The LHC Dark Matter Working Group

Antonio Boveia (Ohio State University)

What is this talk about?

This is an advertisement for the activities of the LHC Dark Matter Working Group (WG)

We'd like more of the community to get involved

What is this talk *not* about?

- It is not about the newest collider results—see the other talks throughout this week

Why the LHC Dark Matter Working Group?

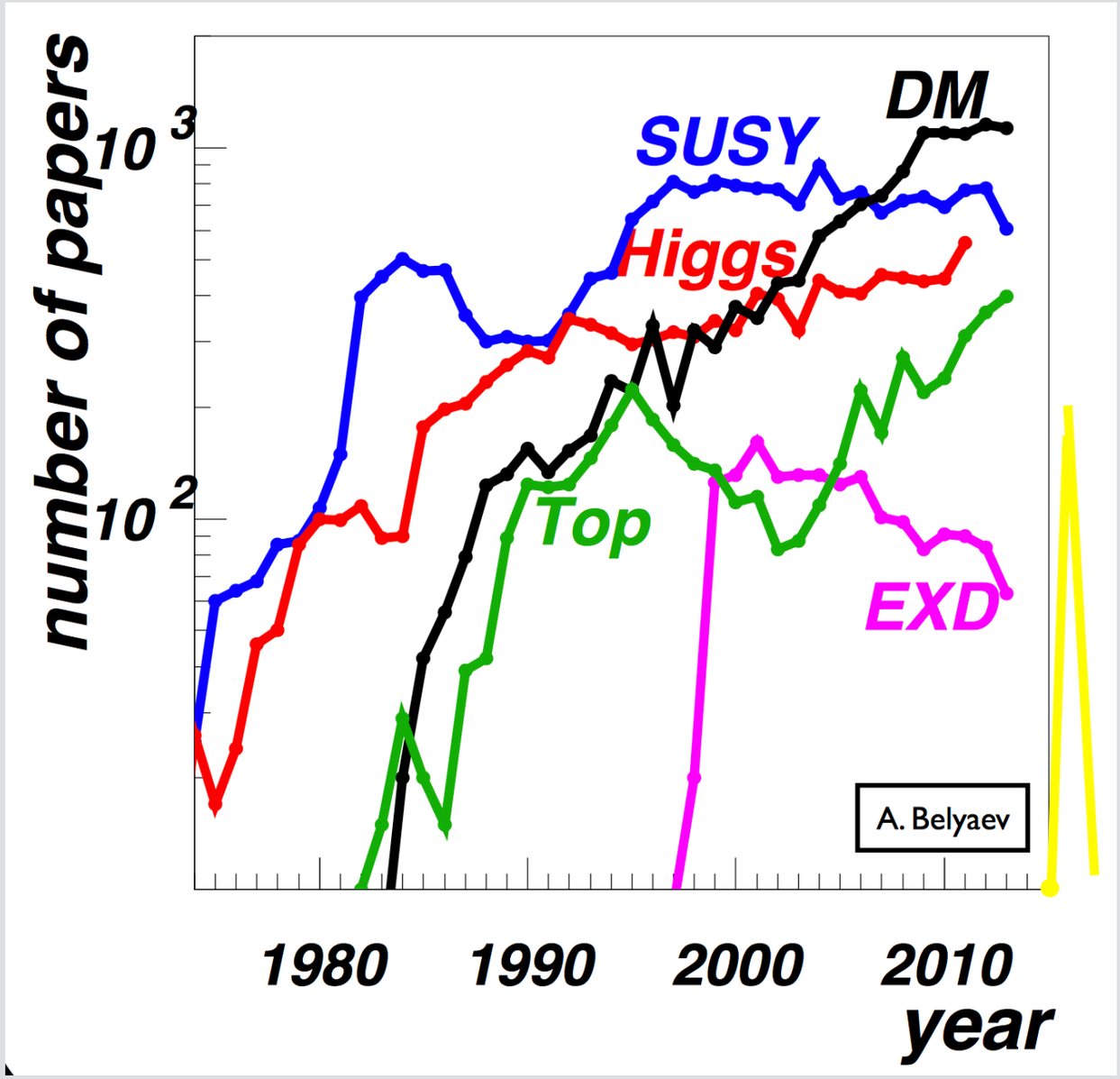
http://lpcc.web.cern.ch/lpcc/index.php?page=dm_wg

Dark matter is a significant and growing focus of the collider experiments

- e.g. an expanding body of theory & phenomenology work targeting DM@LHC
- e.g. many collider DM workshops, many conference talks
- e.g. so many papers on the HEP arXiv

The collider experiments want to strengthen the connections between our work and the broader search for particle dark matter, but we need your help!

- What signals should we look for? (Our searches are critically sensitive to the models we assume!)
- How does our work fit into the other searches being done, and where should we focus our effort to best complement the other approaches?



What is the LHC Dark Matter Working Group?

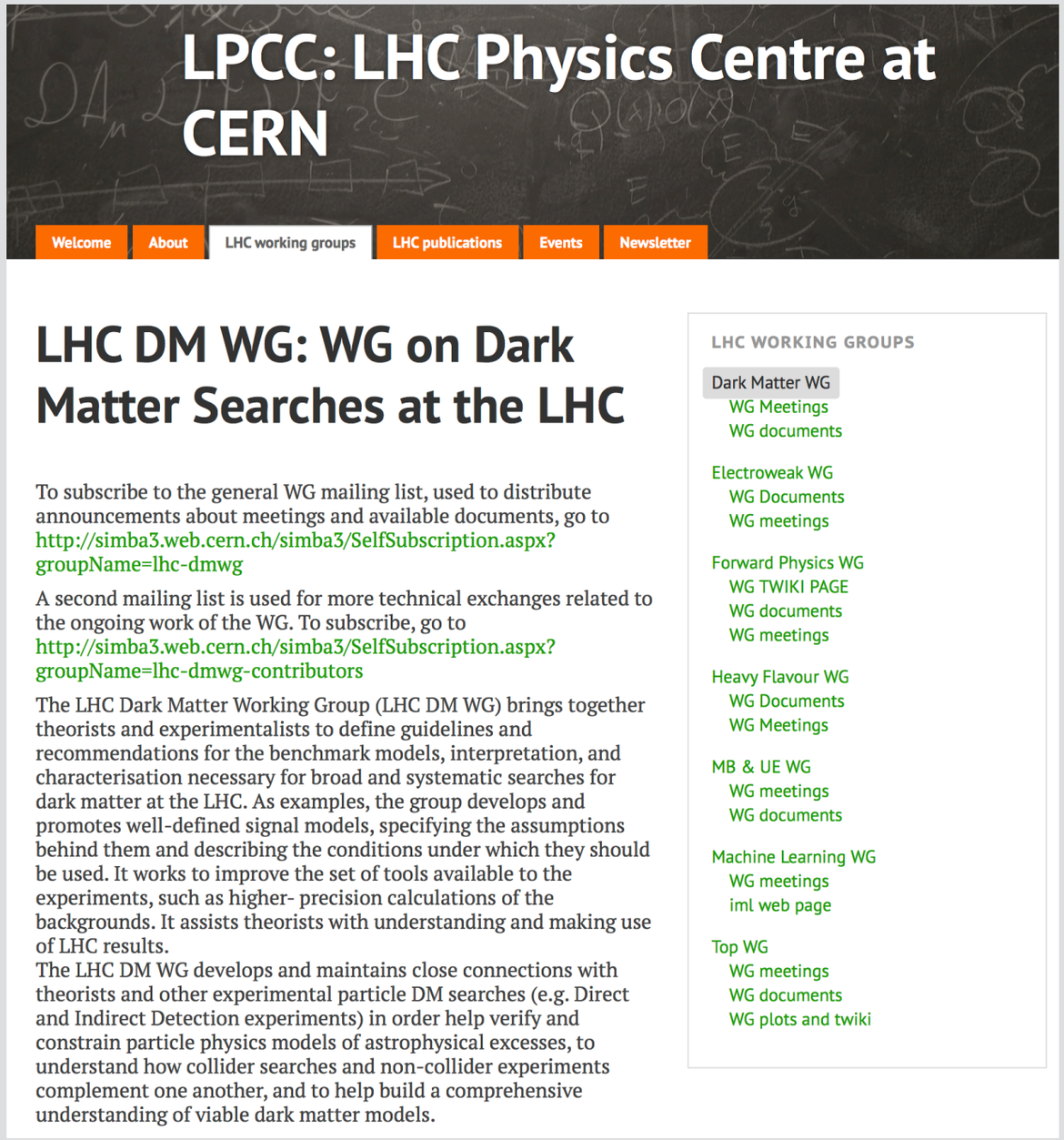
A mechanism

- for **theorists to discuss results with LHC experiments** and **LHC experiments to discuss with each other**
- to share work on **search targets and improved tools,** and to **pay attention to outside feedback on LHC results**

Search targets are especially important: **how can we minimize the chances that we miss (or do not record) a signal?**

Made up of many from ATLAS, CMS, and theory

- Participation from the experimentalists actually working on the DM searches
- Open to all theorists and quite a few are active



Conveners:

- ATLAS: C. Doglioni and A. Boveia
- CMS: K. Hahn and S.Lowette
- TH: U. Haisch and T. Tait
- LPCC: M. Mangano

How does it work?

The DM WG works on focused efforts: selected topics leading to write-ups (CERN LPCC / arXiv)

– suggestions for topics can come at any time

– occasional meetings with short pitches for potential topics

– develop topics in open meetings and smaller groups of interested contributors

– conclude and write up, with circulation and review by the full group (and sometimes outside experts)

– meetings and drafts announced at lhc-dmwg@cern.ch (sign up at egroups.cern.ch)

At the same time, a discussion forum for any topic: lhc-dmwg-contributors@cern.ch

– high volume list for day-to-day discussions in detail

– everyone welcome to raise questions / issues to the attention of the group

What are some examples of what the WG has done?

Summer 2015

[Dark Matter Forum] Provide a common set of benchmark models for ATLAS and CMS early Run-2 searches arXiv:1507.00966 (160pp!)

Winter 2015

Guidelines for comparisons with astroparticle dark matter searches arXiv:1603.04156

Winter 2016

Recommendations for mediator searches and comparisons between invisible and visible collider searches arXiv:1703.05703

Spring 2017

Arrive at a joint estimation of theory uncertainties for precision DM searches at colliders (e.g. mono-jet) arXiv:1705.04664

Spring 2017 (ongoing)

Further develop **extended scalar sector** and **colored scalar** benchmarks

Early Run 2 Benchmarks

Report of the ATLAS+CMS Dark Matter Forum arXiv: 1507.00966

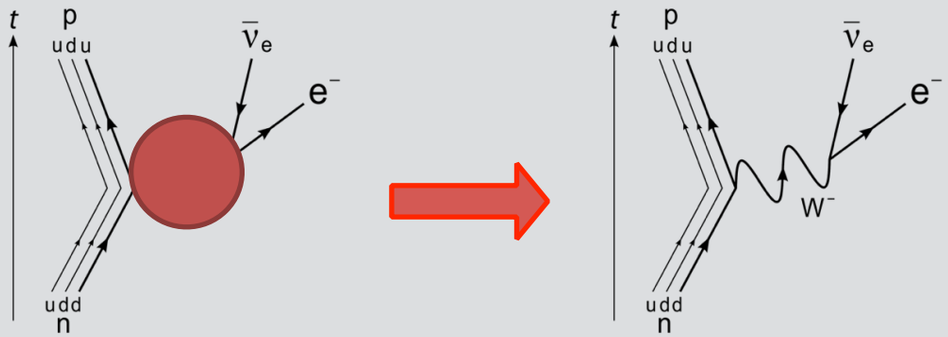
Focused on our searches for Missing Energy + jet/photon/b quark(s)/top quark(s)/W/Z/higgs/etc…

Are these searches looking for realistic signals? (EFT validity)

Provide a basis set of simplified models that complement SUSY searches

General models with SM + fermionic WIMP + mediating particle

- **Z′ or scalar mediators**
- **Colored scalar mediators**
- **Specific mediating processes (e.g. 2HDM-like) for Missing Energy + Higgs**



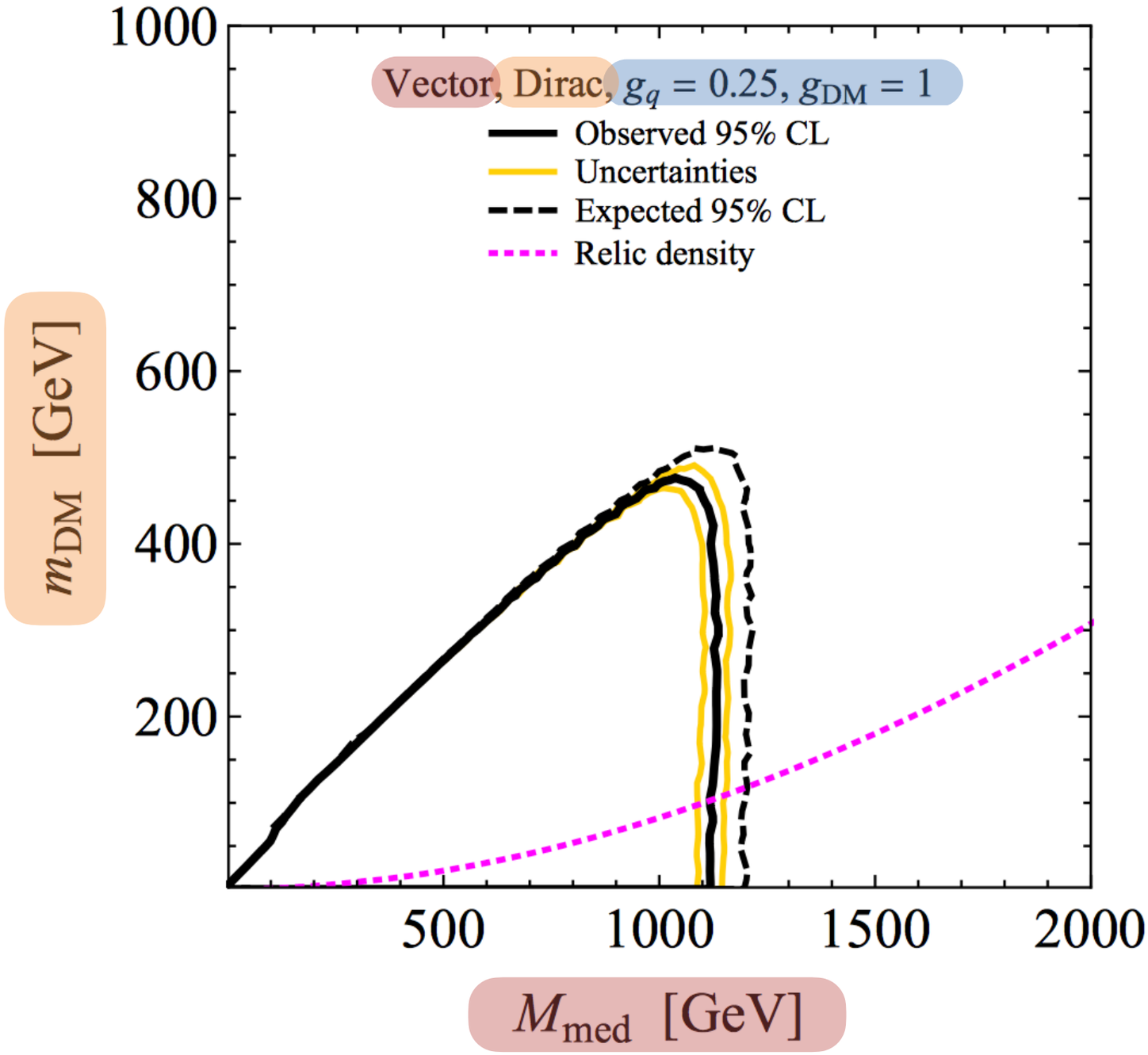
Augmenting EFTs with simplified models

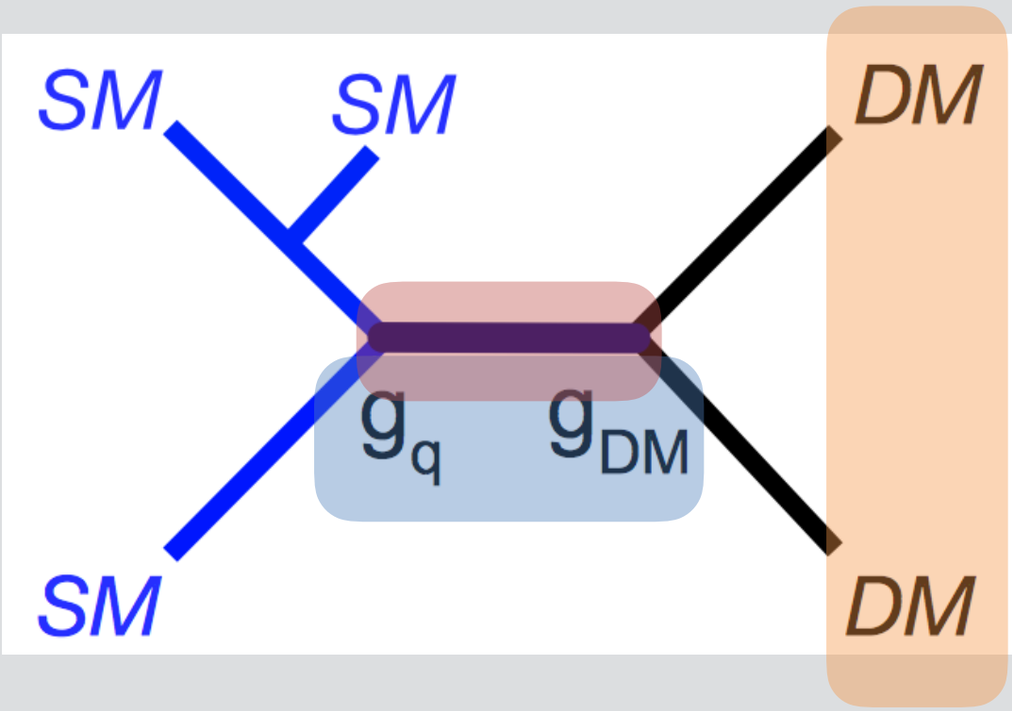
Collider results: mass-mass plots

arXiv:1603.04156

How to display interpretation of collider search using simplified models

1. How to convey the results fairly
2. Issues that should be considered
3. Comparison with the relic density obtained in the absence of further higher-energy physics



