'You Better Run'

Connecting low-energy Dark Matter searches with high-energy physics

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University of Nottingham - 16th June 2016

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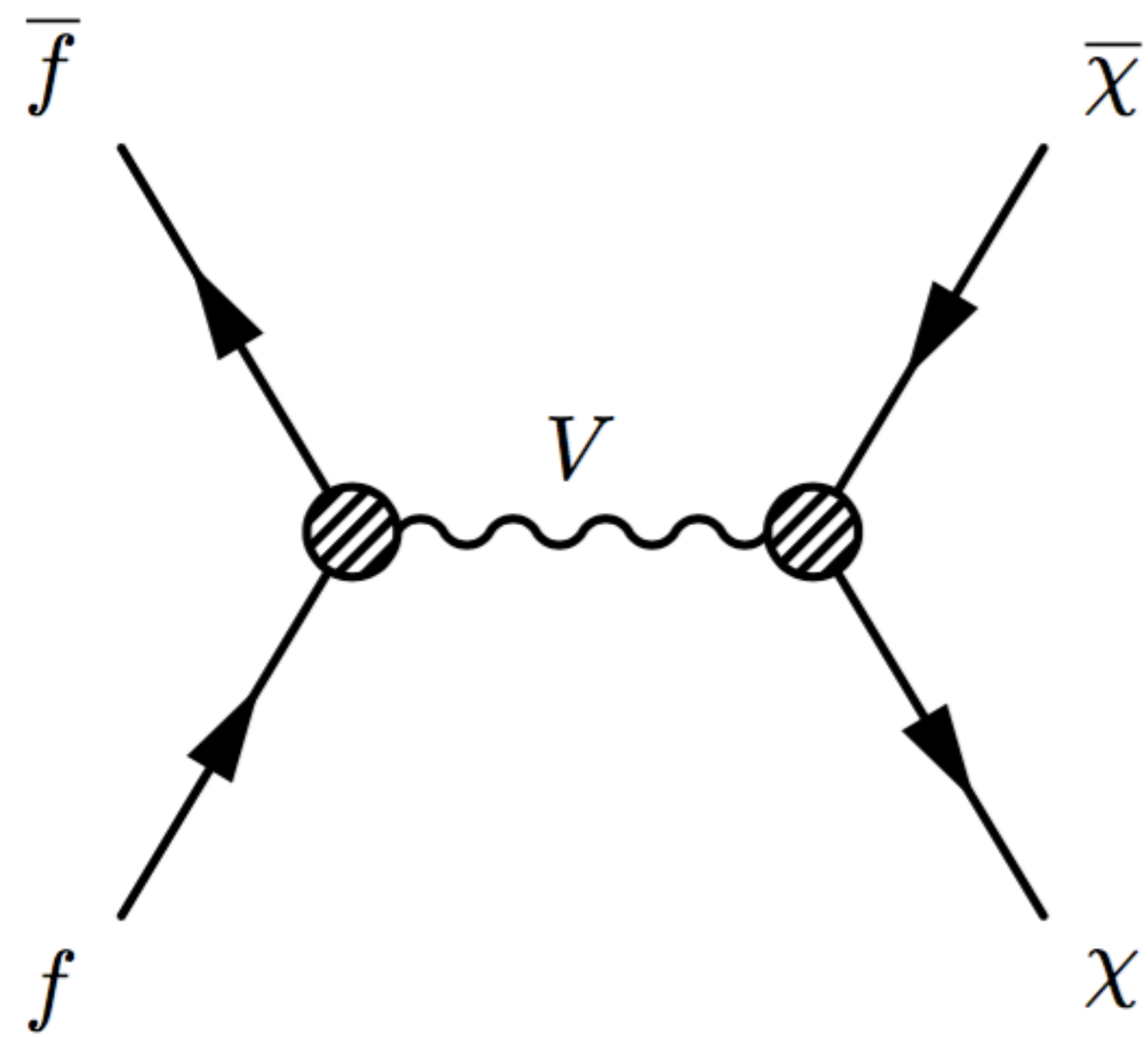
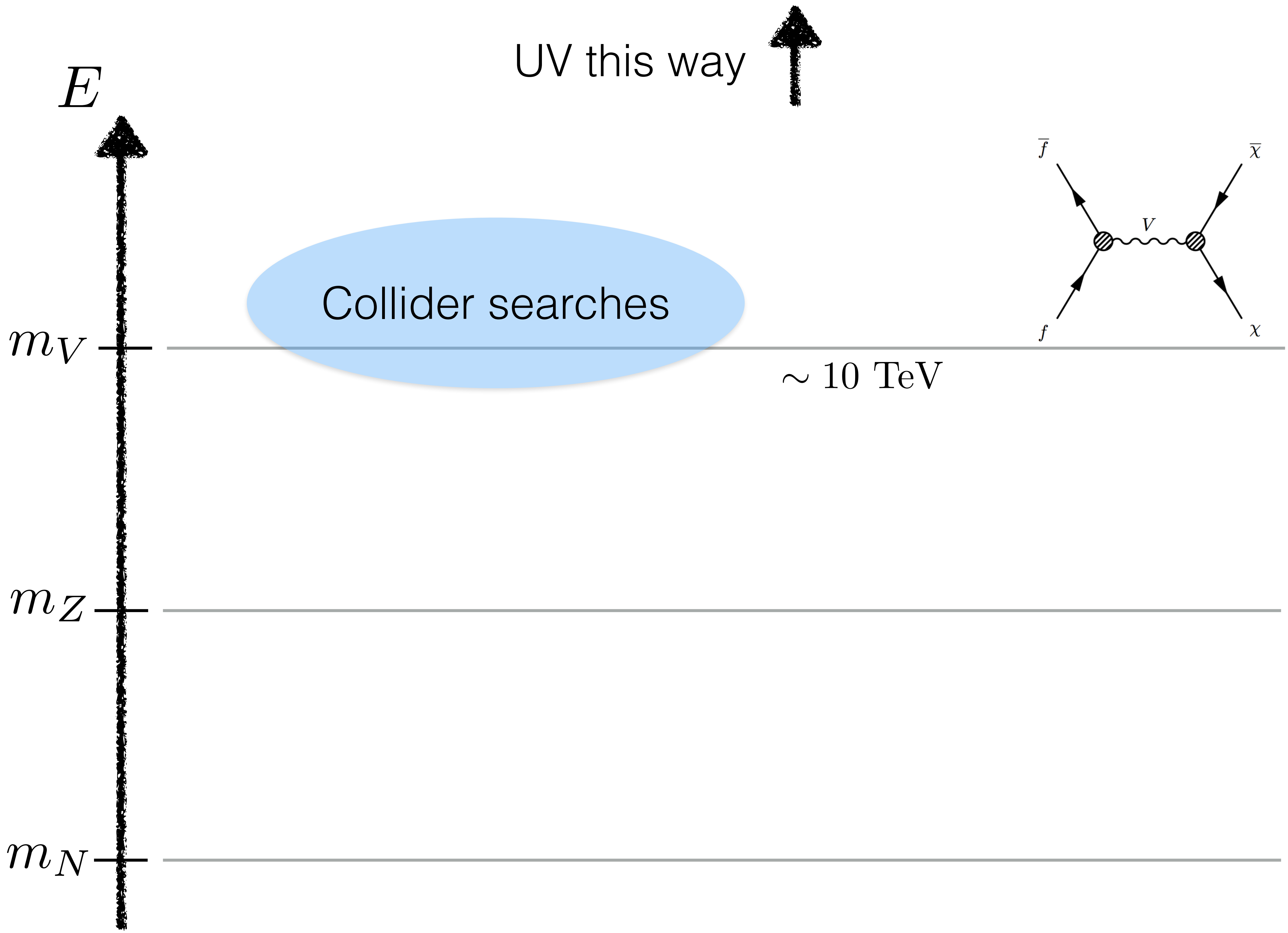
@BradleyKavanagh


$\overline{f}$
$\overline{\chi}$
V
f
χ


UV this way
E
Collider searches
m_V
~ 10 TeV
m_Z
m_N
$\bar{f}$
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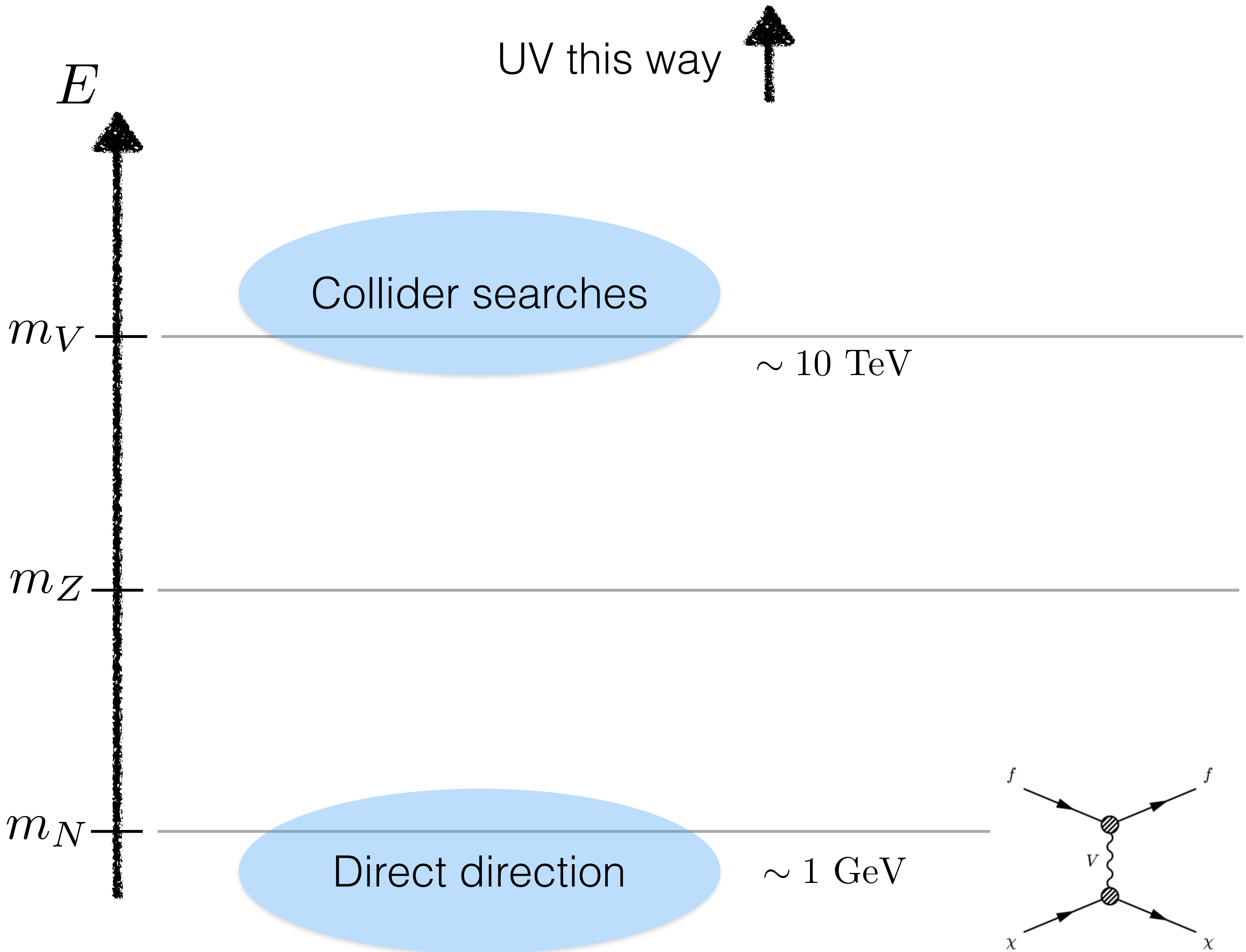
V
f
χ


UV this way
E
m_V
Collider searches
~ 10 TeV
m_Z
m_N
Direct direction
~ 1 GeV
f
f
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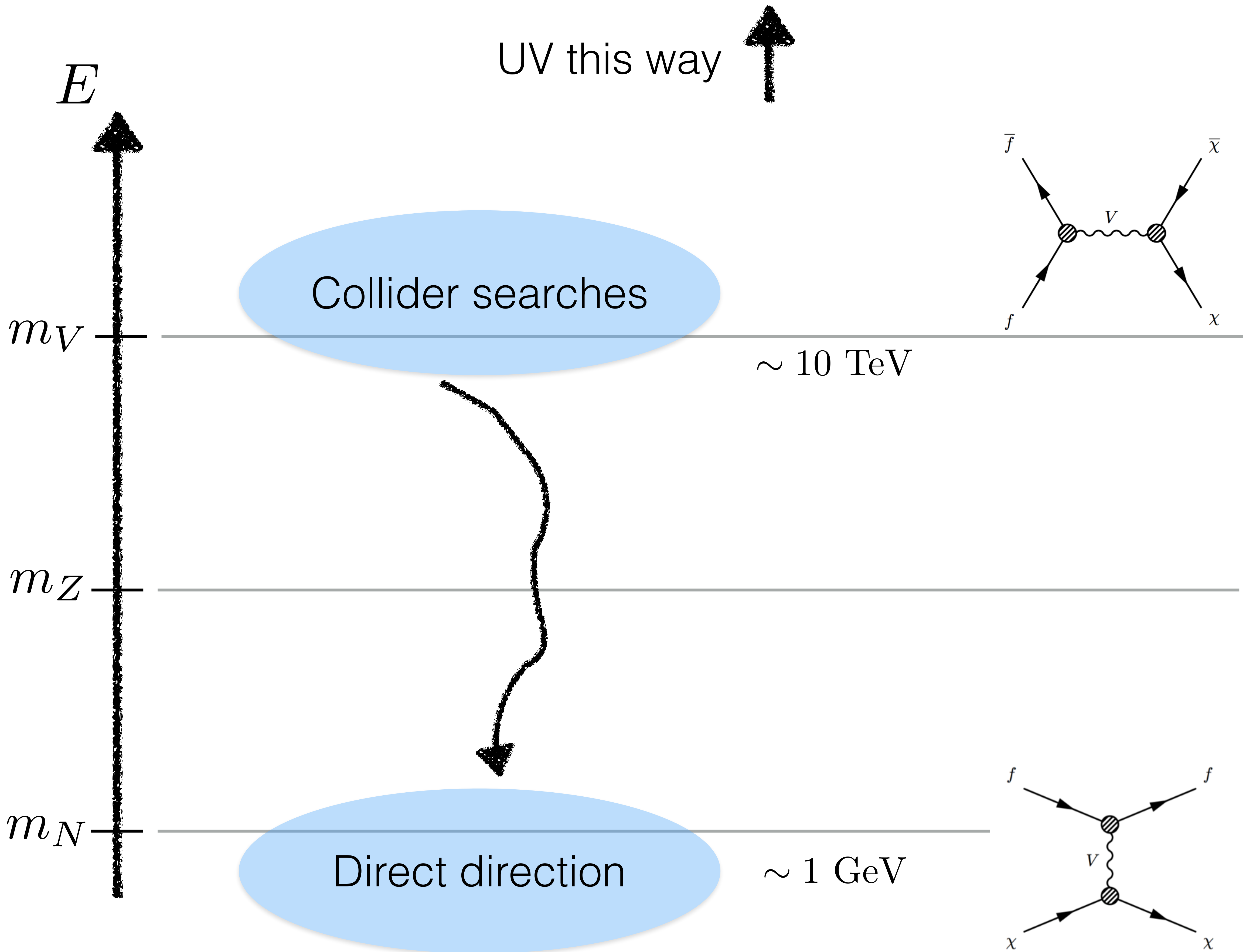
UV this way
E
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Direct direction
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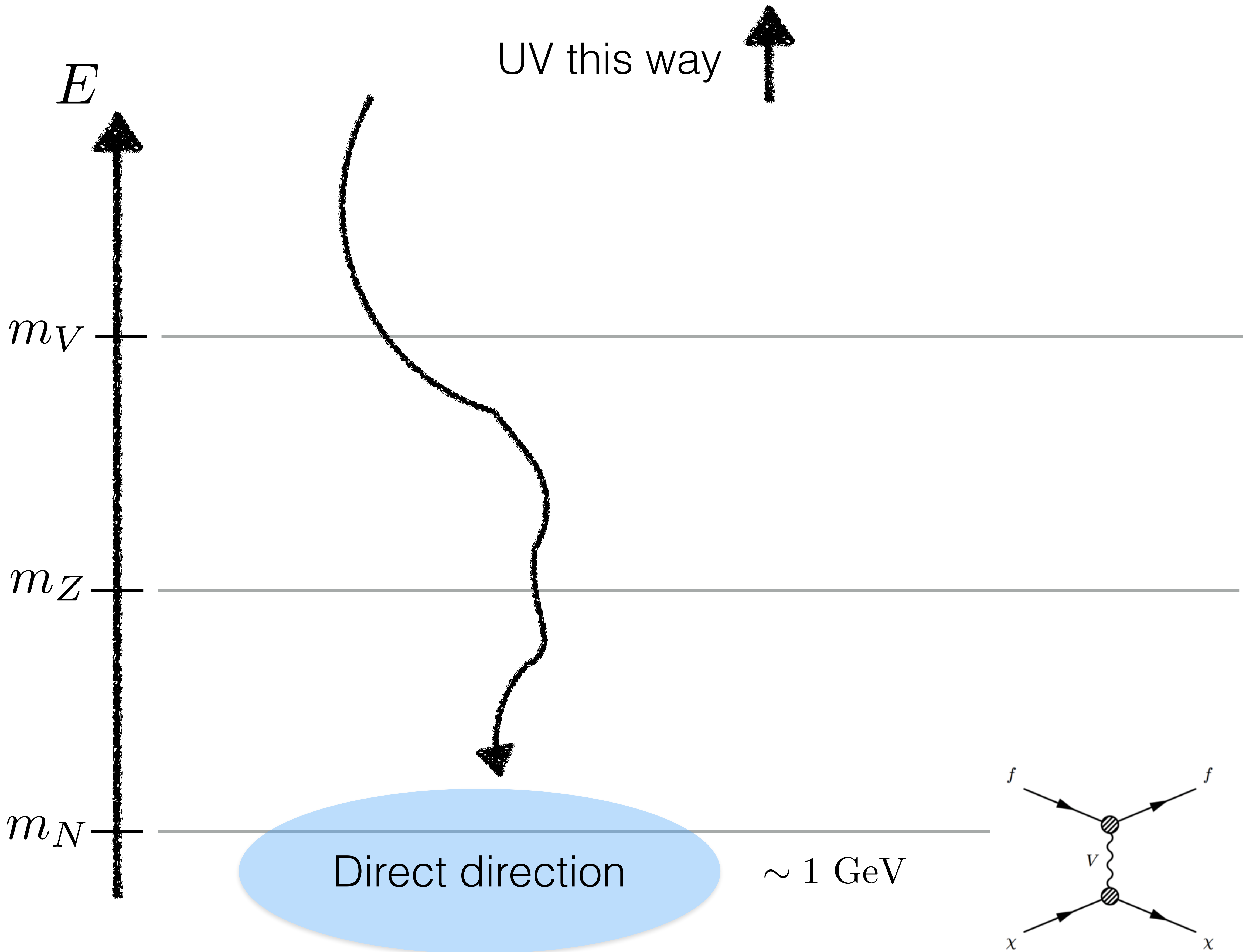

UV this way
E
m_V
m_Z
m_N
Direct direction
~ 1 GeV
f
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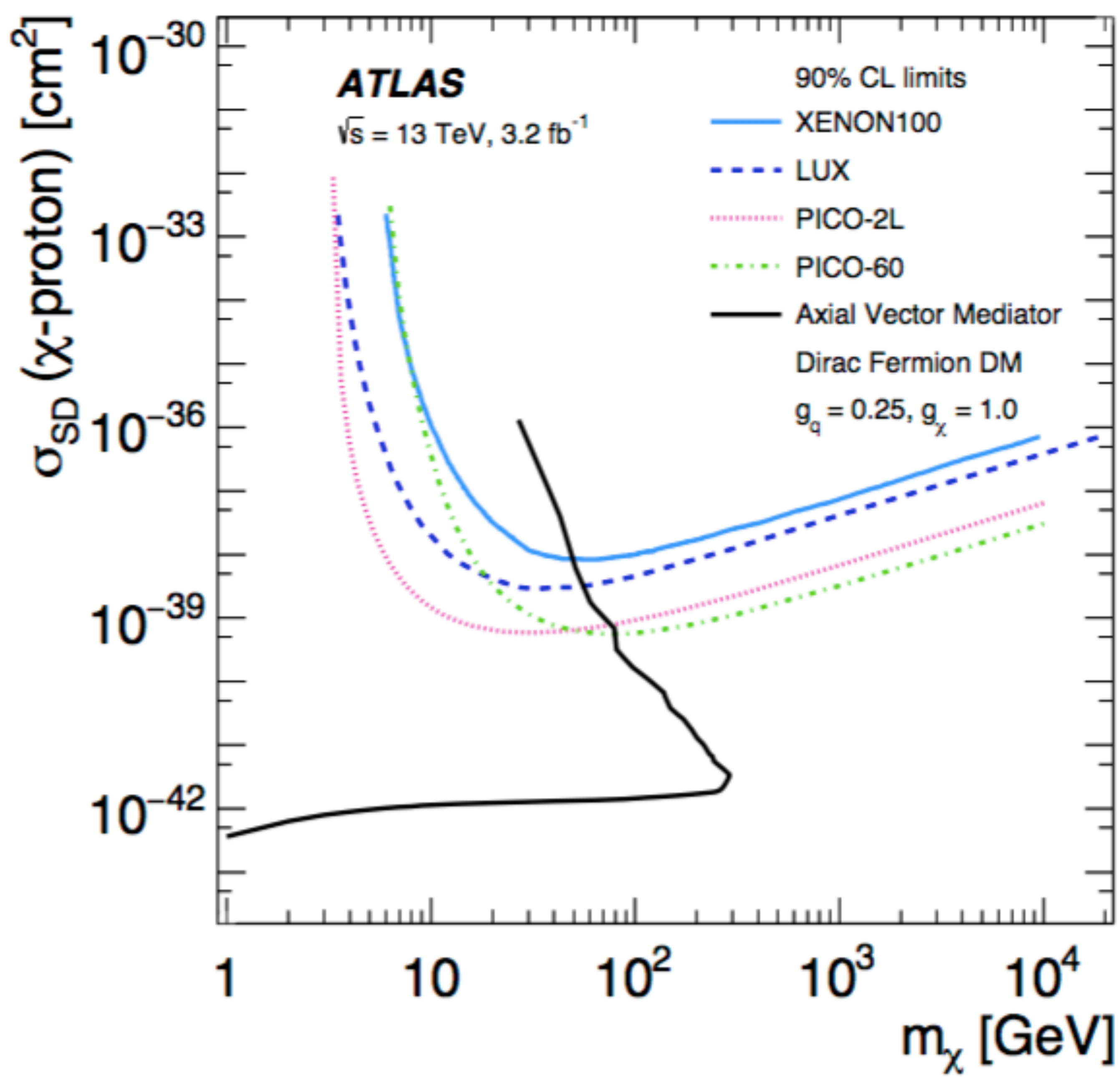
χ
χ

Comparing different searches



ATLAS [1604.07773]

Zemeckis, Hanks (1994)

Outline

Simplified Models

De Simone, Jacques [1603.08002]

RG effects in Simplified Models

Crivellin, D'Eramo, Procura [1402.1173]; D'Eramo, Procura [1411.3342]

Direct detection constraints on Simplified Models

D'Eramo, Procura [1411.3342]; D'Eramo, BJK, Panci [1605.04917]

Comparing DD and LHC searches

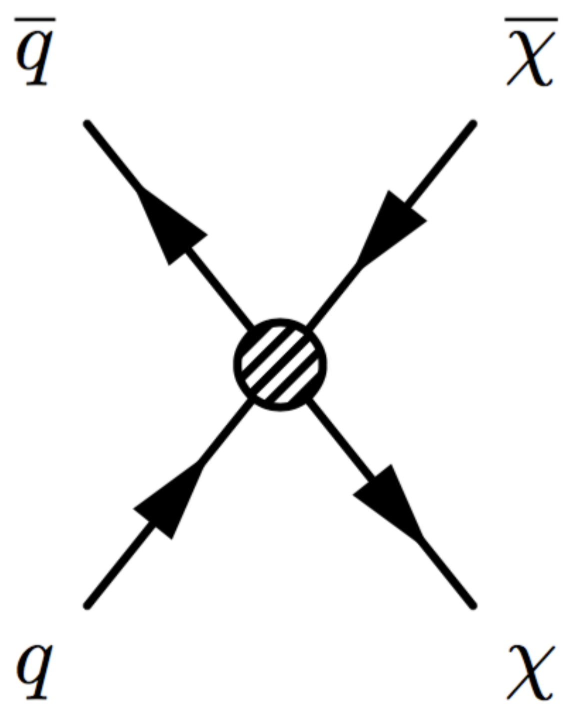
D'Eramo, BJK, Panci [1605.04917]

Simplified Models

Effective Field Theory

Assume mass of mediator is much larger than momentum transfer

integrate out mediator to obtain a contact interaction

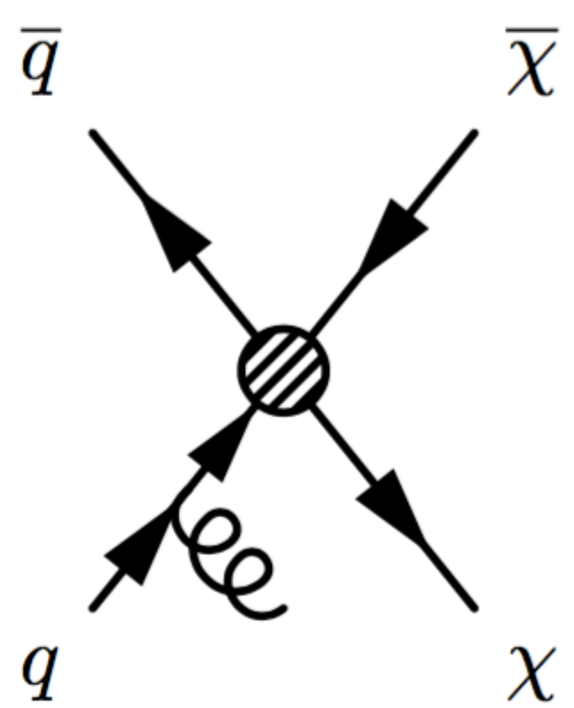


Name	Operator	Coefficient
D1	$\bar{\chi}\chi\bar{q}q$	m_q/M_*^3
D2	$\bar{\chi}\gamma^5\chi\bar{q}q$	im_q/M_*^3
D3	$\bar{\chi}\chi\bar{q}\gamma^5 q$	im_q/M_*^3
D4	$\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$	m_q/M_*^3
D5	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D6	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
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

