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?

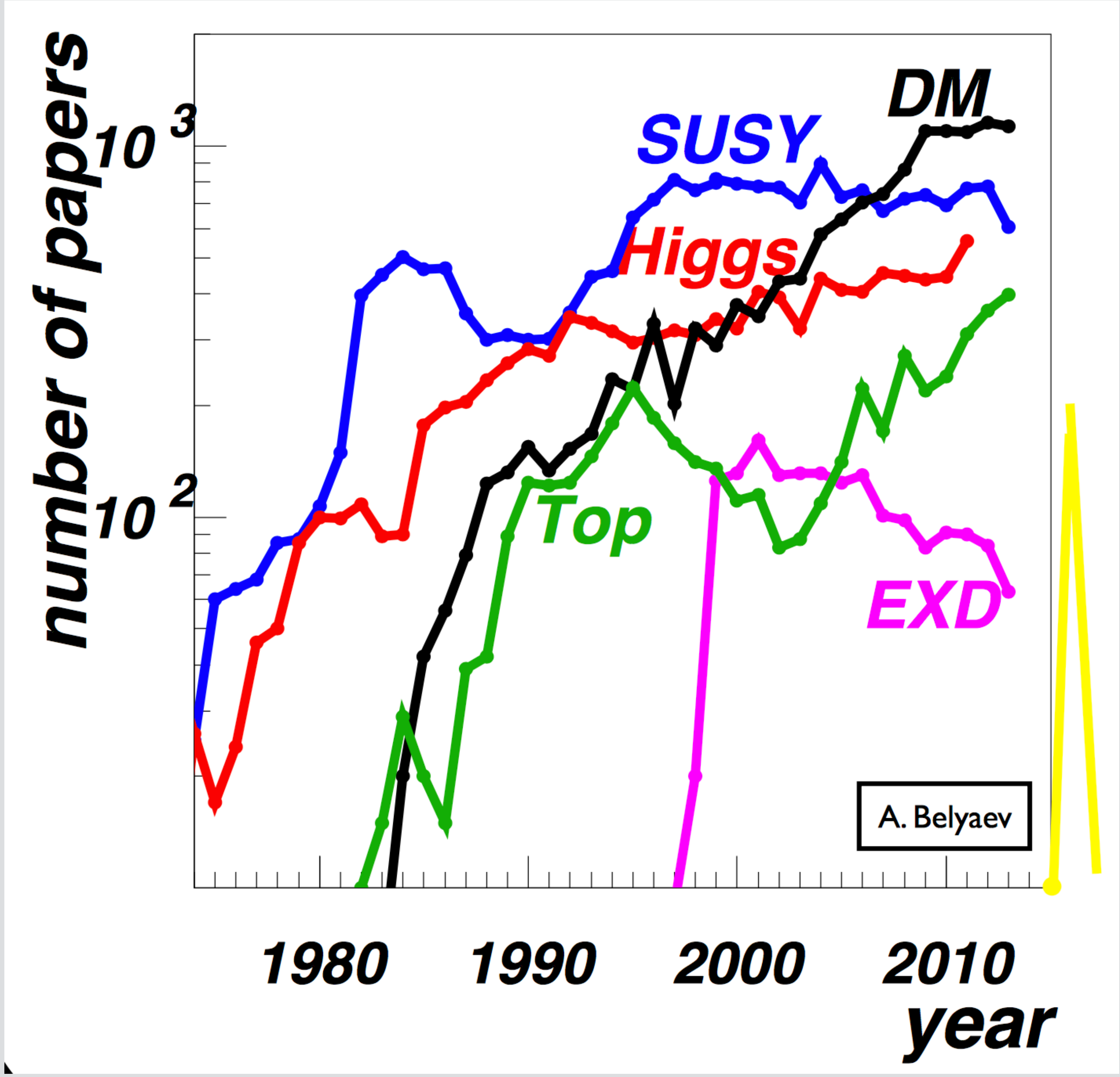
http://lpcc.web.cern.ch/lpcc/index.php?page=dm_wg

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 our work to be useful to 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?

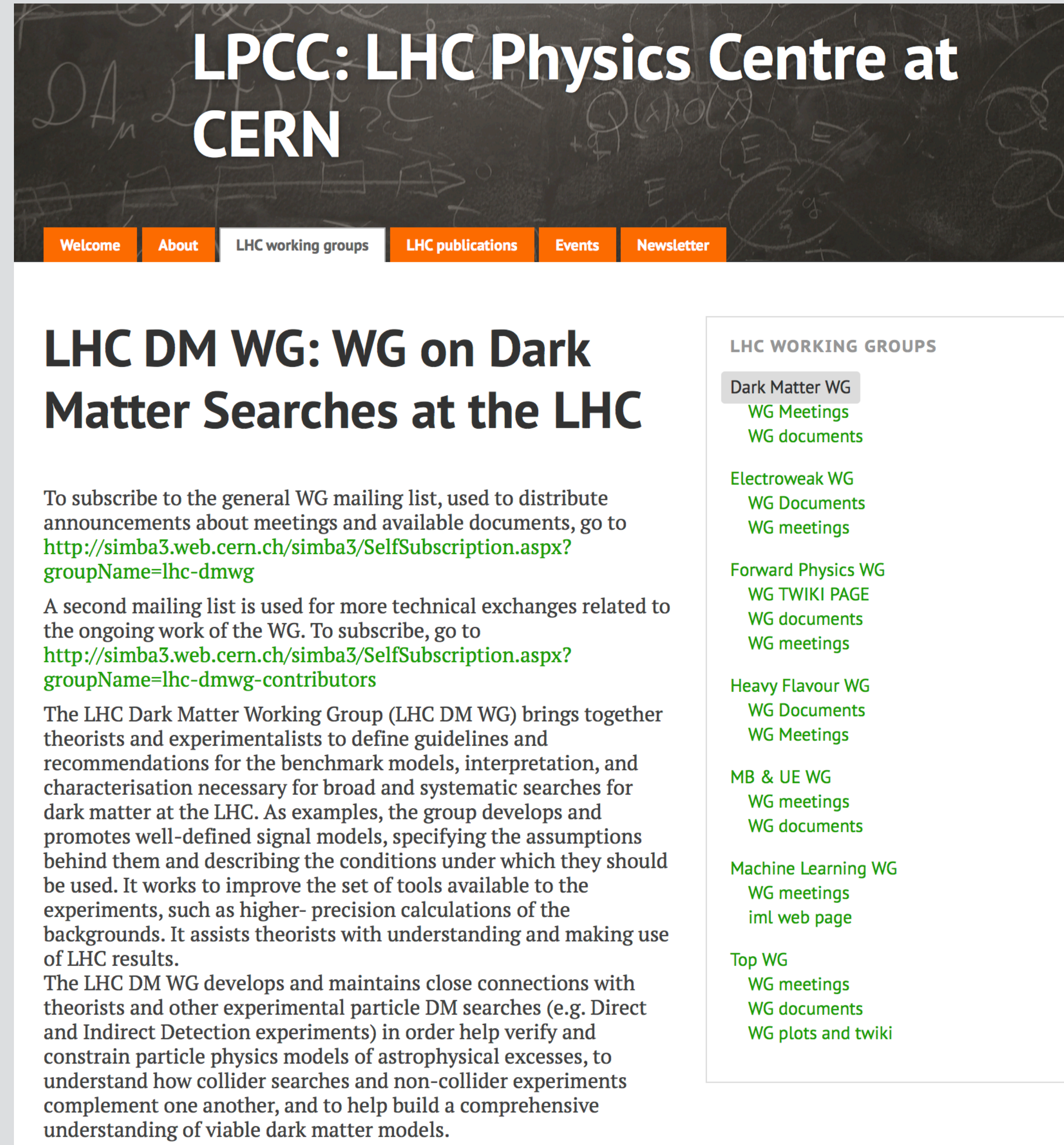
A mechanism

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


LPCC: LHC Physics Centre at CERN

Welcome | About | LHC working groups | LHC publications | Events | Newsletter

LHC DM WG: WG on Dark Matter Searches at the LHC

To subscribe to the general WG mailing list, used to distribute announcements about meetings and available documents, go to http://simba3.web.cern.ch/simba3/SelfSubscription.aspx?groupName=lhc-dmwg

A second mailing list is used for more technical exchanges related to the ongoing work of the WG. To subscribe, go to http://simba3.web.cern.ch/simba3/SelfSubscription.aspx?groupName=lhc-dmwg-contributors

The LHC Dark Matter Working Group (LHC DM WG) brings together theorists and experimentalists to define guidelines and recommendations for the benchmark models, interpretation, and characterisation necessary for broad and systematic searches for dark matter at the LHC. As examples, the group develops and promotes well-defined signal models, specifying the assumptions behind them and describing the conditions under which they should be used. It works to improve the set of tools available to the experiments, such as higher- precision calculations of the backgrounds. It assists theorists with understanding and making use of LHC results.
The LHC DM WG develops and maintains close connections with theorists and other experimental particle DM searches (e.g. Direct and Indirect Detection experiments) in order help verify and constrain particle physics models of astrophysical excesses, to understand how collider searches and non-collider experiments complement one another, and to help build a comprehensive understanding of viable dark matter models.

LHC WORKING GROUPS

Dark Matter WG
- WG Meetings
- WG documents

Electroweak WG
- WG Documents
- WG meetings

Forward Physics WG
- WG TWIKI PAGE
- WG documents
- WG meetings

Heavy Flavour WG
- WG Documents
- WG Meetings

MB & UE WG
- WG meetings
- WG documents

Machine Learning WG
- WG meetings
- iml web page

Top WG
- WG meetings
- WG documents
- WG plots and twiki

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 CERN LPCC / arXiv write-ups

– 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


CERN-LPCC-2016-001

arXiv:1603.04156v1 [hep-ex] 14 Mar 2016

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

CERN-LPCC-2017-01

arXiv:1703.05703v2 [hep-ex] 17 Mar 2017

CERN-TH-2017-102
CERN-LPCC-2017-02
FERMILAB-PUB-17-152-T
IPPP/17/38
ZU-TH 12/17

arXiv:1705.04664v1 [hep-ph] 12 May 2017

Precise predictions for V+jets dark matter backgrounds

J. M. Lindert[1], S. Pozzorini[2], R. Boughezal[3], J. M. Campbell[4], A. Denner[5], S. Dittmaier[6], A. Gehrmann-De Ridder[2,7], T. Gehrmann[2], N. Glover[1], A. Huss[7], S. Kallweit[8], P. Maierhöfer[6], M. L. Mangano[8], T.A. Morgan[1], A. Mück[9], F. Petriello[3,10], G. P. Salam[*8], M. Schönherr[2], and C. Williams[11]

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[2] *Physik-Institut, Universität Zürich, Winterthurerstrasse 190, CH-8057 Zürich, Switzerland*
[3] *High Energy Physics Division, Argonne National Laboratory, Argonne, IL 60439, USA*
[4] *Fermilab, P.O.Box 500, Batavia, IL 60510, USA*
[5] *Universität Würzburg, Institut für Theoretische Physik und Astrophysik, 97074 Würzburg, Germany*
[6] *Albert-Ludwigs-Universität Freiburg, Physikalisches Institut, 79104 Freiburg, Germany*
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[8] *Theoretical Physics Department, CERN, CH-1211 Geneva 23, Switzerland*
[9] *Institut für Theoretische Teilchenphysik und Kosmologie, RWTH Aachen University, D-52056 Aachen, Germany*
[10] *Department of Physics & Astronomy, Northwestern University, Evanston, IL 60208, USA*
[11] *Department of Physics, University at Buffalo, The State University of New York, Buffalo 14260 USA*

Abstract

High-energy jets recoiling against missing transverse energy (MET) are powerful probes of dark matter at the LHC. Searches based on large MET signatures require a precise control of the $Z(\nu\bar{\nu})$+jet background in the signal region. This can be achieved by taking accurate data in control regions dominated by $Z(\ell^+\ell^-)$+jet, $W(\ell\nu)$+jet and γ+jet production, and extrapolating to the $Z(\nu\bar{\nu})$+jet background by means of precise theoretical predictions. In this context, recent advances in perturbative calculations open the door to significant sensitivity improvements in dark matter searches. In this spirit, we present a combination of state-of-the-art calculations for all relevant V+jets processes, including throughout NNLO QCD corrections and NLO electroweak corrections supplemented by Sudakov logarithms at two loops. Predictions at parton level are provided together with detailed recommendations for their usage in experimental analyses based on the reweighting of Monte Carlo samples. Particular attention is devoted to the estimate of theoretical uncertainties in the framework of dark matter searches, where subtle aspects such as correlations across different V+jet processes play a key role. The anticipated theoretical uncertainty in the $Z(\nu\bar{\nu})$+jet background is at the few percent level up to the TeV range.

*on leave from CNRS, UMR 7589, LPTHE, F-75005, Paris, France

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]

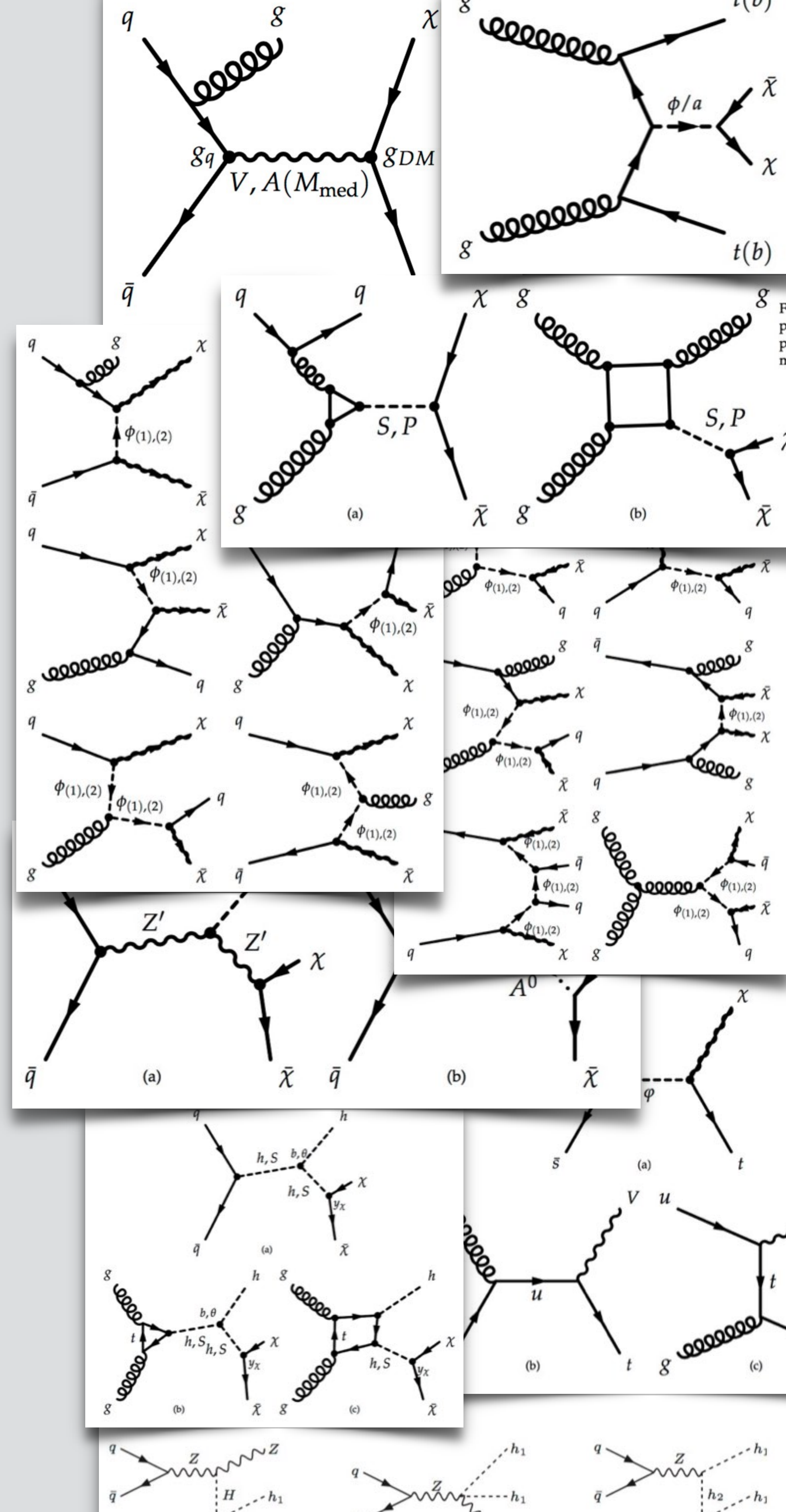
Focused on our searches for Missing Energy + jet/photon/b quark(s)/top quark(s)/W/Z/higgs/etc…

