LHC Dark Matter (DM) Working Group (WG) activities: Science relevant to Fermi-LAT

Uli Haisch
University of Oxford

Fermi-LAT collaboration meeting,
29 March 2017, CERN

LHC DM WG in a 

Bring together experimentalists & theorists with goal to

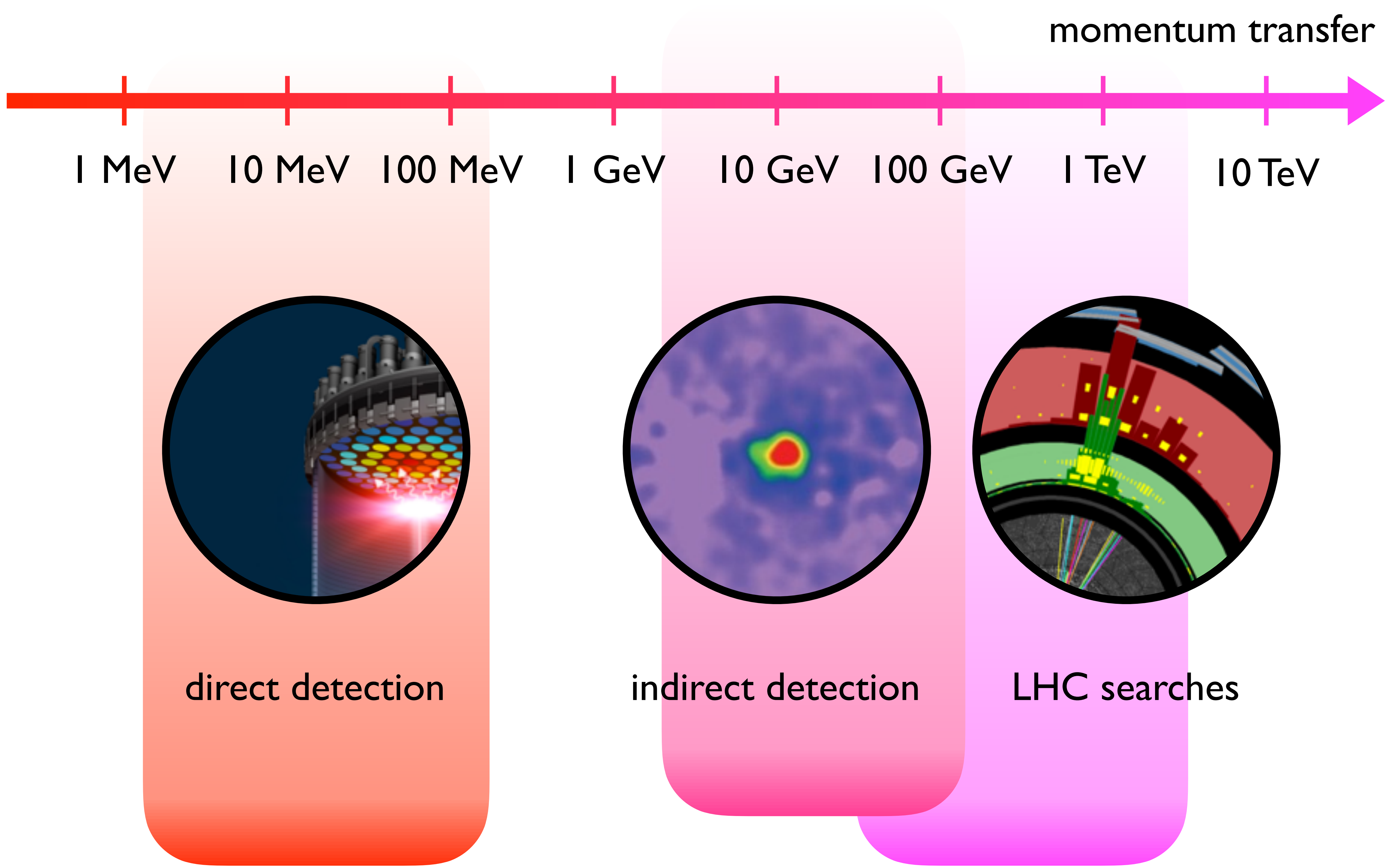
- define benchmark models that allow for a systematic characterisation/interpretation of DM searches at LHC
- connect with broader DM community (e.g. direct & indirect detection experiments) to help build a comprehensive understanding of viable DM scenarios

Public meetings on selected topics followed up by lively discussions on mailing list lhc-dmwg-contributors@cern.ch

Process so far lead to two arXiv write-ups 1603.04156 & 1703.05703

[see https://lpcc.web.cern.ch/lpcc/index.php?page=dm_wg for further details]

Scales in DM searches



DM-nucleon scattering

To describe DM-nucleon (DM-N) interactions can use effective field theory (EFT) that contains 14 operators & induce 6 nuclear response functions:

$$\mathcal{O}_1 = 1_\chi 1_N$$

$$\mathcal{O}_3 = i\vec{S}_N \cdot \left[\frac{\vec{q}}{m_N} \times \vec{v}^\perp\right]$$

$$\mathcal{O}_4 = \vec{S}_\chi \cdot \vec{S}_N$$

$$\mathcal{O}_5 = i\vec{S}_\chi \cdot \left[\frac{\vec{q}}{m_N} \times \vec{v}^\perp\right]$$

$$\mathcal{O}_6 = \left[\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right]\left[\vec{S}_N \cdot \frac{\vec{q}}{m_N}\right]$$

$$\mathcal{O}_7 = \vec{S}_N \cdot \vec{v}^\perp$$

$$\mathcal{O}_8 = \vec{S}_\chi \cdot \vec{v}^\perp$$

$$\mathcal{O}_9 = i\vec{S}_\chi \cdot \left[\vec{S}_N \times \frac{\vec{q}}{m_N}\right]$$

$$\mathcal{O}_{10} = i\vec{S}_N \cdot \frac{\vec{q}}{m_N}$$

$$\mathcal{O}_{11} = i\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}$$

$$\mathcal{O}_{12} = \vec{S}_\chi \cdot \left[\vec{S}_N \times \vec{v}^\perp\right]$$

$$\mathcal{O}_{13} = i\left[\vec{S}_\chi \cdot \vec{v}^\perp\right]\left[\vec{S}_N \cdot \frac{\vec{q}}{m_N}\right]$$

$$\mathcal{O}_{14} = i\left[\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right]\left[\vec{S}_N \cdot \vec{v}^\perp\right]$$

$$\mathcal{O}_{15} = -\left[\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right]\left[\left(\vec{S}_N \times \vec{v}^\perp\right) \cdot \frac{\vec{q}}{m_N}\right]$$

spin-independent (SI)

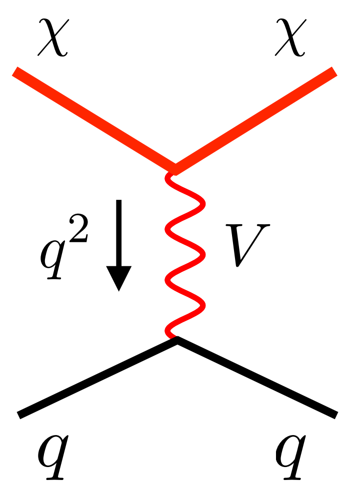
spin-dependent (SD)

[see for instance Fitzpatrick et al., 1203.3542, 1211.2818; Anand et al., 1308.2288, 1405.6690]

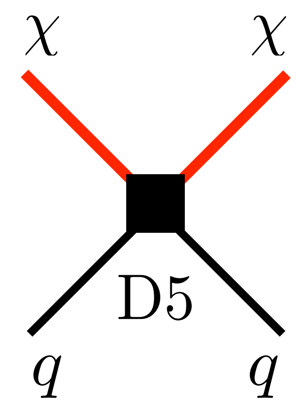
How-to describe SI couplings at LHC?

E

$$\mathcal{L}_V \supset g_\chi \, \bar{\chi}\gamma_\mu\chi \, V^\mu + g_q \, \bar{q}\gamma_\mu q \, V^\mu$$



$$= \quad -\frac{g_\chi g_q}{M_V^2} \cdot$$



$$+ \, \mathcal{O}(q^2/M_V^2)$$

$$\mathrm{D5} = \bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$$

$$\mathcal{O}_1 = 1_\chi \, 1_N$$

How-to describe SI couplings at LHC?

E

$$\mathcal{L}_V \supset g_\chi \, \bar{\chi}\gamma_\mu\chi \, V^\mu + g_q \, \bar{q}\gamma_\mu q \, V^\mu$$

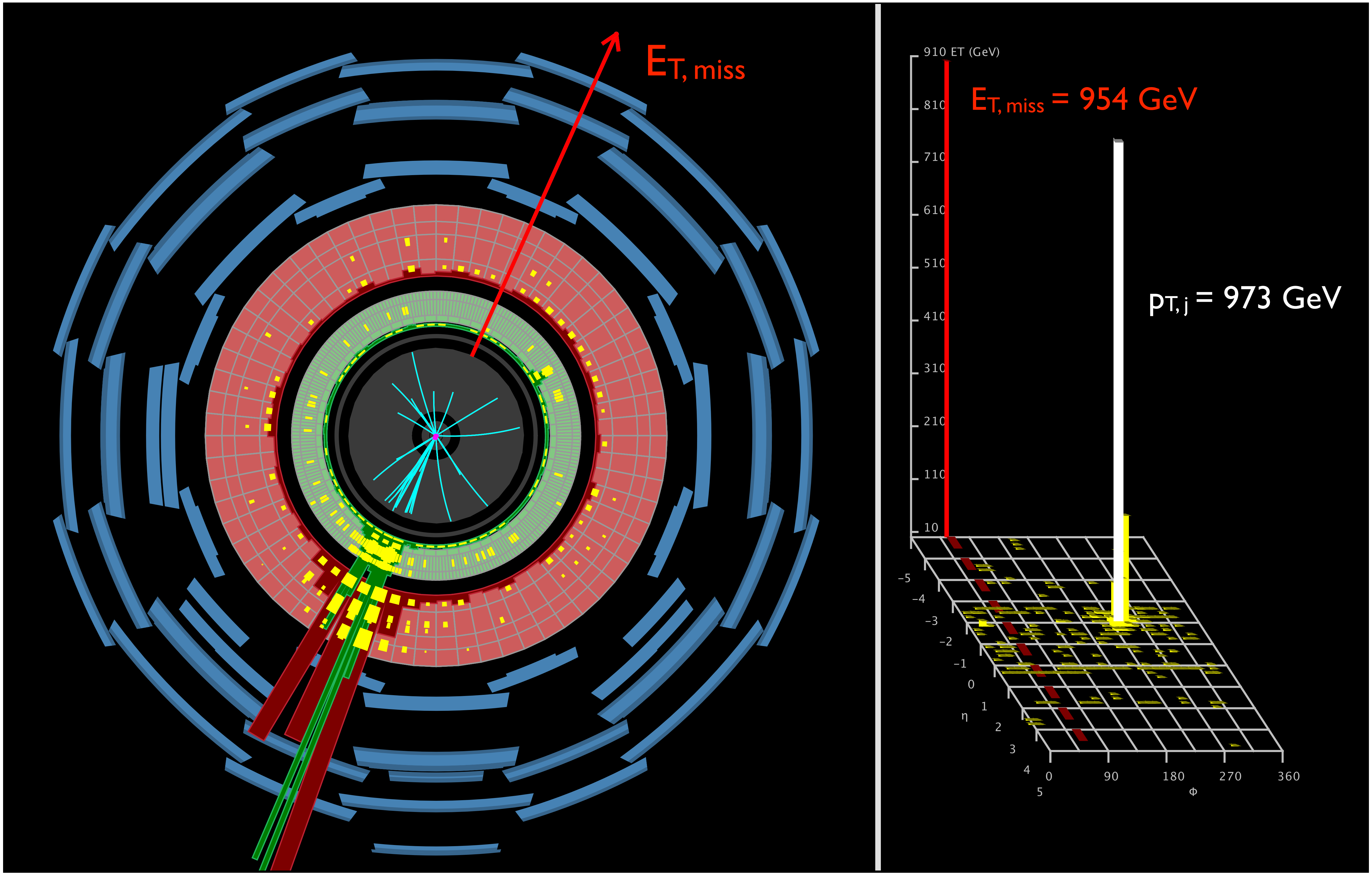
Is it necessary to go from an EFT description to a simplified model in context of LHC DM searches?

