

# **'You Better Run'**

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

Bradley J. Kavanagh  
LPTHE & IPhT (CEA/Saclay)

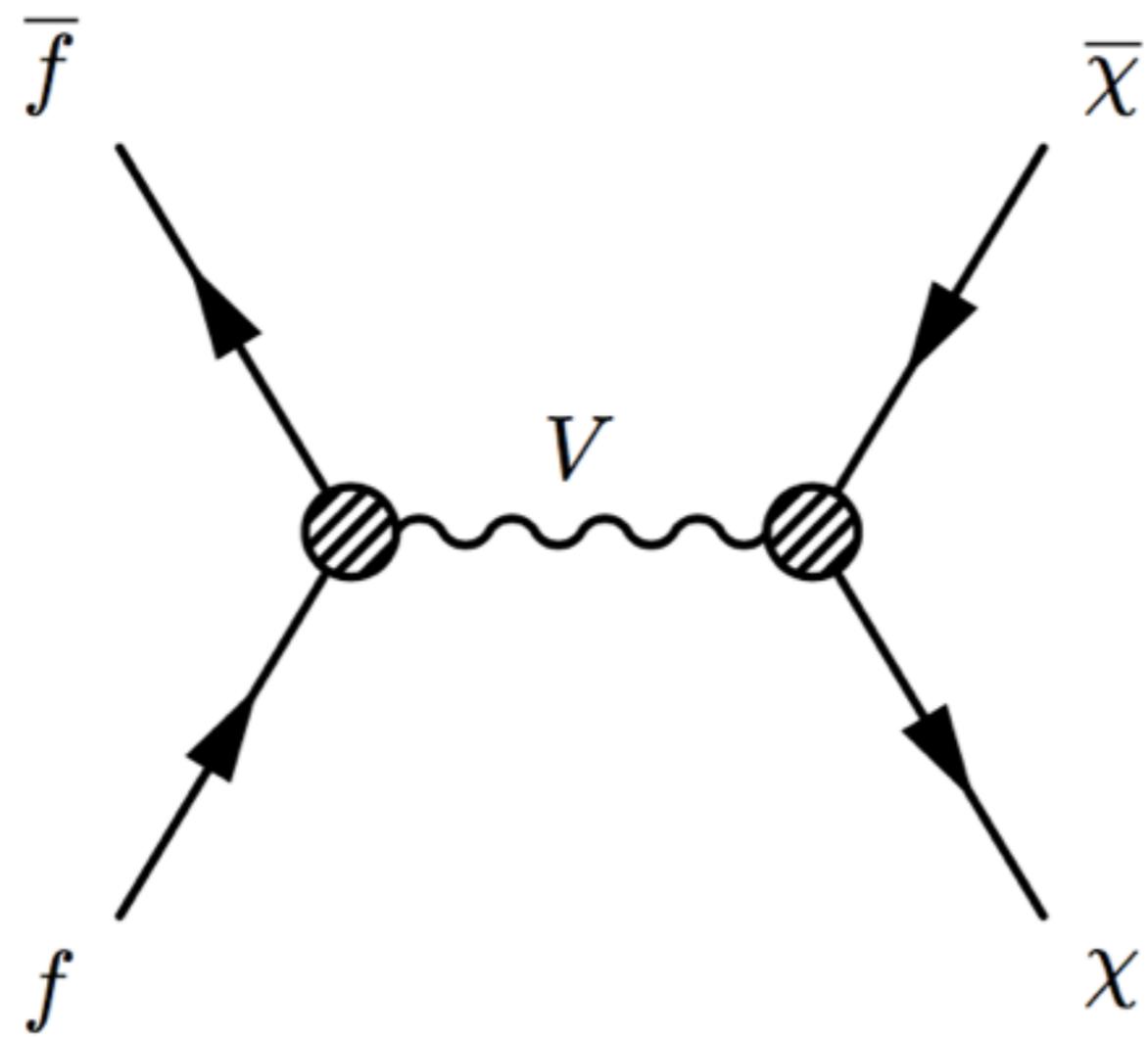
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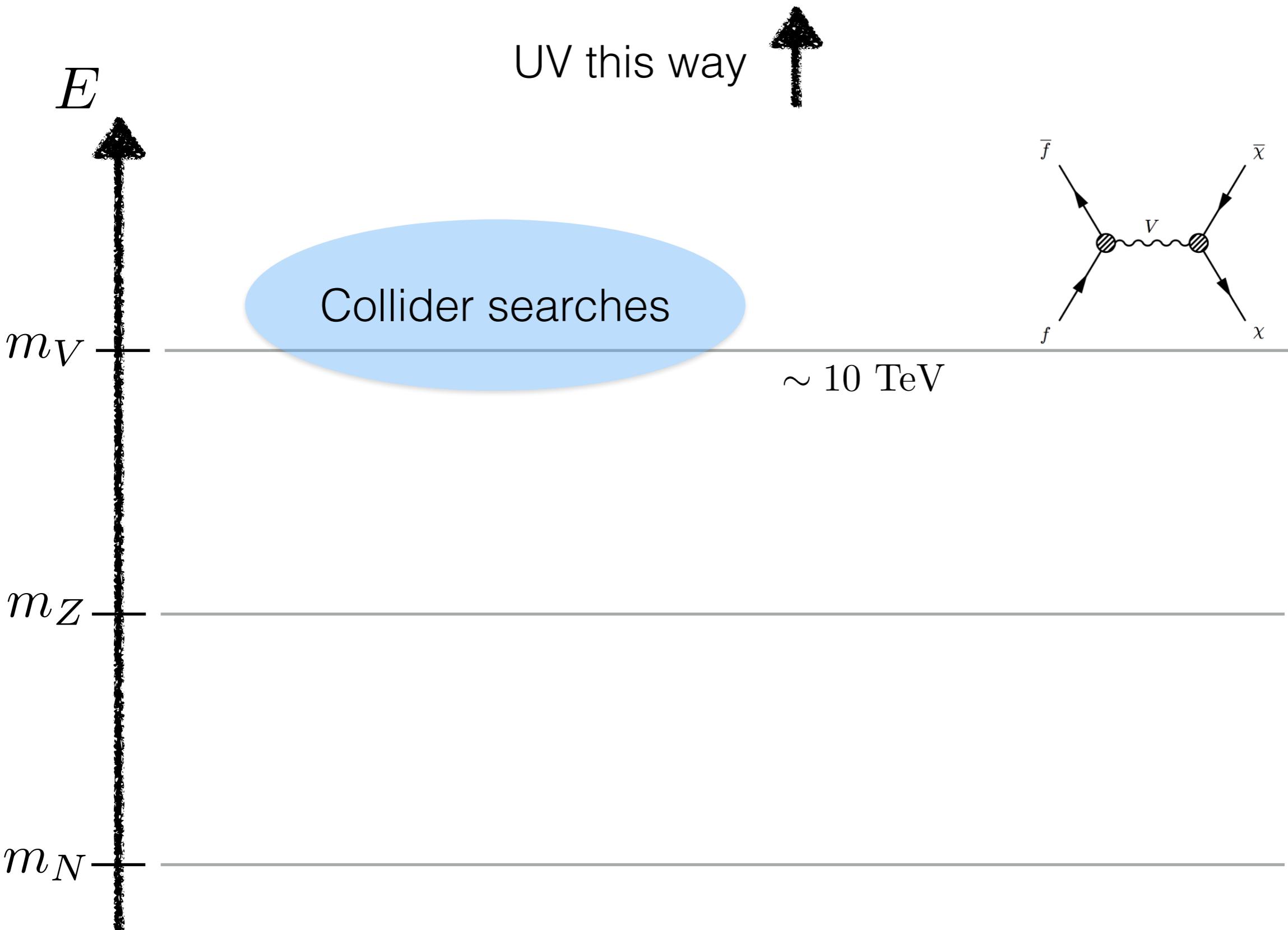


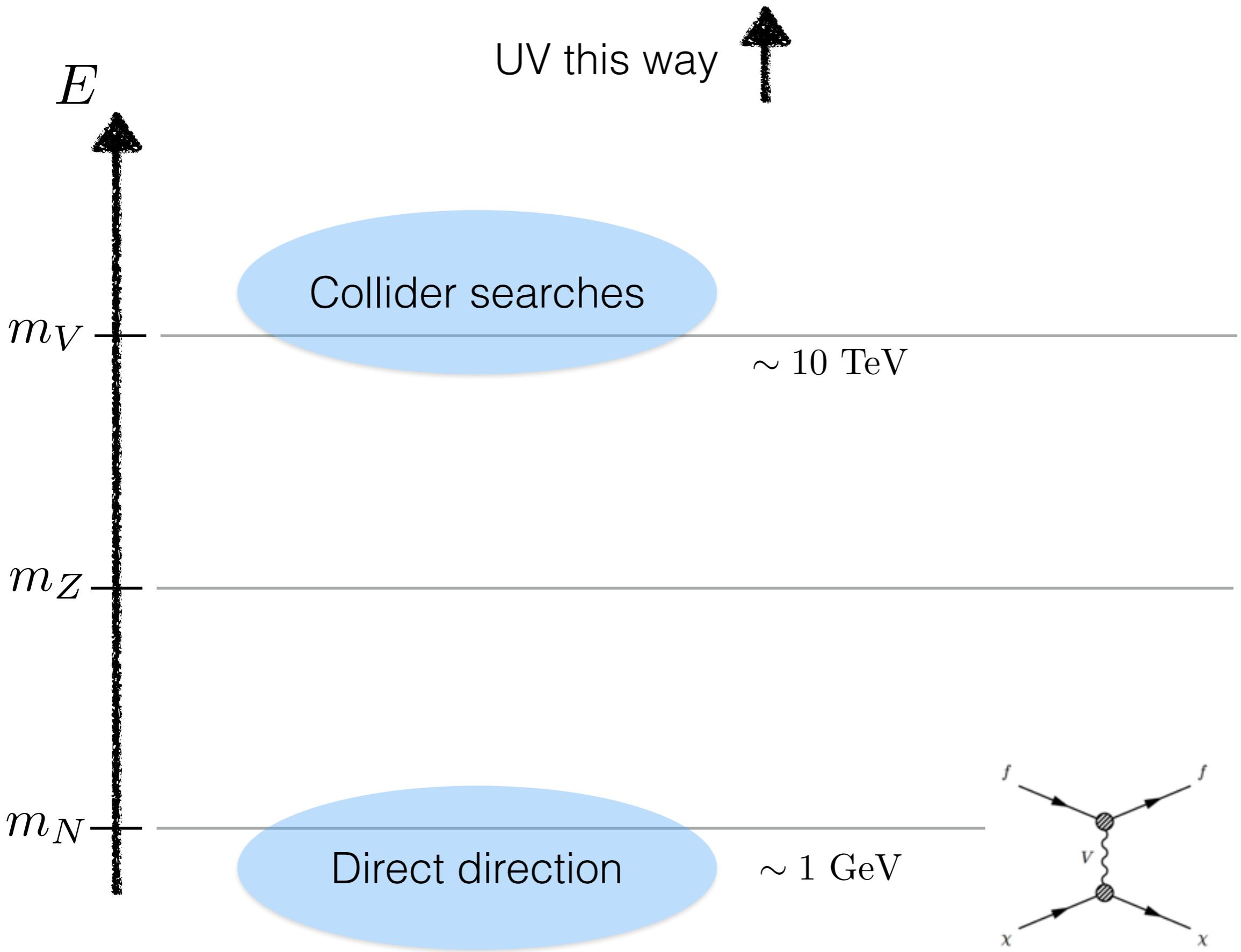
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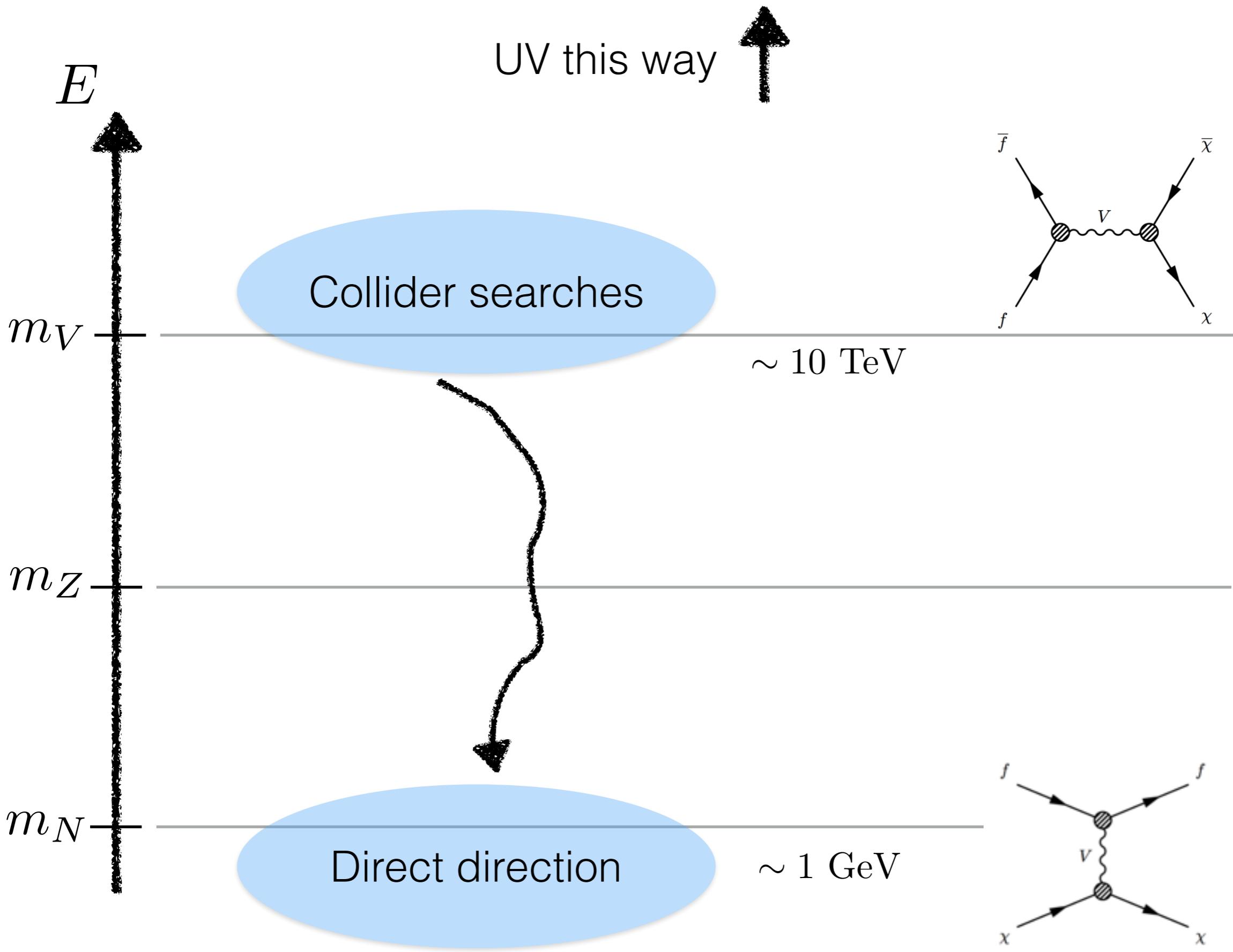


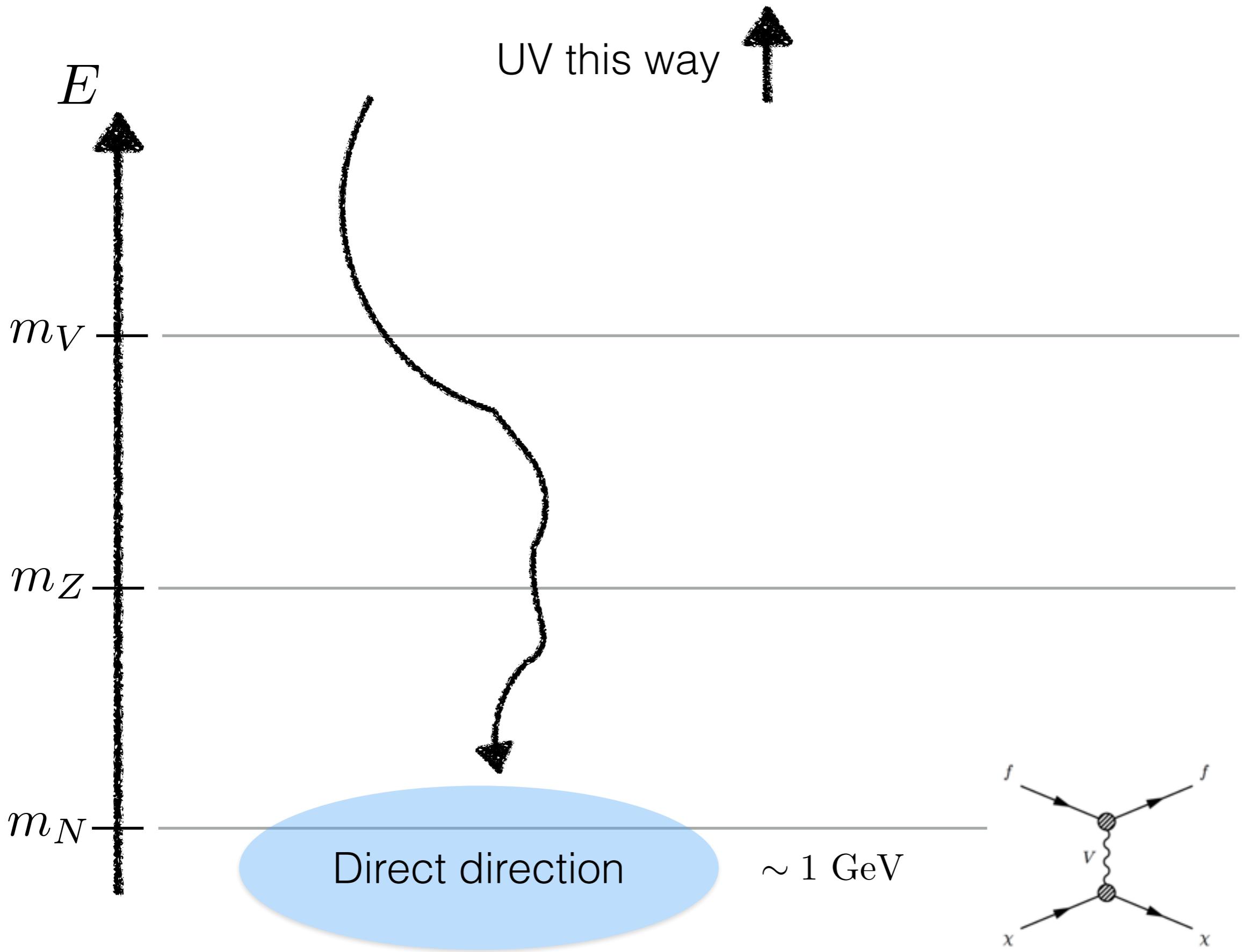
bradley.kavanagh@lpthe.jussieu.fr  
 @BradleyKavanagh



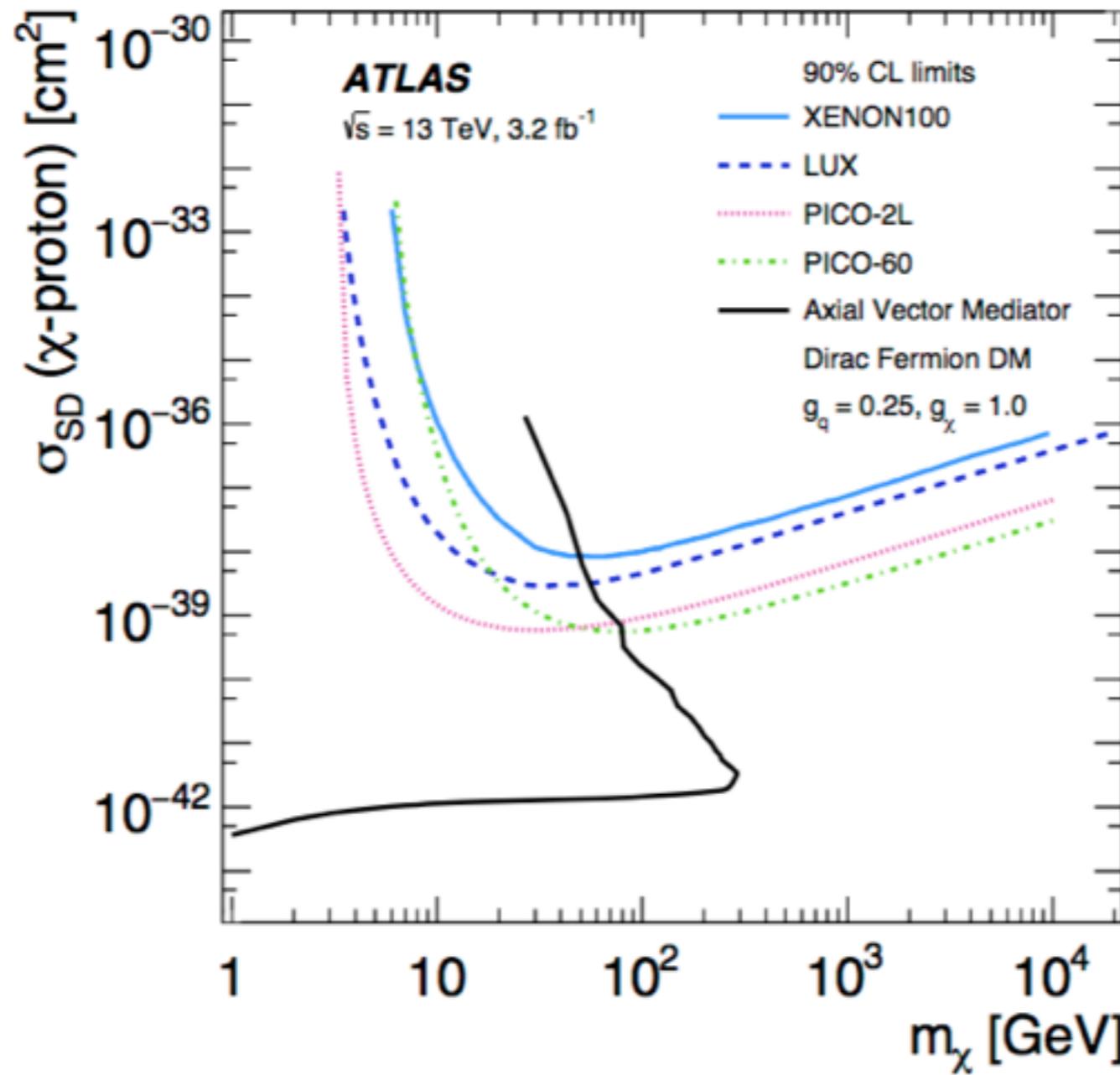








# Comparing different searches



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

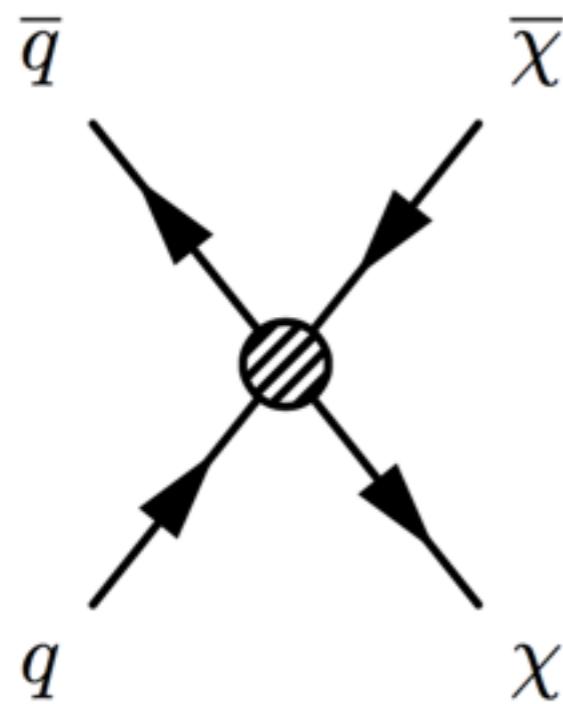
D'Eramo, BJK, Panci [1605.04917]