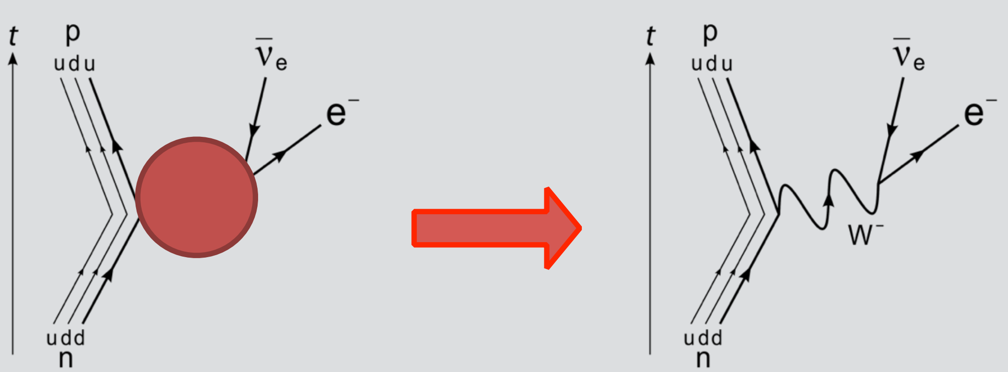
Are these searches looking for realistic signals? (EFT validity)