$$\mathrm{D5} = \bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$$

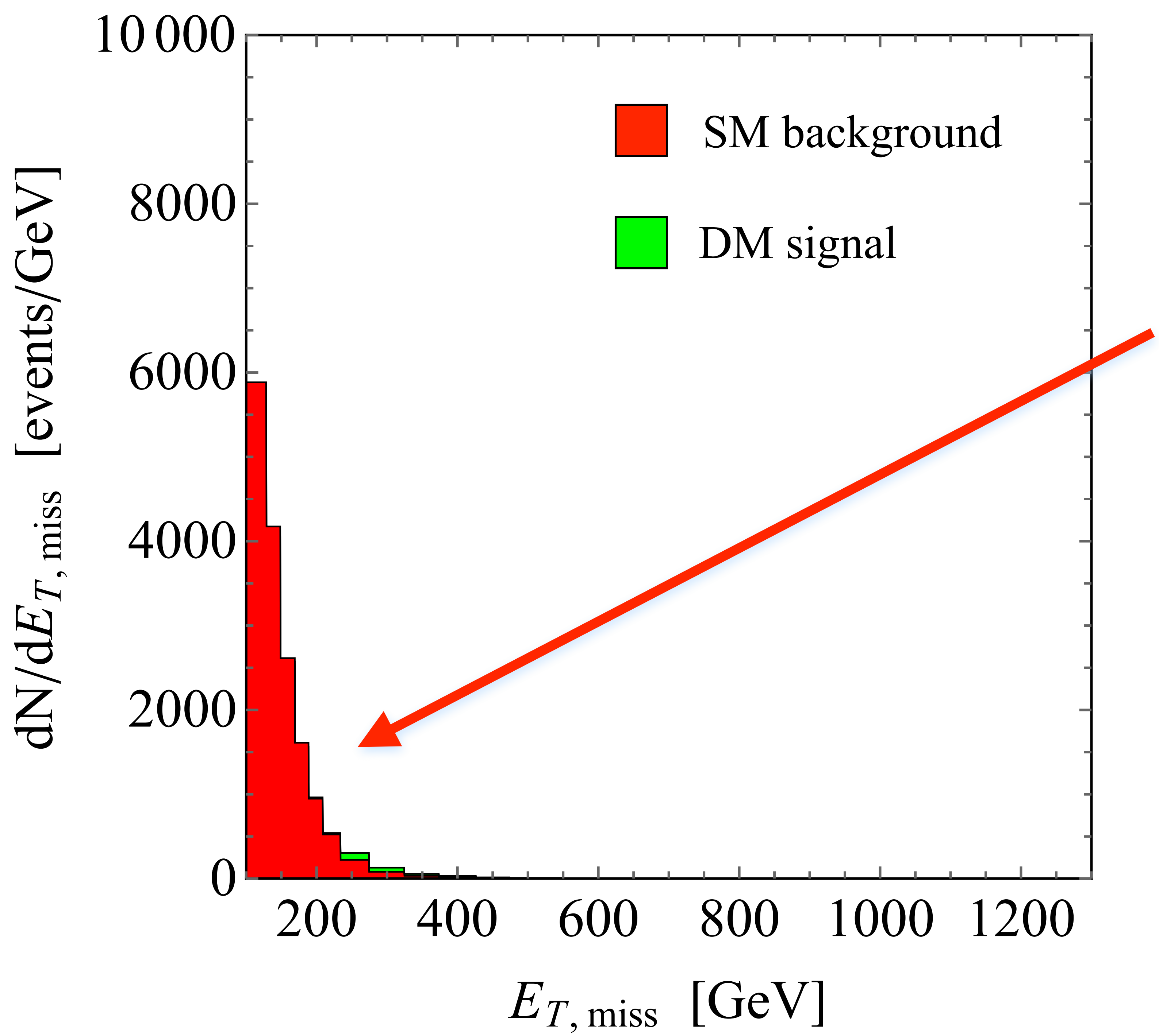
$$\mathcal{O}_1 = 1_\chi \, 1_N$$

Mono-jet searches

[2015 ATLAS data (event 606734214, run 279284)]

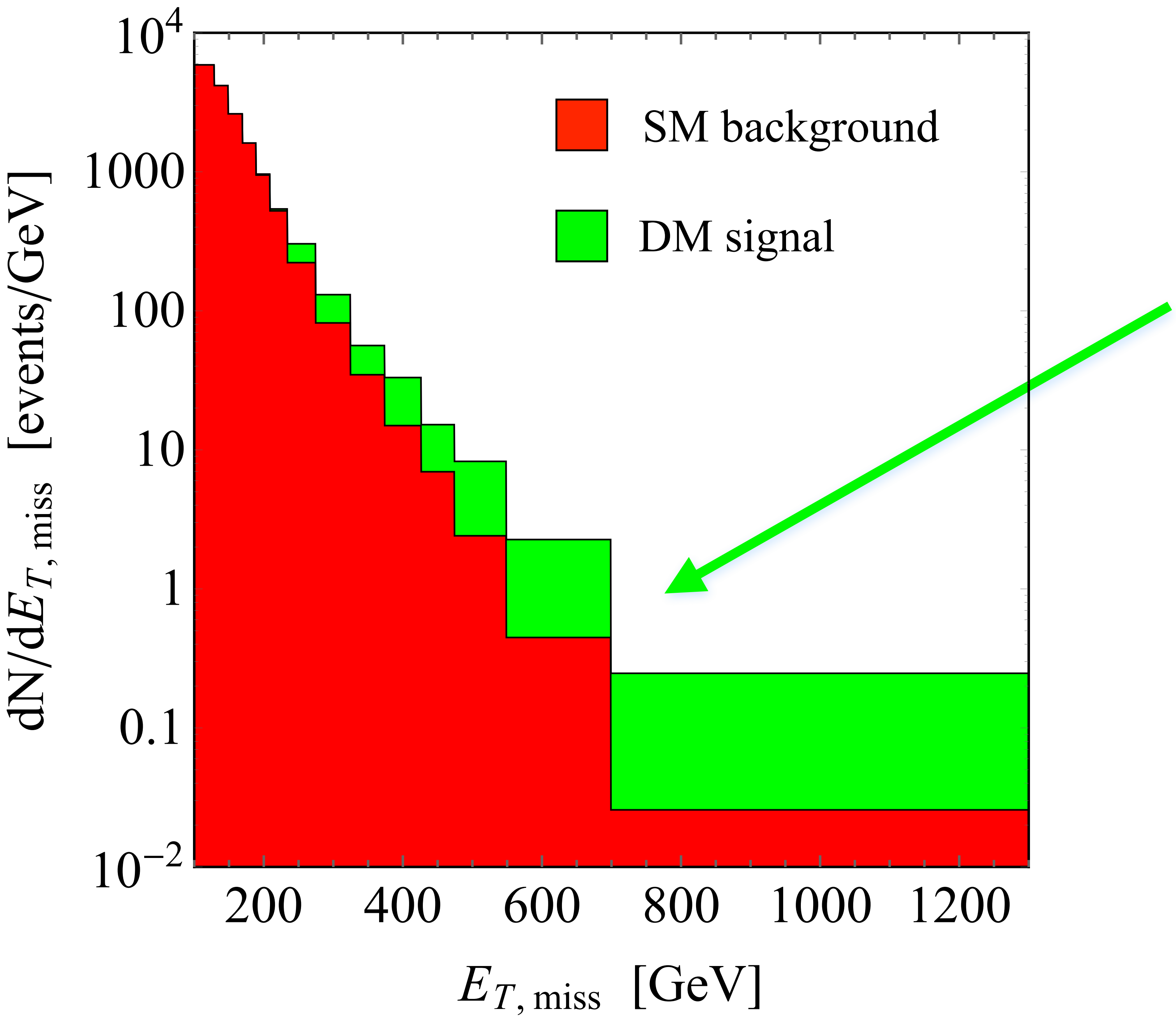


Signal vs. background



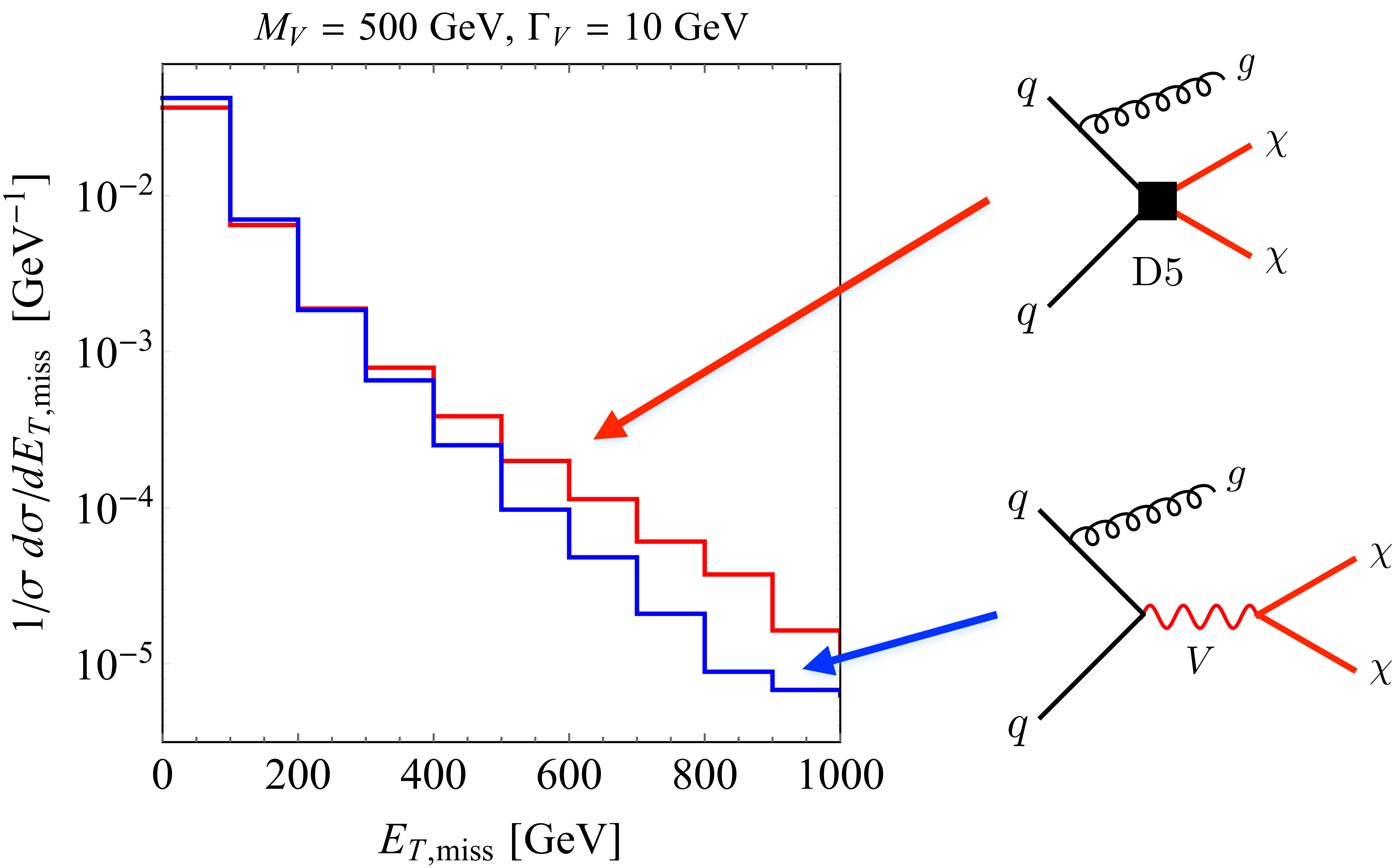
Huge Standard Model (SM) background, that arises in case of mono-jet searches from Z+jet production with Z boson decaying to neutrinos

