# A careful comparison between LHC and direct detection

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SCIPP
Santa Cruz Institute for Particle Physics

Dark Matter at the LHC 2016
Amsterdam – 31 March 2016

# LHC vs Direct Detection

## LHC


$$pp \to \chi\chi j$$

$$\sqrt{s} = 13\,\mathrm{TeV}$$

## Direct Detection


$$\chi\mathcal{N} \to \chi\mathcal{N}$$

$$\langle E_{\mathrm{recoil}} \rangle \simeq 2\frac{m_{\mathrm{DM}}^2 M_{\mathcal{N}}}{(m_{\mathrm{DM}} + M_{\mathcal{N}})^2}\, v^2 \simeq 50\,\mathrm{keV}$$

Xe and $m_{\mathrm{DM}} = 100\,\mathrm{GeV}$

# LHC vs Direct Detection

Energy Scale

## LHC


$$pp \to \chi\chi j$$

$$\sqrt{s} = 13\,\mathrm{TeV}$$

Energy scales:
LHC ≫ Direct Detection

## Direct Detection


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# LHC vs Direct Detection

Energy Scale

## In this talk

Deal with scale separation by using Effective Field Theory (EFT) techniques

Mandatory for a careful comparison between LHC and DD

# A known SM example

B meson decay: B -> D π $\mathcal{M}_{B\to D\pi} = \langle D\pi|\mathcal{L}_{\rm SM}|B\rangle$

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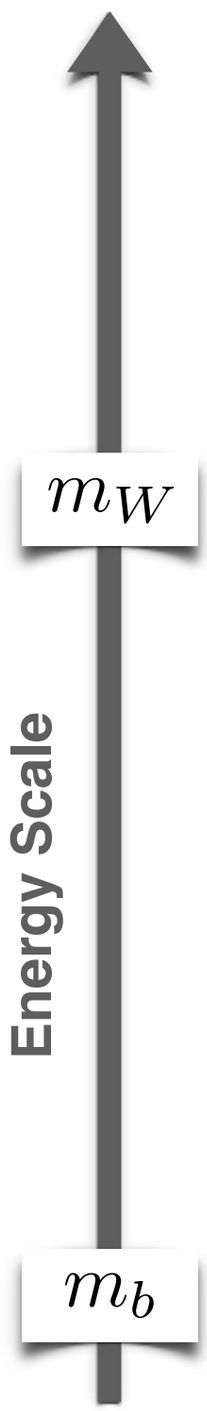


Direct calculation hard:

W boson mediates the decay in the B rest frame

$$m_W \gg m_B$$

EFT: systematically deal with one scale at the time

*and*

arbitrarily improve the calculation precision

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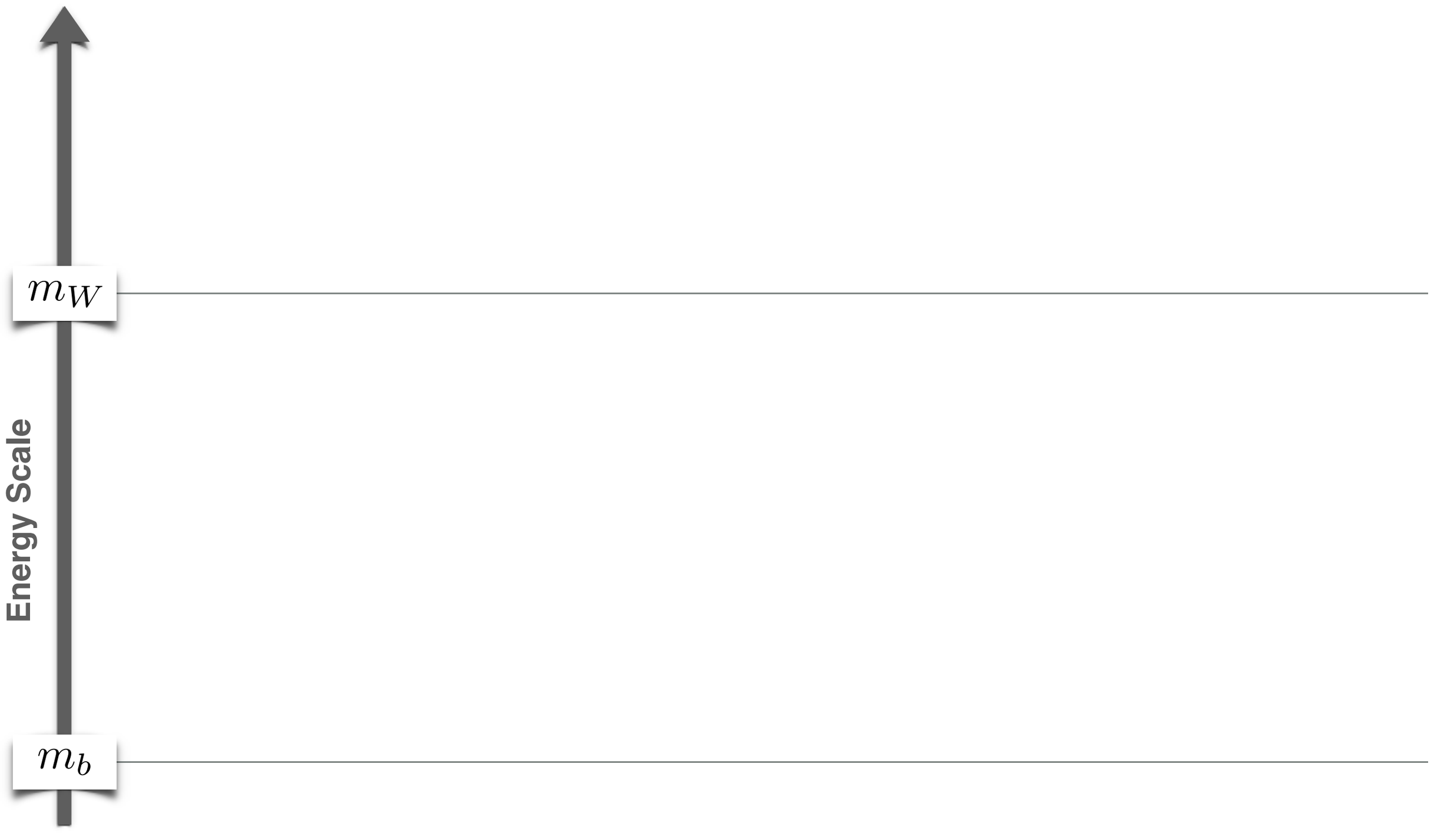

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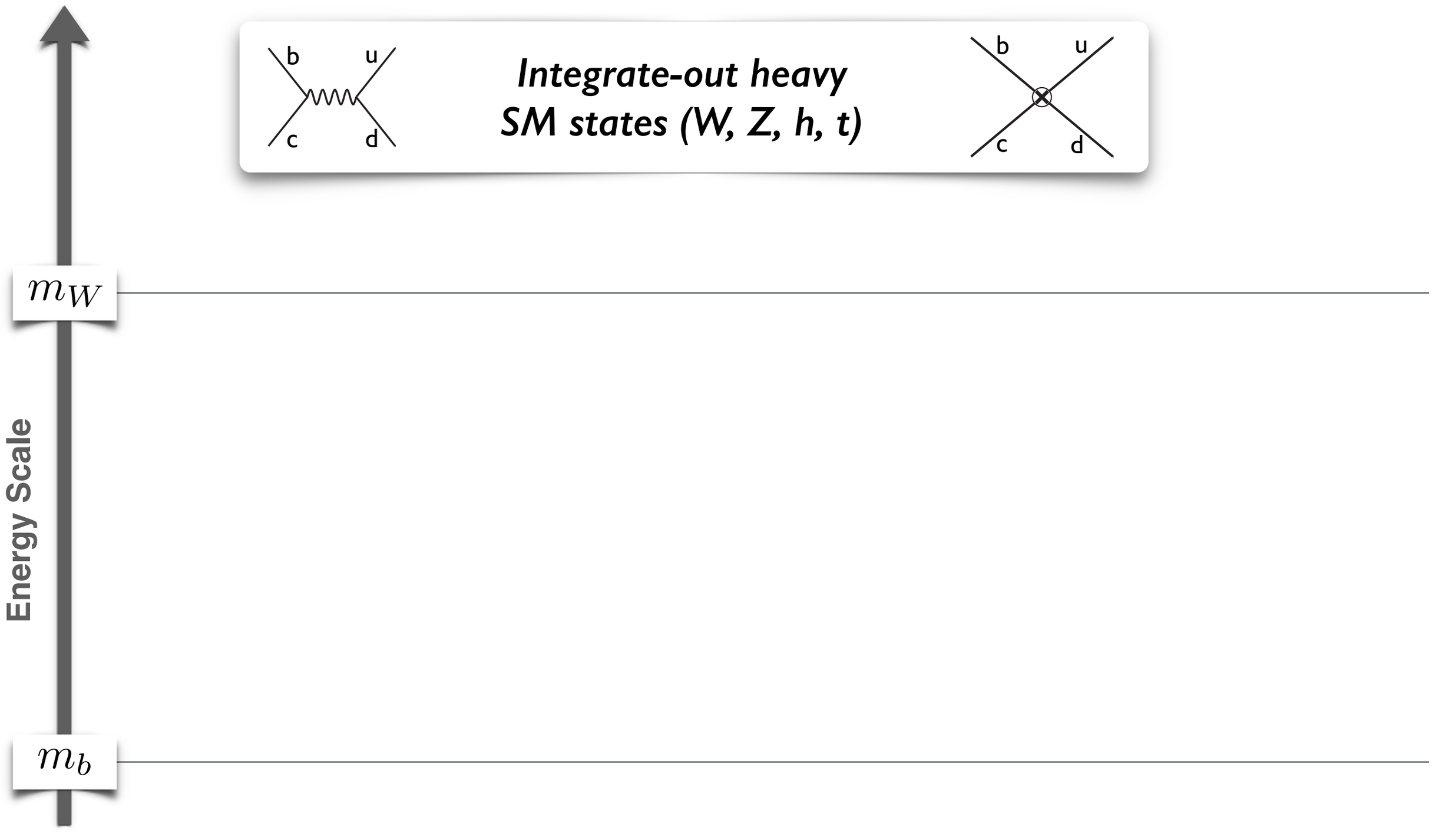

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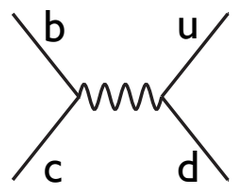
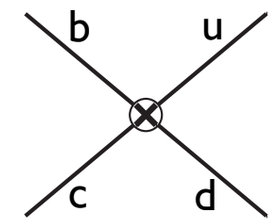