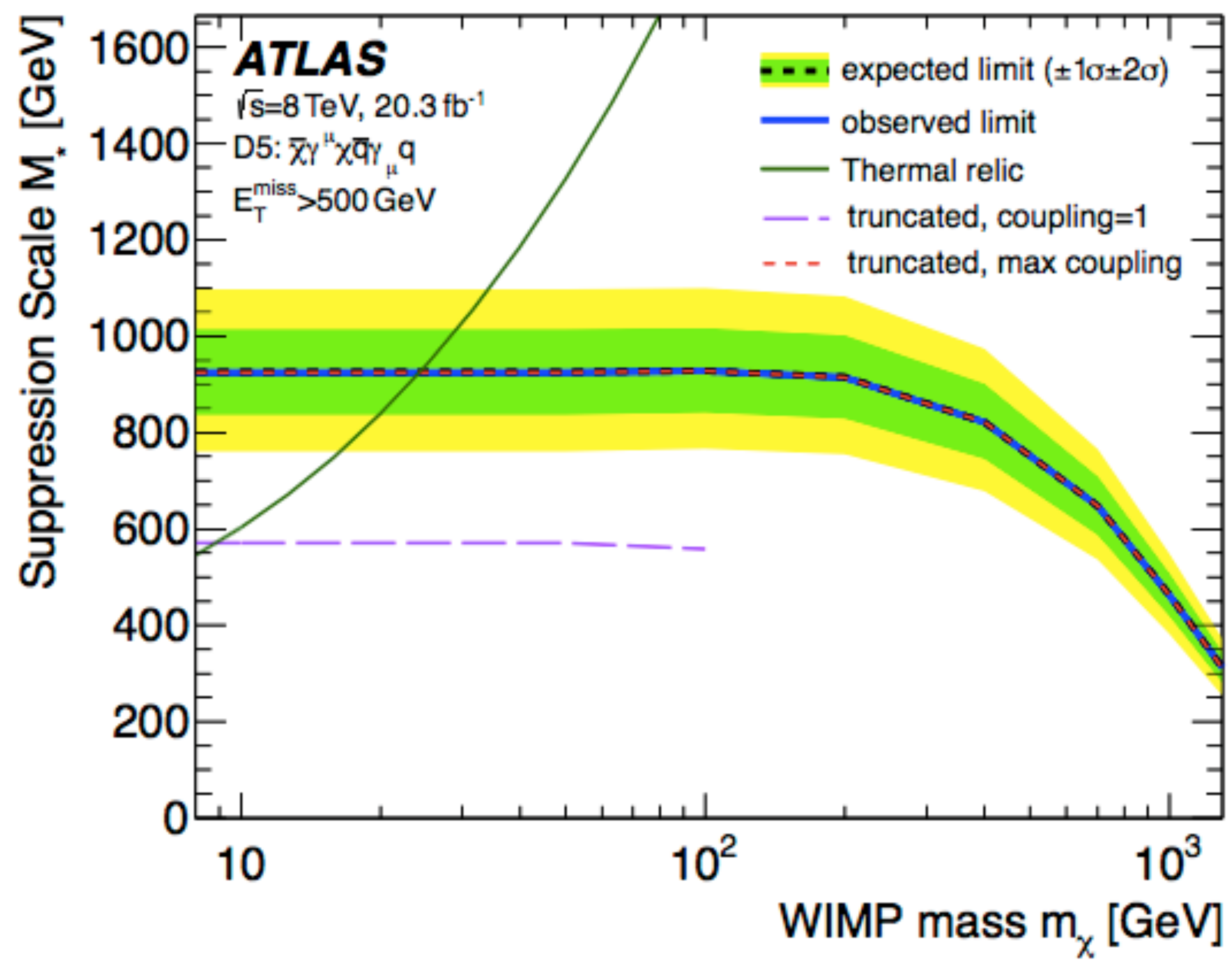
Goodman et al. [1008.1783]

Only have to deal with two parameters: m_χ, Λ

Limits on EFT

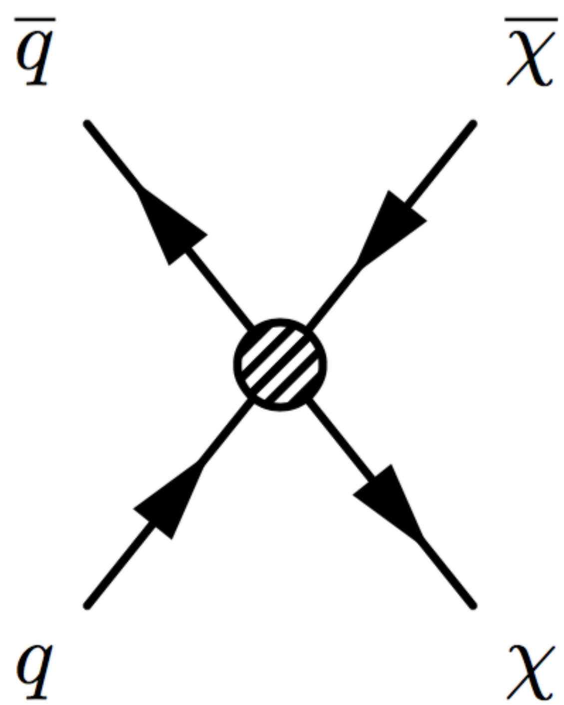


D5	$\bar{\chi}\gamma^{\mu}\chi\bar{q}\gamma_{\mu}q$	$1/M_*^2$

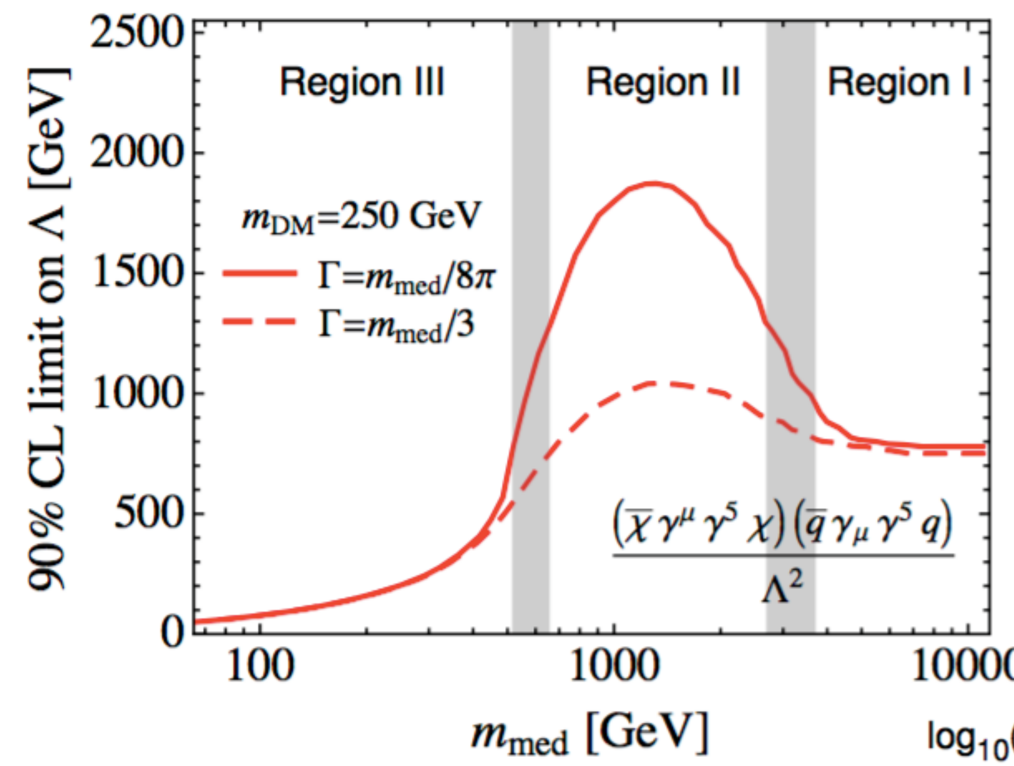


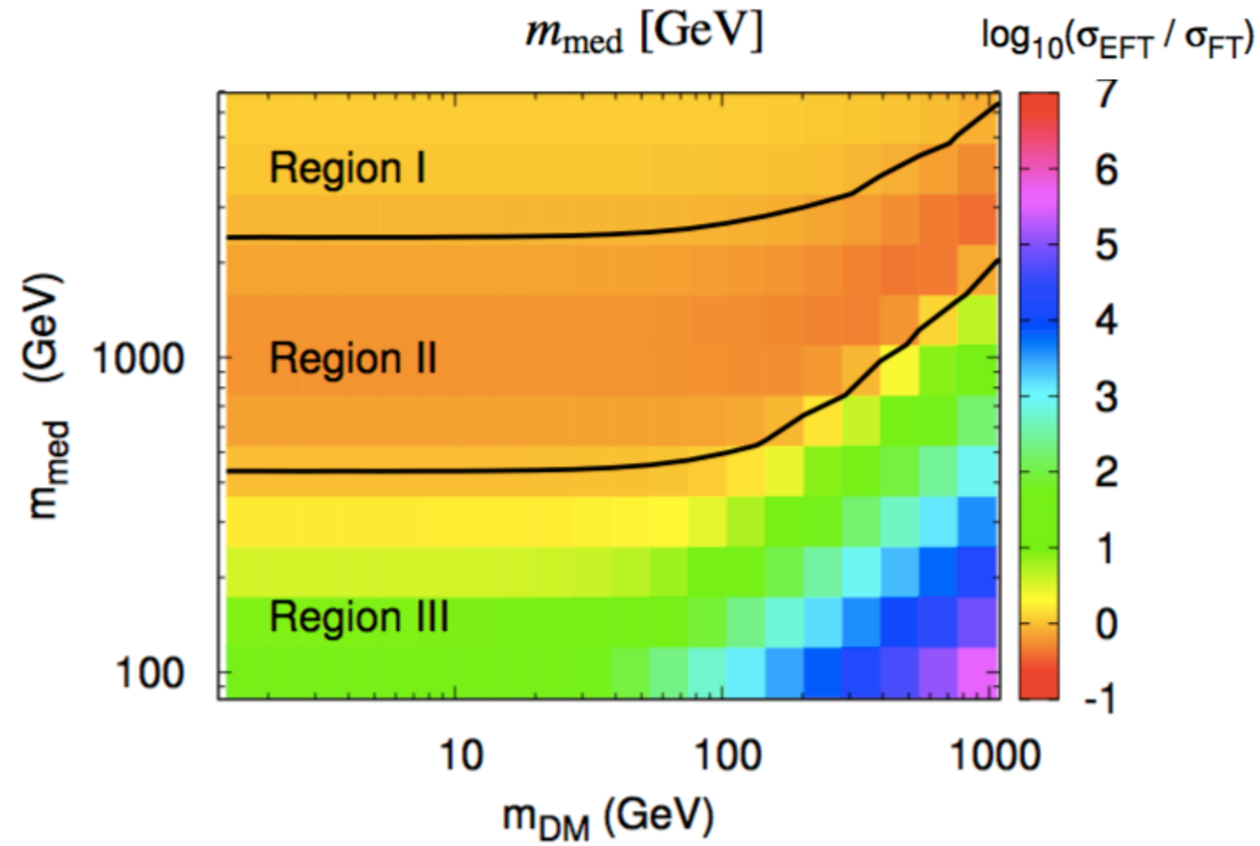
ATLAS [1502.01518]

The problem with EFTs



Frandsen et al. [1204.3839],
Buchmueller et al. [1407.8257],
Malik et al. [1409.4075],
Abdallah et al. [1506.03116],
and many others…

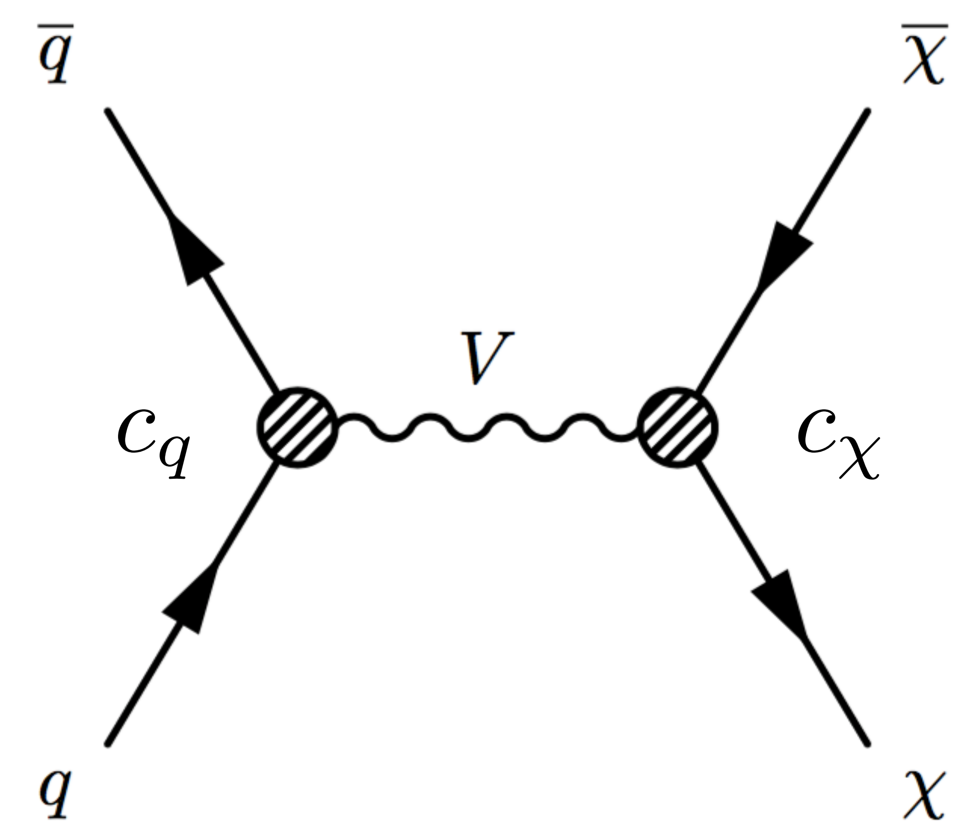


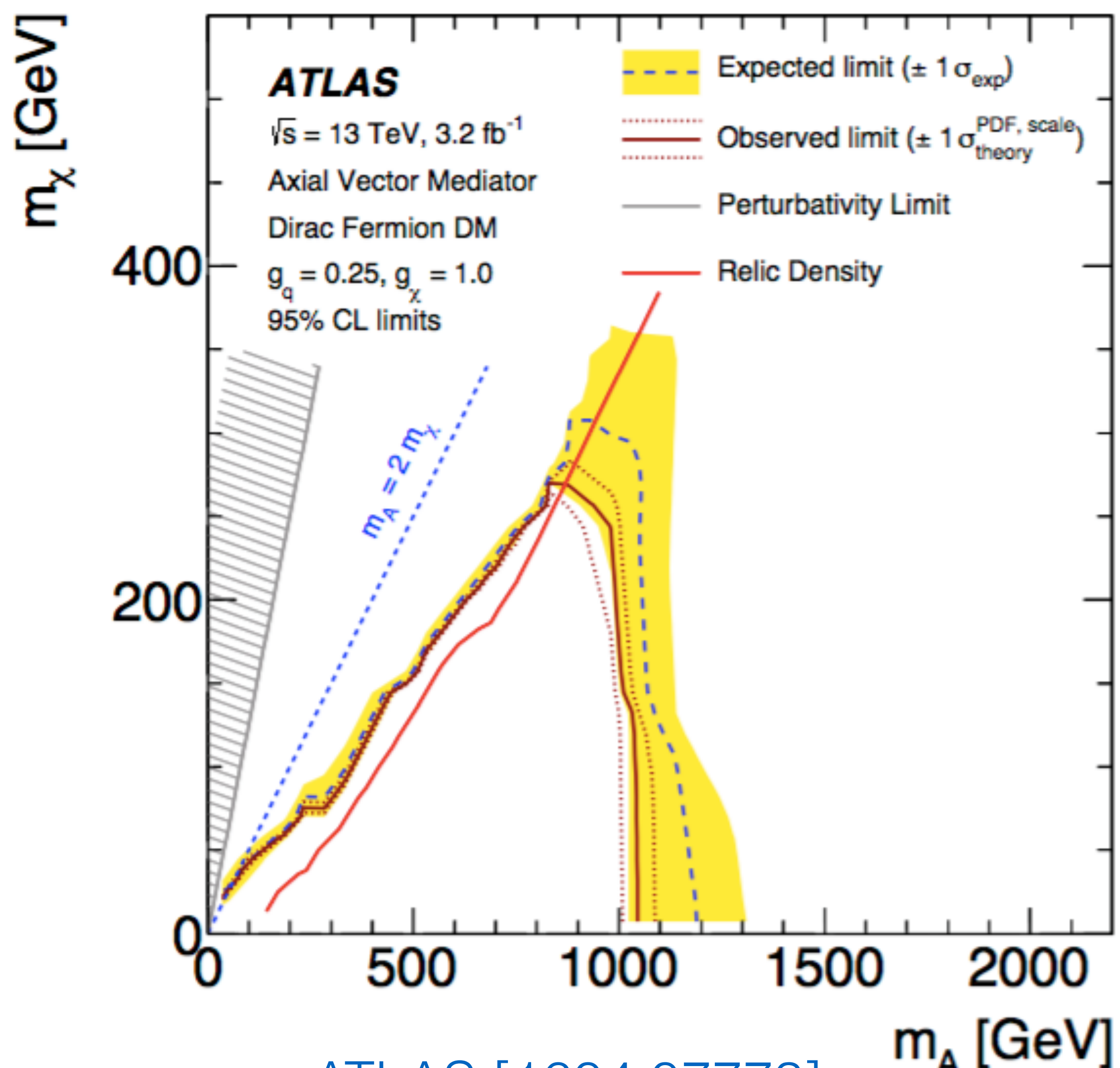


Buchmueller et al. [1308.6799]

Simplified Models to the rescue

Review: De Simone, Jacques [1603.08002]





ATLAS [1604.07773]

Now have to deal with more parameters: c_q, c_χ, m_χ, m_V

Our Simplified Model

Vector mediator simplified model

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \mathcal{L}_{\mathrm{DM}} + \mathcal{L}_{\mathrm{V}} + J^{\mu}_{\mathrm{DM}} V_{\mu} + J^{\mu}_{\mathrm{SM}} V_{\mu}$$

Vector mediator simplified model

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \boxed{\mathcal{L}_{\mathrm{DM}}} + \mathcal{L}_{\mathrm{V}} + J^{\mu}_{\mathrm{DM}} V_{\mu} + J^{\mu}_{\mathrm{SM}} V_{\mu}$$

$$\mathcal{L}_{\mathrm{DM}} \sim \begin{cases} |\partial_\mu \phi|^2 - m_\phi^2 |\phi|^2 & \text{complex scalar DM} \\ \overline{\chi}\left(i\partial\!\!\!/ - m_\chi\right)\chi & \text{fermion DM} \end{cases}$$

Vector mediator simplified model

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \mathcal{L}_{\mathrm{DM}} + \boxed{\mathcal{L}_{\mathrm{V}}} + J^{\mu}_{\mathrm{DM}} V_{\mu} + J^{\mu}_{\mathrm{SM}} V_{\mu}$$

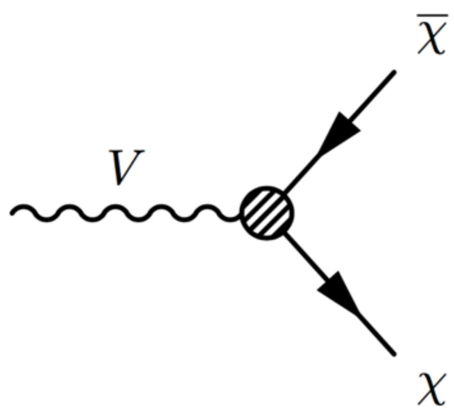
$$\boxed{\mathcal{L}_{\mathrm{V}} = -\frac{1}{4} V^{\mu\nu} V_{\mu\nu} + \frac{1}{2} m_{\mathrm{V}}^2 V^{\mu} V_{\mu}}$$

Massive spin-1 mediator V

Vector mediator simplified model

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \mathcal{L}_{\mathrm{DM}} + \mathcal{L}_{\mathrm{V}} + \boxed{J^{\mu}_{\mathrm{DM}}} V_{\mu} + J^{\mu}_{\mathrm{SM}} V_{\mu}$$

$$J^{\mu}_{\mathrm{DM}} \sim \begin{cases} c_{\phi}\, \phi^{\dagger}\, \overleftrightarrow{\partial}_{\mu} \phi & \text{complex scalar DM} \\ c_{\chi V}\, \overline{\chi}\gamma^{\mu}\chi + c_{\chi A}\, \overline{\chi}\gamma^{\mu}\gamma^{5}\chi & \text{fermion DM} \end{cases}$$

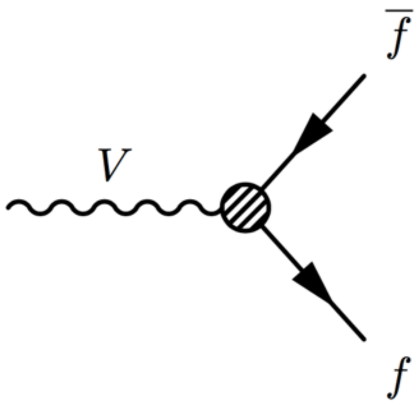


Vector mediator simplified model

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \mathcal{L}_{\mathrm{DM}} + \mathcal{L}_{\mathrm{V}} + J^\mu_{\mathrm{DM}} V_\mu + \boxed{J^\mu_{\mathrm{SM}}} V_\mu$$

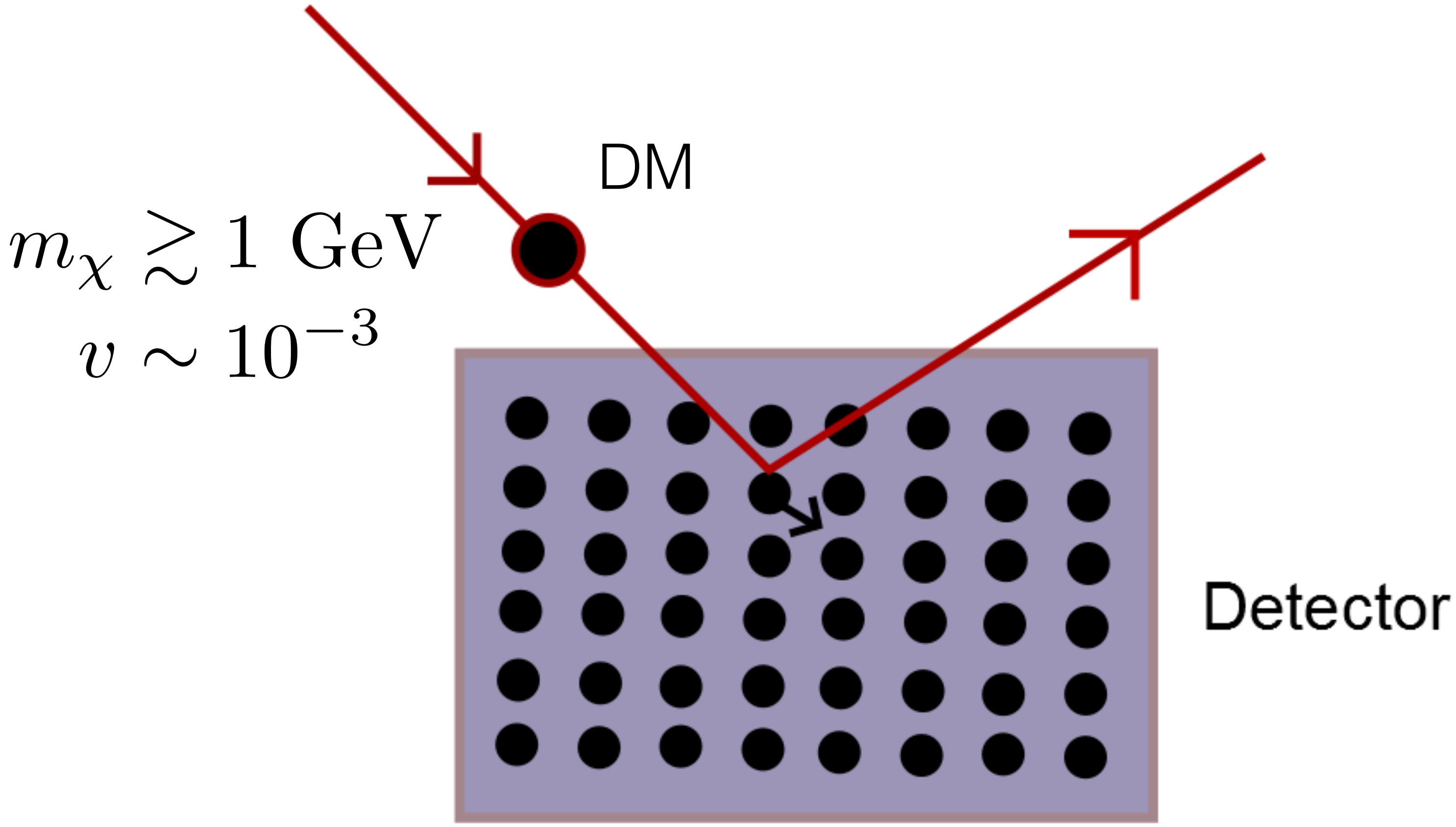
$$J^\mu_{\mathrm{SM}} = \sum_{i=1}^{3} \left[c_q^{(i)}\, \overline{q_L^i} \gamma^\mu q_L^i + c_u^{(i)}\, \overline{u_R^i} \gamma^\mu u_R^i + c_d^{(i)}\, \overline{d_R^i} \gamma^\mu d_R^i + c_l^{(i)}\, \overline{l_L^i} \gamma^\mu l_L^i + c_e^{(i)}\, \overline{e_R^i} \gamma^\mu e_R^i \right]$$