Signal vs. background

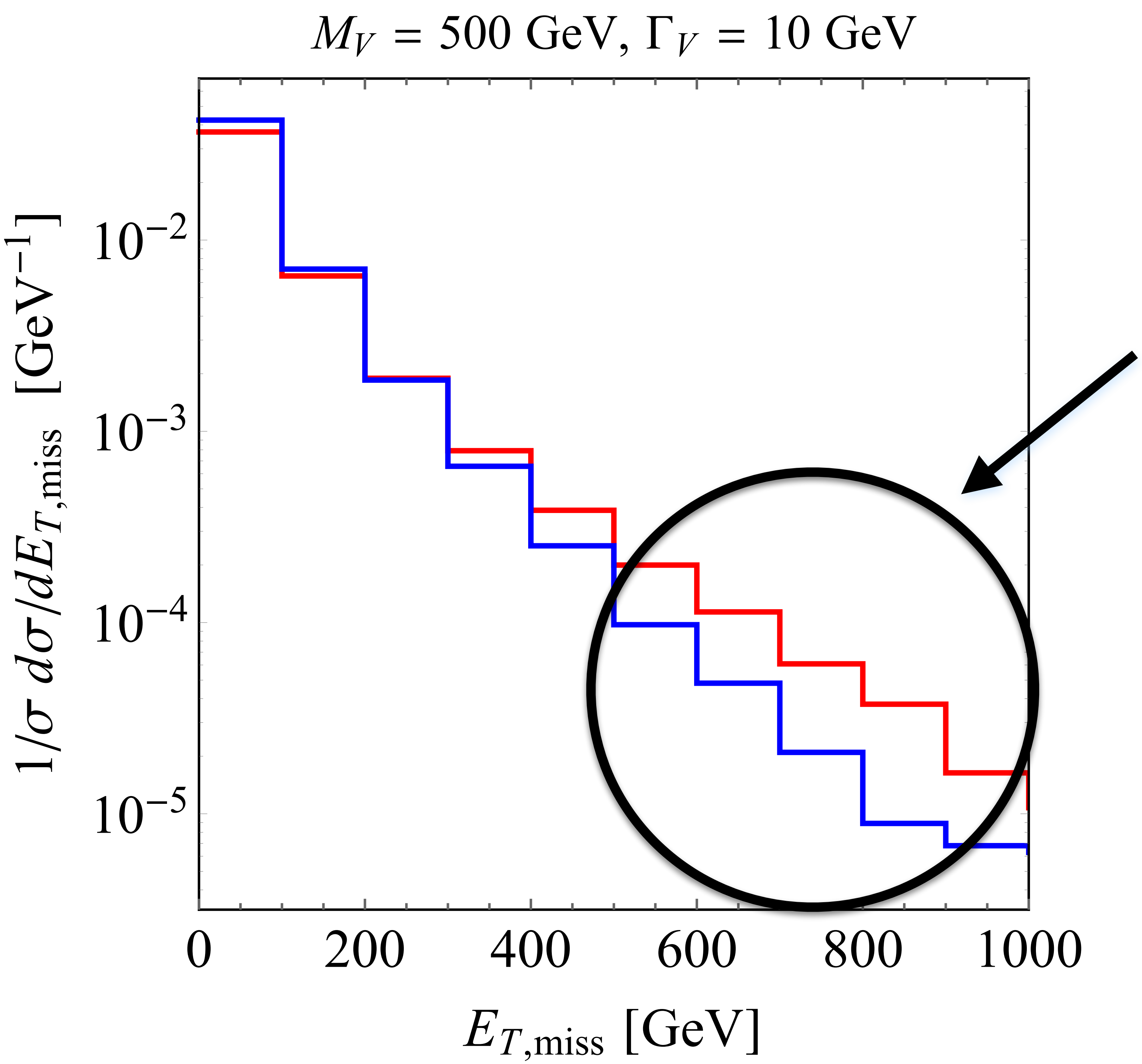


Presence of DM manifests itself in small enhancement in tail of missing energy $E_{T,\text{miss}}$ distribution

EFT vs. vector simplified model



EFT vs. vector simplified model



EFT overestimates tail of $E_{T,\text{miss}}$ spectrum. This flaw prompted ATLAS & CMS to start using simplified models when interpreting DM searches at Run II

Proposed simplified models

Spin-1:

$$\mathcal{L}_V \supset g_\chi \bar{\chi}\gamma^\mu \chi V_\mu + \sum_q g_q \bar{q}\gamma^\mu q V_\mu$$ vector mediator

$$\mathcal{L}_A \supset g_\chi \bar{\chi}\gamma^\mu \gamma_5 \chi A_\mu + \sum_q \bar{q}\gamma^\mu \gamma_5 q A_\mu$$ axial-vector mediator

Spin-0:

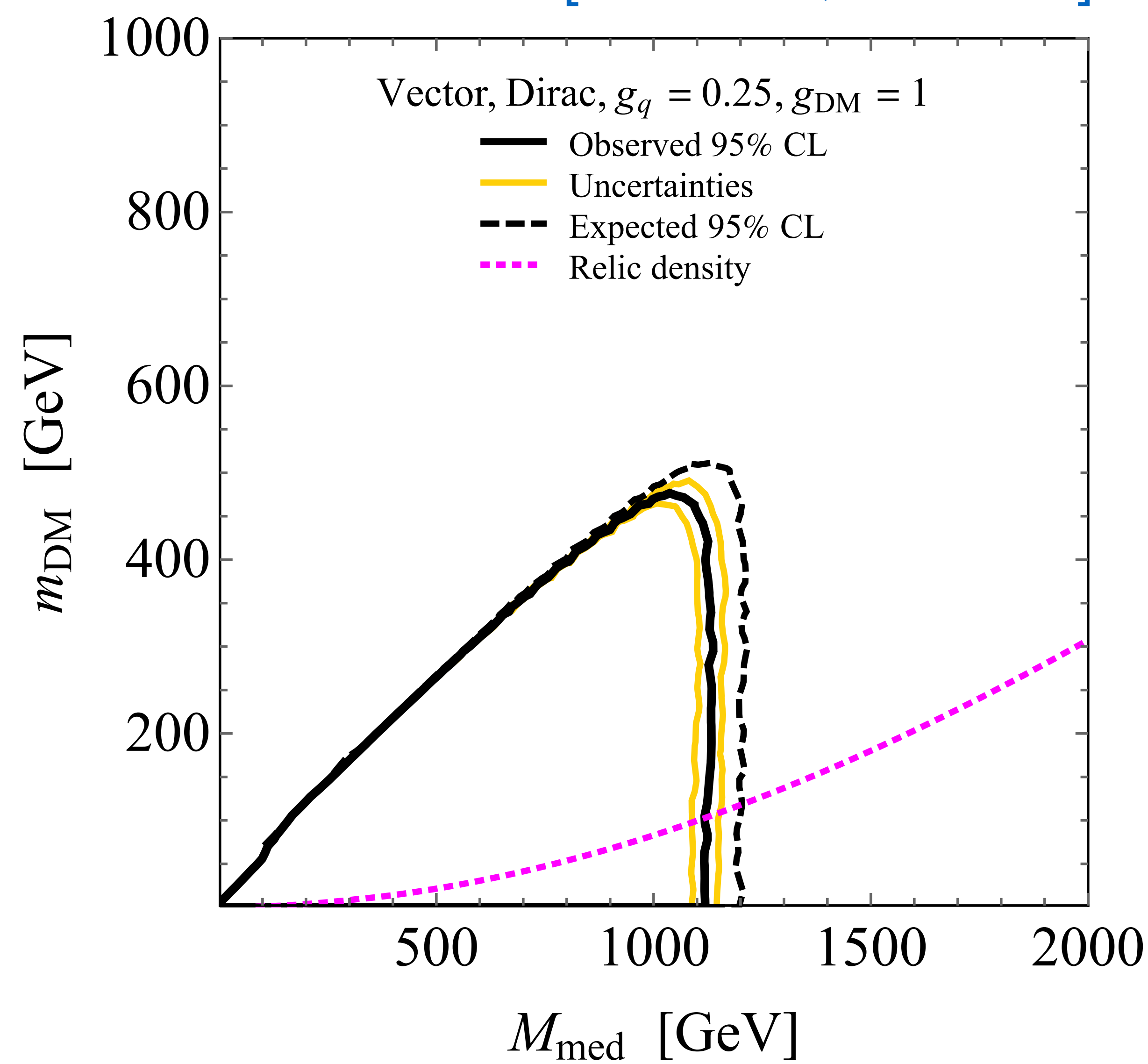
$$\mathcal{L}_S \supset g_\chi \bar{\chi}\chi S + \sum_q \frac{g_q y_q}{\sqrt{2}} \bar{q} q S$$ scalar mediator

$$\mathcal{L}_P \supset g_\chi \bar{\chi} i\gamma_5 \chi P + \sum_q \frac{g_q y_q}{\sqrt{2}} \bar{q} i\gamma_5 q P$$ pseudo-scalar mediator

[see for instance Boveia et al., 1603.04156]

LHC limits on vector mediators

[Boveia et al., 1603.04156]



LHC searches provide most stringent constraints in on-shell region, $M_{med} > 2m_{DM}$, of mass-mass plane. Off-shell region, $M_{med} < 2m_{DM}$, can be probed by mediator searches in SM final state for instance di-jets

LHC vs. direct detection

$$\boxed{\mathcal{L}_V} \longrightarrow \bar{\chi}\gamma_\mu\chi\bar{q}\gamma^\mu q \longrightarrow \boxed{\mathcal{O}_1 = 1_\chi 1_N}$$

$$\sigma_{\rm SI} = \frac{f^2(g_q) g_{\rm DM}^2 \mu_{n\chi}^2}{\pi M_{\rm med}^4}\,, \qquad \mu_{n\chi} = \frac{m_n m_{\rm DM}}{m_n + m_{\rm DM}}\,, \qquad m_n \simeq 0.939\,{\rm GeV}$$

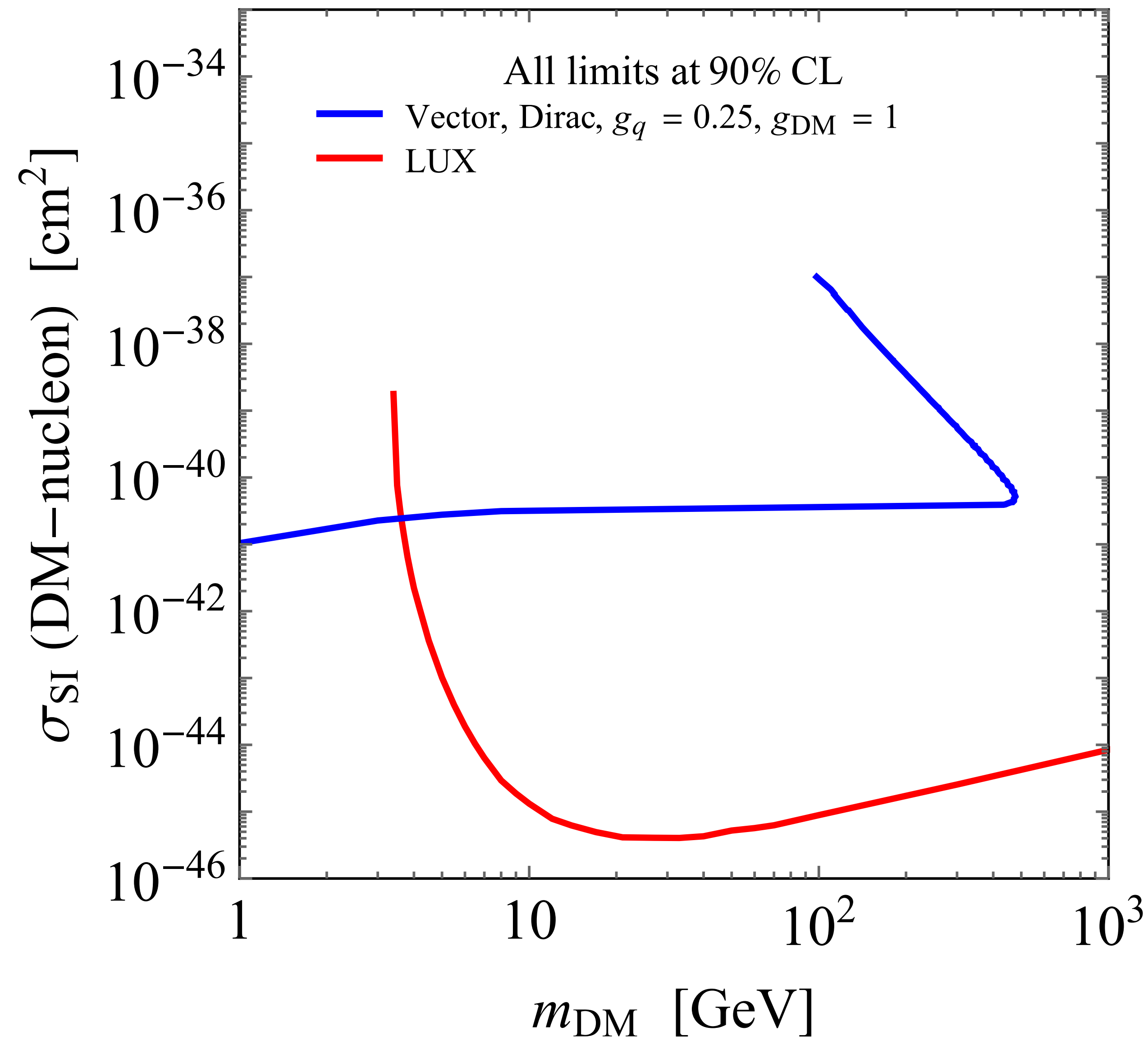
$$f(g_q) = 3 g_q$$

$$\sigma_{\rm SI} \simeq 6.9 \cdot 10^{-41}~{\rm cm}^2 \left(\frac{g_q g_{\rm DM}}{0.25}\right)^2 \left(\frac{1\,{\rm TeV}}{M_{\rm med}}\right)^4 \left(\frac{\mu_{n\chi}}{1\,{\rm GeV}}\right)^2$$