# Simplified Models

# Effective Field Theory

Assume mass of mediator is much larger than momentum transfer

integrate out mediator to obtain a contact interaction

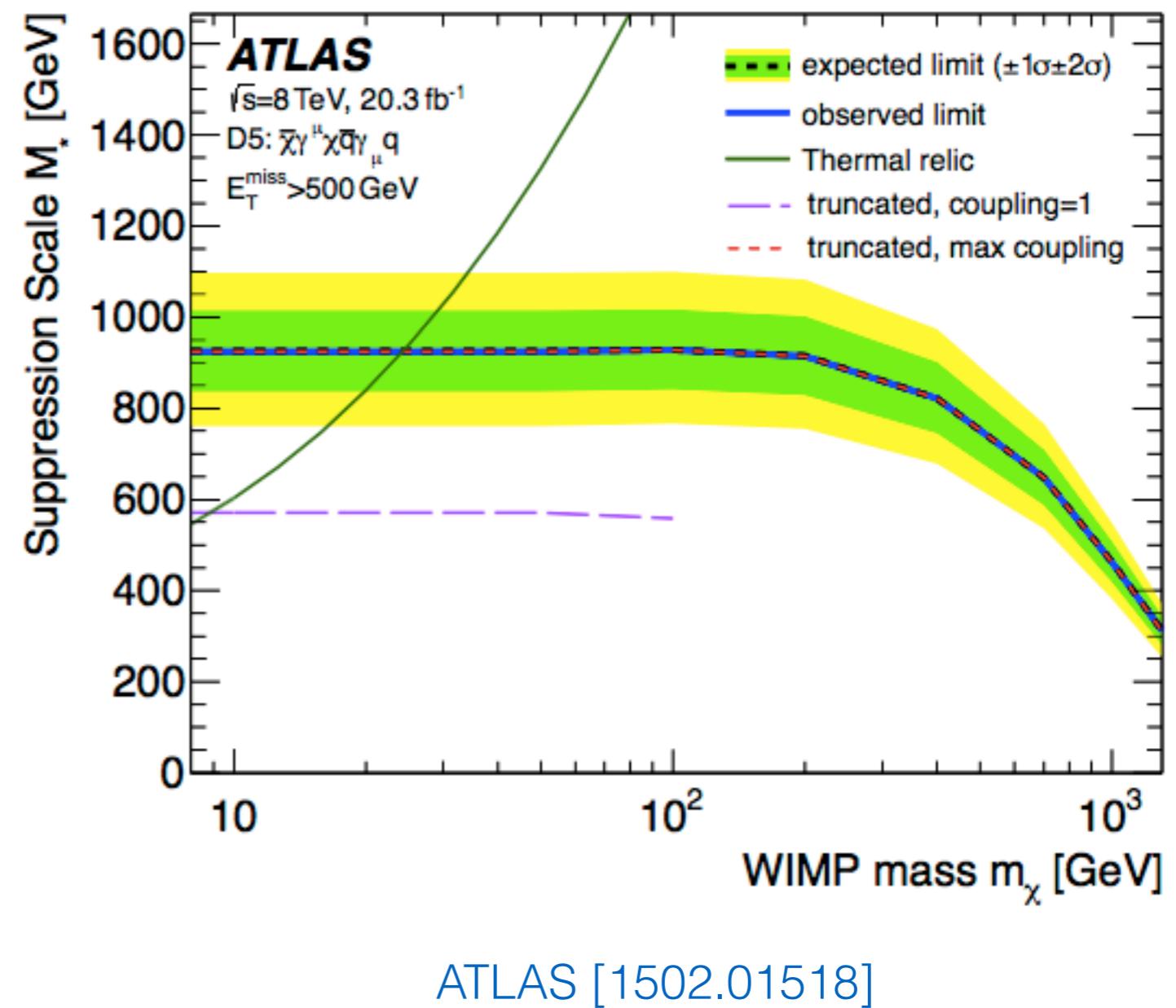
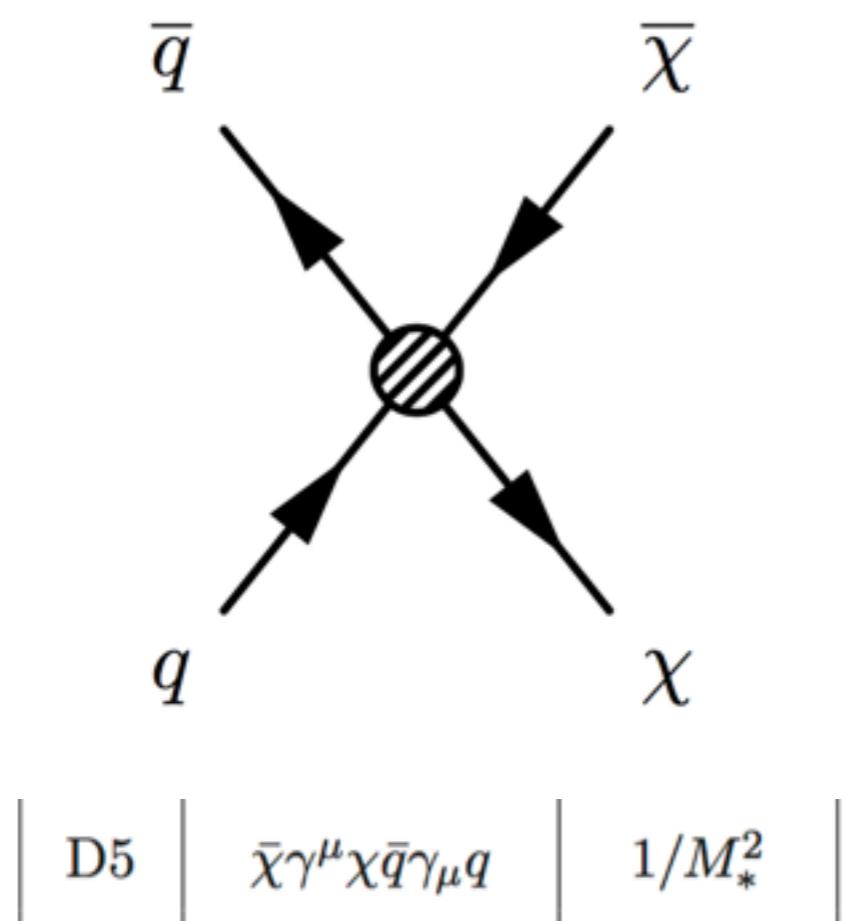


Name	Operator	Coefficient
D1	$\bar{\chi}\chi\bar{q}q$	$m_q/M_*^3$
D2	$\bar{\chi}\gamma^5\chi\bar{q}q$	$im_q/M_*^3$
D3	$\bar{\chi}\chi\bar{q}\gamma^5q$	$im_q/M_*^3$
D4	$\bar{\chi}\gamma^5\chi\bar{q}\gamma^5q$	$m_q/M_*^3$
D5	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D6	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D7	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5q$	$1/M_*^2$
D8	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5q$	$1/M_*^2$
D9	$\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$	$1/M_*^2$
D10	$\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi\bar{q}\sigma_{\alpha\beta}q$	$i/M_*^2$

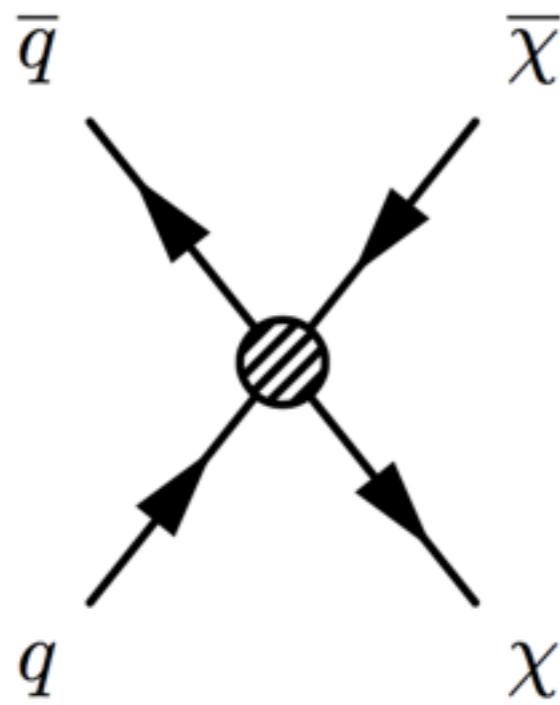
Goodman et al. [1008.1783]

Only have to deal with two parameters:  $m_\chi, \Lambda$

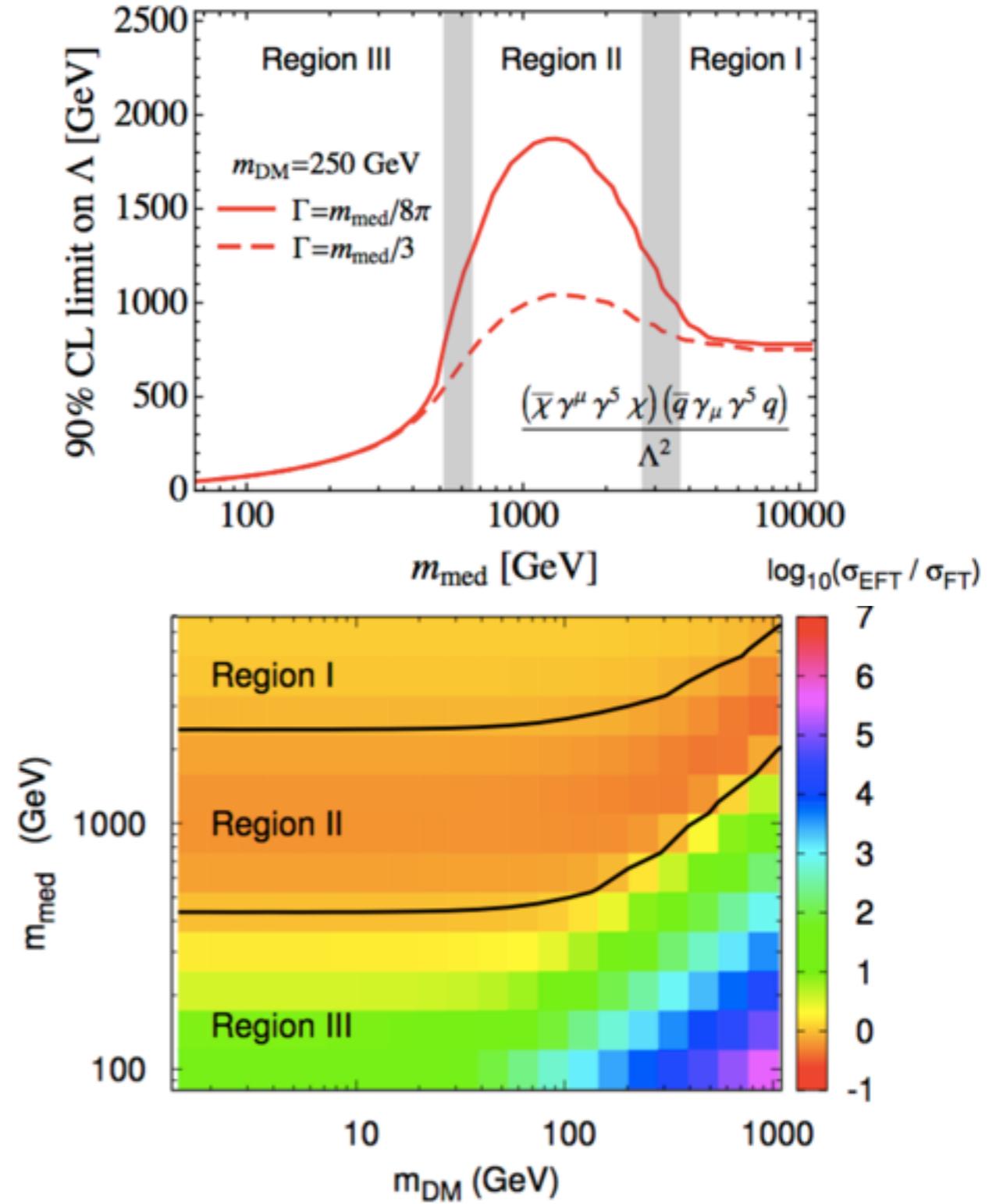
# Limits on EFT



# The problem with EFTs



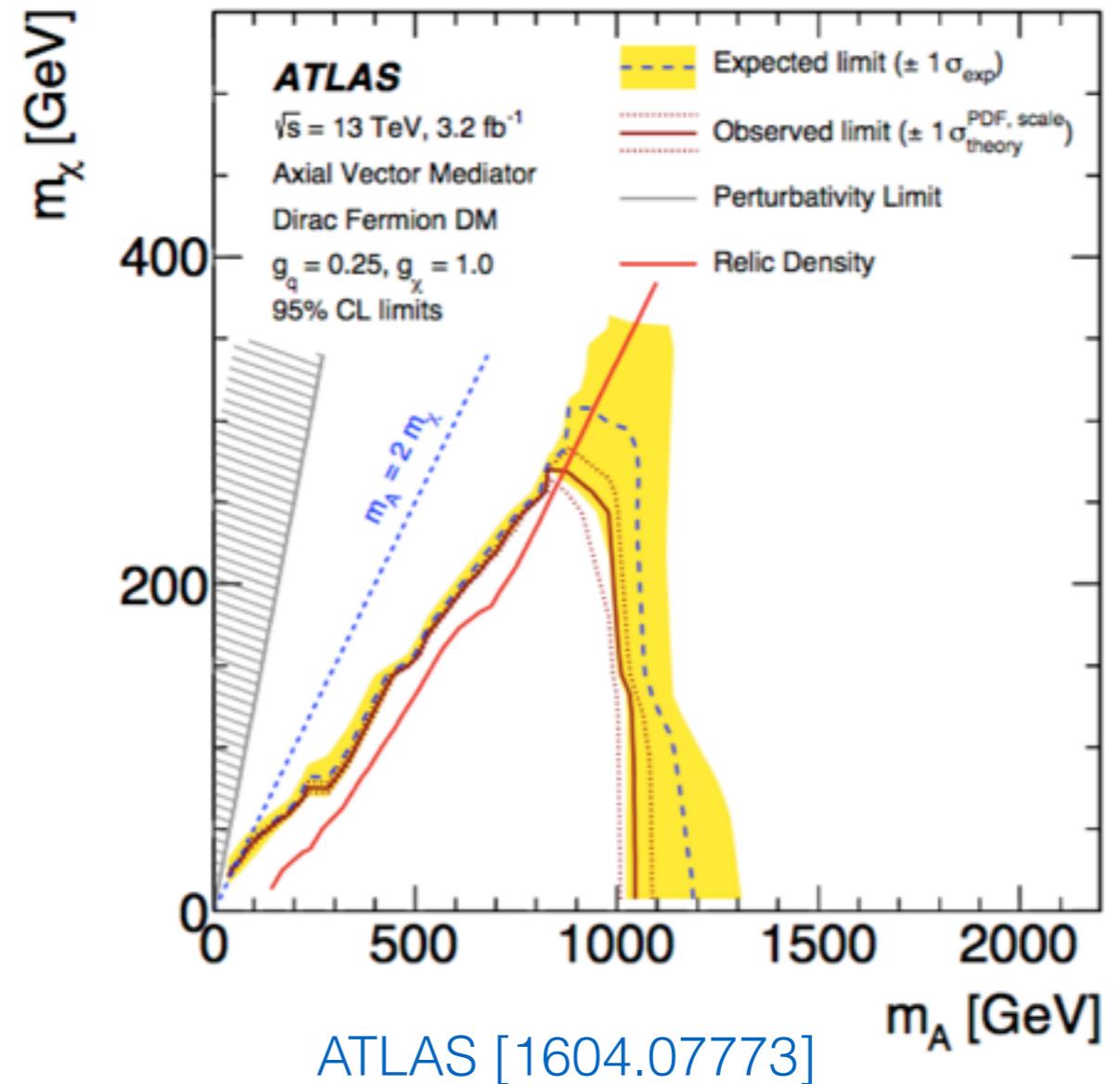
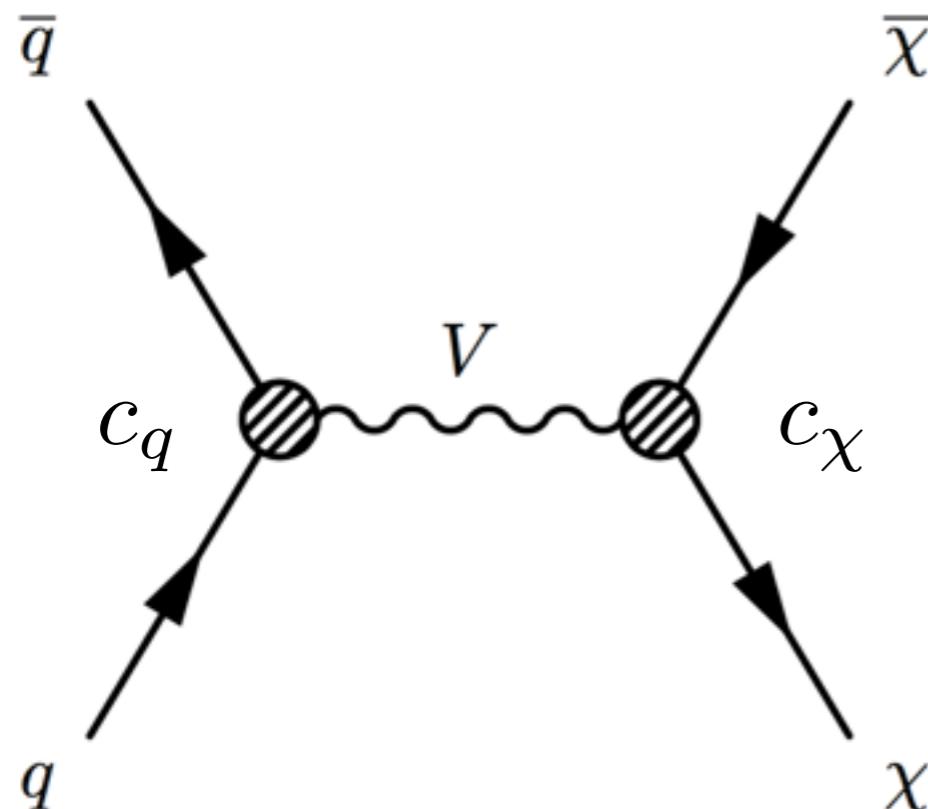
Frandsen et al. [1204.3839],  
Buchmueller et al. [1407.8257],  
Malik et al. [1409.4075],  
Abdallah et al. [1506.03116],  
and many others...



Buchmueller et al. [1308.6799]

# Simplified Models to the rescue

Review: De Simone, Jacques [1603.08002]



Now have to deal with more parameters:  $c_q, c_\chi, m_\chi, m_V$

# Our Simplified Model

# Vector mediator simplified model

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{DM}} + \mathcal{L}_V + J_{\text{DM}}^\mu V_\mu + J_{\text{SM}}^\mu V_\mu$$

# Vector mediator simplified model

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{DM}} + \mathcal{L}_V + J_{\text{DM}}^\mu V_\mu + J_{\text{SM}}^\mu V_\mu$$



$$\mathcal{L}_{\text{DM}} \sim \begin{cases} |\partial_\mu \phi|^2 - m_\phi^2 |\phi|^2 & \text{complex scalar DM} \\ \bar{\chi} (i\cancel{\partial} - m_\chi) \chi & \text{fermion DM} \end{cases}$$

# Vector mediator simplified model

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{DM}} + \mathcal{L}_V + J_{\text{DM}}^\mu V_\mu + J_{\text{SM}}^\mu V_\mu$$



$$\mathcal{L}_V = -\frac{1}{4} V^{\mu\nu} V_{\mu\nu} + \frac{1}{2} m_V^2 V^\mu V_\mu$$

Massive spin-1 mediator  $V$

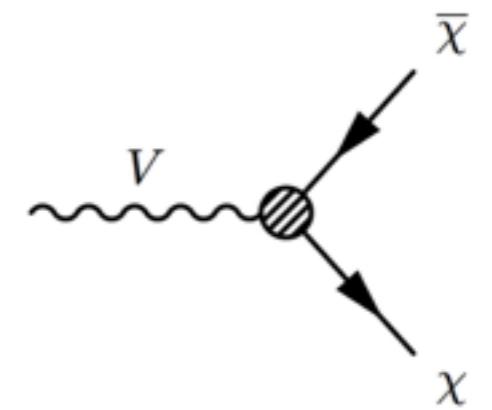
# Vector mediator simplified model

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{DM}} + \mathcal{L}_V + J_{\text{DM}}^\mu V_\mu + J_{\text{SM}}^\mu V_\mu$$



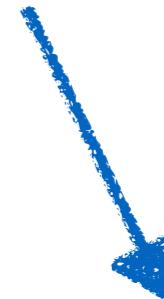
$$J_{\text{DM}}^\mu \sim \begin{cases} c_\phi \phi^\dagger \overleftrightarrow{\partial}_\mu \phi \\ c_{\chi V} \bar{\chi} \gamma^\mu \chi + c_{\chi A} \bar{\chi} \gamma^\mu \gamma^5 \chi \end{cases}$$

complex scalar DM  
fermion DM



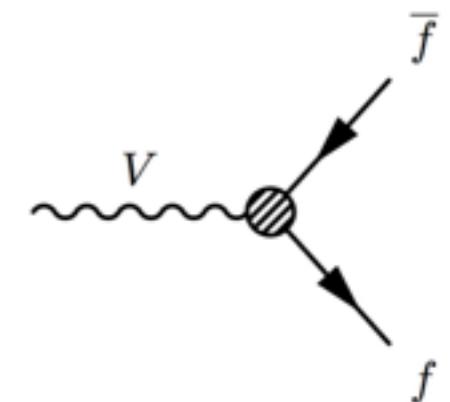
# Vector mediator simplified model

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{DM}} + \mathcal{L}_V + J_{\text{DM}}^\mu V_\mu + J_{\text{SM}}^\mu V_\mu$$



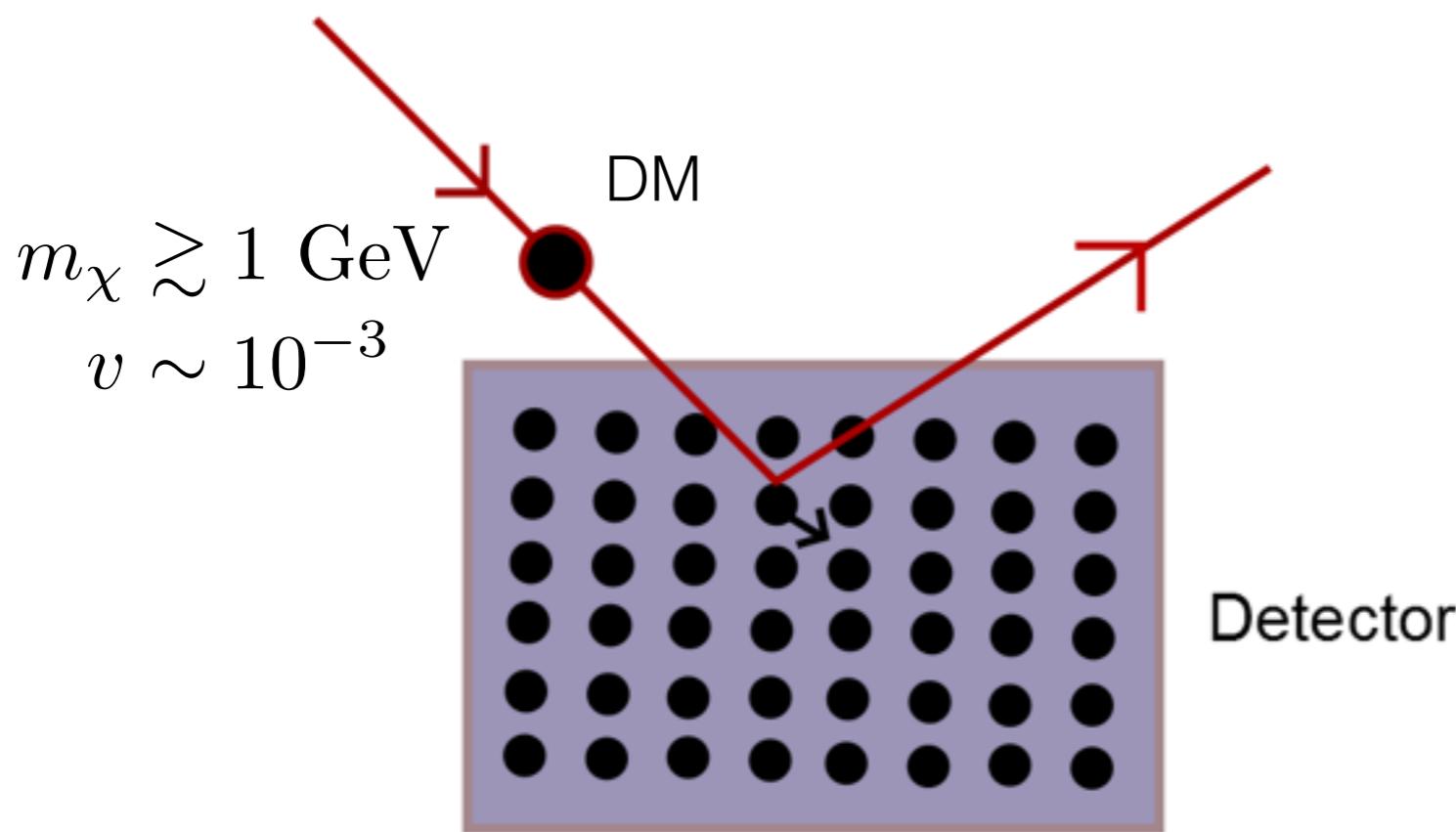
$$J_{\text{SM}}^\mu = \sum_{i=1}^3 \left[ c_q^{(i)} \overline{q_L^i} \gamma^\mu q_L^i + c_u^{(i)} \overline{u_R^i} \gamma^\mu u_R^i + c_d^{(i)} \overline{d_R^i} \gamma^\mu d_R^i + c_l^{(i)} \overline{l_L^i} \gamma^\mu l_L^i + c_e^{(i)} \overline{e_R^i} \gamma^\mu e_R^i \right]$$