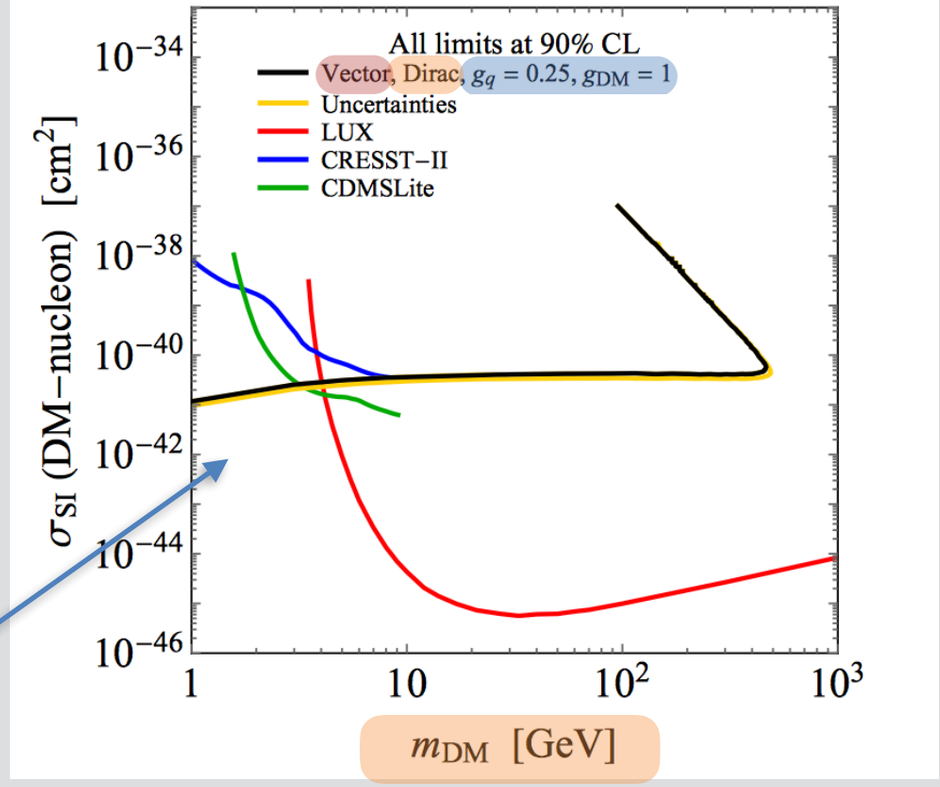


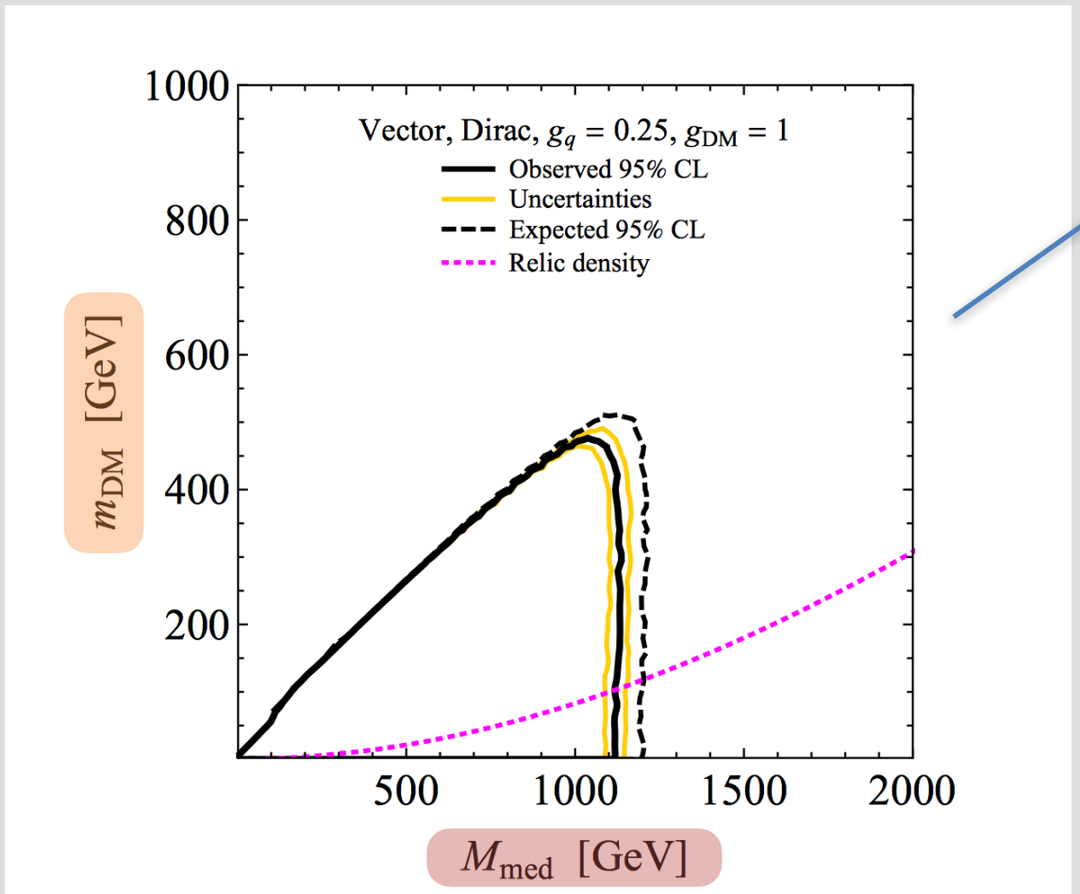
Comparison to non-collider results

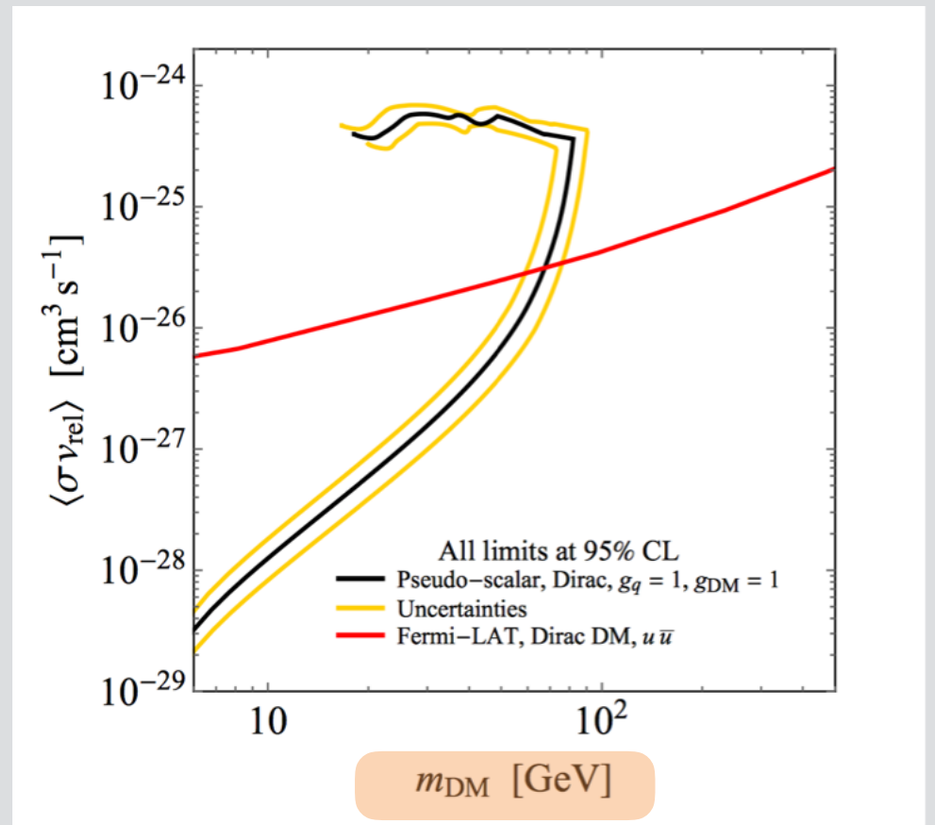
arXiv:1603.04156

How to display collider searches alongside DD/ID

1. Mapping from the simplified models to DD/ID variables (correspondence M_{Med}, M_{DM}, g_q, g_{DM} ⇔ σ)
2. Spells out well-defined translation formulas, reference relic abundances for benchmarks
3. Reference/pedagogical discussion of the strengths and limitations of collider searches and how they complement other approaches







Comparison to non-collider results

arXiv:1603.04156

How to display collider searches alongside DD/ID

1. Mapping from the simplified models to DD/ID variables (correspondence M
2. Spells out well-def abundances for be
3. Reference/pedago limitations of colli other approaches

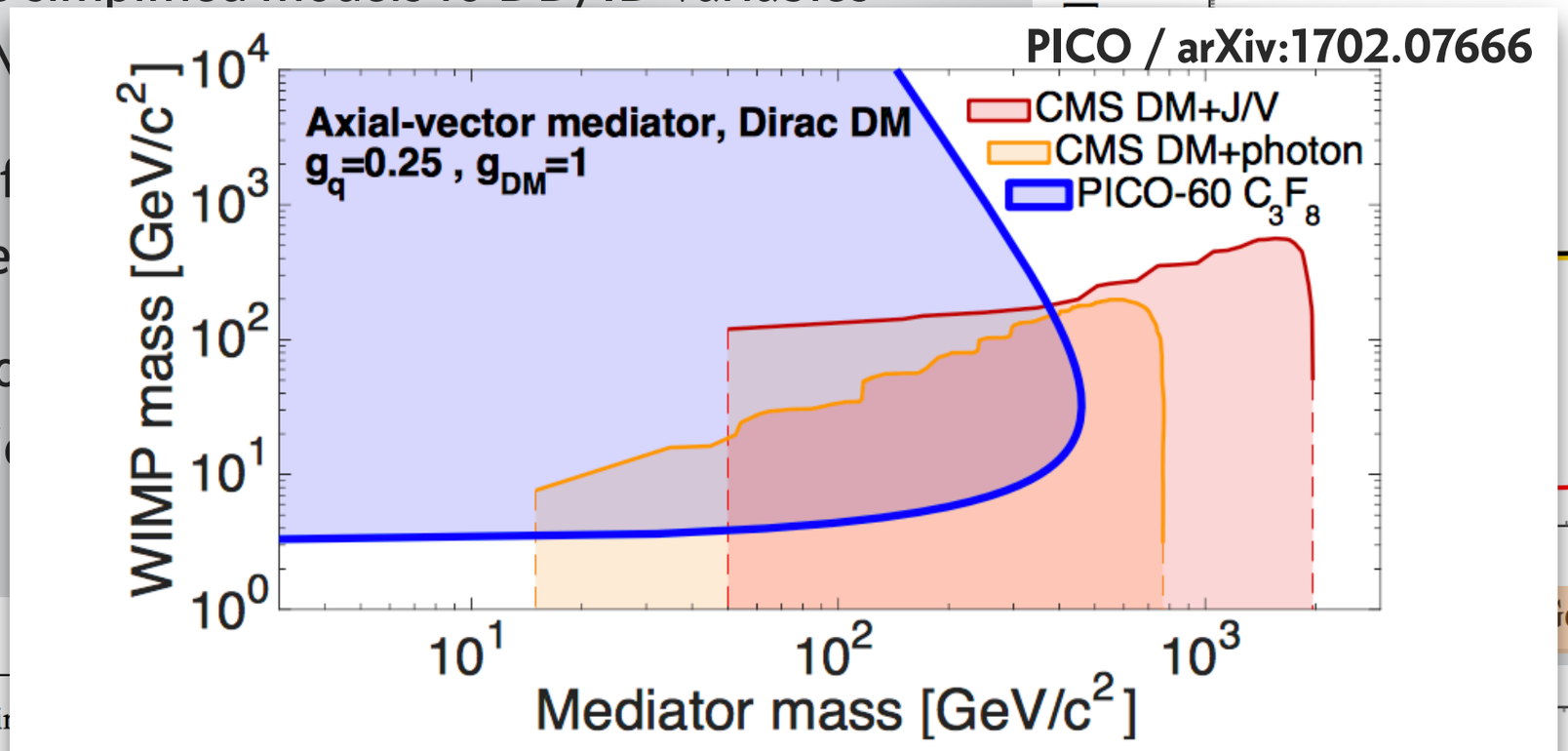
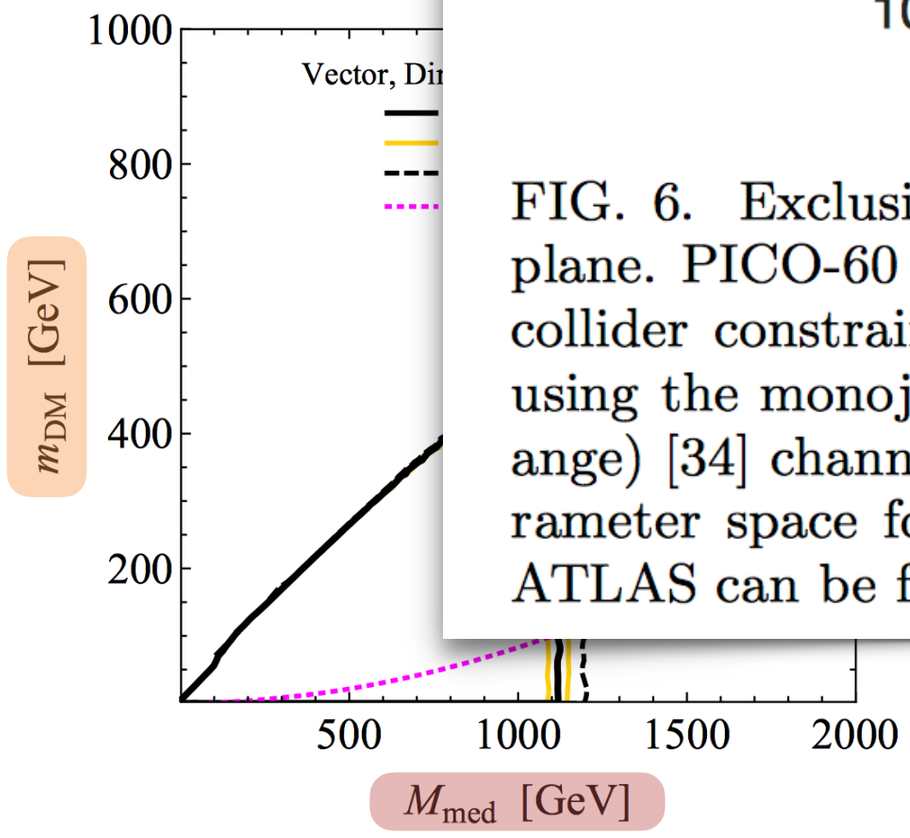
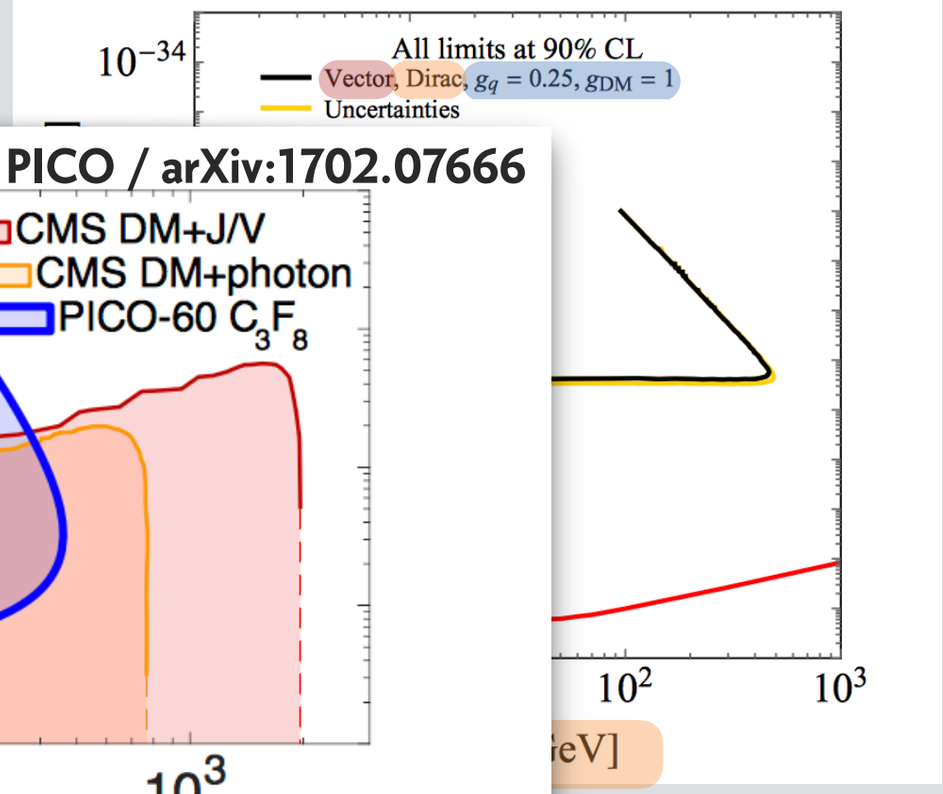
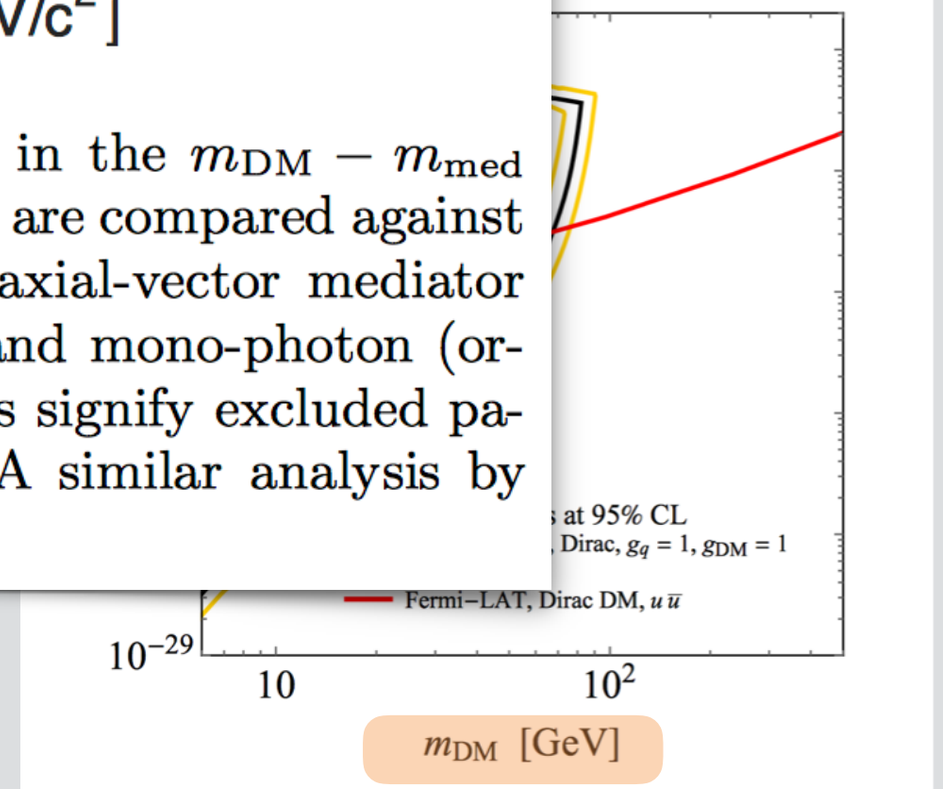