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**





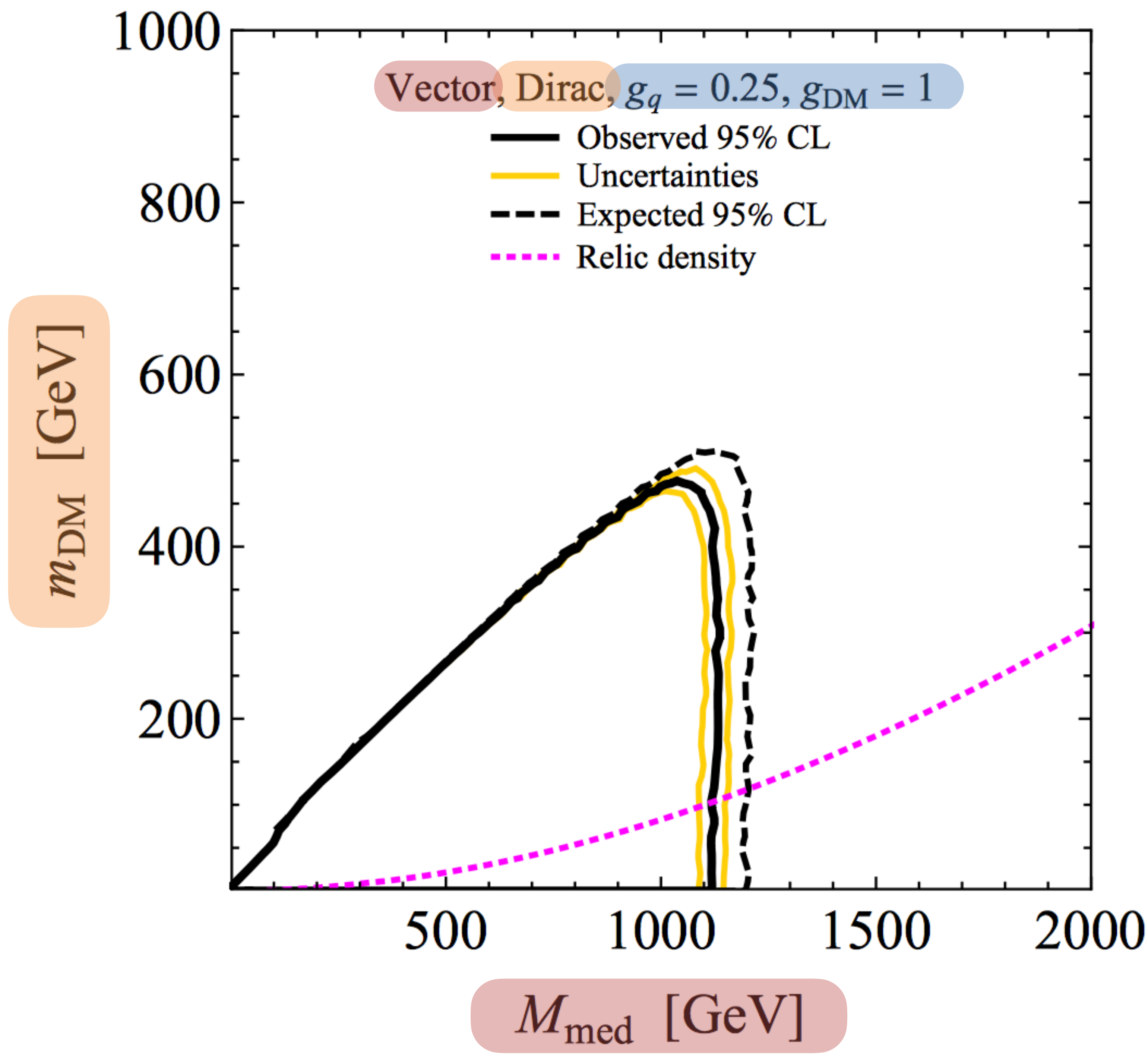
Augmenting EFTs with simplified models

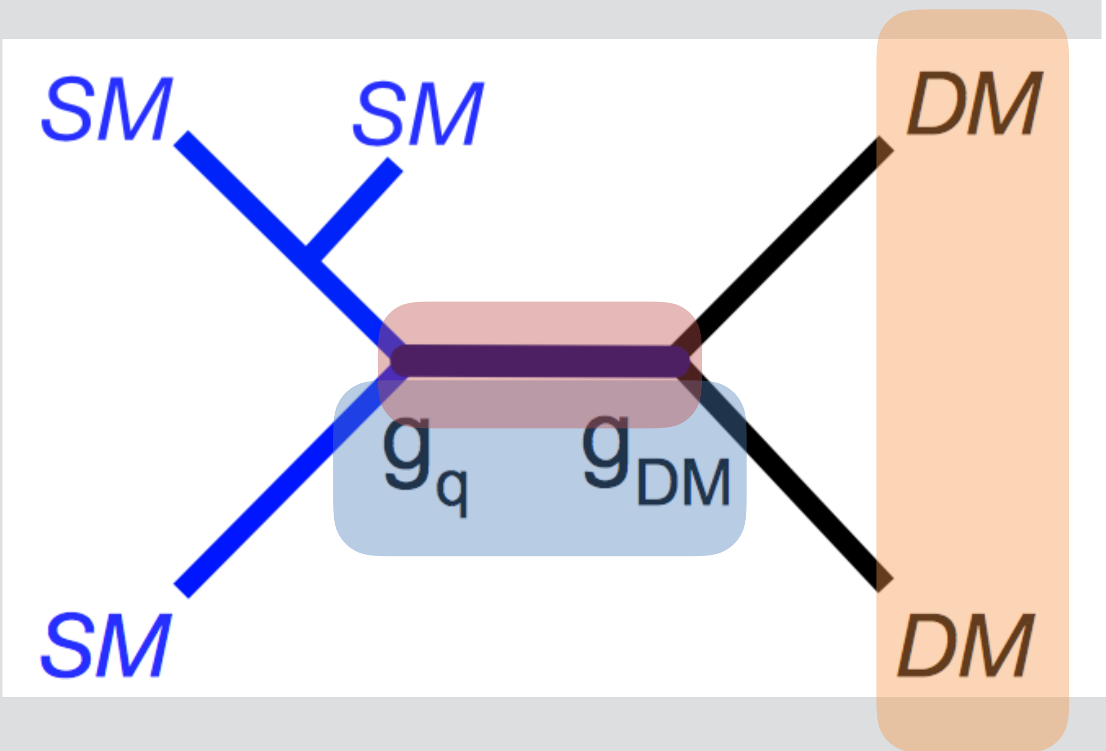
Collider results: mass-mass plots

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



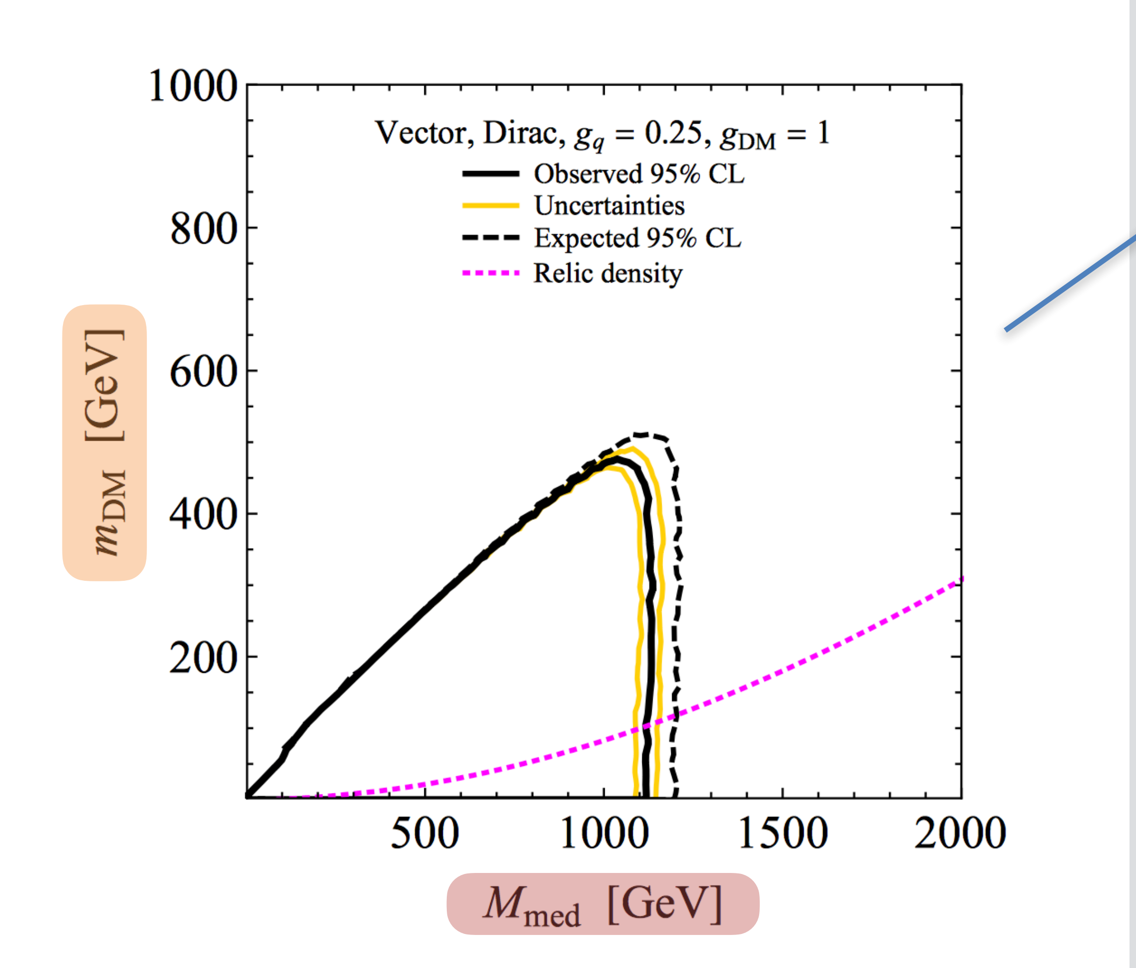


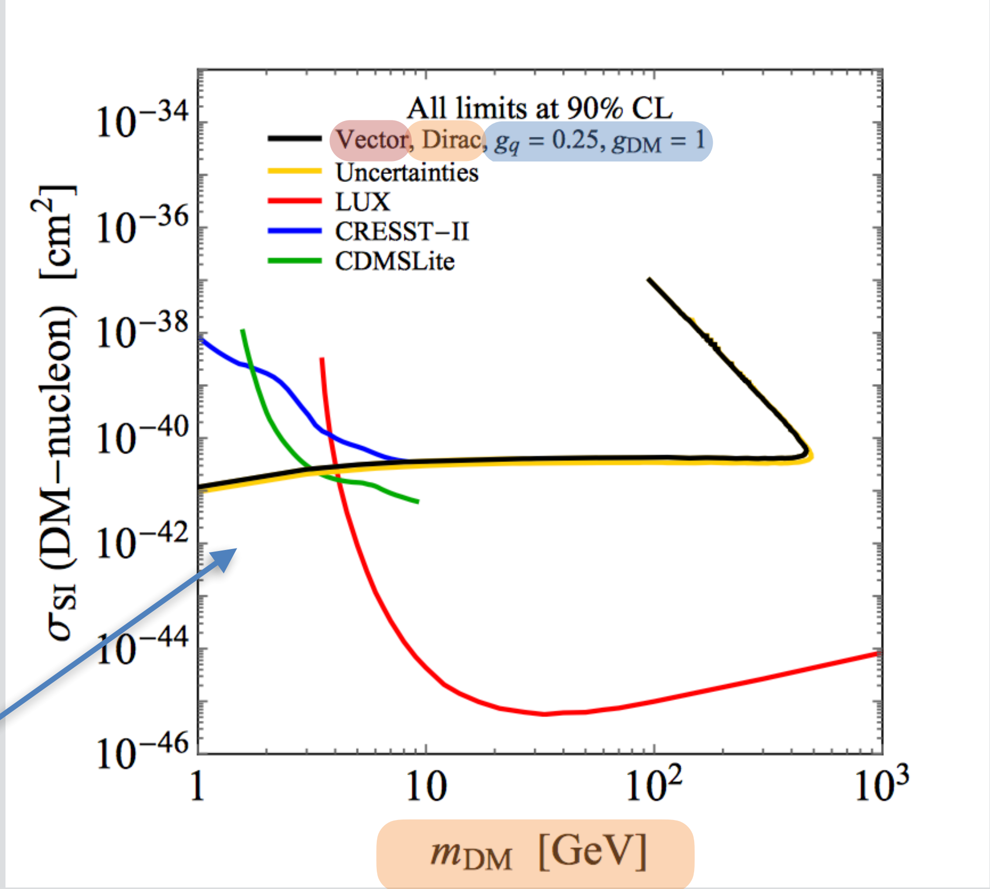
Comparison to non-collider results

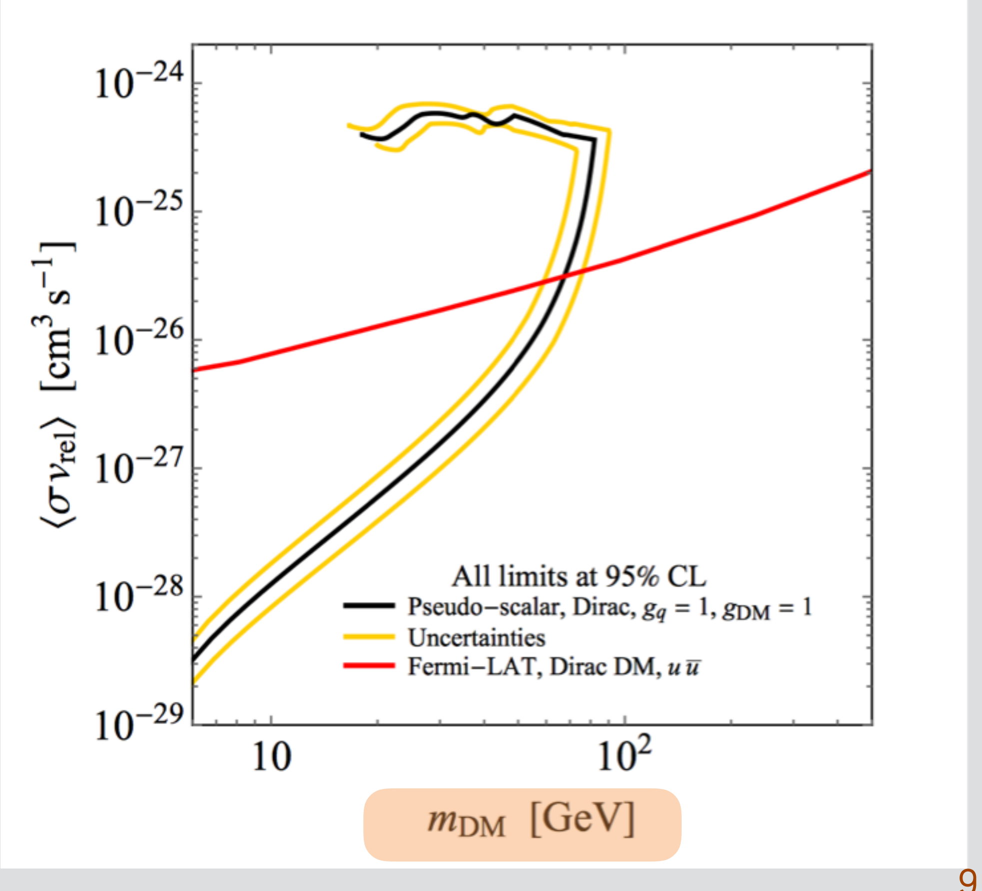
arXiv:1603.04156

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







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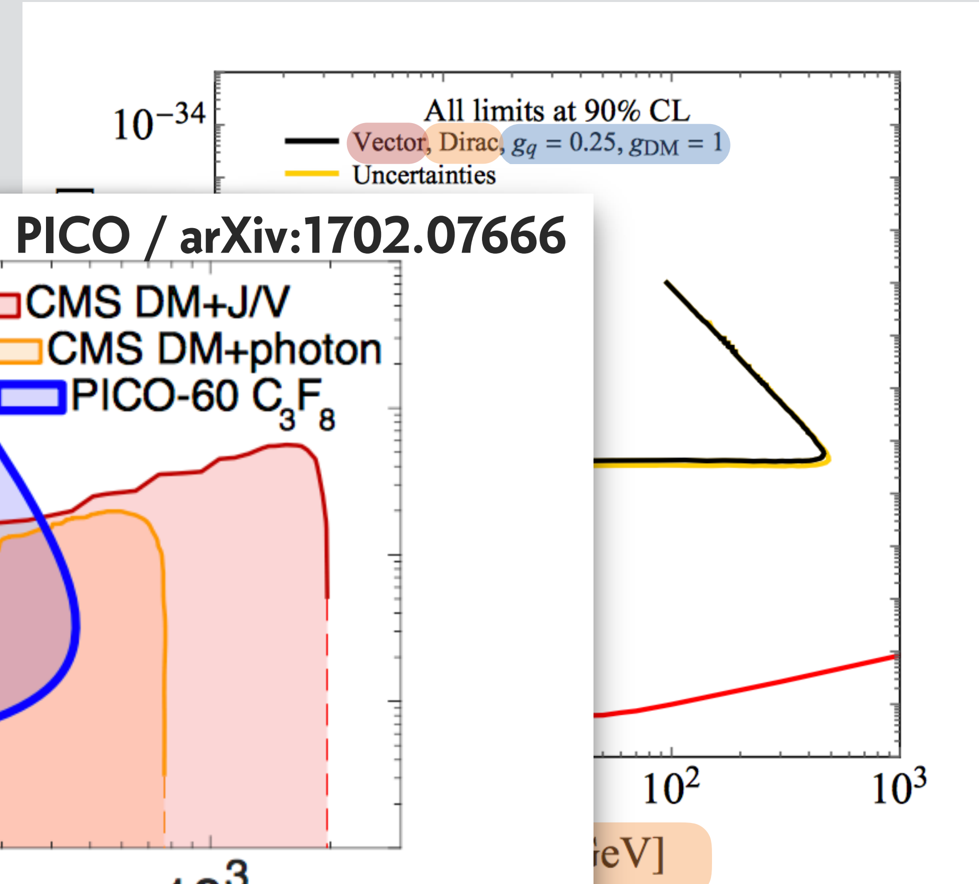


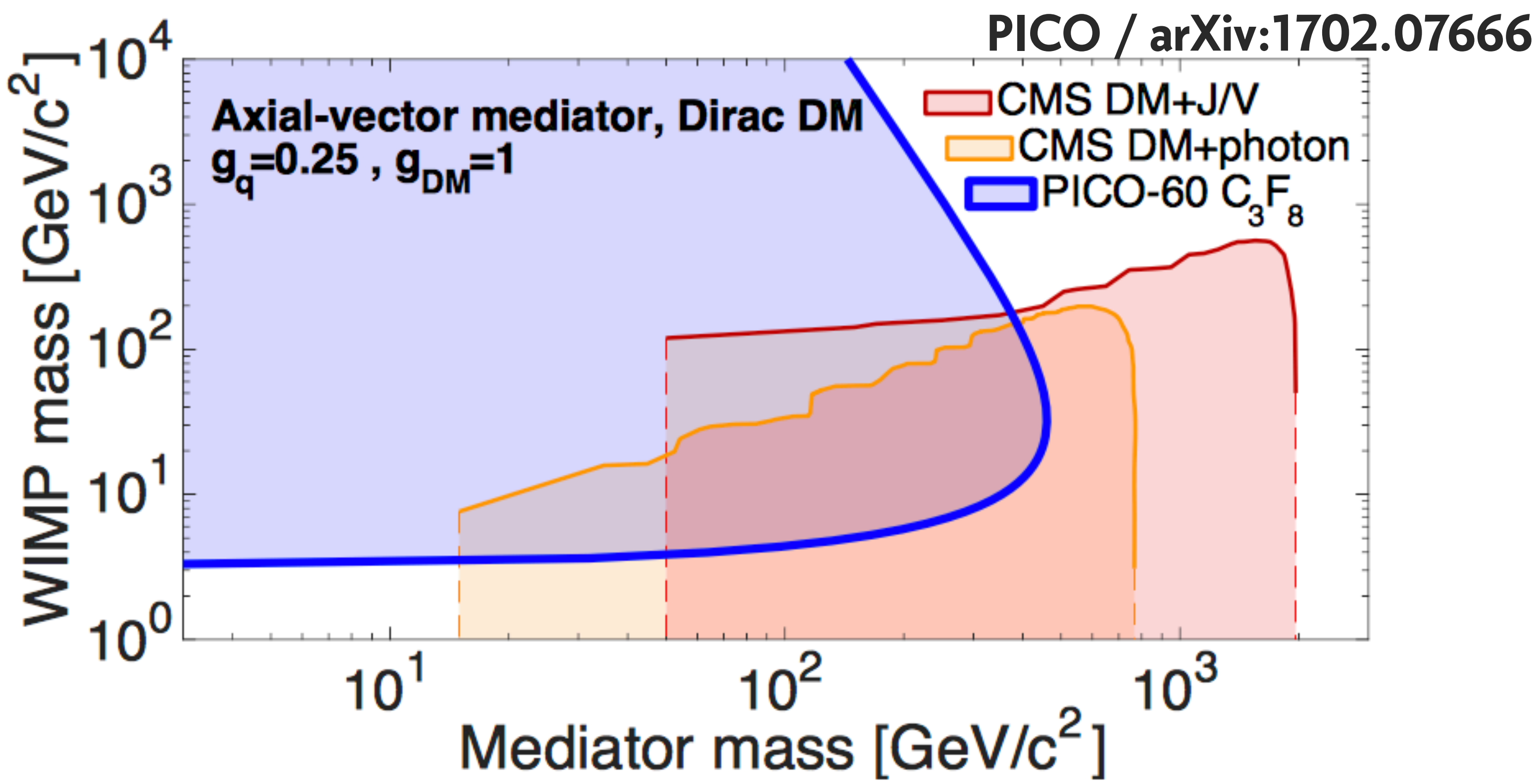
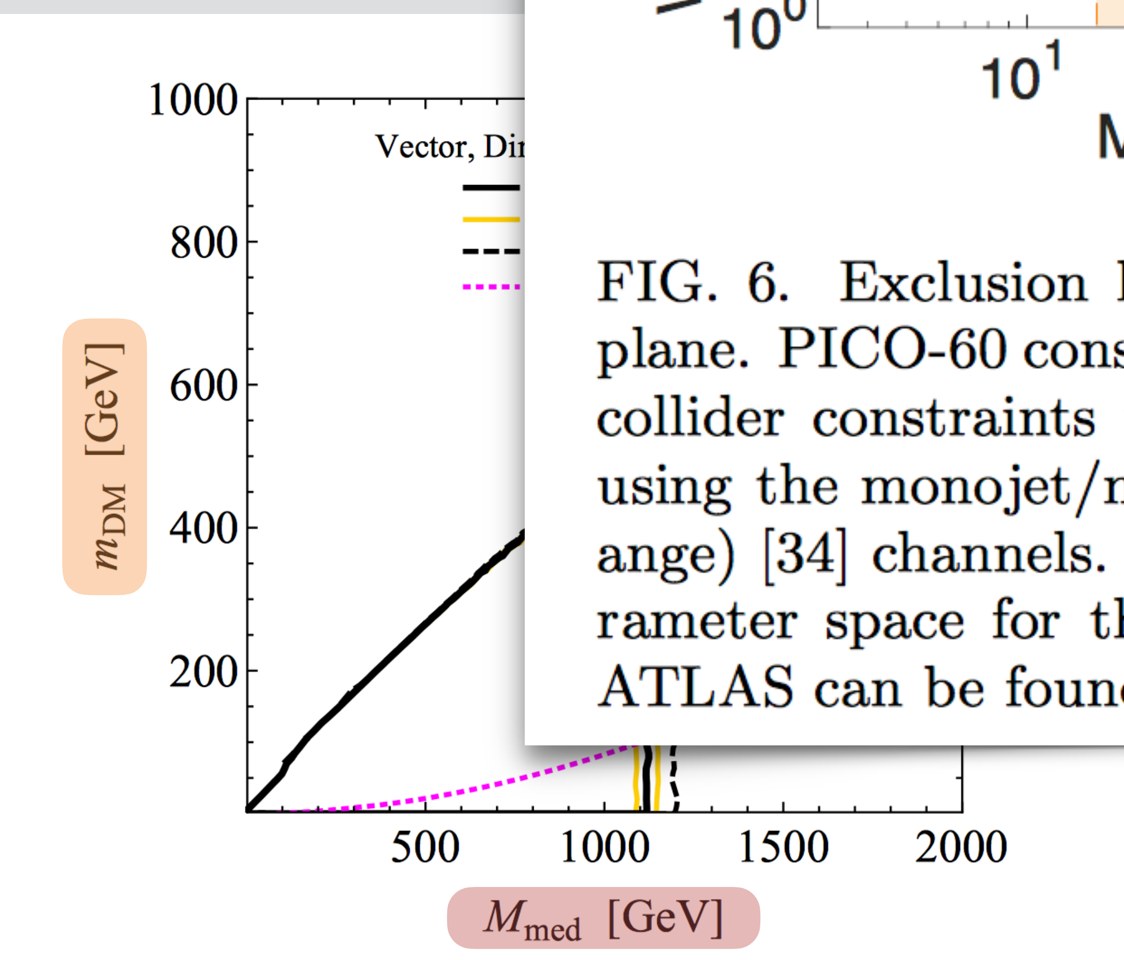
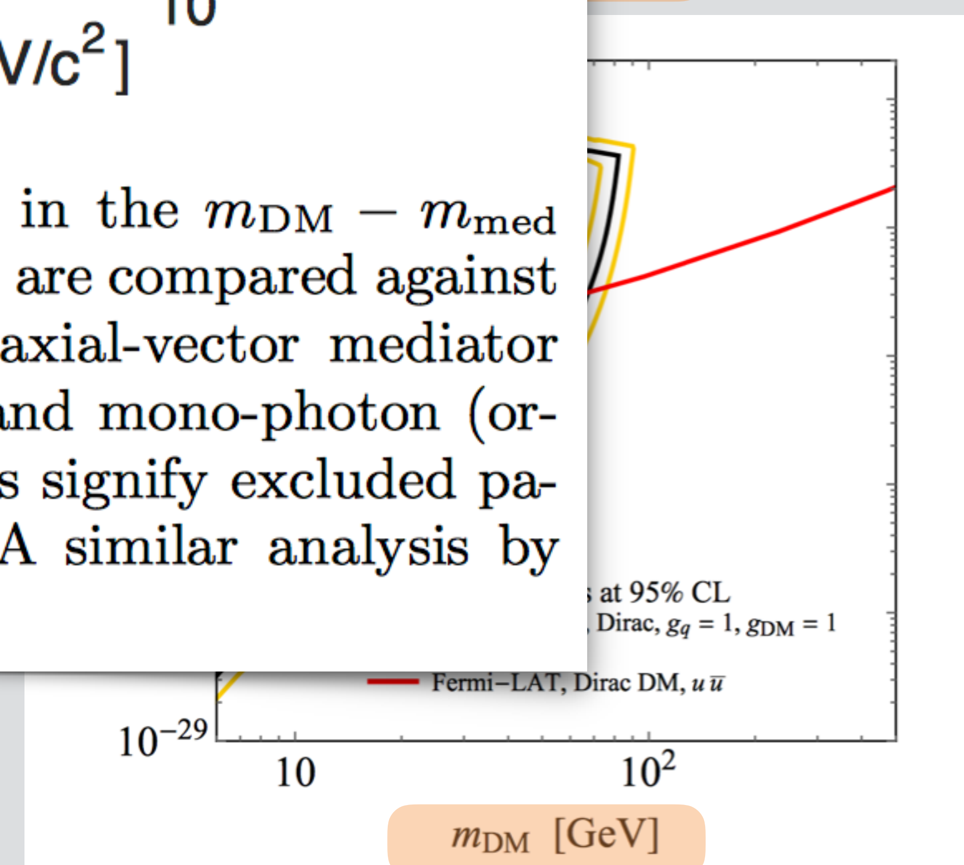


FIG. 6. Exclusion limits at 95% C.L. in the $m_{DM} - m_{med}$ plane. PICO-60 constraints (thick blue) are compared against collider constraints from CMS for an axial-vector mediator using the monojet/mono-V (red) [33] and mono-photon (orange) [34] channels. The shaded regions signify excluded parameter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