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



# Calculating the direct detection rate

# Direct detection



Look for low energy -  $\mathcal{O}(\text{keV})$  - recoils of detector nuclei

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

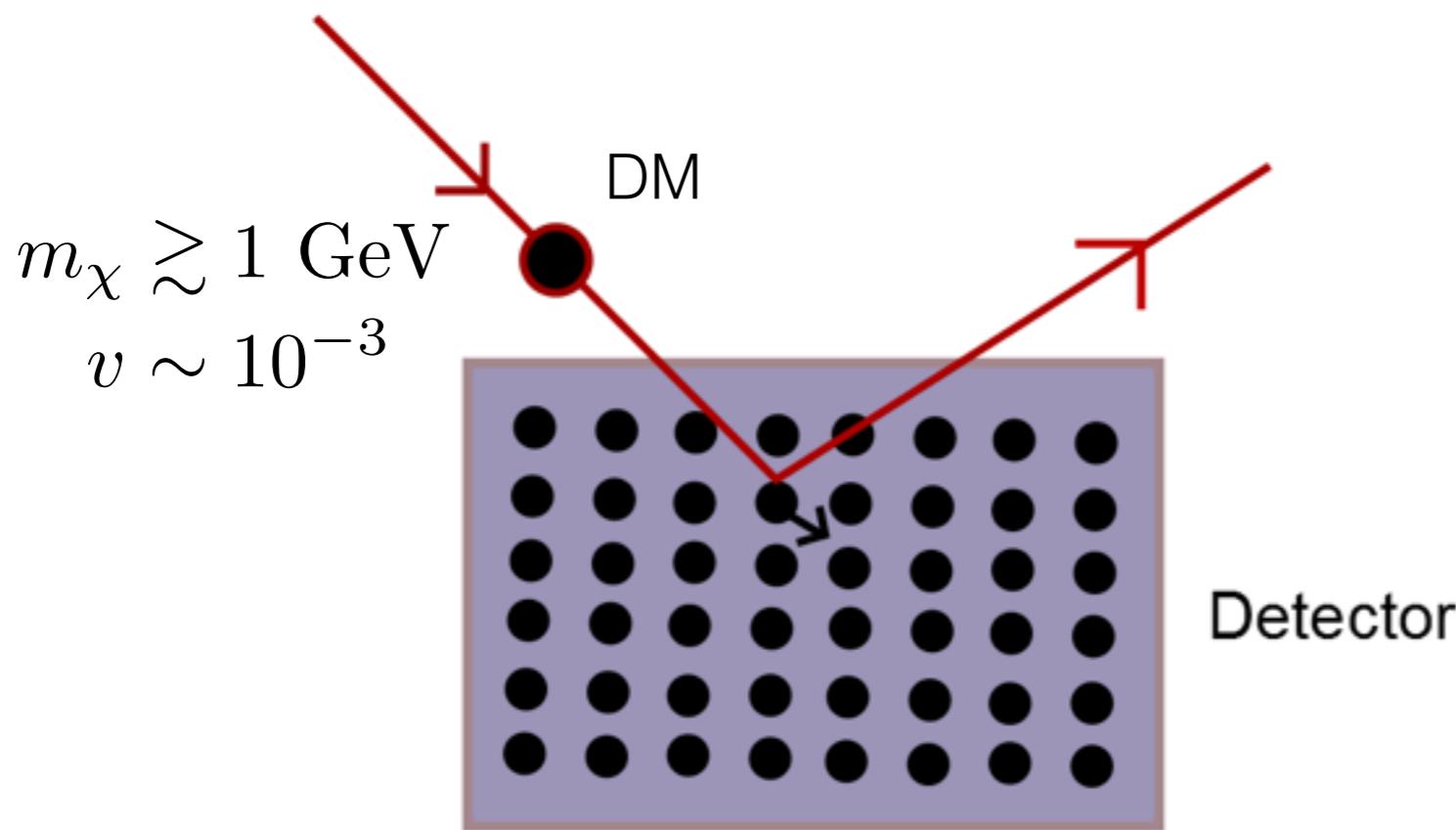
$$\bar{\chi}\gamma^\mu\chi \bar{q}\gamma_\mu q$$

$$\bar{\chi}\gamma^\mu\chi \bar{q}\gamma_\mu\gamma^5 q$$

$$\bar{\chi}\gamma^\mu\gamma^5\chi \bar{q}\gamma_\mu q$$

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# Direct detection



Look for low energy -  $\mathcal{O}(\text{keV})$  - recoils of detector nuclei

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

Standard SI

$$\bar{\chi}\gamma^\mu\chi \bar{q}\gamma_\mu q$$

$$\bar{\chi}\gamma^\mu\chi \bar{q}\gamma_\mu\gamma^5 q$$

$$\bar{\chi}\gamma^\mu\gamma^5\chi \bar{q}\gamma_\mu q$$

$$\bar{\chi}\gamma^\mu\gamma^5\chi \bar{q}\gamma_\mu\gamma^5 q$$

Standard SD

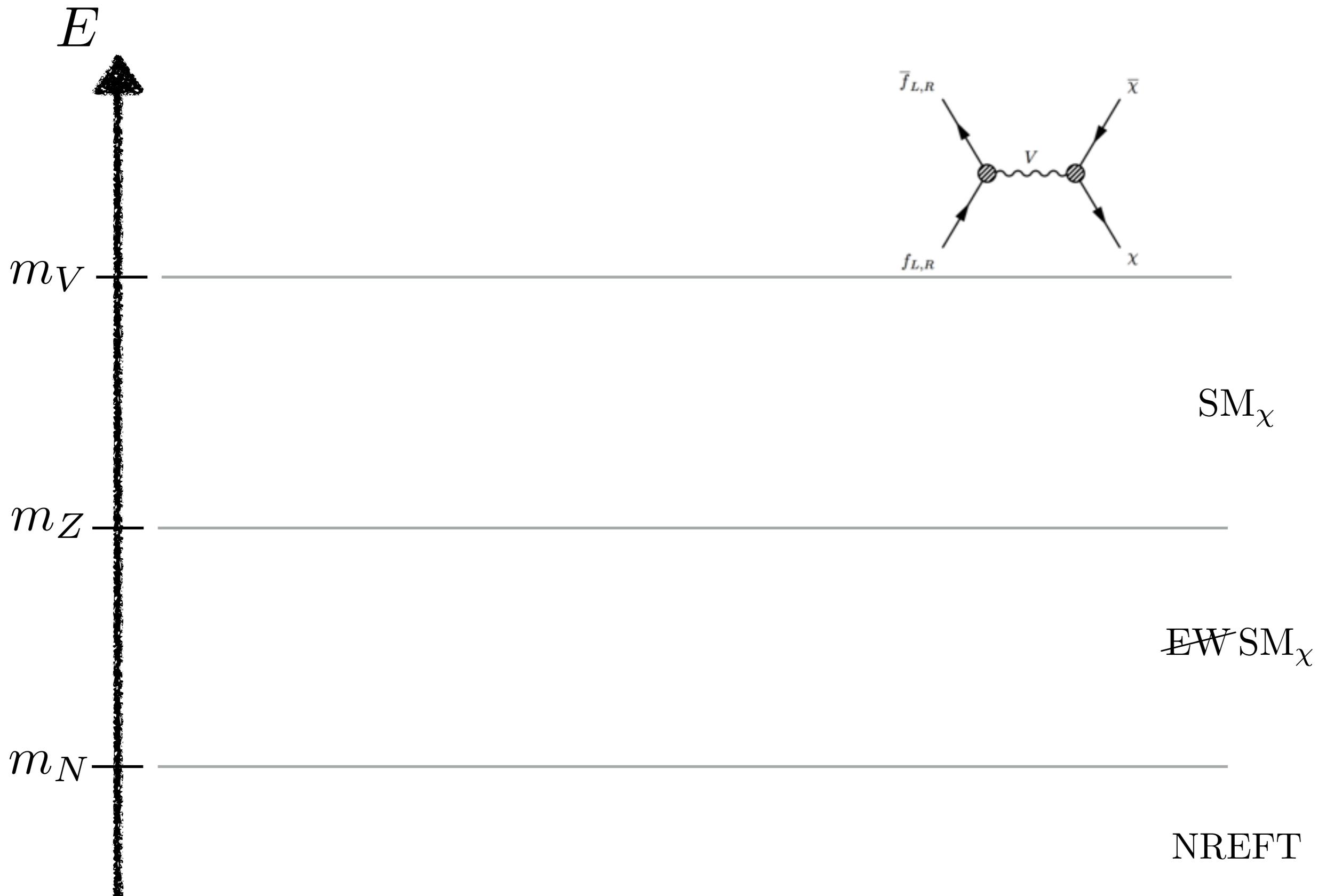
# Connecting high and low scales

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

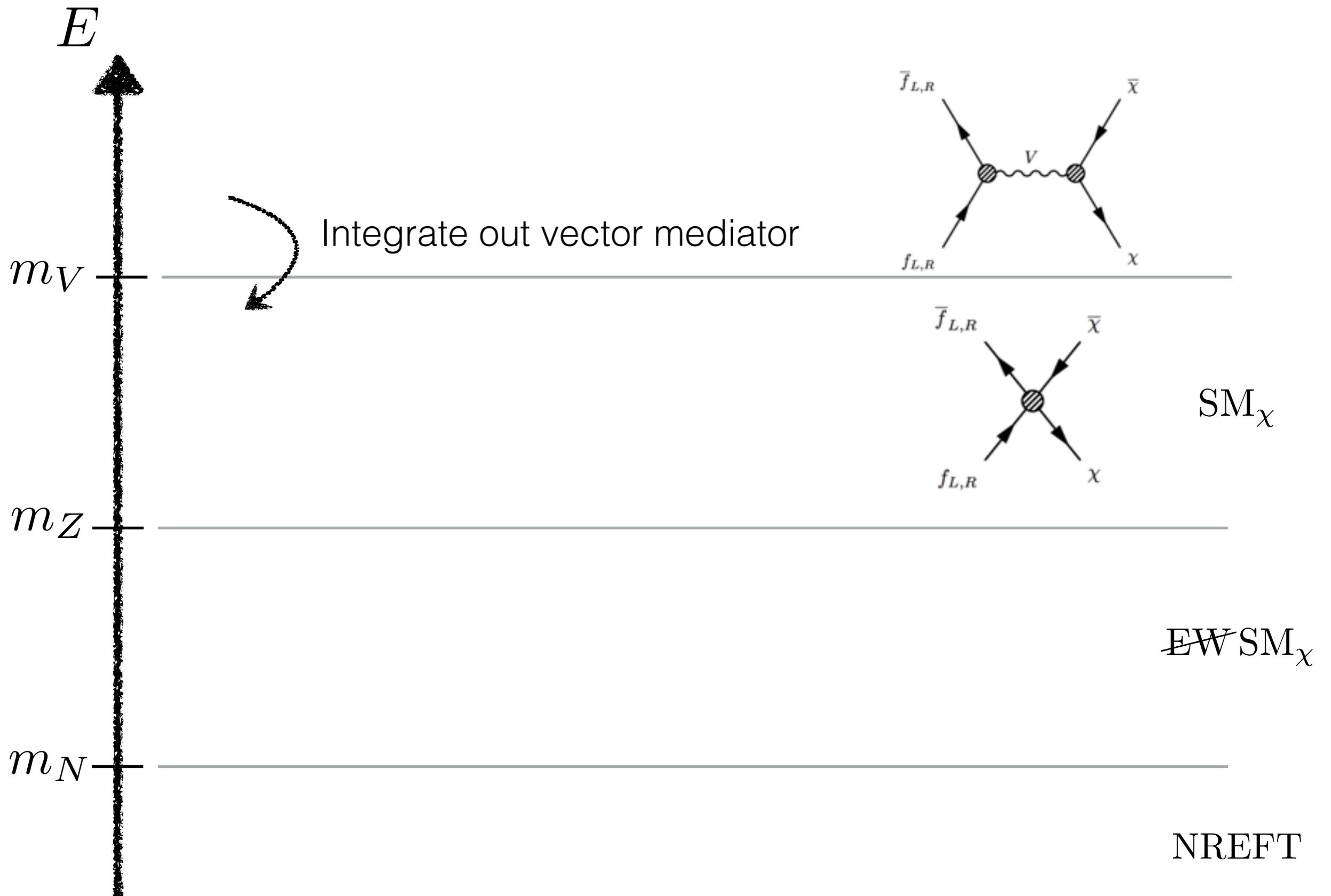
Running can change the DD rate by orders of magnitude.  
Examples in specific models:

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

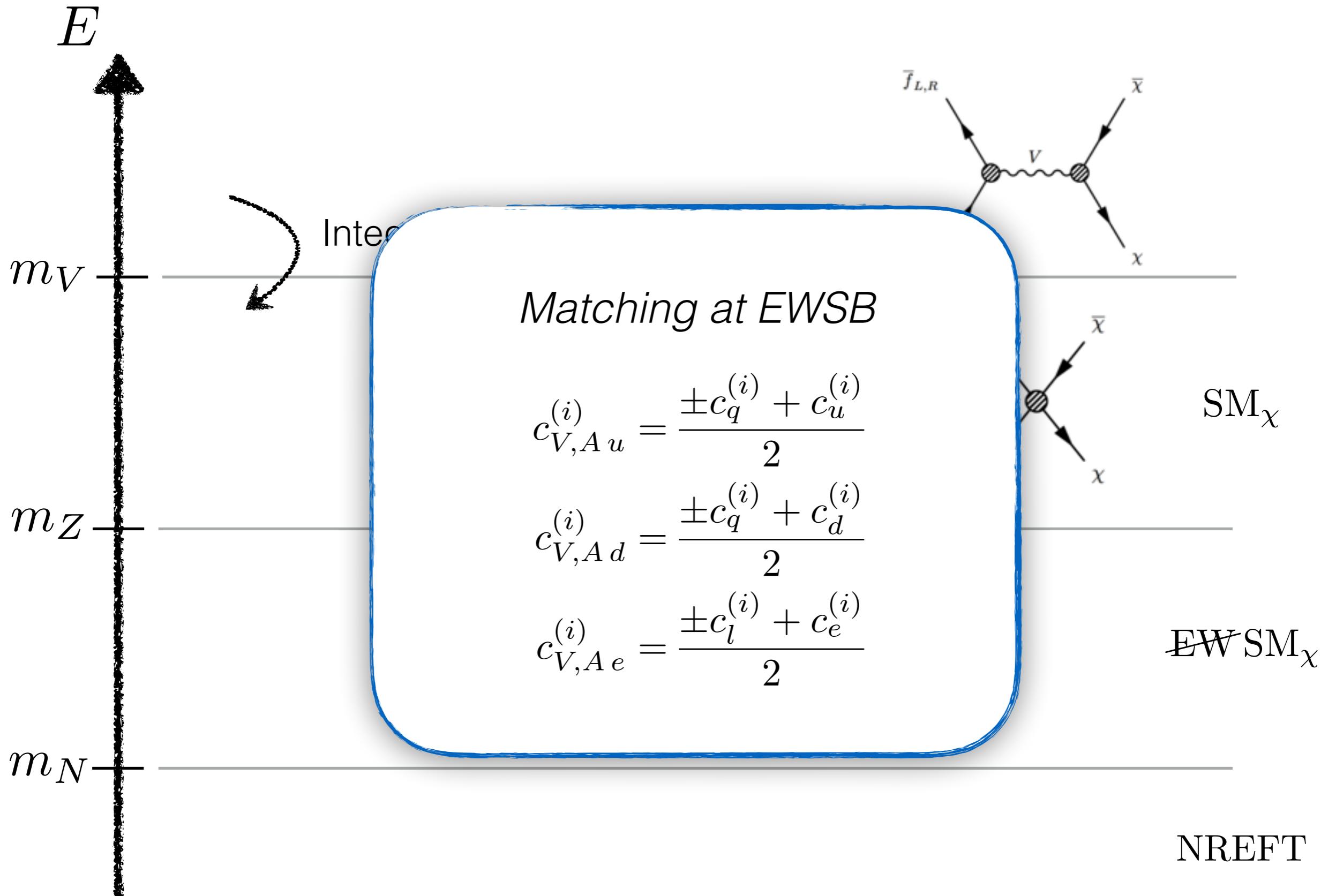
- Use EFT techniques and RG flow to study the effects for general interactions
- Include all relevant DD interactions (not just naive ‘leading order’)



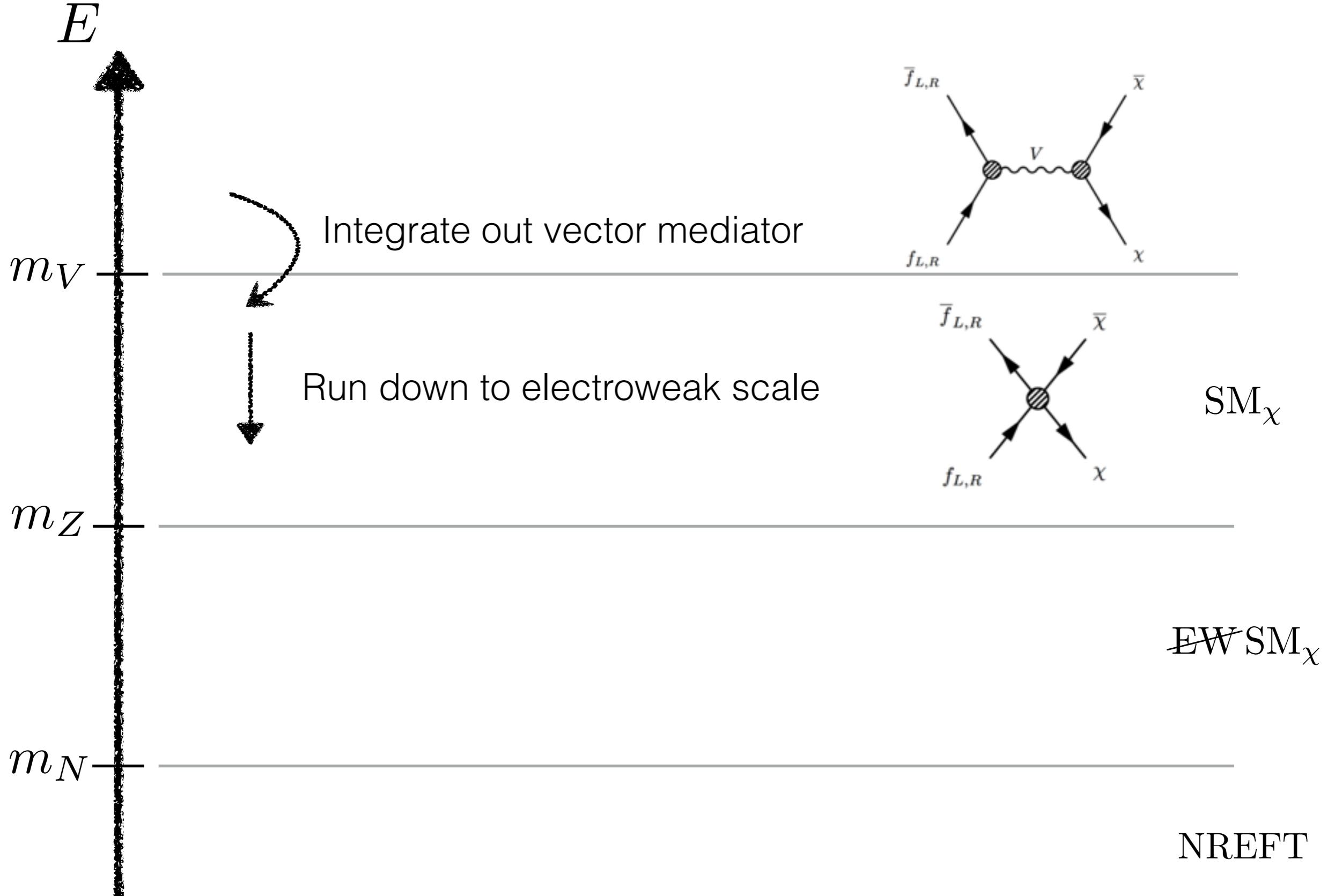
D'Eramo, Procura [1411.3342]