*Integrate-out heavy SM states (W, Z, h, t)*




Energy Scale

$m_W$

***ElectroWeak Hamiltonian***

$$\mathcal{H}_W = \mathcal{V}\, G_F\, \left[C_1\, \overline{c_\alpha}\gamma^\mu P_L b_\alpha\, \overline{d_\beta}\gamma^\mu P_L u_\beta + C_2\, \overline{c_\alpha}\gamma^\mu P_L b_\beta\, \overline{d_\beta}\gamma^\mu P_L u_\alpha\right]$$

Buras, hep-ph/9806471

$m_b$

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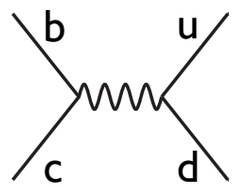


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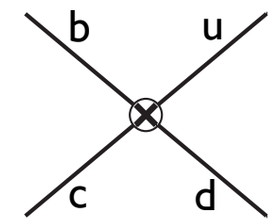


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$$C_1(m_W) = 1 \quad C_2(m_W) = 0$$

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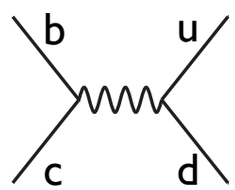


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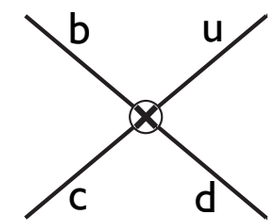


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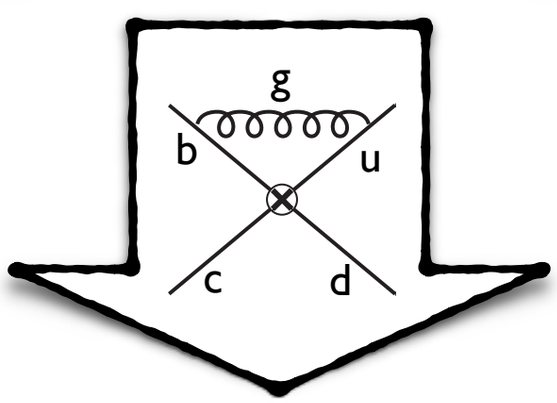


***Renormalization Group Evolution (RGE)***

$m_b$

$$C_1(m_b) \simeq 1.12 \quad C_2(m_b) \simeq -0.28$$

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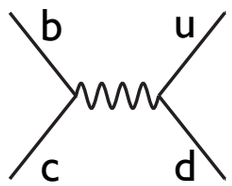


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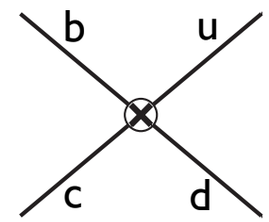


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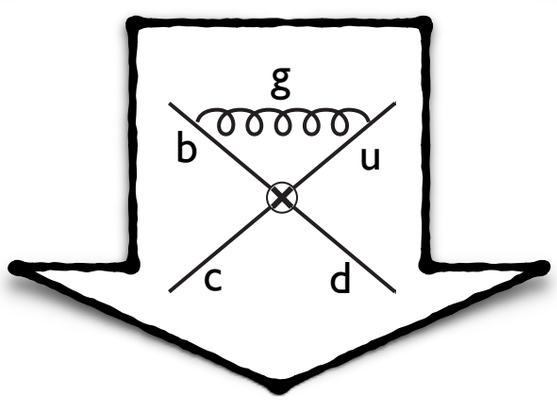



***Renormalization Group Evolution (RGE)***

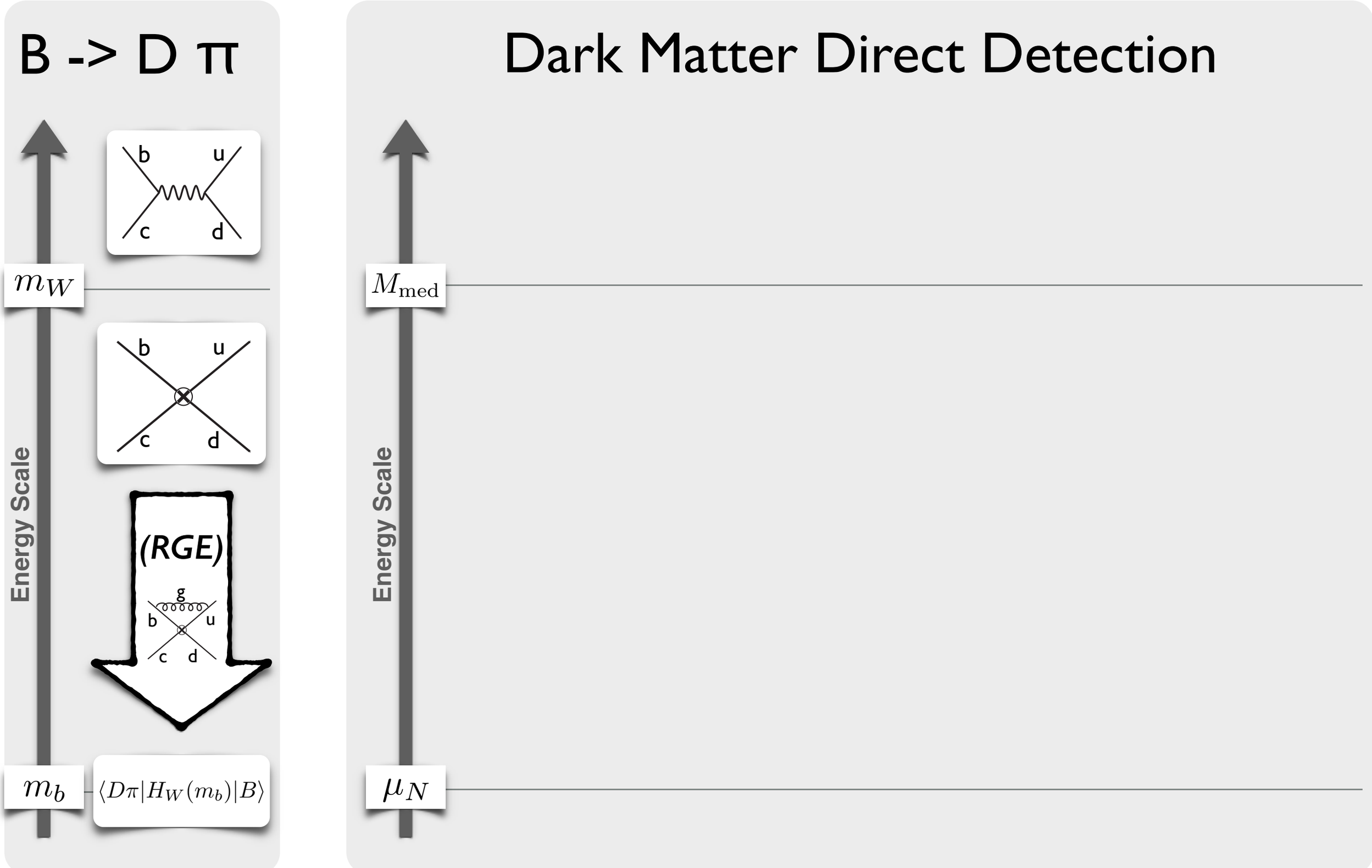
$m_b$

$$C_1(m_b) \simeq 1.12 \quad C_2(m_b) \simeq -0.28$$

***Effective couplings at the scale $m_b$***

$$\langle D\pi|H_W(m_b)|B\rangle$$

# DM Direct Detection



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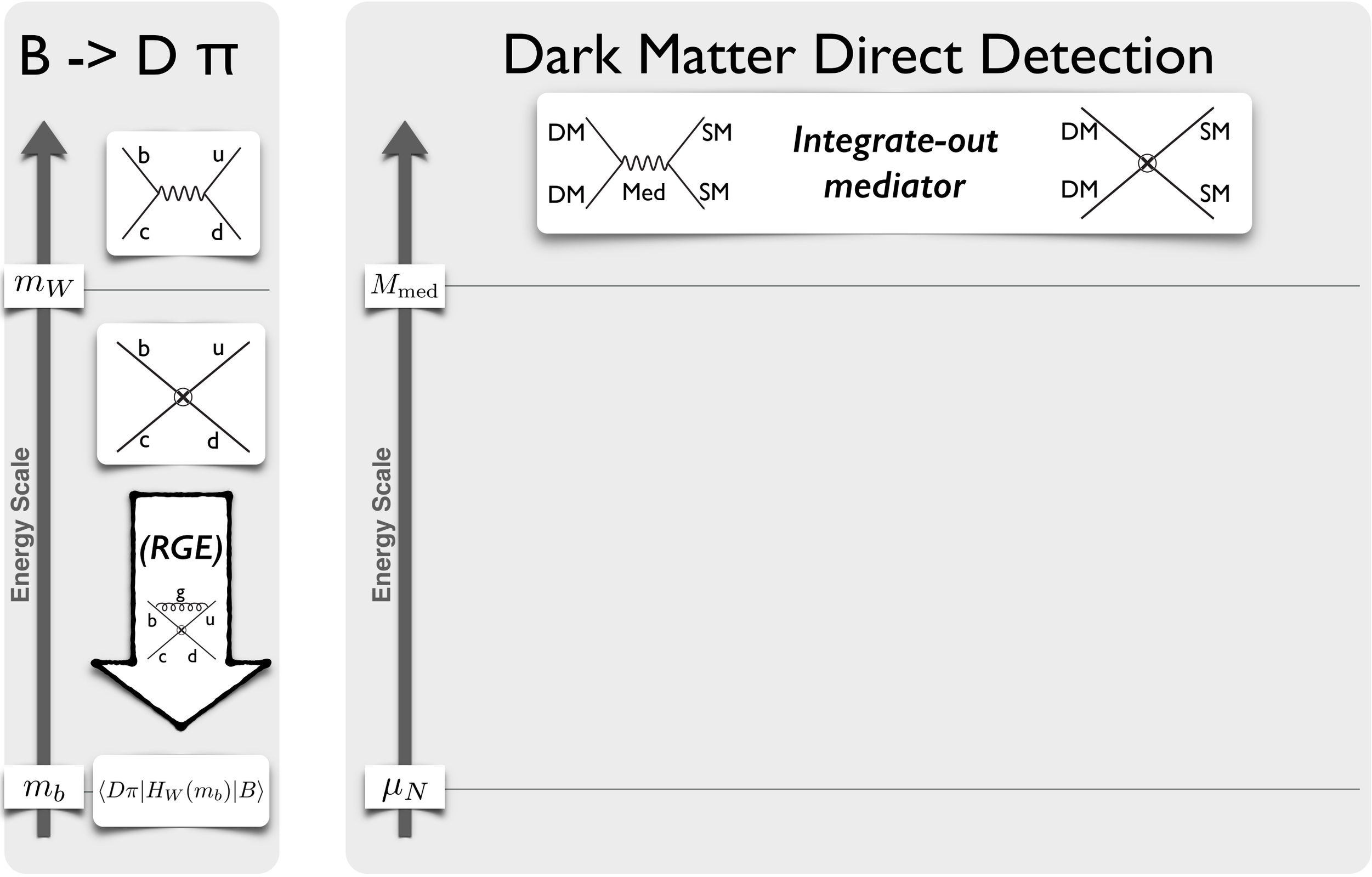