15 independent, $SU(2)_L \times U(1)_Y$ gauge-invariant couplings



Calculating the direct detection rate

Direct detection



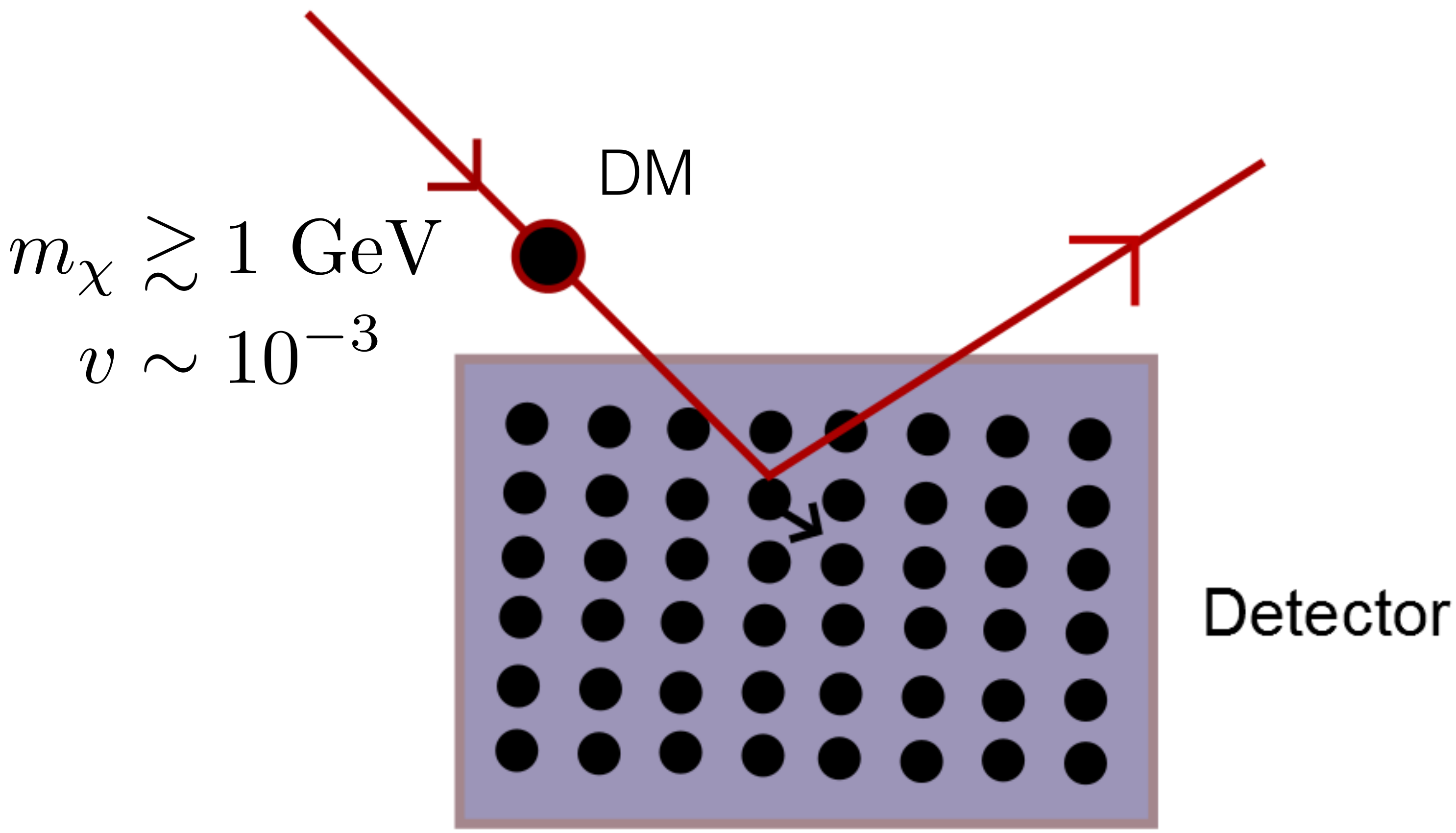
Look for low energy - O(keV) - recoils of detector nuclei

Rate driven by coupling of DM to light quarks (u, d, s):

$$\overline{\chi}\gamma^\mu\chi\ \overline{q}\gamma_\mu q \qquad \overline{\chi}\gamma^\mu\chi\ \overline{q}\gamma_\mu\gamma^5 q$$

$$\overline{\chi}\gamma^\mu\gamma^5\chi\ \overline{q}\gamma_\mu q \qquad \overline{\chi}\gamma^\mu\gamma^5\chi\ \overline{q}\gamma_\mu\gamma^5 q$$

Direct detection



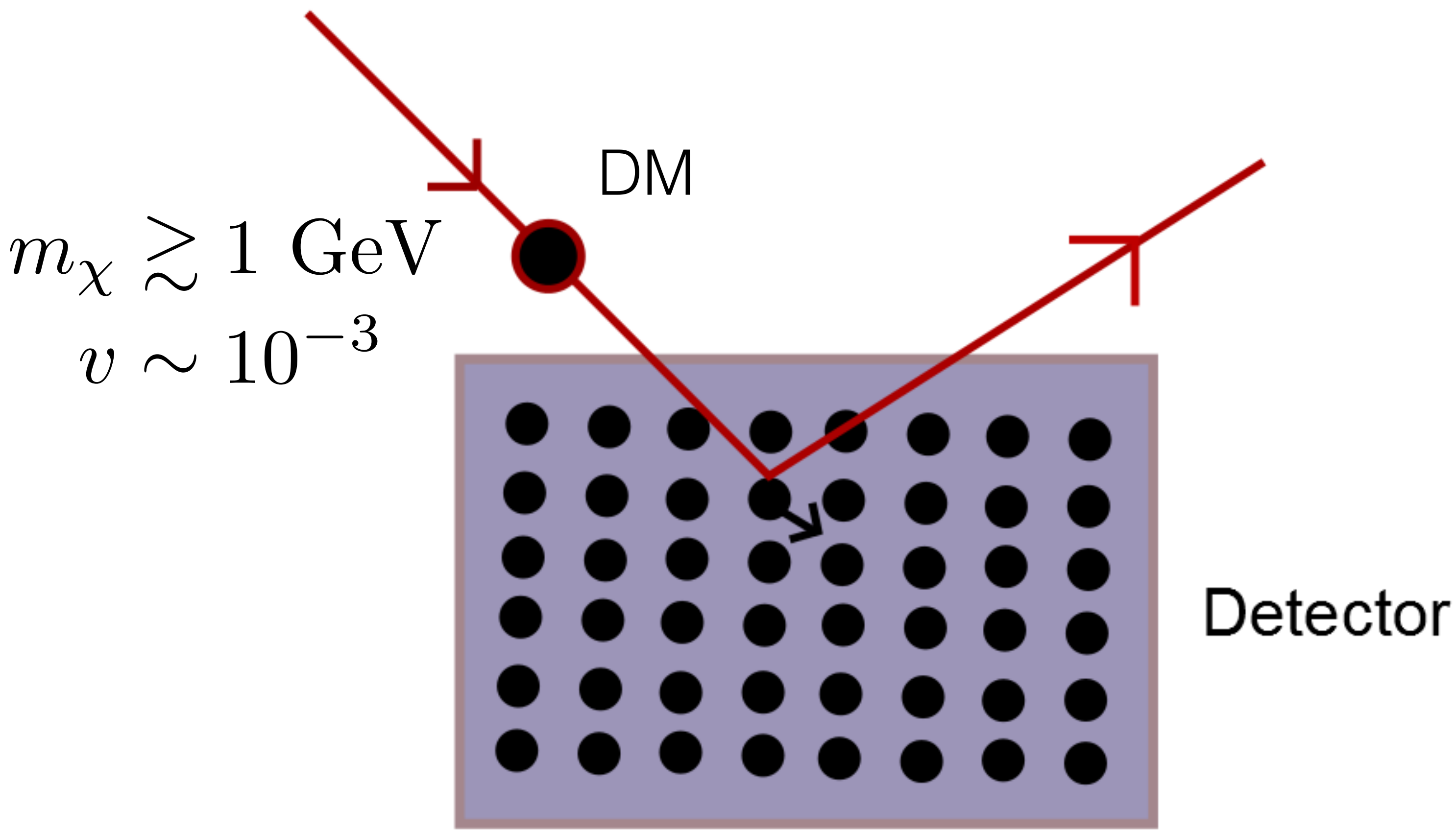
Look for low energy - O(keV) - recoils of detector nuclei

Rate driven by coupling of DM to light quarks (u, d, s):

Standard SI $\overline{\chi}\gamma^\mu\chi\,\overline{q}\gamma_\mu q$ $\overline{\chi}\gamma^\mu\chi\,\overline{q}\gamma_\mu\gamma^5 q$

$\overline{\chi}\gamma^\mu\gamma^5\chi\,\overline{q}\gamma_\mu q$ $\overline{\chi}\gamma^\mu\gamma^5\chi\,\overline{q}\gamma_\mu\gamma^5 q$ Standard SD

Direct detection



Look for low energy - O(keV) - recoils of detector nuclei

Rate driven by coupling of DM to light quarks (u, d, s):

$$\overline{\chi}\gamma^\mu\chi\, \overline{q}\gamma_\mu q \qquad \overline{\chi}\gamma^\mu\chi\, \overline{q}\gamma_\mu\gamma^5 q$$

Velocity suppressed

$$\overline{\chi}\gamma^\mu\gamma^5\chi\, \overline{q}\gamma_\mu q \qquad \overline{\chi}\gamma^\mu\gamma^5\chi\, \overline{q}\gamma_\mu\gamma^5 q$$

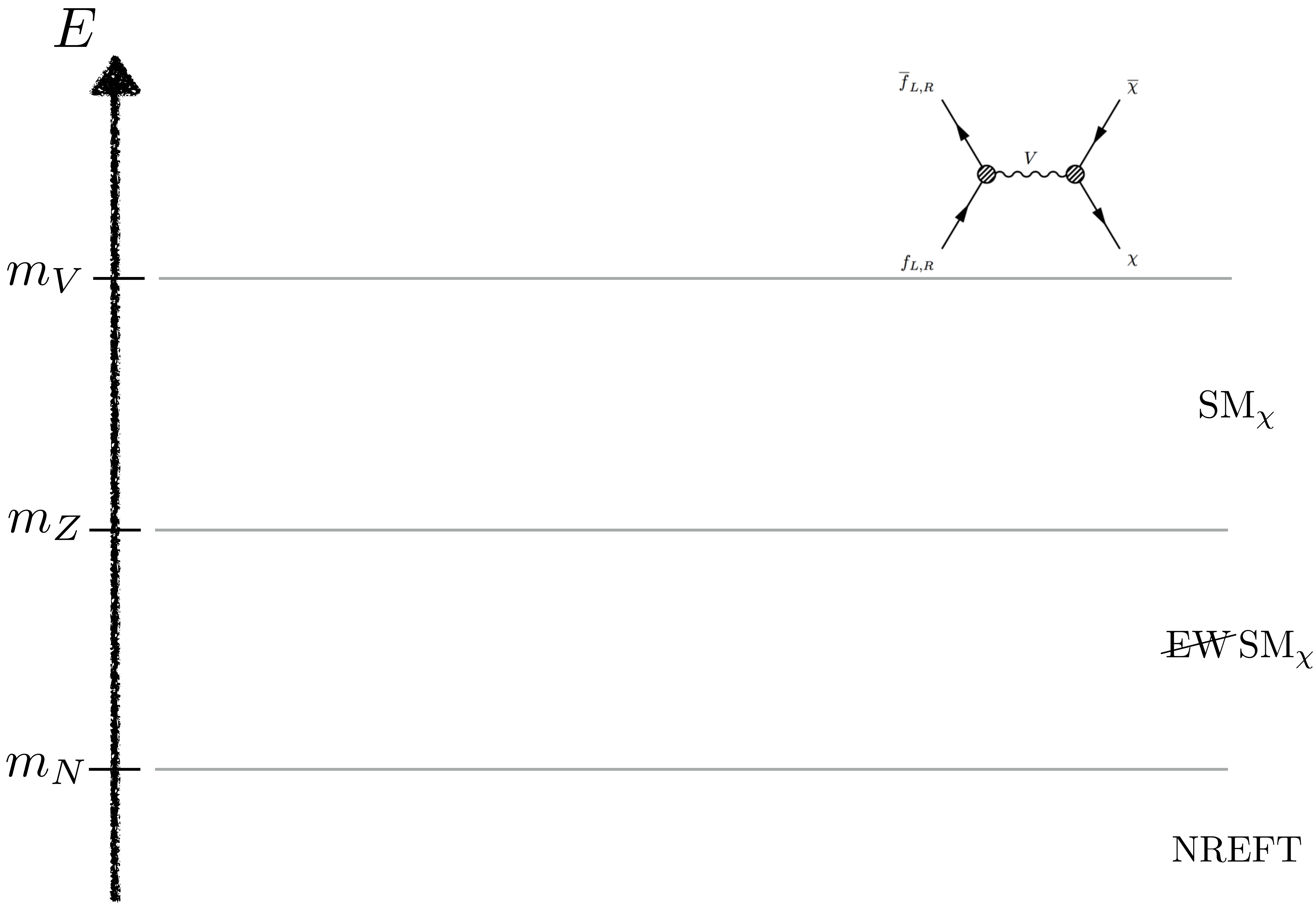
Connecting high and low scales

Define couplings at high energy scale (mediator mass), but need to calculate direct detection rate at low energy

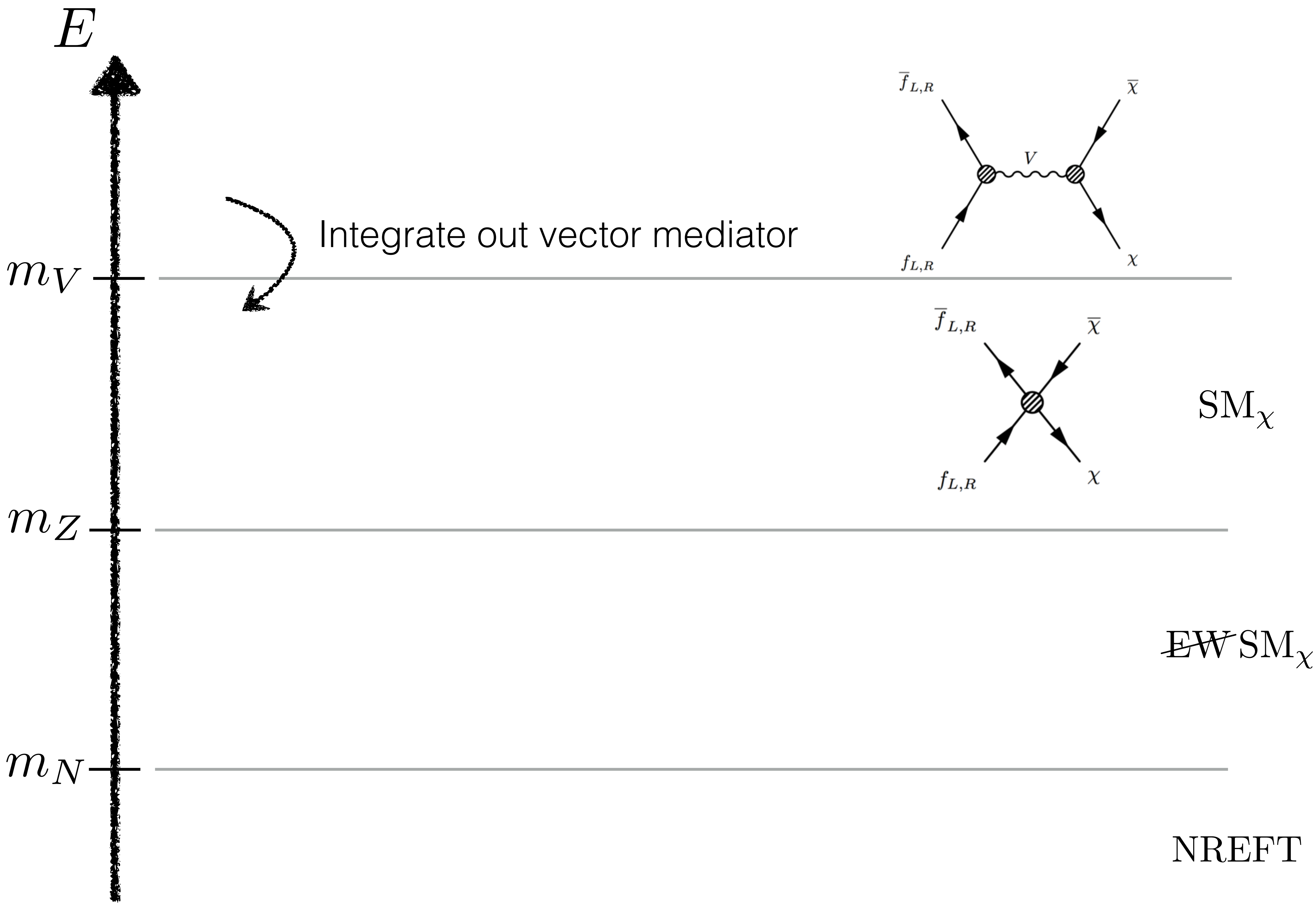
Running can change the DD rate by orders of magnitude. Examples in specific models:

Kopp et al. [0907.3159], Frandsen et al. [1207.3971], Haisch, Kahlhoefer [1302.4454], Kopp et al. [1401.6457], Crivellin, Haisch [1408.5046]

- Use EFT techniques and RG flow to study the effects for general interactions
- Include all relevant DD interactions (not just naive 'leading order')



D'Eramo, Procura [1411.3342]



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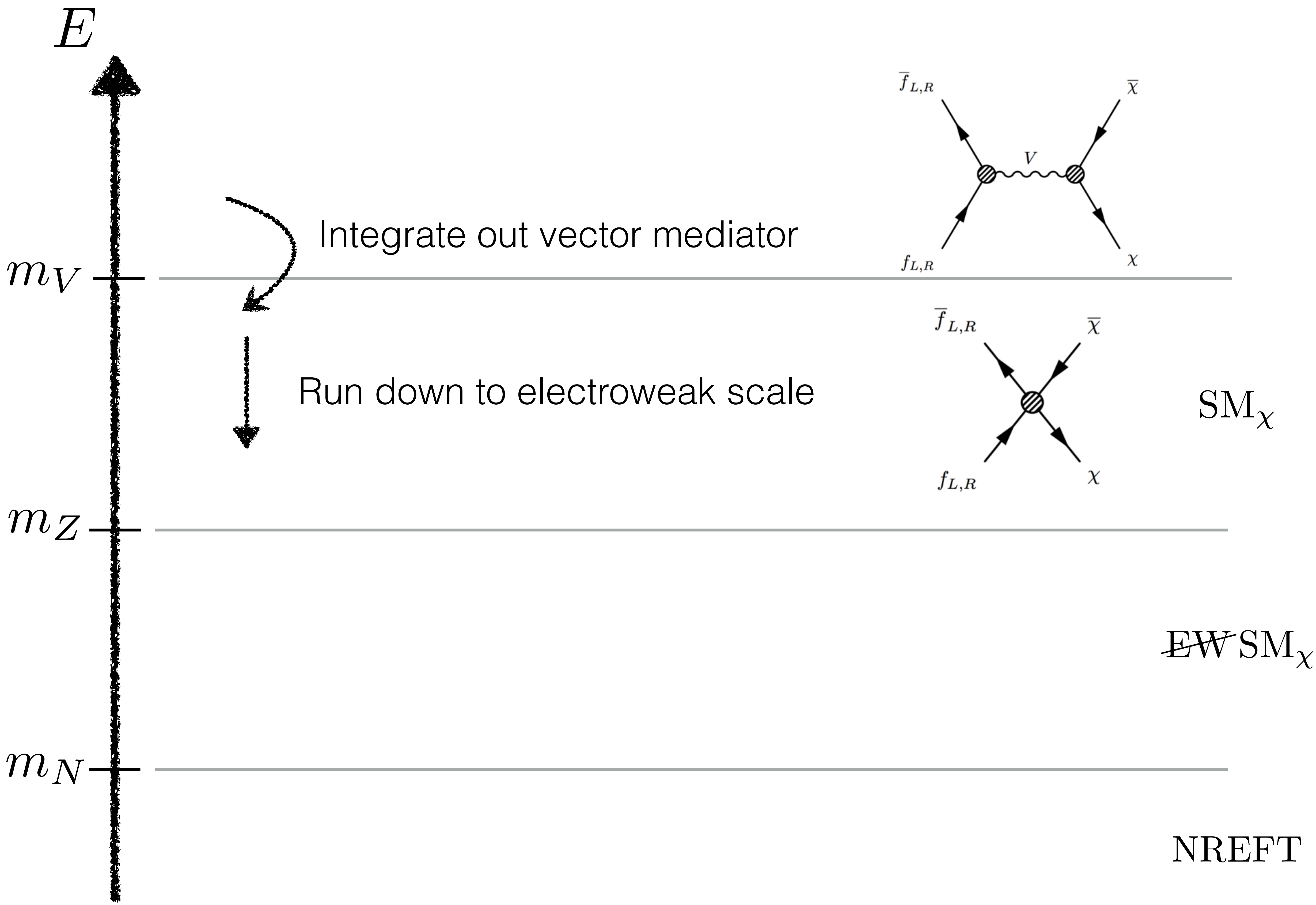

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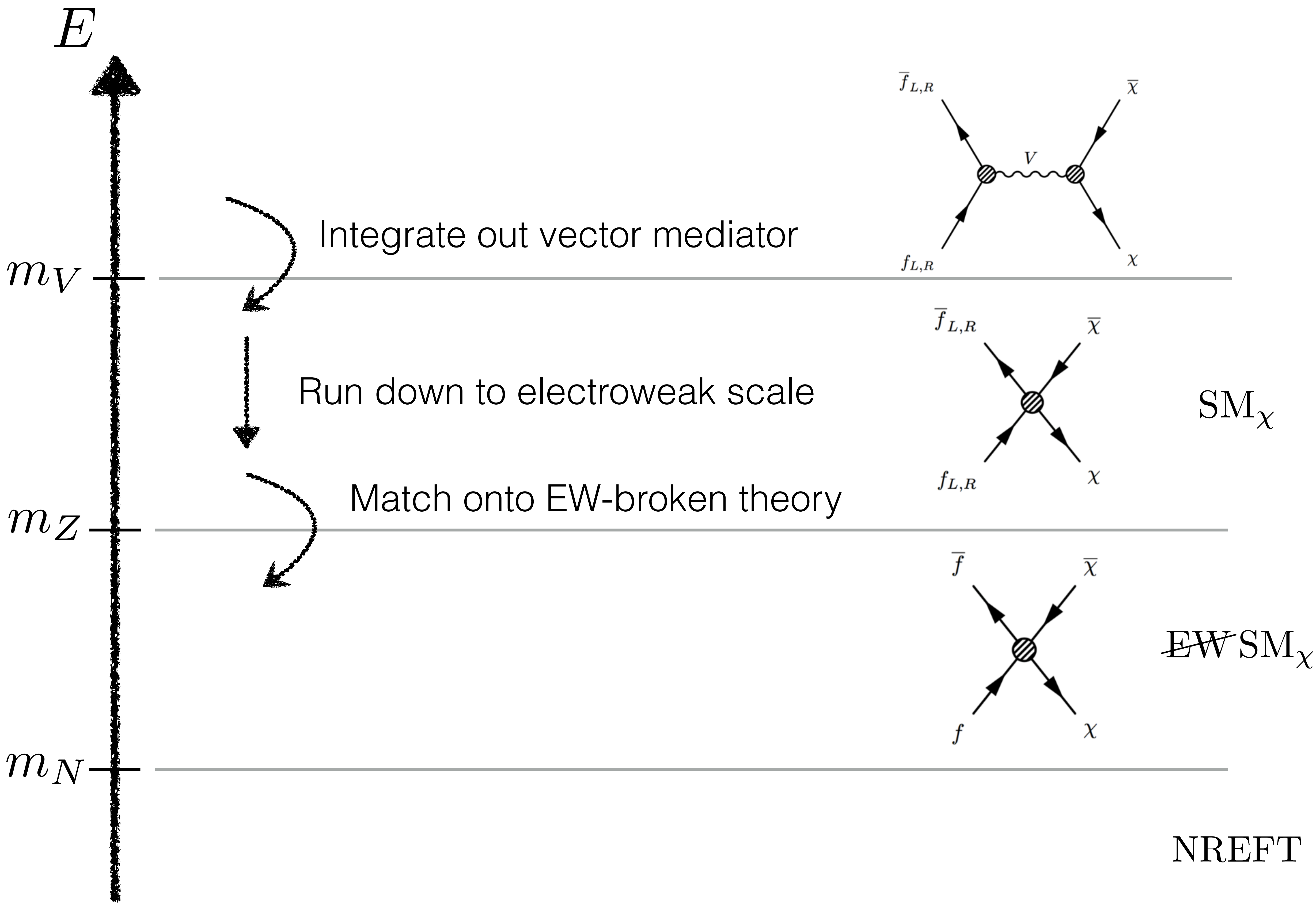