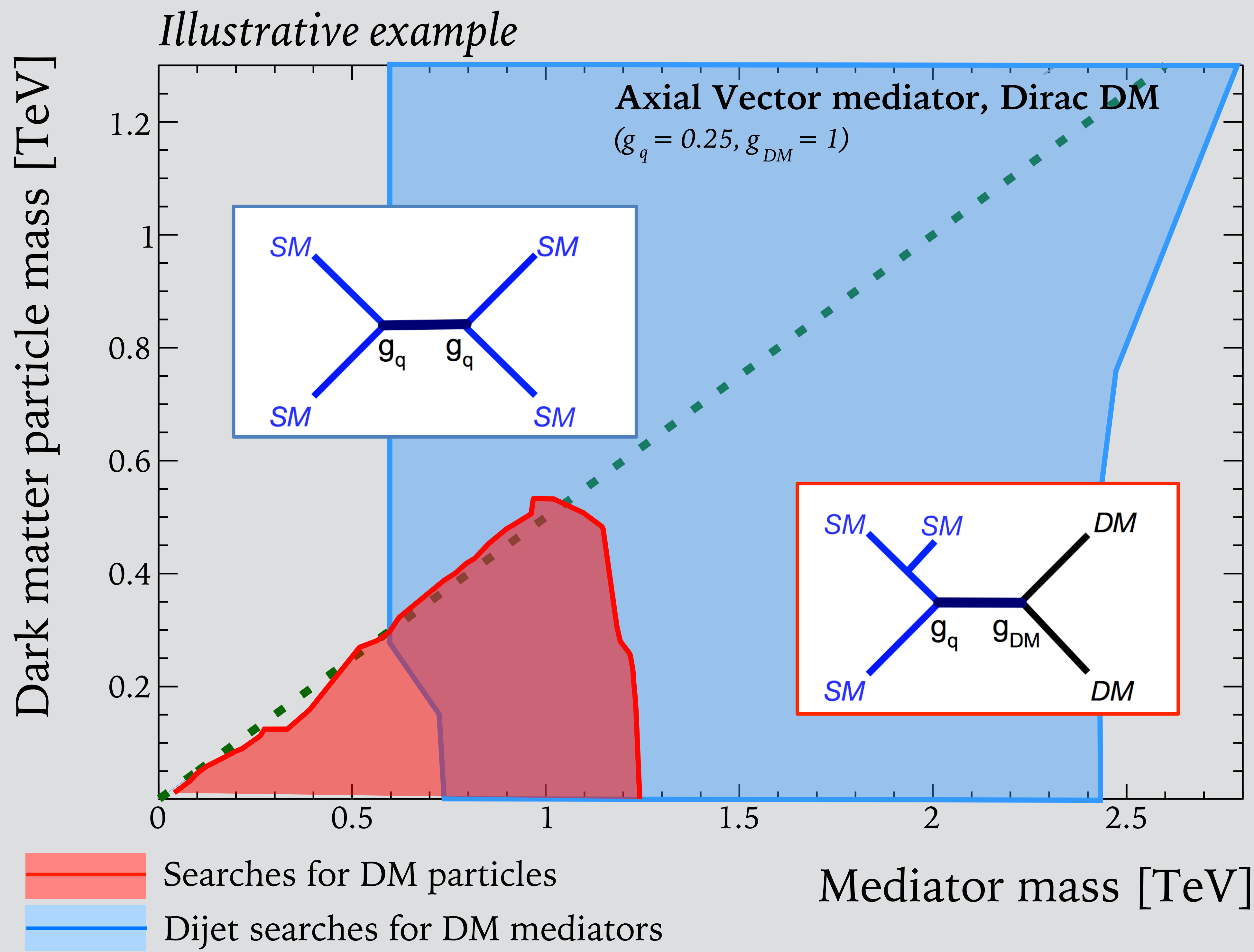




Visible/invisible mediator searches

arXiv:1703.05703

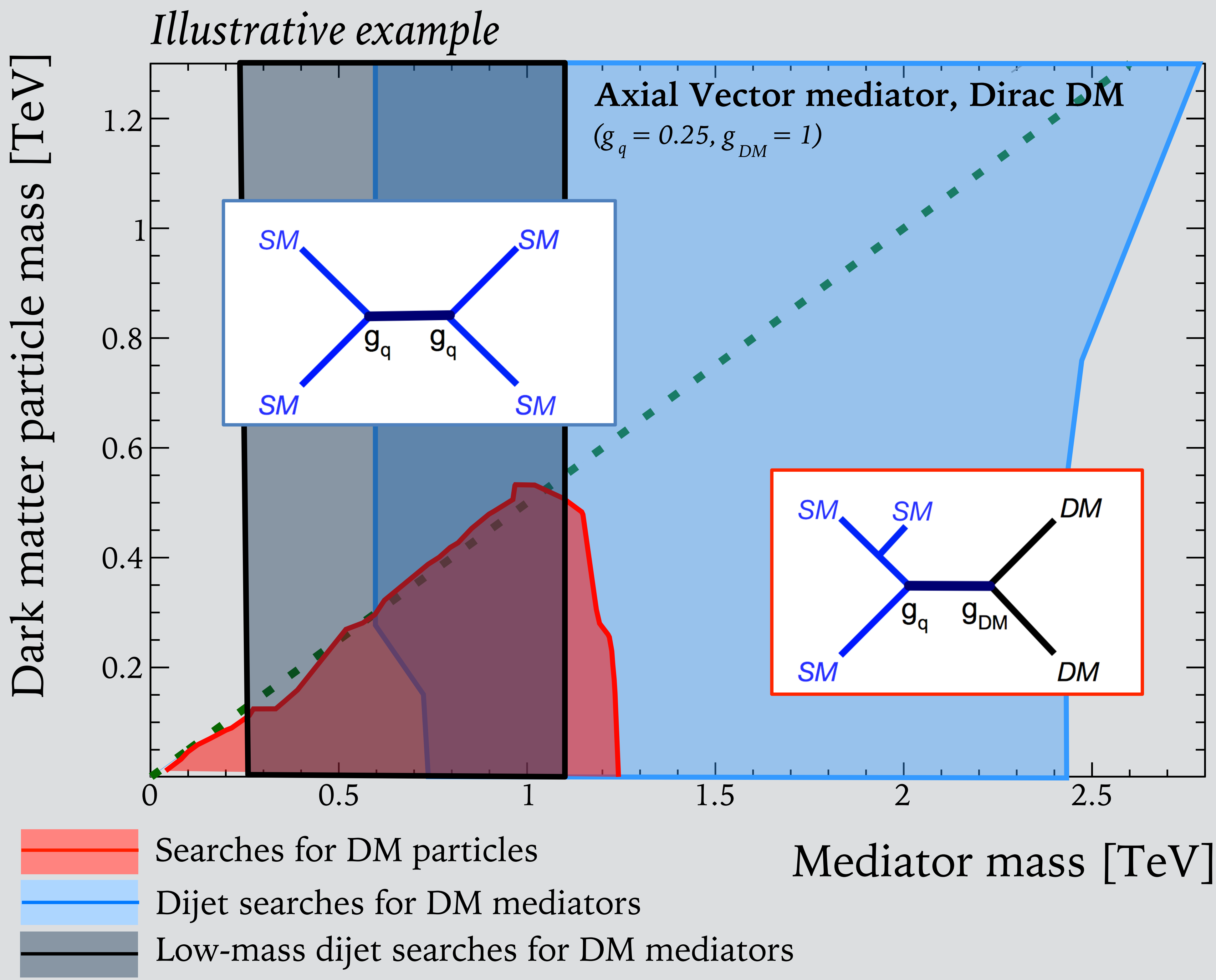
Are we looking for all the signatures of these models? e.g. Z′ → WIMPs or Z′→jet+jet



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

Visible/invisible mediator searches

arXiv:1703.05703



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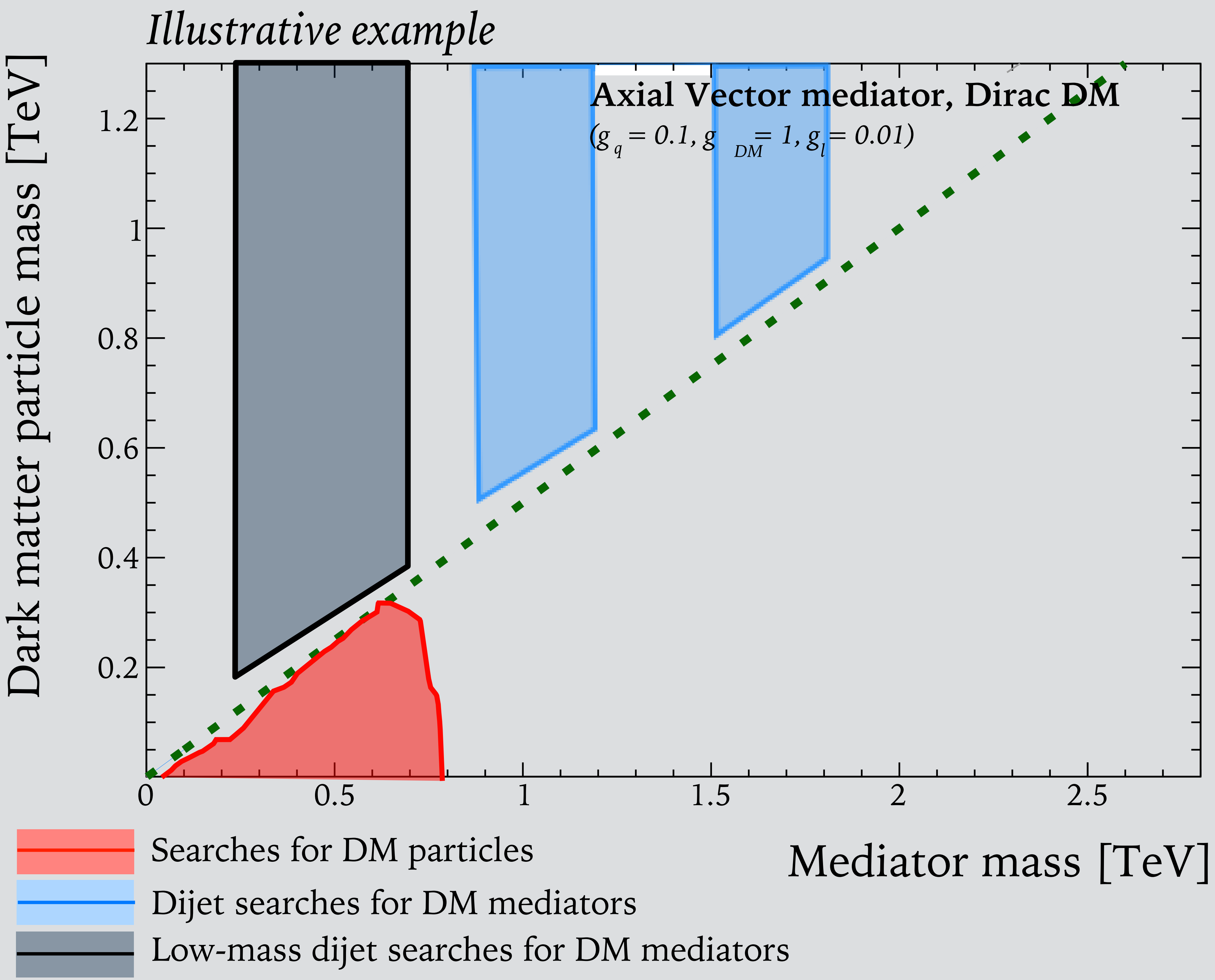

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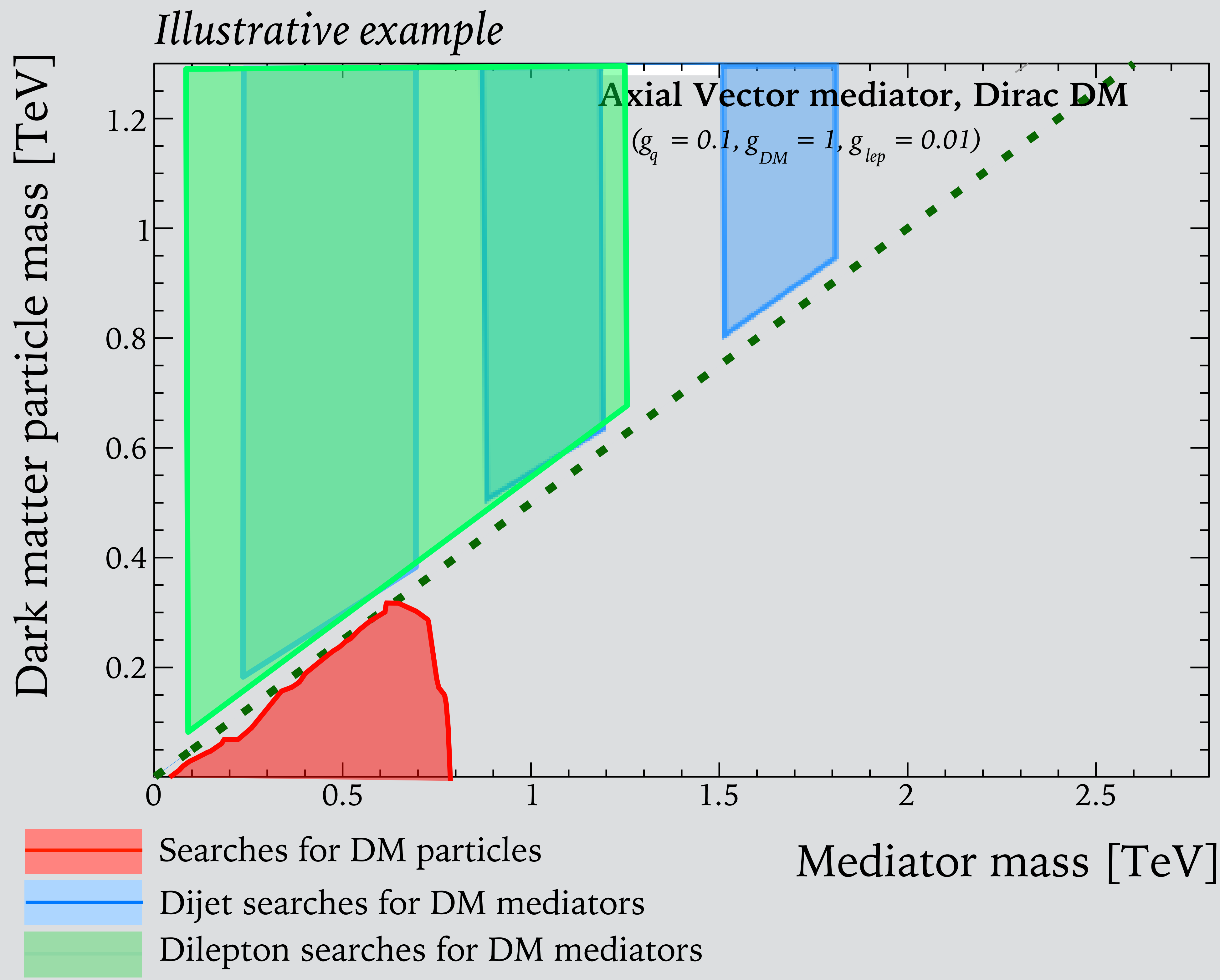
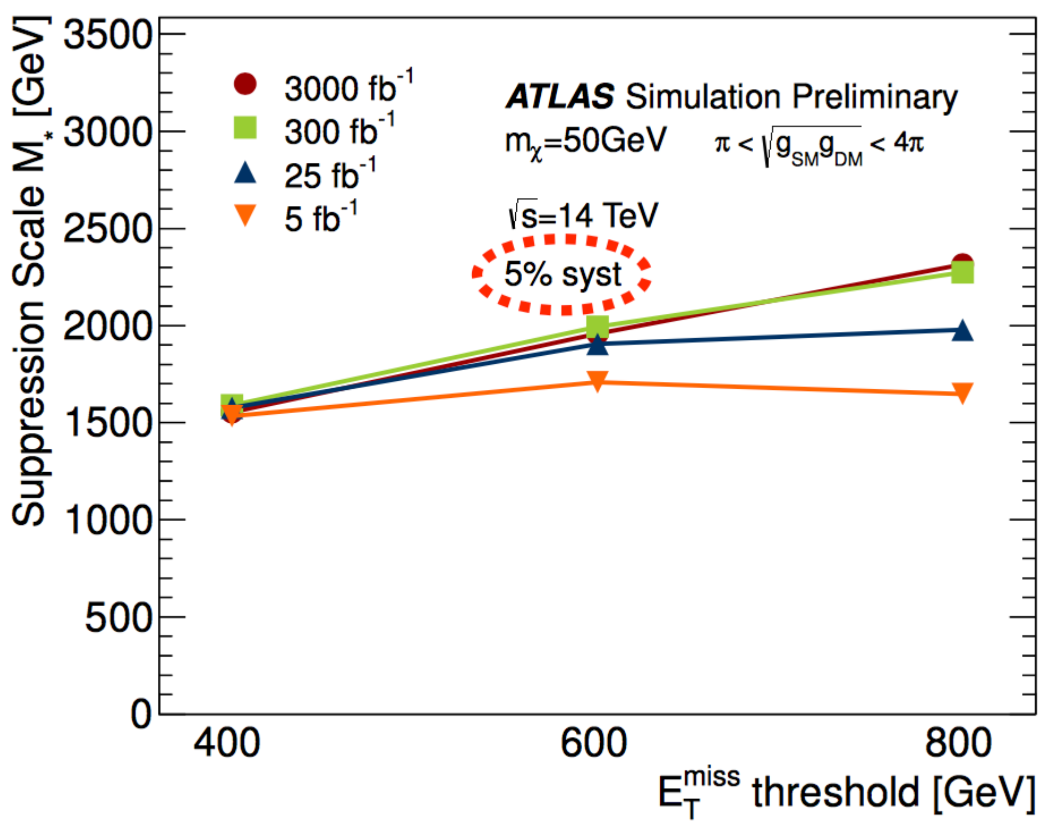