FIG. 6. Exclusion limits at 95% C.L. in the $m_{\rm DM} - m_{\rm med}$ plane. PICO-60 constraints (thick blue) are compared against collider constraints from CMS for an axial-vector mediator using the monojet/mono-V (red) [33] and mono-photon (orange) [34] channels. The shaded regions signify excluded parameter space for the chosen model. A similar analysis by ATLAS can be found in [52].



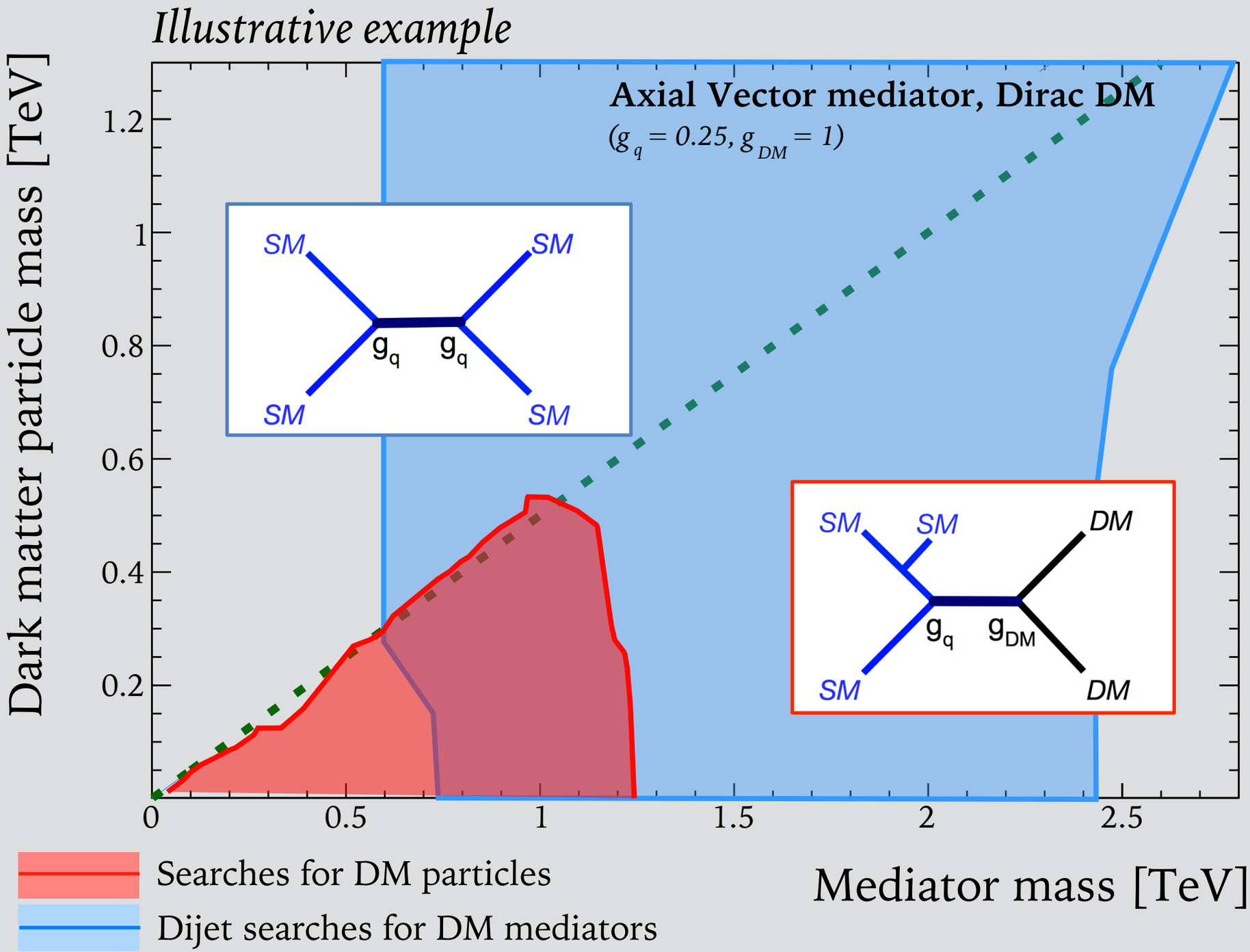




Visible/invisible mediator searches

arXiv:1703.05703

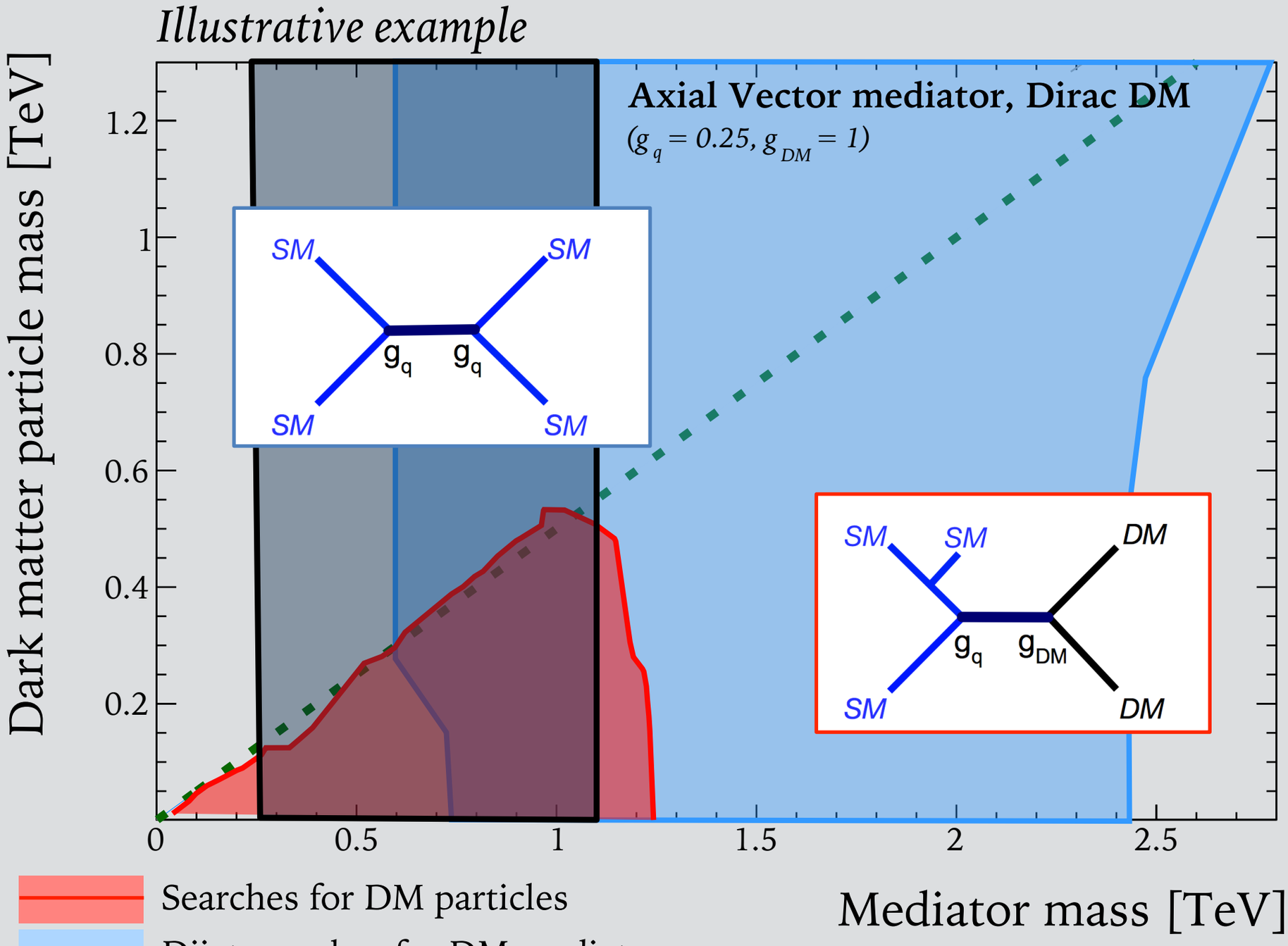
Are we looking for all the signatures of these models? e.g. Z′ → WIMPs or Z′→jet+jet



Visible decays are an important strength of colliders
(Think MET+jet vs specific SUSY cascade decay)

Visible/invisible mediator searches

arXiv:1703.05703

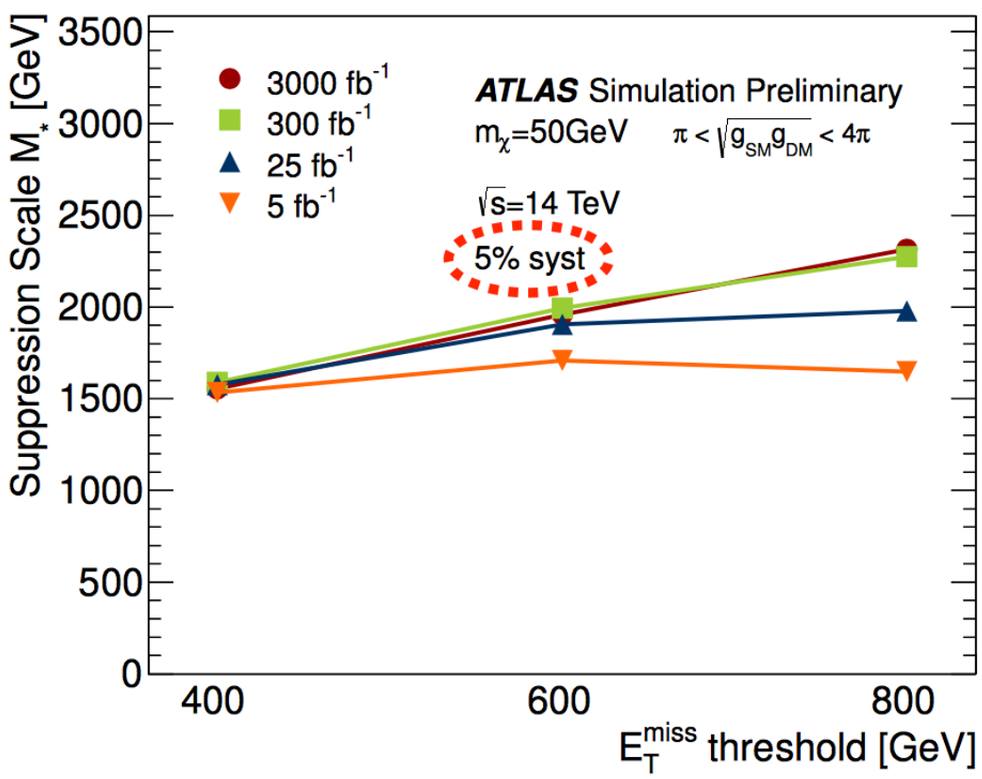


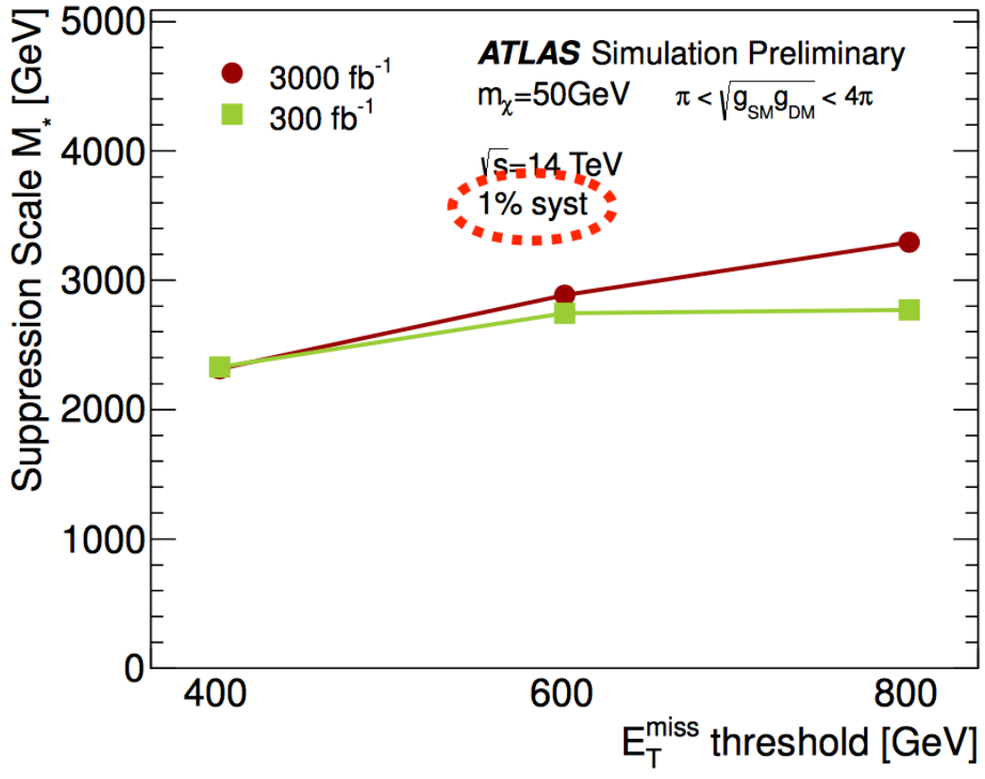
How to improve missing-energy searches?