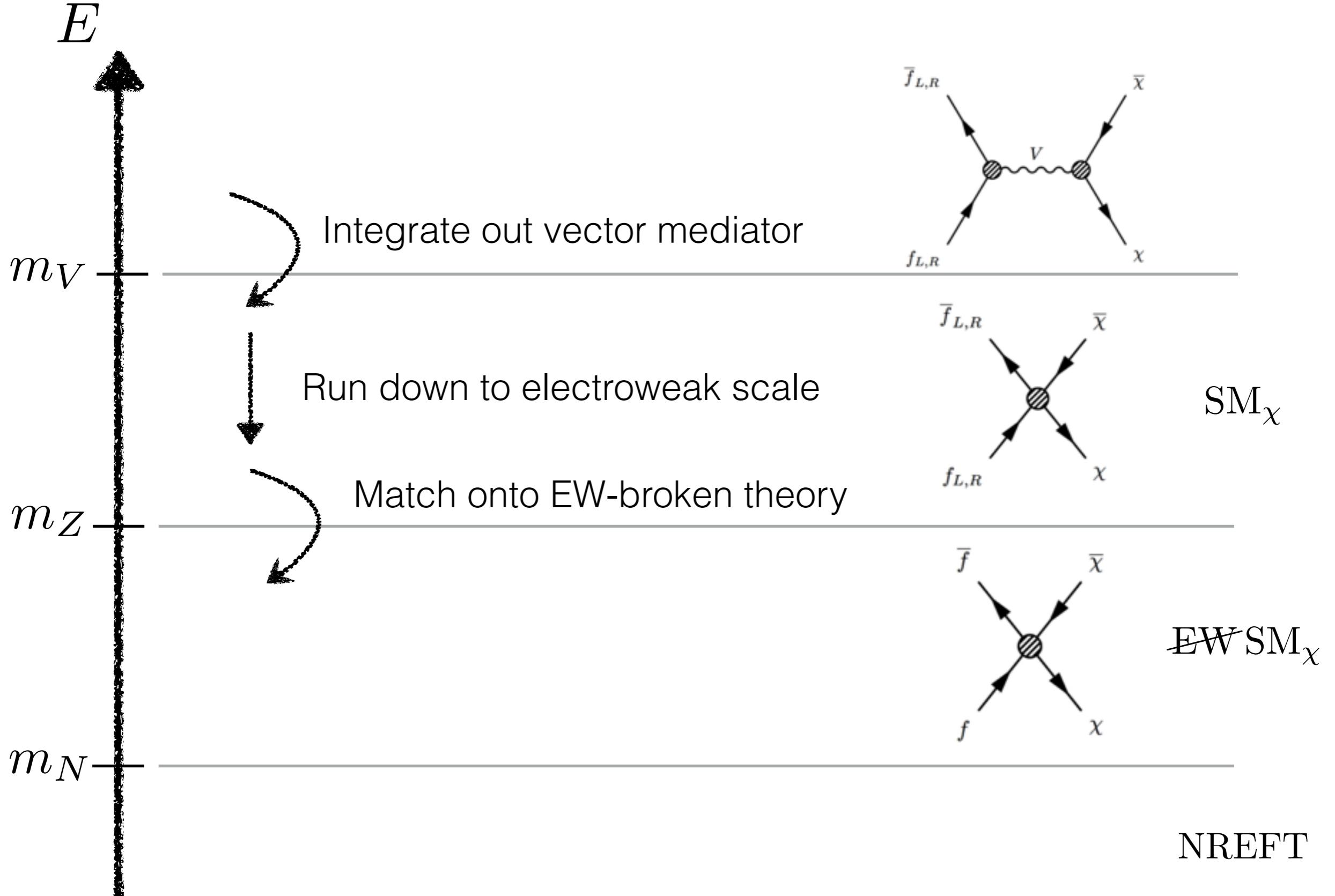
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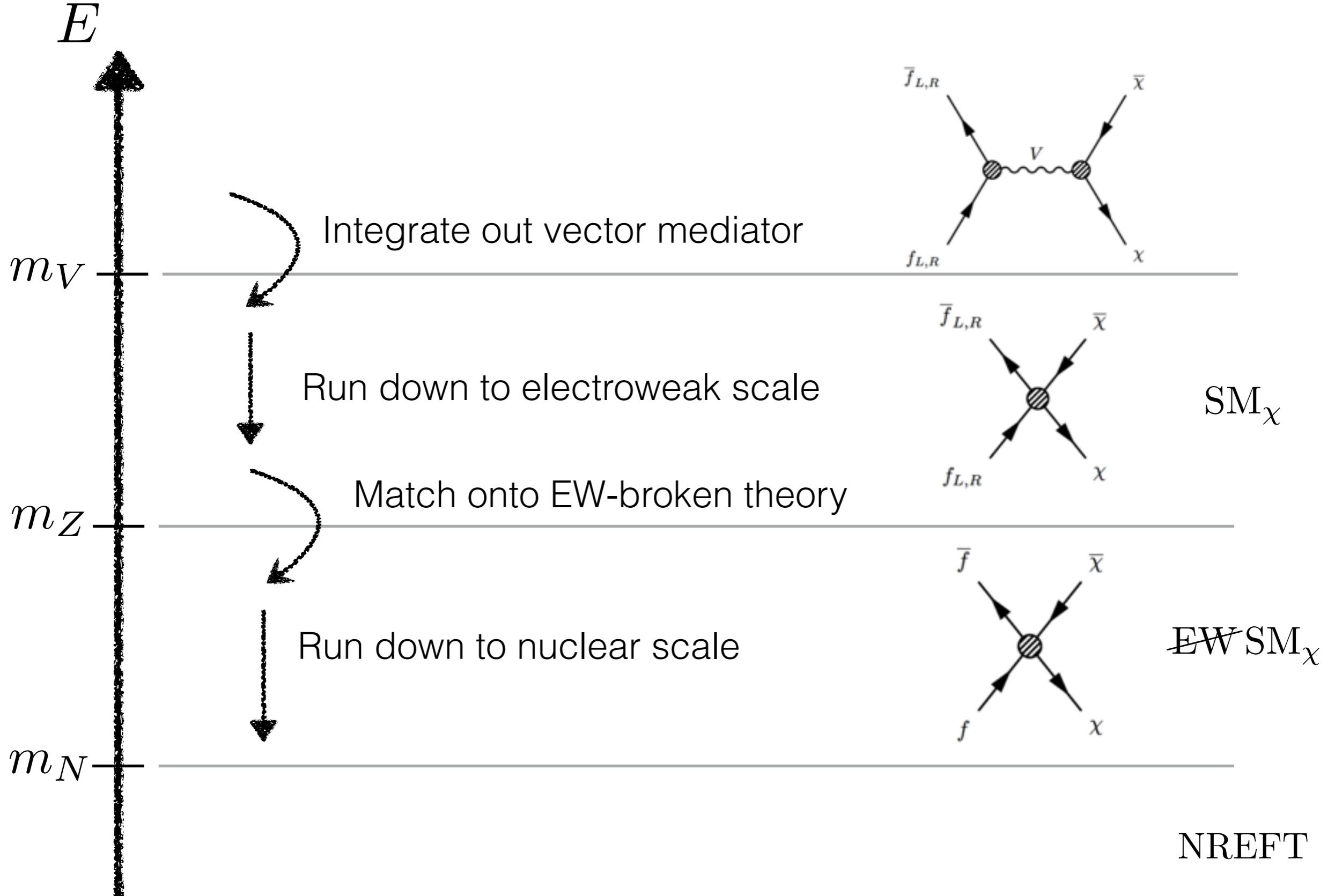
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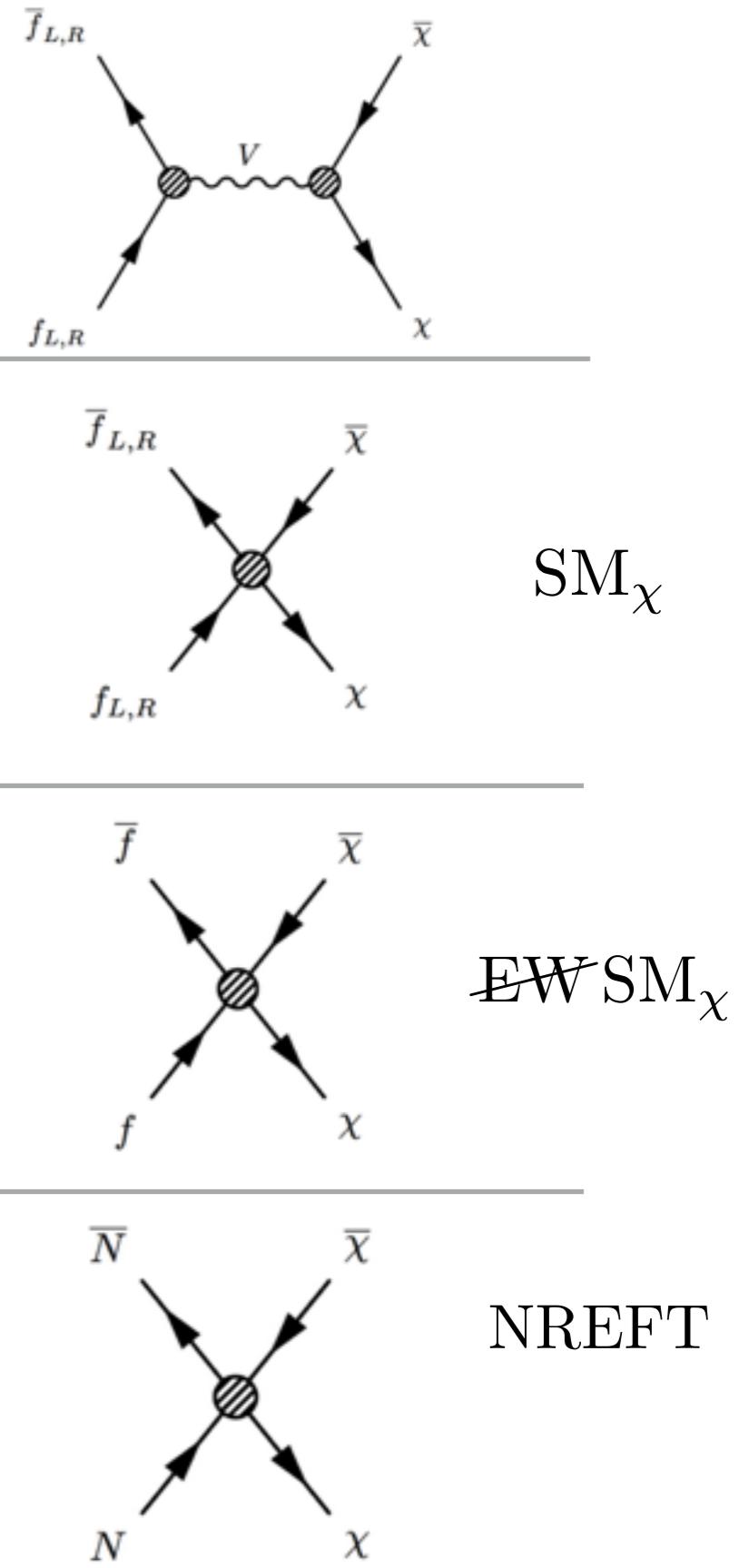
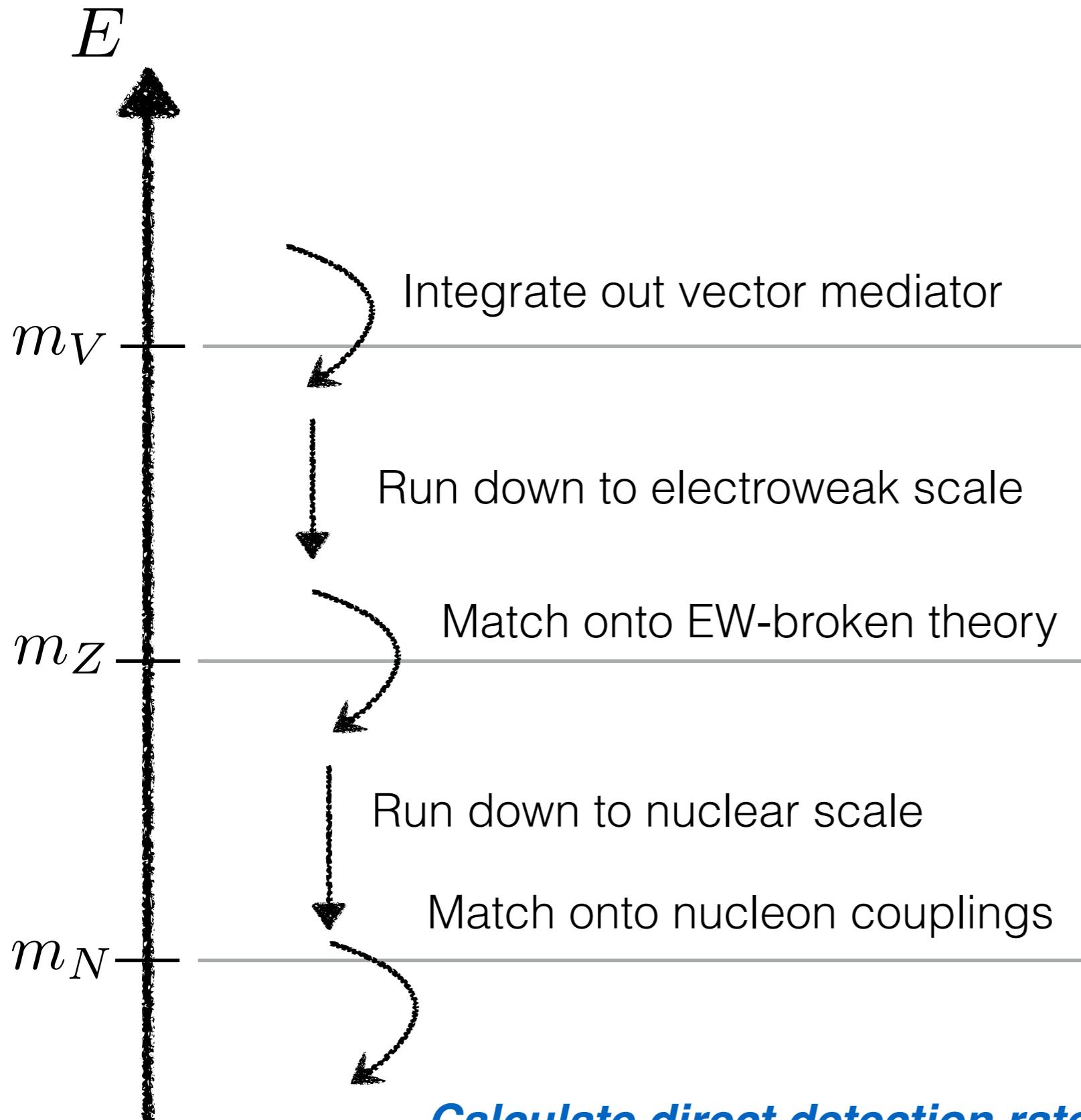
D'Eramo, Procura [1411.3342]



D'Eramo, Procura [1411.3342]



D'Eramo, Procura [1411.3342]



**Calculate direct detection rate**

D'Eramo, Procura [1411.3342]

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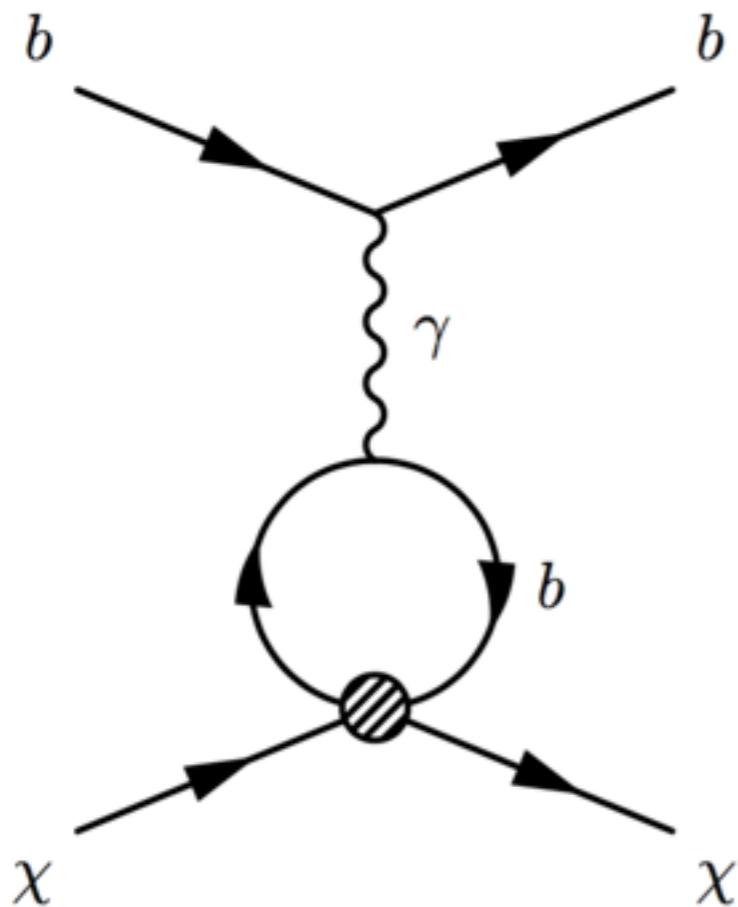
'You Better Run'



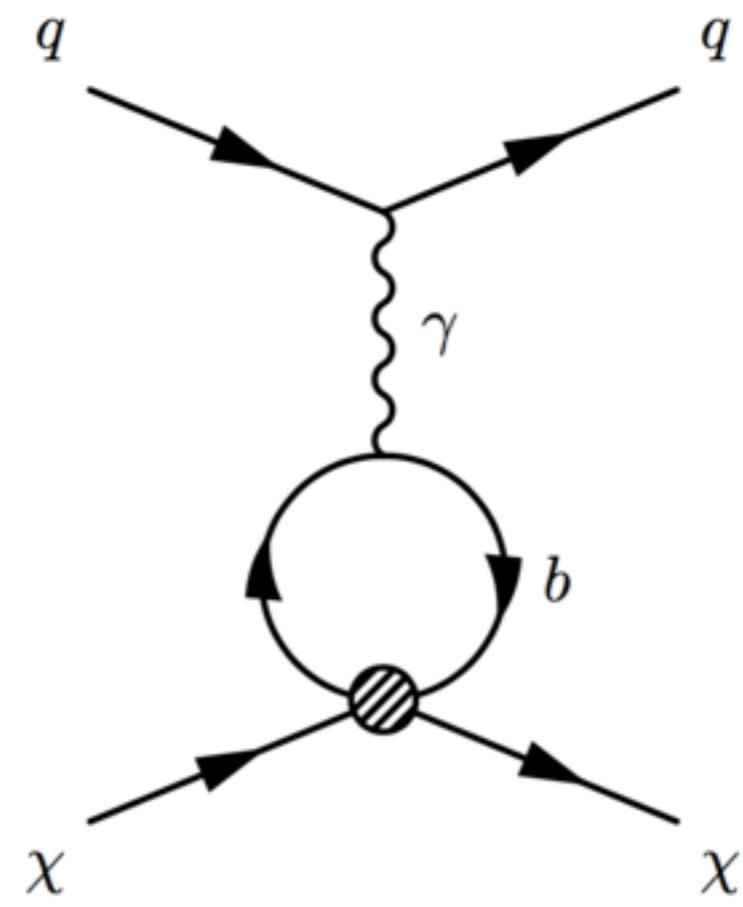
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# RGE effects

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.



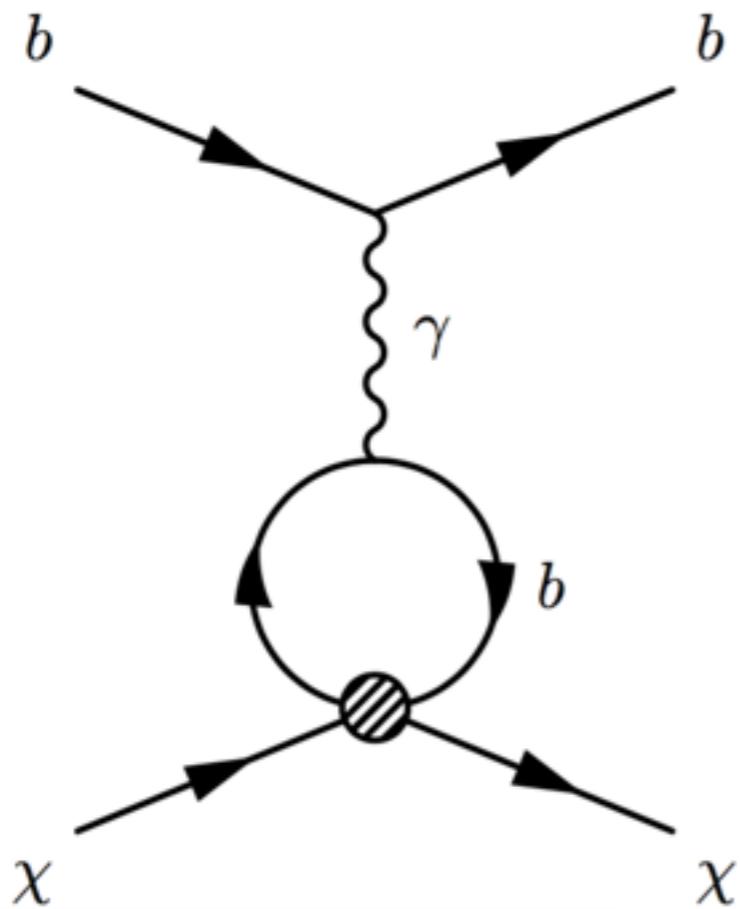
Self-renormalisation



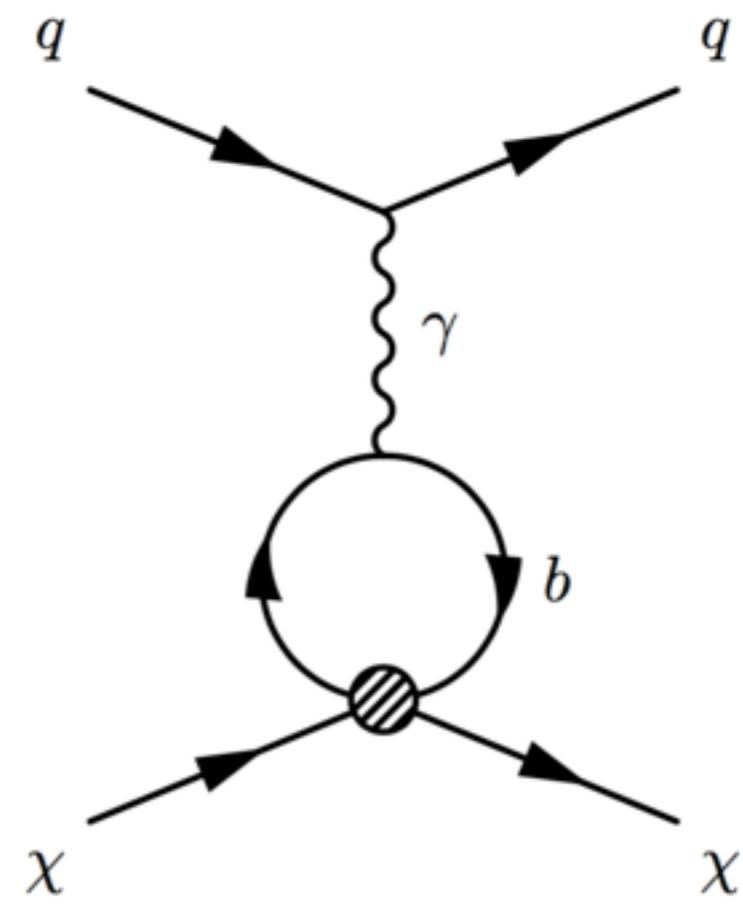
Operator mixing

# RGE effects

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Self-renormalisation

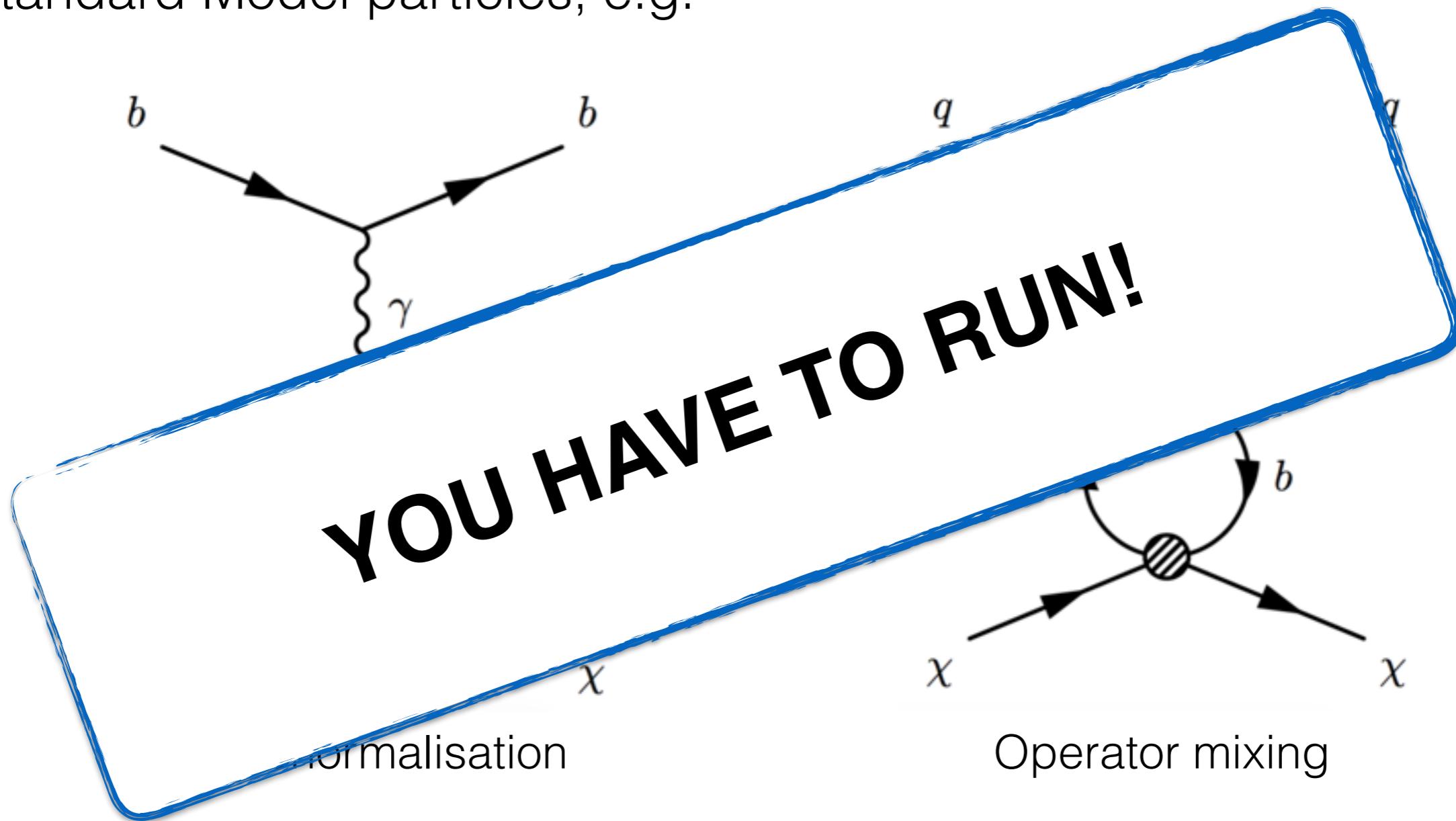


Operator mixing

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

# RGE effects

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

# runDM - a code for the RGE

runDM v1.0 - examples

With *runDMC*, It's Tricky. With *runDM*, it's not.

*runDM* is a tool for calculating the running of the couplings of Dark Matter (DM) to the Standard Model (SM) in simplified models with vector mediators. By specifying the mass of the mediator and the couplings of the mediator to SM fields at high energy, the code can be used to calculate the couplings at low energy, taking into account the mixing of all dimension-6 operators. The code can also be used to extract the operator coefficients relevant for direct detection, namely low energy couplings to up, down and strange quarks and to protons and neutrons. See the manual and [arXiv:1605.04917](https://arxiv.org/abs/1605.04917) for more details.

