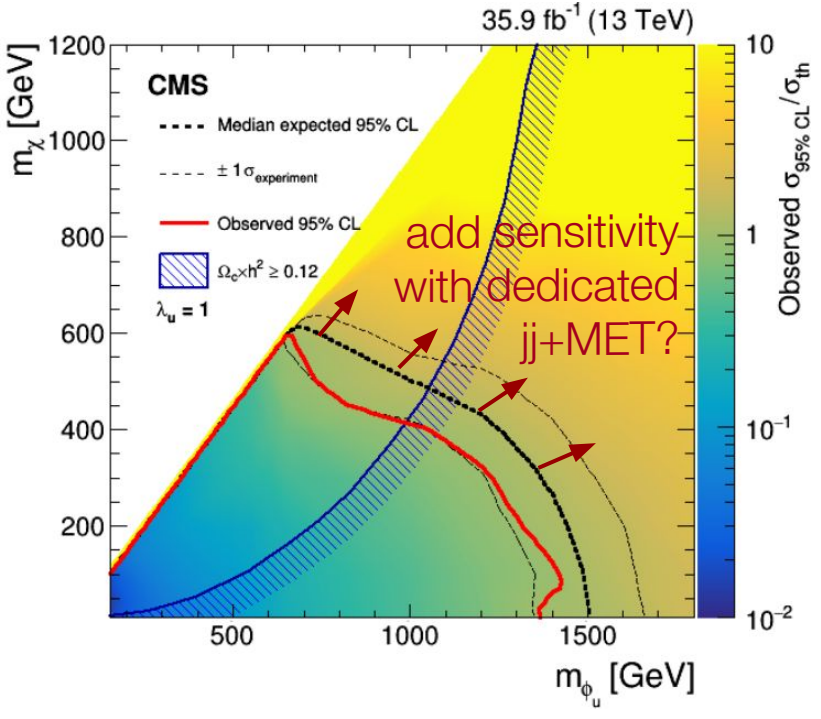
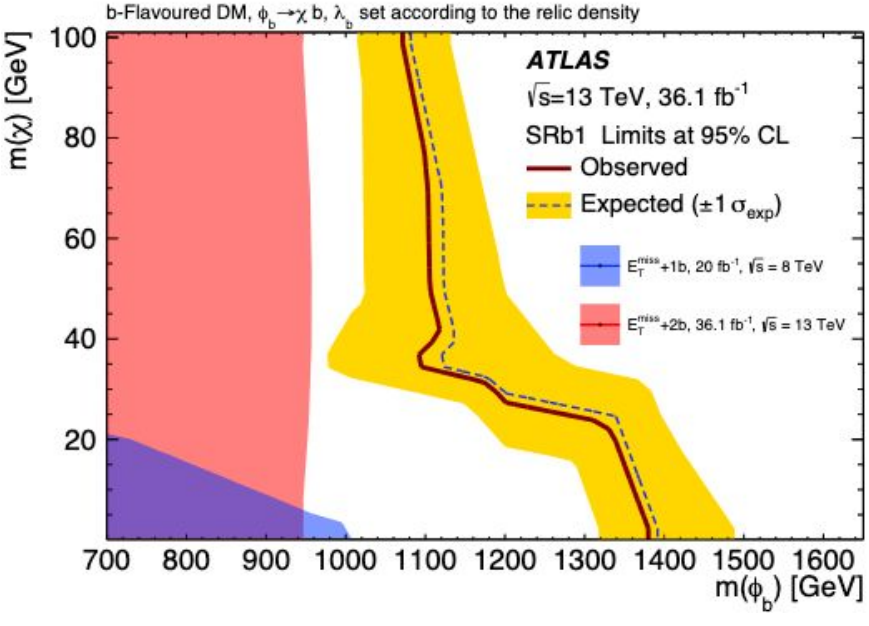
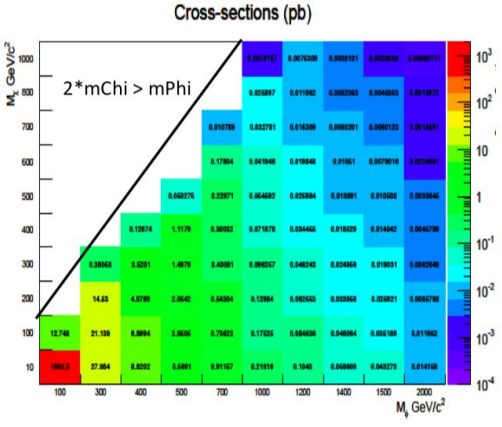
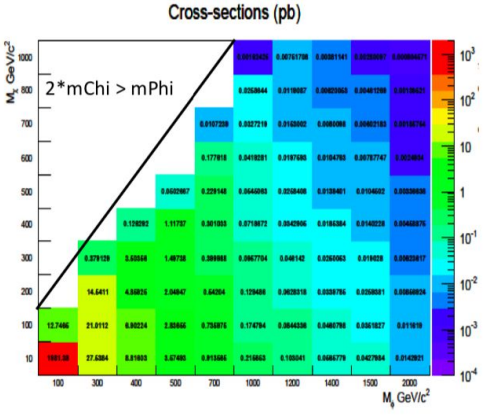