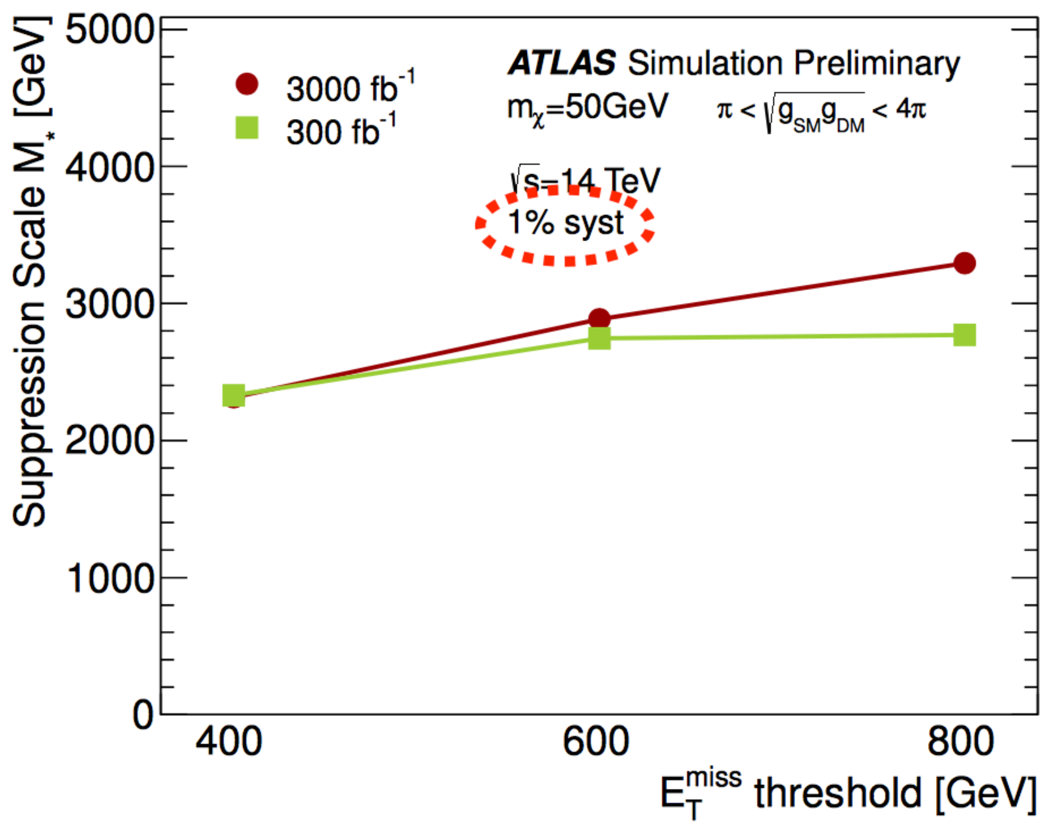
How to improve missing-energy searches?

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]



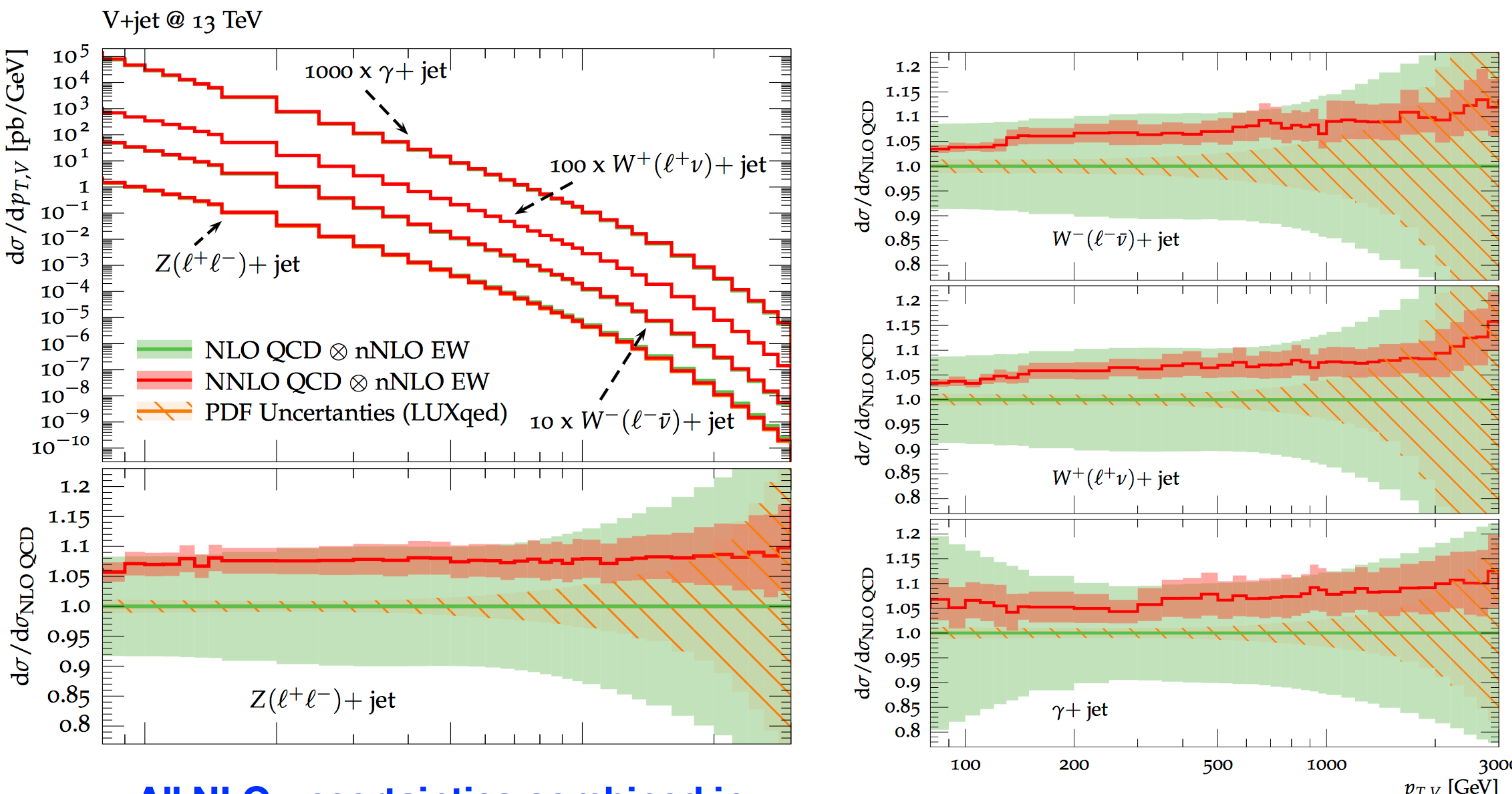


Precise predictions for V+jets dark matter backgrounds

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(νν̄)+ 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?

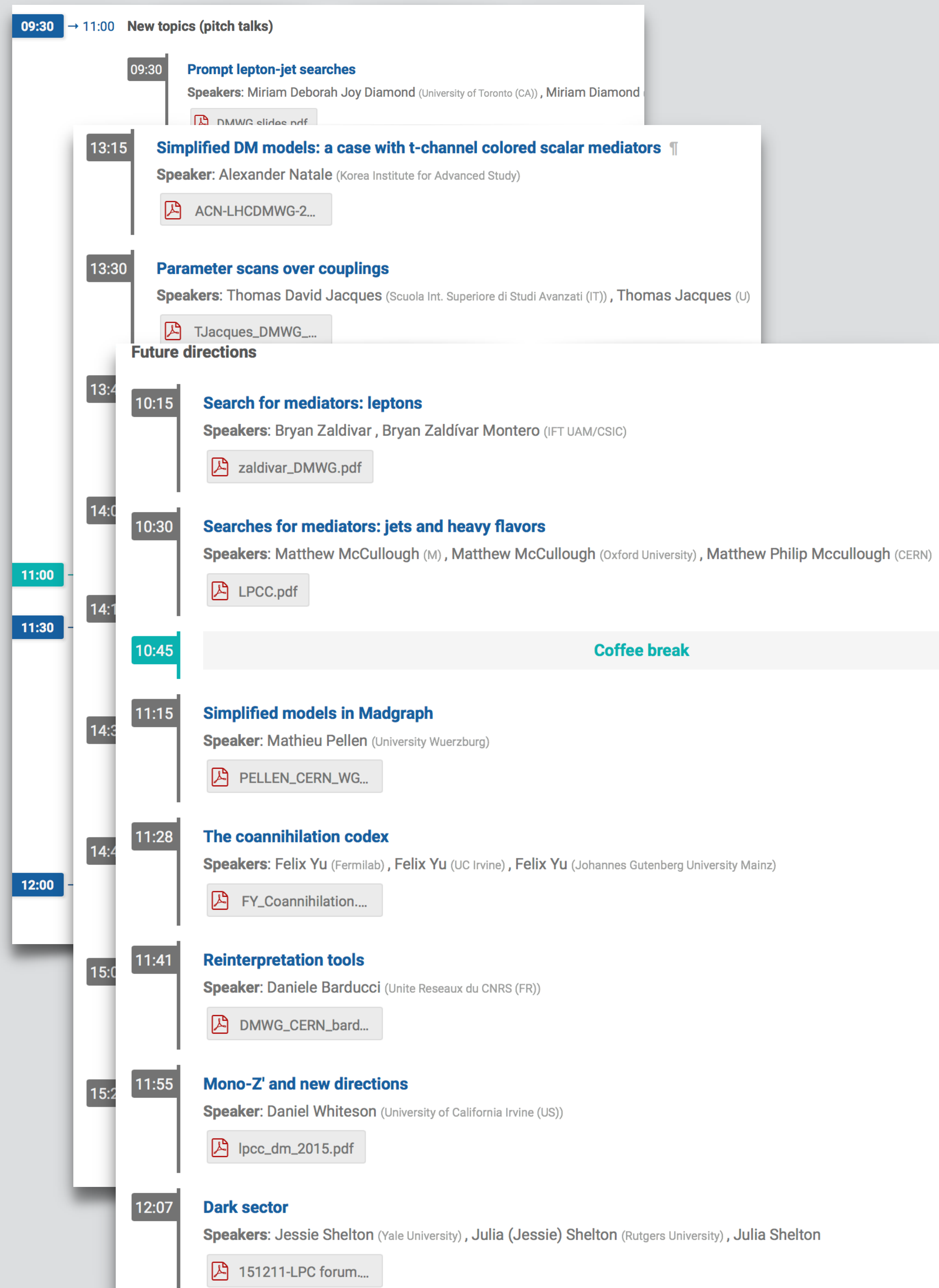
http://lpcc.web.cern.ch/lpcc/index.php?page=dm_wg

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 $e^+e^- \to \nu\overline{\nu}\gamma$. All are obtained from LEP runs in the E^{ee}_{cm} 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
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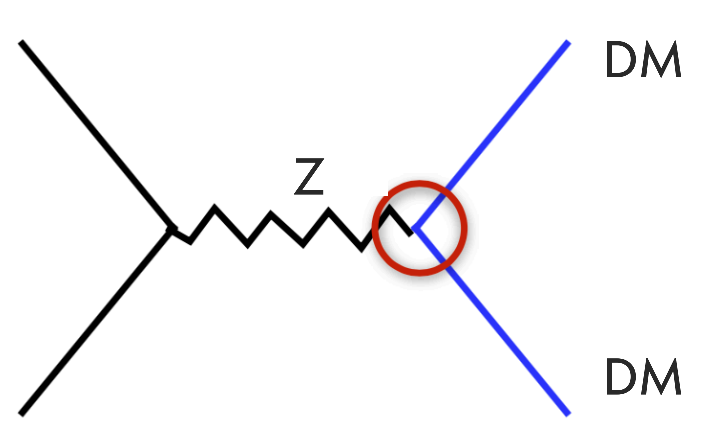
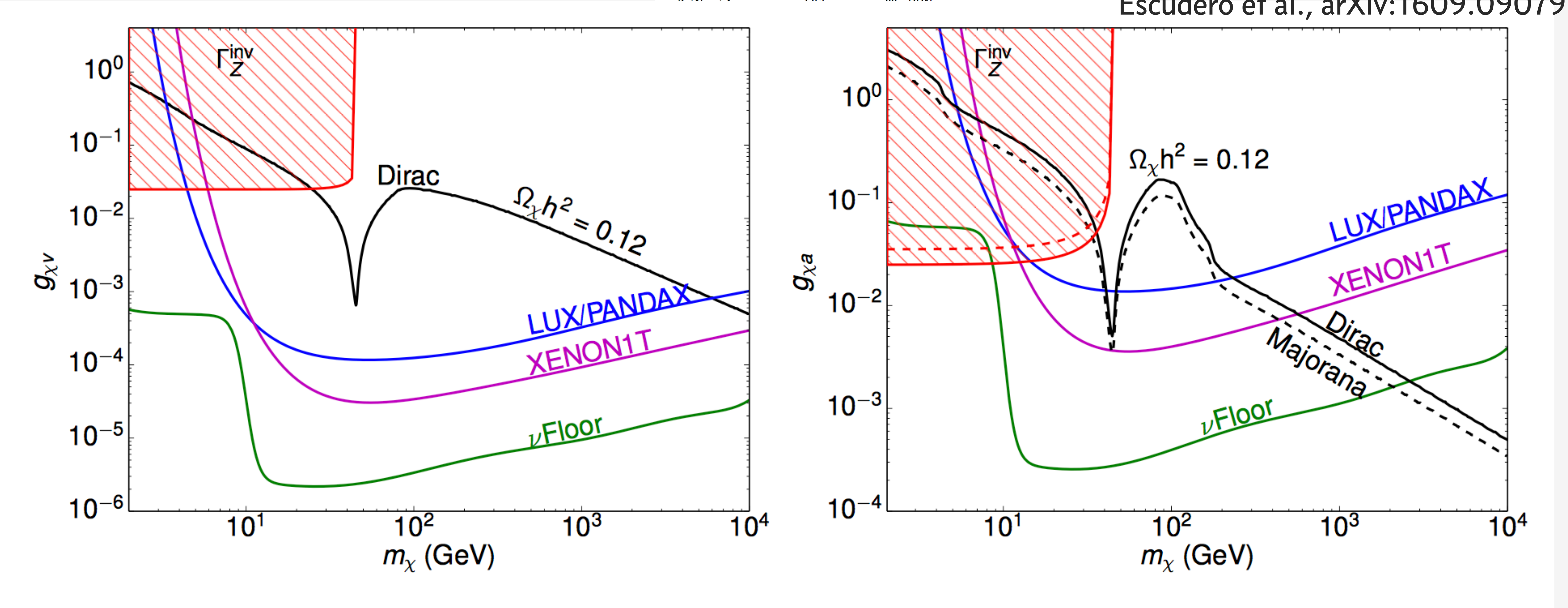
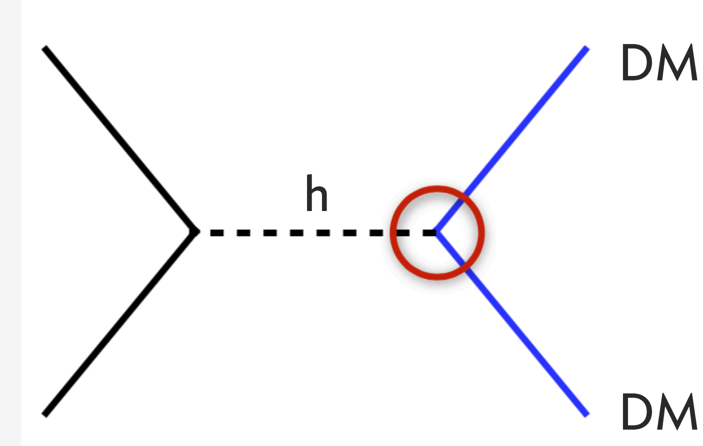