**Initialisation**

Let's start by loading in the *runDM* code.

```
Get[NotebookDirectory[] <> "runDM.m"];
```

First, let's specify the couplings at high energy. This will be a 1-D array with 16 elements, defined in Eq. 4 of the manual. *runDM* comes with a number of pre-defined benchmarks, which can be accessed using *setBenchmark*.

```
chigh = setBenchmark["UniversalAxial"];
Print["Axial-vector coupling to all SM fermions: " <> ToString[chigh]];
chigh = setBenchmark["LeptonsVector"];
Print["Vector coupling to all SM leptons: " <> ToString[chigh]];

Axial-vector coupling to all SM fermions: {-1.,
 1., 1., -1., 1., 1., -1., 1., -1., 1., 1., 0.}
Vector coupling to all SM leptons: {0.,
 0., 0., 1., 0., 0., 0., 1., 0., 0., 0., 1., 1., 0.}
```

Alternatively, you can specify each coupling individually. You can use *initCouplings[]* to generate an empty array of couplings and then go ahead. But any array of 16 elements will do.

jupyter  
nbviewer

runDM / python

## runDM v1.0 - examples

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**Initialisation** [1](#)

Let's start by importing the *runDM* module:

```
In [9]: %matplotlib inline
import numpy as np
import matplotlib
from matplotlib import pyplot as pl
import runDM
```

First, let's specify the couplings at high energy. This will be an 1-D array with 16 elements. *runDM* comes with a number of pre-defined benchmarks, which can be accessed using *setBenchmark*.

```
In [3]: c_high = runDM.setBenchmark("UniversalVector")
```

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

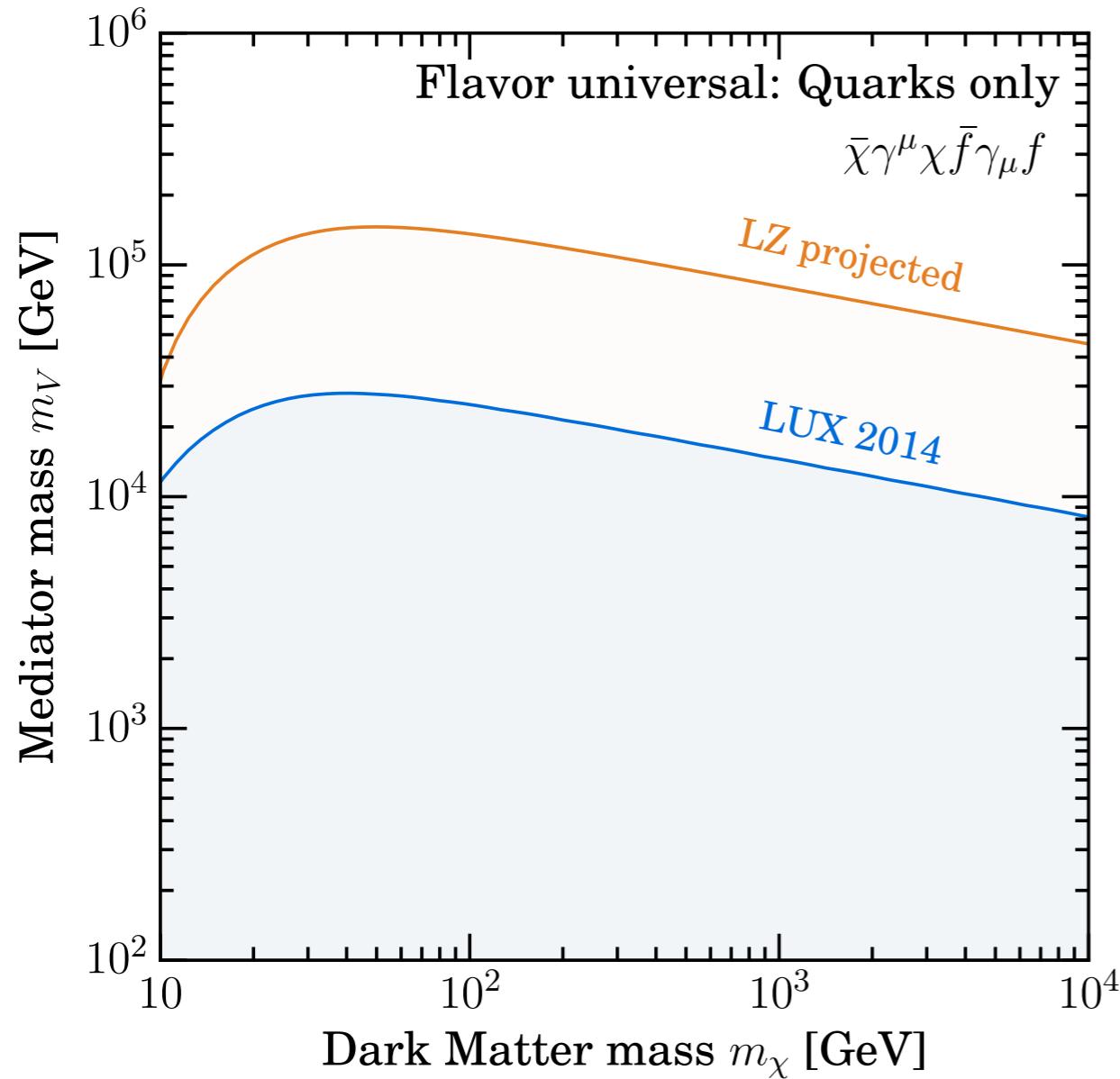
Mathematica and Python versions available at:

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

# Direct detection constraints

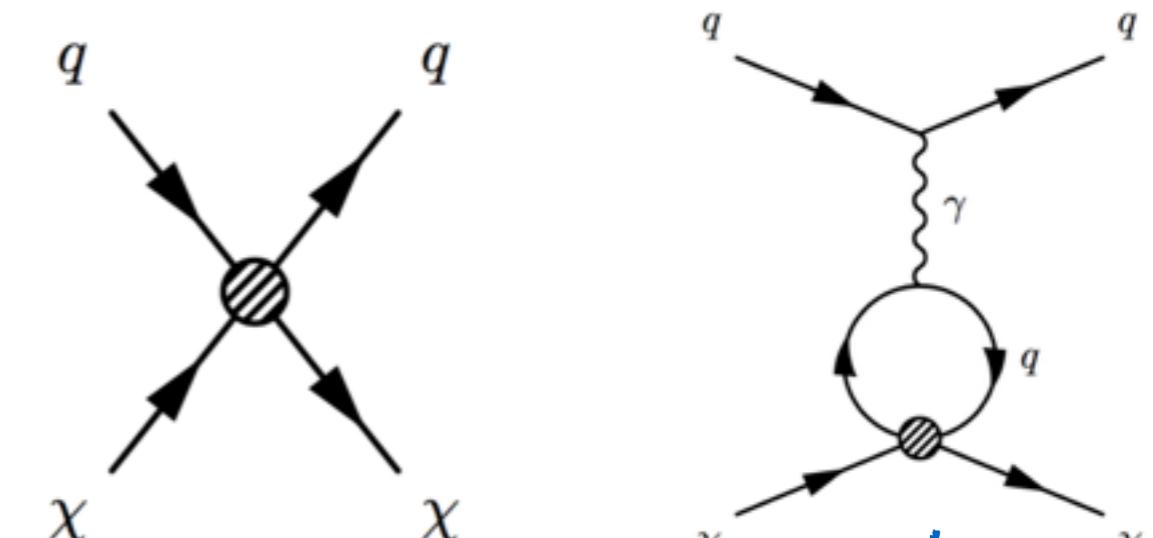
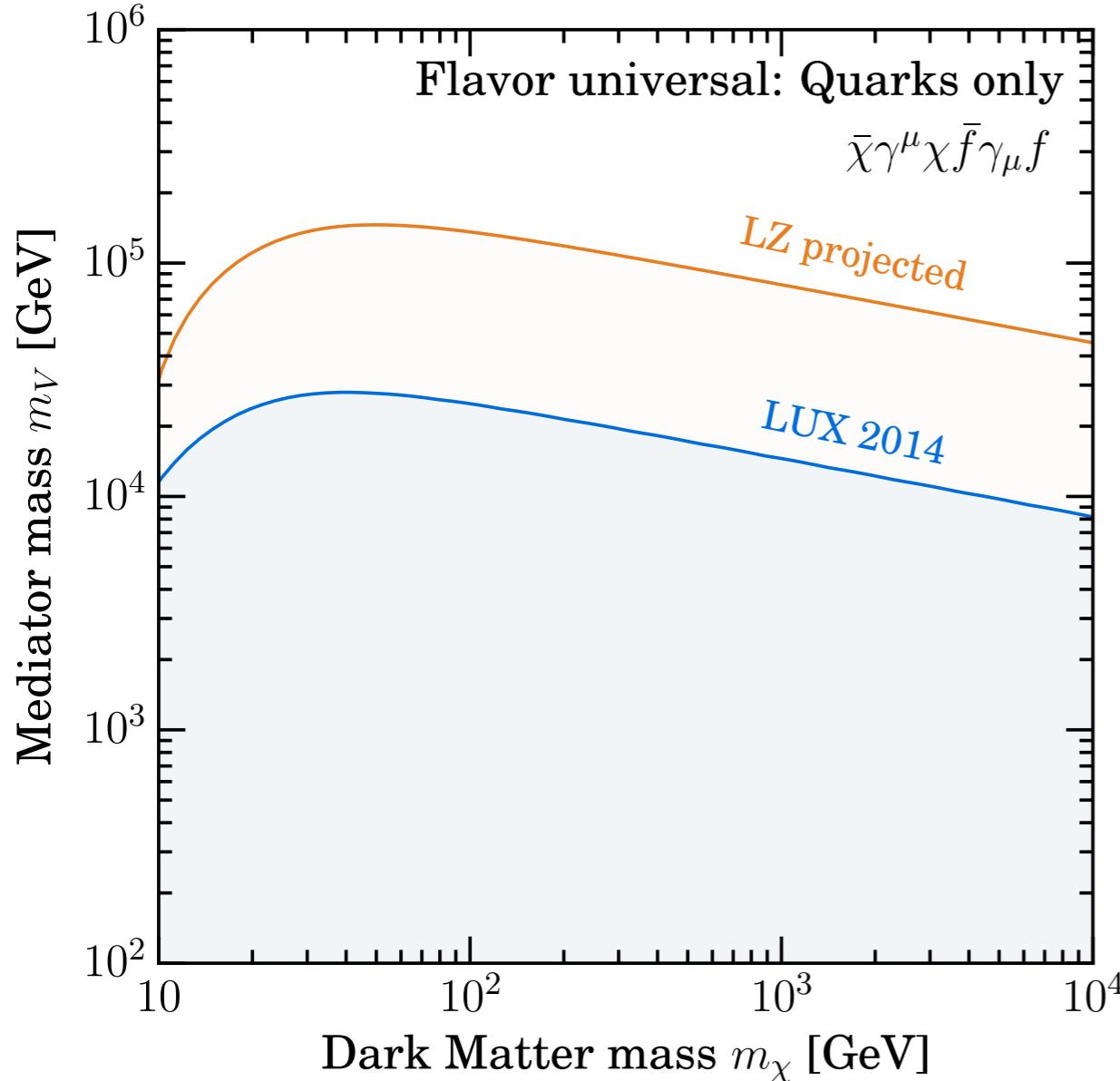
# Results I - quarks vector

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



# Results I - quarks vector

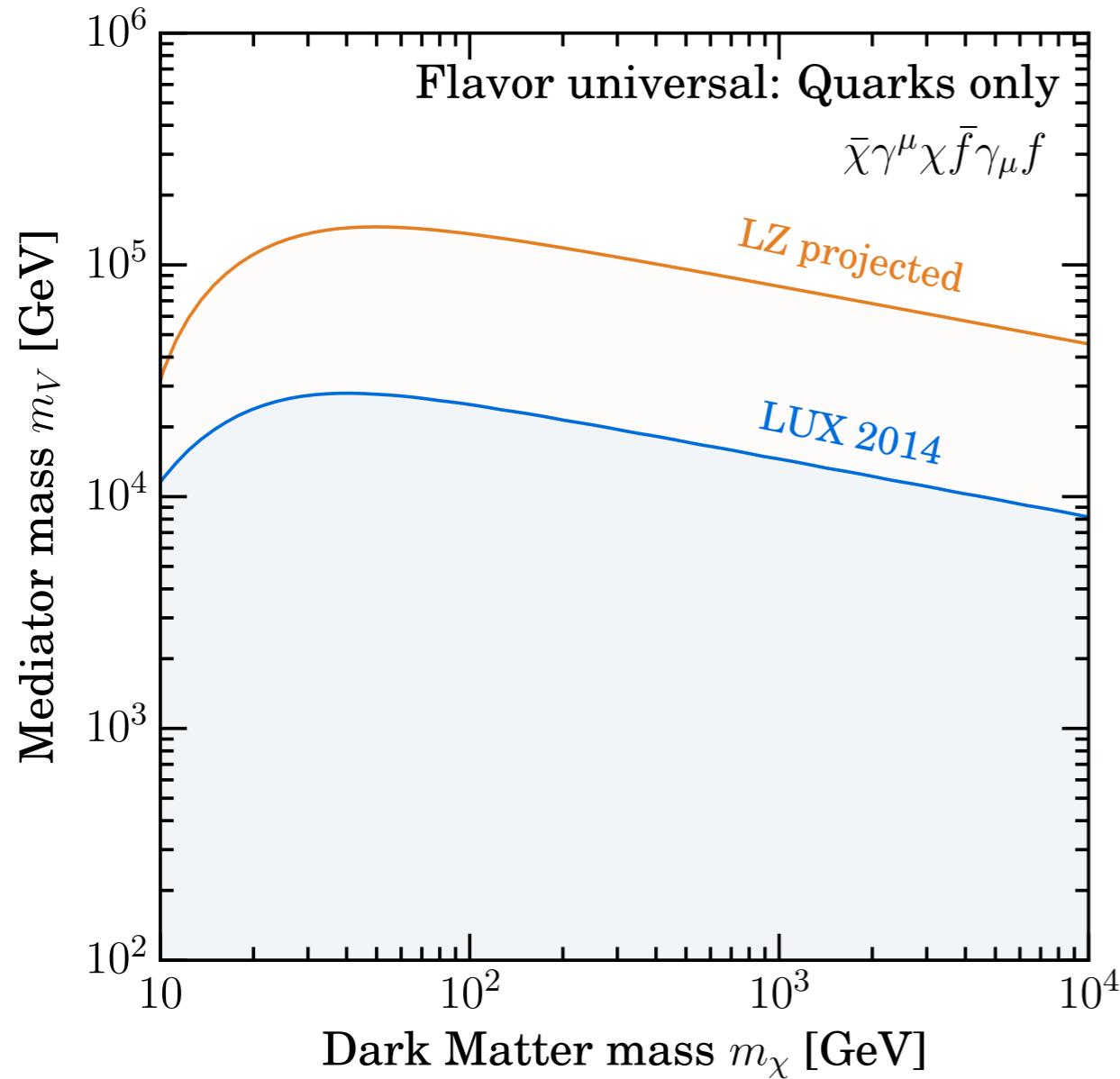
$$\mathcal{L}_{\text{EFT}} = -\frac{1}{m_V^2} J_{\text{DM}} \mu \sum_{i=1}^3 \left[ \bar{u^i} \gamma^\mu u^i + \bar{d^i} \gamma^\mu d^i \right]$$



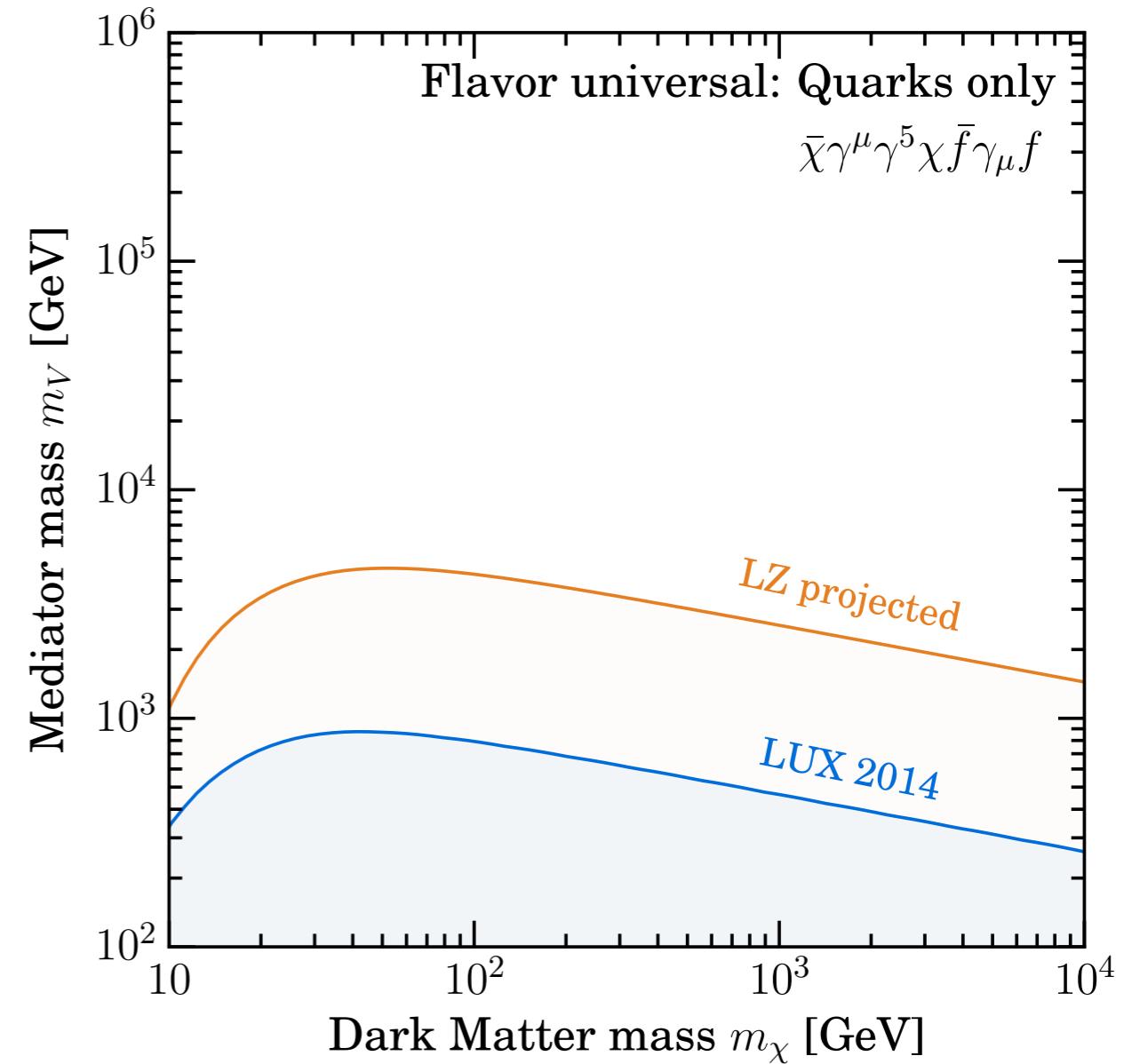
$$c_V^{(q)} \sim 1 + \# \frac{e^2}{16\pi^2} \ln(m_V/m_N)$$

# Results I - quarks vector

$$\mathcal{L}_{\text{EFT}} = -\frac{1}{m_V^2} J_{\text{DM}} \mu$$

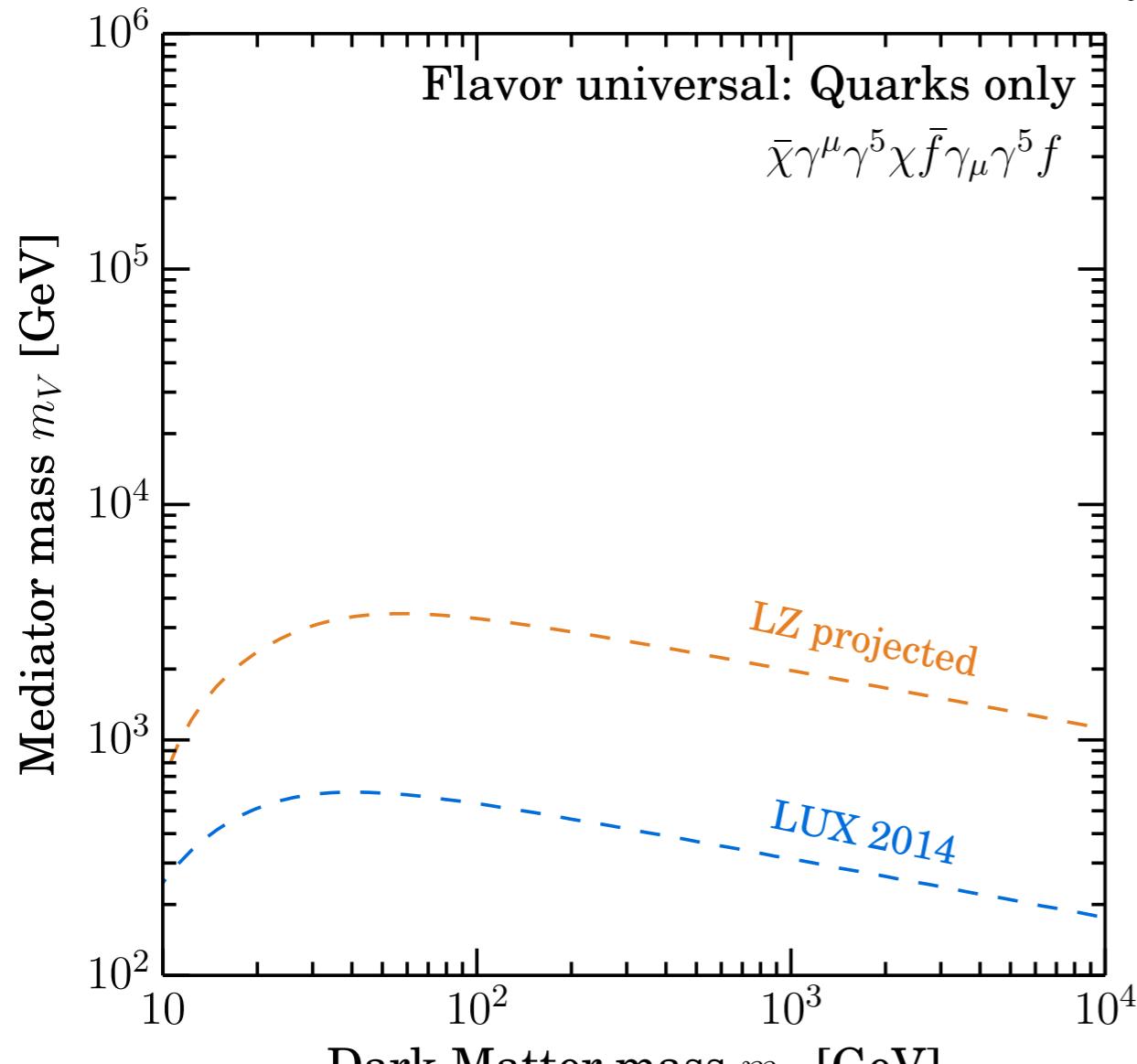


$$\sum_{i=1}^3 \left[ \bar{u^i} \gamma^\mu u^i + \bar{d^i} \gamma^\mu d^i \right]$$



# Results II - quarks axial-vector

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

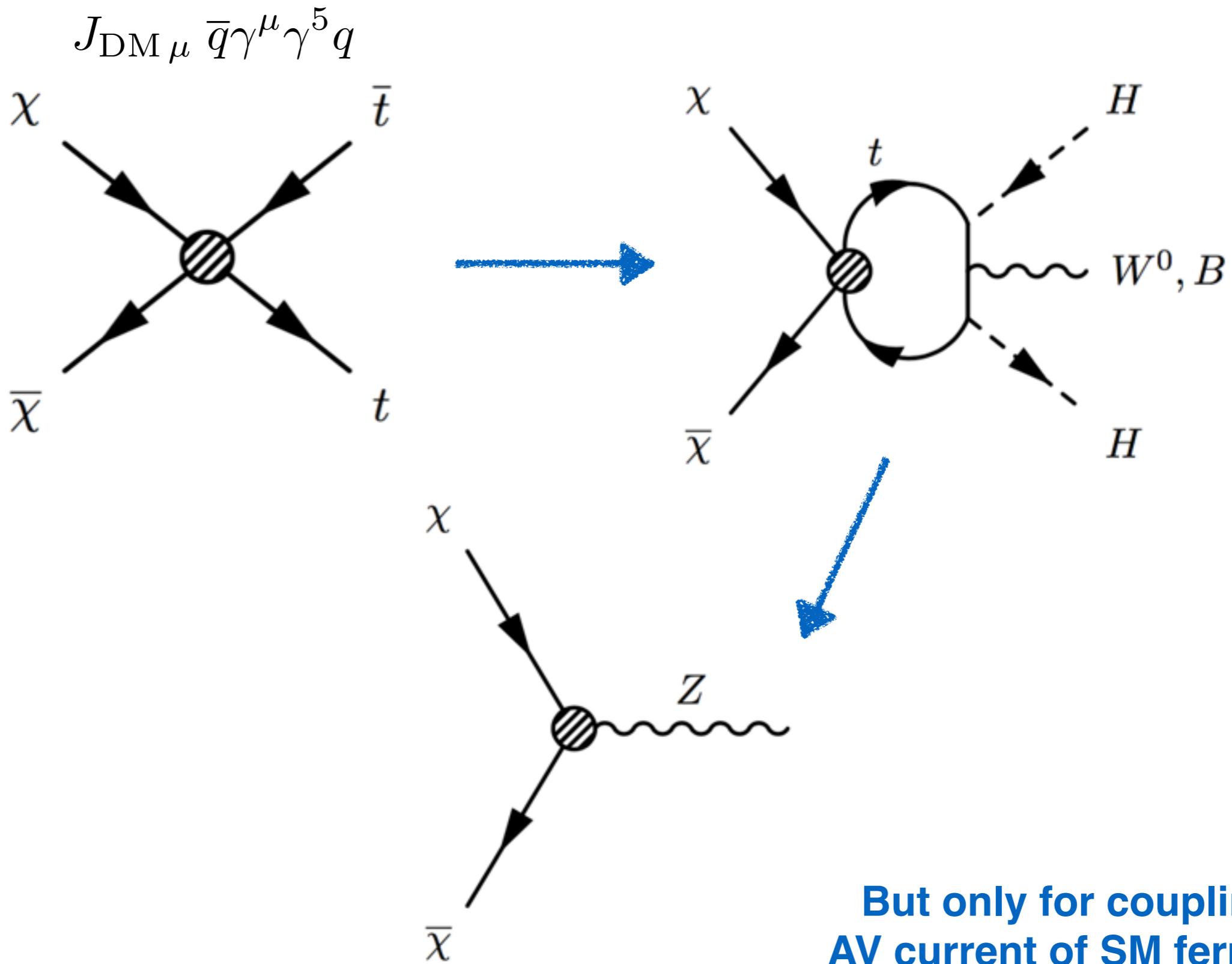


## No running

# Running

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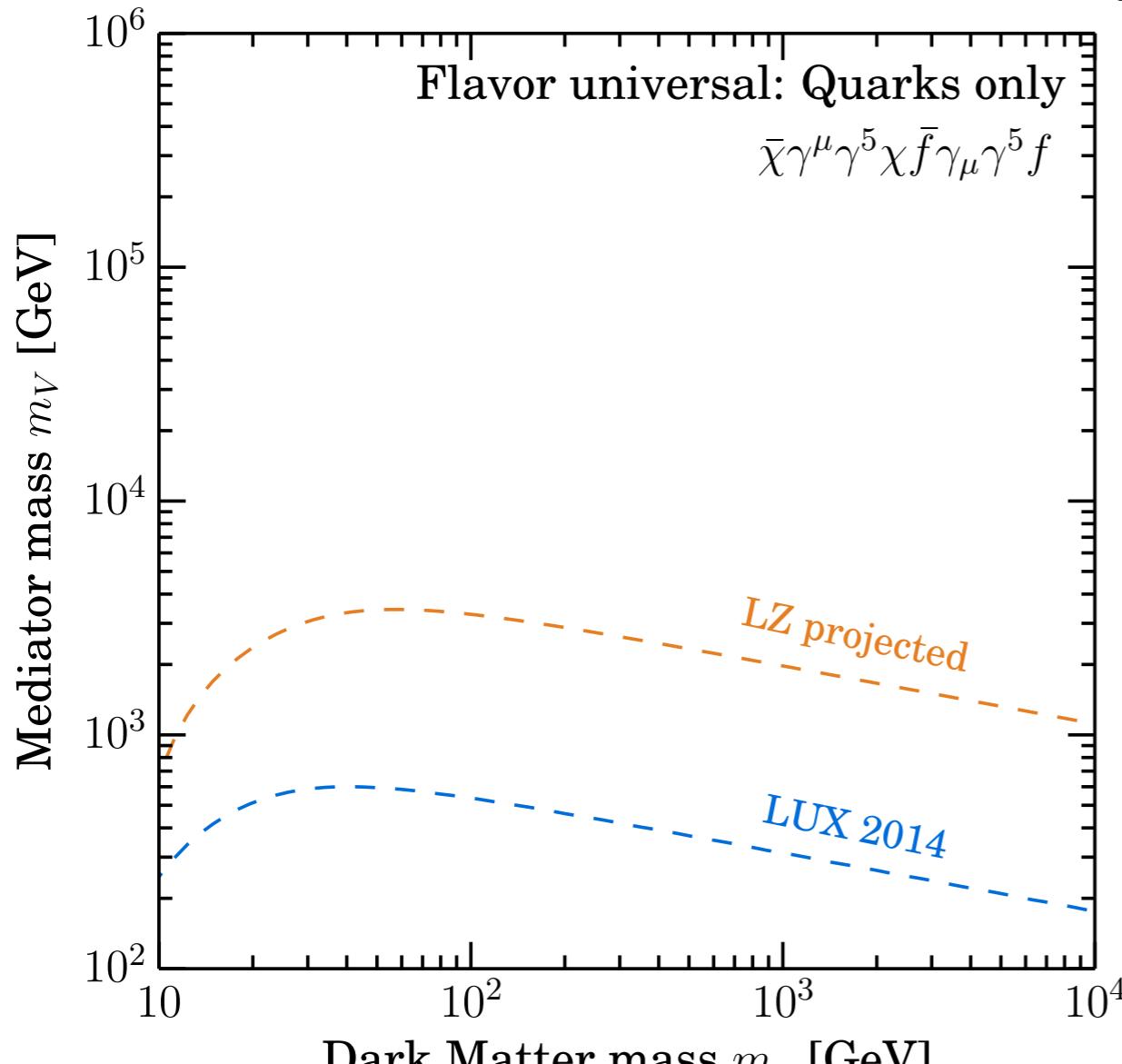
# Aside: SM axial-vector current