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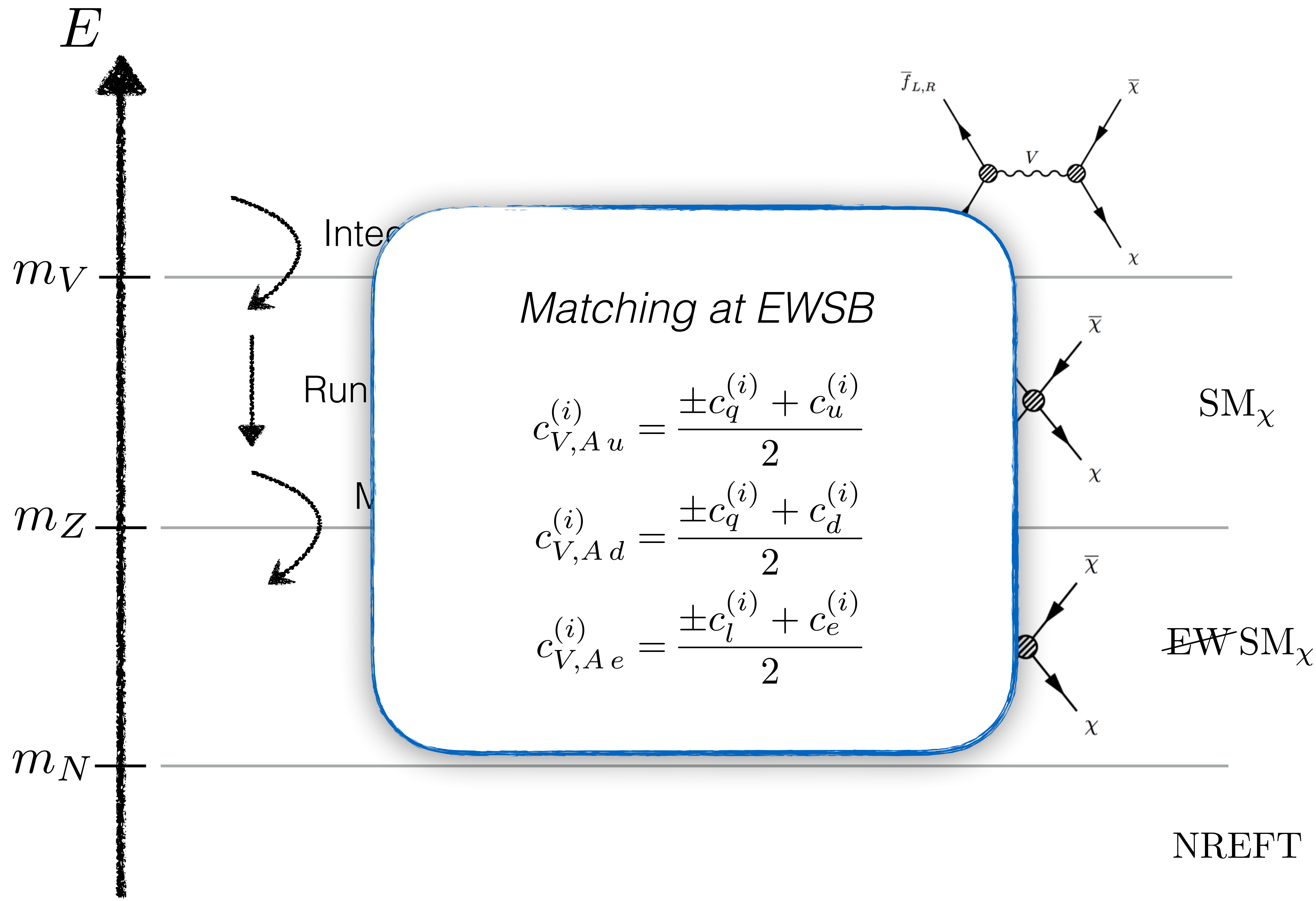


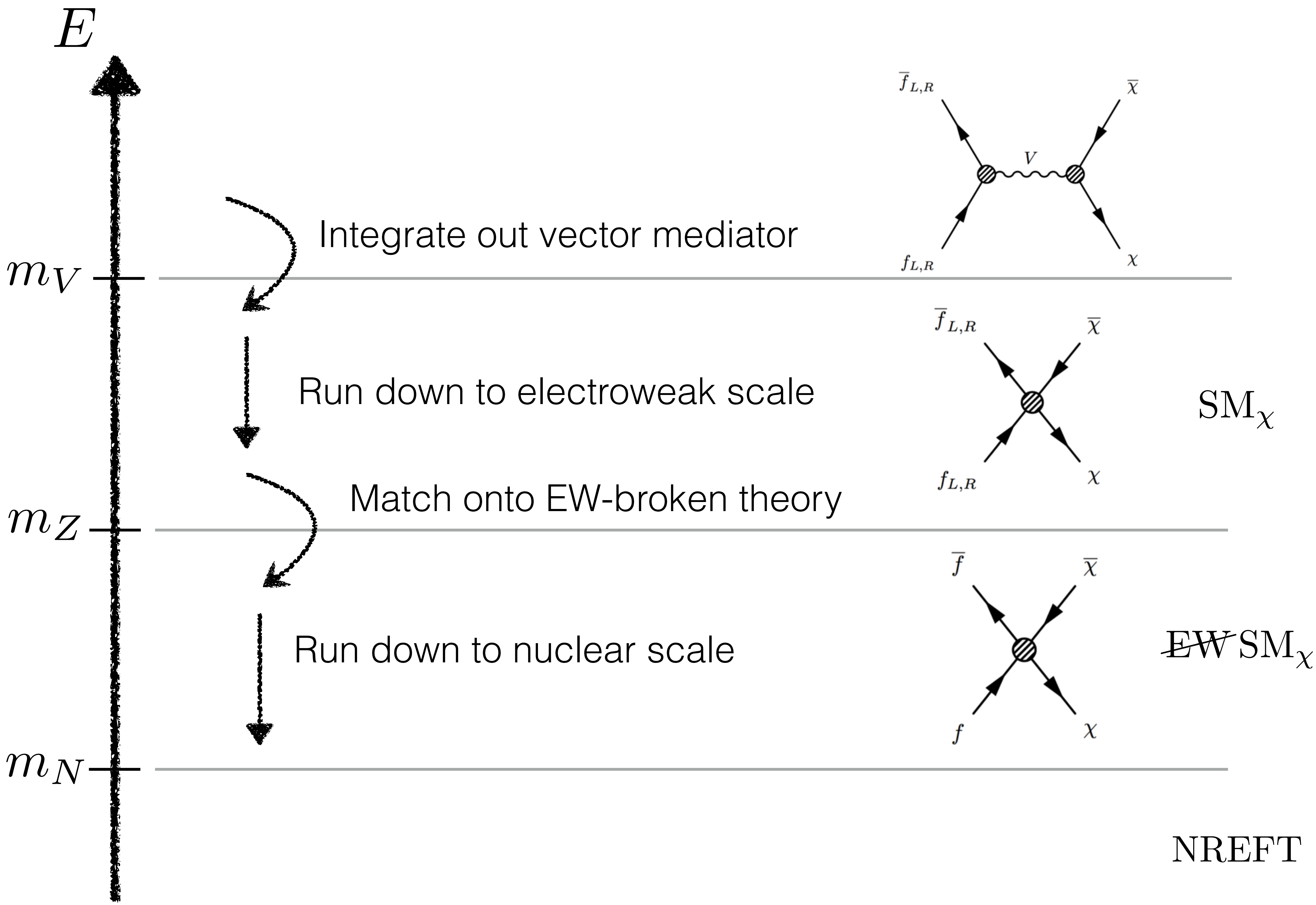
Matching at EWSB

$$c^{(i)}_{V,A\,u} = \frac{\pm c_q^{(i)} + c_u^{(i)}}{2}$$

$$c^{(i)}_{V,A\,d} = \frac{\pm c_q^{(i)} + c_d^{(i)}}{2}$$

$$c^{(i)}_{V,A\,e} = \frac{\pm c_l^{(i)} + c_e^{(i)}}{2}$$

D'Eramo, Procura [1411.3342]



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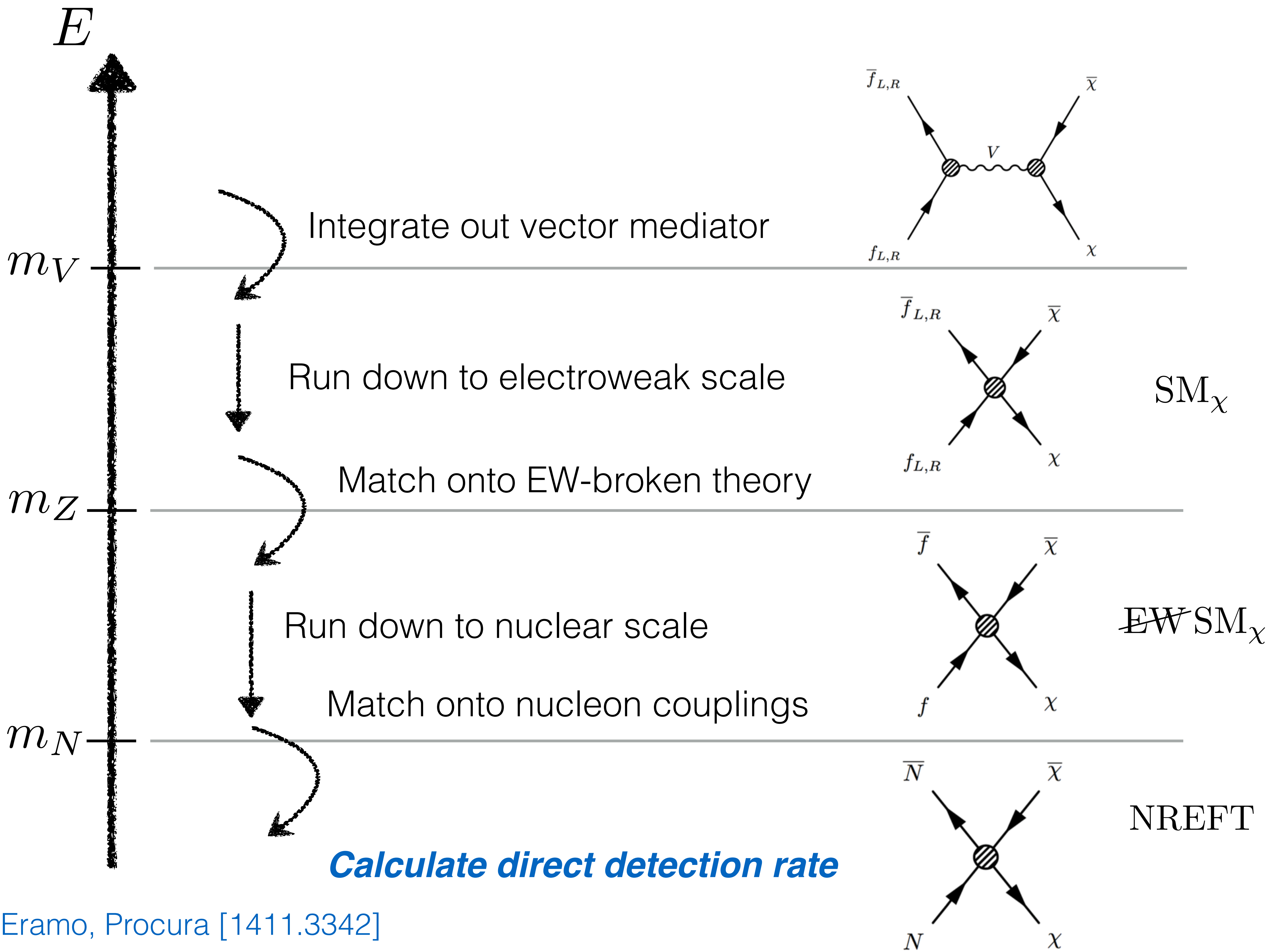
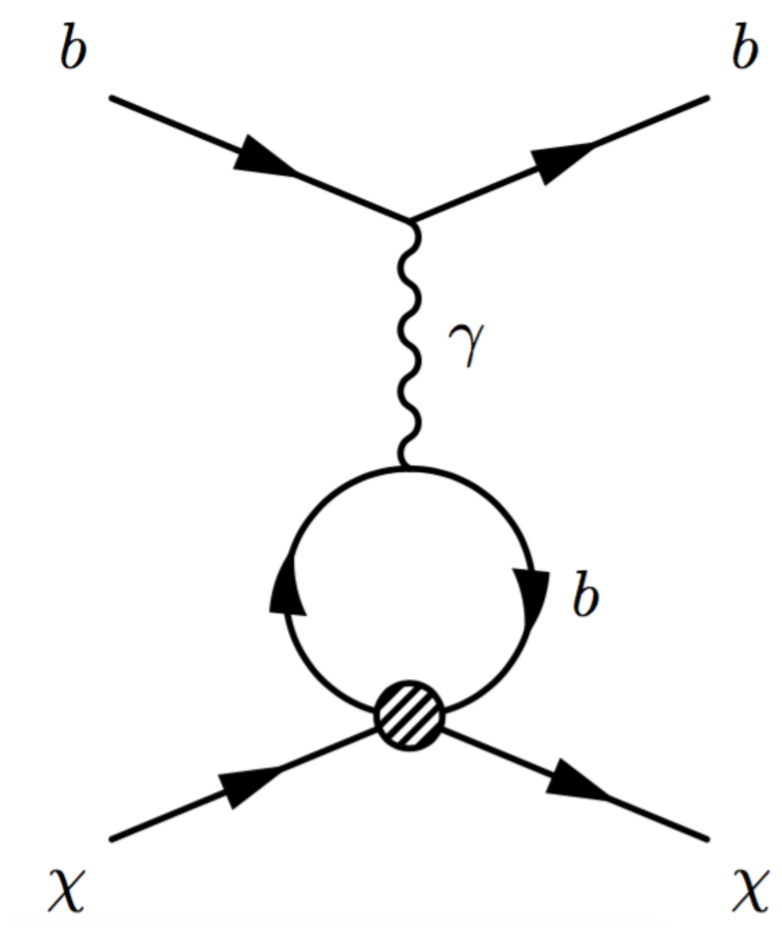


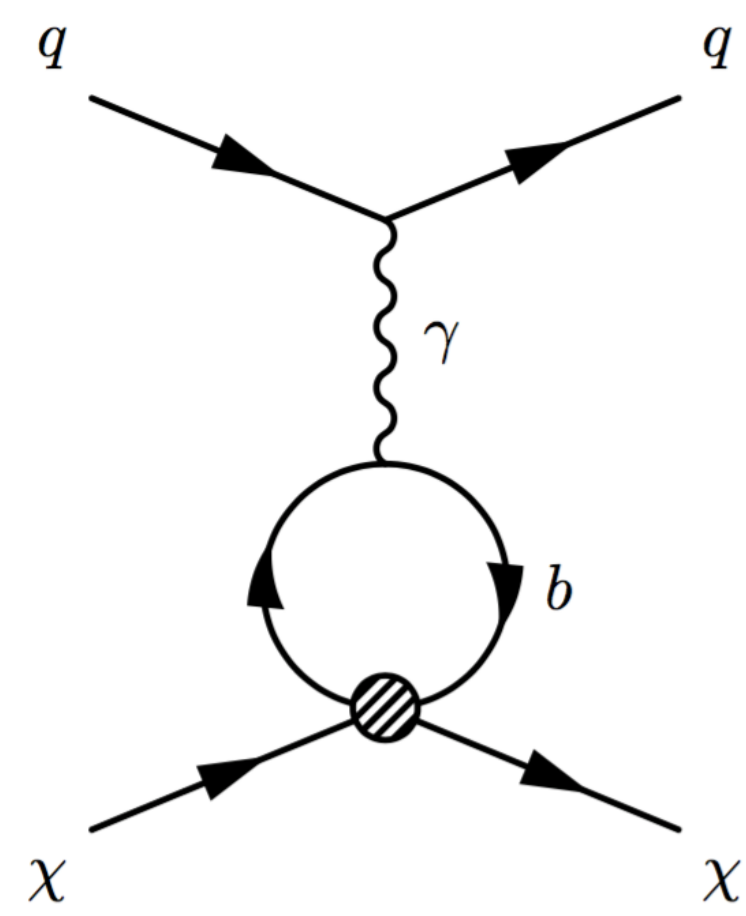
D'Eramo, Procura [1411.3342]

RGE effects

As we move between the different scales, we have to take into account the running of the couplings, due only to loops of Standard Model particles, e.g.



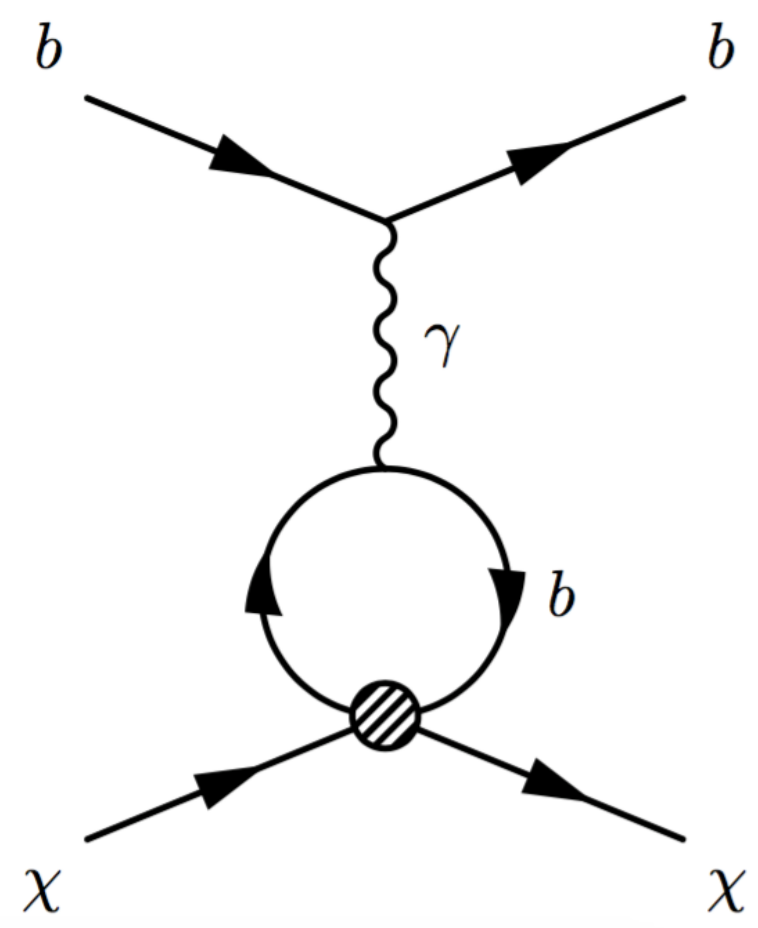
Self-renormalisation



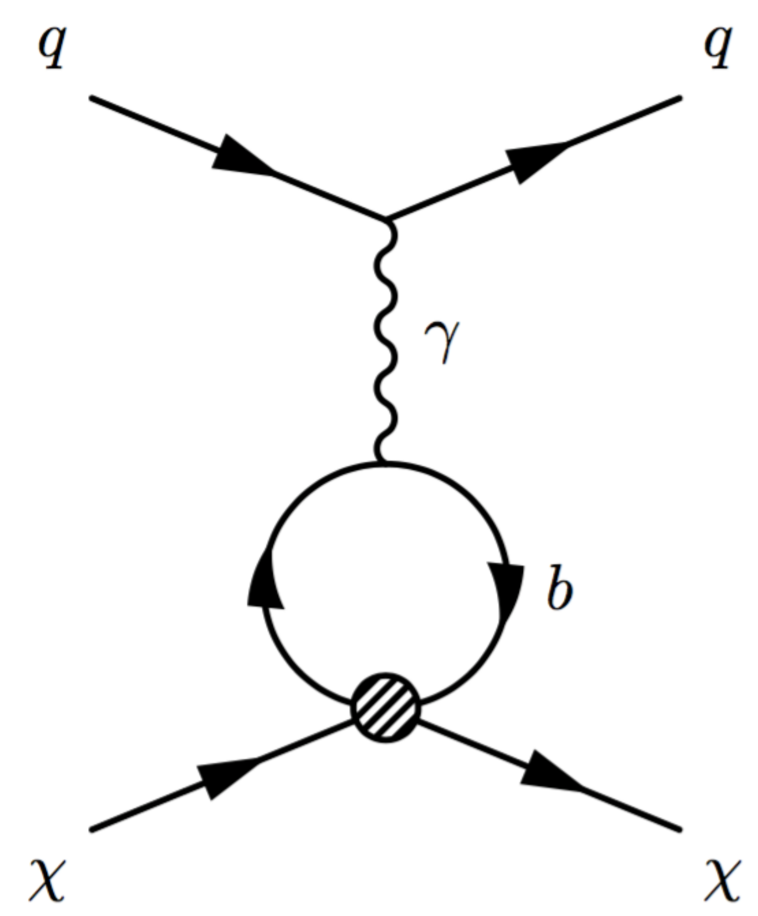
Operator mixing

RGE effects

As we move between the different scales, we have to take into account the running of the couplings, due only to loops of Standard Model particles, e.g.



Self-renormalisation



Operator mixing

The running doesn't depend on the properties of the Dark Sector.

RGE effects

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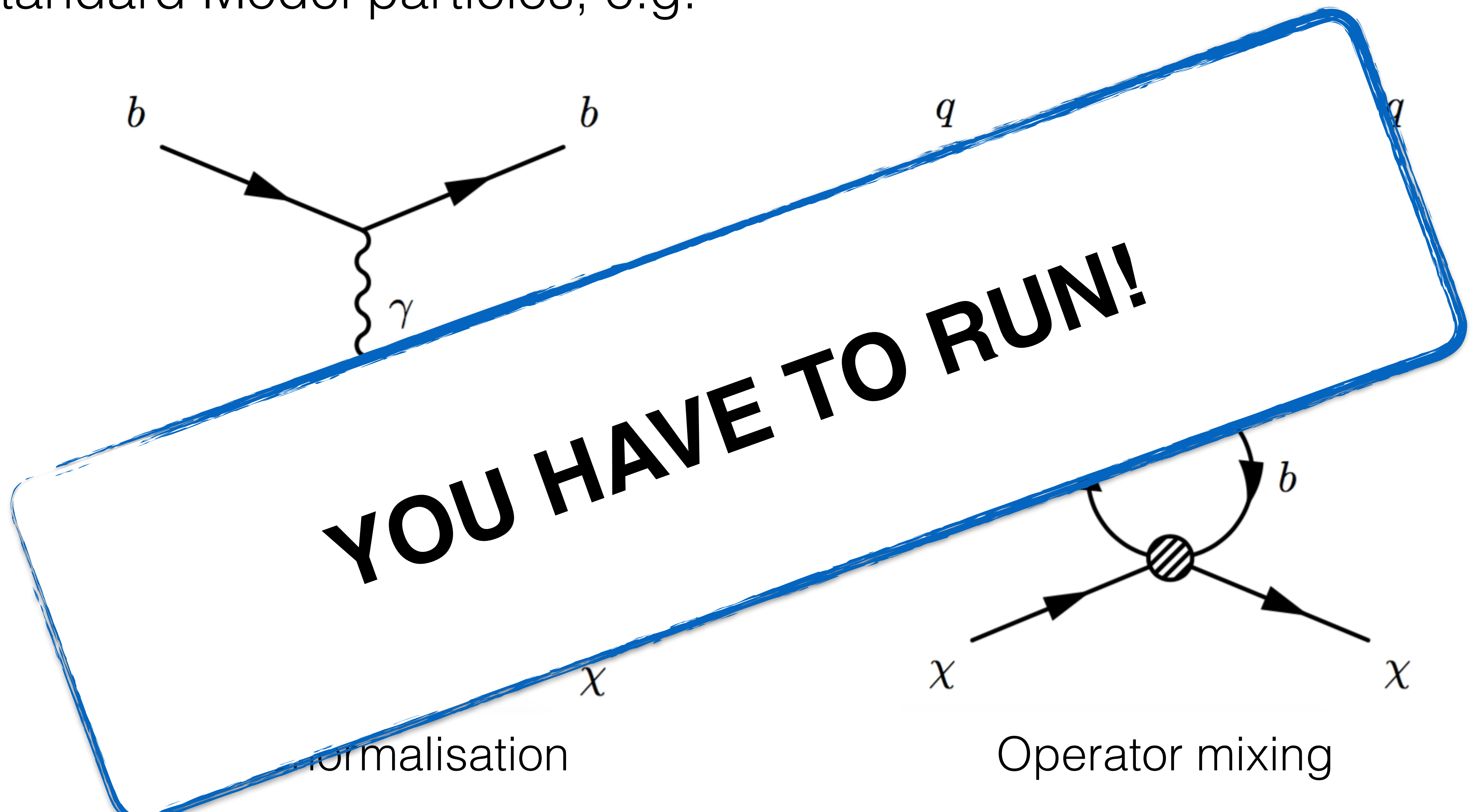
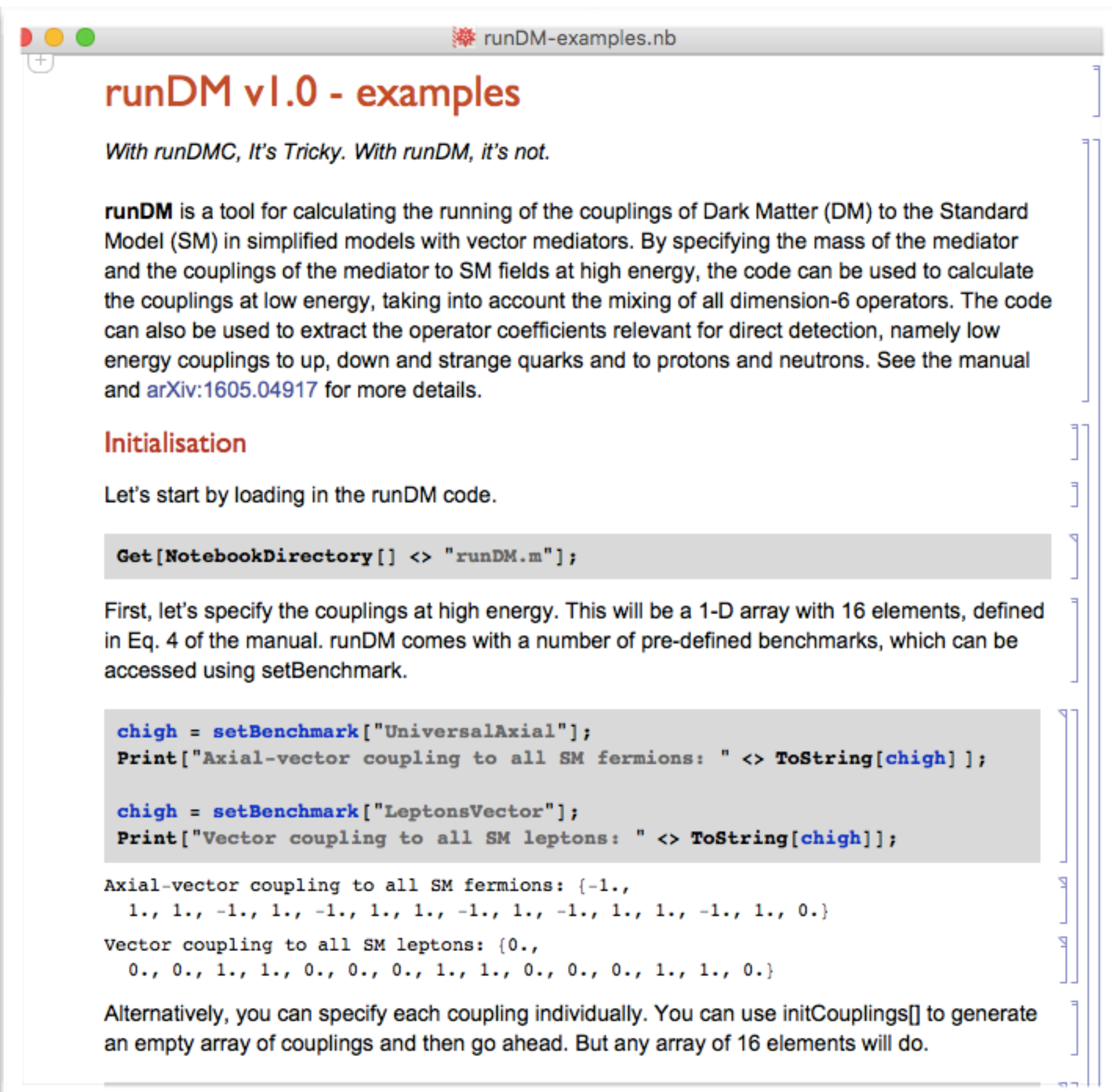