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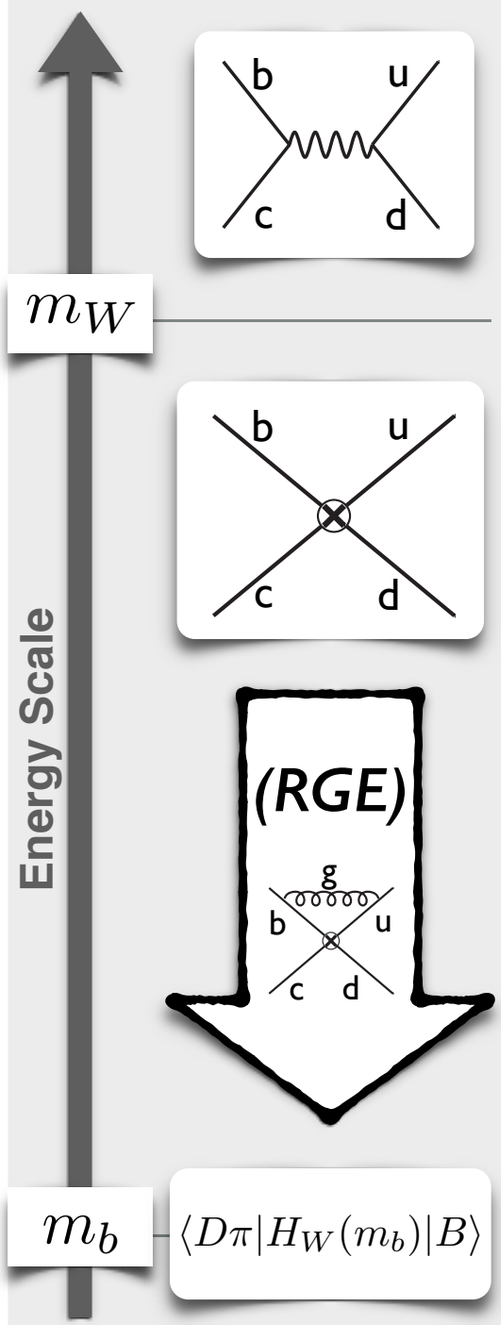
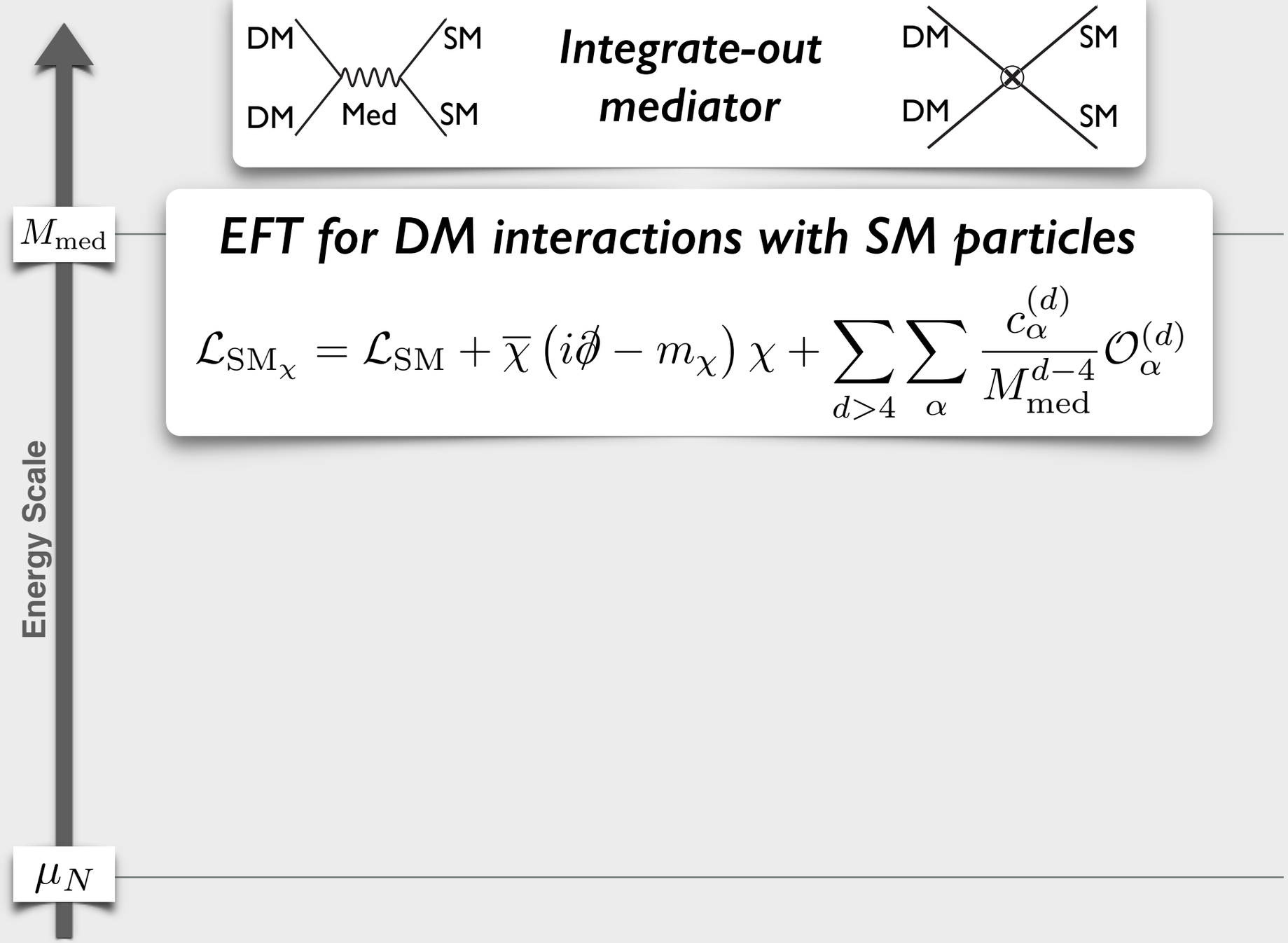



## Dark Matter Direct Detection




***EFT for DM interactions with SM particles***

$$\mathcal{L}_{\mathrm{SM}_\chi} = \mathcal{L}_{\mathrm{SM}} + \overline{\chi}\left(i\partial\!\!\!/ - m_\chi\right)\chi + \sum_{d>4}\sum_{\alpha}\frac{c_\alpha^{(d)}}{M_{\rm med}^{d-4}}\mathcal{O}_\alpha^{(d)}$$

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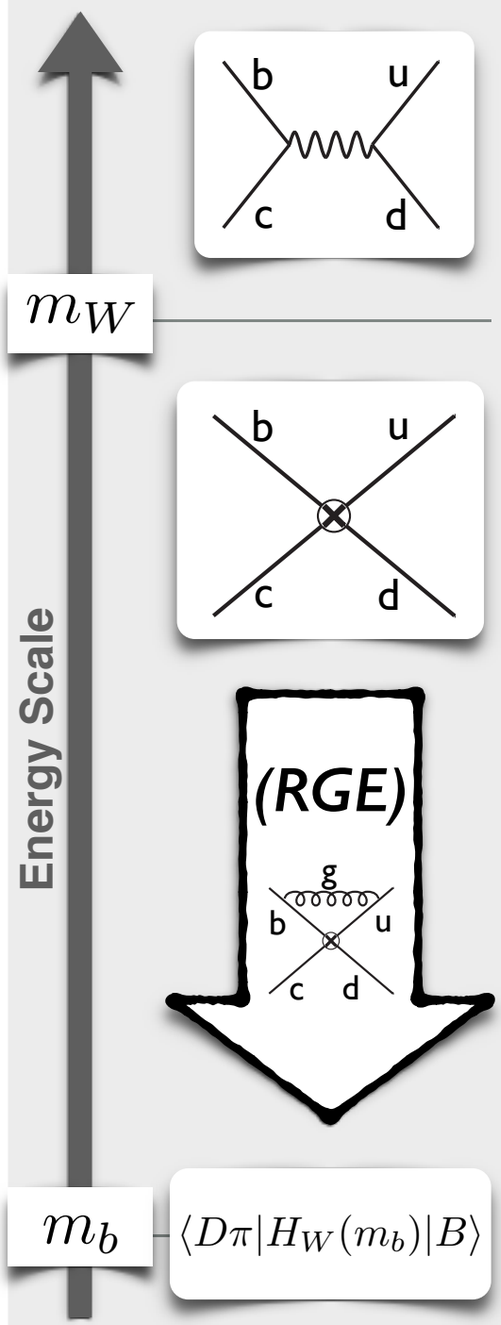