†formula for $f(g_q)$ assumes universal couplings to quarks

LHC vs. direct detection

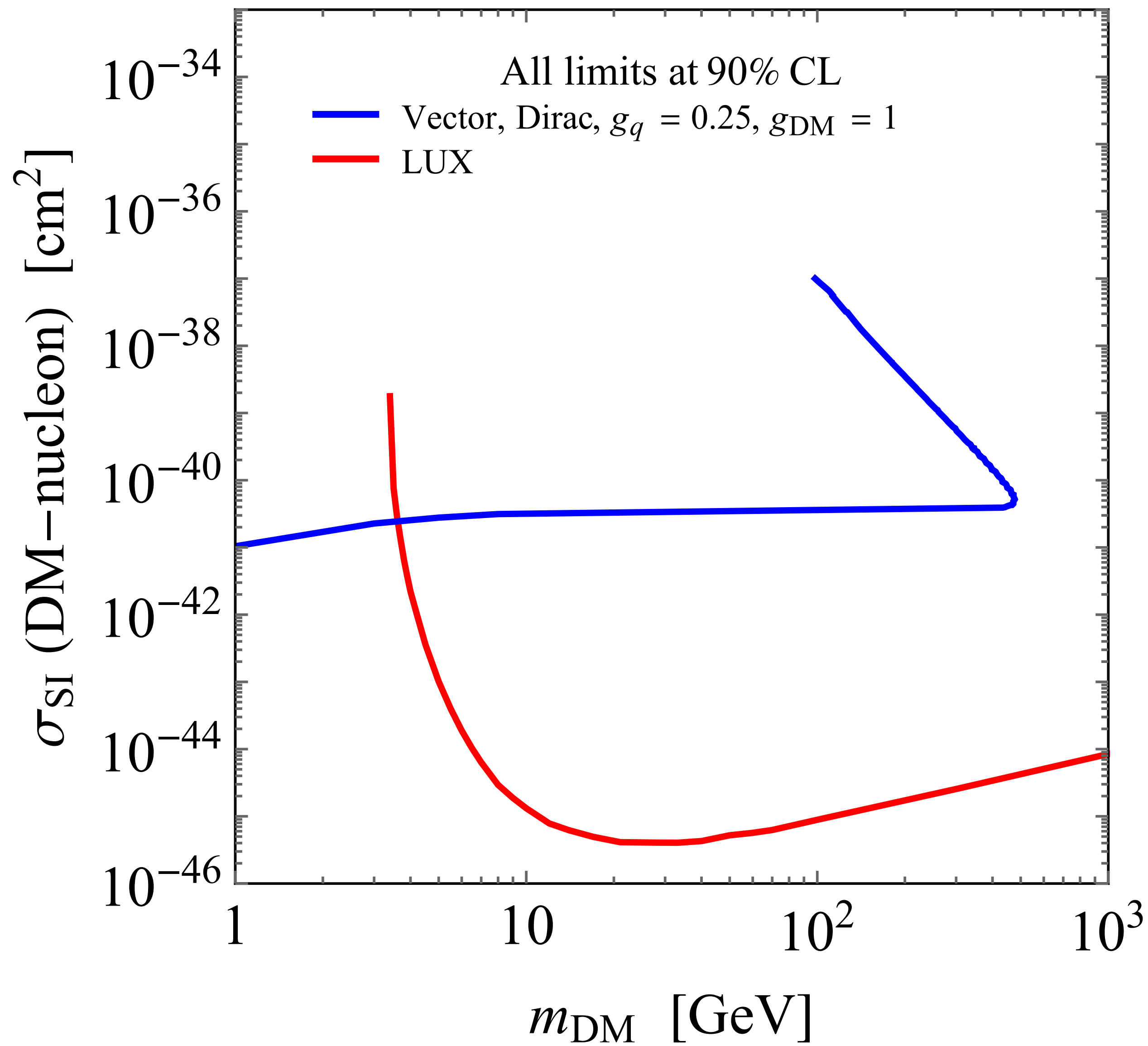
[Boveia et al., 1603.04156]



Like direct detection also mono-jet bound assumes that χ constitutes all of DM in Universe. If this is not case direct detection limit would become weaker, while LHC bound would remain unchanged

LHC vs. direct detection

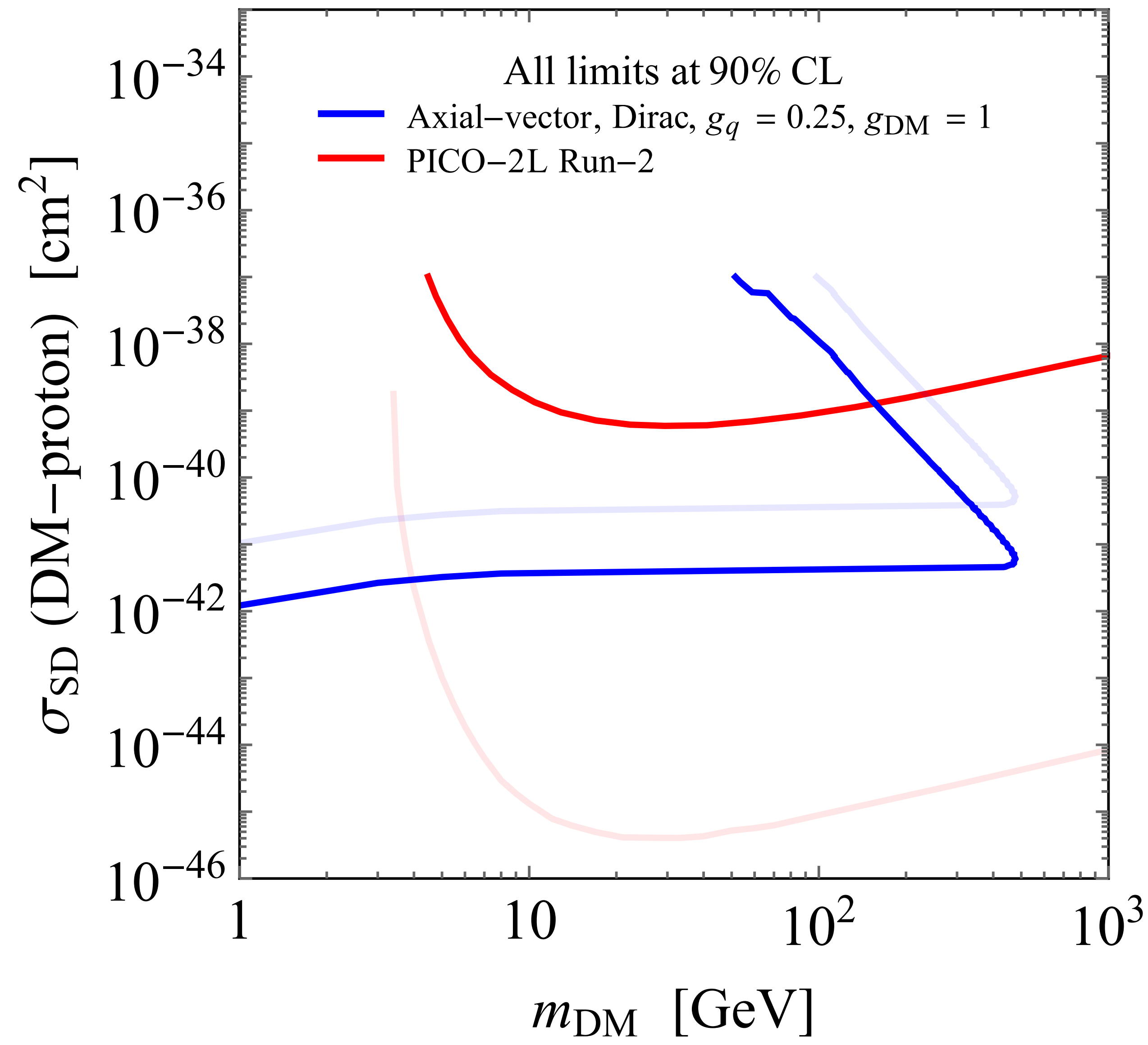
[Boveia et al., 1603.04156]



For SI interactions LHC only competitive for low DM mass, where direct detection is challenging due to small nuclear recoil

LHC vs. direct detection

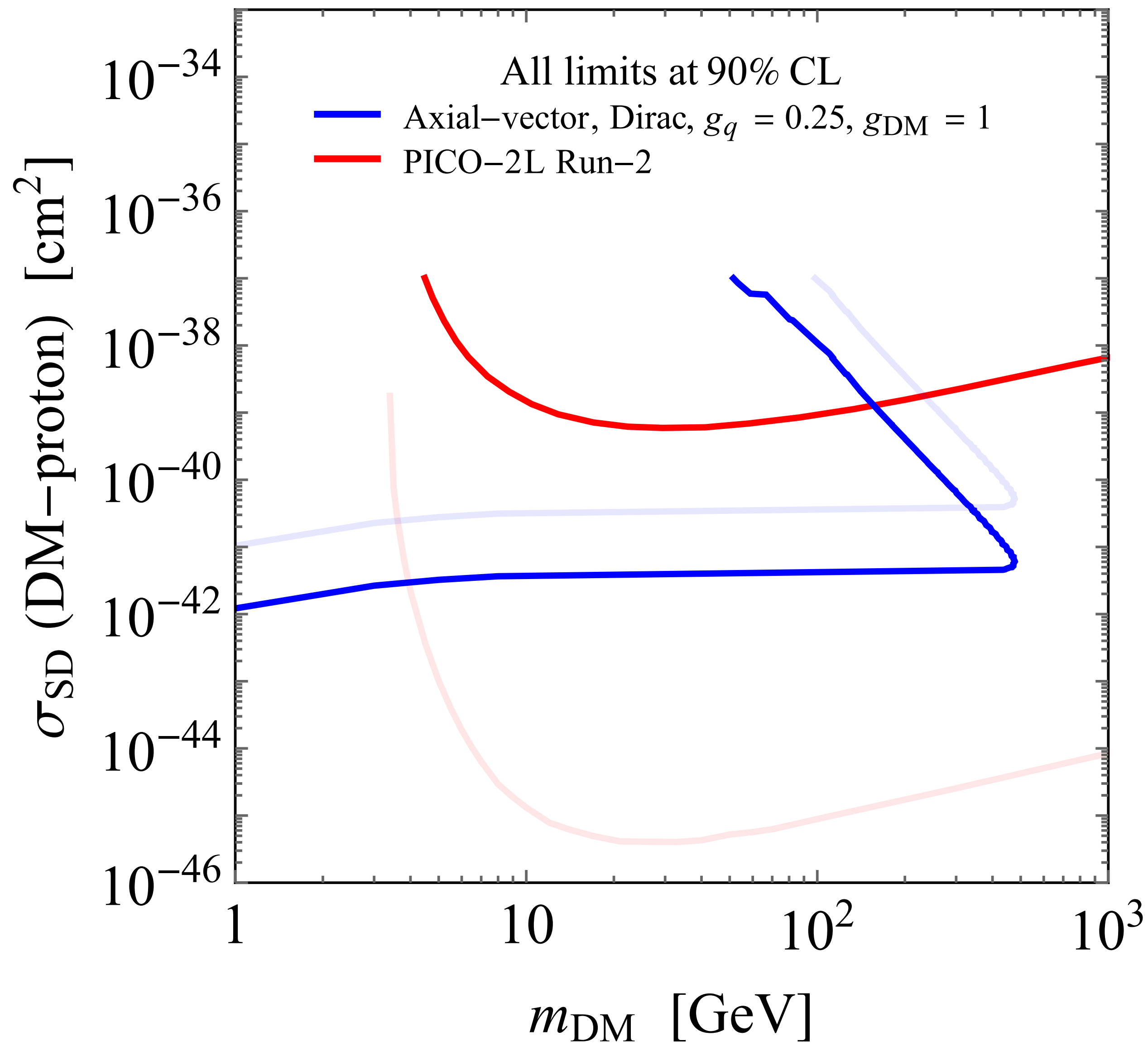
[Boveia et al., 1603.04156]



$\mathcal{L}_A$ ⟶ $\bar{\chi}\gamma_\mu\gamma_5\chi\bar{q}\gamma^\mu\gamma_5 q$ ⟶ $\mathcal{O}_4 = \vec{S}_\chi \cdot \vec{S}_N$

LHC vs. direct detection

[Boveia et al., 1603.04156]



While LHC limit quite similar, direct detection weakened significantly since DM-nucleon scattering is incoherent in SD case

DM-N scattering for spin-0 mediators

$$\mathcal{L}_S \longrightarrow \bar{\chi}\chi\bar{q}q \longrightarrow \mathcal{O}_1 = 1_\chi 1_N$$

$$\mathcal{L}_P \longrightarrow \bar{\chi}i\gamma_5\chi\bar{q}i\gamma_5 q \longrightarrow \mathcal{O}_6 = \frac{1}{m_N^2}\left(\vec{S}_\chi \cdot \vec{q}\right)\left(\vec{S}_N \cdot \vec{q}\right)$$

SI

SD & momentum suppressed

Due to loss of coherence & since q = O(0.1 GeV) resulting DM-N cross section O(10^{-11}) lower than σ_{SI}. As a result very poor direct detection limits