Ambitious program of LHC mono-X searches up to HL-LHC needs:

- Very precise (~1%) uncertainties on theoretical modelling of W/Z+jets processes
- Detailed understanding correlations between background uncertainty sources

[ATL-COM-PHYS-2014-549]



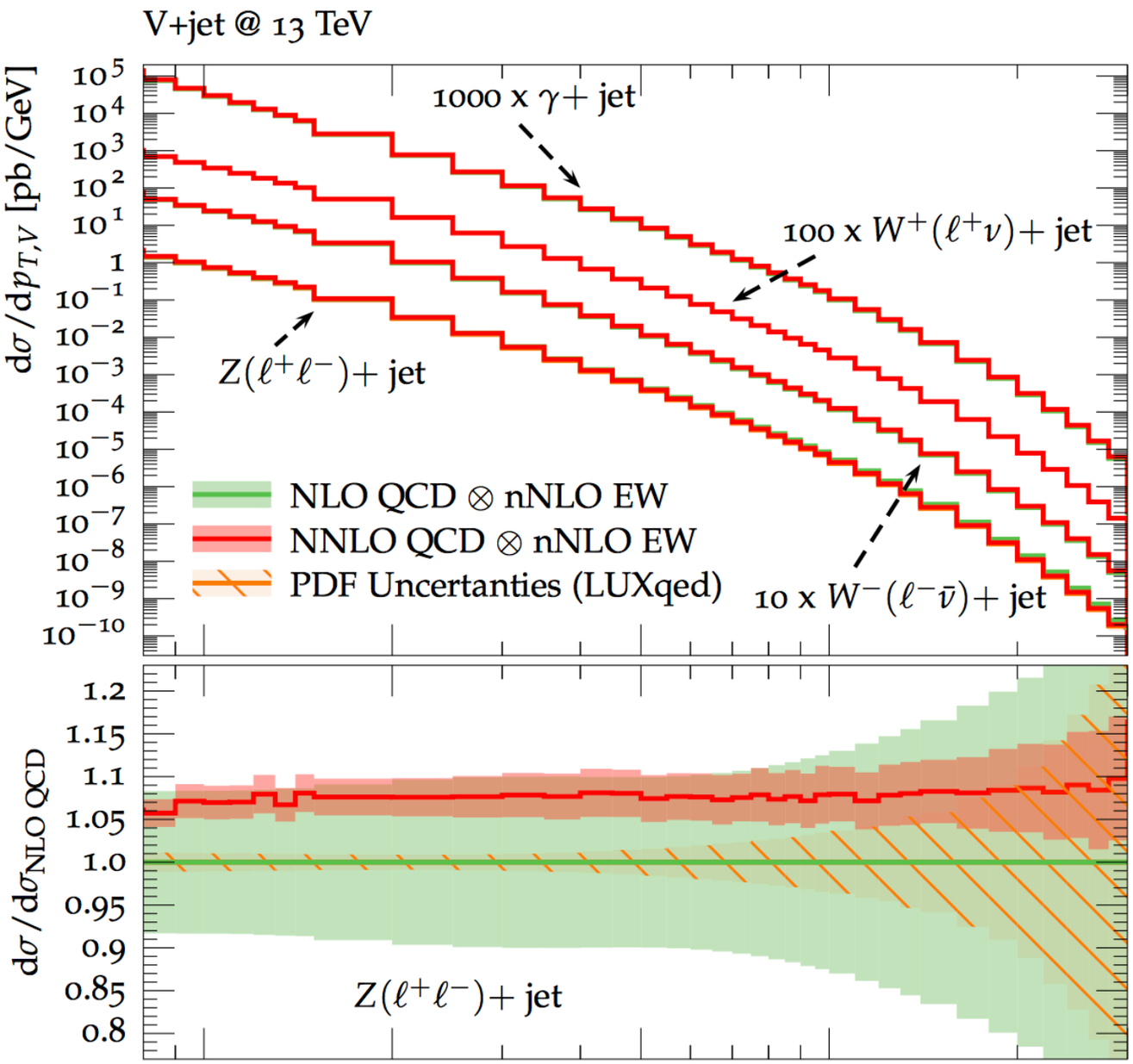


Precise predictions for V+jets dark matter backgrounds

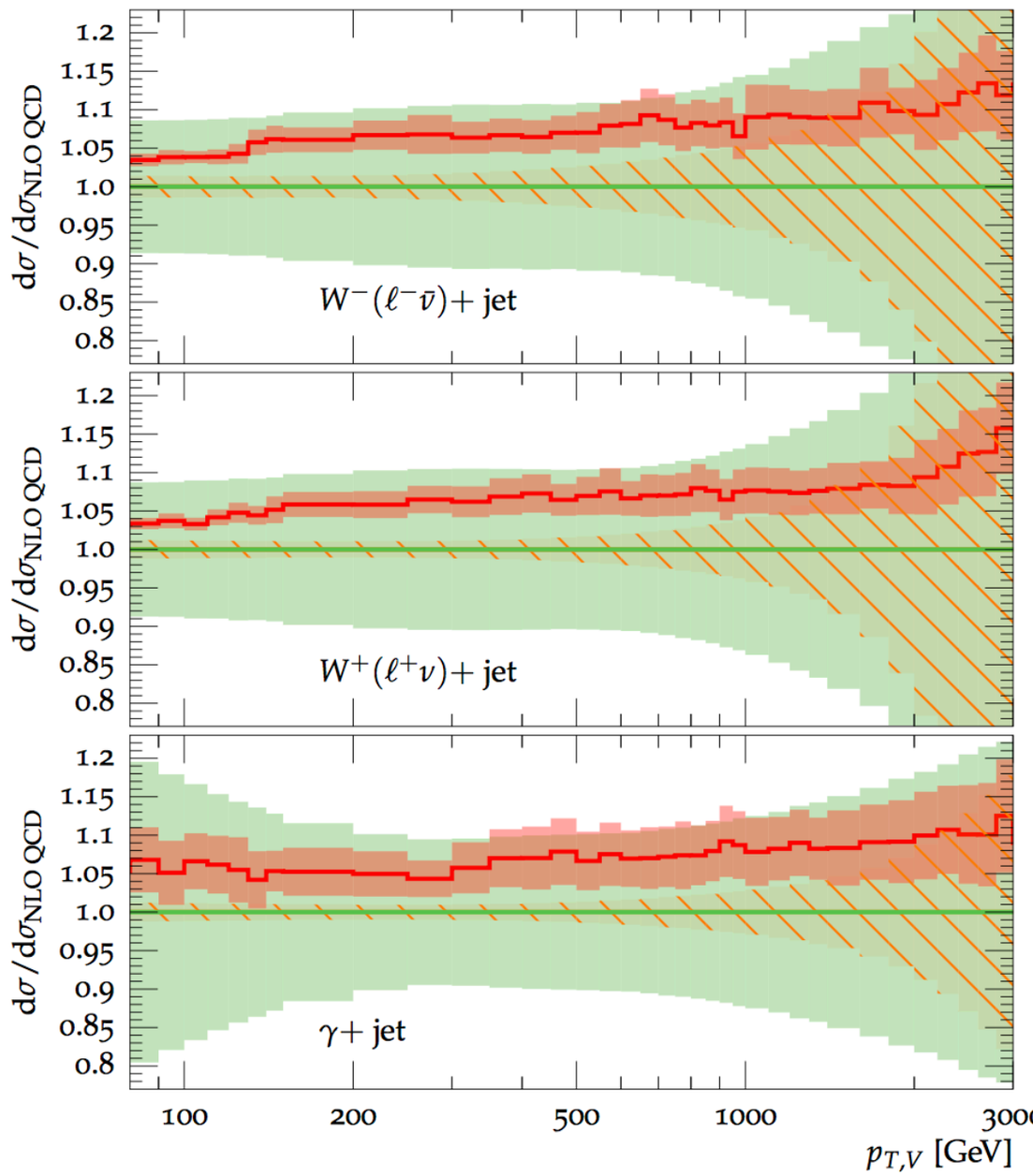
arXiv:1705.04664

Combined state-of-the-art calculations for all relevant V + jets processes to mono-jet searches, including **NNLO QCD corrections** and **NLO electroweak corrections** supplemented by **Sudakov logarithms at two loops**

Theoretical uncertainty on $Z(\nu\bar{\nu})$+ jet background at the few percent level up to the TeV range.



All NLO uncertainties combined in quadrature (NLO), except for PDFs



[NNLO: scale uncertainty only]

What will the group do in the future?

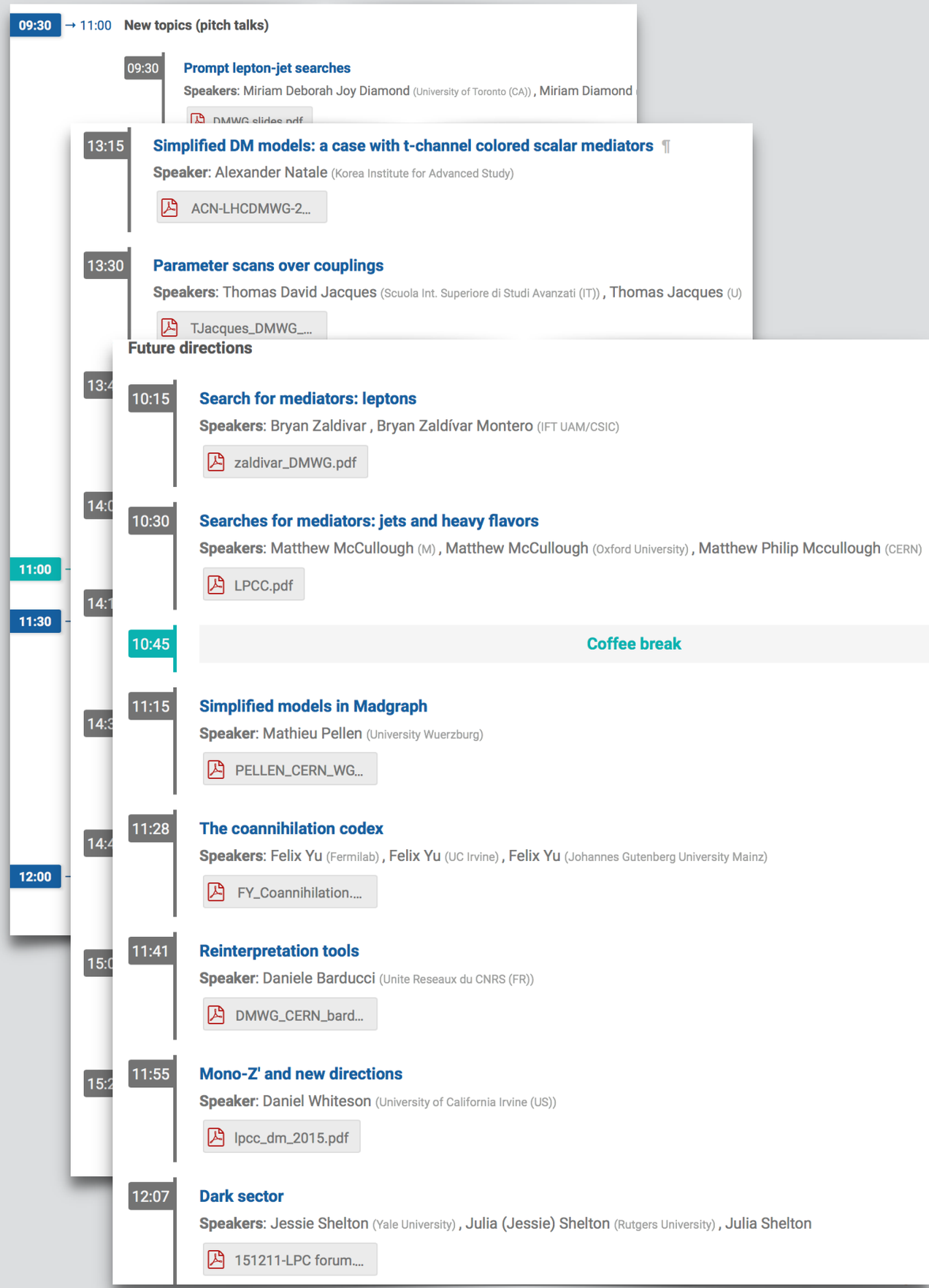
http://lpcc.web.cern.ch/lpcc/index.php?page=dm_wg

Periodic calls for new topics from the community —another call soon (subscribe to lhc-dmwg@cern.ch at https://e-groups.cern.ch)

Attention remains on

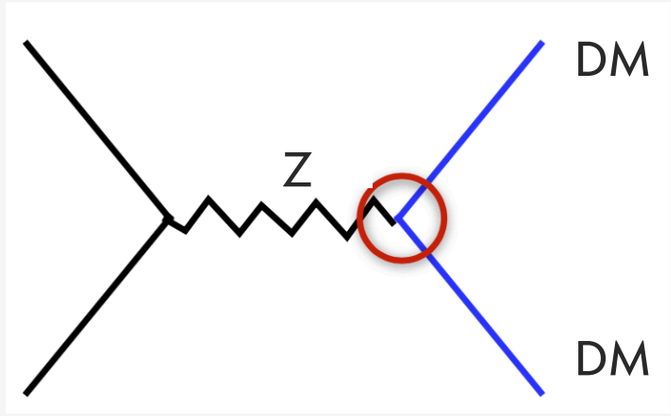
- Developing dialogue with theory and non-collider communities
- Motivating searches that are not being done
- Earlier example: effort on hadronic resonances at the EW scale rather than TeV scale
- Mediator consequences
- Connecting to other neighboring efforts, such as for long-lived particle searches

Please contact us and join!



Additional Slides

If the Z boson mediates SM-DM interaction...



PDG (LEP) Invisible Decay Width of the Z

VALUE (MeV)	EVTS	DOCUMENT ID		TECN
499.0 ± 1.5	**OUR FIT**			
503 ± 16	**OUR AVERAGE** Error includes scale factor of 1.2.			
498 ±12 ±12	1791	ACCIARRI	1998G	L3
539 ±26 ±17	410	AKERS	1995C	OPAL
450 ±34 ±34	258	BUSKULIC	1993L	ALEP
540 ±80 ±40	52	ADEVA	1992	L3

Number from e^+e^- Colliders

Number of Light ν Types

Our evaluation uses the invisible and leptonic widths of the Z boson from our combined fit shown in the Particle Listings for the Z Boson, and the Standard Model value $\Gamma_\nu/\Gamma_\ell = 1.9908 \pm 0.0015$.

VALUE	DOCUMENT ID	TECN
2.994±0.012 OUR EVALUATION	Combined fit to all LEP data.	
• • • We do not use the following data for averages, fits, limits, etc. • • •		
3.00 ±0.05	[1] LEP 92	RVUE

[1] Simultaneous fits to all measured cross section data from all four LEP experiments.

Number of Light ν Types from Direct Measurement of Invisible Z Width

In the following, the invisible Z width is obtained from studies of single-photon events from the reaction $e^+e^- \to \nu\bar{\nu}\gamma$. All are obtained from LEP runs in the $E_{\rm cm}^{ee}$ range 88–94 GeV.

VALUE	DOCUMENT ID	TECN	COMMENT
3.00±0.06 OUR AVERAGE			
3.01±0.08	ACCIARRI 99R	L3	1998 LEP run
2.98±0.07±0.07	ACCIARRI 98G	L3	LEP 1991–1994
2.89±0.32±0.19	ABREU 97J	DLPH	1993–1994 LEP runs
3.23±0.16±0.10	AKERS 95C	OPAL	1990–1992 LEP runs
2.68±0.20±0.20	BUSKULIC 93L	ALEP	1990–1991 LEP runs
• • • We do not use the following data for averages, fits, limits, etc. • • •			
3.1 ±0.6 ±0.1	ADAM 96C	DLPH	$\sqrt{s} = 130$, 136 GeV