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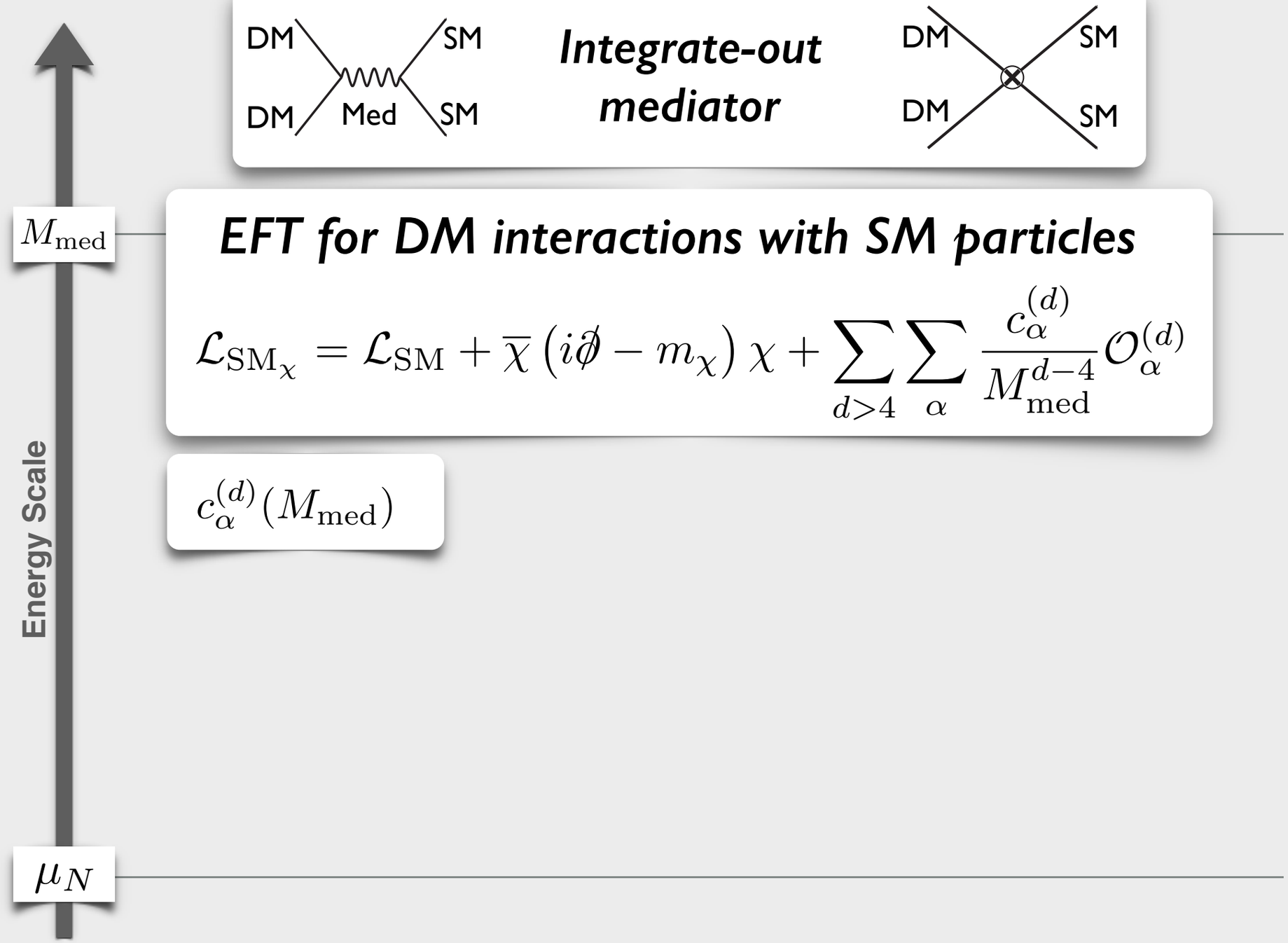


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$c_\alpha^{(d)}(M_{\rm med})$

# DM Direct Detection

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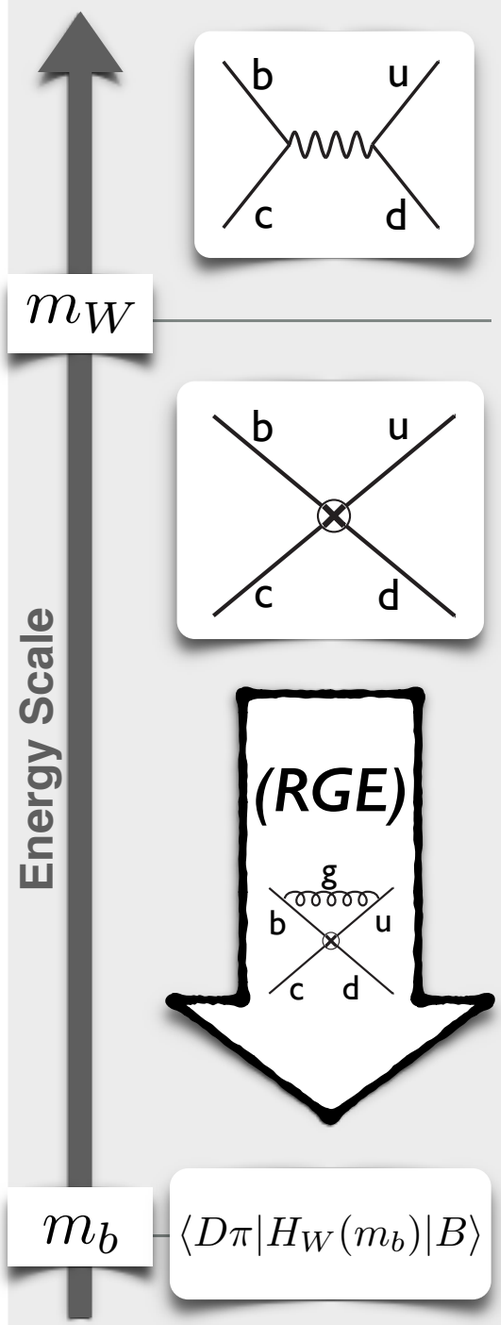


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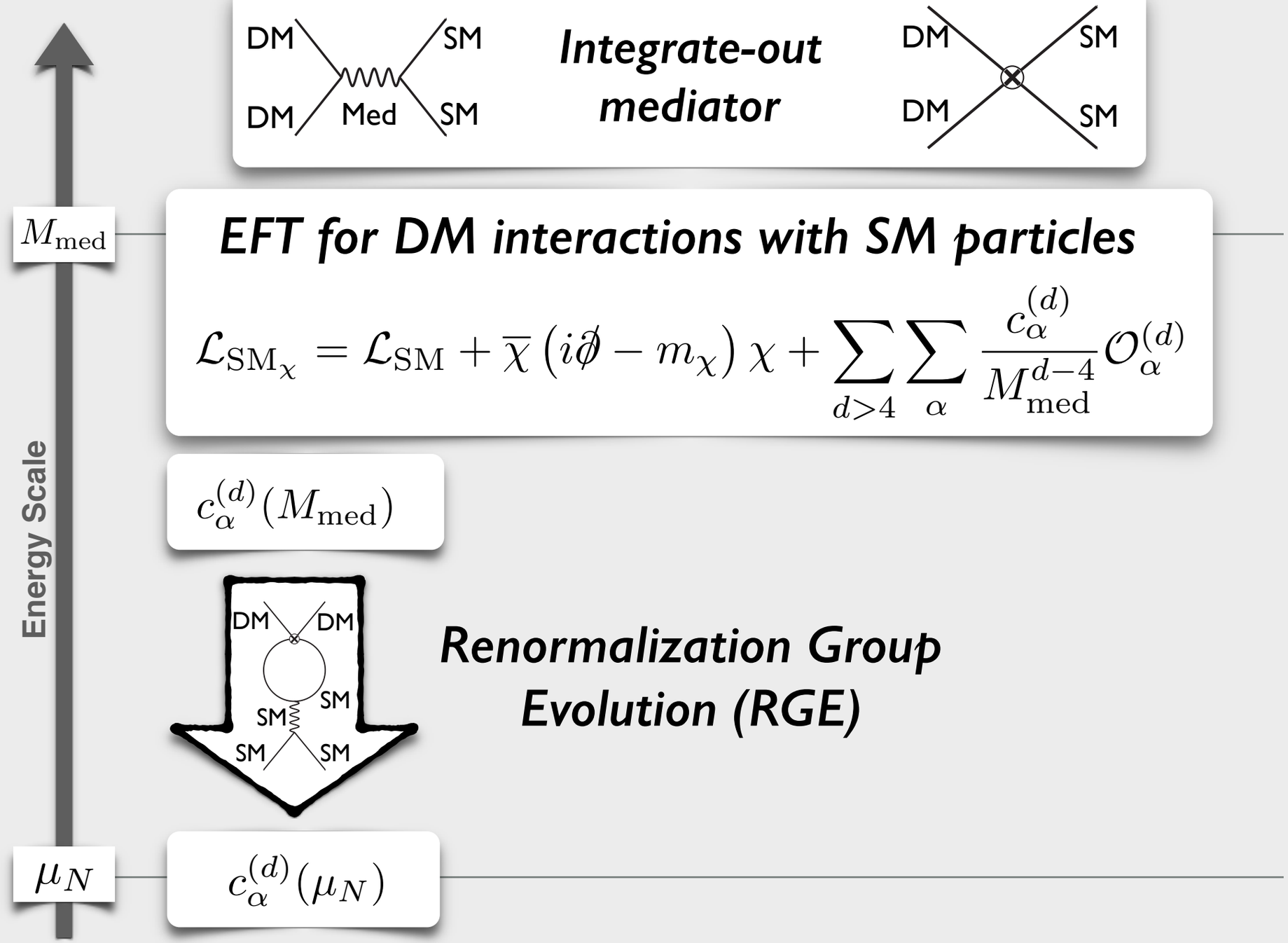

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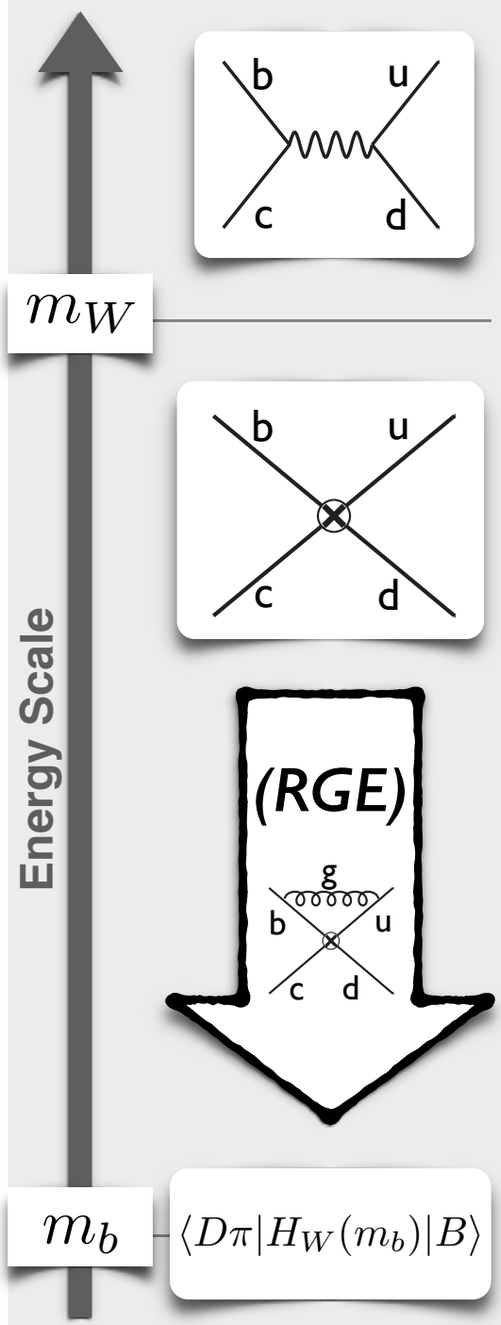