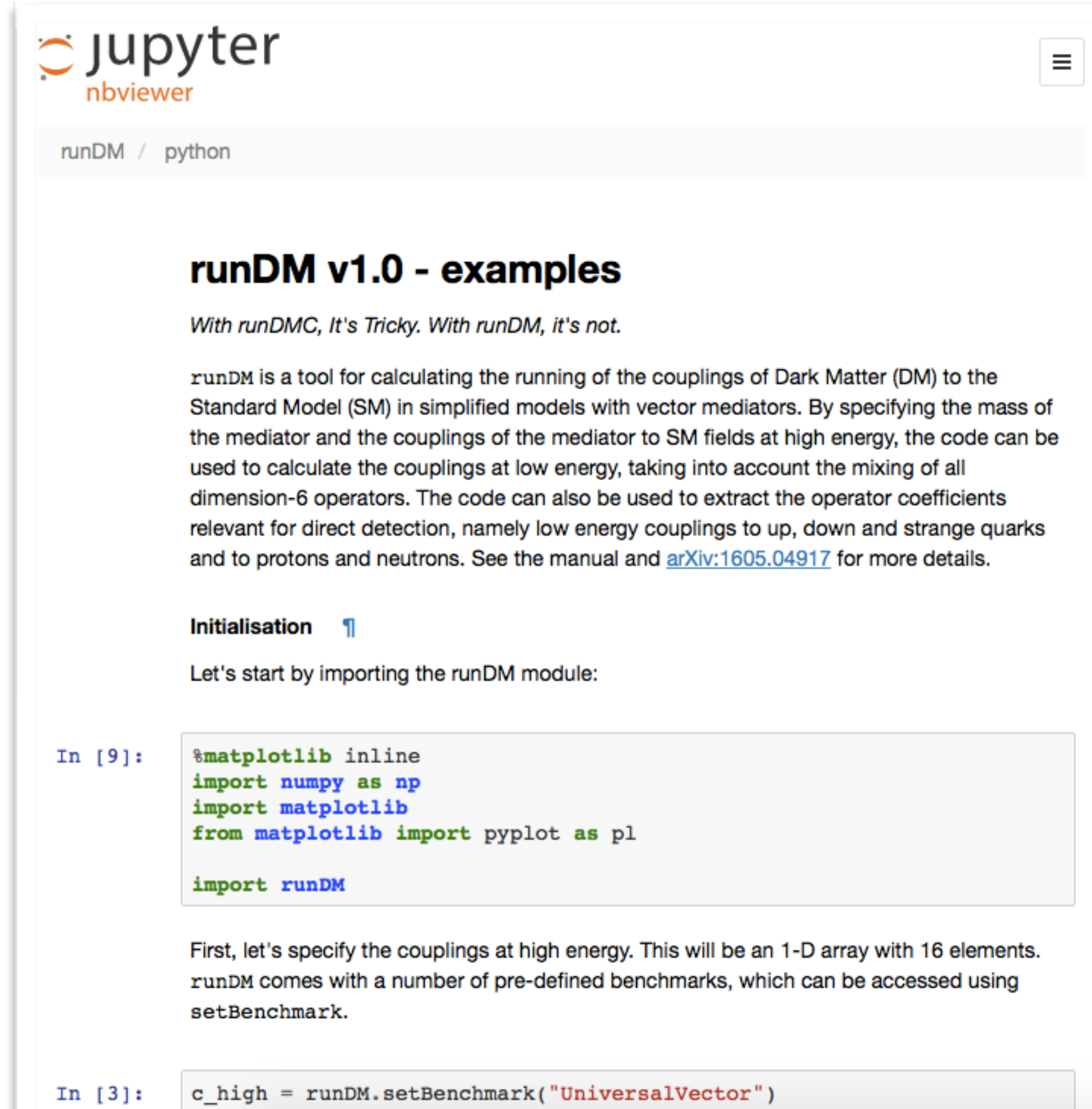
…ormalisation

Operator mixing

The running doesn't depend on the properties of the Dark Sector.

runDM - a code for the RGE





Mathematica and Python versions available at:

https://github.com/bradkav/runDM/

runDM - a code for the RGE

Input:

DM-SM couplings at high energy scale

Output:

DM-SM couplings at another arbitrary energy scale
OR
DM-nucleon couplings at direct detection scale

Mathematica and Python versions available at:
https://github.com/bradkav/runDM/

Direct detection constraints

Fix the couplings of the mediator at high energy (~m_V)

Run the couplings down to low energy (~m_N)

Calculate the total DD cross section:
depends on mediator mass through

$$\sigma \sim \frac{1}{m_V^4} \left|c(m_V)\right|^2$$

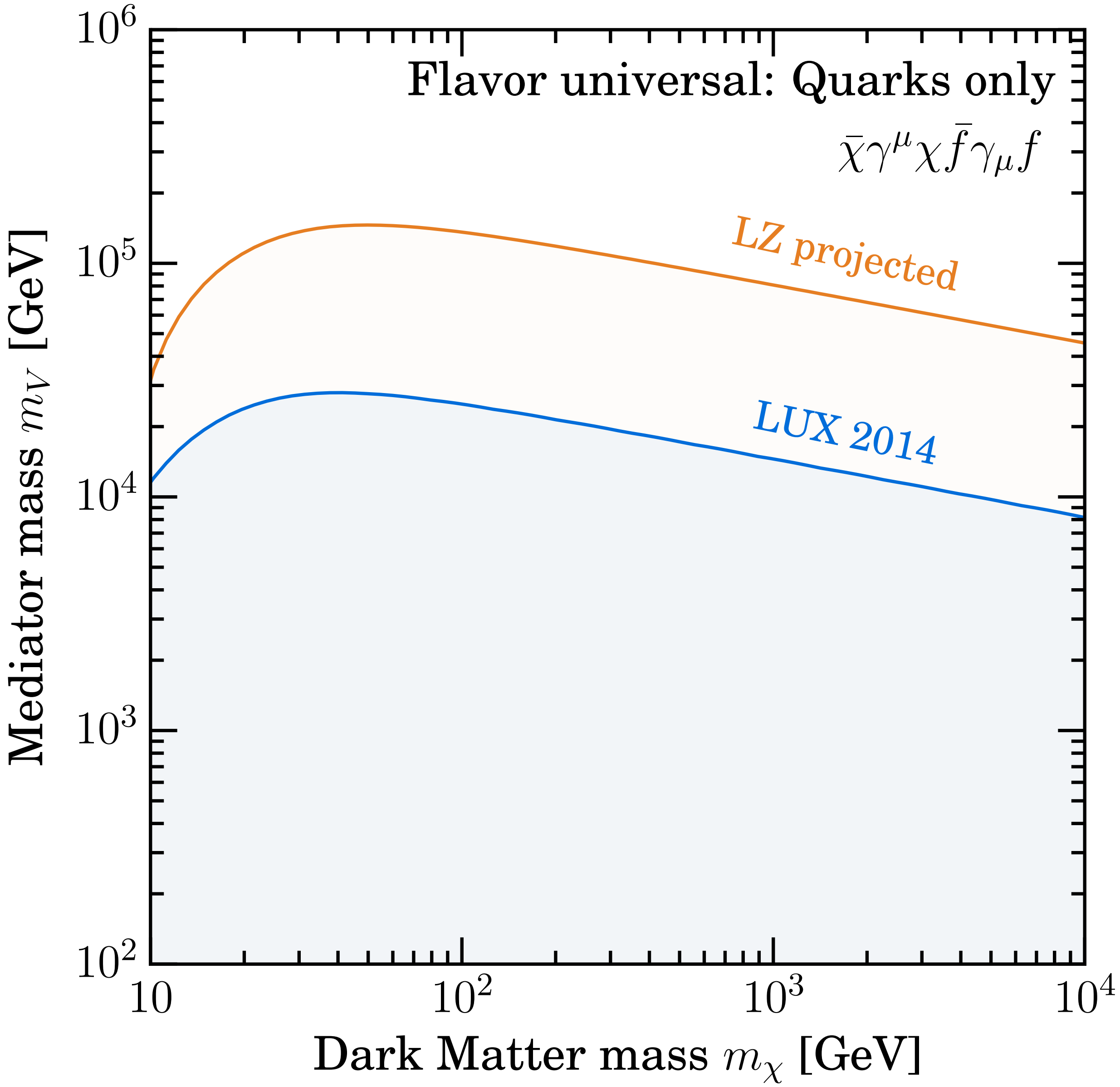
Set lower limit on m_V from DD experiments:

LUX 2014
[1310.8214]

LZ (projected)
[1509.02910]

Results I - quarks vector

$$\mathcal{L}_{\mathrm{EFT}} = -\frac{1}{m_V^2} J_{\mathrm{DM}\,\mu} \sum_{i=1}^{3} \left[\overline{u^i}\gamma^\mu u^i + \overline{d^i}\gamma^\mu d^i\right]$$



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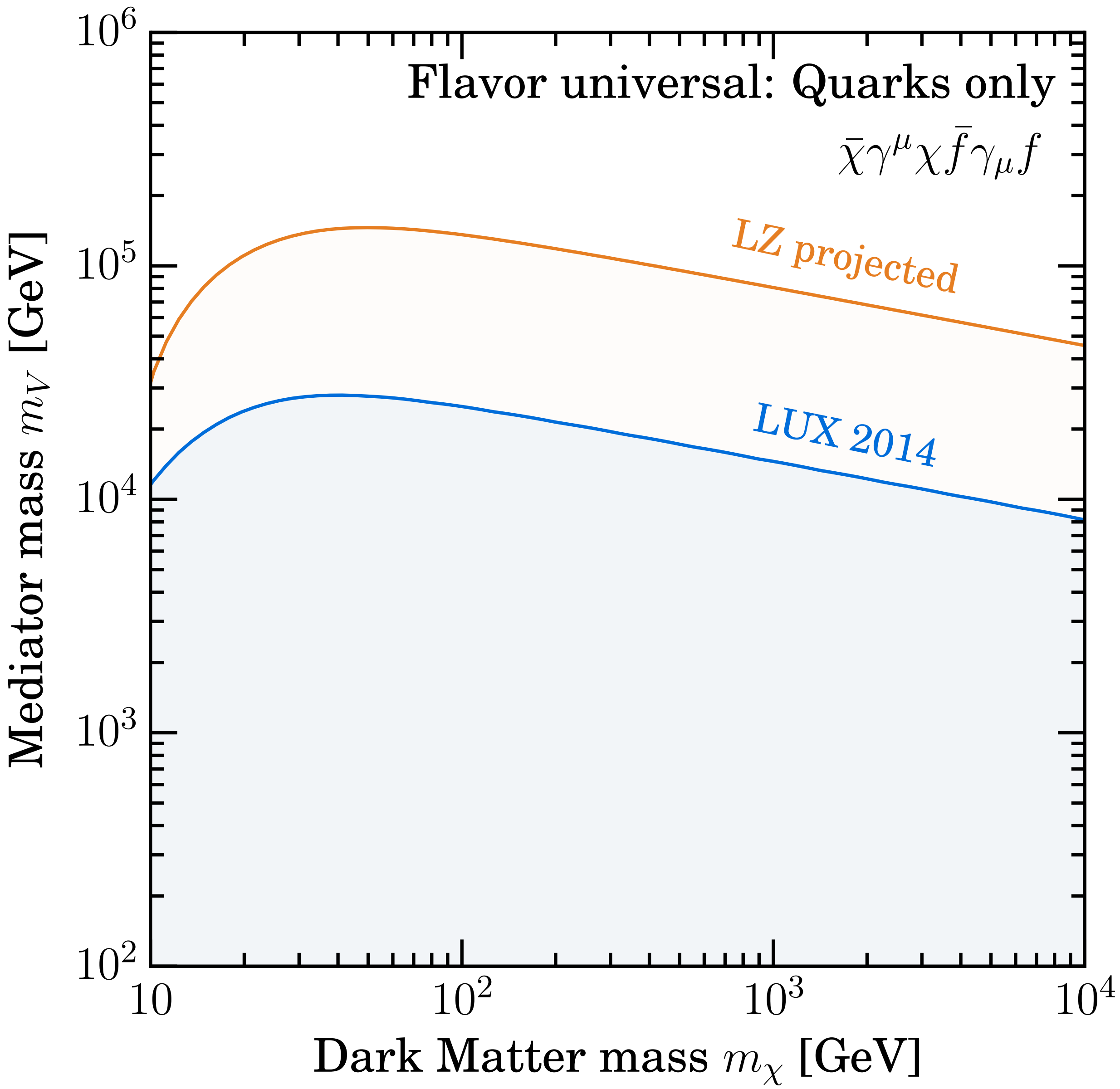

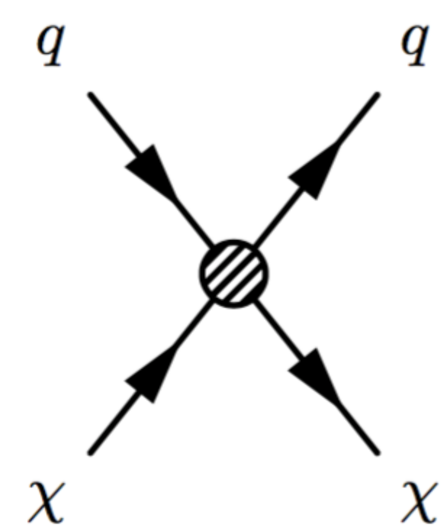

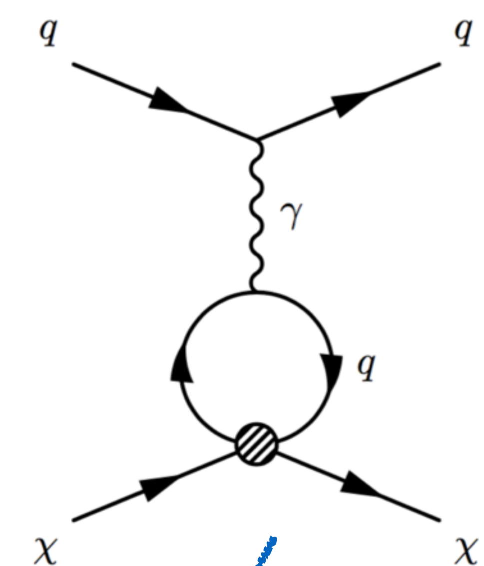

$$c_V^{(q)} \sim 1 + \#\frac{e^2}{16\pi^2}\ln(m_V/m_N)$$

Results I - quarks vector

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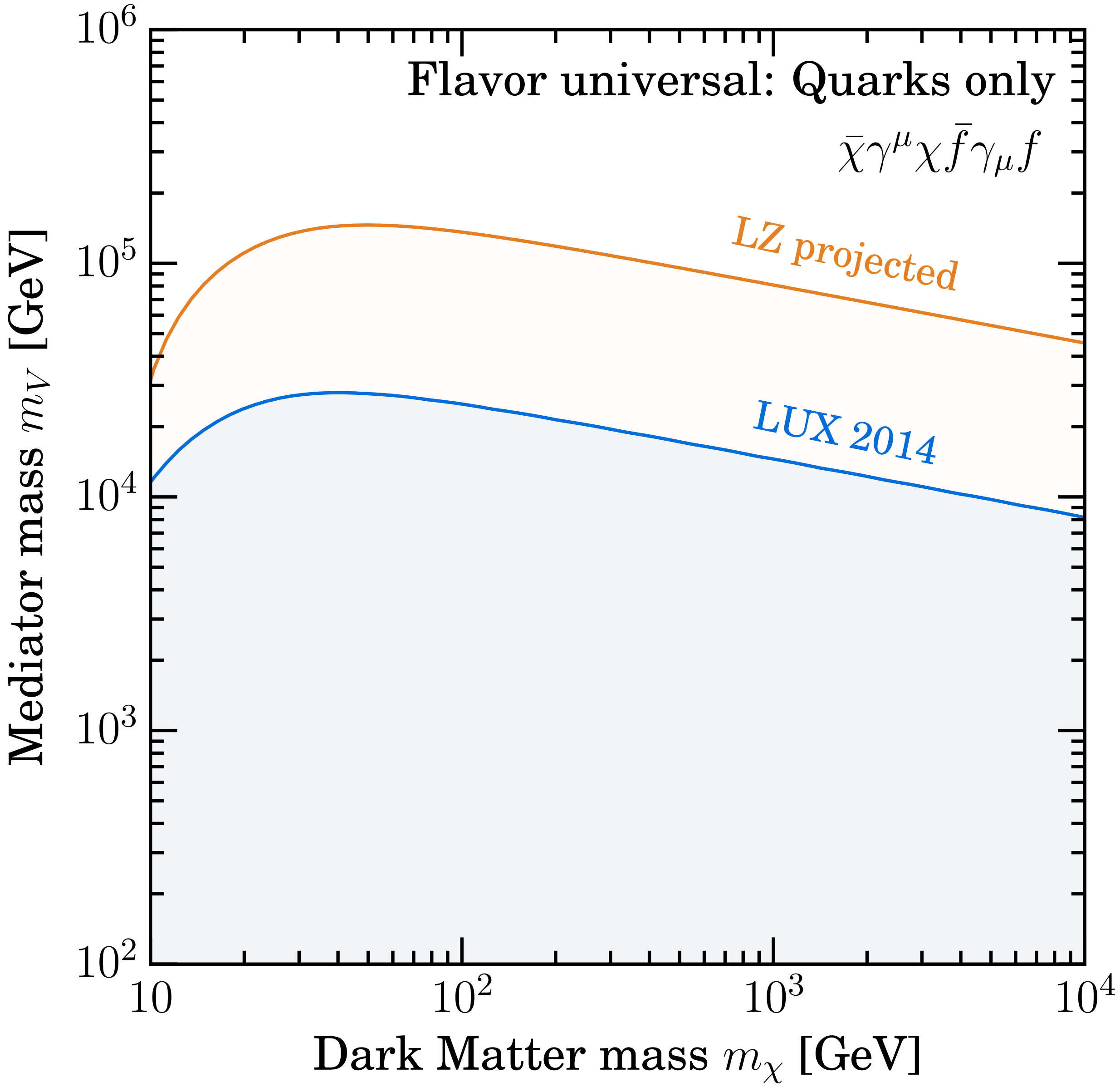
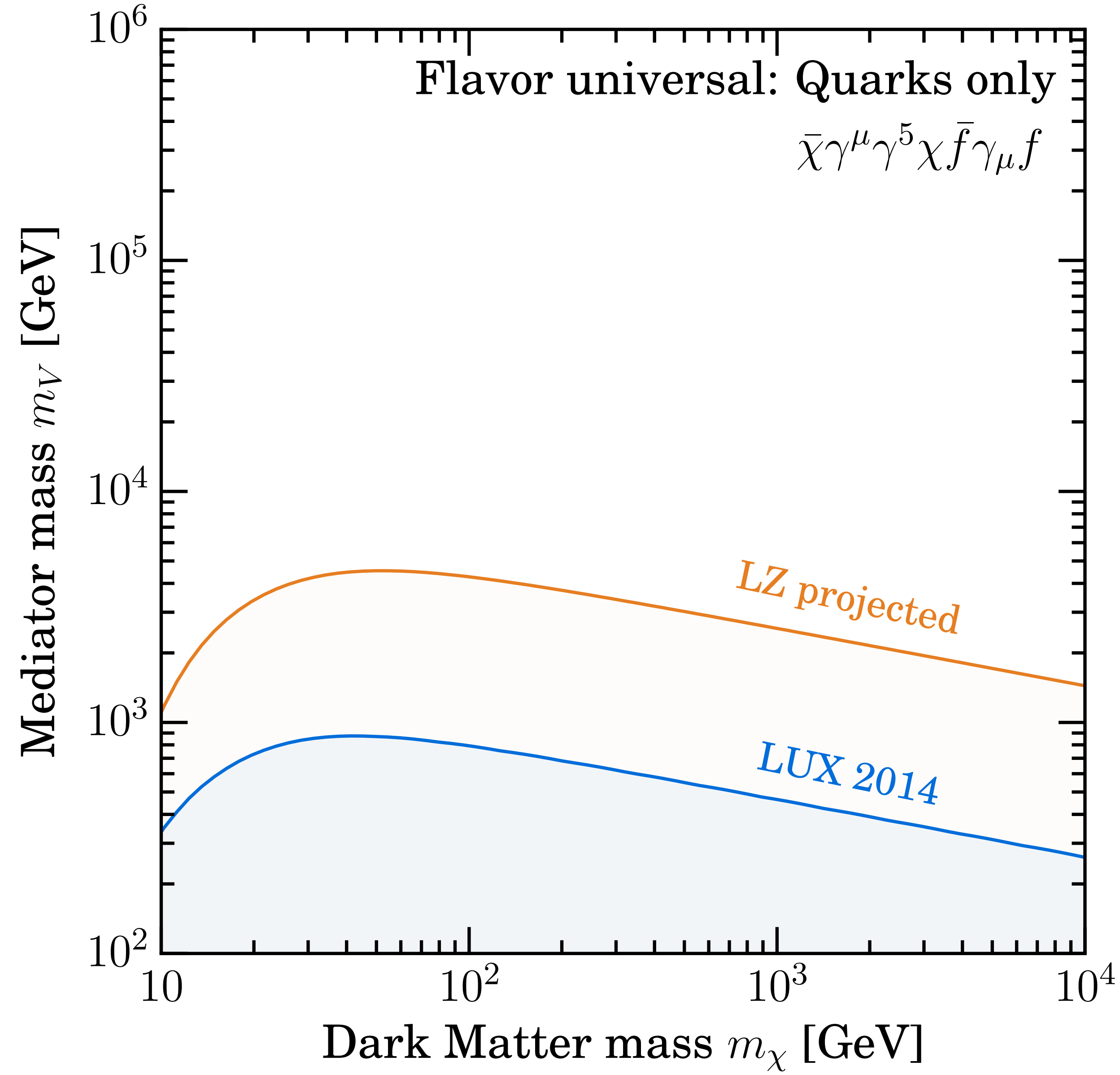
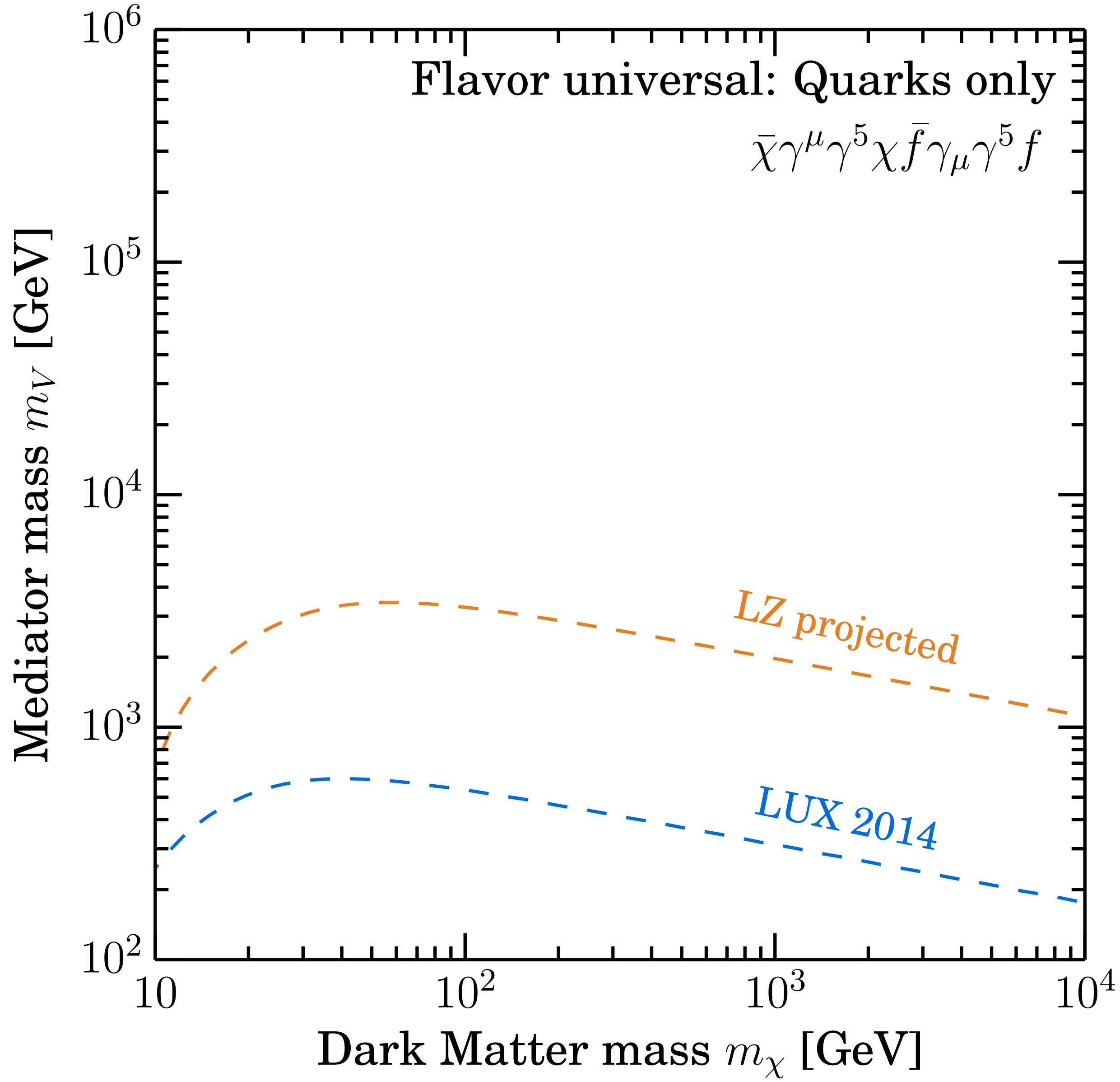