**But only for coupling to  
AV current of SM fermions!**

# Results II - quarks axial-vector

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

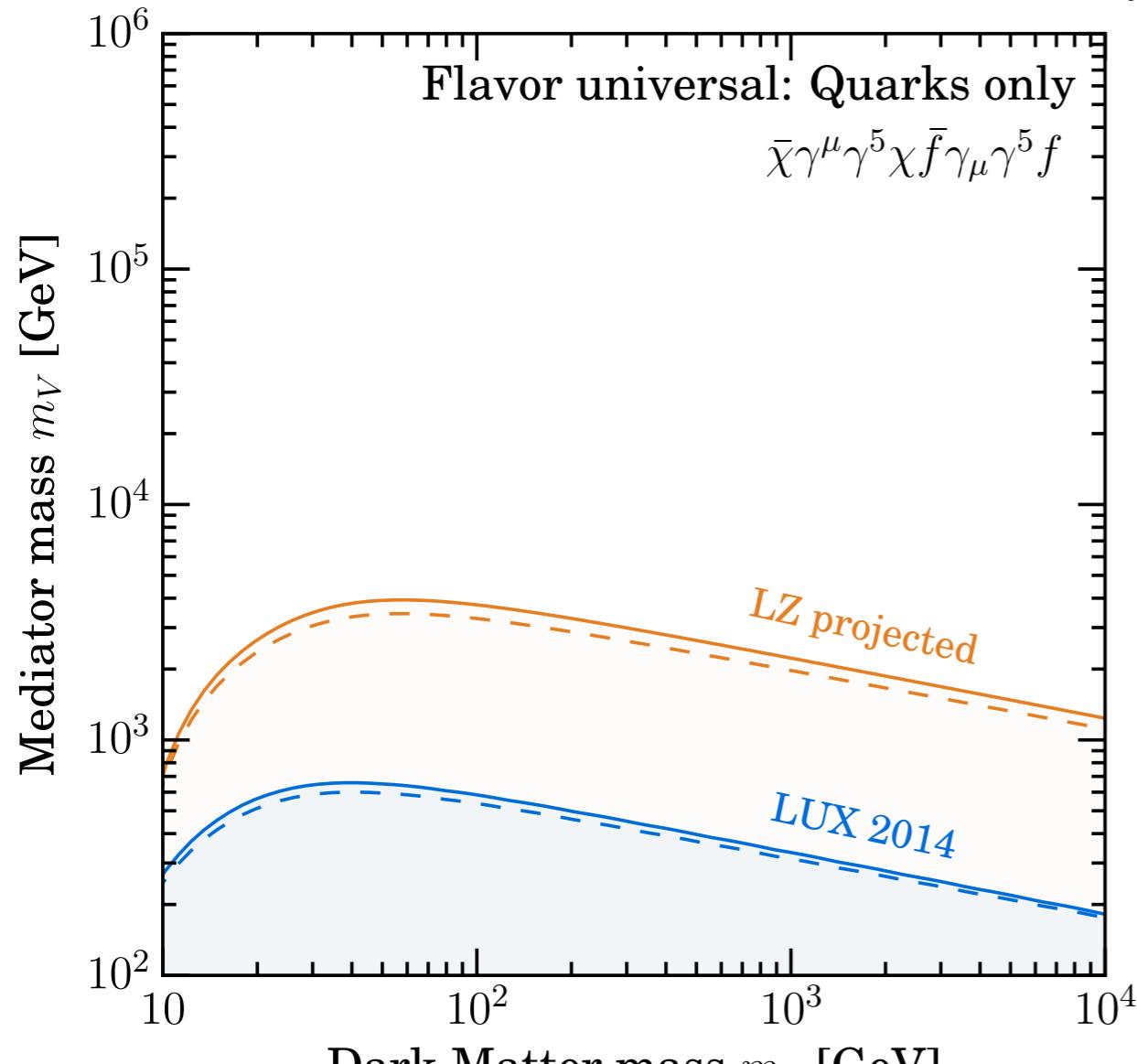


No running    - - - - -

Running    —————

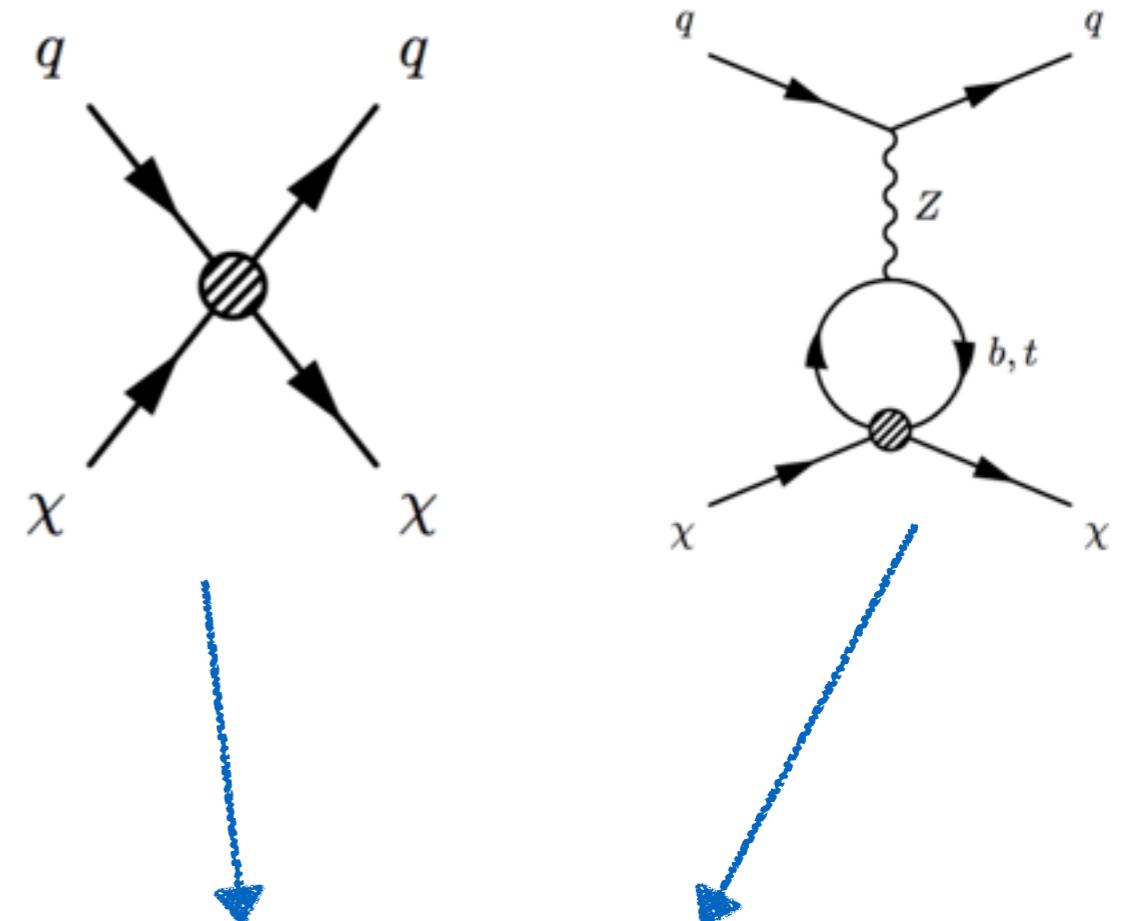
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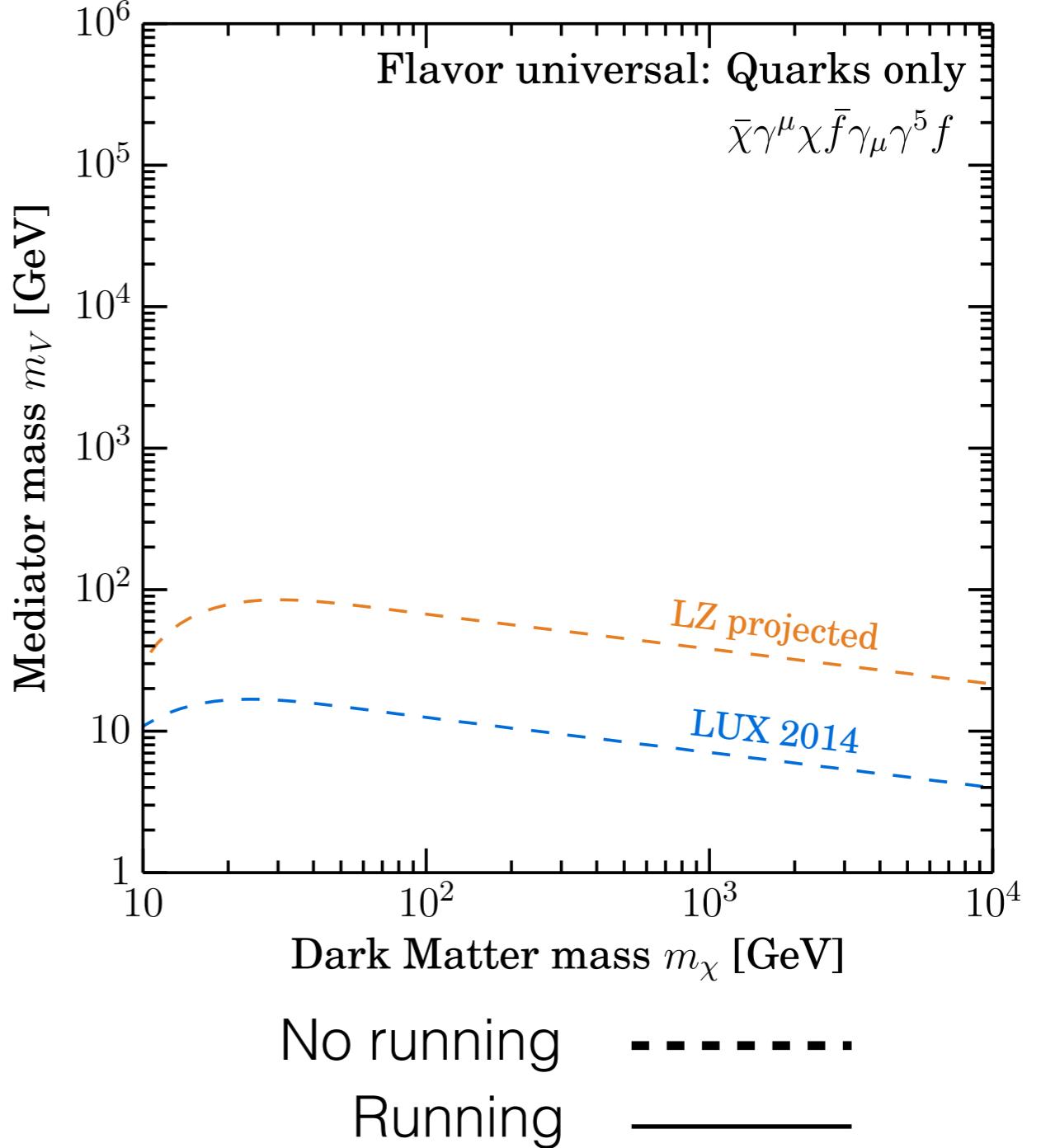
No running        
Running

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



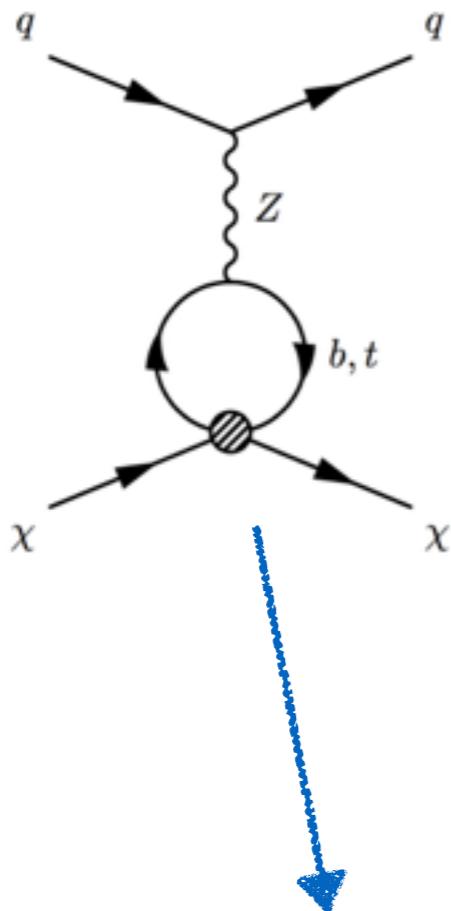
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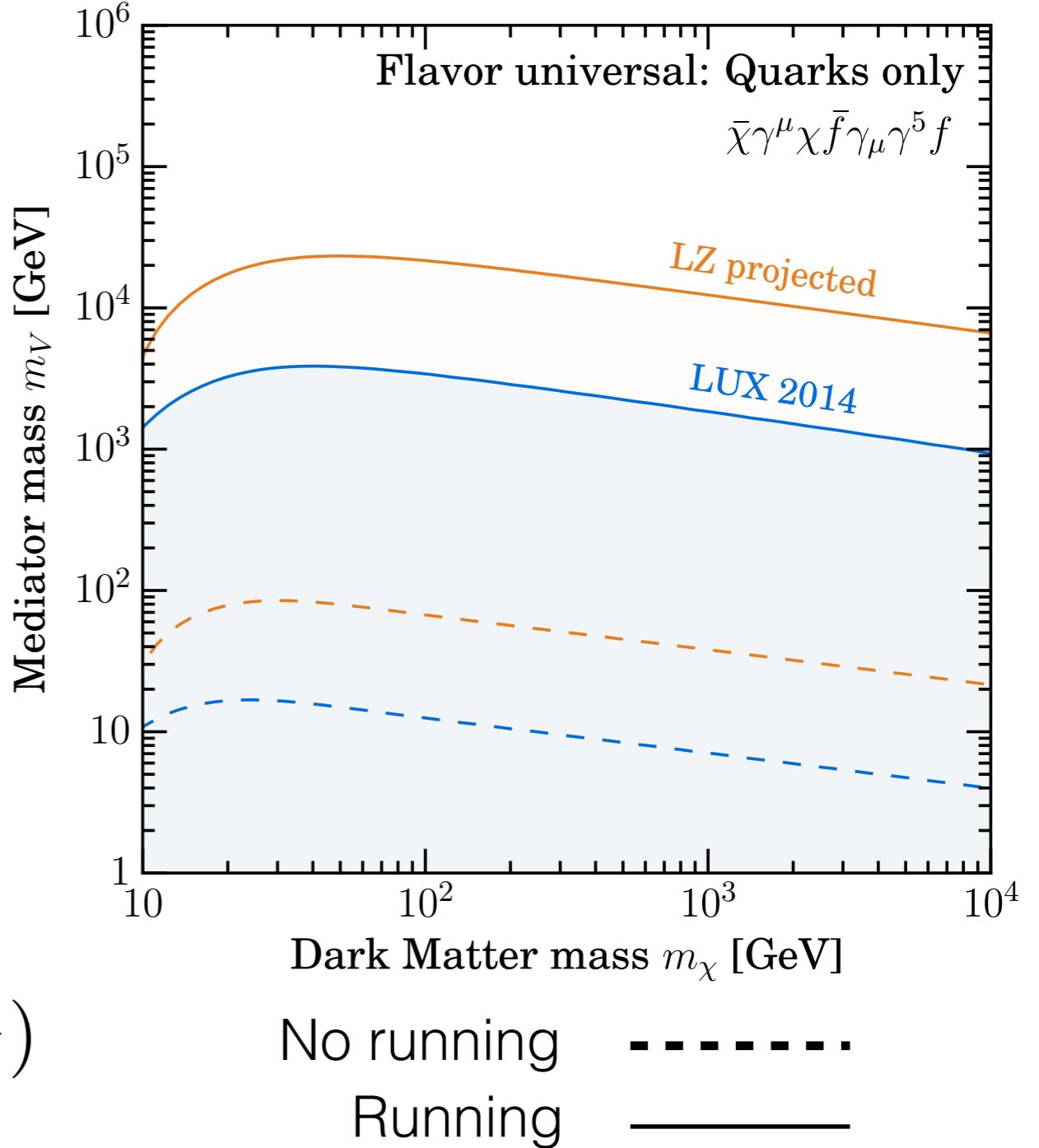


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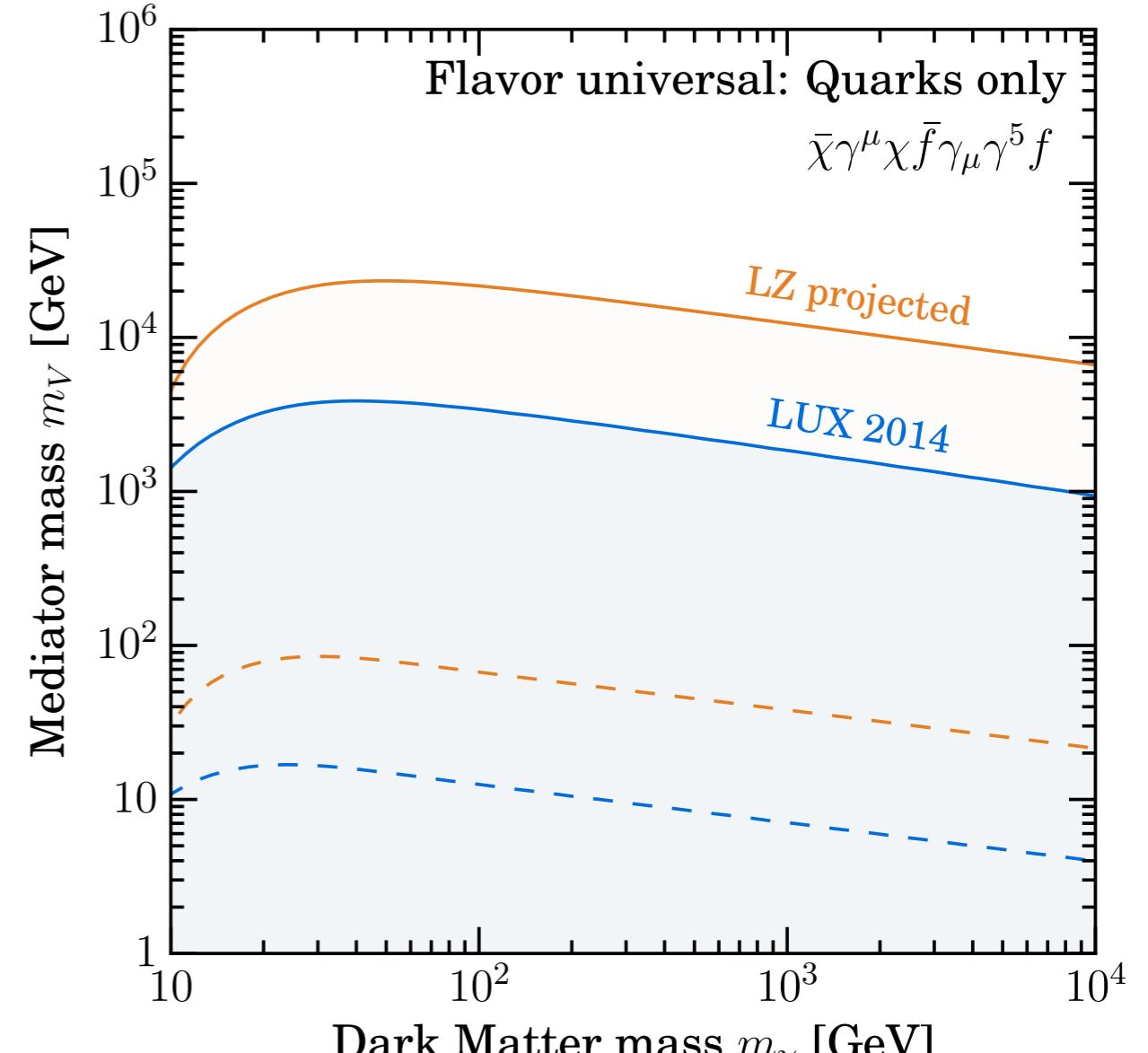
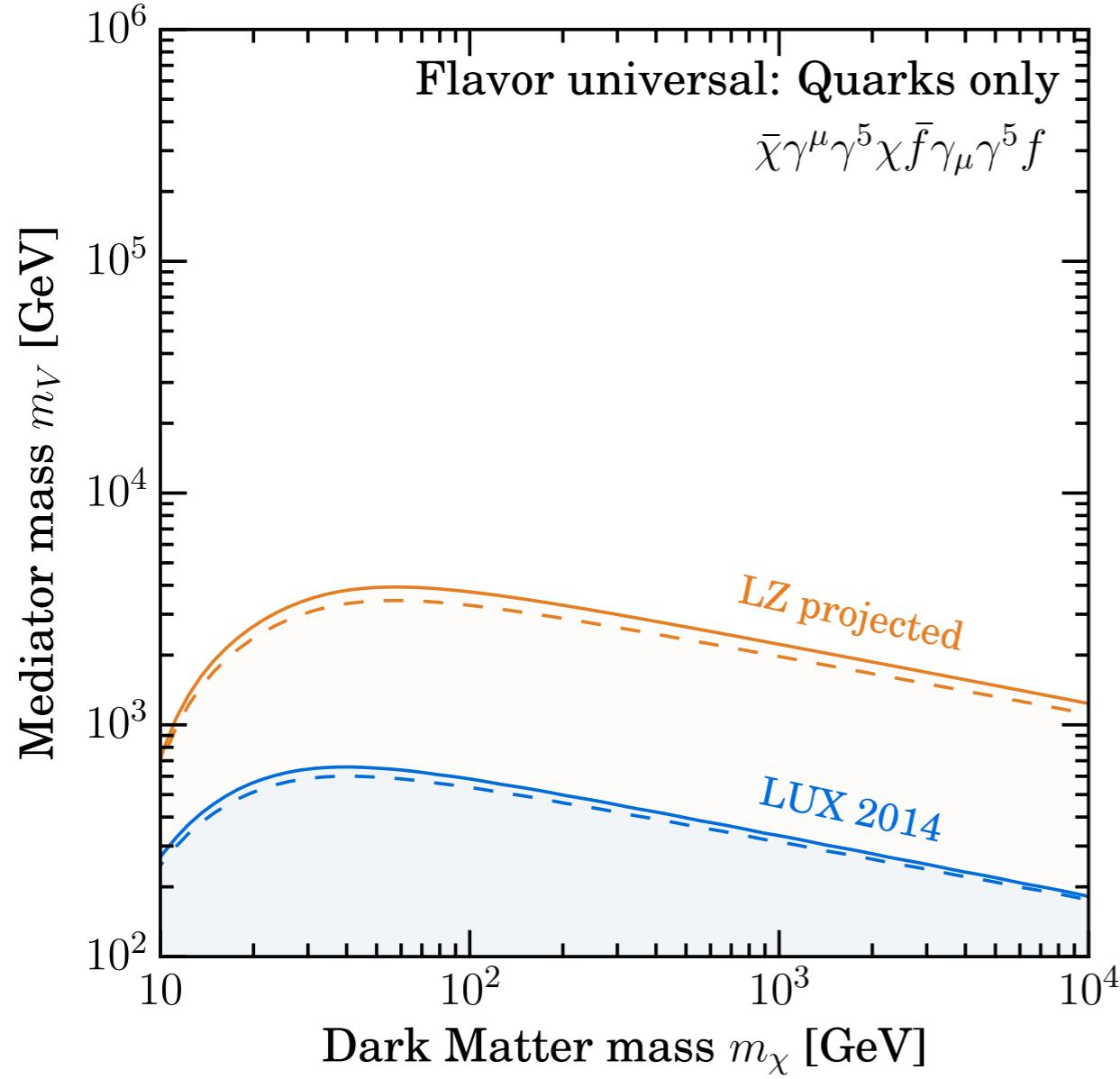