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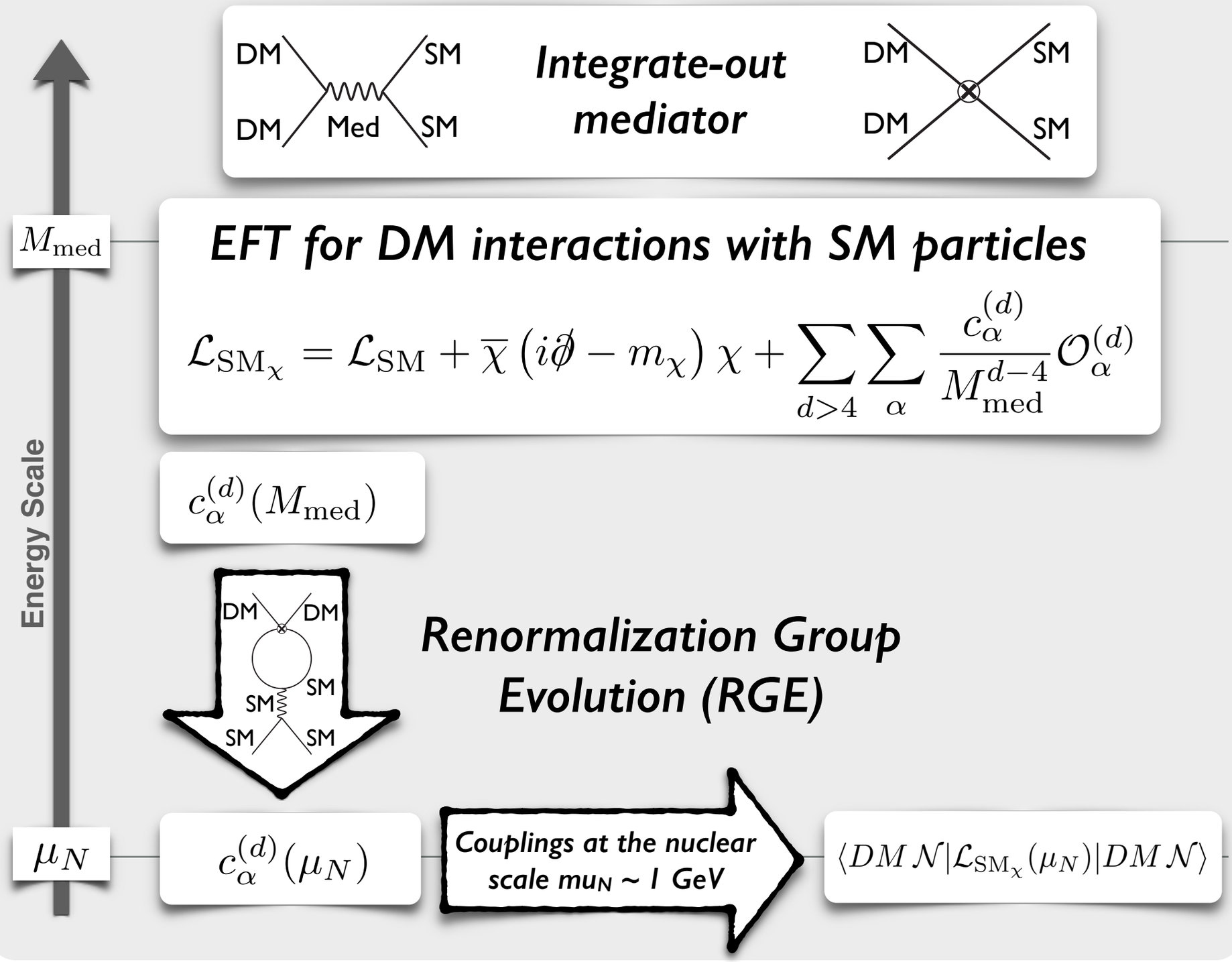

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- changing size of the effective couplings
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## RGE effects

- changing size of the effective couplings
- ***generating new interactions (operator mixing)***

## DM-Nucleus elastic scattering:

only through couplings to light SM degrees of freedom

*and*

very sensitive to the details of the interactions

Goodman and Witten, PRD31 (1985)

# Why is this relevant?

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## RGE effects

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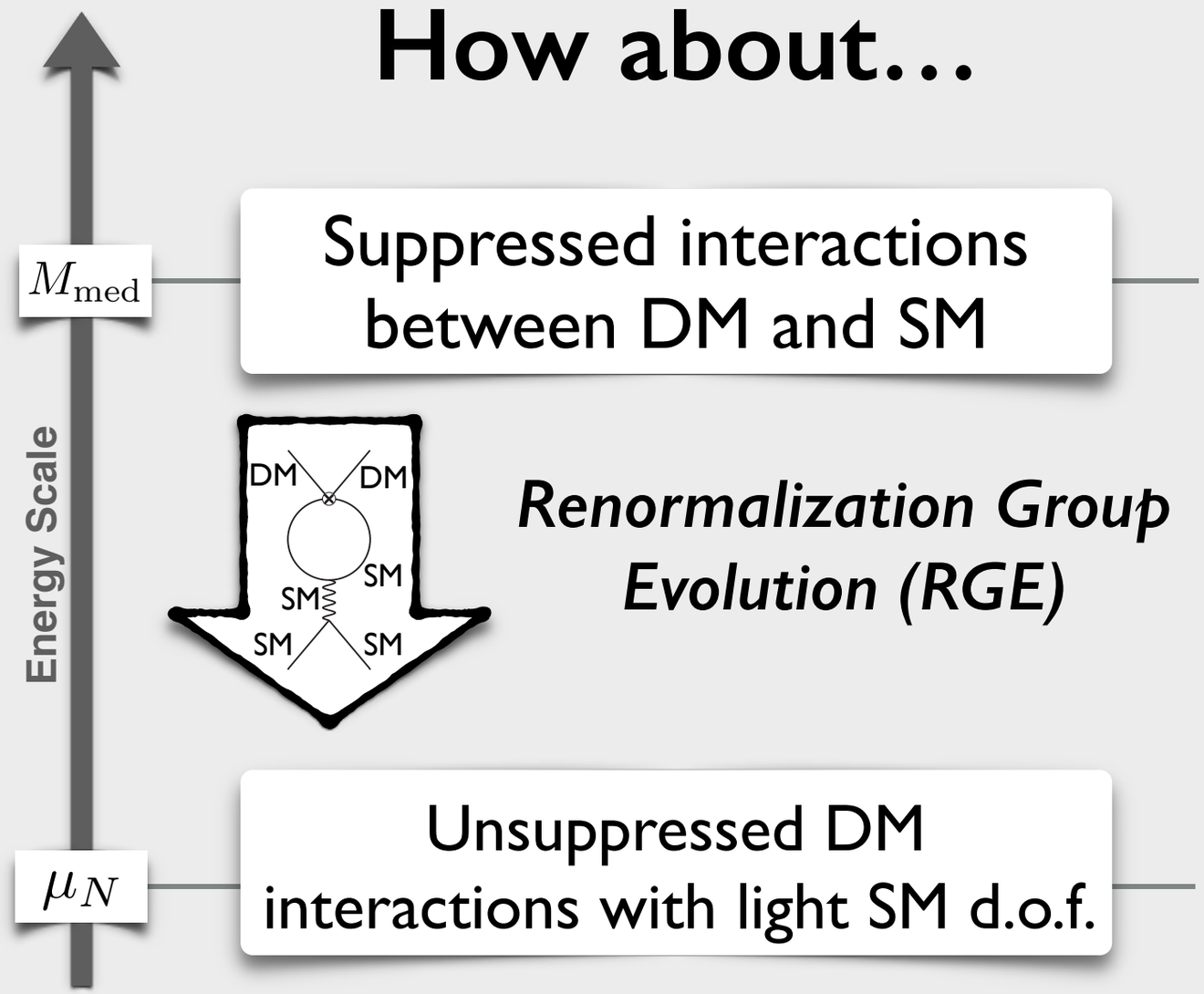
**How about…**



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Direct detection rates can be orders of magnitude larger than the one computed without carefully accounting for the scale separation

Kopp, Niro, Schwetz, Zupan, PRD80 (2009), arXiv:1207.3971;
Frandsen, Haisch, Kahlhoefer, Mertsch, Schmidt-Hoberg, JCAP1210 (2012), arXiv:1207.3971;
Haisch, Kahlhoefer, JCAP1304 (2013), arXiv:1302.4454; Kopp, Michaels, Smirnov, JCAP1404 (2014) arXiv:1401.6457
Crivellin, FD, Procura, PRL112 (2014), arXiv:1402.1173; Crivellin, Haisch, PRD90 (2014), arXiv:1408.5046

# Plan for Today's Talk

## DD for Vector Mediators

FD, Procura, JHEP1504 (2015), arXiv:1411.3342

FD, Kavanagh, Panci, in preparation

## Comparison with mono-jet searches

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## A 750 GeV scalar mediator

FD, de Vries, Panci, arXiv:1601.01571, to appear in JHEP

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FD, de Vries, Panci, arXiv:

# Vector Mediators

## Simplified Model

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm DM} + \mathcal{L}_V + J^\mu_{\rm DM} V_\mu + J^\mu_{\rm SM} V_\mu$$

Compact and powerful tool to explore LHC phenomenology and complementarity among DM searches


Frandsen, Kahlhoefer, Preston, Sarkar, K. Schmidt-Hoberg, JHEP07 (2012), arXiv:1204.3839

Buchmueller, Dolan, McCabe, JHEP01 (2014), arXiv:1308.6799

Alves, Profumo, Queiroz, JHEP04 (2014), arXiv:1312.5281

Arcadi, Mambrini, Tytgat, Zaldivar, JHEP03 (2014), arXiv:1401.0221

Lebedev, Mambrini, PLB734 (2014), arXiv:1403.4837

Buchmueller, Dolan, Malik, McCabe, JHEP01 (2015), arXiv:1407.8257

Harris, Khoze, Spannowsky, Williams, PRD91 (2015), arXiv:1411.0535

Alves, Berlin, Profumo, Queiroz, PRD92 (2015), arXiv:1501.03490

Jacques, Nordström, JHEP06 (2015), arXiv:1502.05721

Chala, Kahlhoefer, McCullough, Nardini, Schmidt-Hoberg, JHEP07 (2015), arXiv:1503.05916