DM annihilation: pseudo-scalar case

$$\langle \sigma v_{\rm rel} \rangle_q = \frac{3m_q^2}{2\pi v^2} \frac{g_q^2 g_{\rm DM}^2 m_{\rm DM}^2}{(M_{\rm med}^2 - 4m_{\rm DM}^2)^2 + M_{\rm med}^2 \Gamma_{\rm med}^2} \sqrt{1 - \frac{m_q^2}{m_{\rm DM}^2}}$$

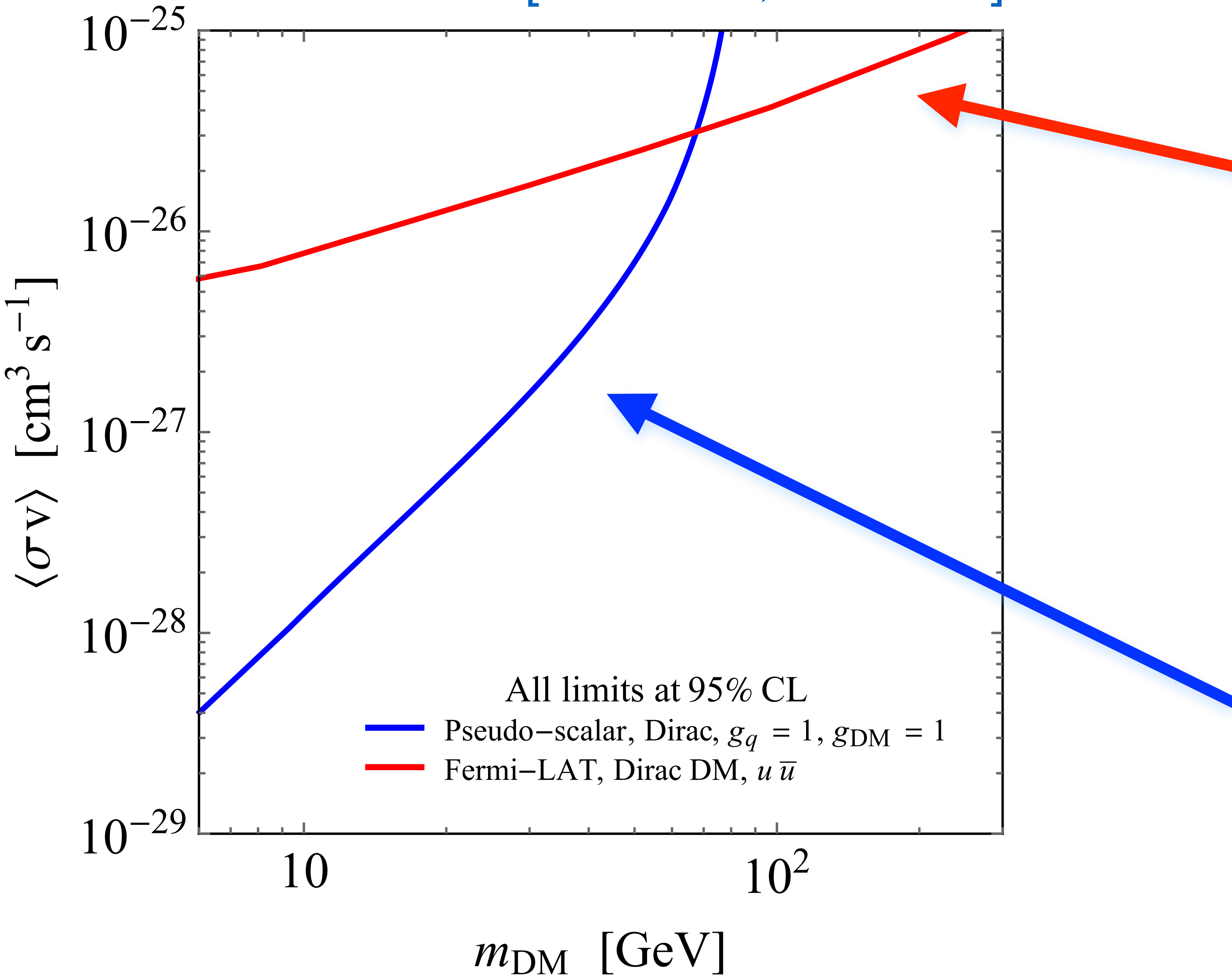
$$\langle \sigma v_{\rm rel} \rangle_g = \frac{\alpha_s^2}{2\pi^3 v^2} \frac{g_q^2 g_{\rm DM}^2}{(M_{\rm med}^2 - 4m_{\rm DM}^2)^2 + M_{\rm med}^2 \Gamma_{\rm med}^2} \left| \sum_q m_q^2 \, f_{\rm pseudo\text{-}scalar} \left(\frac{m_q^2}{m_\chi^2} \right) \right|^2$$

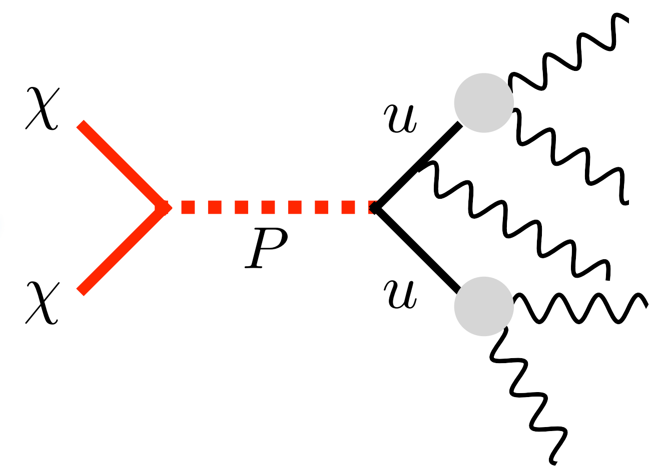
$$f_{\rm pseudo\text{-}scalar}(\tau) = \tau \arctan^2 \left(\frac{1}{\sqrt{\tau - 1}} \right)$$

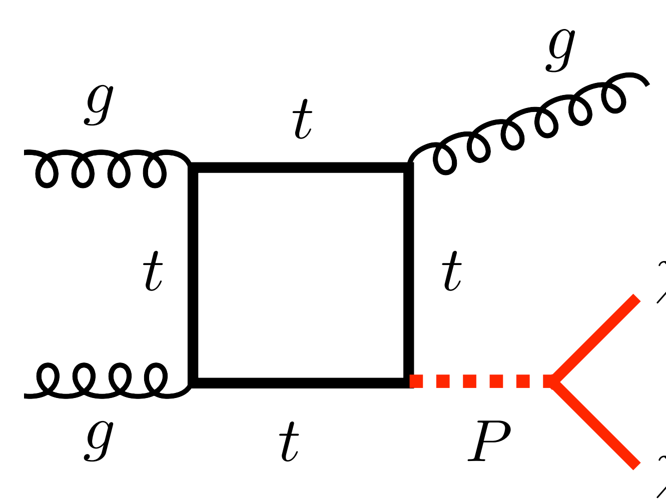
Due to m_q^2 terms annihilation to heaviest kinematically accessible quark dominates total annihilation rate

LHC vs. indirect detection

[Boveia et al., 1603.04156]







For pseudo-scalar mediator model nice complementarity between LHC mono-jet bound & indirect detection limit from Fermi-LAT

Conclusions

- Already a lot of 13 TeV ATLAS & CMS results for a broad range of searches for DM in $E_{T, miss}$+X with X = j, γ, W, Z, h, t, $t\bar{t}$, $b\bar{b}$, … & more to come soon

- Interpretations of LHC searches in context of simplified DM models provide information complementary to other DM searches such as direct & indirect detection experiments

Backup

1st LHC DM WG document

[Boveia et al., 1603.04156]

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

Antonio Boveia,[1,*] Oliver Buchmueller,[2,*] Giorgio Busoni,[3] Francesco D'Eramo,[4] Albert De Roeck,[1,5] Andrea De Simone,[6] Caterina Doglioni,[7,*] Matthew J. Dolan,[3] Marie-Helene Genest,[8] Kristian Hahn,[9,*] Ulrich Haisch,[10,11,*] Philip C. Harris,[1] Jan Heisig,[12] Valerio Ippolito,[13] Felix Kahlhoefer,[14,*] Valentin V. Khoze,[15] Suchita Kulkarni,[16] Greg Landsberg,[17] Steven Lowette,[18] Sarah Malik,[2] Michelangelo Mangano,[11,*] Christopher McCabe,[19,*] Stephen Mrenna,[20] Priscilla Pani,[21] Tristan du Pree,[1] Antonio Riotto,[11] David Salek,[19,22] Kai Schmidt-Hoberg,[14] William Shepherd,[23] Tim M.P. Tait,[24,*] Lian-Tao Wang,[25] Steven Worm[26] and Kathryn Zurek[27]

Document summarises proposal of LHC DM WG on how-to present LHC results on s-channel simplified DM models & how-to compare them to direct & indirect detection experiments

2nd LHC DM WG document

[Albert et al., 1703.05703]

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

Andreas Albert,[1,*] Mihailo Backović,[2] Antonio Boveia,[3,*]
Oliver Buchmueller,[4,*] Giorgio Busoni,[5,*] Albert De Roeck,[6,7]
Caterina Doglioni,[8,*] Tristan DuPree,[9,*] Malcolm Fairbairn,[10,*]
Marie-Hélène Genest,[11] Stefania Gori,[12] Giuliano Gustavino,[13]
Kristian Hahn,[14,*] Ulrich Haisch,[15,16,*] Philip C. Harris,[7]
Dan Hayden,[17] Valerio Ippolito,[18] Isabelle John,[8]
Felix Kahlhoefer,[19,*] Suchita Kulkarni,[20] Greg Landsberg,[21]
Steven Lowette,[22] Kentarou Mawatari,[11] Antonio Riotto,[23]
William Shepherd,[24] Tim M.P. Tait,[25,*] Emma Tolley,[3]
Patrick Tunney,[10,*] Bryan Zaldivar,[26,*] Markus Zinser[24]

Document suggests an extension of spin-1 simplified models to include couplings of mediators to leptons & emphasises importance of t-channel contributions in relic density calculations

DM-N cross section: scalar case

$$\sigma_{\rm SI} = \frac{f^2(g_q) g_{\rm DM}^2 \mu_{n\chi}^2}{\pi M_{\rm med}^4} \,, \qquad \mu_{n\chi} = \frac{m_n m_{\rm DM}}{m_n + m_{\rm DM}} \,, \qquad m_n \simeq 0.939\,{\rm GeV}$$

$$f(g_q) = 1.16 \cdot 10^{-3}\, g_q$$

$$\sigma_{\rm SI} \simeq 6.9 \cdot 10^{-43}\ {\rm cm}^2 \left(\frac{g_q g_{\rm DM}}{1}\right)^2 \left(\frac{125\,{\rm GeV}}{M_{\rm med}}\right)^4 \left(\frac{\mu_{n\chi}}{1\,{\rm GeV}}\right)^2$$