Results II - quarks axial-vector

$$\mathcal{L}_{\mathrm{EFT}} = -\frac{1}{m_V^2} J_{\mathrm{DM}\,\mu} \sum_{i=1}^{3} \left[\overline{u^i}\gamma^\mu\gamma^5 u^i + \overline{d^i}\gamma^\mu\gamma^5 d^i\right]$$

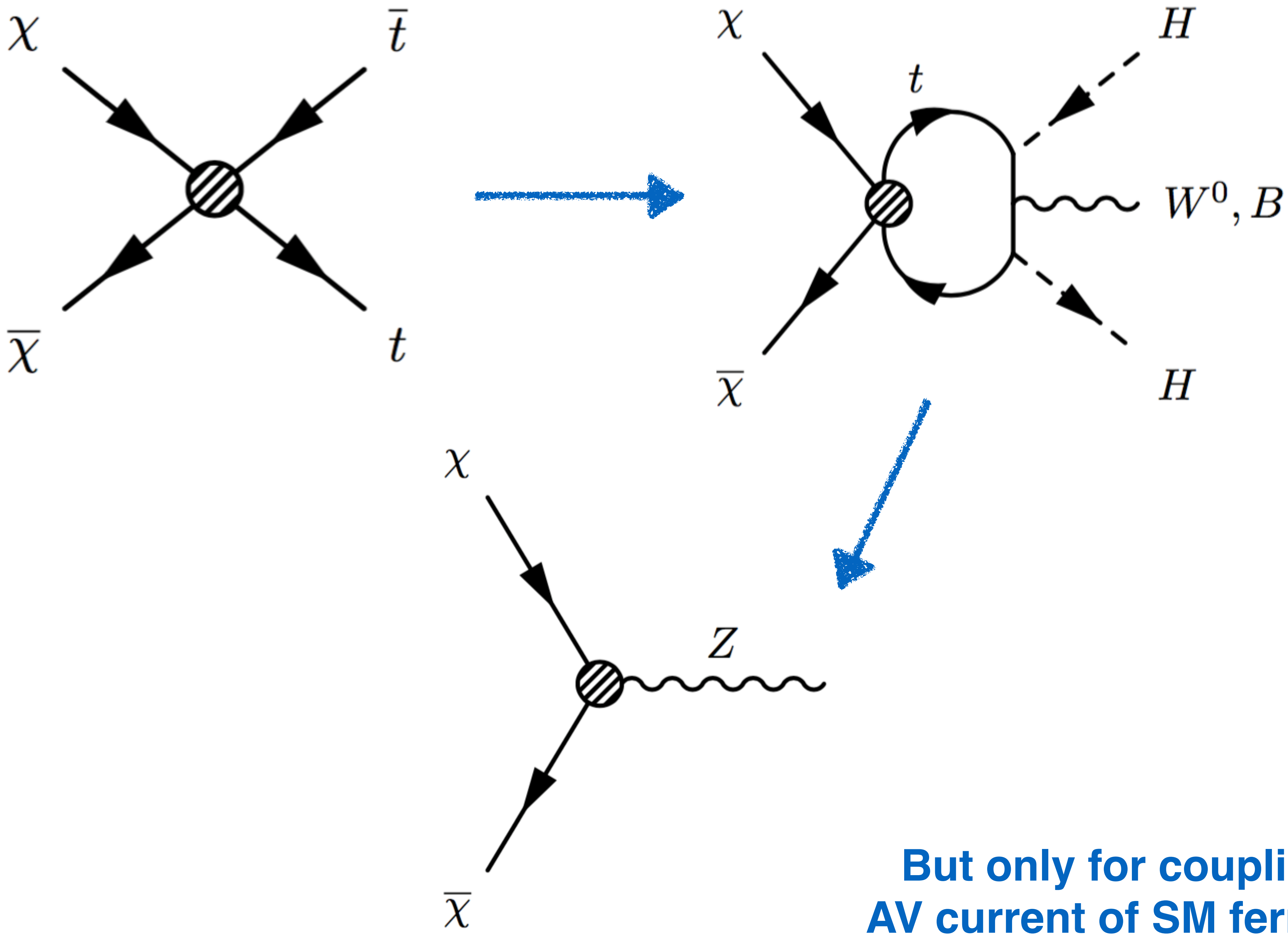


No running - - - - - -

Running ———

Aside: SM axial-vector current

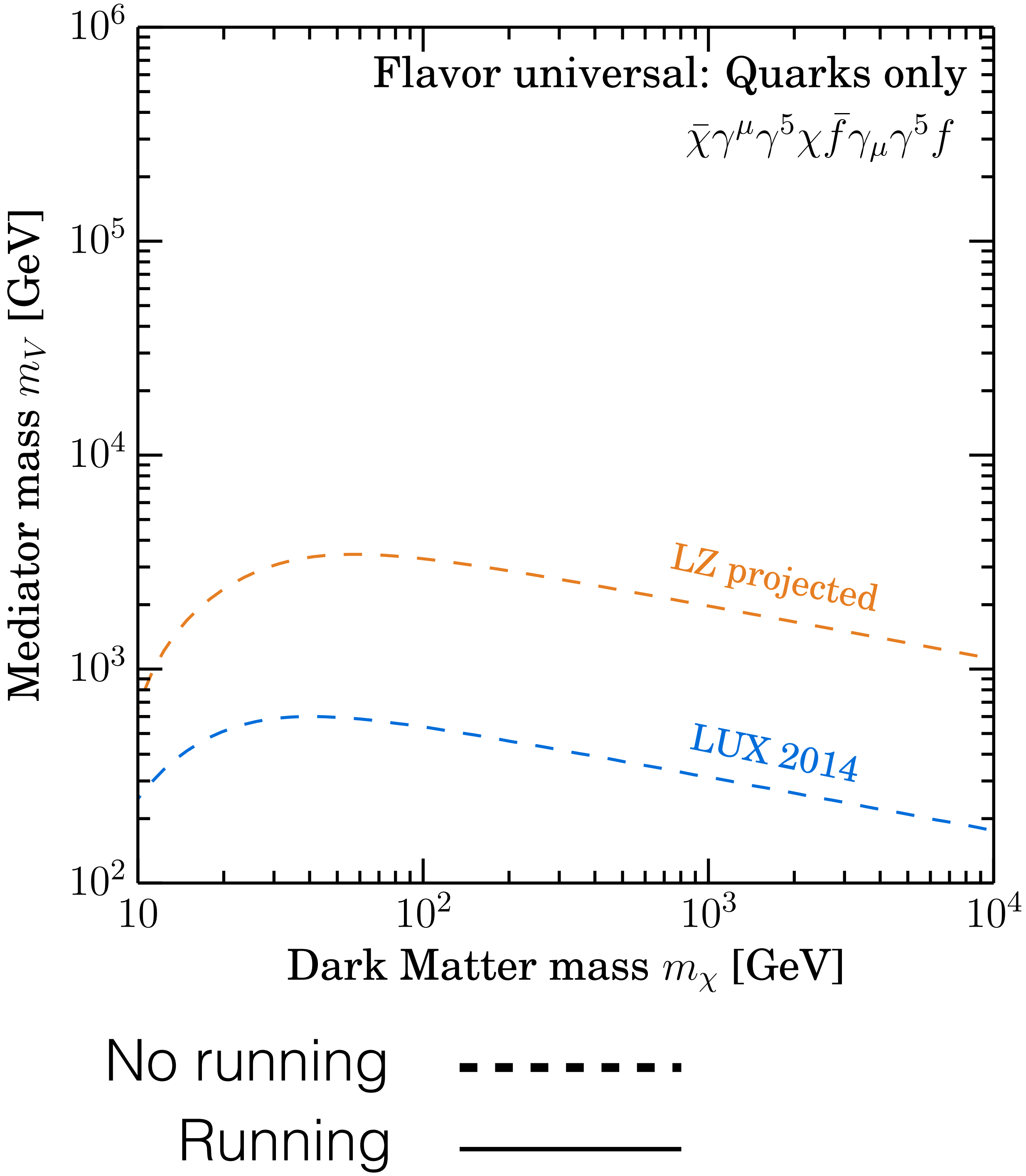
$J_{\mathrm{DM}\,\mu}\, \overline{q}\gamma^\mu\gamma^5 q$



But only for coupling to AV current of SM fermions!

Results II - quarks axial-vector

$$\mathcal{L}_{\mathrm{EFT}} = -\frac{1}{m_V^2}\, J_{\mathrm{DM}\,\mu} \sum_{i=1}^{3} \left[\overline{u^i}\gamma^\mu\gamma^5 u^i + \overline{d^i}\gamma^\mu\gamma^5 d^i\right]$$



Results II - quarks axial-vector

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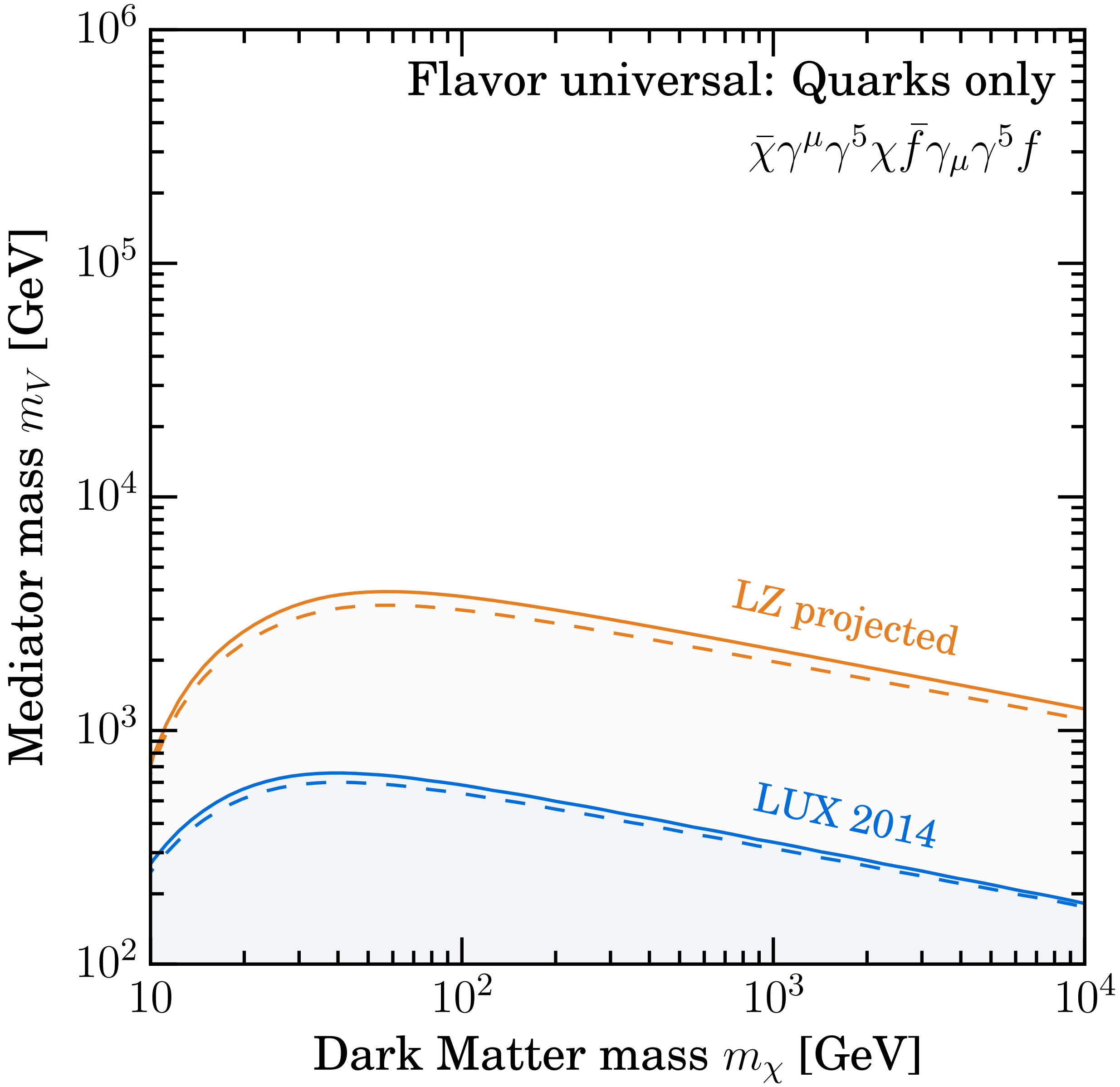

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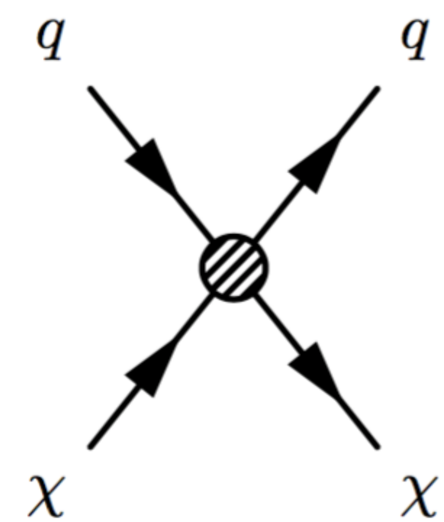
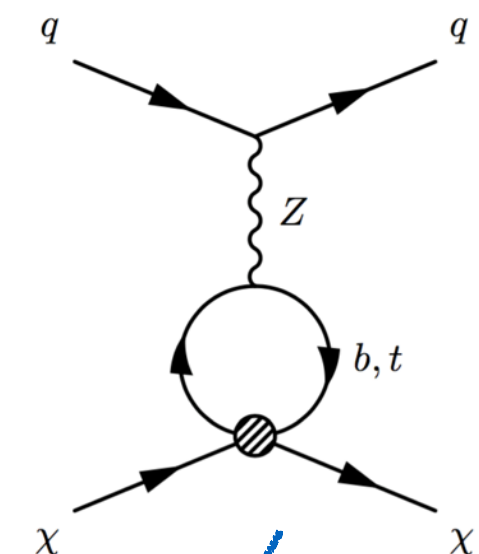
Running ———





$$c_A^{(q)} \sim 1 + \# \frac{\lambda_{b,t}^2}{16\pi^2} \ln(m_V/m_N)$$

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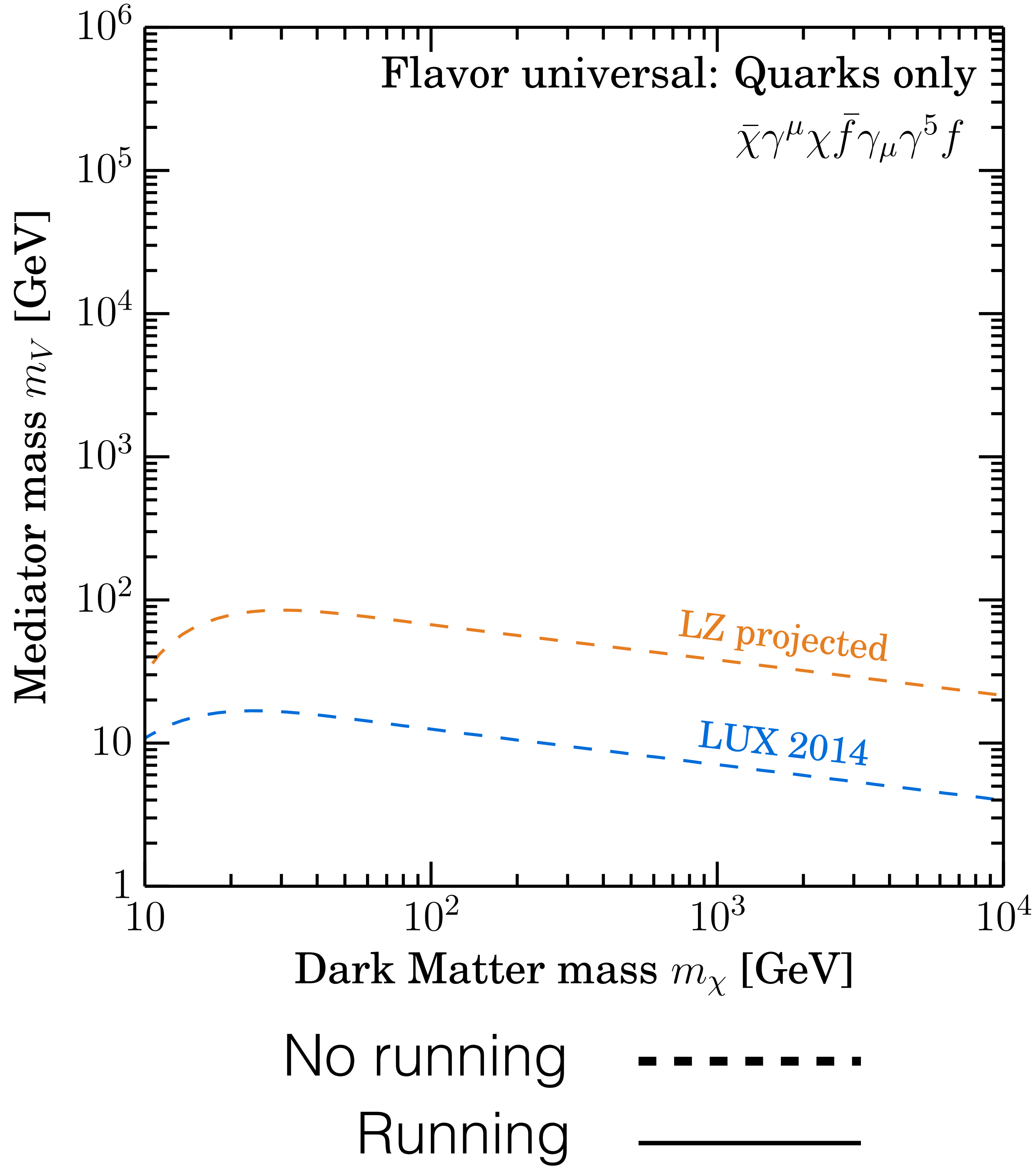

Results II - quarks axial-vector

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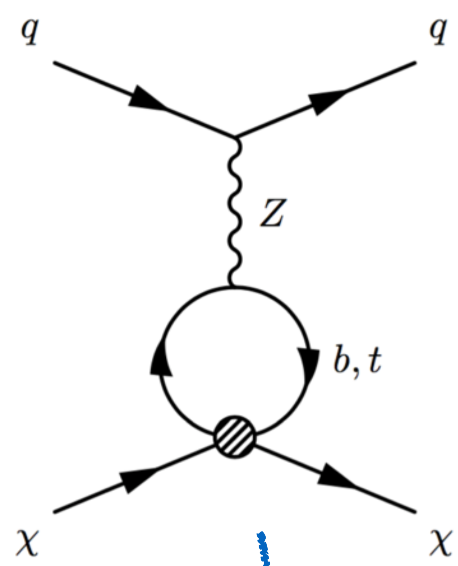
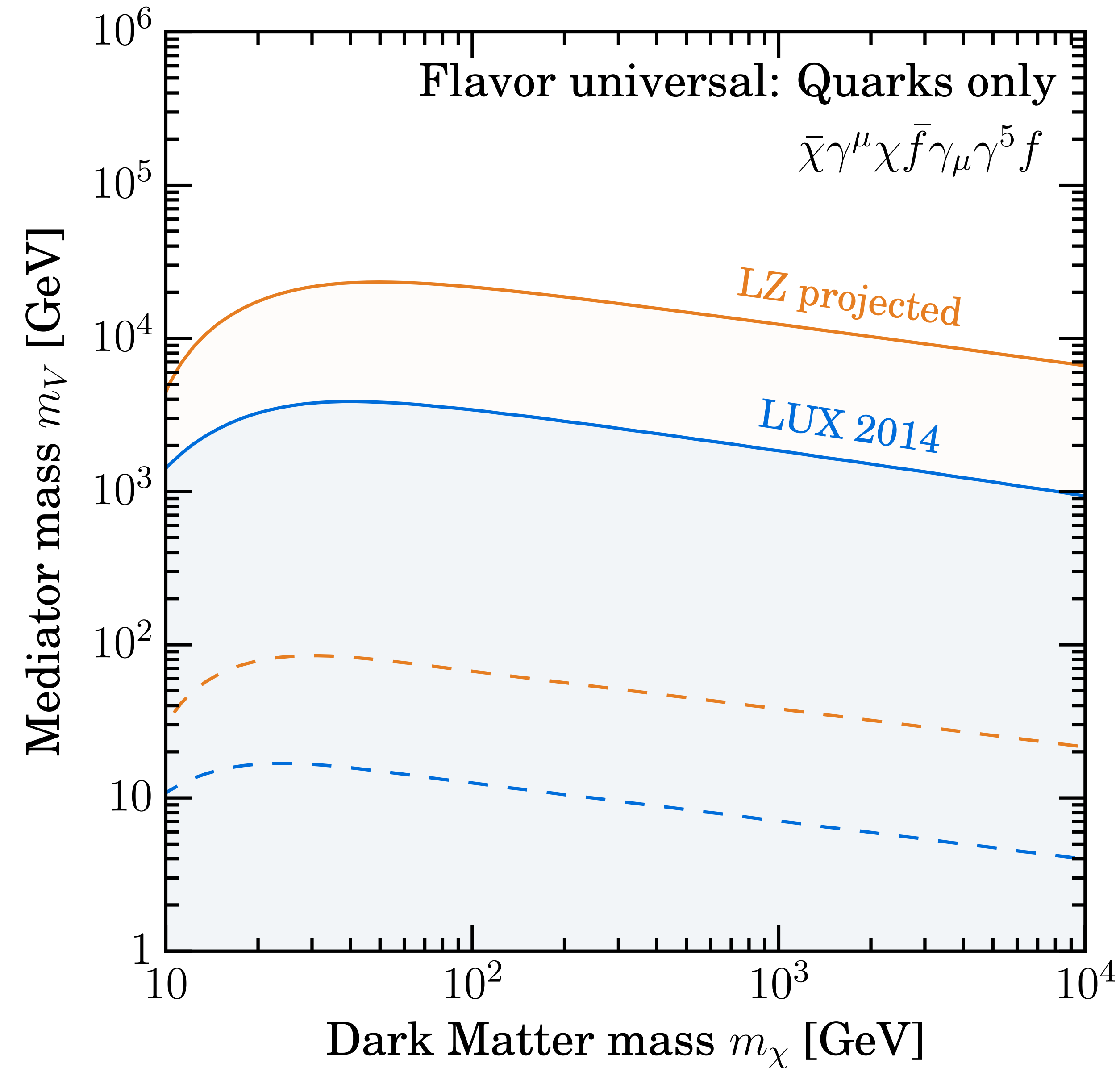