# Vector Mediators

## Simplified Model

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm DM} + \mathcal{L}_V + J^\mu_{\rm DM} V_\mu + J^\mu_{\rm SM} V_\mu$$

Both scalar DM (complex) and
fermion DM (Dirac or Majorana)

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

$$\mathcal{K}_\chi = \begin{cases} 1 & \text{Dirac} \\ 1/2 & \text{Majorana} \end{cases}$$

# Vector Mediators

## Simplified Model

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm DM} + \mathcal{L}_V + J^\mu_{\rm DM} V_\mu + J^\mu_{\rm SM} V_\mu$$

Spin-1 massive mediator

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

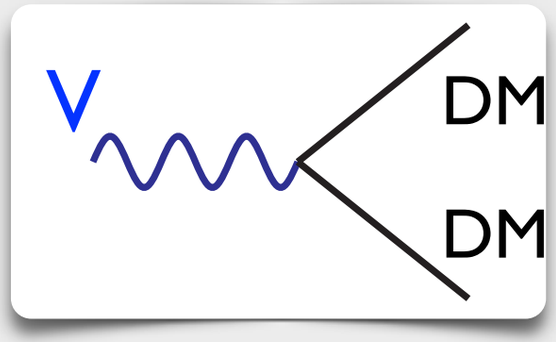
# Vector Mediators

## Simplified Model

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm DM} + \mathcal{L}_V + J^\mu_{\rm DM}\, V_\mu + J^\mu_{\rm SM}\, V_\mu$$

Mediator coupled to spin-1 DM currents

$$J^\mu_{\rm DM} = \begin{cases} c_\phi\, \phi^\dagger \overleftrightarrow{\partial}_\mu \phi & \text{scalar DM} \\ \mathcal{K}_\chi \left( c_{\chi V}\, \overline{\chi}\gamma^\mu \chi + c_{\chi A}\, \overline{\chi}\gamma^\mu\gamma^5 \chi \right) & \text{fermion DM} \end{cases}$$



# Vector Mediators

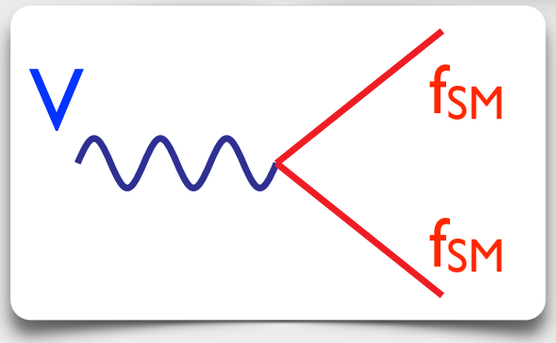
## Simplified Model

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm DM} + \mathcal{L}_V + J^\mu_{\rm DM} V_\mu + J^\mu_{\rm SM} V_\mu$$

Mediator coupled to spin-1 currents of SM fermions

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

15 independent $SU(2)_L \times U(1)_Y$ gauge invariant couplings to SM fermions



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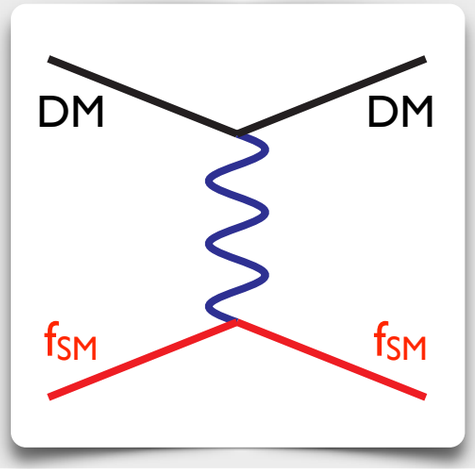
## Simplified Model

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm DM} + \mathcal{L}_V + J^\mu_{\rm DM} V_\mu + J^\mu_{\rm SM} V_\mu$$

Apply EFT techniques to evaluate direct detection rates for this broad class of models

# Direct Detection Rates

**STEP 1: Integrate-out mediator**

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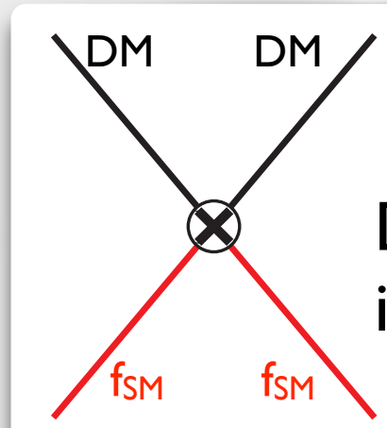


EFT:
DM contact interactions

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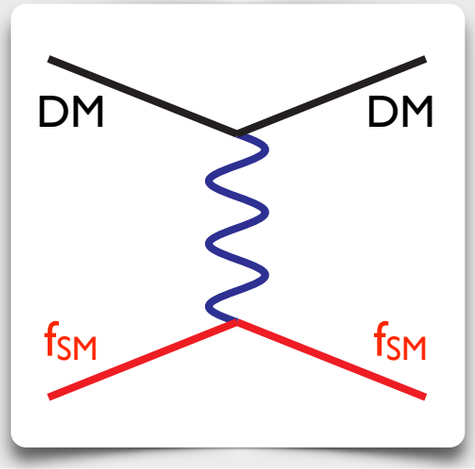


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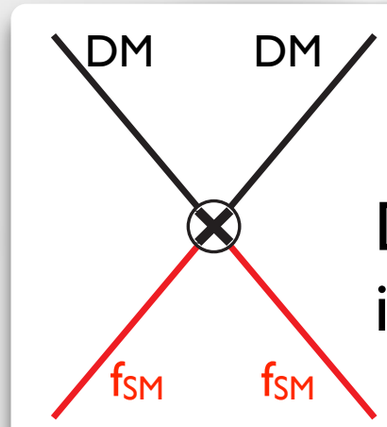
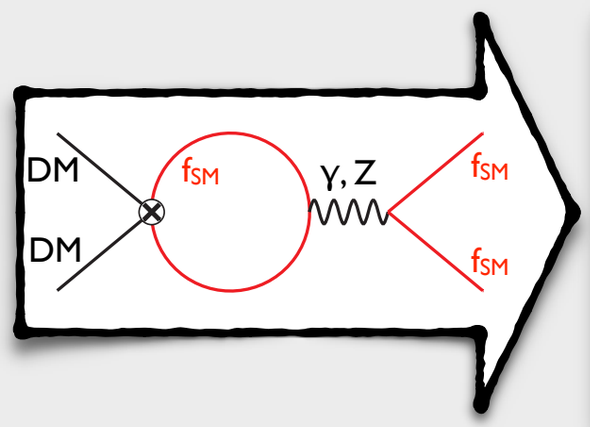



EFT: DM contact interactions

**STEP II: Connecting Energy Scales**

EFT couplings at the scale $m_V$




Nuclear scale

- size couplings changed
- new interactions are generated (mixing)

# Direct Detection Rates

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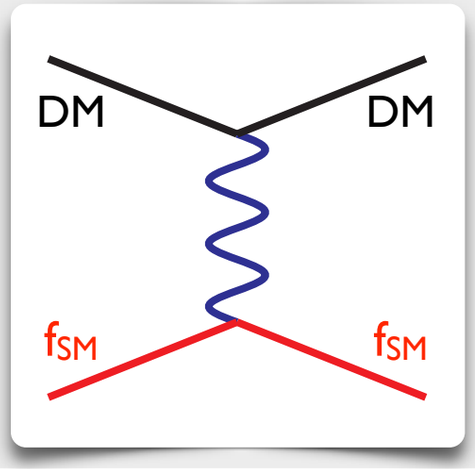
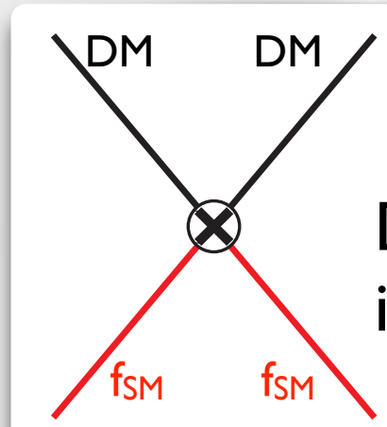


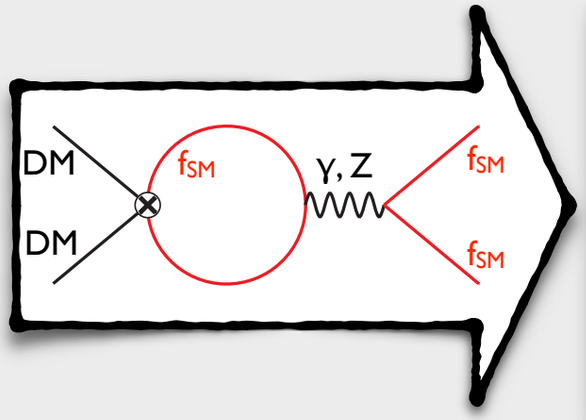

$$\frac{1}{q^2 - m_V^2} \simeq -\frac{1}{m_V^2}$$




EFT: DM contact interactions

**STEP II: Connecting Energy Scales**

EFT couplings at the scale $m_V$




Nuclear scale

- size couplings changed
- new interactions are generated (mixing)