Limits from Astrophysics and Cosmology

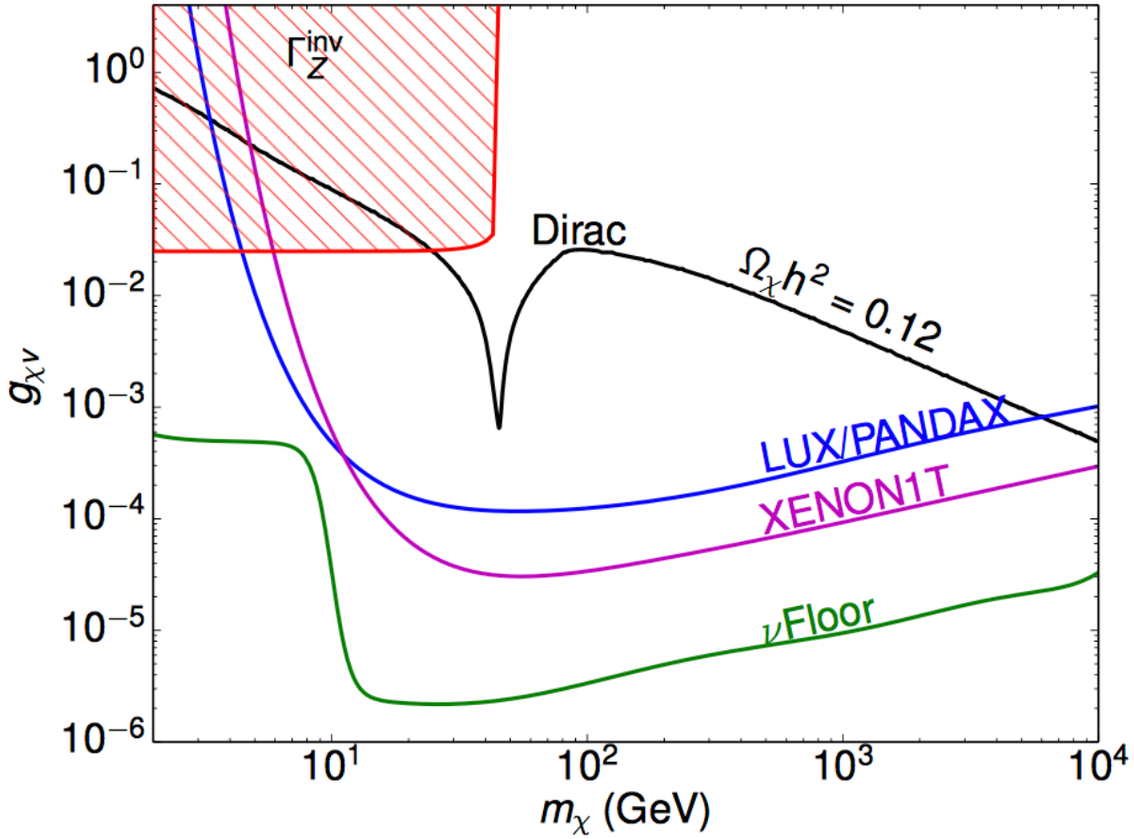
Number of Light ν Types

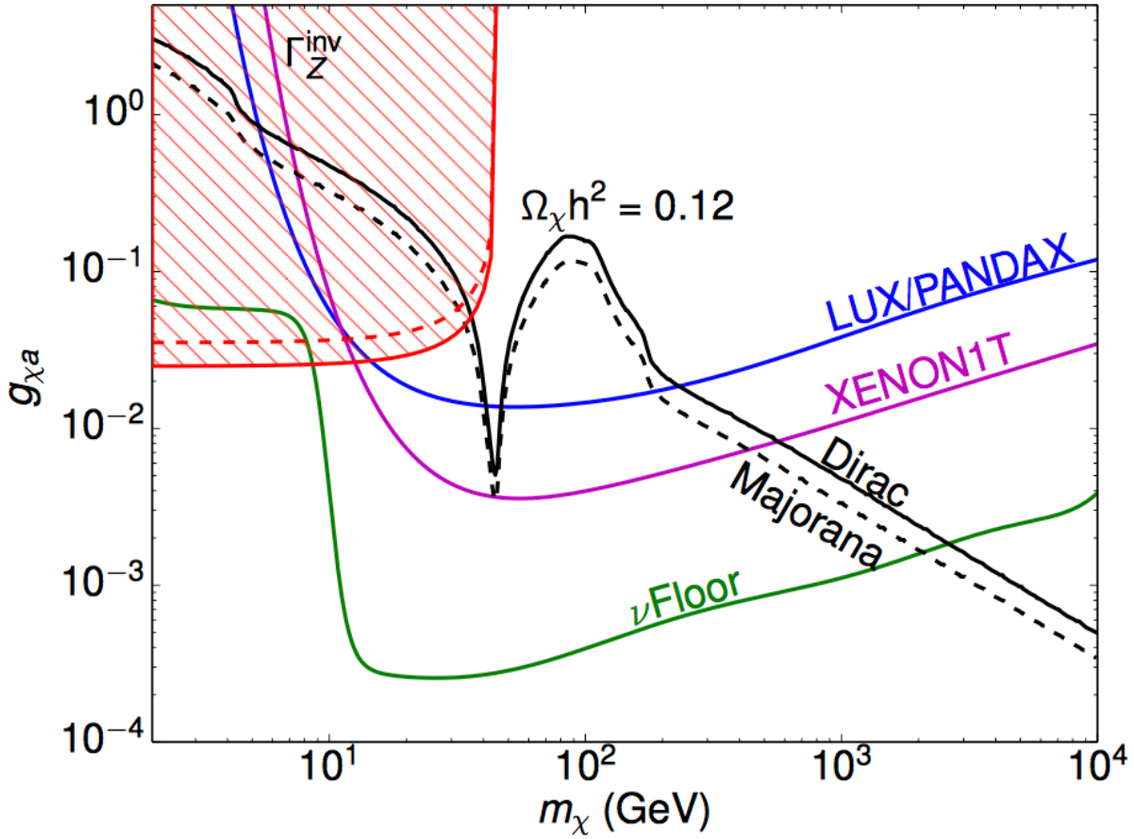
("light" means < about 1 MeV). See also OLIVE 81. For a review of limits based on Nucleosynthesis, Supernovae, and also on terrestial experiments, see DENEGRI 90. Also see "Big-Bang Nucleosynthesis" in this *Review*.

VALUE	DOCUMENT ID	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •		

Fermionic DM

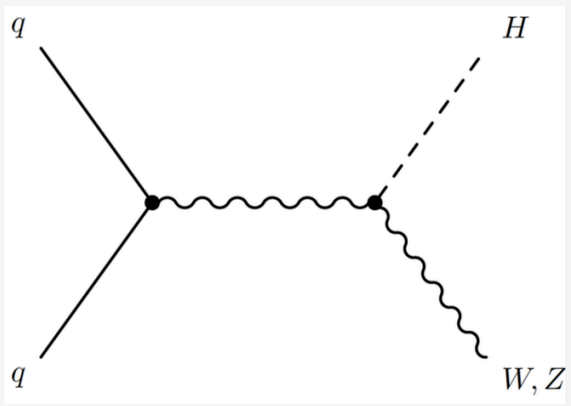
Escudero et al., arXiv:1609.09079

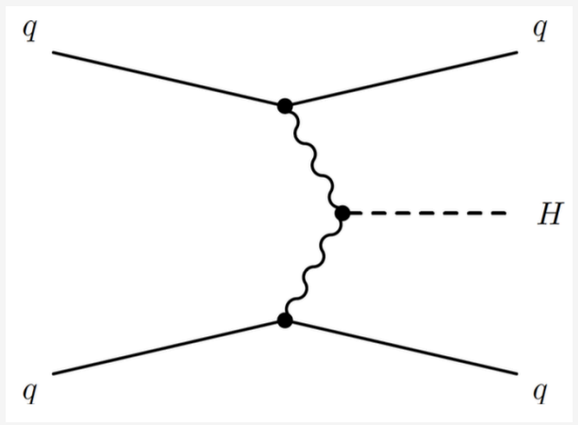


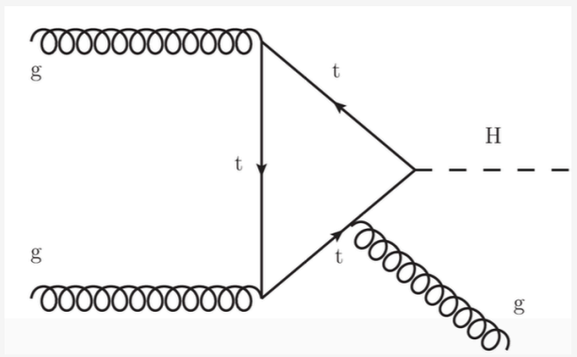


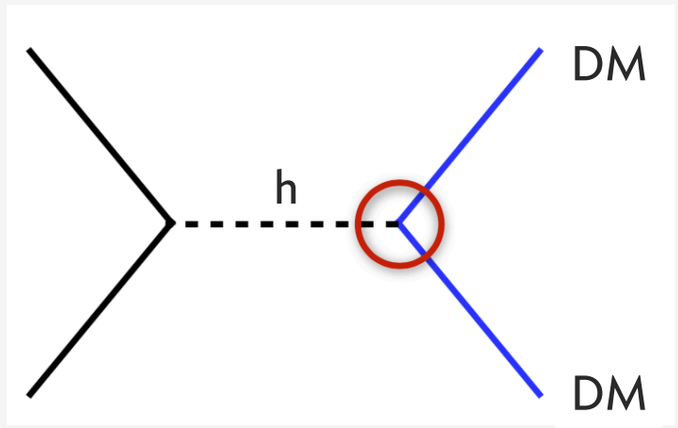
If the Higgs boson mediates SM-DM interaction...

LHC data can constrain the Higgs→invisible branching fraction, which is 10^{-3} in the SM

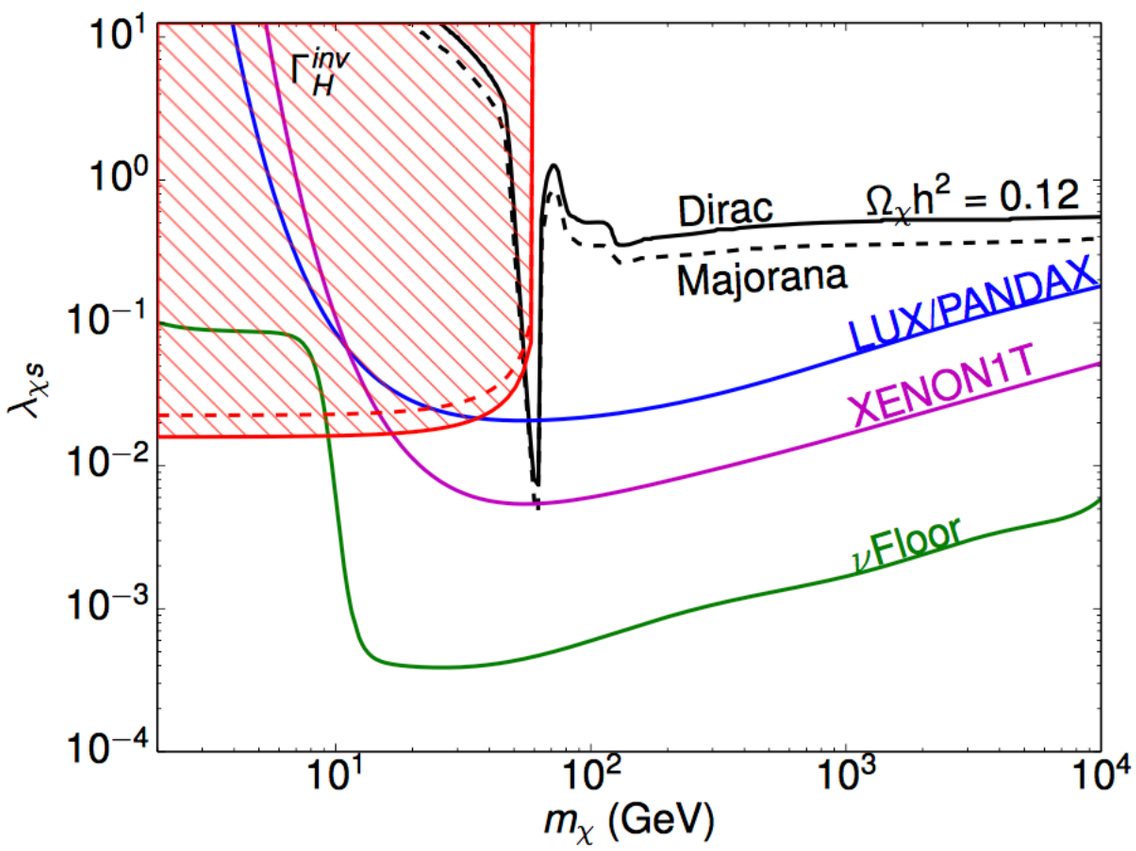




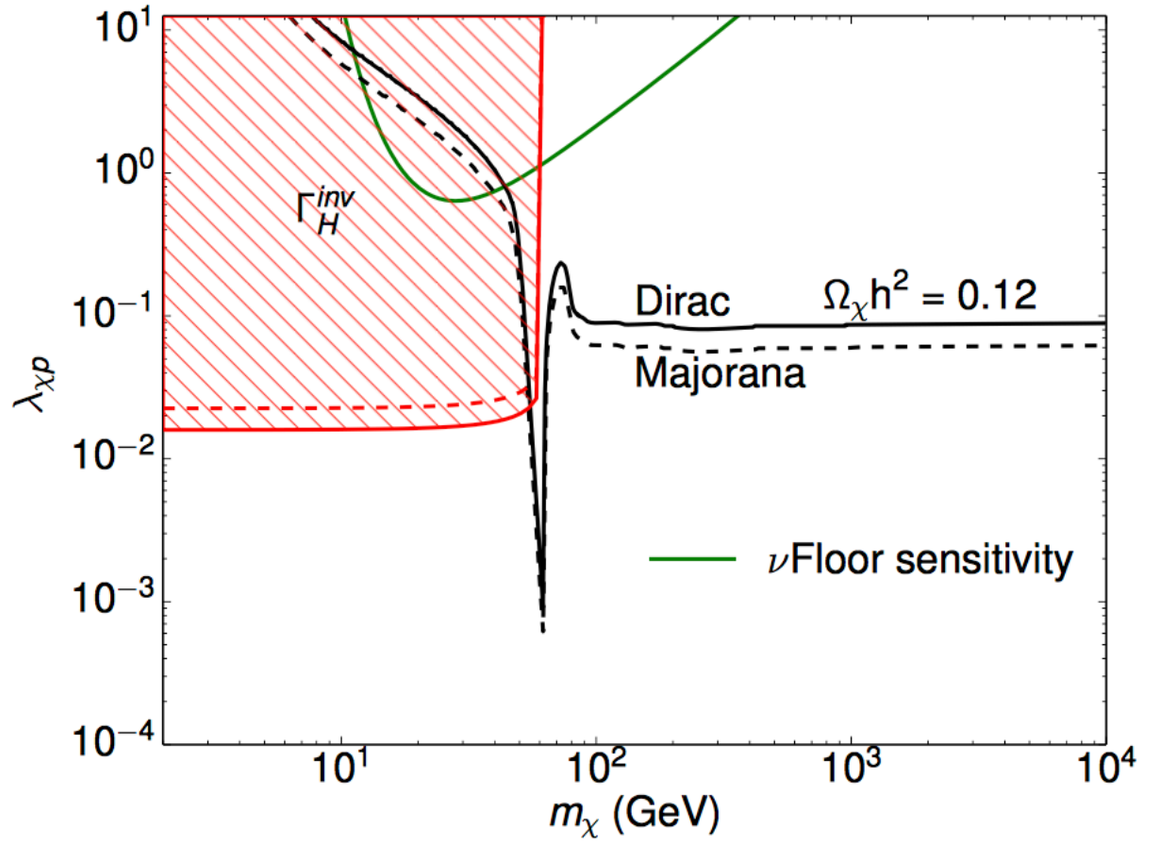




Fermionic DM

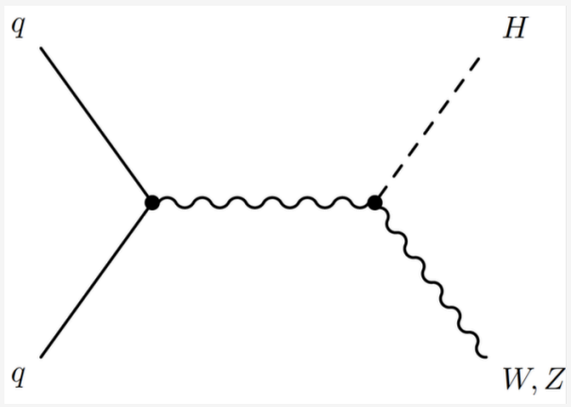


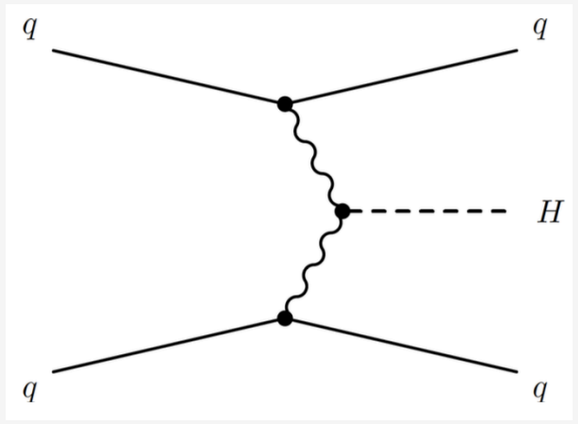
Escudero et al., arXiv:1609.09079

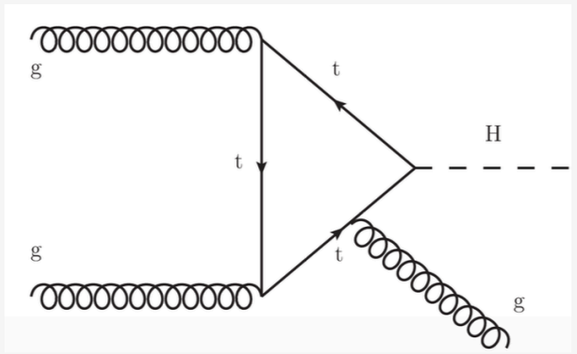


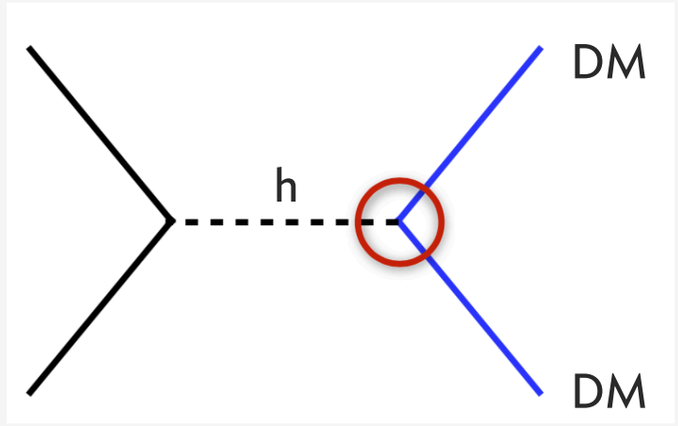
If the Higgs boson mediates SM-DM interaction...