$$c_V^{(q)} \sim 0 + \#\frac{\lambda_{b,t}^2}{16\pi^2}\ln(m_V/m_N)$$



No running
Running

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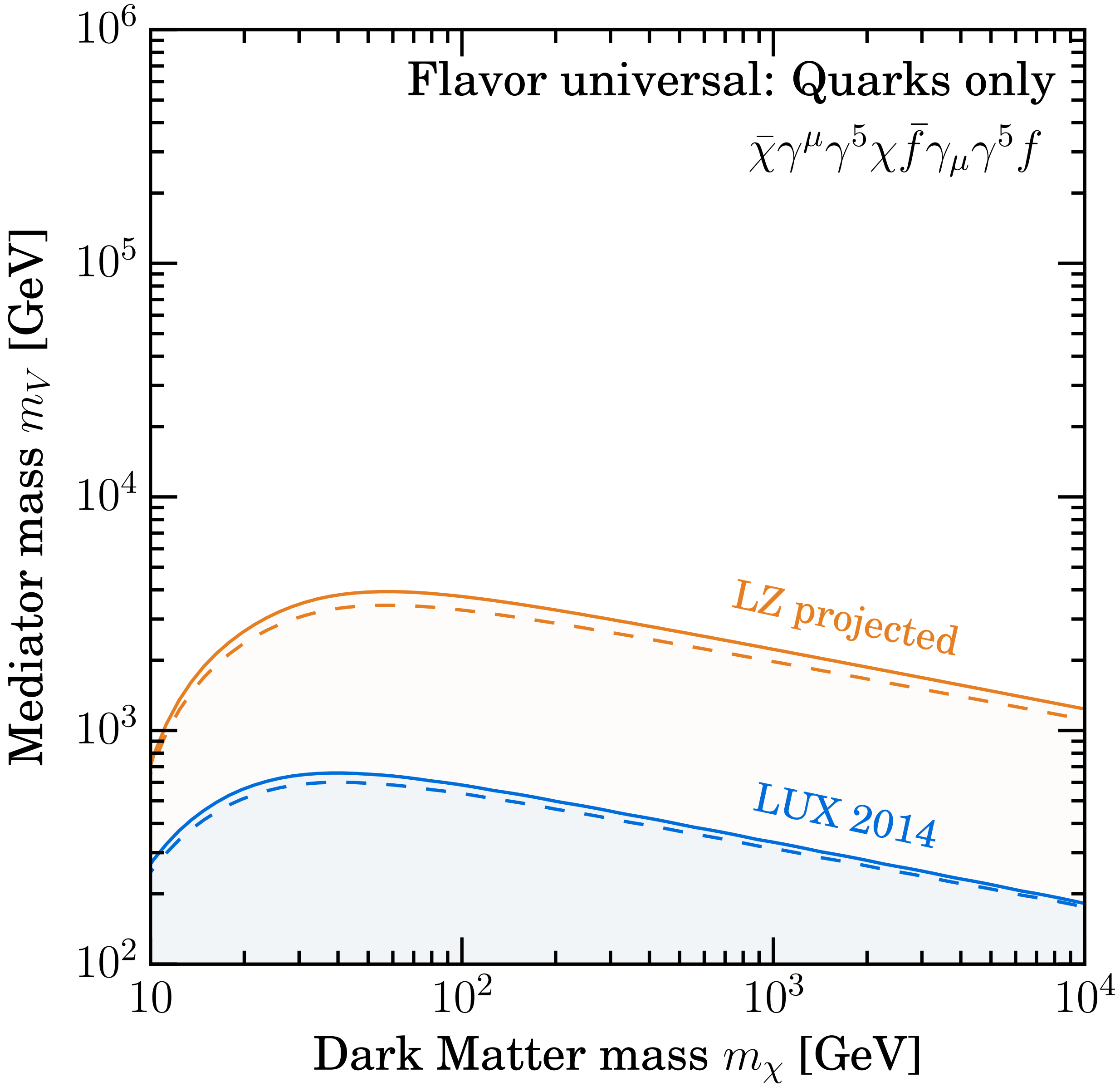
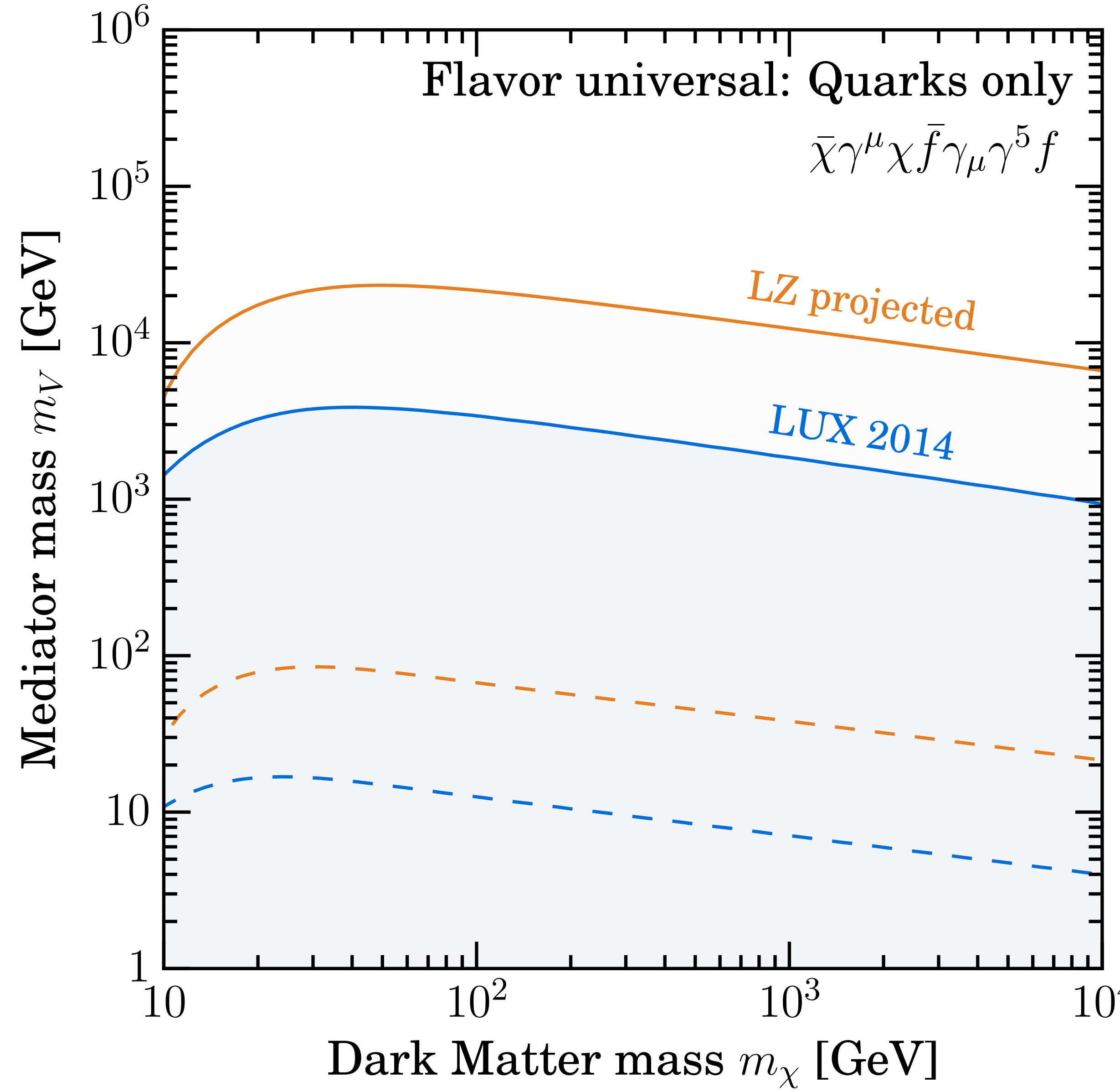


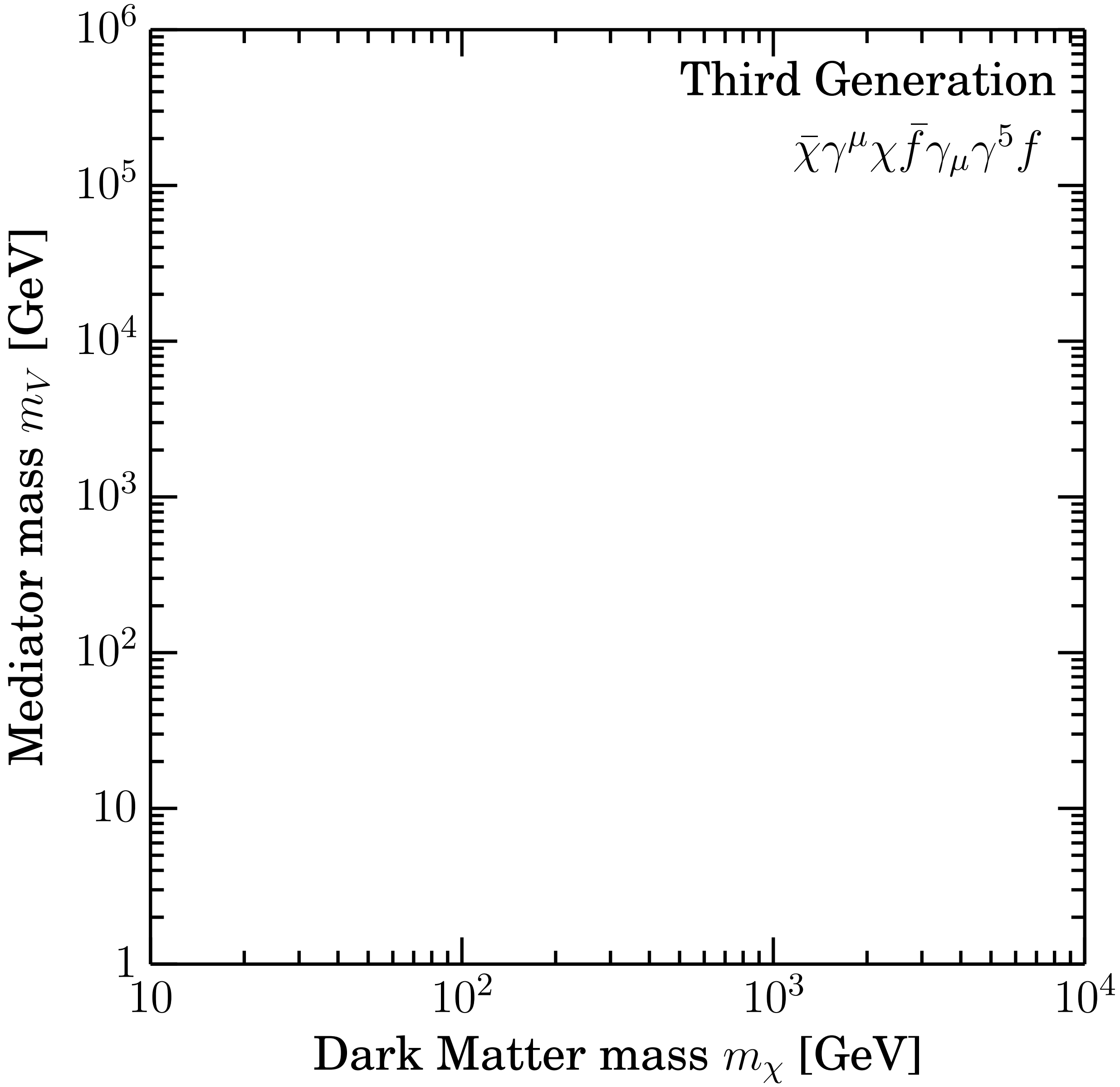


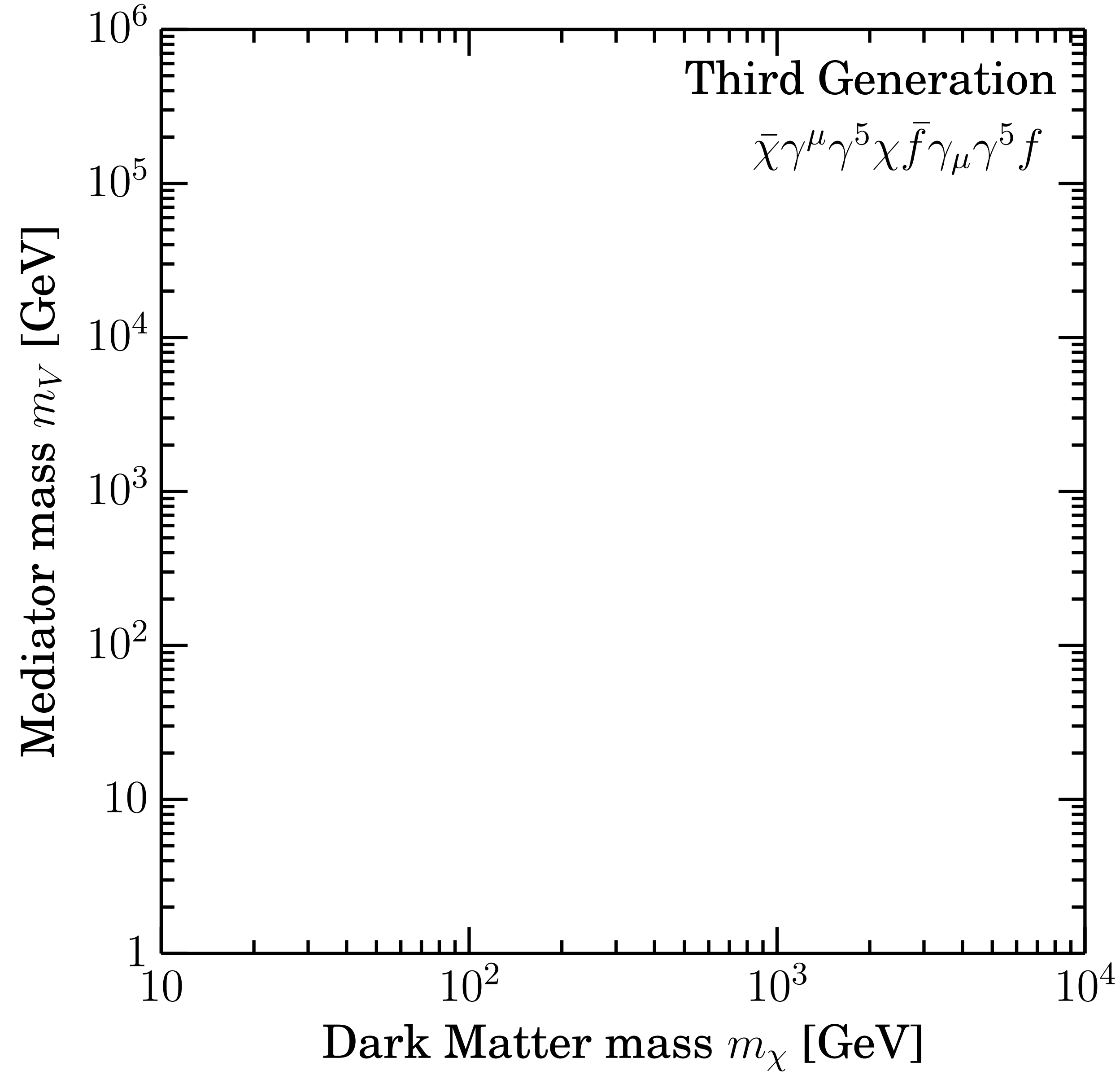
No running

Running

Results III - 3rd Generation axial-vector

$$\mathcal{L}_{\mathrm{EFT}} = -\frac{1}{m_V^2} J_{\mathrm{DM}\,\mu} \left[\bar{t}\gamma^\mu\gamma^5 t + \bar{b}\gamma^\mu\gamma^5 b + \bar{\tau}\gamma^\mu\gamma^5\tau\right]$$





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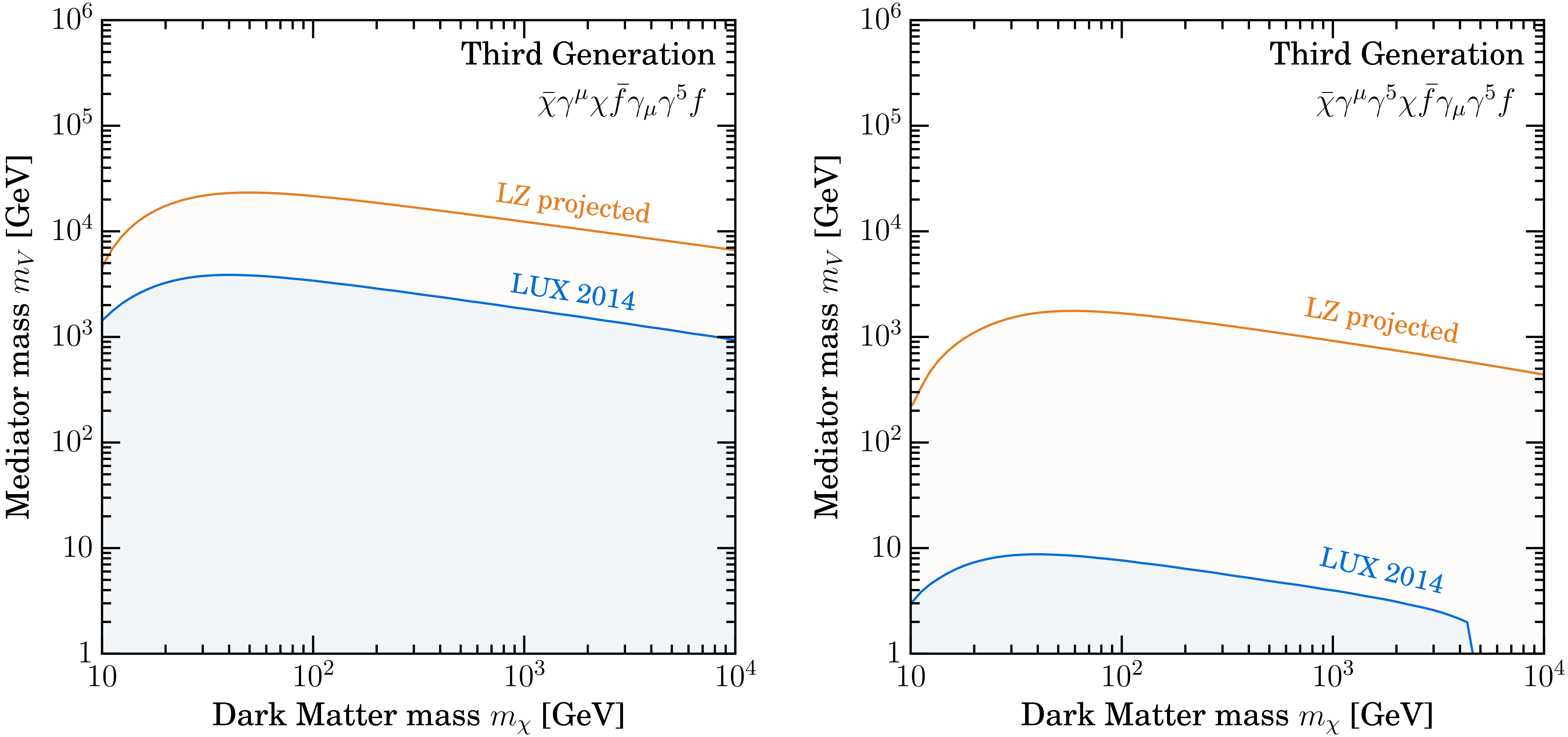
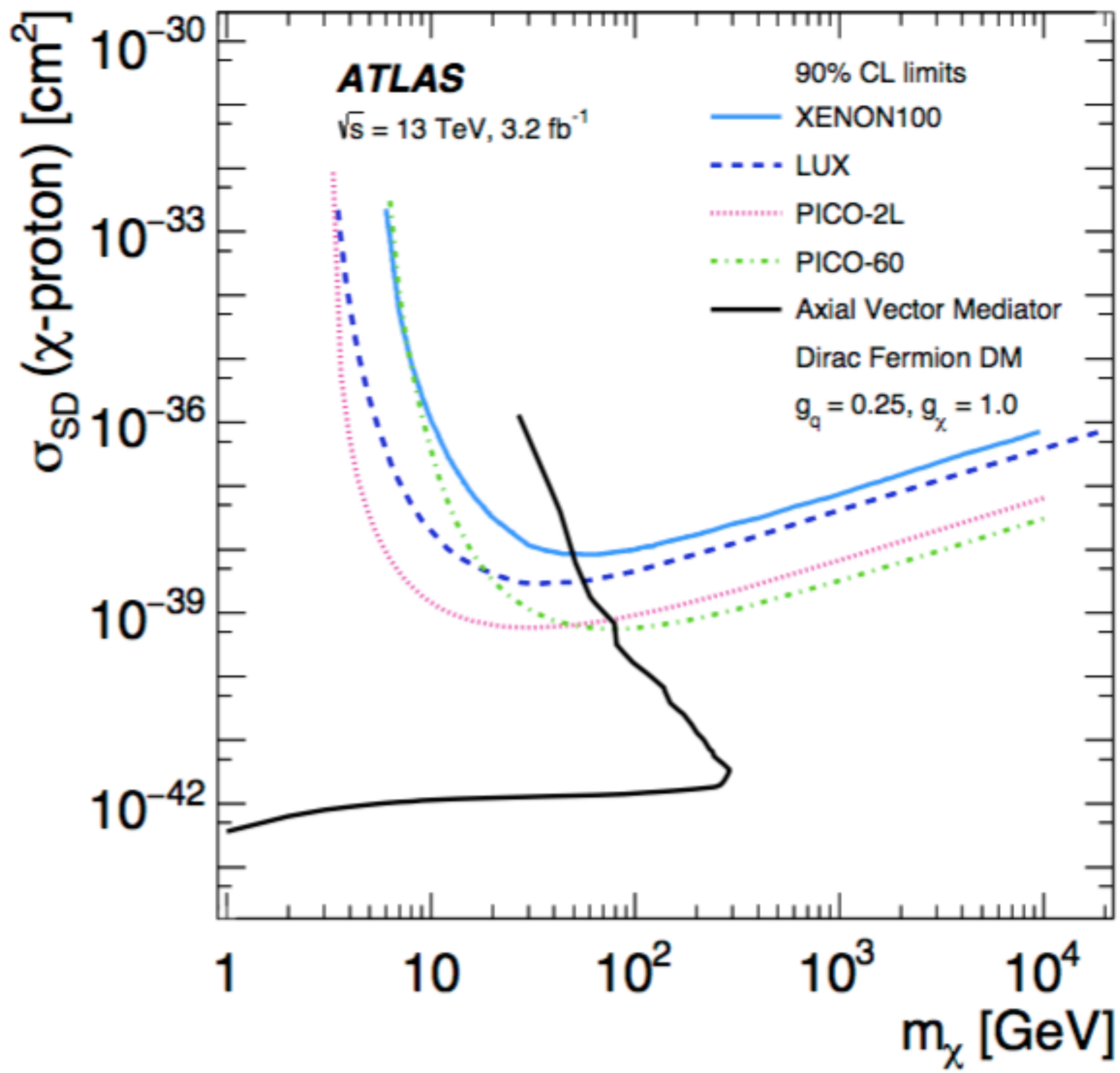
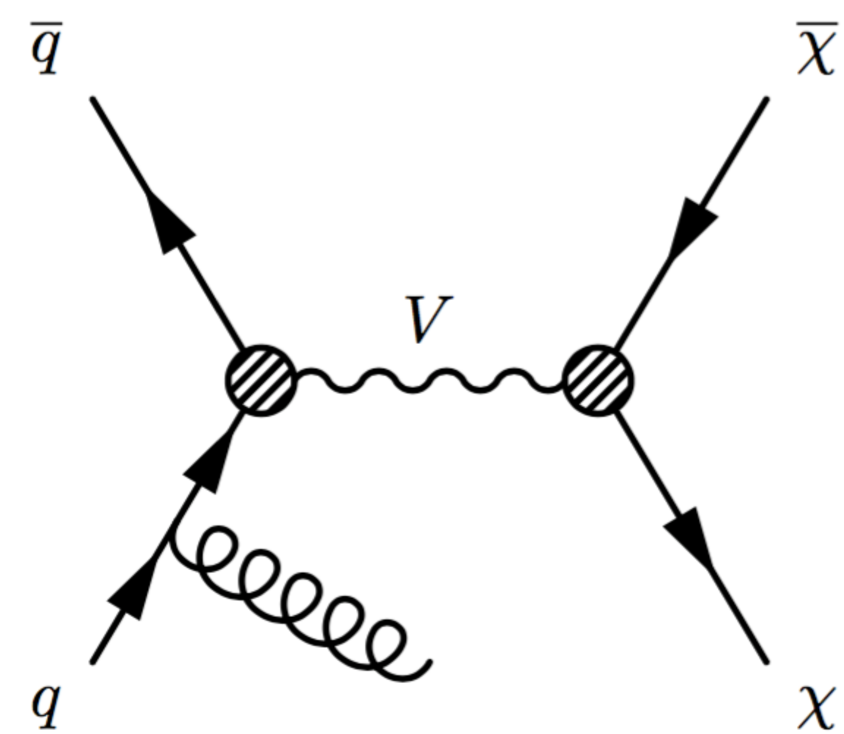


Comparing DD and LHC searches

LHC mono-X searches

$$\mathcal{L}_{\mathrm{AV}} = g_\chi V_\mu \,\overline{\chi}\gamma^\mu\gamma^5\chi + g_q V_\mu \sum_q \overline{q^i}\gamma^\mu\gamma^5 q^i$$





ATLAS [1604.07773]

LHC mono-X searches

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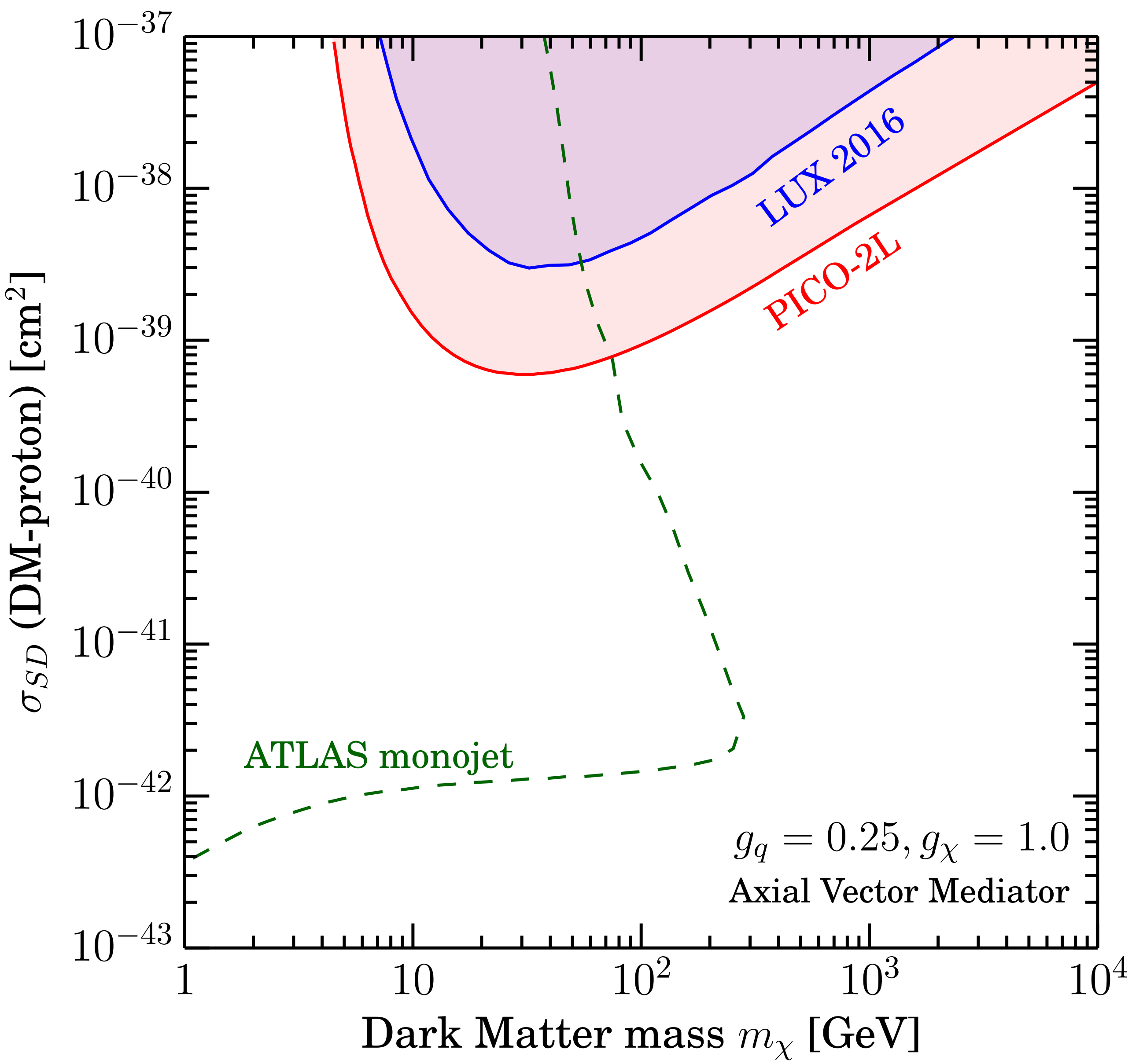