† formula for $f(g_q)$ assumes universal couplings to quarks

DM-N cross section: axial-vector case

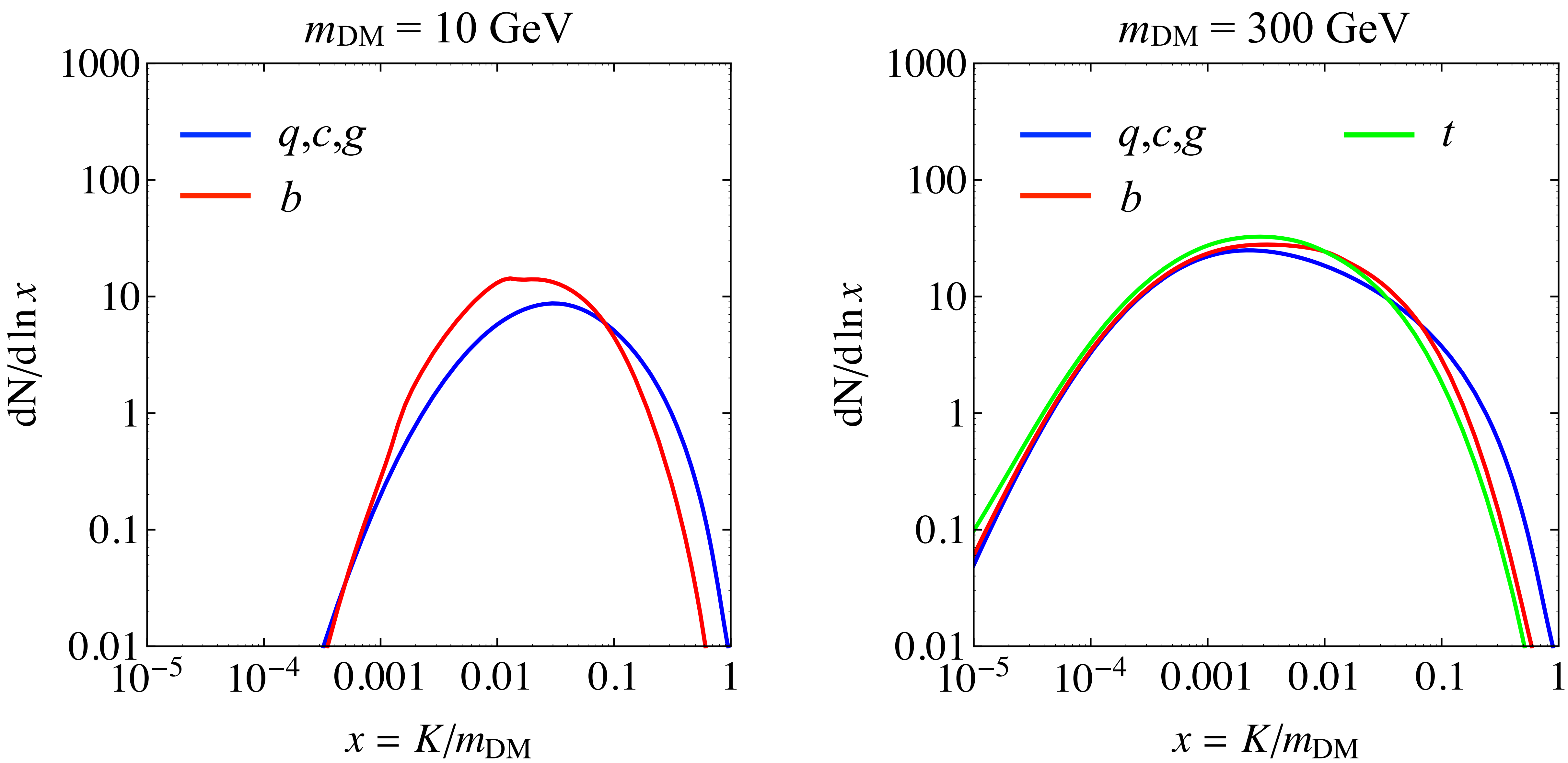
$$\sigma_{\rm SD} = \frac{3 f^2(g_q) g_{\rm DM}^2 \mu_{n\chi}^2}{\pi M_{\rm med}^4}\,, \qquad \mu_{n\chi} = \frac{m_n m_{\rm DM}}{m_n + m_{\rm DM}}\,, \qquad m_n \simeq 0.939\,{\rm GeV}$$

$$f(g_q) = 0.32\, g_q$$

$$\sigma_{\rm SD} \simeq 2.4 \cdot 10^{-42}\ {\rm cm}^2 \left(\frac{g_q g_{\rm DM}}{0.25}\right)^2 \left(\frac{1\,{\rm TeV}}{M_{\rm med}}\right)^4 \left(\frac{\mu_{n\chi}}{1\,{\rm GeV}}\right)^2$$

† formula for $f(g_q)$ assumes universal couplings to quarks

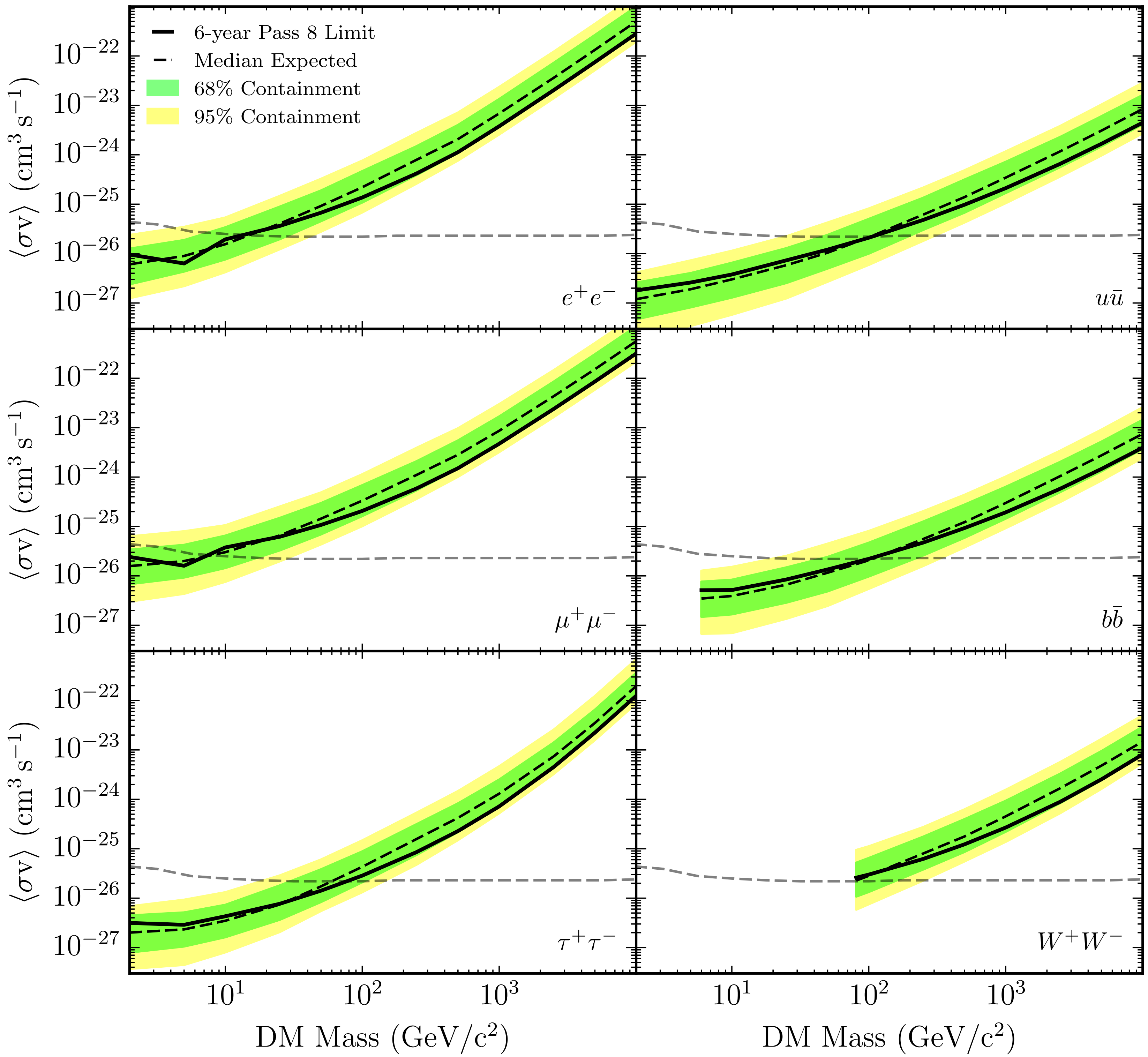
γ-ray spectra from DM annihilation



[UH using results from Cirelli et al., 1012.4515; http://www.marcocirelli.net/PPPC4DMID.html]

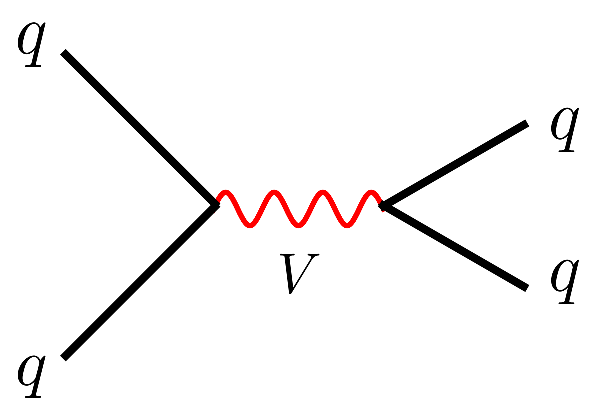
DM annihilation bounds from dwarfs

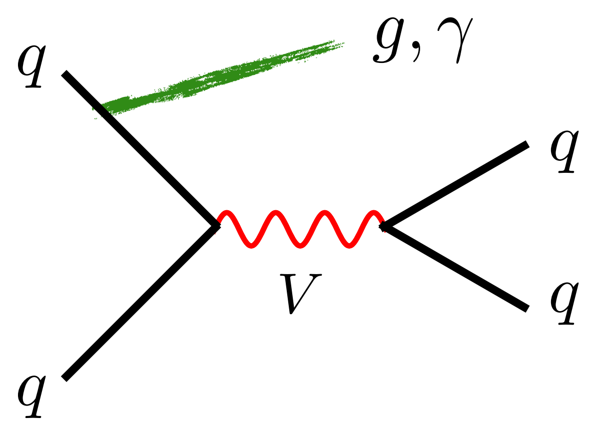
[Fermi-LAT, 1503.02641]

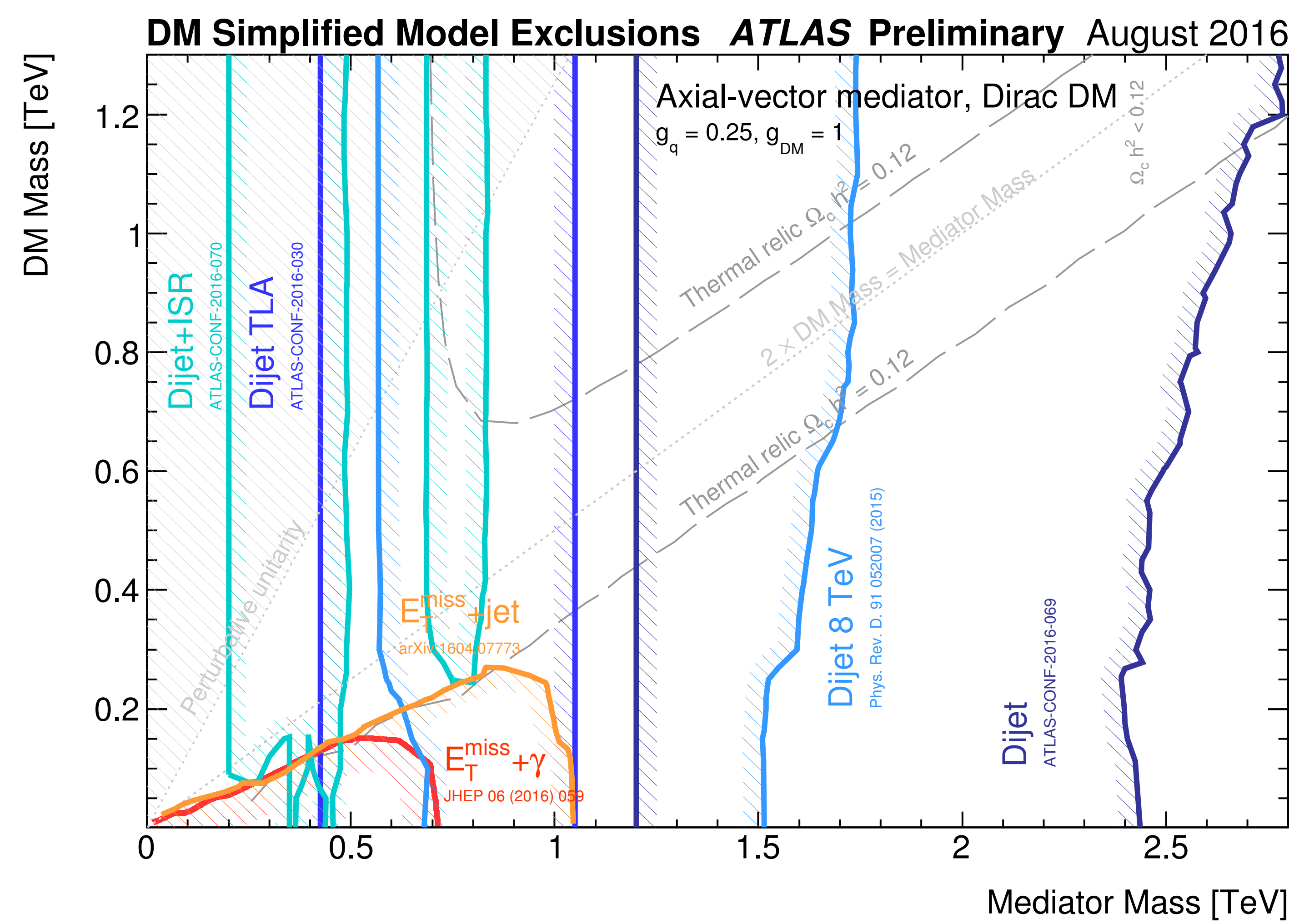


Spin-1 simplified models: di-jet limits

[https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults]