LHC data can constrain the Higgs→invisible branching fraction, which is 10^{-3} in the SM



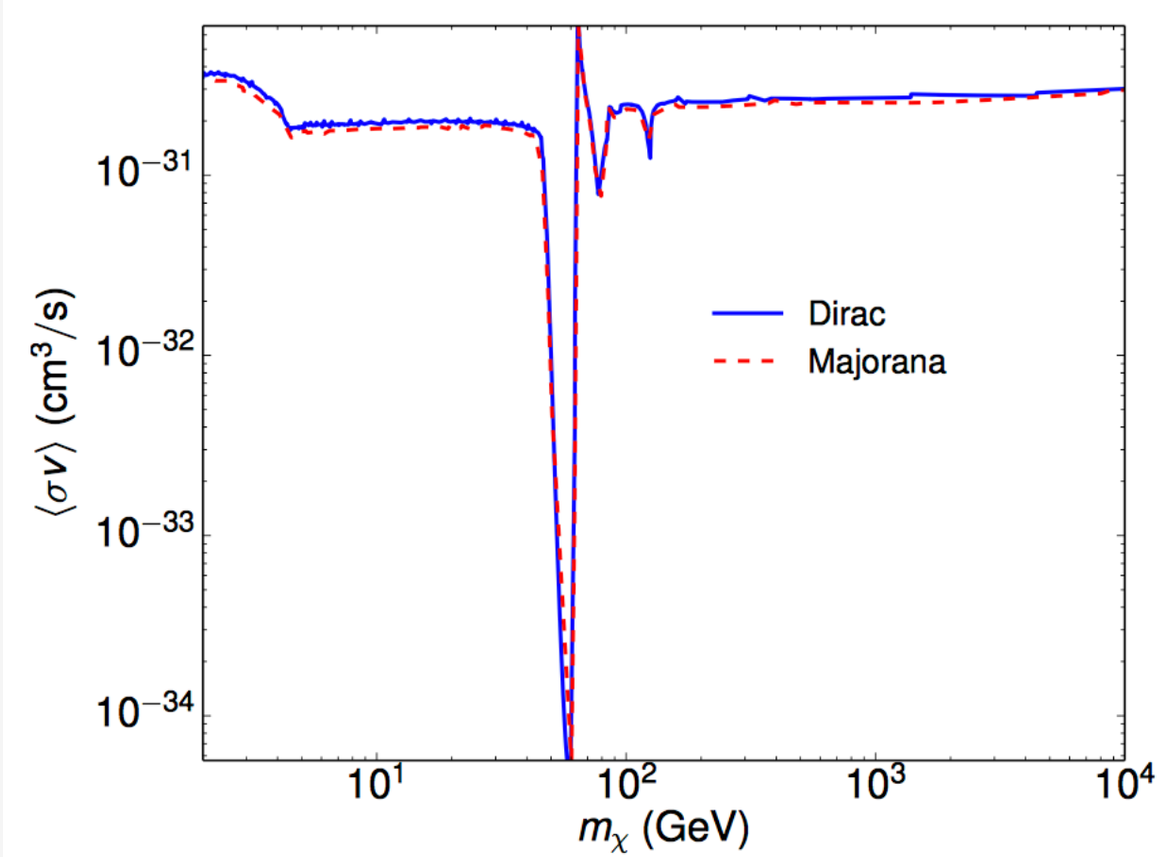


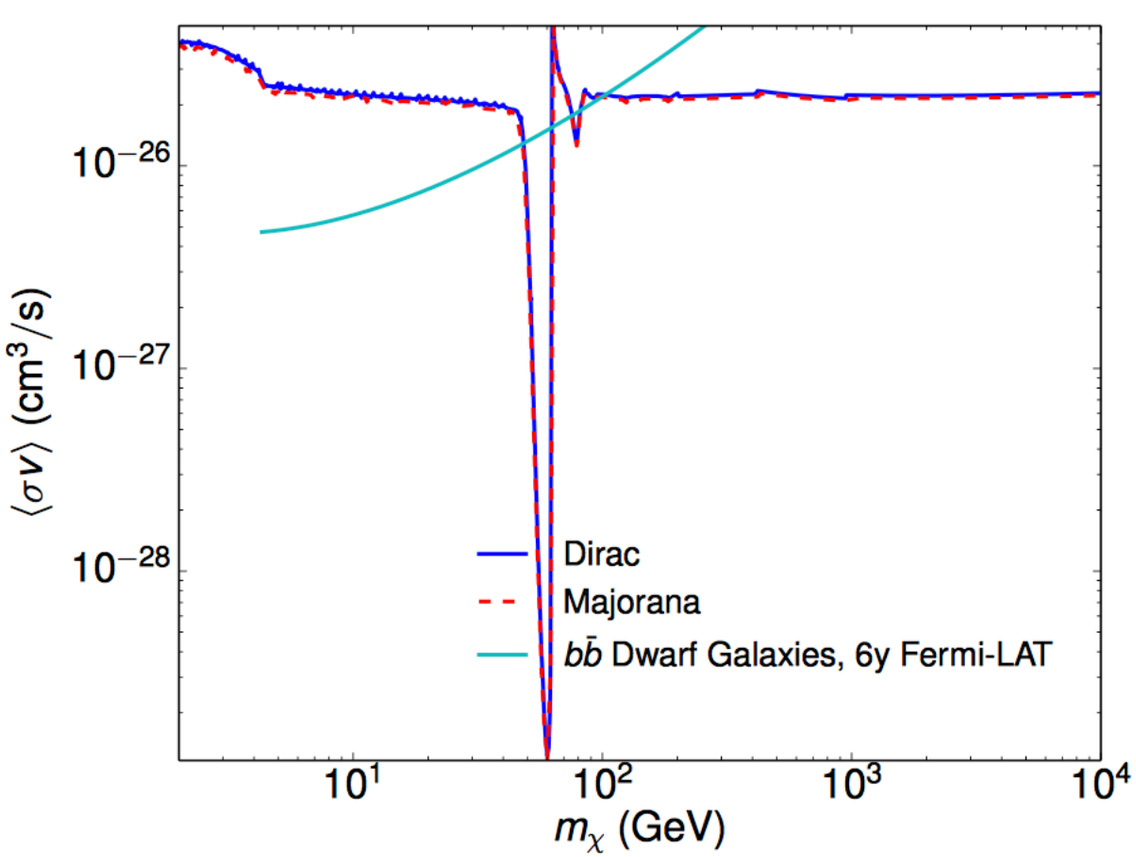




Fermionic DM

Escudero et al., arXiv:1609.09079





Theories of Dark Matter

?

MSSM

R-parity violating

NMSSM

Supersymmetry

WIMPless DM

Hidden Sector DM

Self-Interacting DM

mSUGRA

pMSSM

Gravitino DM

Q-balls

Techni-baryons

Dark Photon

Dirac DM

R-parity Conserving

Asymmetric DM

Light Force Carriers

Extra Dimensions

Dynamical DM

Warm DM

Solitonic DM

UED DM

Sterile Neutrinos

Quark Nuggets

6d

5d

Warped Extra Dimensions

RS DM

T-odd DM

Axion DM

Little Higgs

QCD Axions

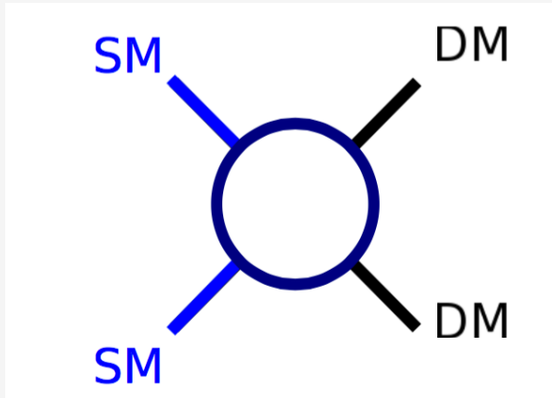
Axion-like Particles

Littlest Higgs

T Tait

TABLE I. Operators coupling WIMPs to SM particles. The operator names beginning with D, C, R apply to WIMPS that are Dirac fermions, complex scalars or real scalars, respectively.

Name	Operator	Coefficient
D1	$\bar{\chi}\chi\bar{q}q$	m_q/M_*^3
D2	$\bar{\chi}\gamma^5\chi\bar{q}q$	im_q/M_*^3
D3	$\bar{\chi}\chi\bar{q}\gamma^5 q$	im_q/M_*^3
D4	$\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$	m_q/M_*^3
D5	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D6	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D7	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D8	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D9	$\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$	$1/M_*^2$
D10	$\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi\bar{q}\sigma_{\alpha\beta}q$	i/M_*^2
D11	$\bar{\chi}\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^3$
D12	$\bar{\chi}\gamma^5\chi G_{\mu\nu}G^{\mu\nu}$	$i\alpha_s/4M_*^3$
D13	$\bar{\chi}\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^3$
D14	$\bar{\chi}\gamma^5\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\alpha_s/4M_*^3$
C1	$\chi^\dagger\chi\bar{q}q$	m_q/M_*^2
C2	$\chi^\dagger\chi\bar{q}\gamma^5 q$	im_q/M_*^2
C3	$\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu q$	$1/M_*^2$
C4	$\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu\gamma^5 q$	$1/M_*^2$
C5	$\chi^\dagger\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^2$
C6	$\chi^\dagger\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^2$
R1	$\chi^2\bar{q}q$	$m_q/2M_*^2$
R2	$\chi^2\bar{q}\gamma^5 q$	$im_q/2M_*^2$
R3	$\chi^2 G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/8M_*^2$
R4	$\chi^2 G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/8M_*^2$



Colliders (EFT)

Problem (when applying to LHC):

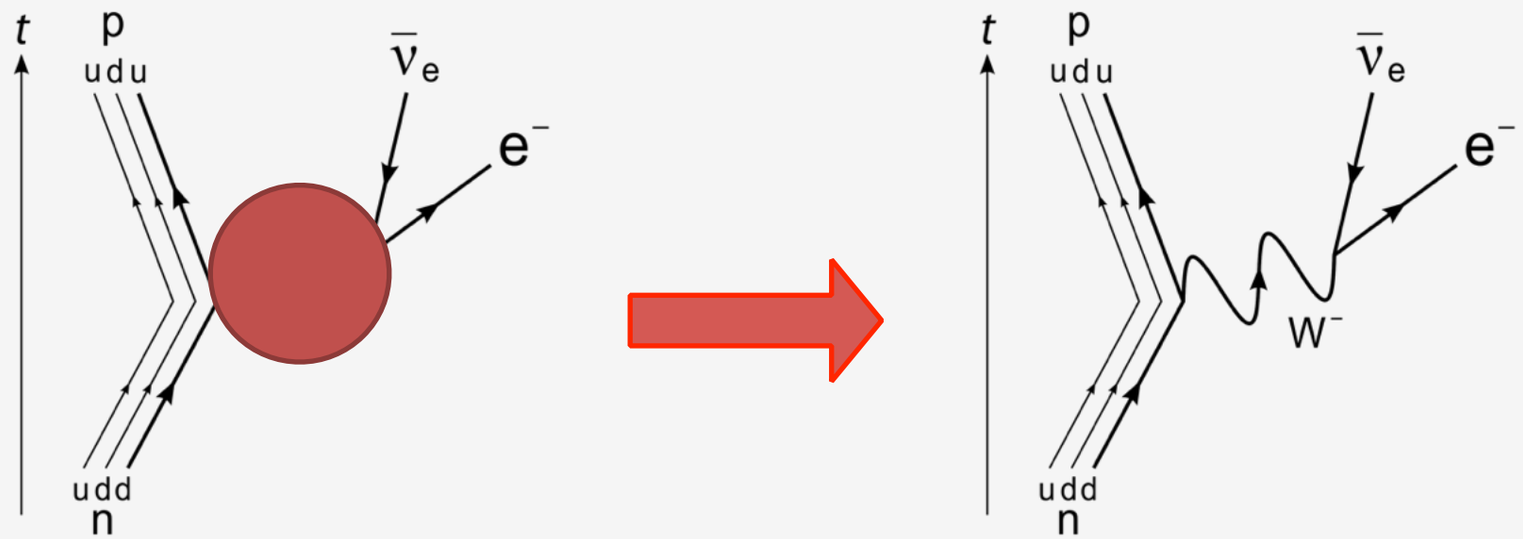
In typical completions, the inaccessible physics must be too strongly coupled to produce observable signals

e.g. s-channel mediator: rate depends on

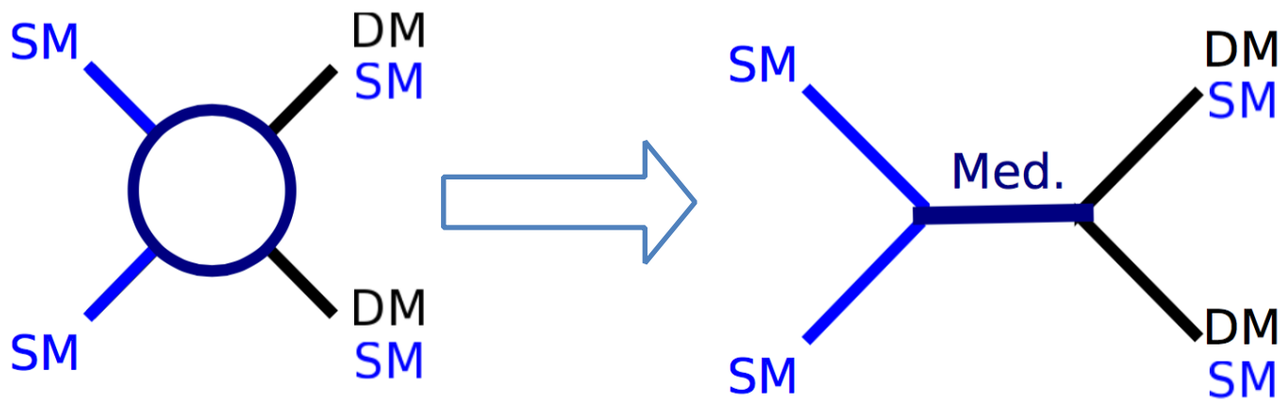
$$M_\star = M_{\rm med}/\sqrt{g_q\, g_\chi}$$

High enough rate implies either:

- heavy mediator, non-perturbative couplings
- light mediator (EFT incorrect theory)



LHC probes ‘high’ energy scales
If ‘high’ is high enough, it can discovery and characterize the interactions between normal and dark matter



Colliders (Contact interaction)

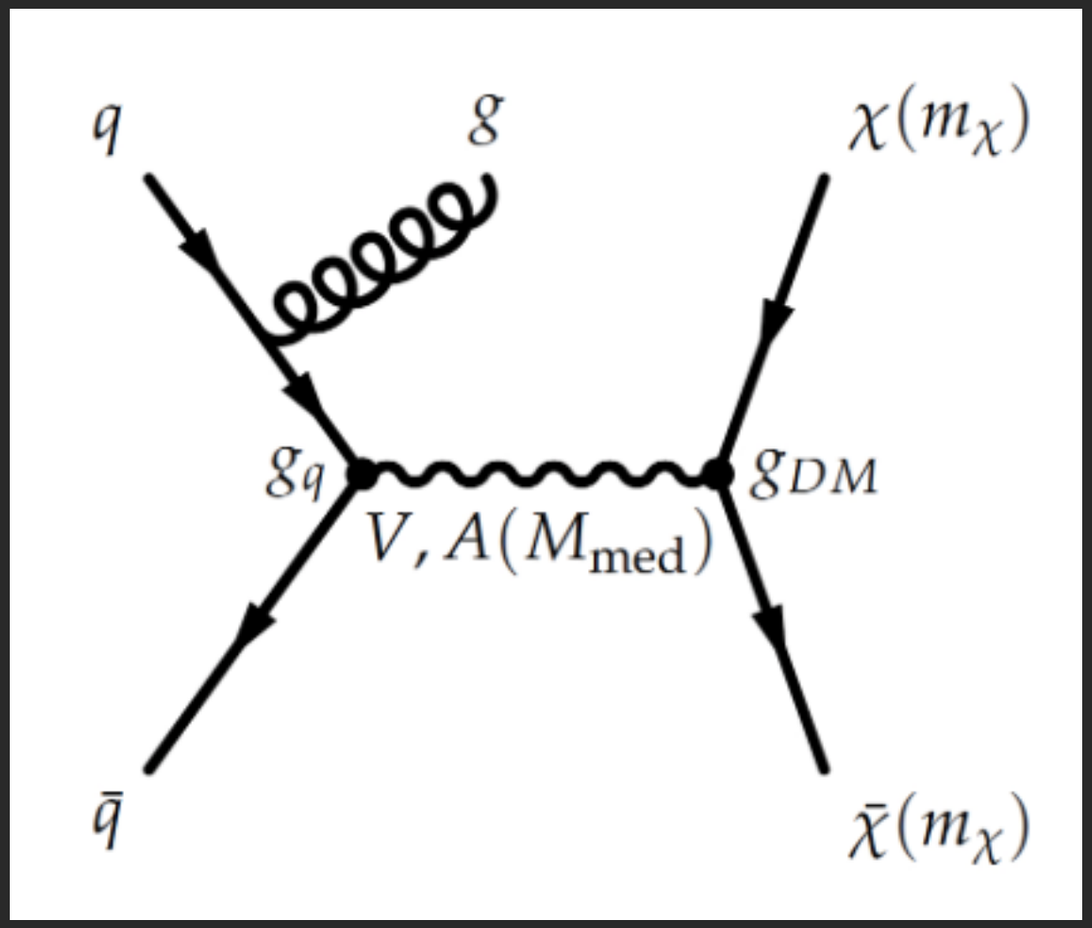
Colliders (Simplified Models)