$$c_V^{(q)} \sim 0 + \# \frac{\lambda_{b,t}^2}{16\pi^2} \ln(m_V/m_N)$$



# Results II - quarks axial-vector

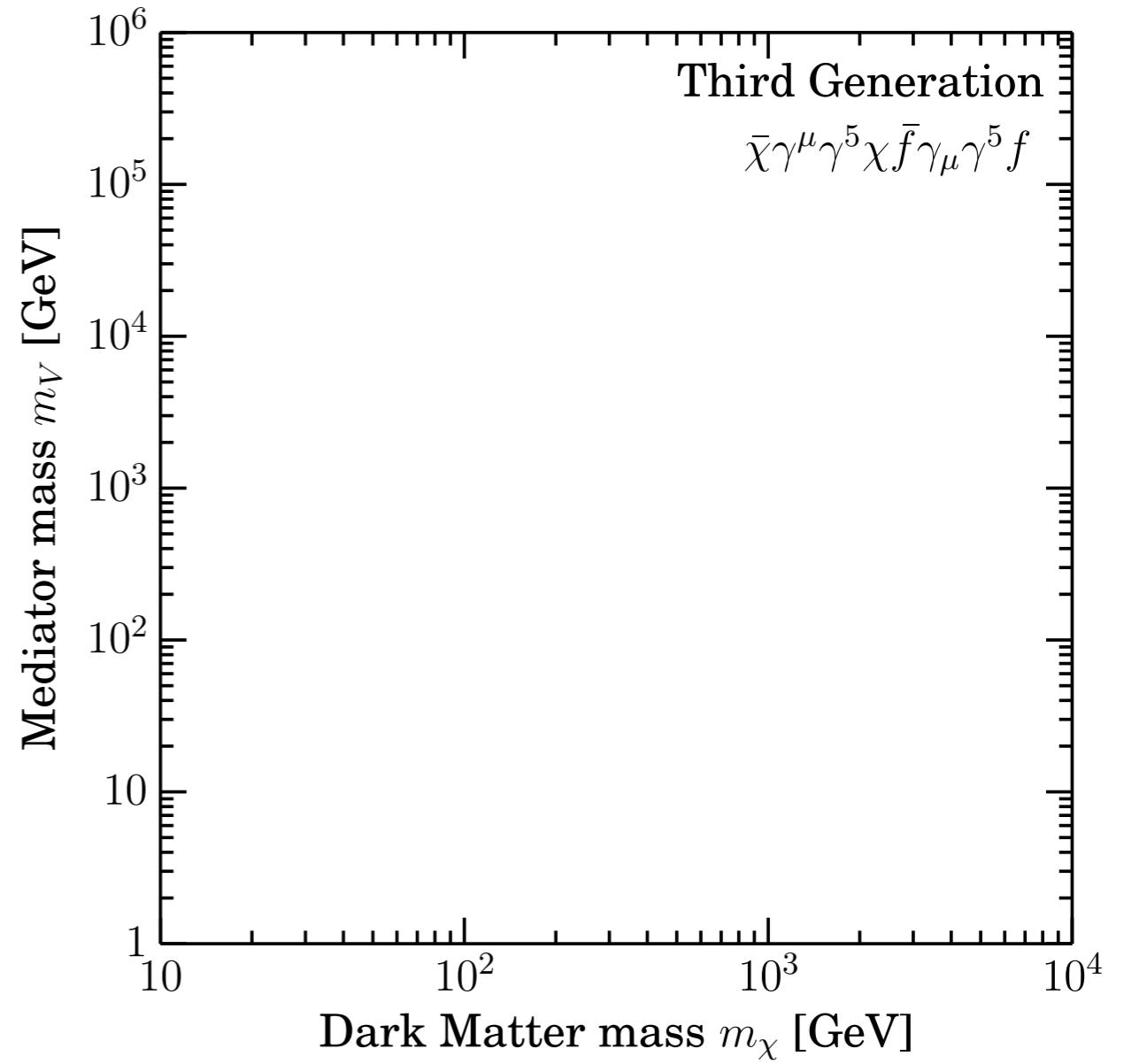
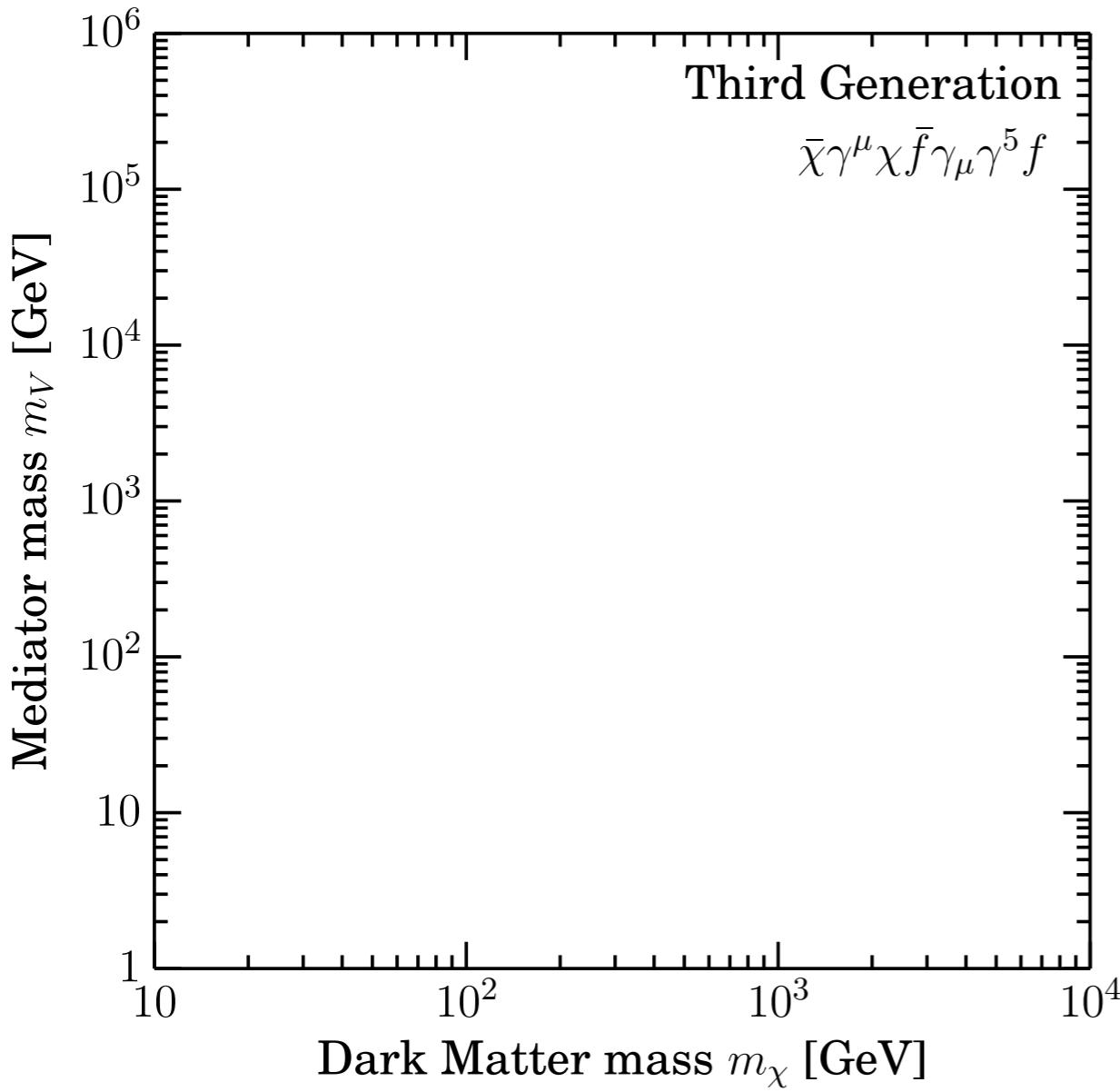
$$\mathcal{L}_{\text{EFT}} = -\frac{1}{m_V^2} J_{\text{DM}} \mu \sum_{i=1}^3 \left[ \bar{u}^i \gamma^\mu \gamma^5 u^i + \bar{d}^i \gamma^\mu \gamma^5 d^i \right]$$



No running    ······  
 Running    ———

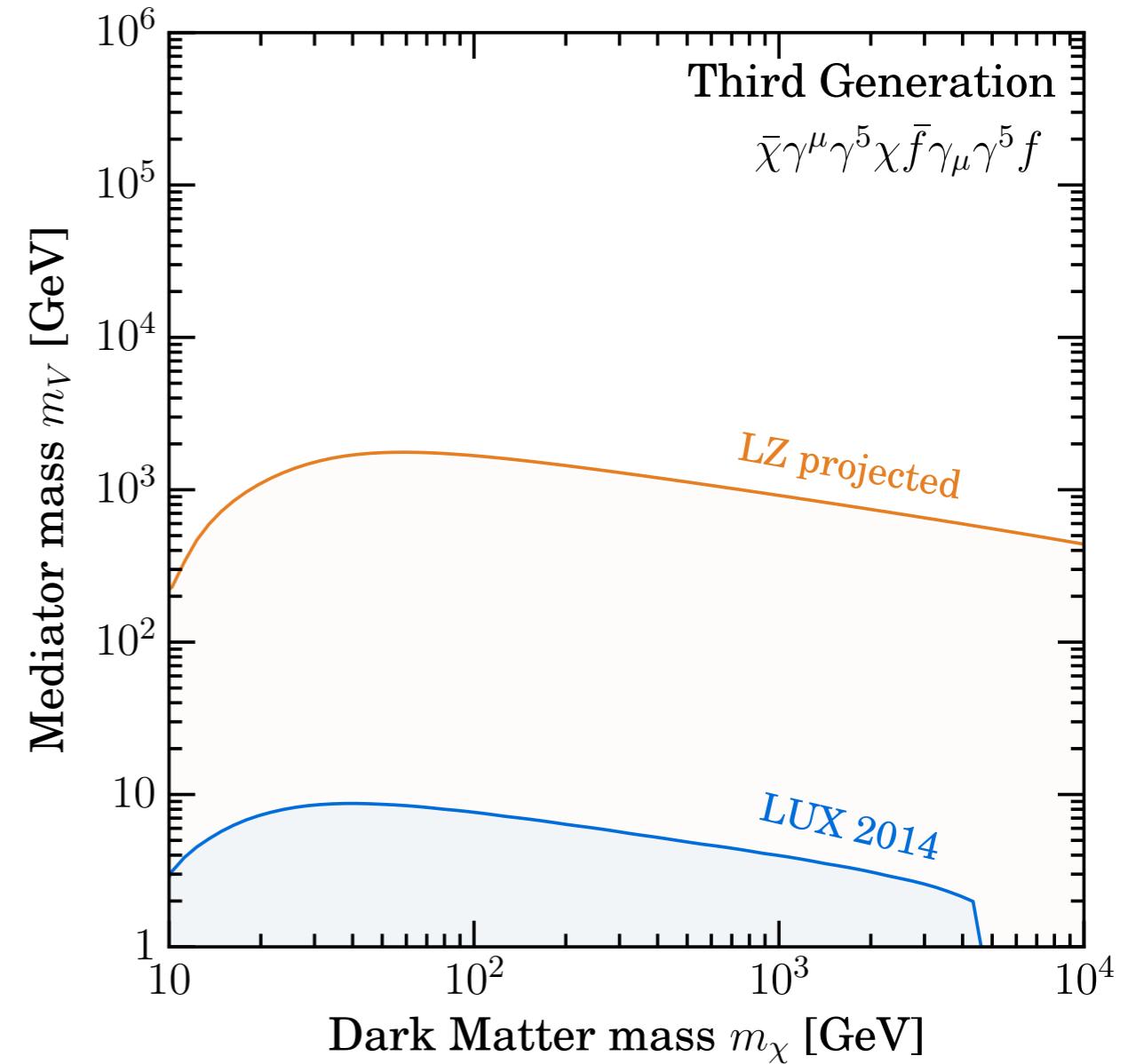
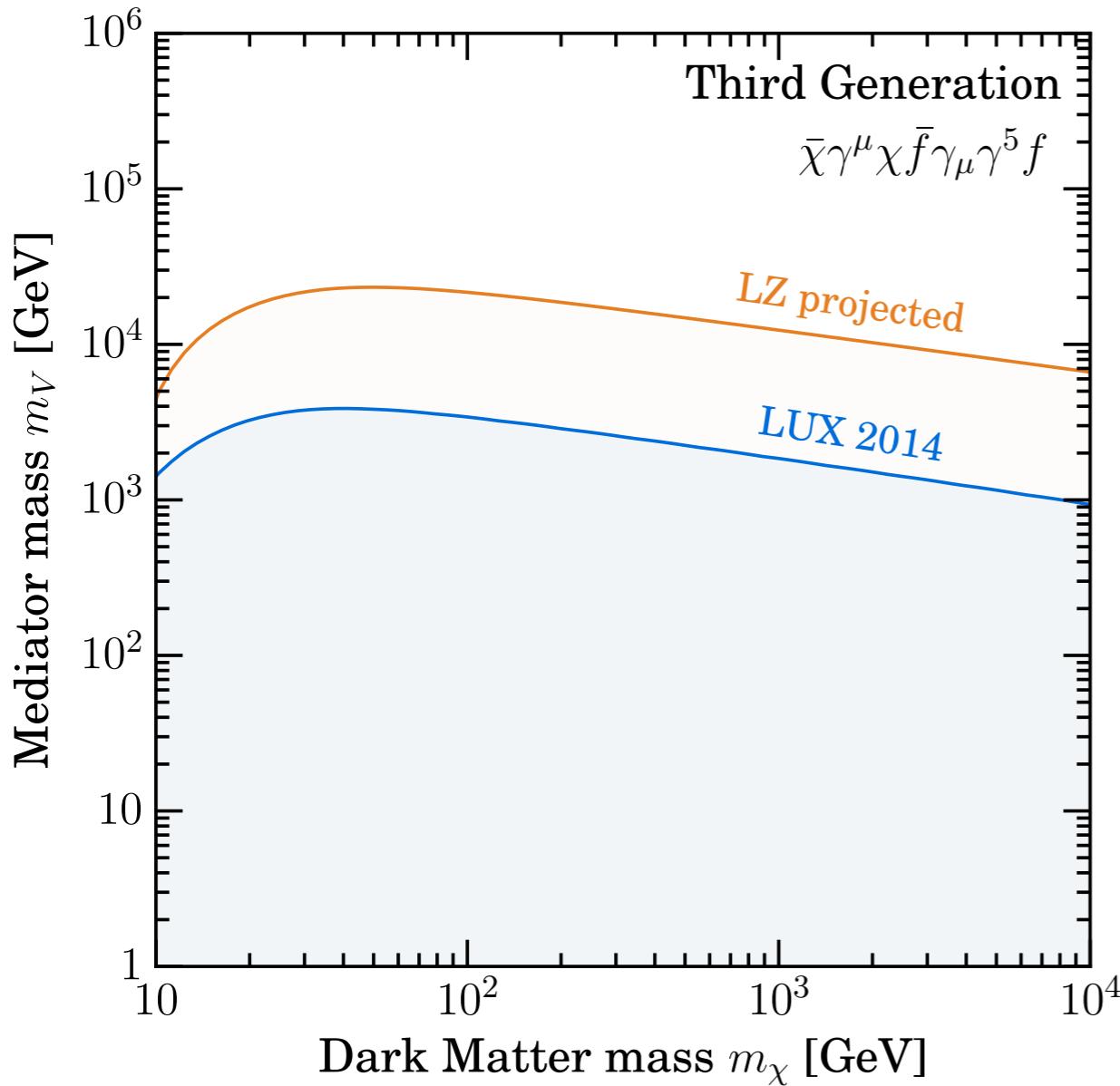
# Results III - 3rd Generation axial-vector

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



# Results III - 3rd Generation axial-vector

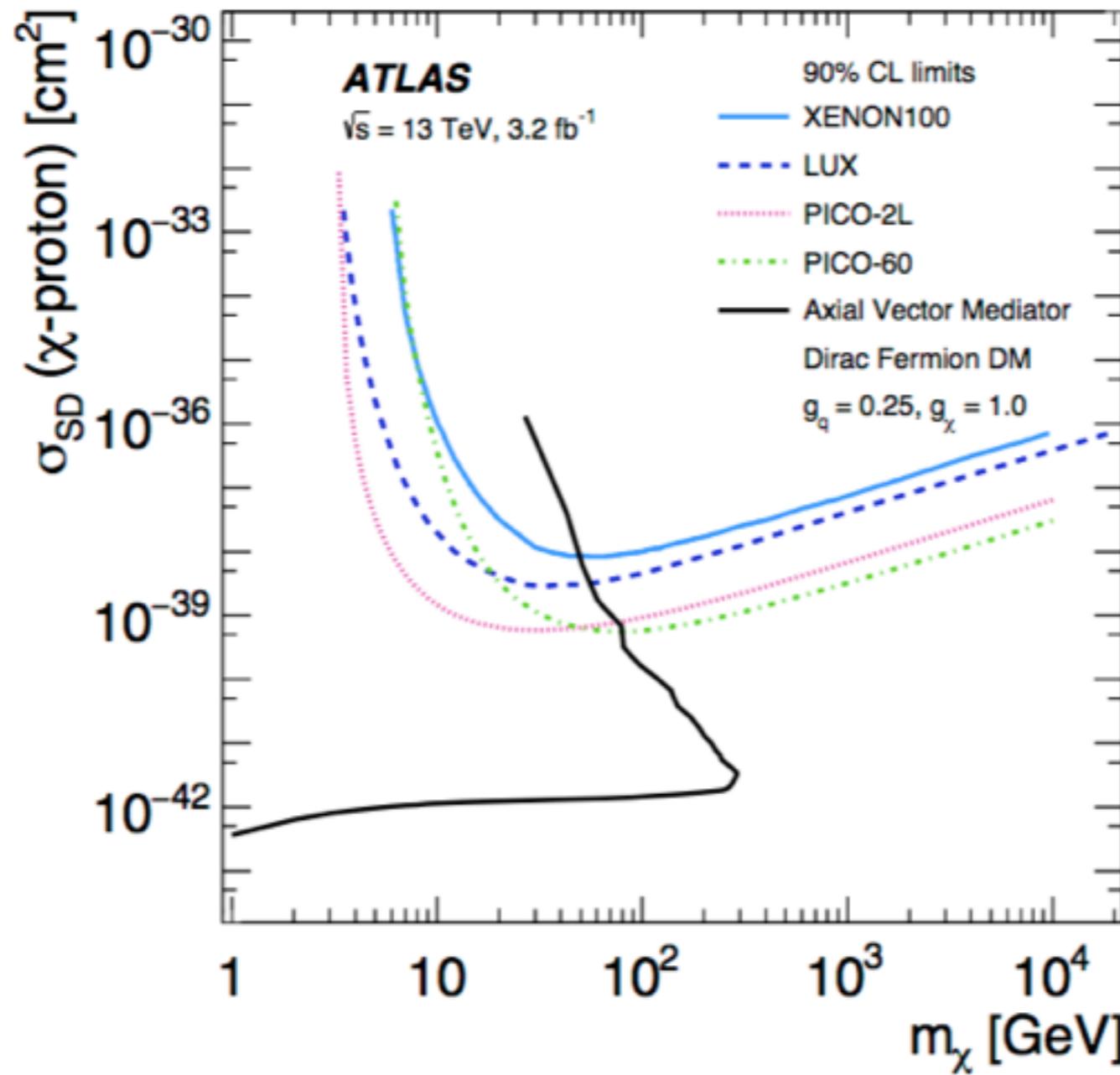
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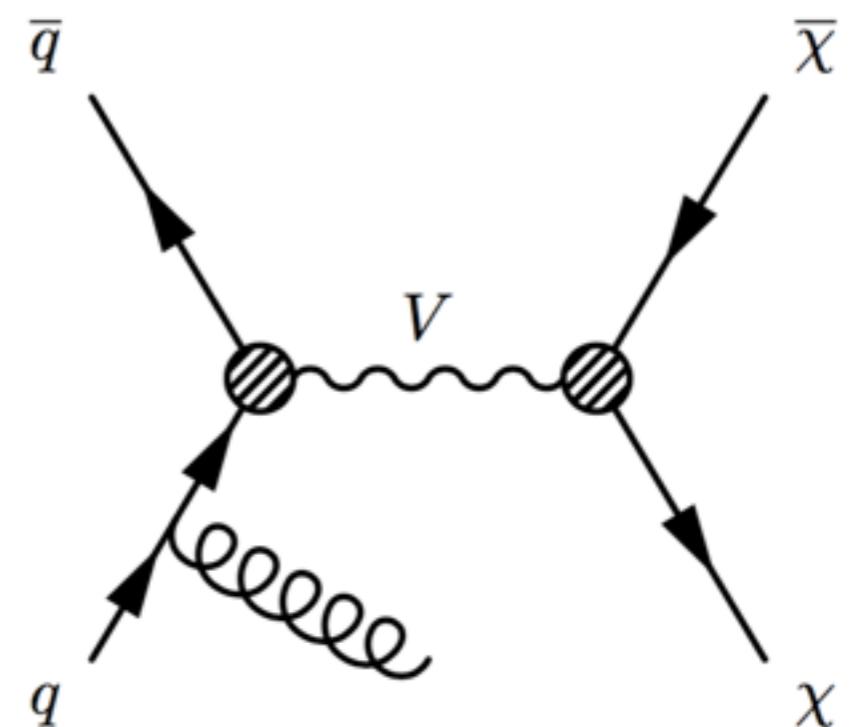
# Comparing DD and LHC searches