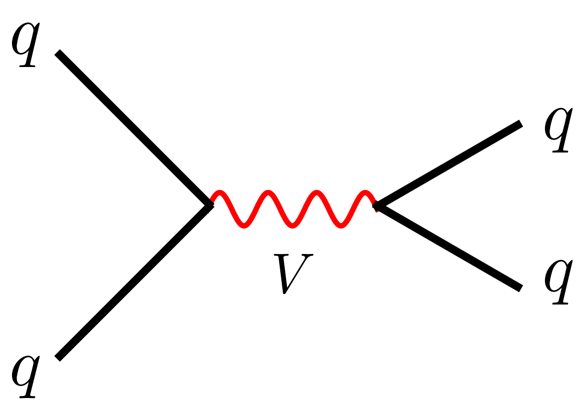


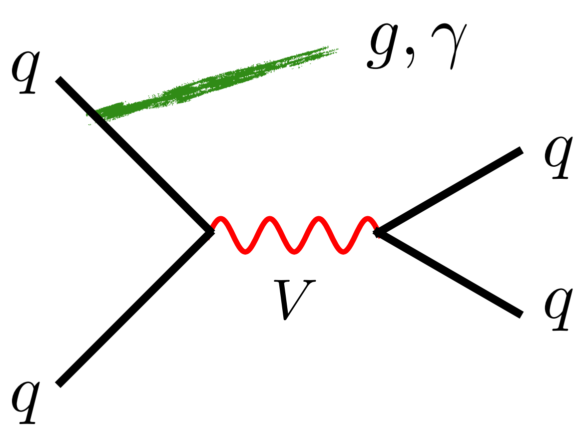


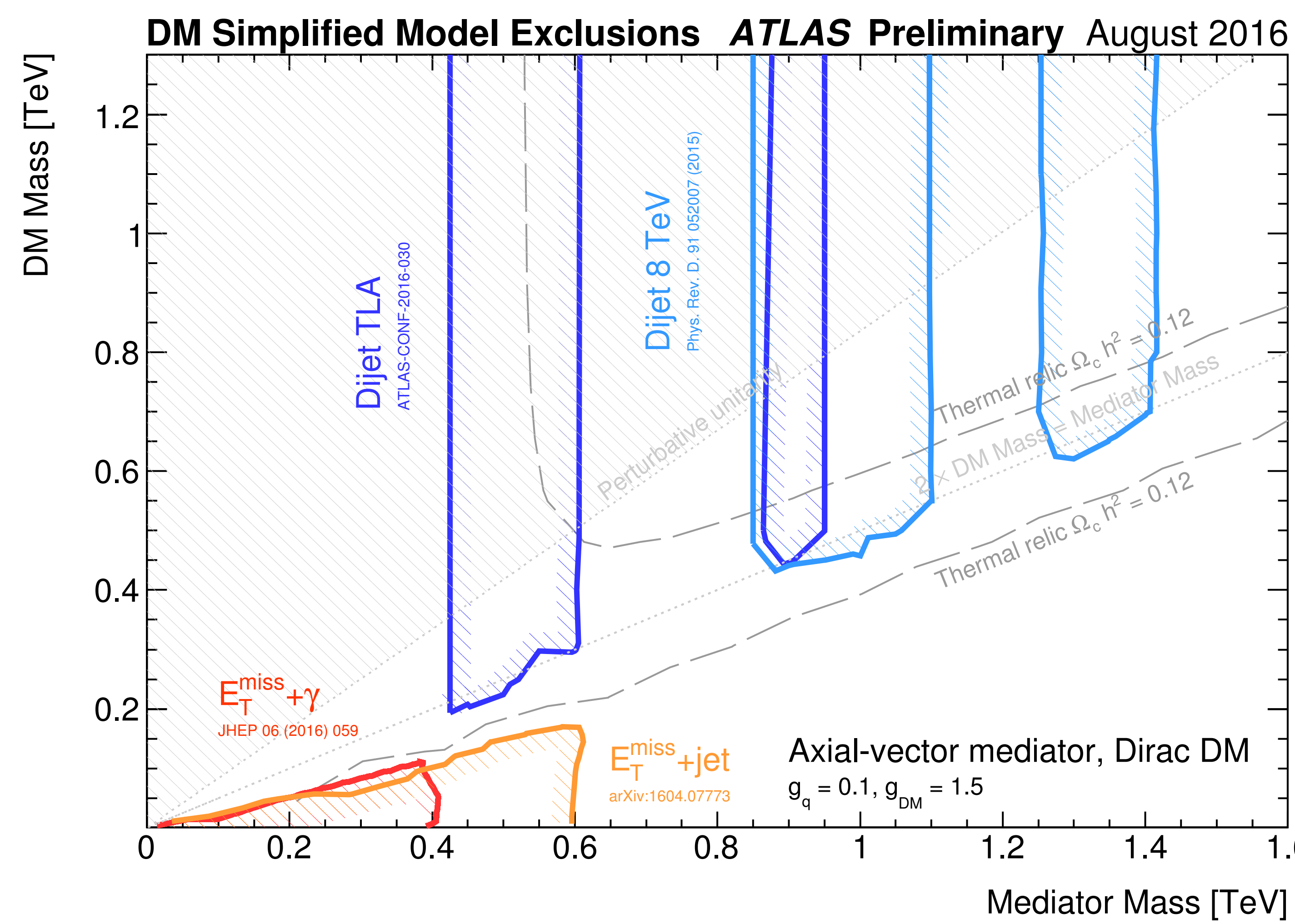
For coupling choice $g_q = 0.25$, $g_\chi = 1$ di-jet searches provide complementary constraints & exclude mediator masses from 200 GeV to 2.8 TeV

Spin-1 simplified models: di-jet limits

[https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults]



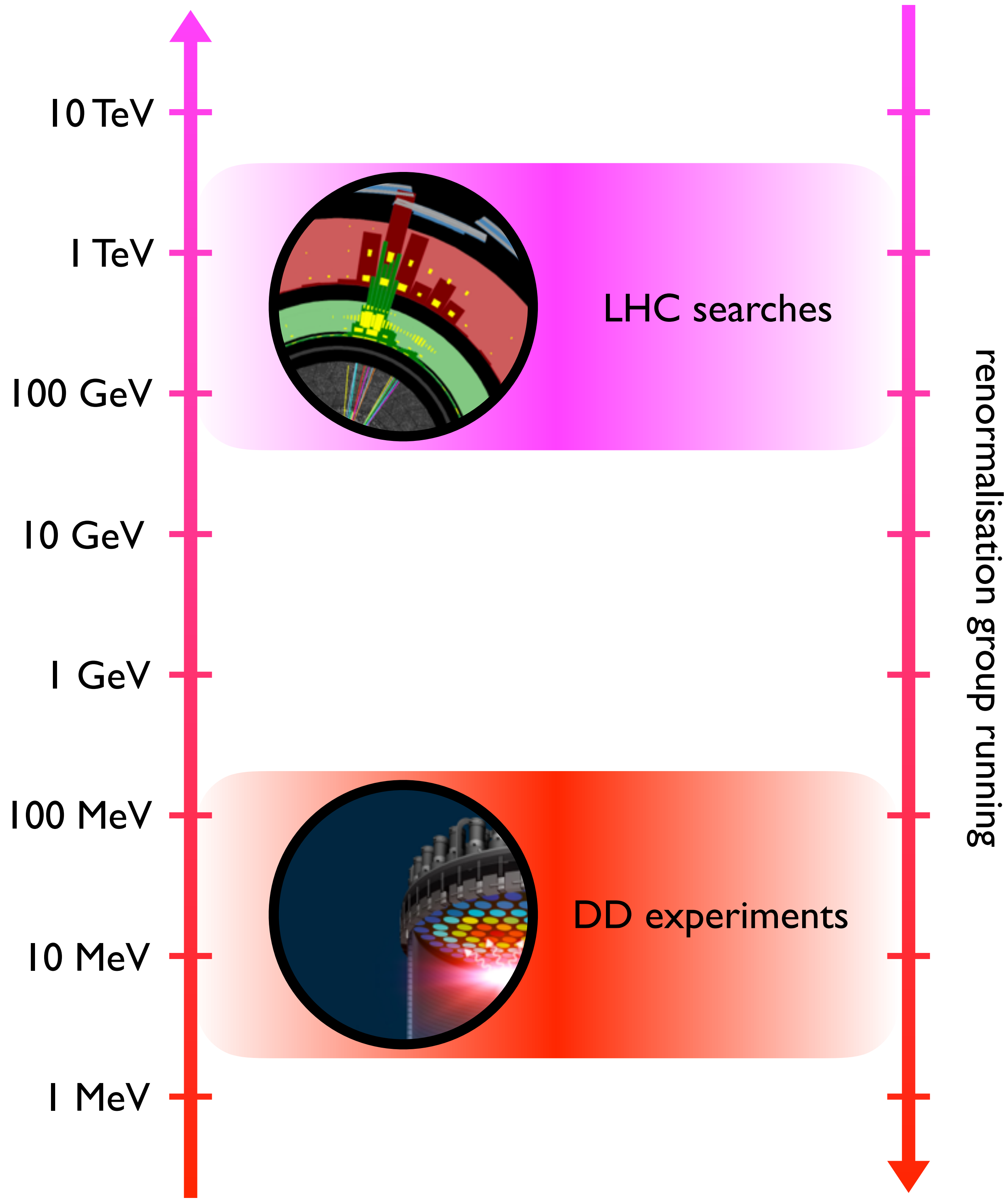




Di-jet limits can be weakened by reducing mediator-quark couplings g_q.