**STEP III: Matrix Elements**

EFT for DM interactions with quarks and gluons

matching onto EFT with nucleons

Nuclear Matrix Elements

# Direct Detection Rates

**STEP I: Integrate-out mediator**

Straightforward for vector mediator

**STEP II: Connecting Energy Scales**

Complete one-loop RGE analysis done for spin-1 currents

FD, Procura, JHEP1504 (2015), arXiv:1411.3342

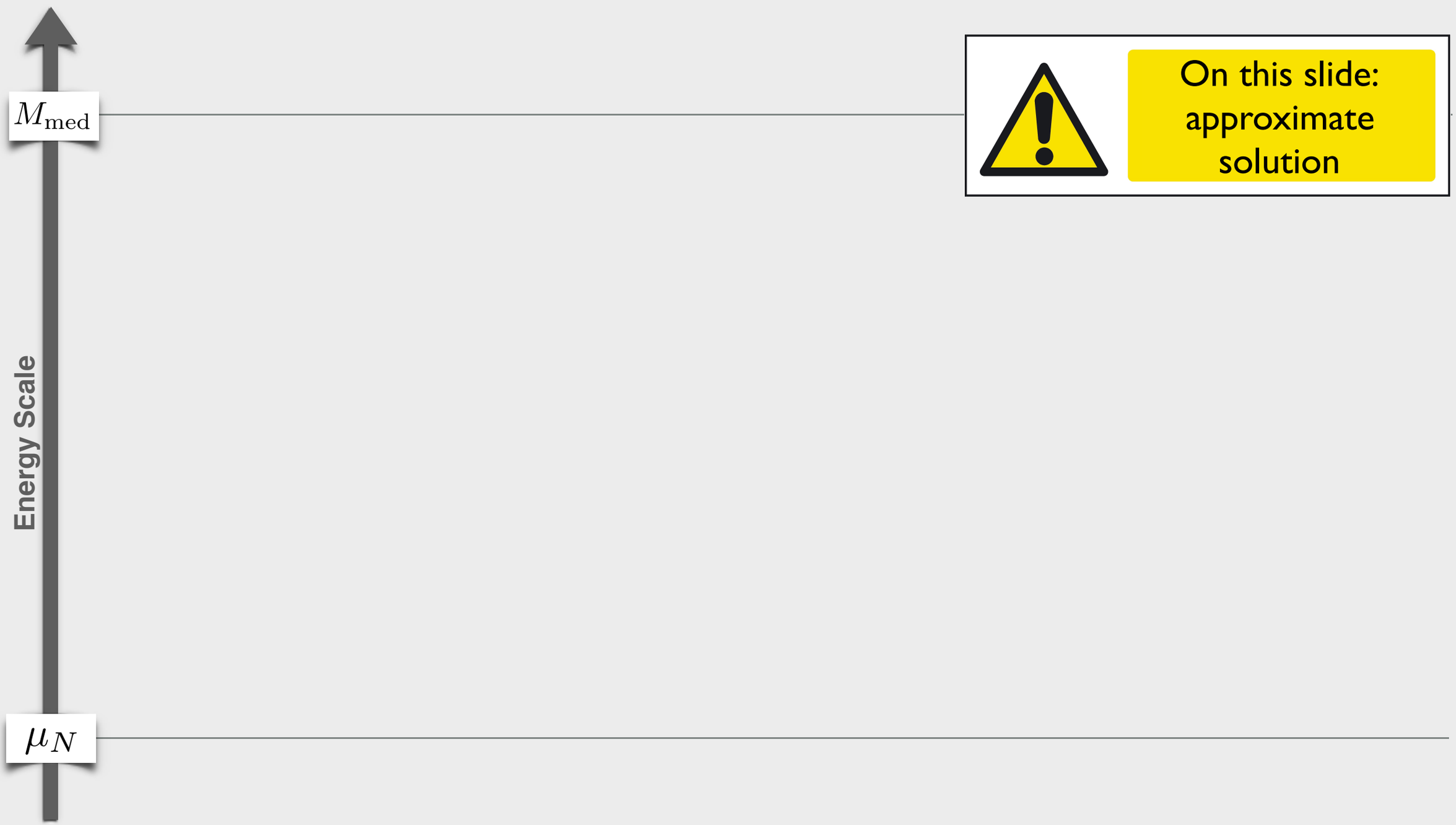
**STEP III: Matrix Elements**

Matching to nucleons and nuclear matrix elements known for spin-1 currents

Fitzpatrick, Haxton, Katz, Lubbers, Xu, JCAP1302 (2013), arXiv:1203.3542
Cirelli, Del Nobile, Panci, JCAP1310 (2013), arXiv:1307.5955

# RGE Handbook

## Interested in the RGE-induced currents with light quarks



# RGE Handbook

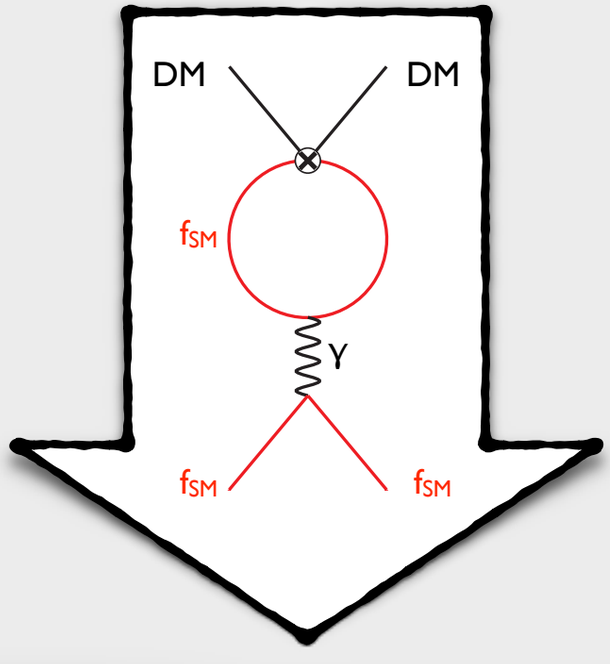
## Interested in the RGE-induced currents with light quarks

Energy Scale

$M_{\rm med}$

V coupled to vector currents of SM fermions

On this slide: approximate solution




Important if V not coupled to light quarks (e.g. leptons or heavy quarks)

Otherwise O(1%) correction

$\mu_N$

RGE-induced vector current of light quarks

$$\Delta c_V \simeq \frac{e^2}{16\pi^2} \ln(m_V/\mu_N)$$

# RGE Handbook

## Interested in the RGE-induced currents with light quarks

Energy Scale

$M_{\rm med}$

V coupled to axial currents of SM fermions

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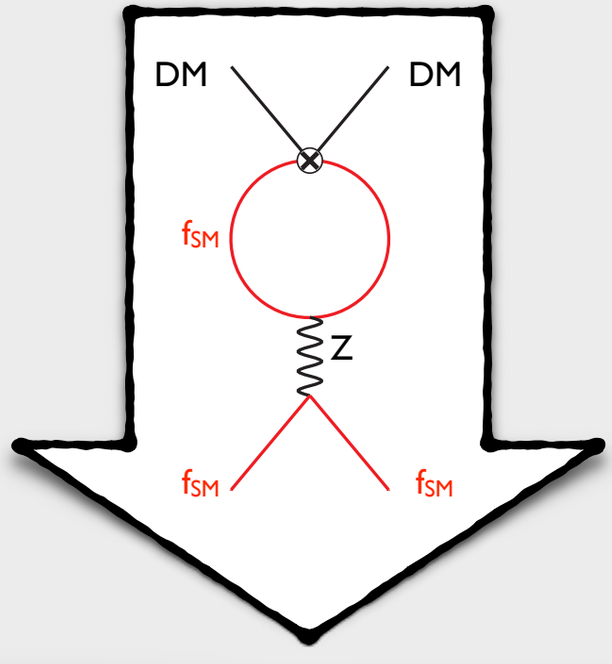



Phenomenologically important

Dominated by heavy SM fermions (prop. to Yukawa)

$\mu_N$

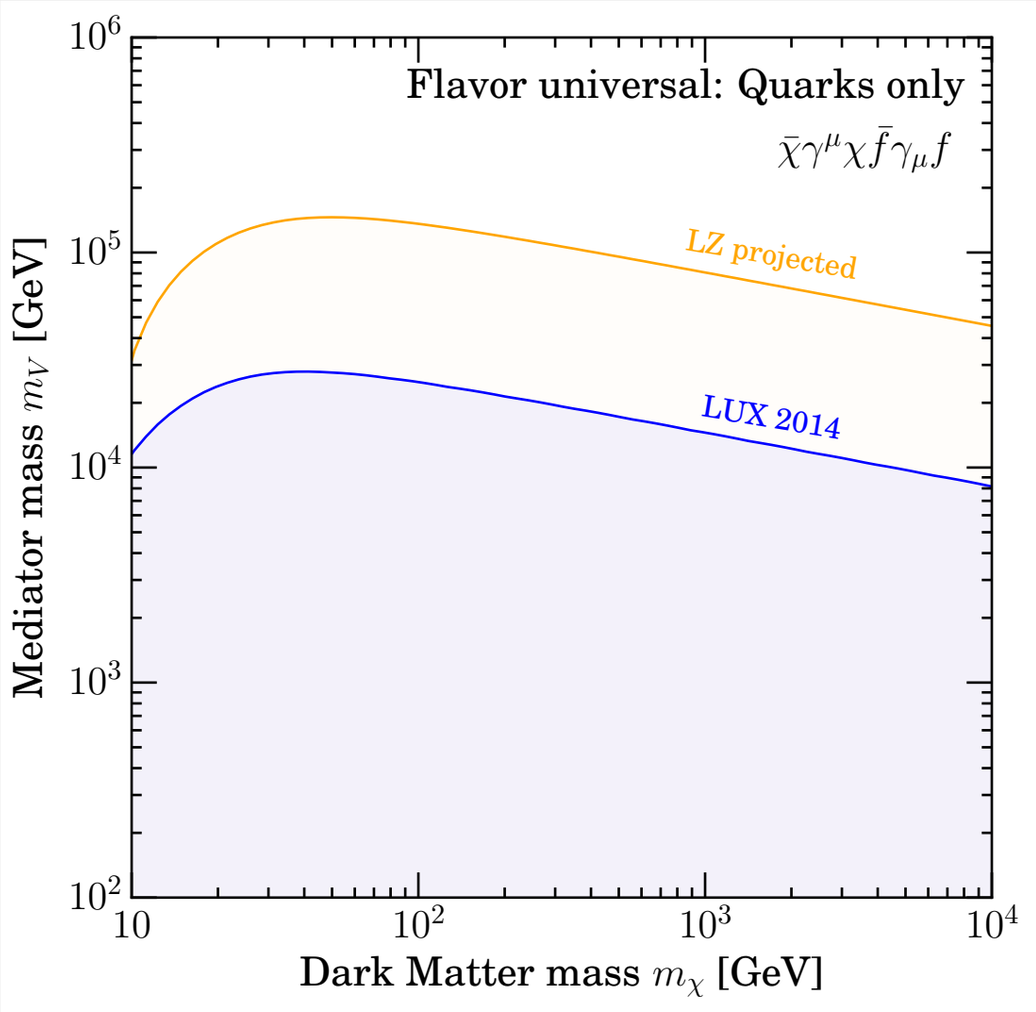
RGE-induced vector and axial current of light quarks