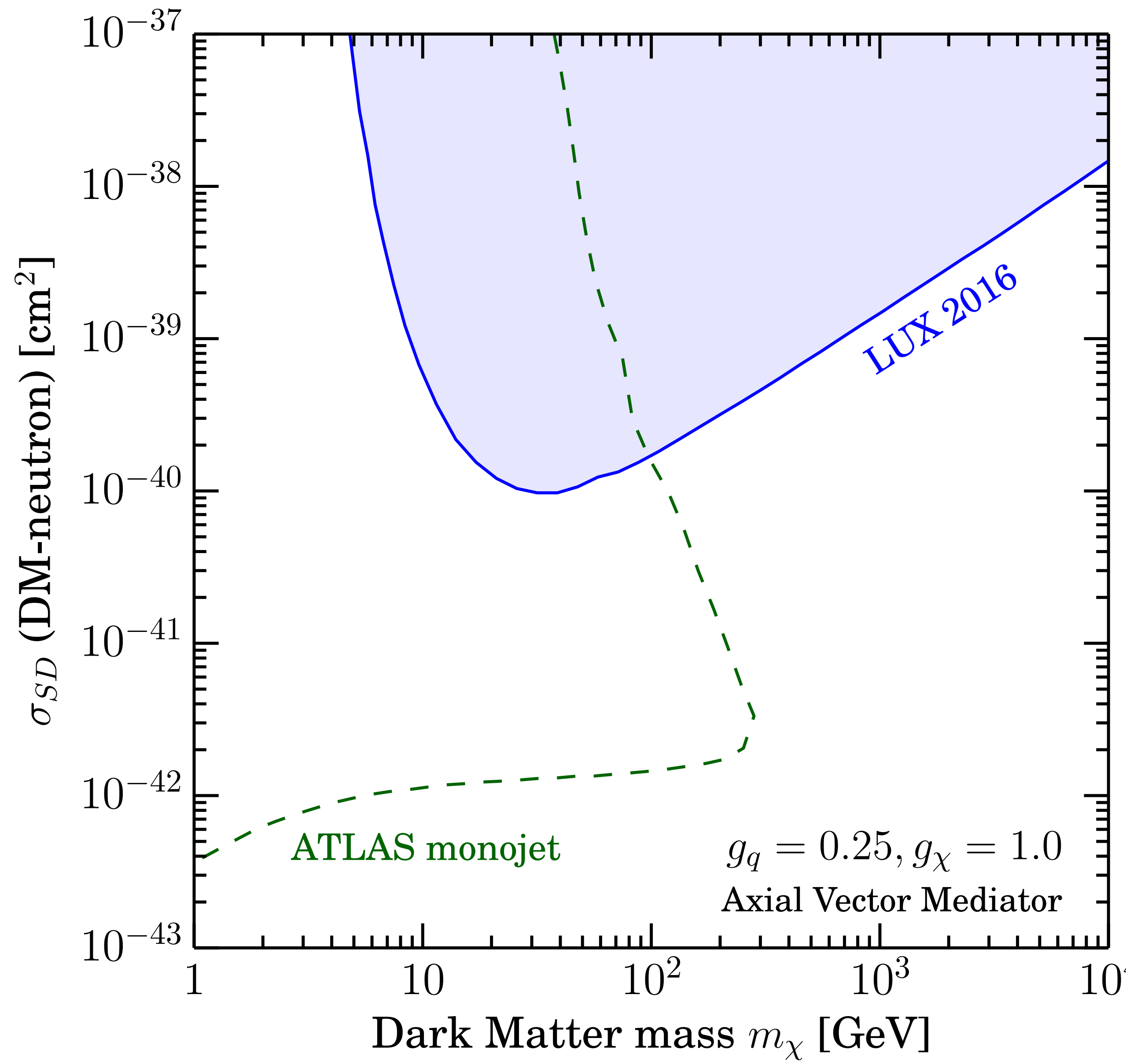

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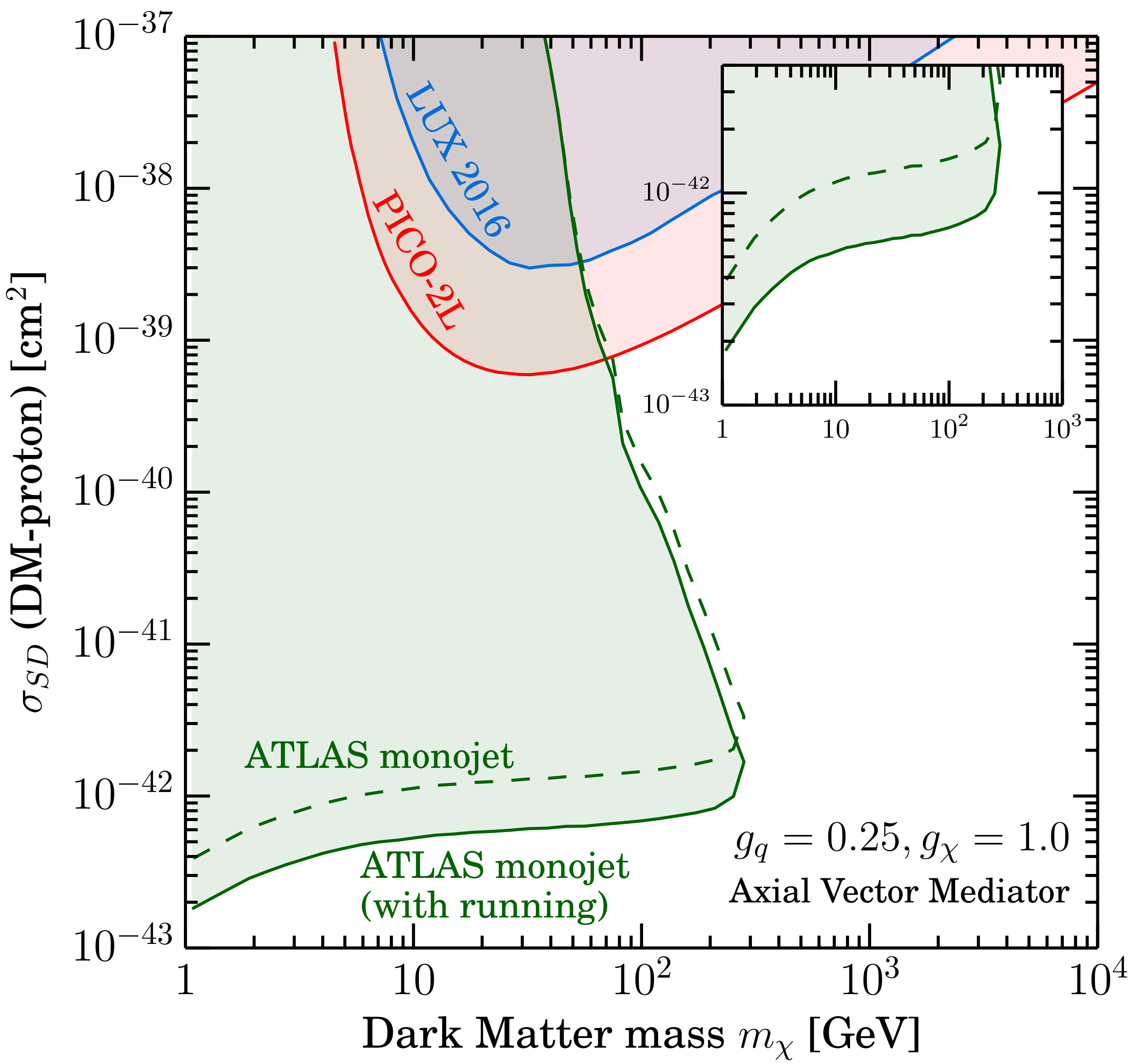
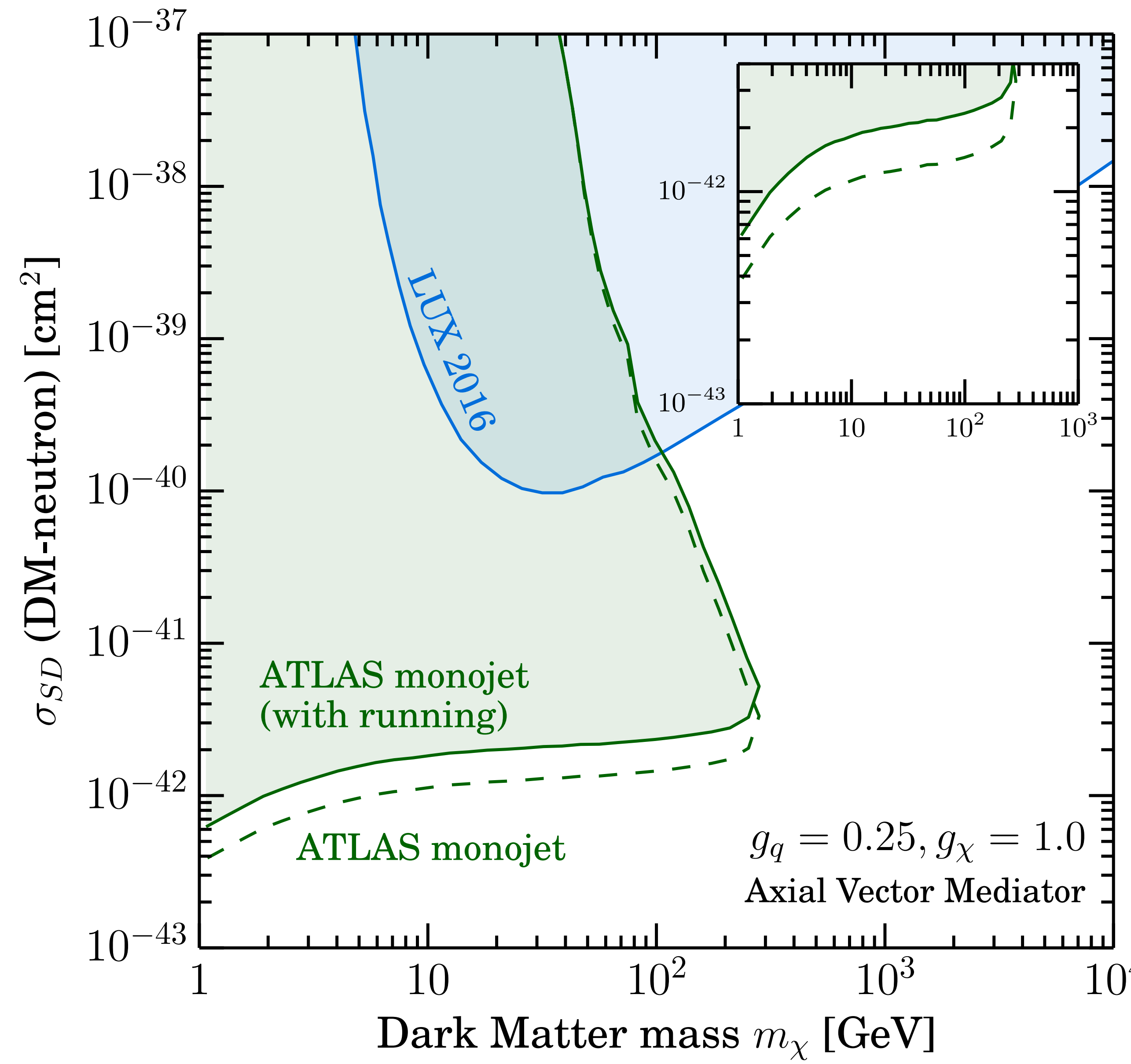
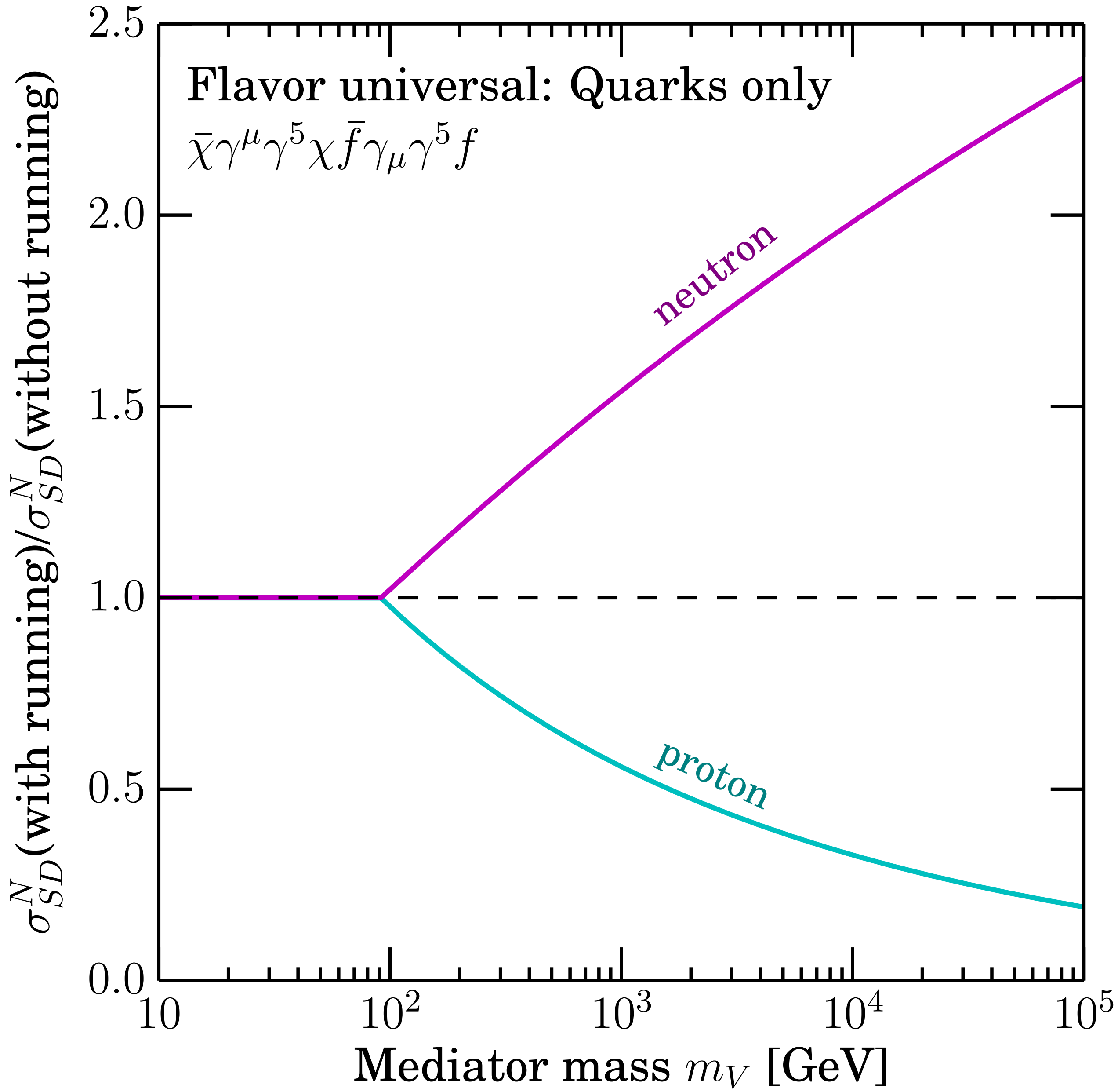




Isospin violation

$$\mathcal{L}_{\mathrm{AV}} = g_\chi V_\mu \, \overline{\chi}\gamma^\mu\gamma^5\chi + g_q V_\mu \sum_q \overline{q^i}\gamma^\mu\gamma^5 q^i$$



$$\mathcal{C}_A^{(N)} = g_q \left[\sum_{q=u,d,s} \Delta_q^{(N)}\right] + \frac{3g_q}{2\pi}\left(\Delta_d^{(N)} + \Delta_s^{(N)} - \Delta_u^{(N)}\right)\left[\alpha_t \ln(m_V/m_Z) - \alpha_b \ln(m_V/\mu_N)\right]$$

Other interactions

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	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$

Standard SI

Standard SD

Goodman et al. [1008.1783]

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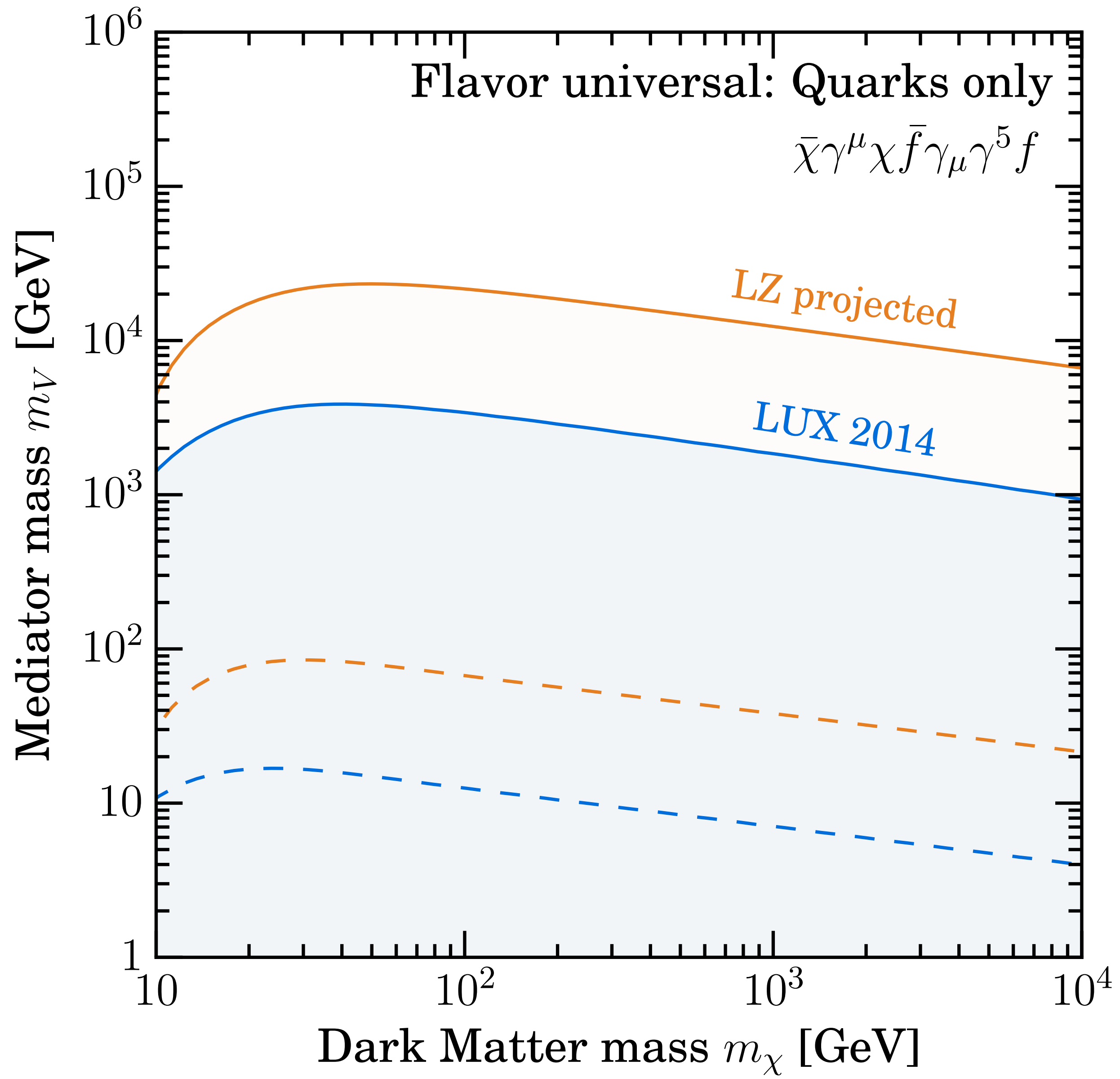

Caveats

If we add extra degrees of freedom, the phenomenology may be different

E.g. Jackson et al. [1303.4717]

May want to include mass and/or kinetic mixing of the mediator

Langacker [0801.1345]

$$\mathcal{L}_{\mathrm{KM}} \sim \epsilon Z_{\mu\nu} V^{\mu\nu}$$

but we expect this to *strengthen* the limits

In general, we need to worry about the UV completion (e.g. anomaly cancellation, Higgling of the U(1)', etc.)

But if we stick to the Simplified Model framework, our results are valid - and unavoidable!

Summary

Need to take into account separation of scales

→ RGE (use **runDM** code)

Low-E couplings changed and new operators induced

→ limits on heavy mediators affected (sometimes by OoM!)

Running is important for search complementarity

→ req. for translating LHC searches into DD plane

Isospin violation (factor of ~few) is automatic

→ arising only from SM loops

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YOU HAVE TO RUN!

Backup slides

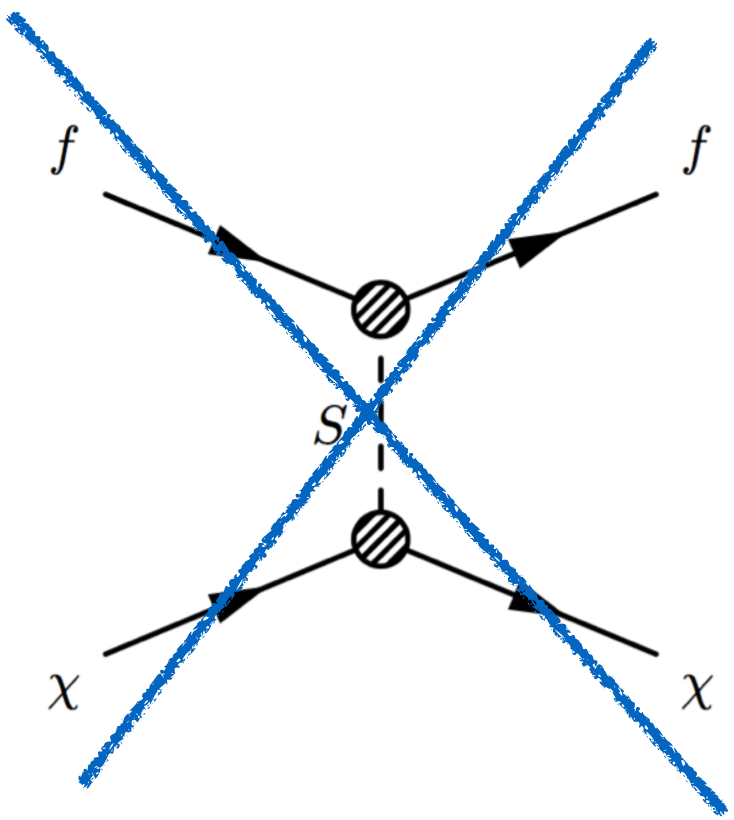
Scalar Mediators

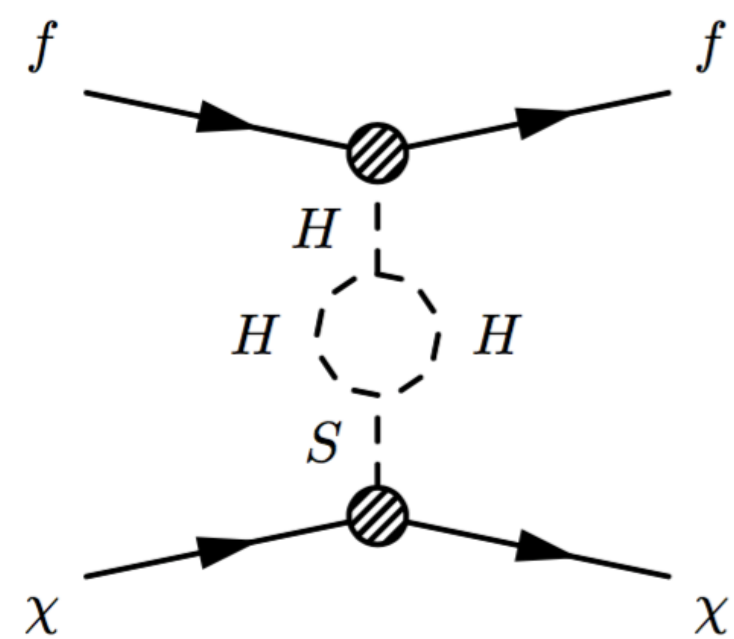
Interactions through a scalar mediator appear at dimension-7, with rates typically suppressed by the quark mass

$$O^S_{gg} = \frac{\alpha_s}{\Lambda^3}\,\bar{\chi}\chi\,G_{\mu\nu}G^{\mu\nu}\,, \quad O^{SS}_{qq} = \frac{m_q}{\Lambda^3}\,\bar{\chi}\chi\,\bar{q}q\,,$$

Crivellin, D'Eramo, Procura [1402.1173]

Buckley et al. [1410.6497]





Scalar mediator: 750 GeV

A 750 GeV Portal:
LHC Phenomenology
and Dark Matter Candidates

Francesco D'Eramo[a,b], Jordy de Vries[c], Paolo Panci[d]

D'Eramo, de Vries, Panci [1601.01571]

$$\mathcal{L}_{\rm EFT}^{m_S<\mu<\Lambda} = \sum_{q=u,d,s,c,b,t} \frac{c_{yq}\, y_q}{\Lambda} S\, (\bar{q}_L H q_R + \text{h.c.}) + \frac{c'_{GG}\, \alpha_s}{\Lambda} S\, G^{A\,\mu\nu} G^A_{\mu\nu}\ ,$$

$$\mathcal{C}_q(\mu_N) \simeq -5.86\, \mathcal{C}_{GG}(m_S)\ ,$$
$$\mathcal{C}_{GG}(\mu_N) \simeq 4.01\, \mathcal{C}_{GG}(m_S)\ .$$

Substantial RG effects!

The operator basis

Complete the operator basis

$$\frac{J_{\mathrm{DM}\,\mu}\, H^\dagger\, i \overleftrightarrow{D}^{\mu} H}{m_V^2}$$

Redundant Operator (E.O.M.)

$$\frac{J_{\mathrm{DM}\,\mu}\, \partial_\nu B^{\mu\nu}}{m_V^2}$$