If g_χ kept perturbative mono-jet bounds also mitigated in such a case

Classification of DM-N interactions

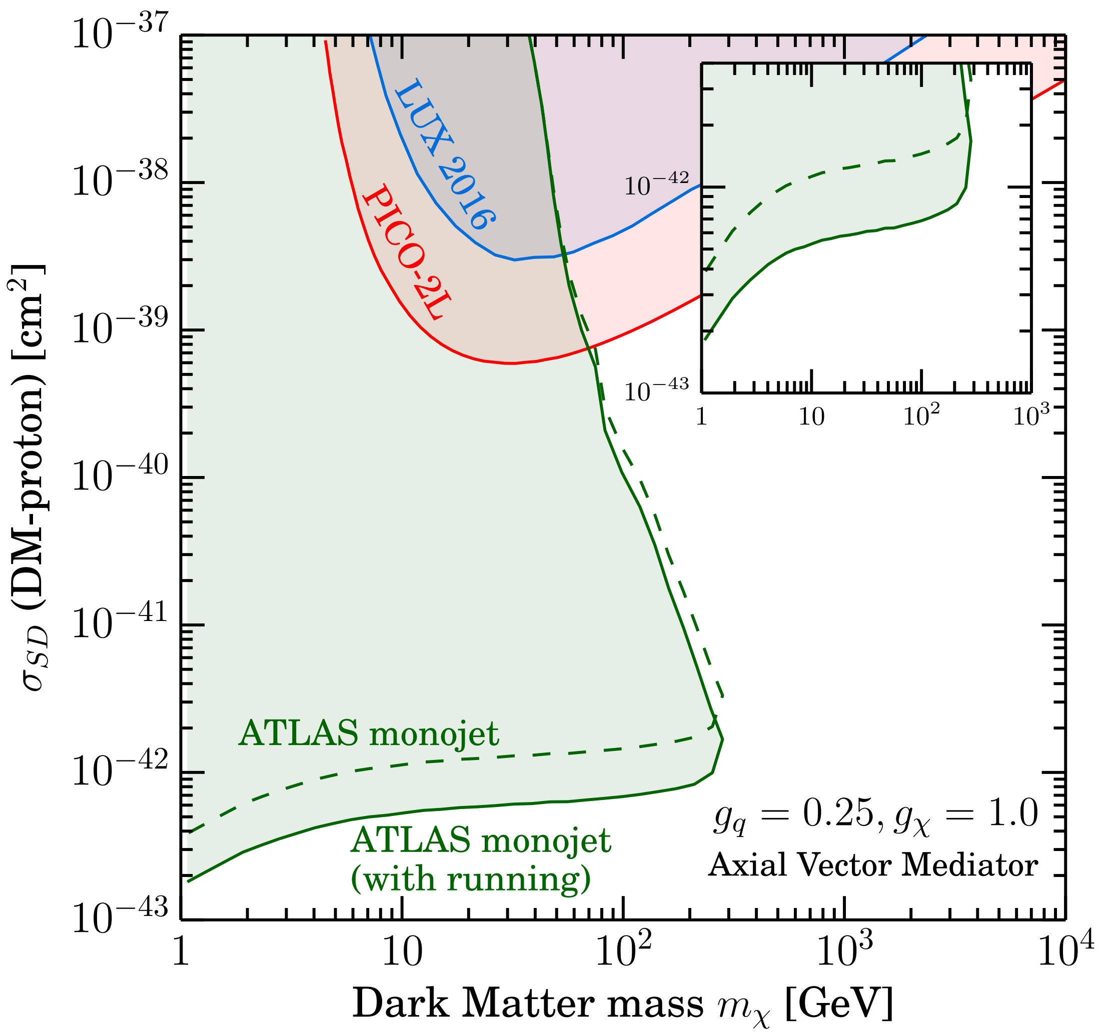


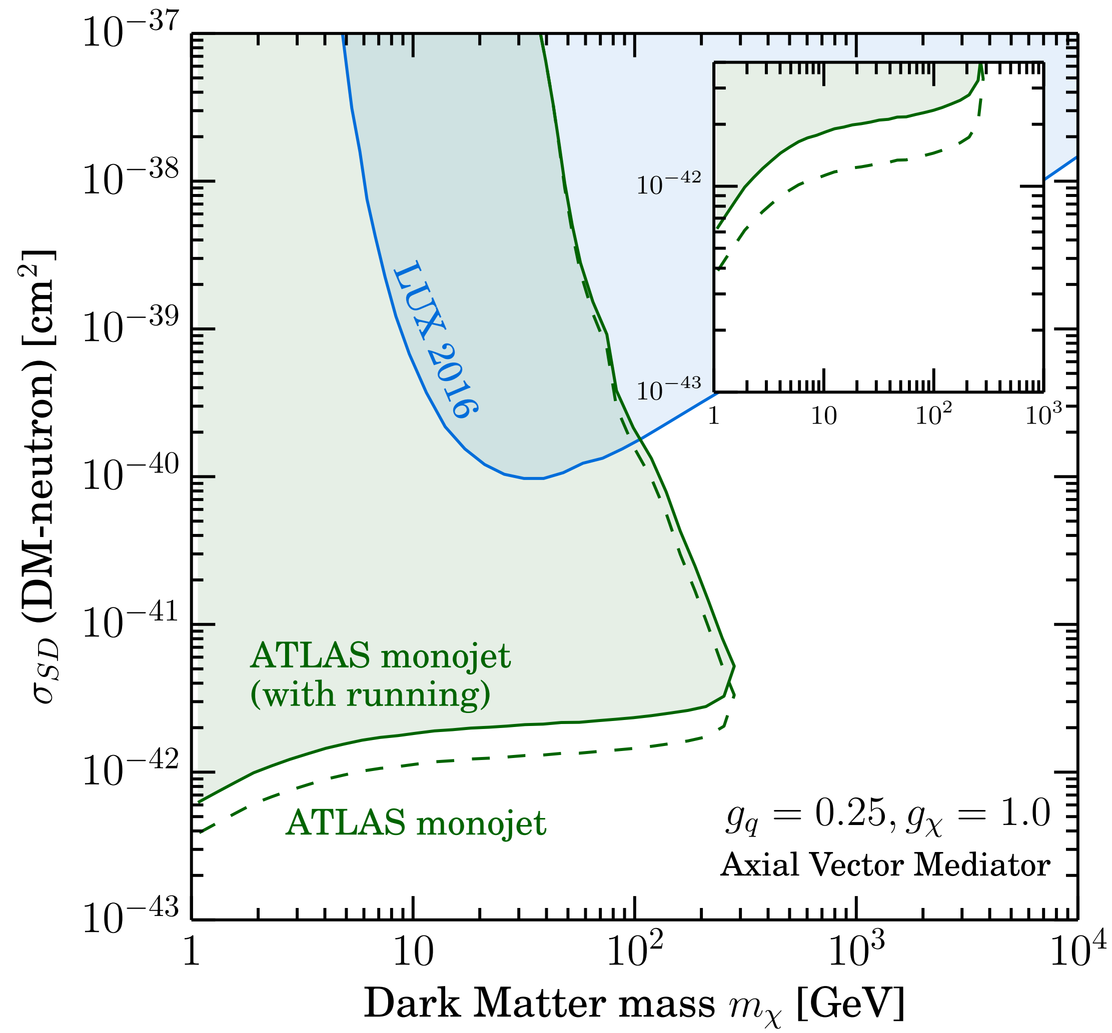
Distinction between SI & SD (or q-suppressed) DM-N couplings not stable under radiative corrections. Effects particular important for mixing of suppressed into unsuppressed operators

[Kopp et al., 0907.3159; Freytsis & Ligeti, 1012.5317;
Hill & Solon, 1111.0016; UH & Kahlhoefer 1302.4454;
Crivellin et al. 1402.1173, 1408.5046;
D'Eramo et al. 1409.2893; …]

Spin-1 simplified models: running effects

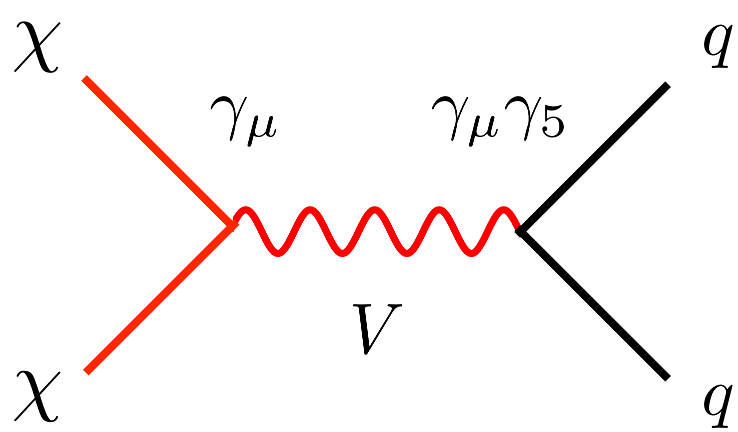
[D'Eramo et al., 1605.04917]





In vector mediator model running effects are negligible, while in axialvector case cross-section bounds are changed by a factor of 2

From SD to SI DM-N interactions



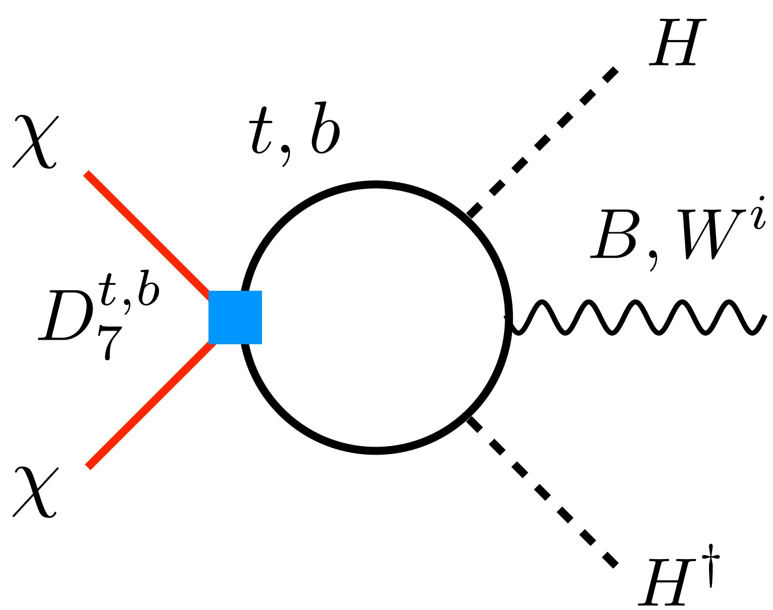
$$= C_7^q D_7^q$$

$$C_7^q = -\frac{g_\chi g_q}{M_V^2}\,, \qquad D_7^q = \bar{\chi}\gamma^\mu \chi \bar{q}\gamma_\mu \gamma_5 q$$

operator leads to SD DM-N interactions
that are both v^2 & q^2 suppressed

From SD to SI DM-N interactions

[Crivellin et al. 1402.1173]

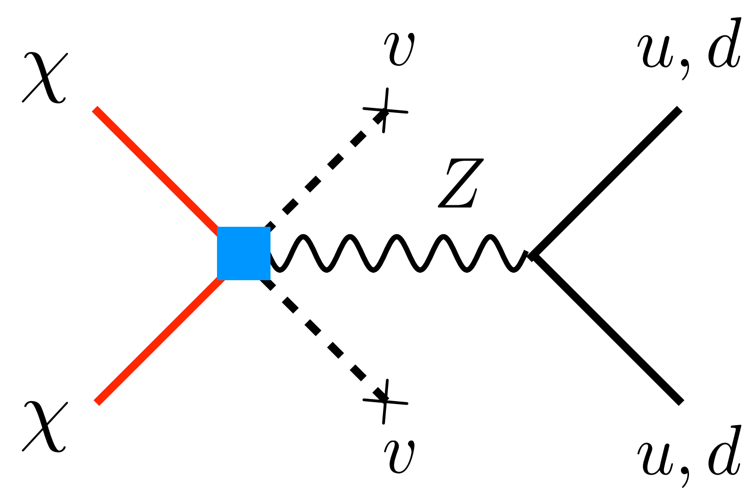


$$= C_H D_H$$

$$C_H = -\sum_{q=t,b} \frac{3y_q^2 T_3^q C_7^q}{2\pi^2} \ln\left(\frac{v}{M_V}\right), \qquad D_H = \bar{\chi}\gamma^\mu\chi \left(H^\dagger i \overleftrightarrow{D}_\mu H\right)$$

From SD to SI DM-N interactions

[Crivellin et al. 1402.1173]



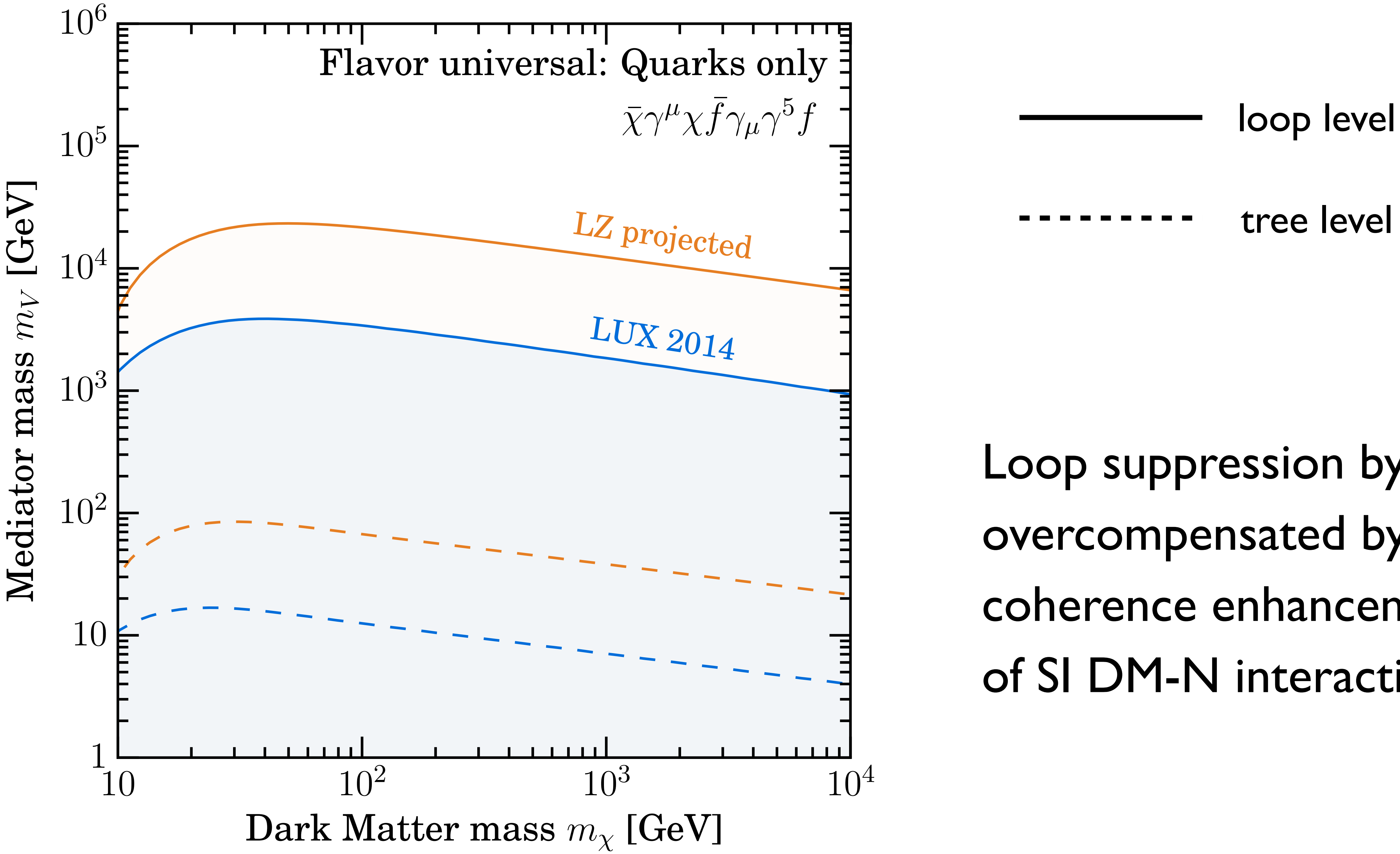
$$= C_5^{u,d} D_5^{u,d}$$

$$C_5^q = \frac{g_\chi}{M_V^2}\left(T_3^q - 2Q_q s_w^2\right)\sum_{p=t,b}\frac{3y_p^2 g_p T_3^p}{2\pi^2}\ln\left(\frac{v}{M_V}\right), \quad D_5^q = \bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$$

operator leads to SI DM-N interactions

From SD to SI DM-N interactions

[D'Eramo et al., 1605.04917]



Loop suppression by far overcompensated by coherence enhancement of SI DM-N interactions