LHC probes 'high' energy scales
If 'high' is high enough, it can discovery and characterize the interactions between normal and dark matter

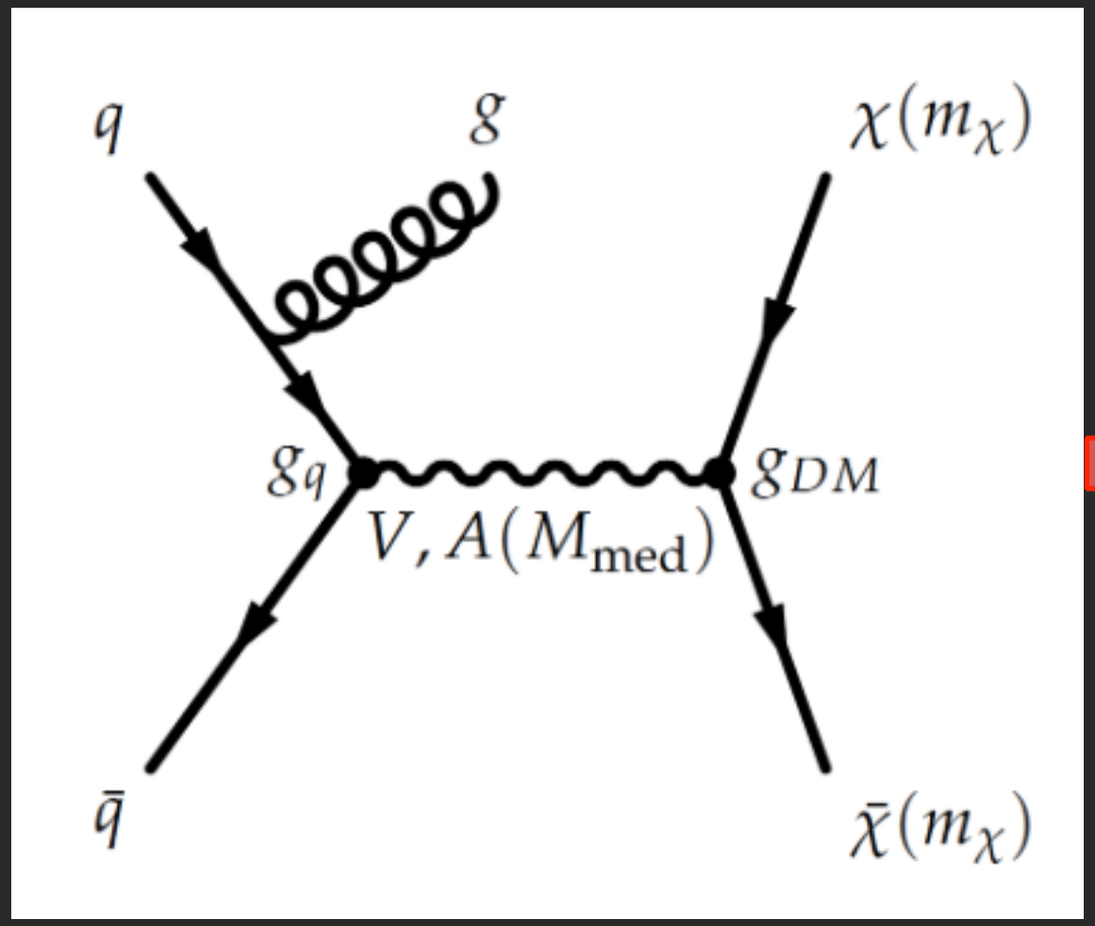
Requires more model assumptions (and parameters)

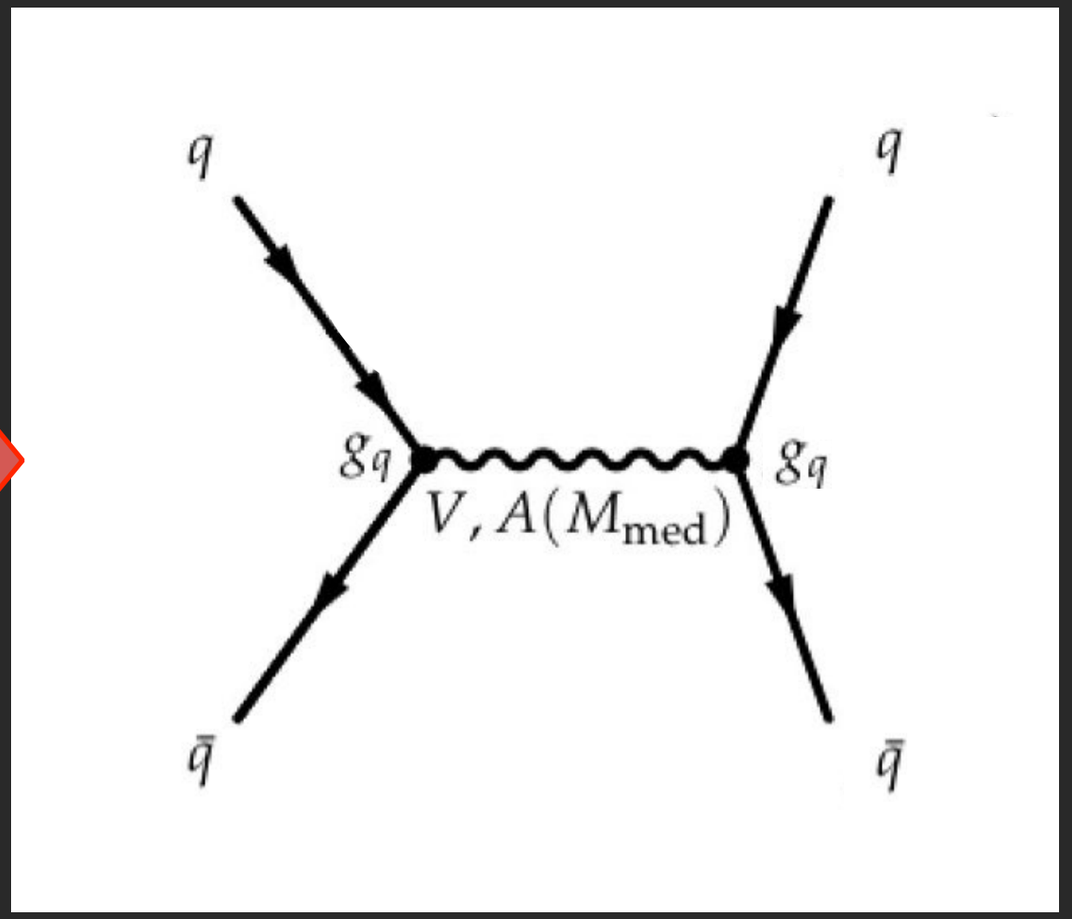
Searching for Dark Matter Production

(or: collider-stable weakly-interacting particles)



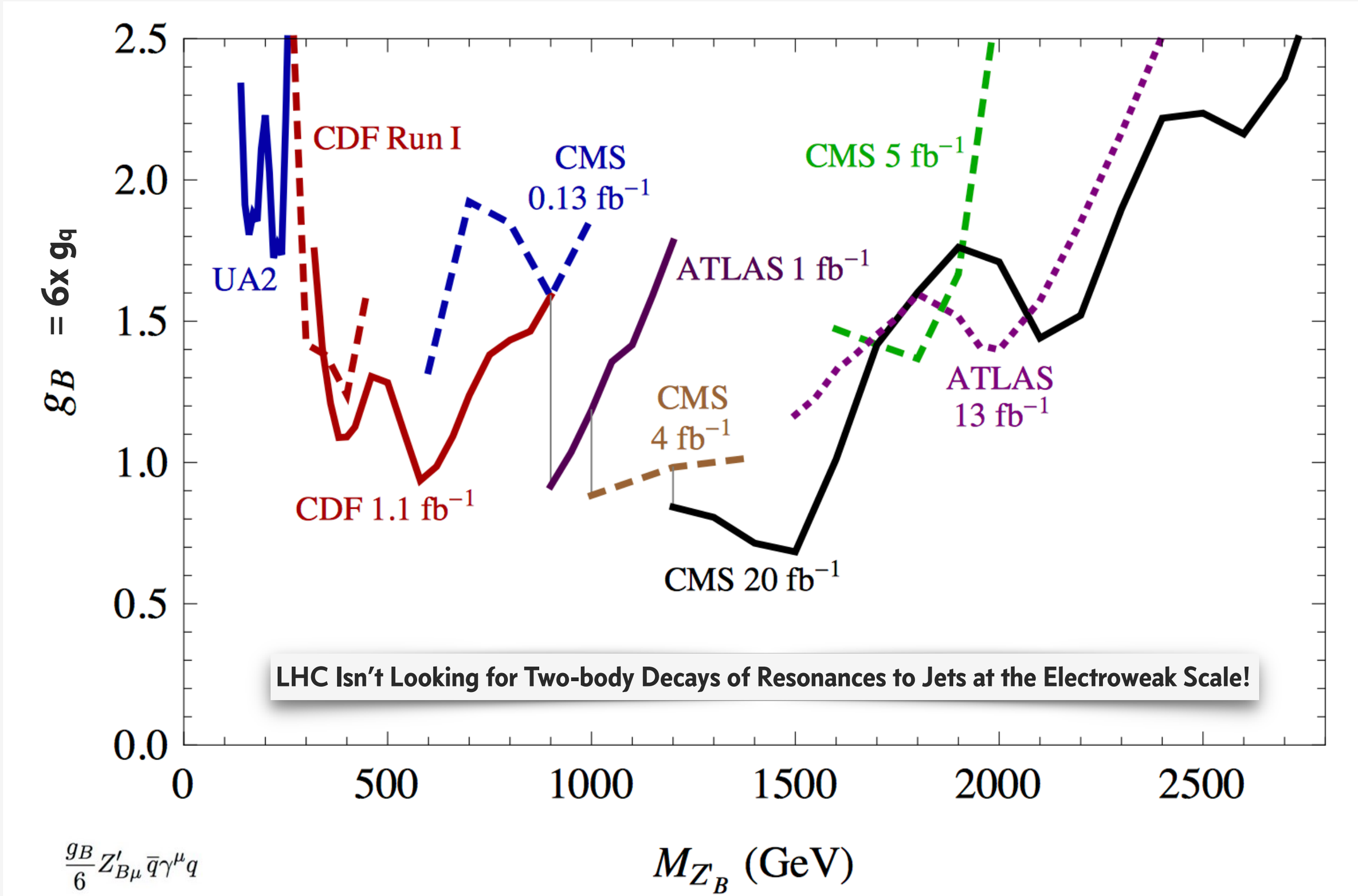
Searching for Dark Sector Interactions





Dijet Resonance Searches circa 2013

Dobrescu, Yu Phys Rev D 88 035021 (2013)



Searches for long-lived particles

Dark matter very weakly-coupled to the SM through **light, long-lived particles**

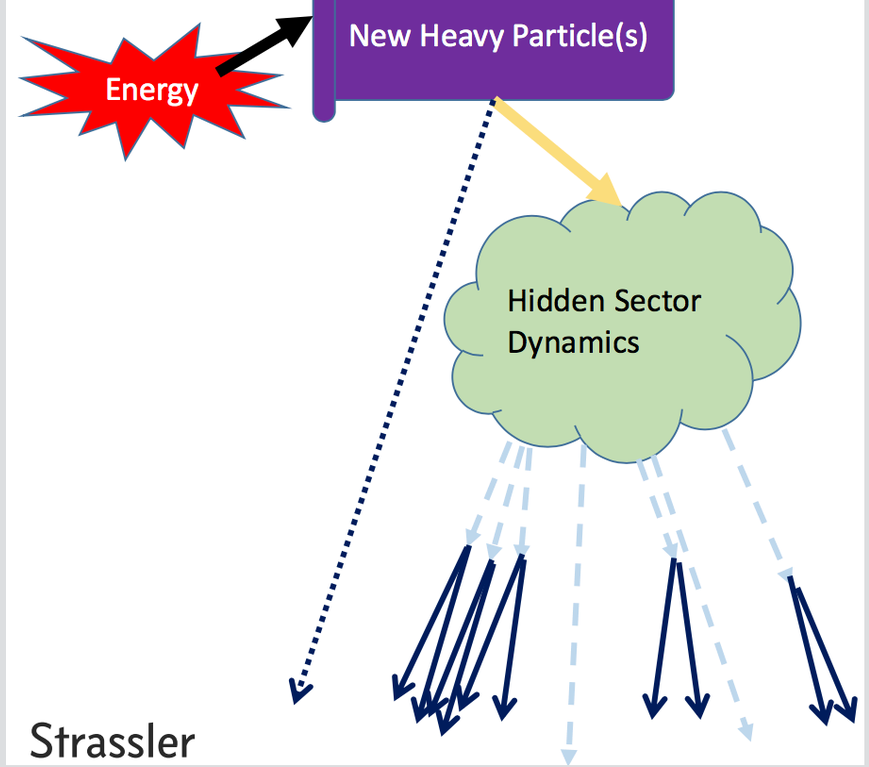
- Displaced decays (e.g. displaced / emerging jets)
- Collimated decay products (lepton jets)

Current detectors not designed for

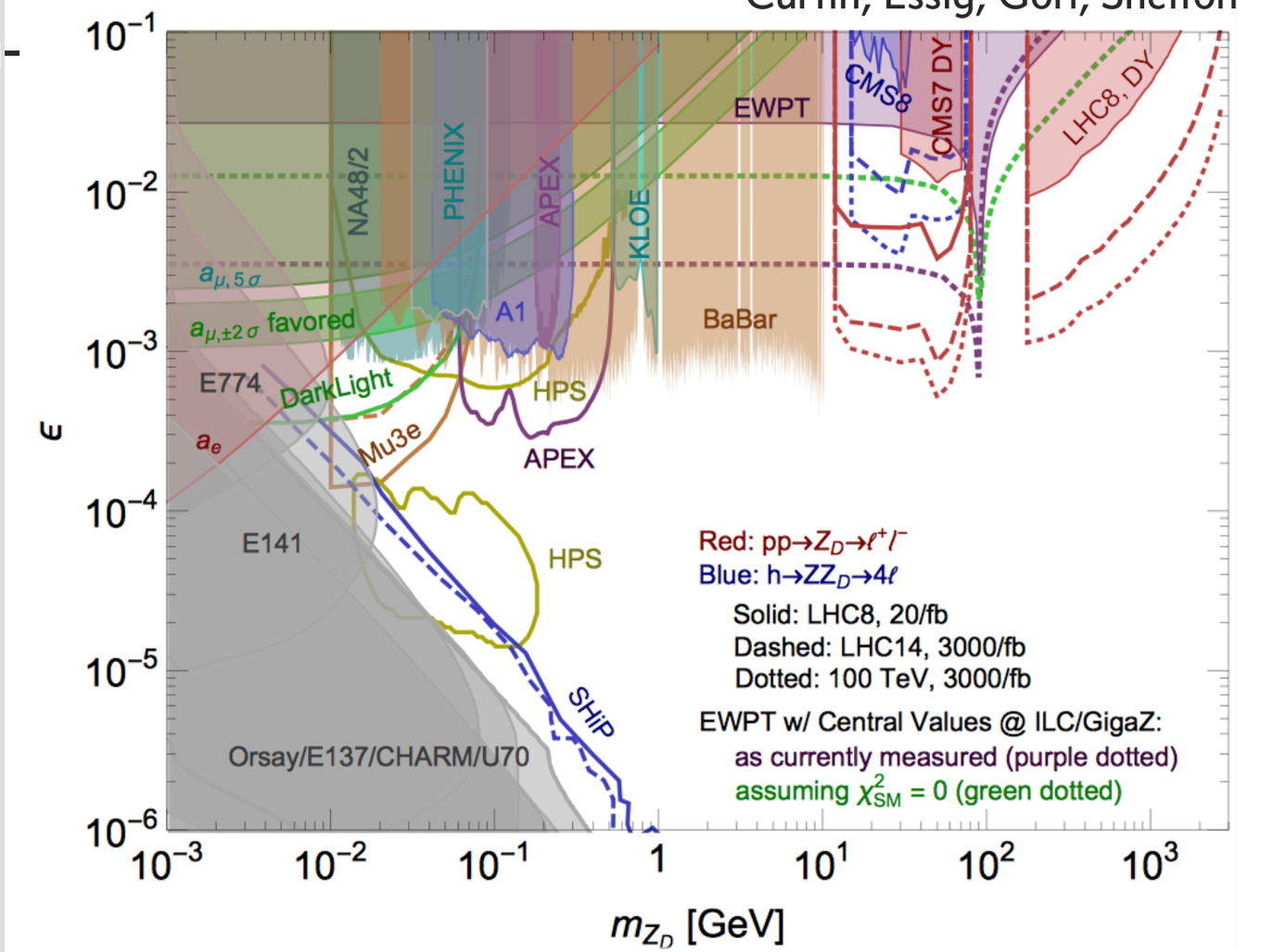
- reconstruction of very odd physics objects
- triggering on displaced decays of neutral long-lived particles
- triggering on ‘low’ energy physics