Fermionic DM

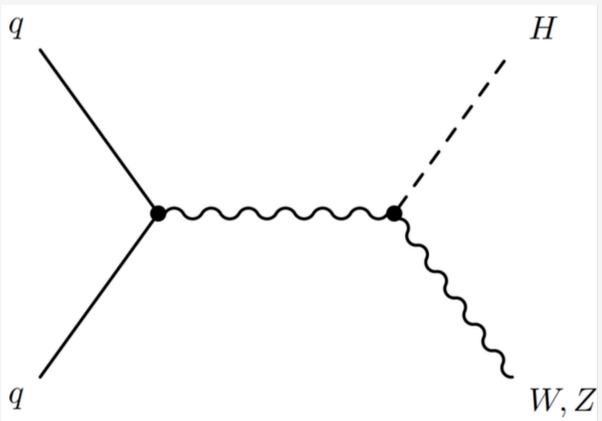
Escudero et al., arXiv:1609.09079

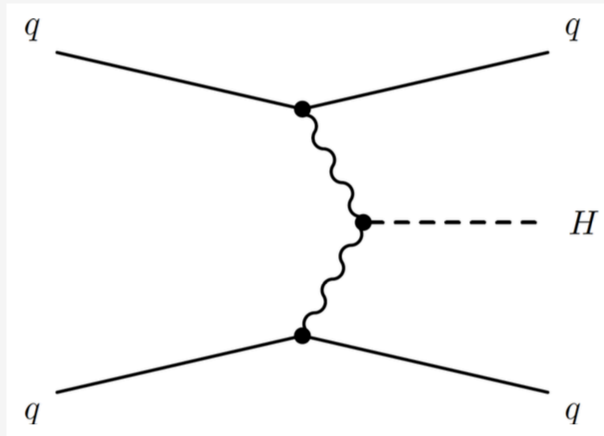


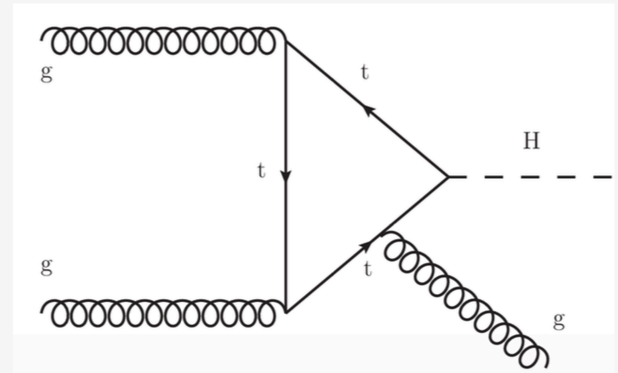
If the Higgs boson mediates SM-DM interaction...



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







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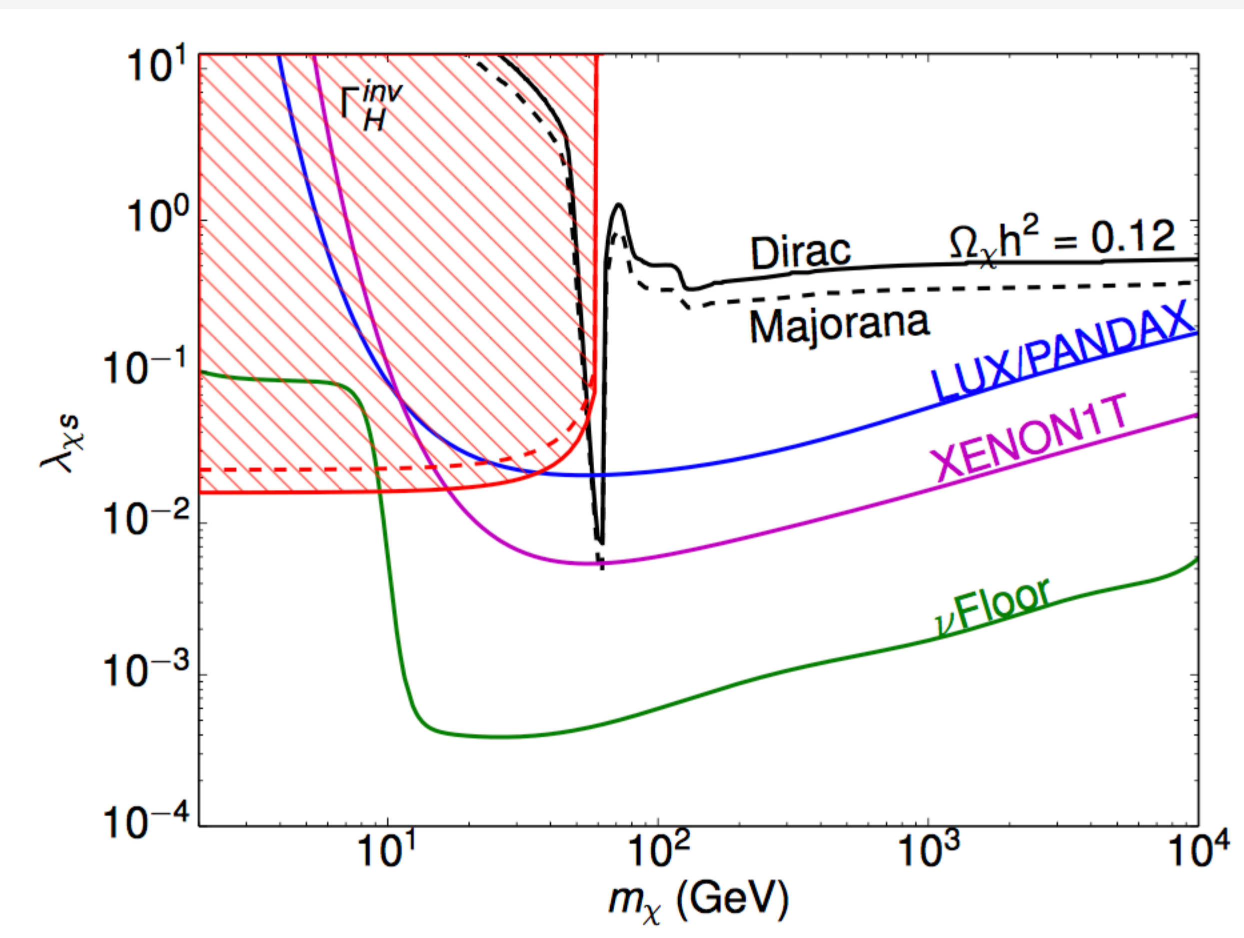

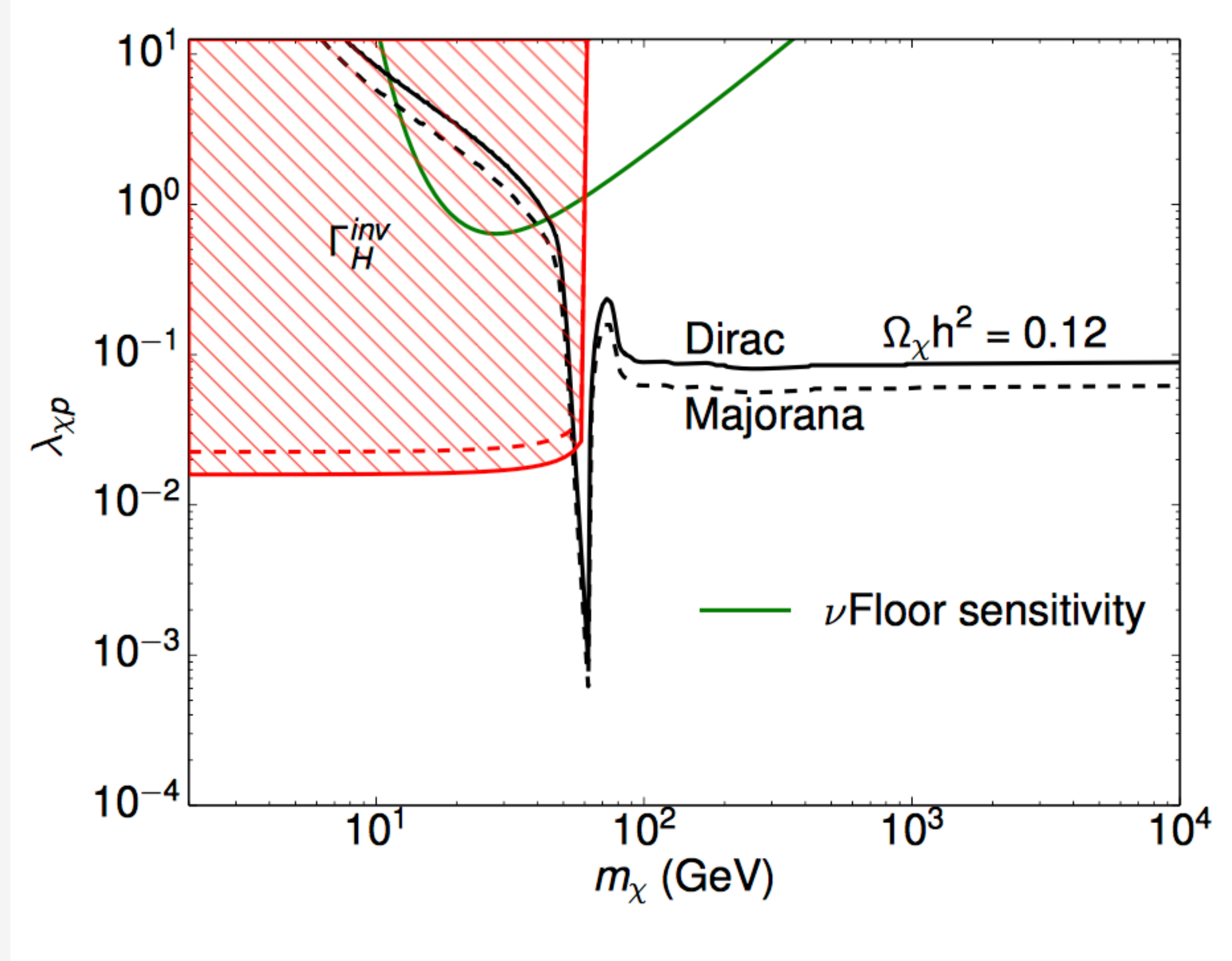

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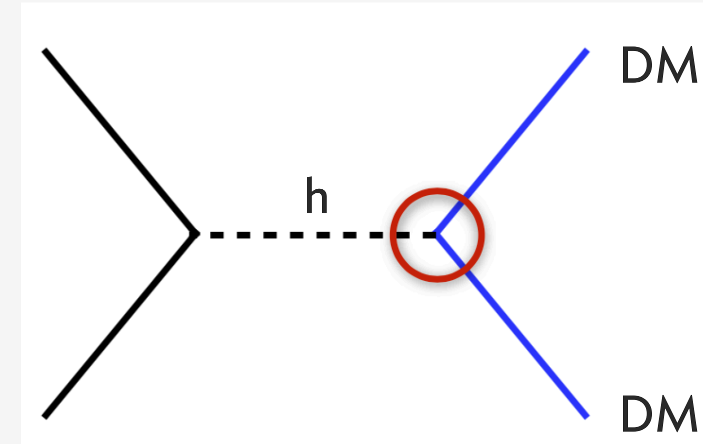

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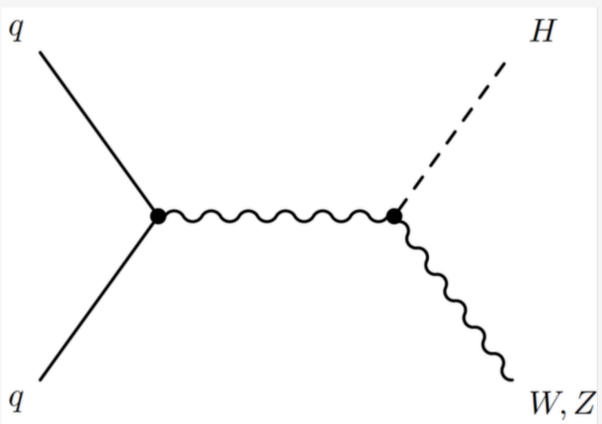