# LHC mono-X searches

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

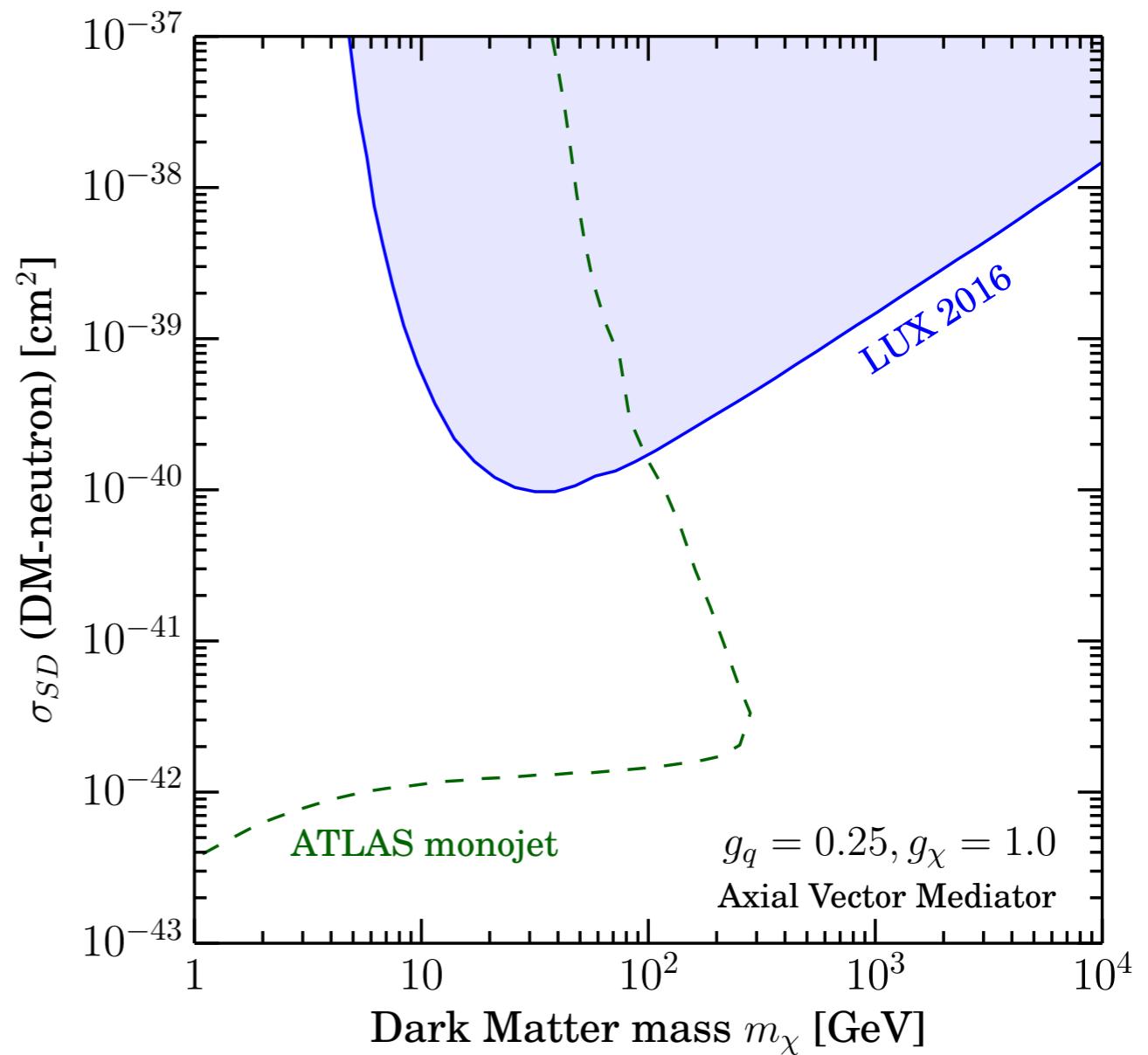
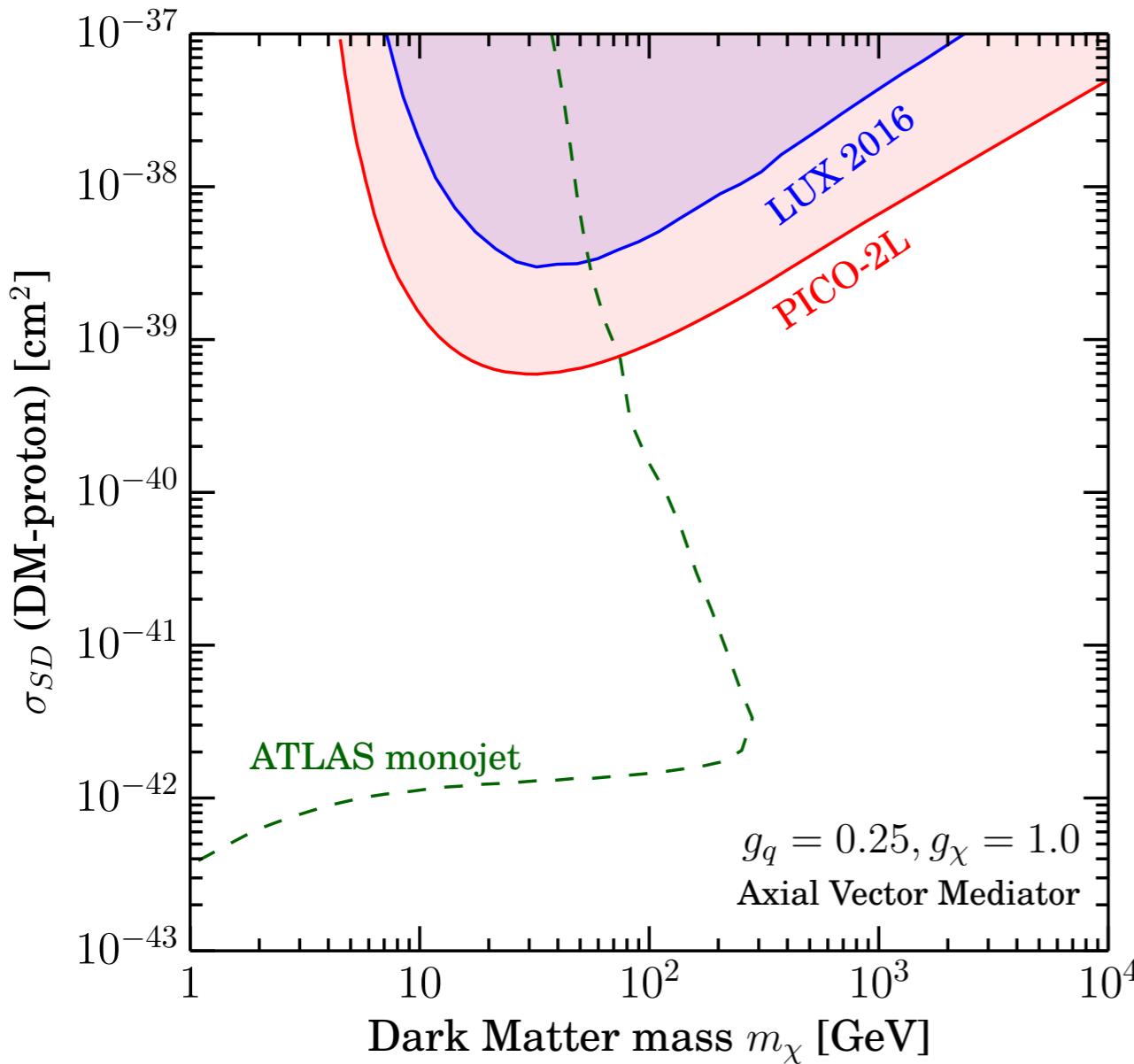


ATLAS [1604.07773]



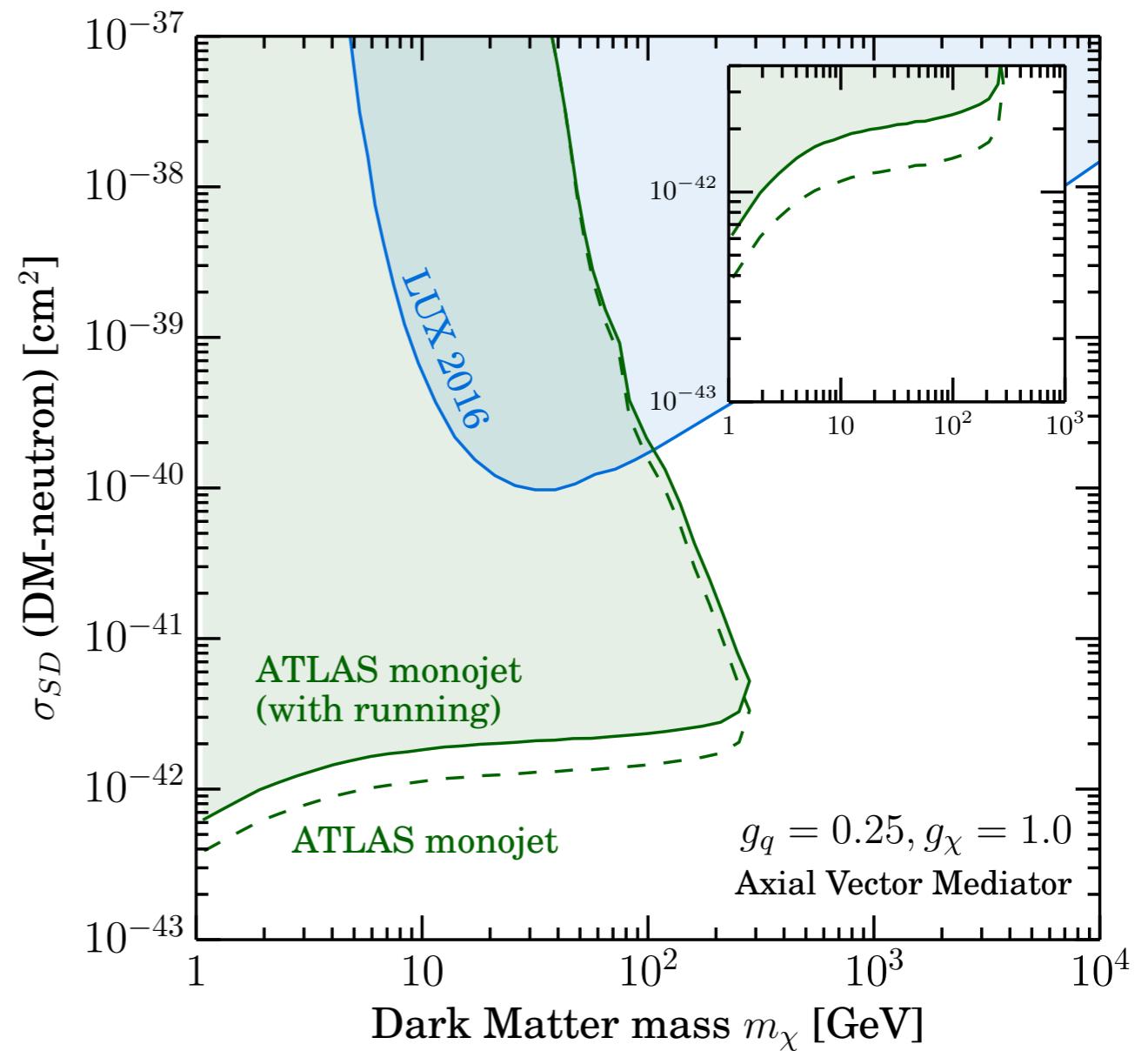
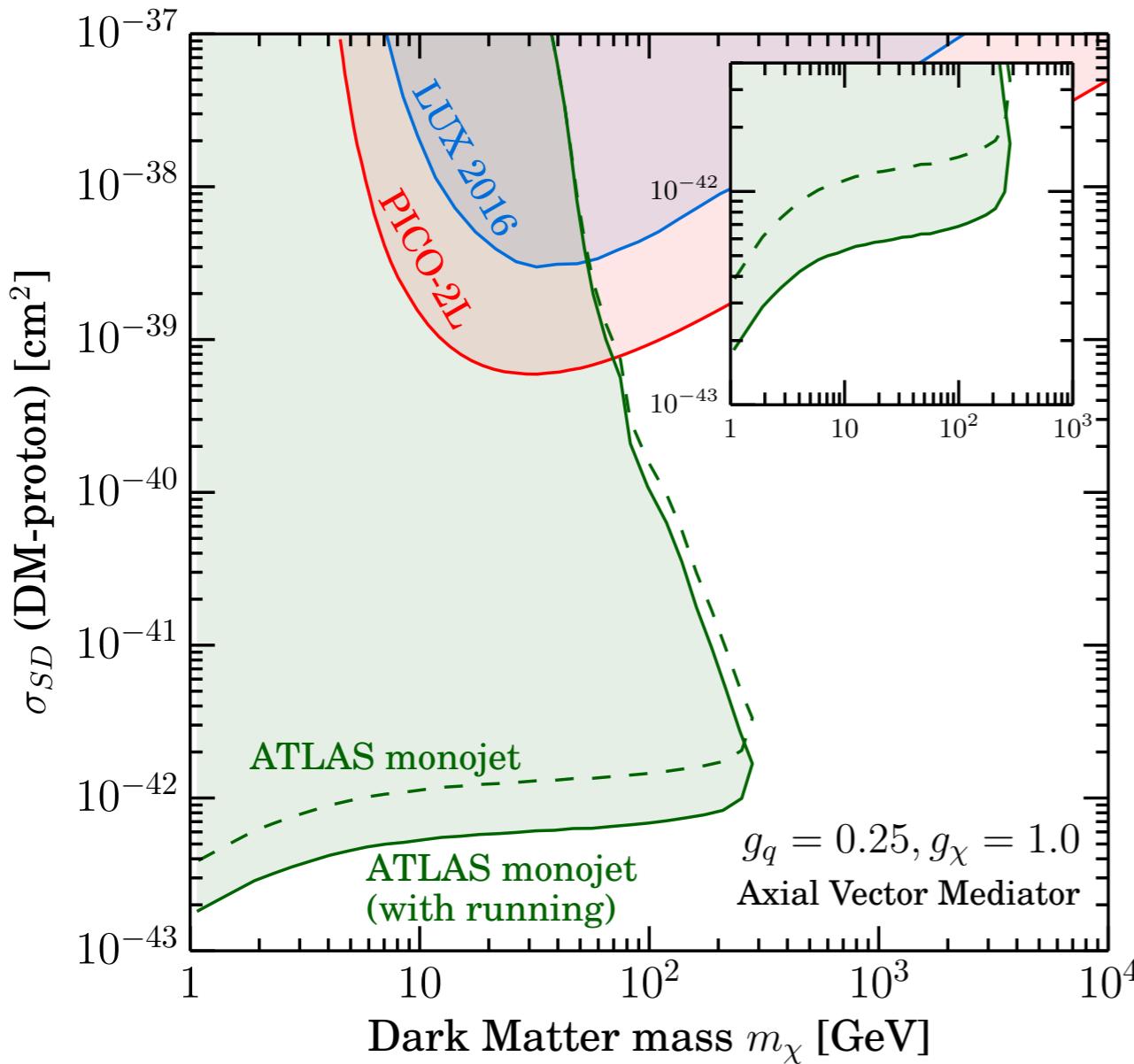
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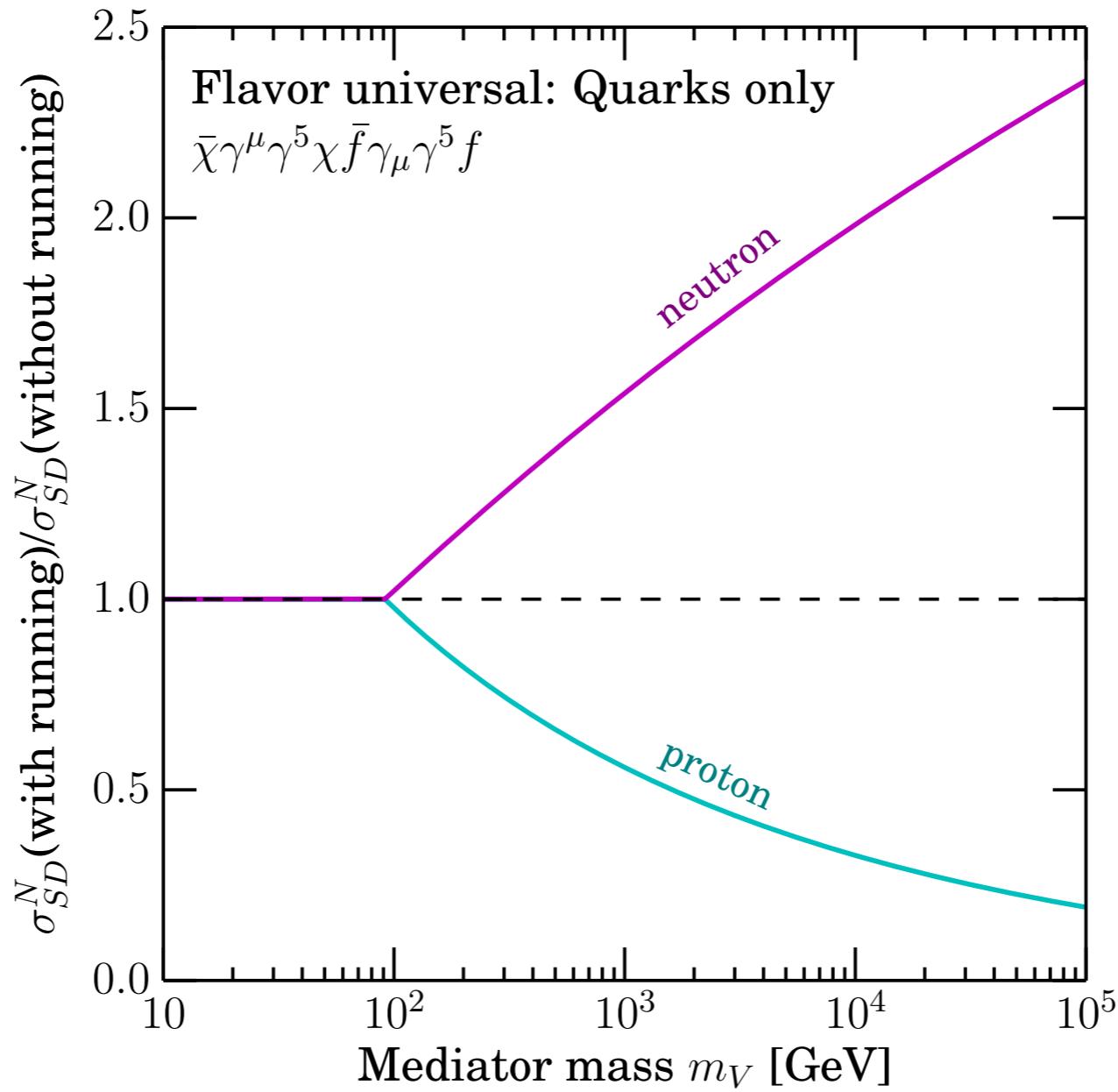
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# Isospin violation

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



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

# 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	$\bar{\chi}\chi\bar{q}\gamma^5q$	$im_q/M_*^3$
D4	$\bar{\chi}\gamma^5\chi\bar{q}\gamma^5q$	$m_q/M_*^3$
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	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5q$	$1/M_*^2$
D8	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5q$	$1/M_*^2$

Standard SI

Standard SD

Goodman et al. [1008.1783]

# Other interactions

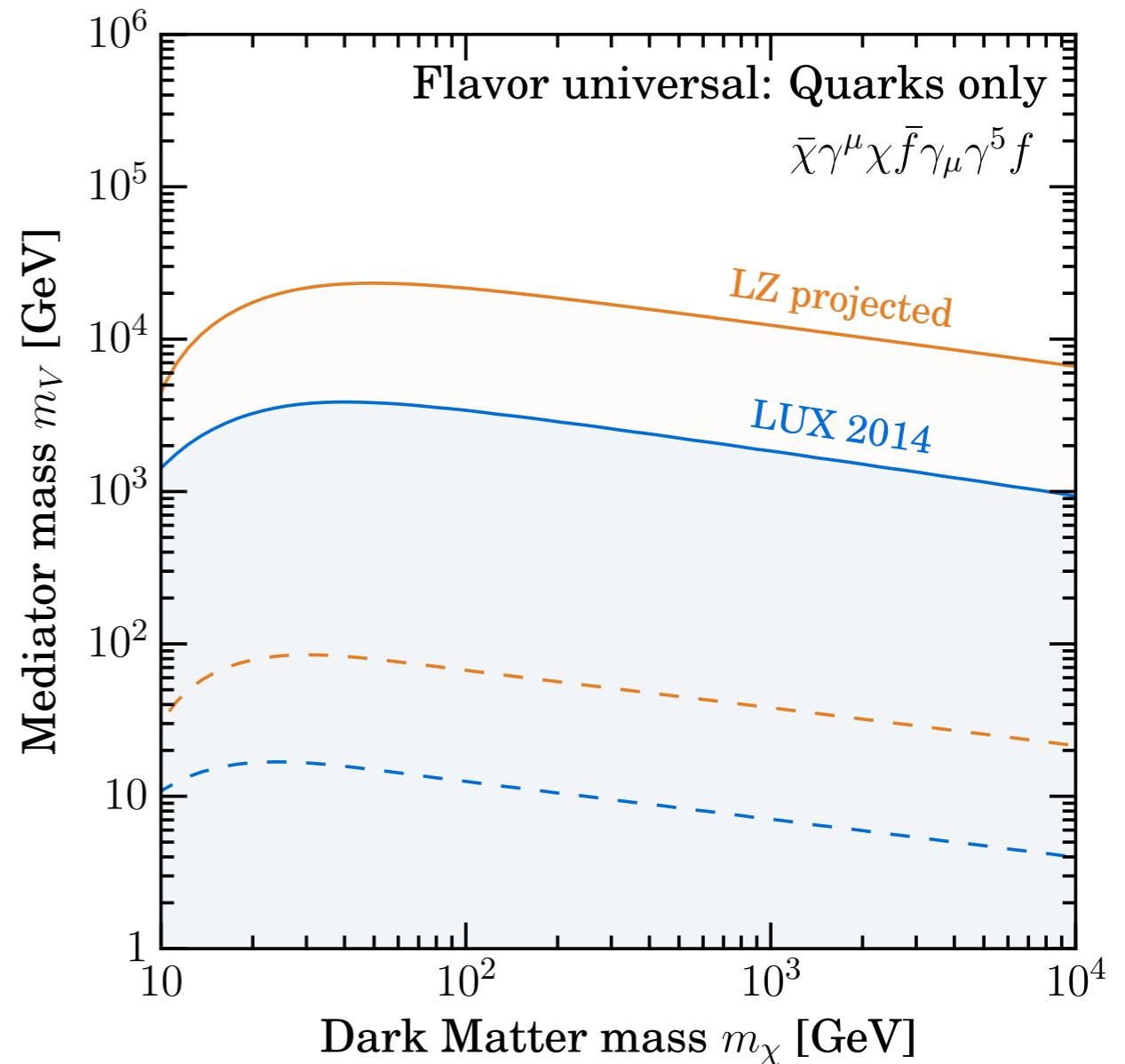
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Goodman et al. [1008.1783]



# 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

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

Langacker [0801.1345]



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

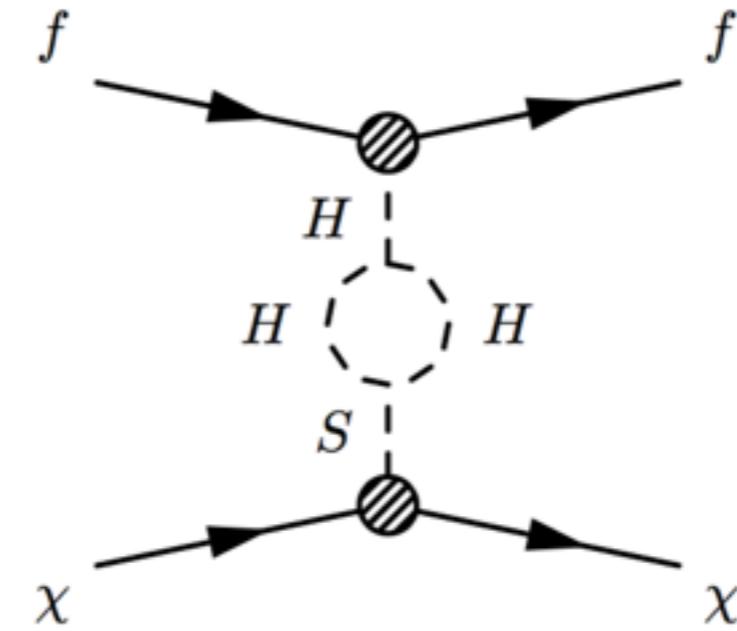
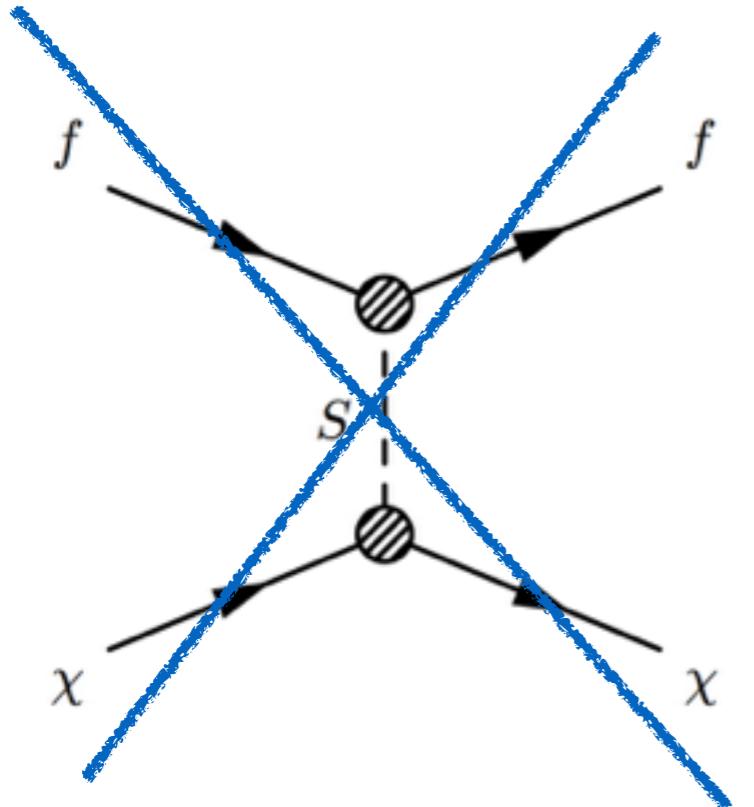
# Scalar Mediators

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

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

Crivellin, D'Eramo, Procura [1402.1173]

Buckley et al. [1410.6497]



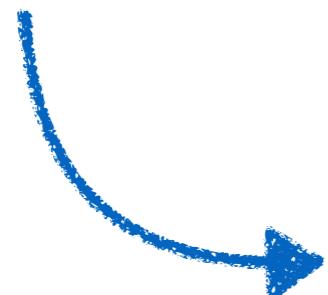
# Scalar mediator: 750 GeV

## A 750 GeV Portal: LHC Phenomenology and Dark Matter Candidates

Francesco D'Eramo <sup>a,b</sup>, Jordy de Vries <sup>c</sup>, Paolo Panci <sup>d</sup>

D'Eramo, de Vries, Panci [1601.01571]

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



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

Substantial RG effects!

# The operator basis

Complete the  
operator basis

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

Redundant  
Operator  
(E.O.M.)

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