Partial wish list

- Better online reconstruction capability
- Timing information and dE/dx
- Detector design for very displaced objects cases (e.g. disappearing tracks)

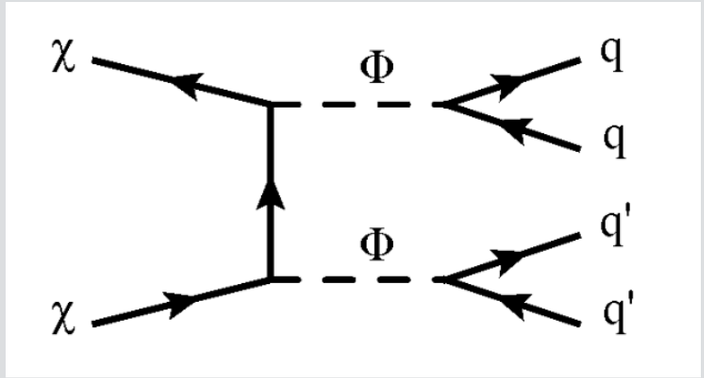


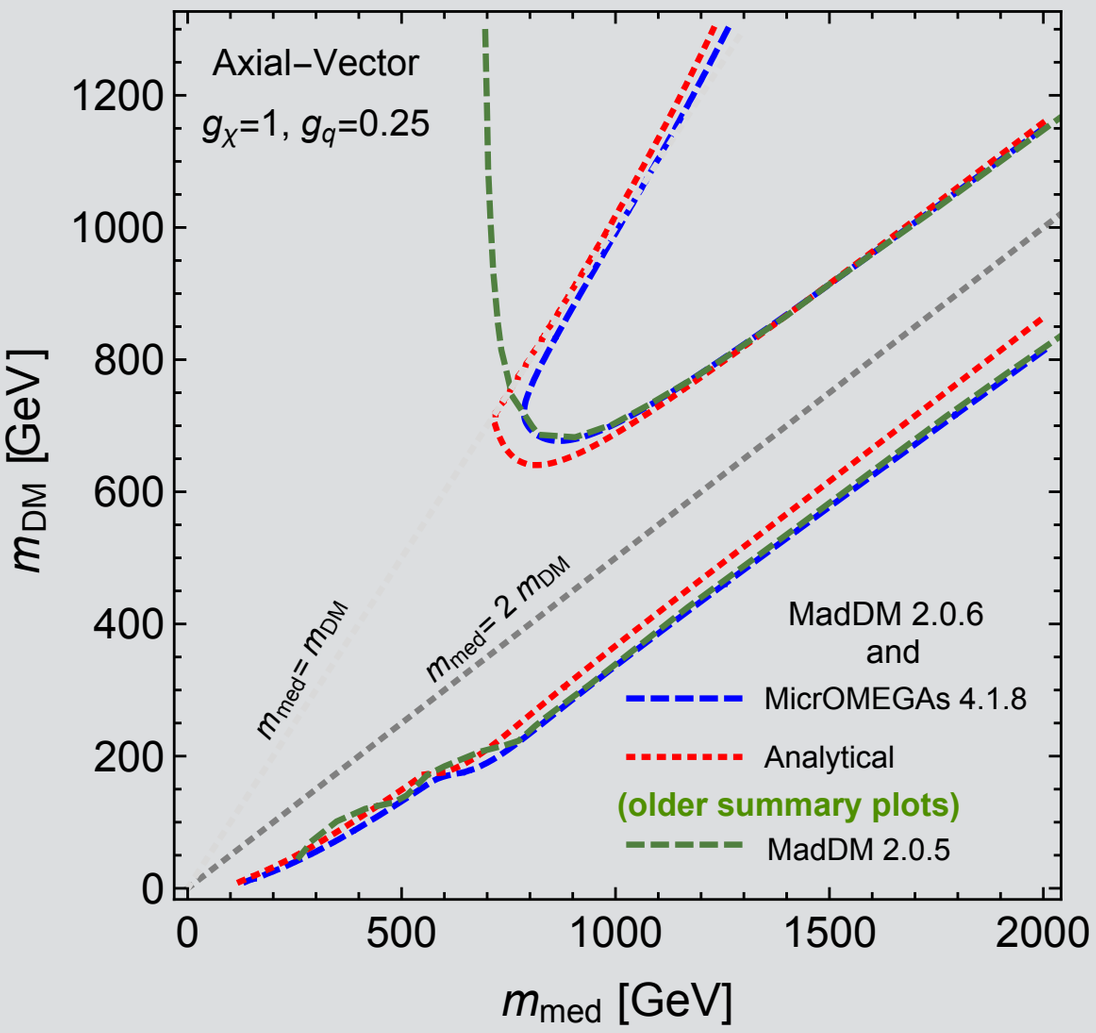
Curtin, Essig, Gori, Shelton

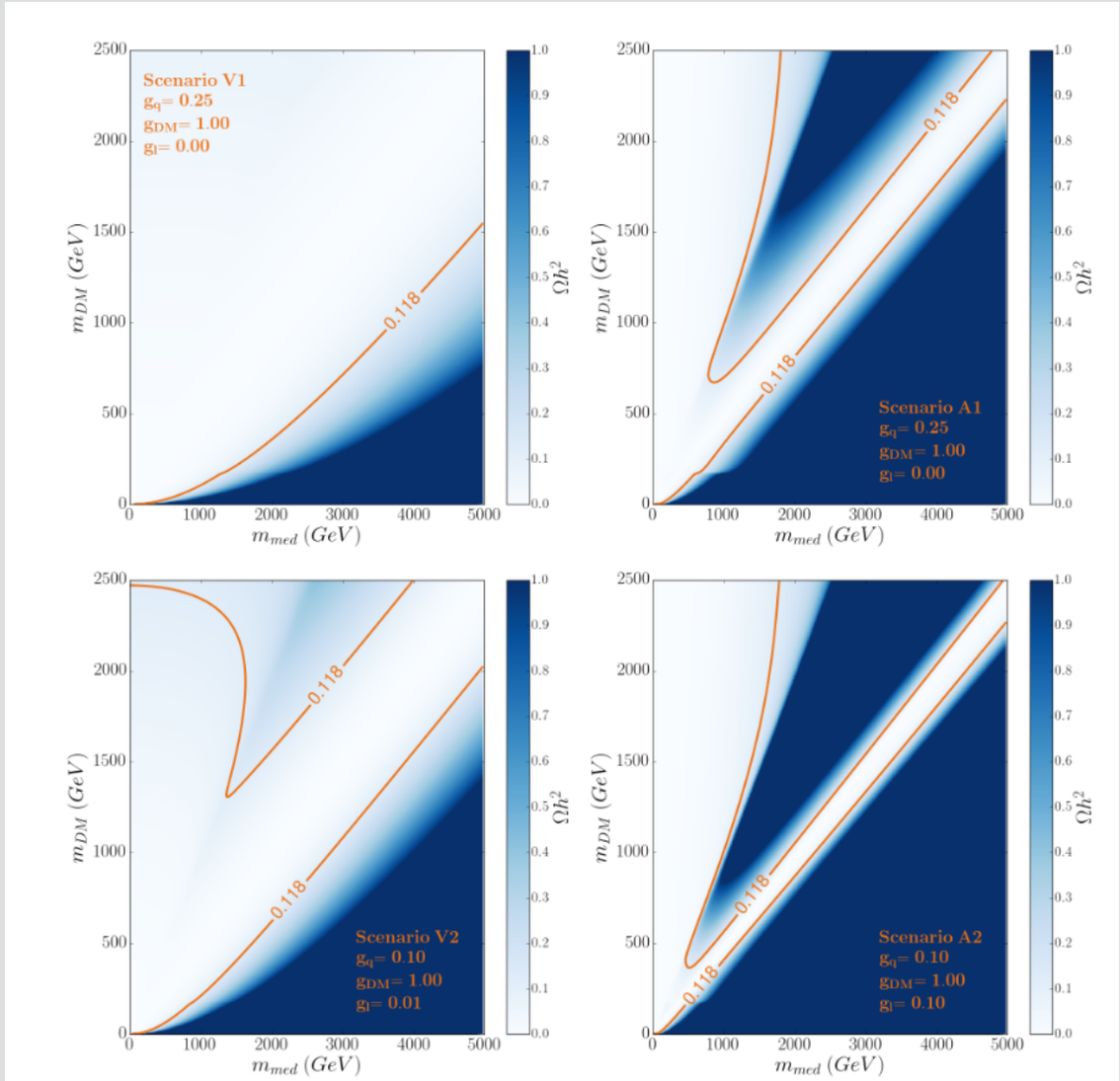


Relic density for summary plots

- Previous relic density calculation with MadDM: missing t-channel annihilation for $\chi\bar{\chi} \to 2$ mediators
- Now fixed in MadDM 2.0.6
- New curves for summary plots provided centrally by DMWG [link to git repository]



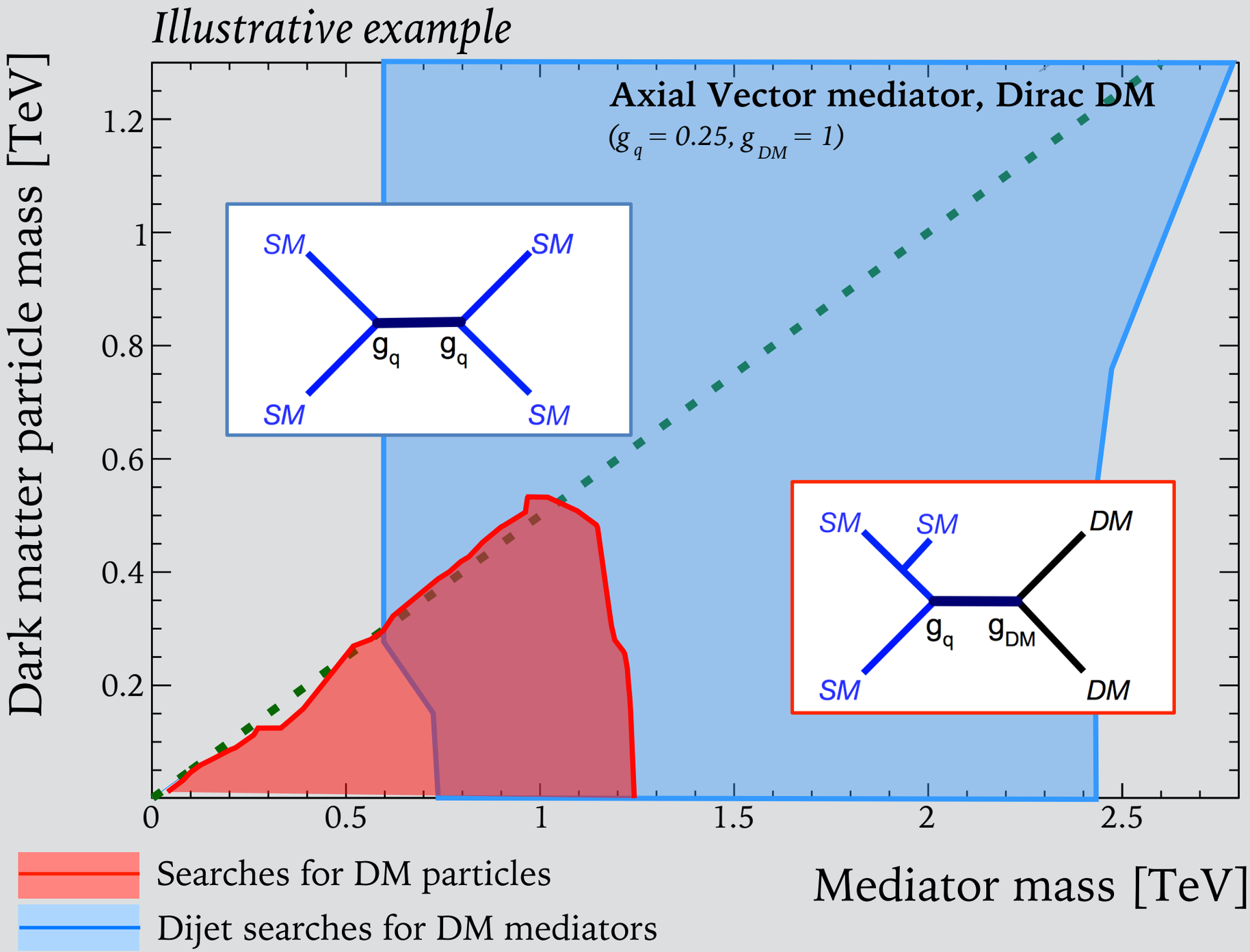




Visible/invisible mediator searches

arXiv:1703.05703

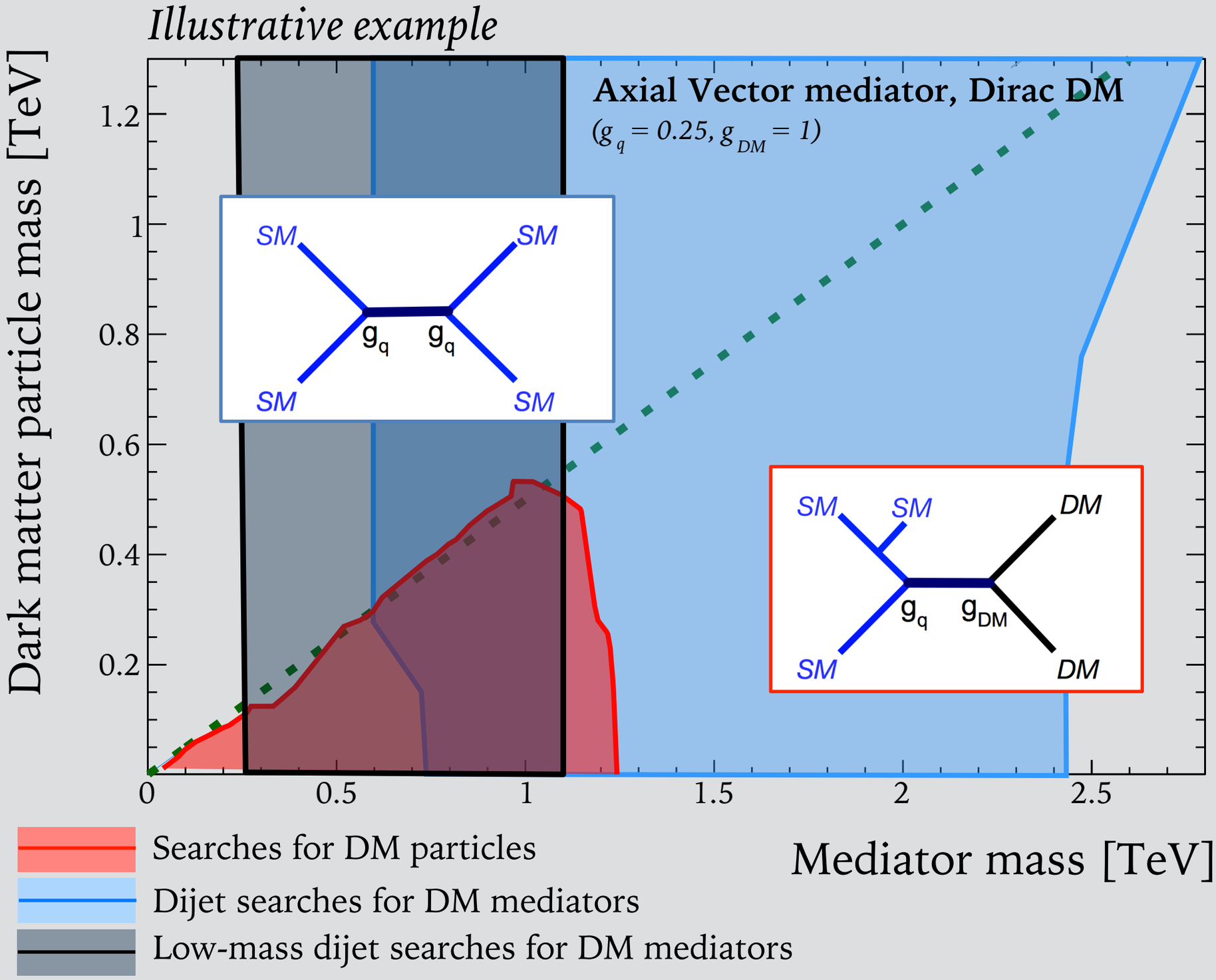
Are we looking for all the signatures of these models? e.g. Z′ → WIMPs or Z′→jet+jet



Visible decays are an important strength of colliders
(Think MET+jet vs specific SUSY cascade decay)

Visible/invisible mediator searches

arXiv:1703.05703



Visible/invisible mediator searches

arXiv:1703.05703