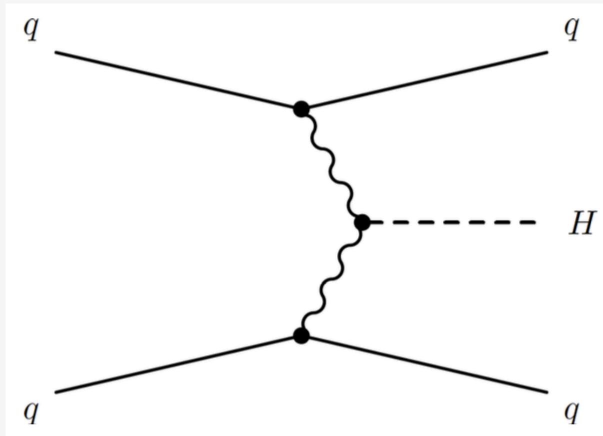

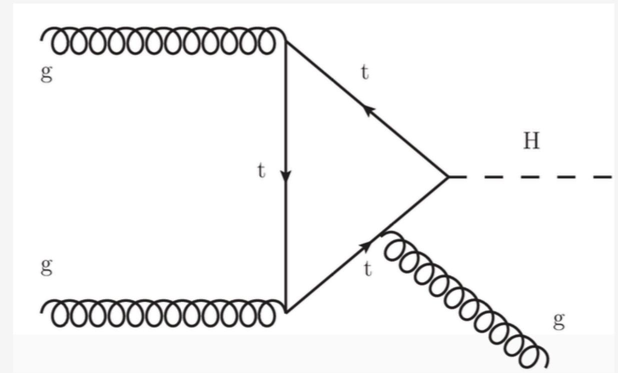

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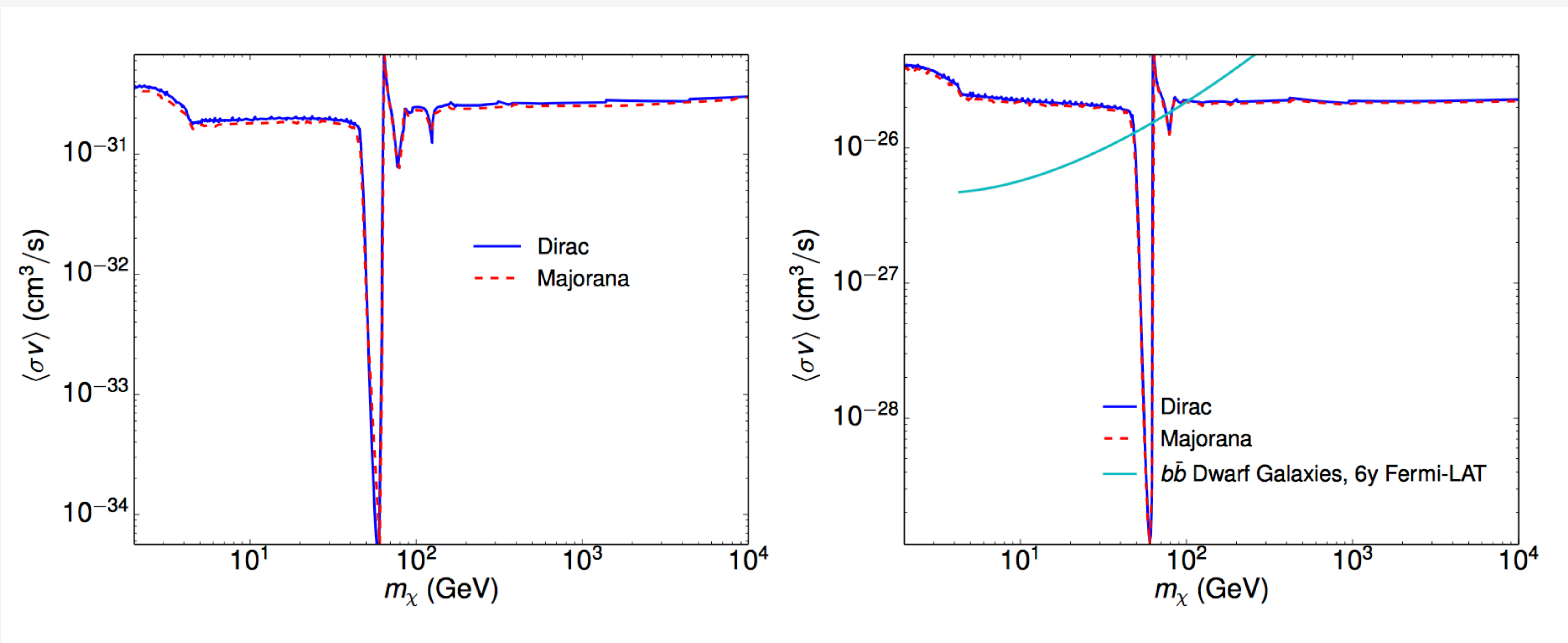
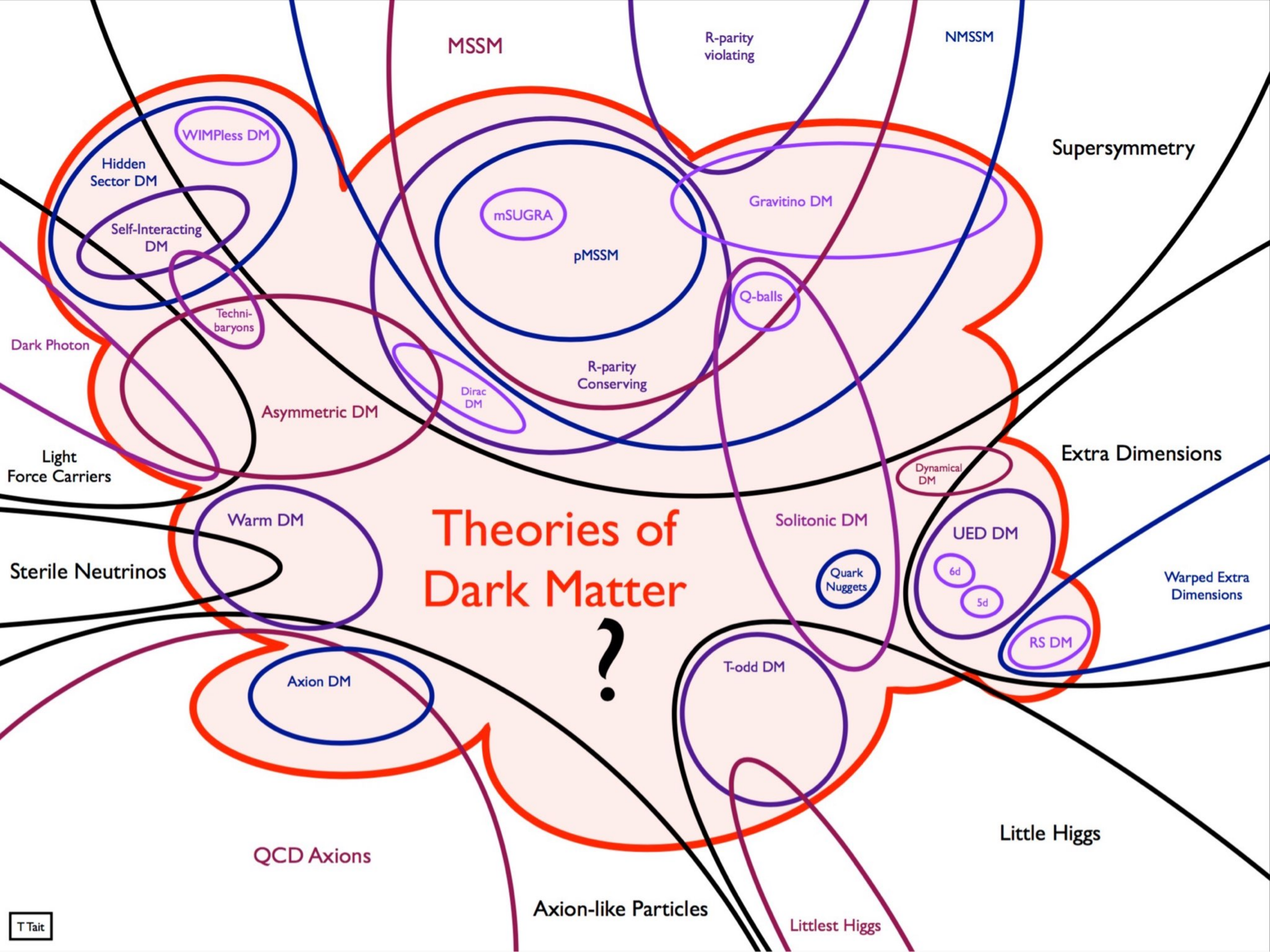
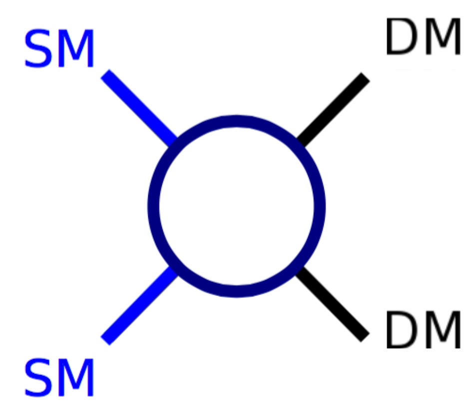



MSSM
R-parity violating
NMSSM
Supersymmetry
WIMPless DM
Hidden Sector DM
Self-Interacting DM
mSUGRA
pMSSM
Gravitino DM
Q-balls
Techni-baryons
Dark Photon
R-parity Conserving
Dirac DM
Asymmetric DM
Light Force Carriers
Dynamical DM
Extra Dimensions
Warm DM
Theories of Dark Matter
?
Solitonic DM
UED DM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

PHYSICAL REVIEW D **82,** 116010 (2010)

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):

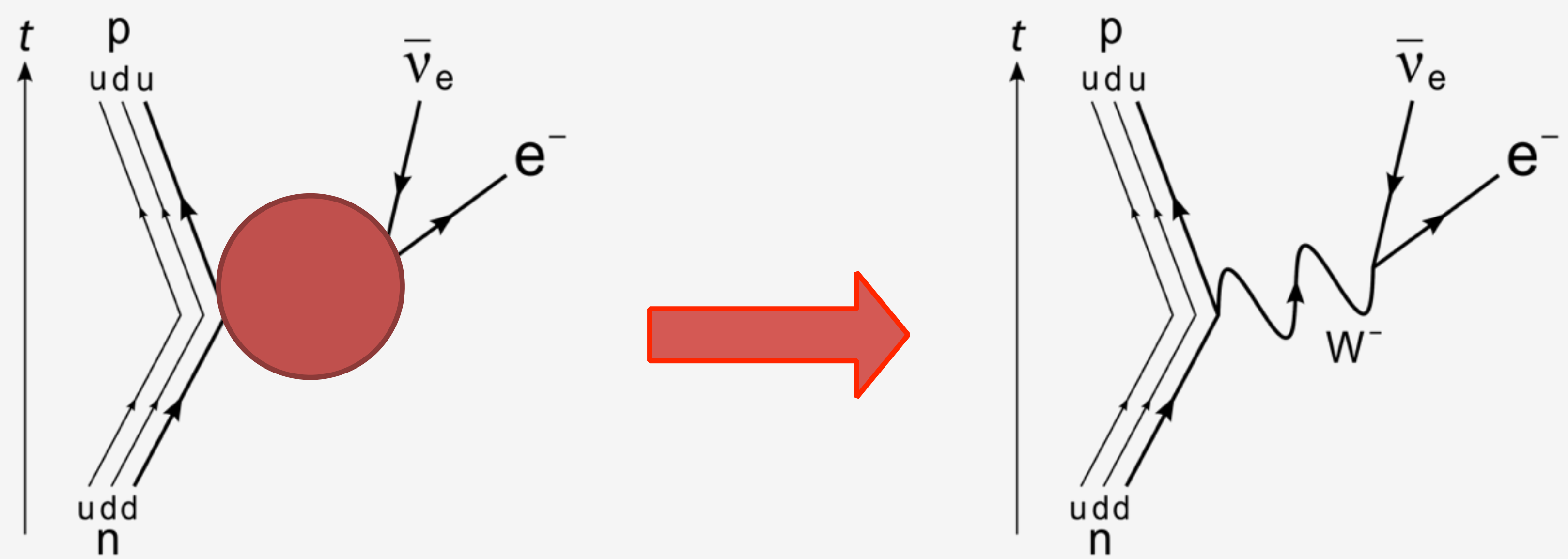
In typical completions, the inaccessible physics must be too strongly coupled to produce observable signals

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

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

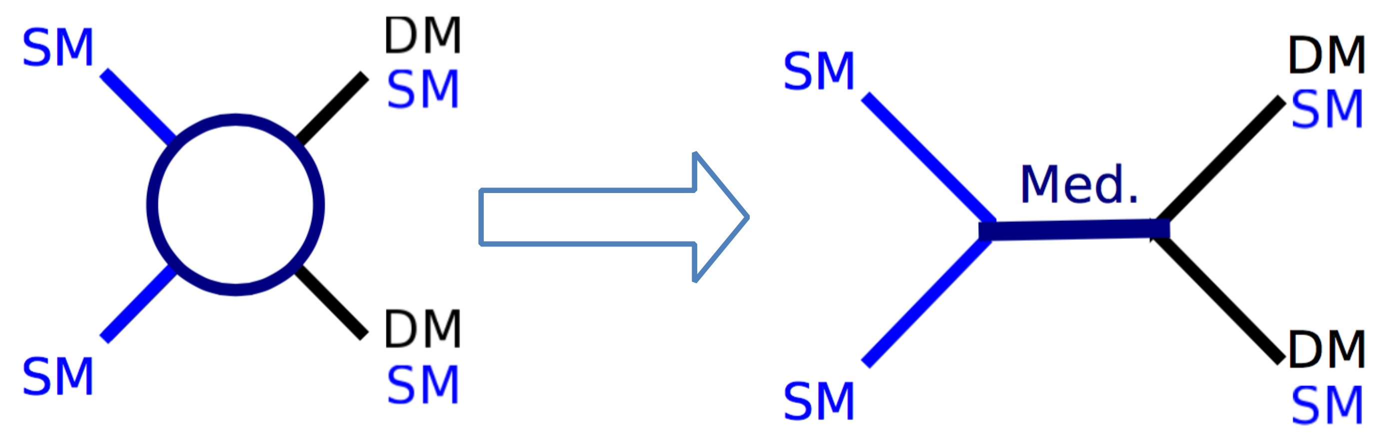
High enough rate implies either:

- 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)

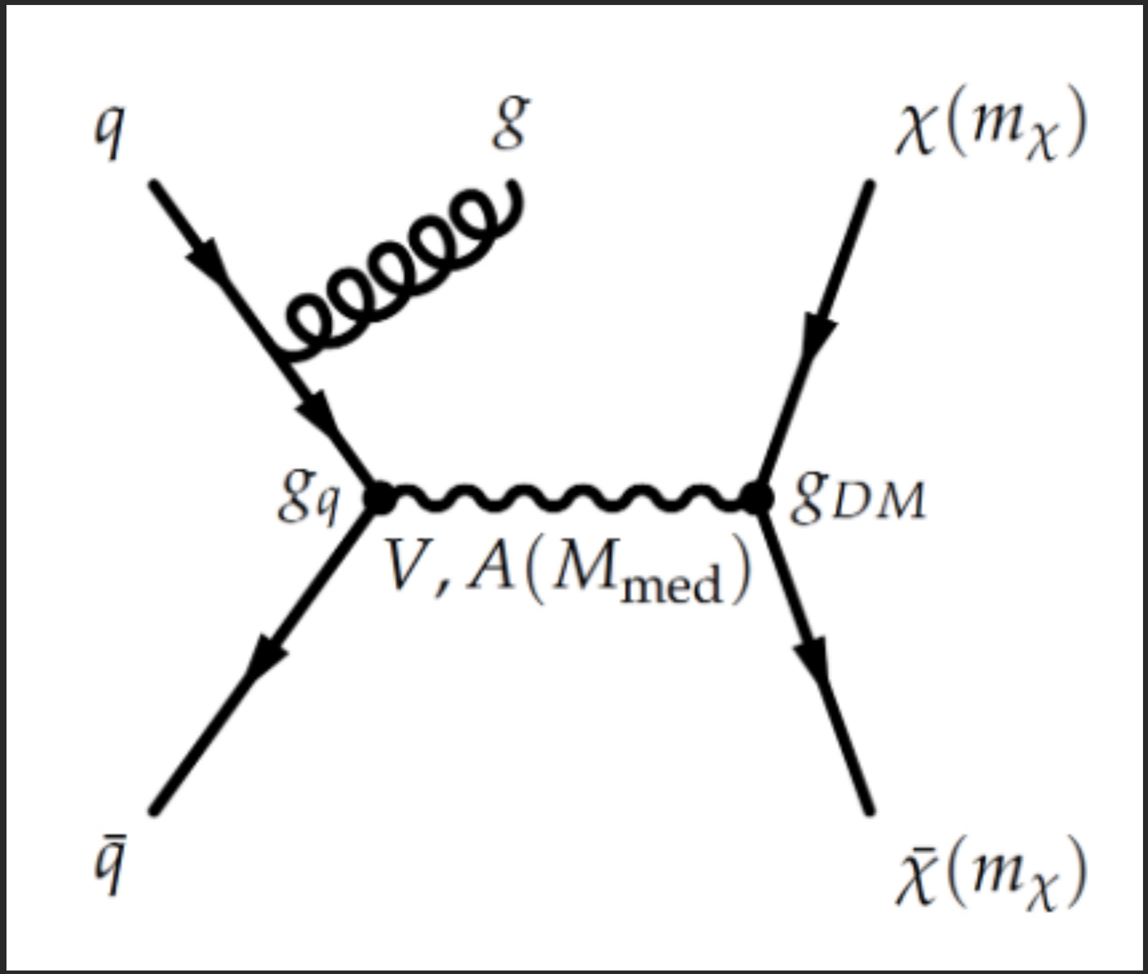
LHC probes 'high' energy scales

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

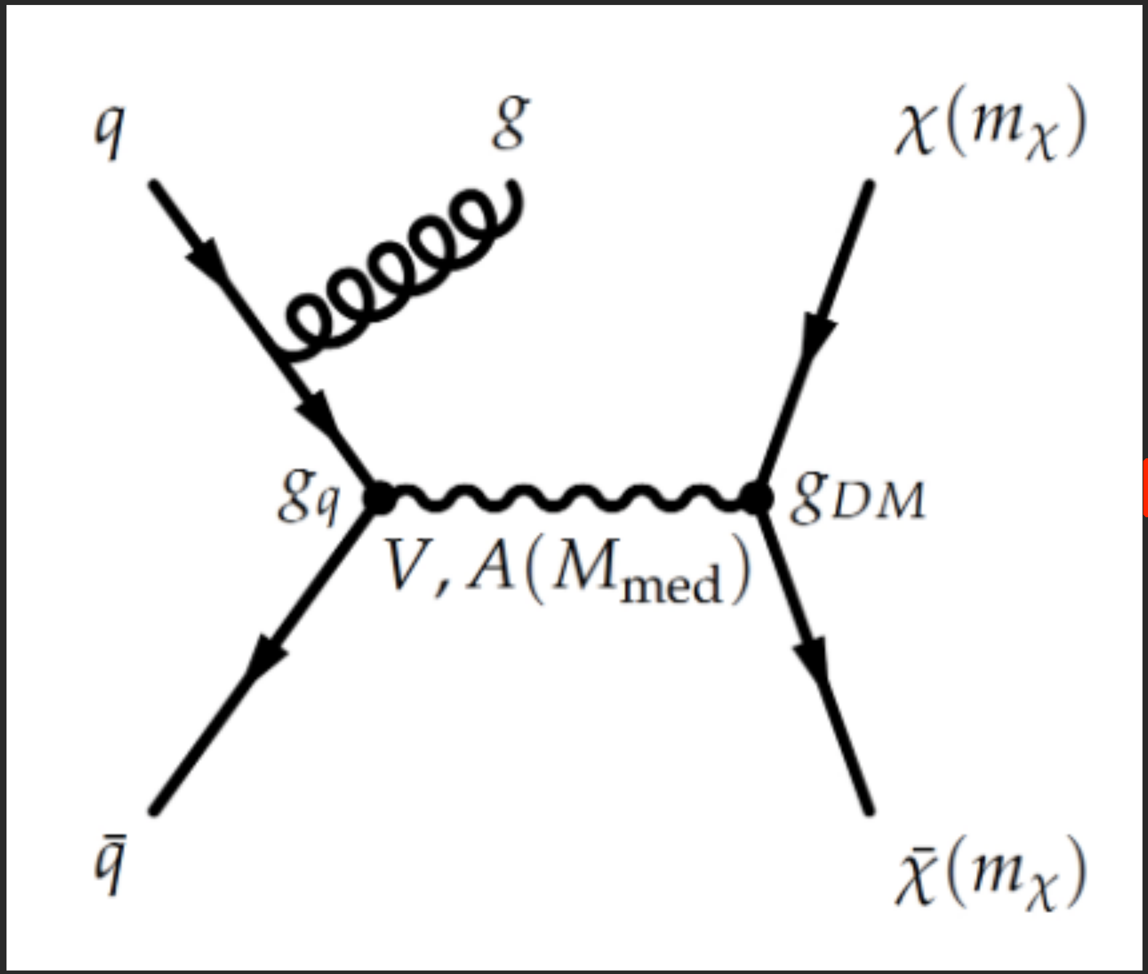
Requires more model assumptions (and parameters)