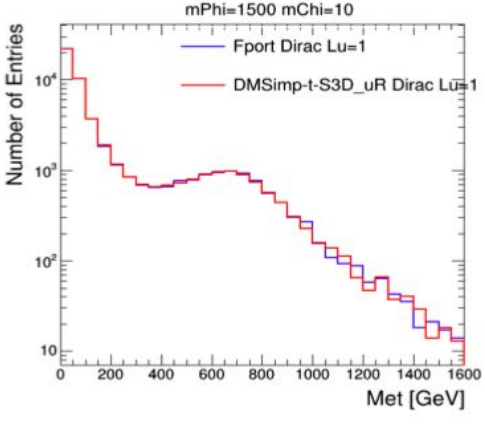
- Scalar color-charged b model [2,3]
  - ATLAS mono-b-jet
  - RH coupling 3rd generation
  - qualitatively similar kinematic behaviour to 1st gen case

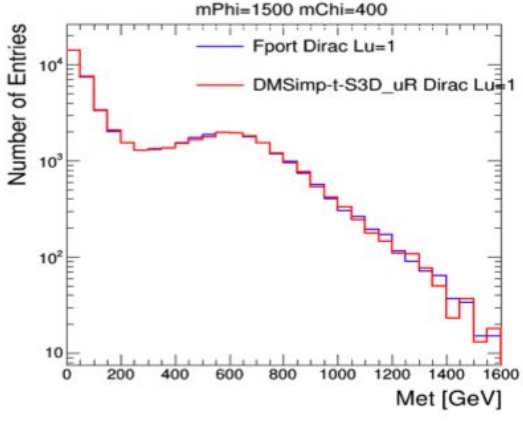


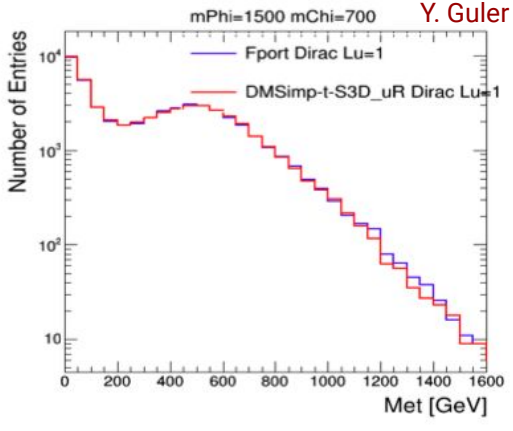
Fermion portal == S3D_uR











Y. Guler