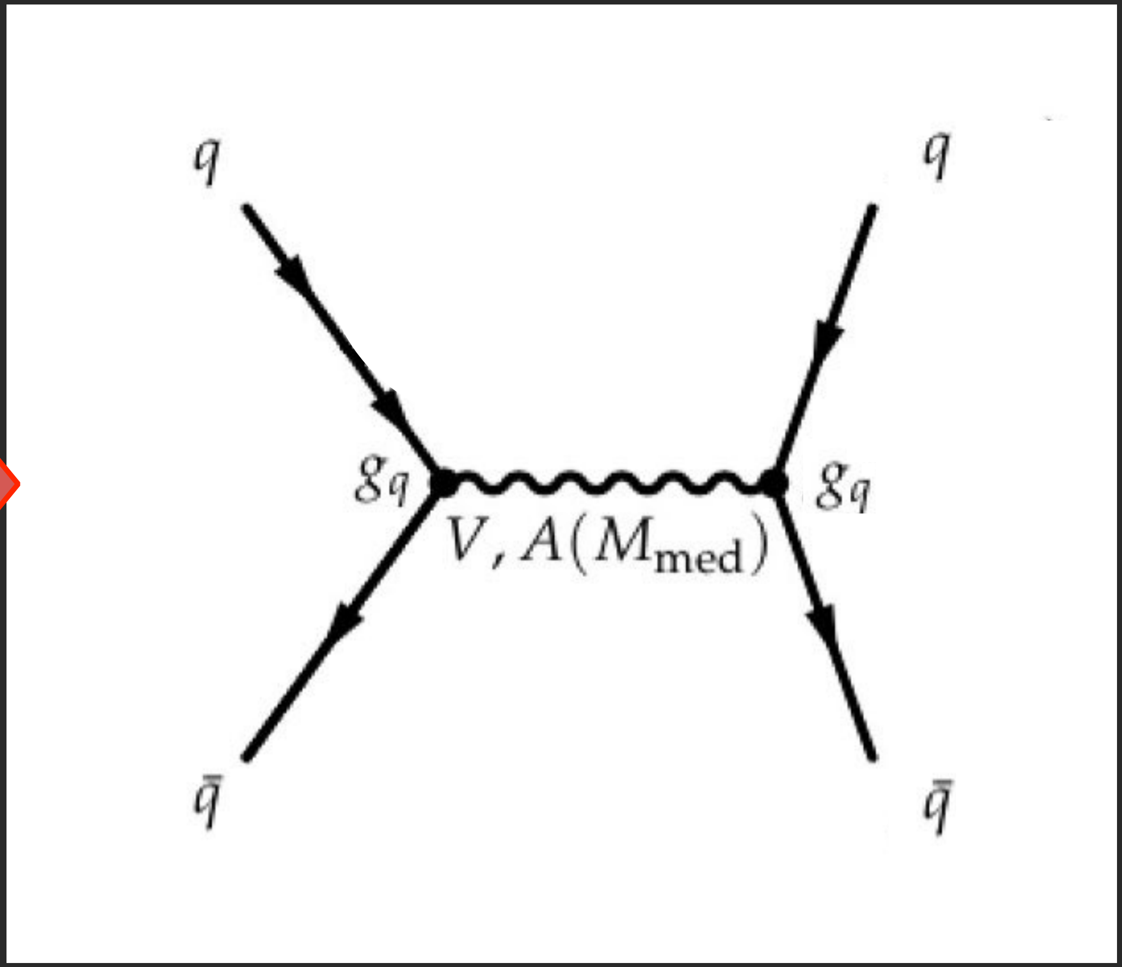
Searching for Dark Matter Production

(or: collider-stable weakly-interacting particles)



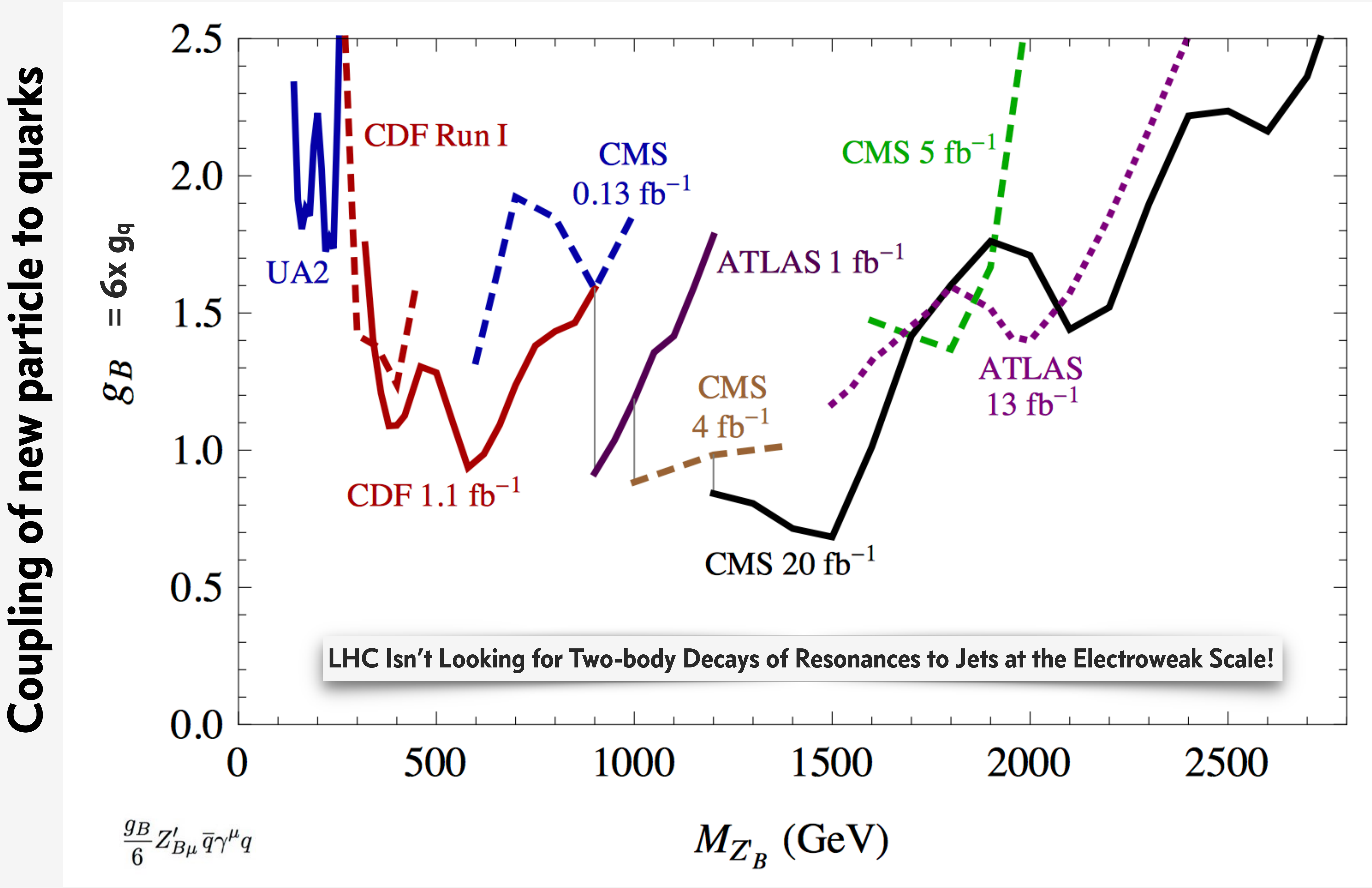
Searching for Dark Sector Interactions





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**

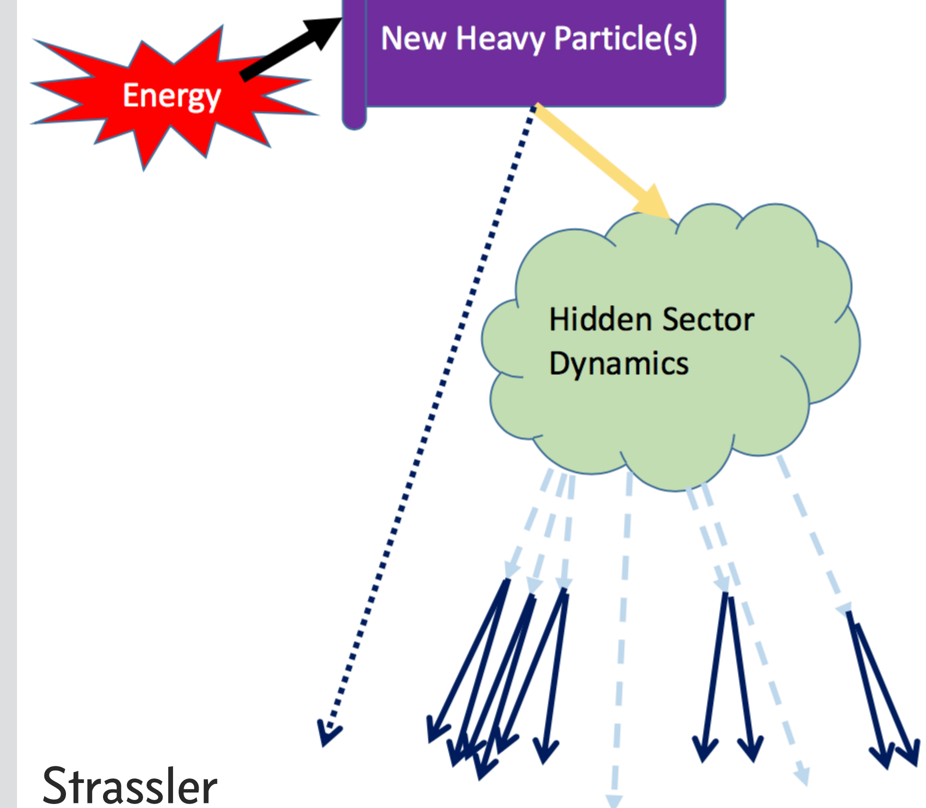
- Displaced decays (e.g. displaced / emerging jets)
- Collimated decay products (lepton jets)

Current detectors not designed for

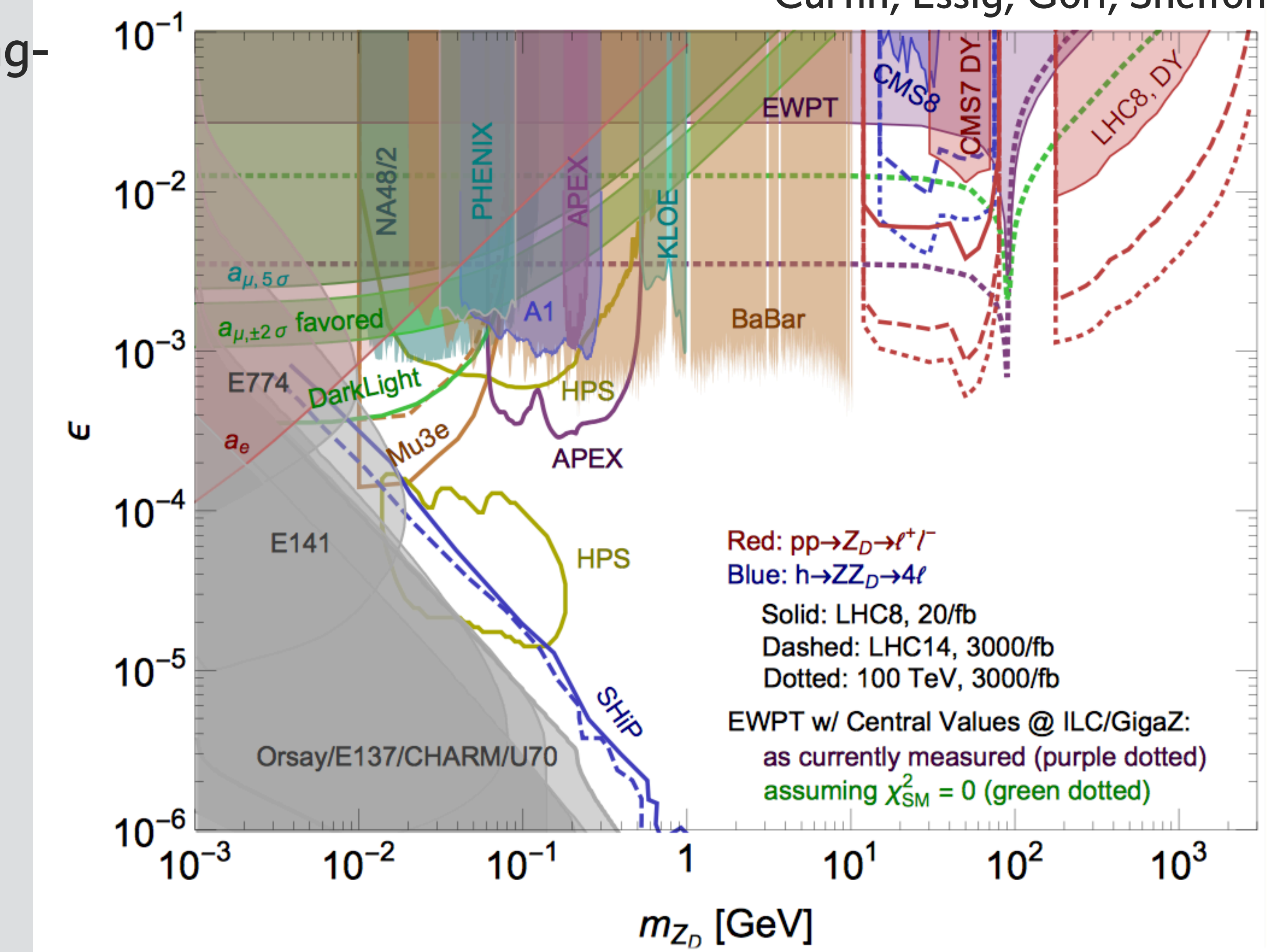
- reconstruction of very odd physics objects
- triggering on displaced decays of neutral long-lived particles
- triggering on ‘low’ energy physics

Partial wish list

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



Strassler



Curtin, Essig, Gori, Shelton

Relic density for summary plots

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