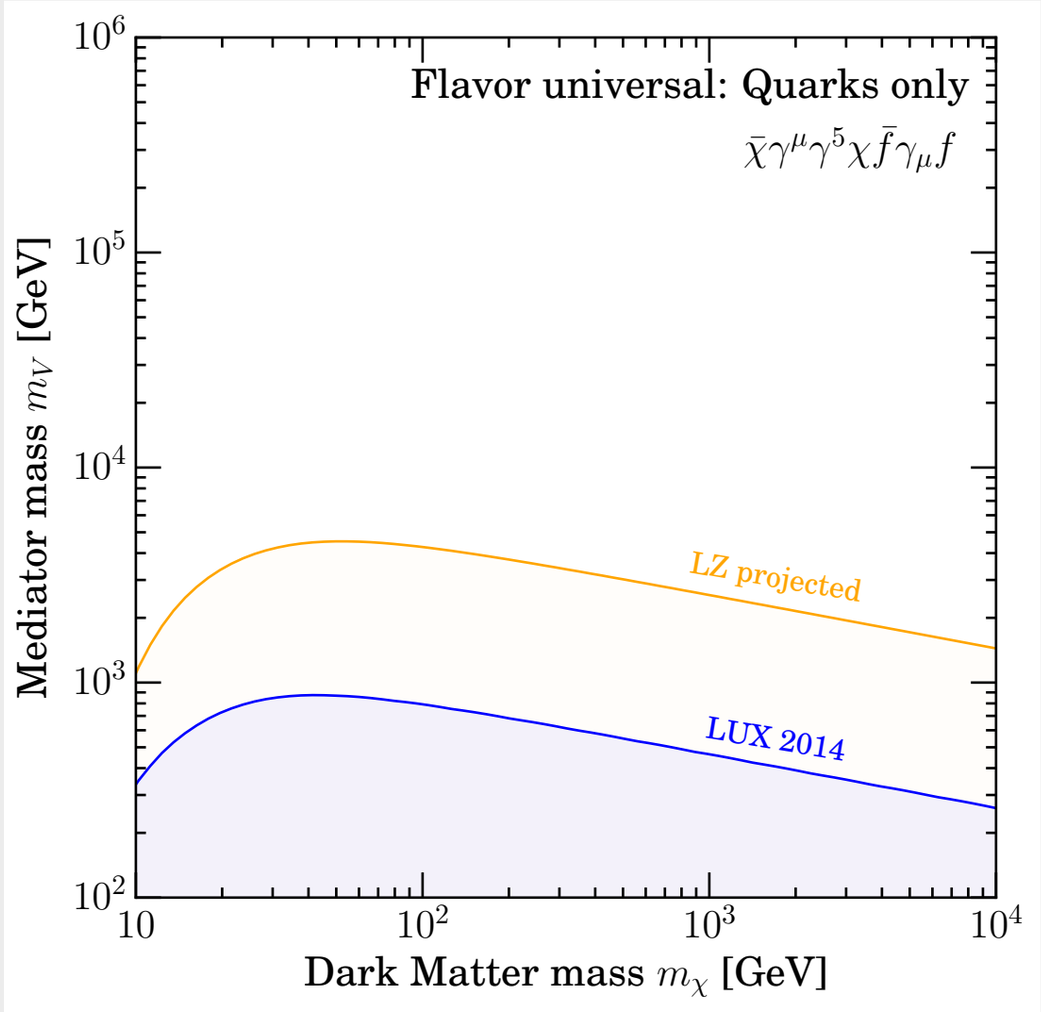
$$\Delta c_{V,A} \simeq \frac{\lambda_f^2}{16\pi^2} \ln(m_V/\mu_N)$$

# Results I: quarks vector

**Mediator with flavor universal couplings to quark vector currents**

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



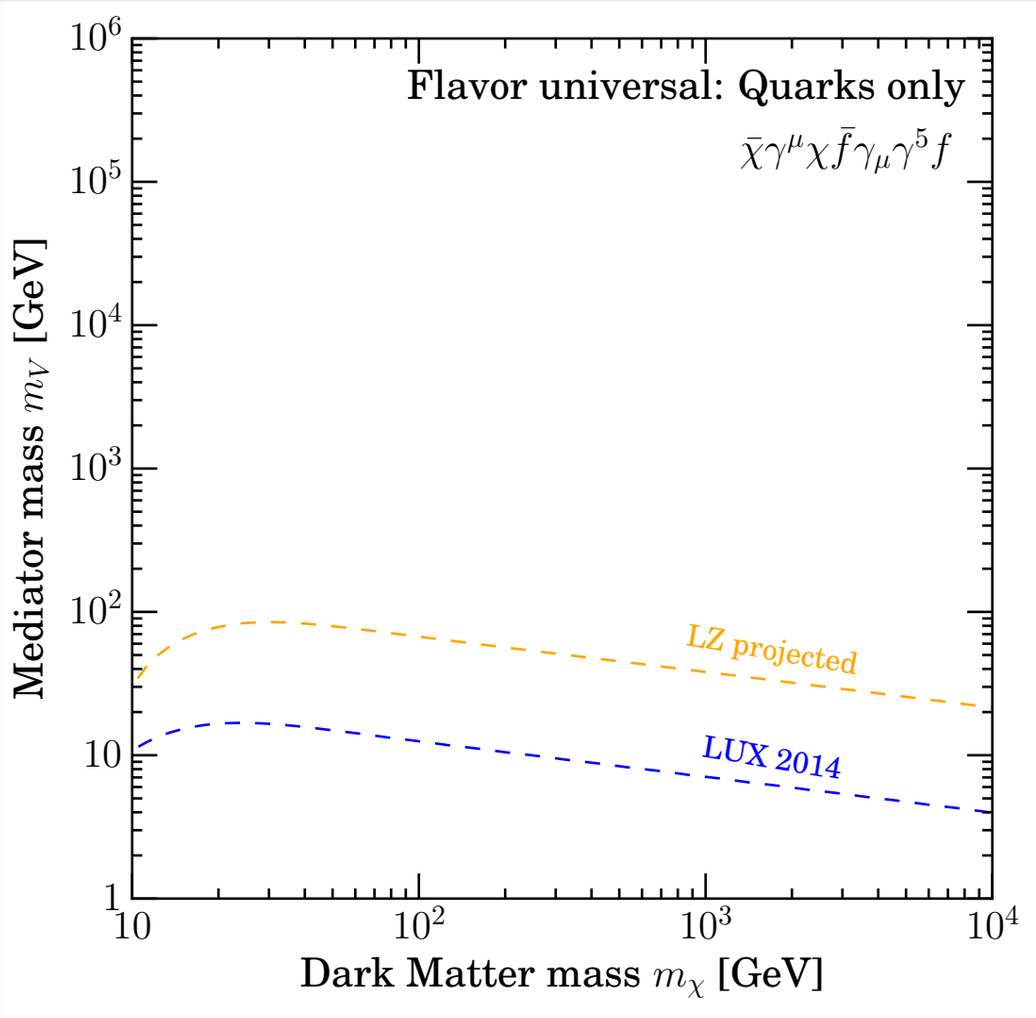

RGE effects are O(1%) correction to EFT couplings

FD, Kavanagh, Panci, in preparation

# Results II: quarks axial

**Mediator with flavor universal couplings to quark axial currents**

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




RGE effects drive by Yukawa couplings alter the rates

FD, Kavanagh, Panci, in preparation

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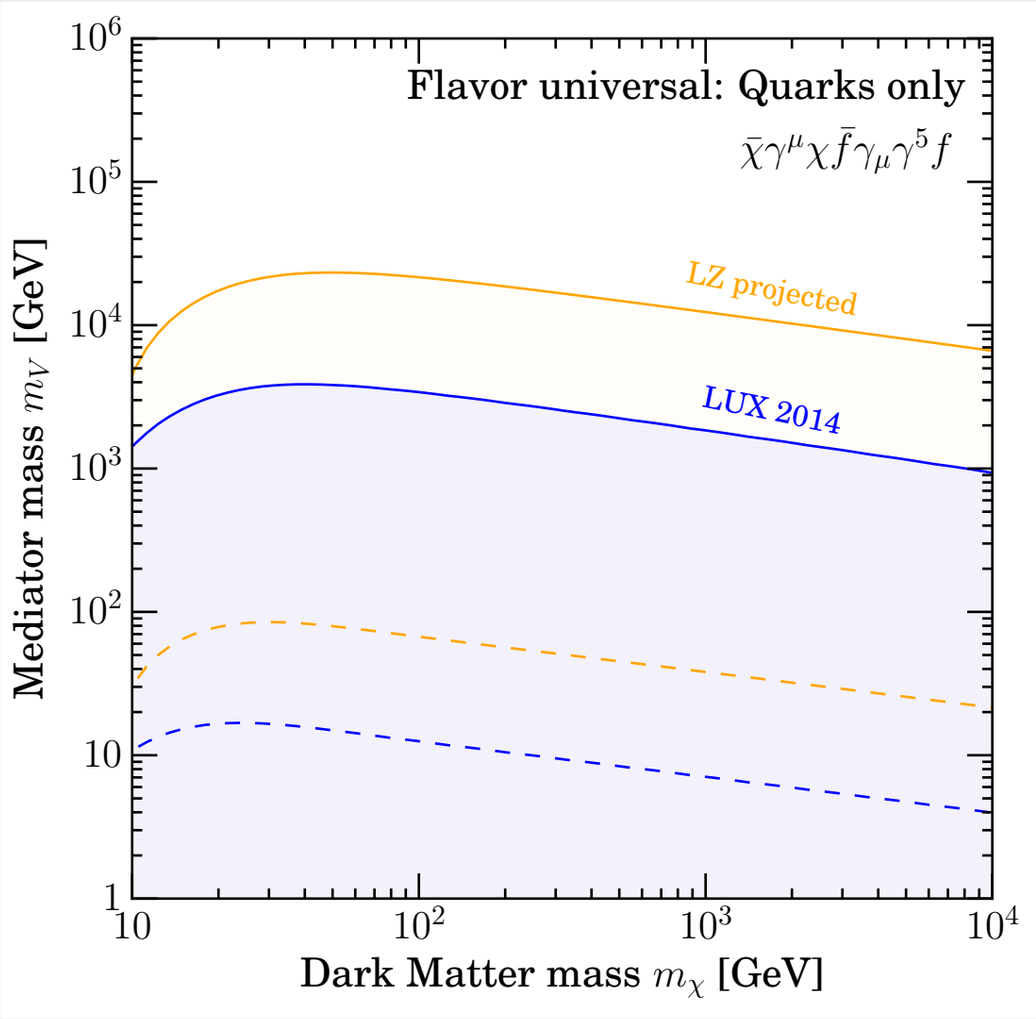


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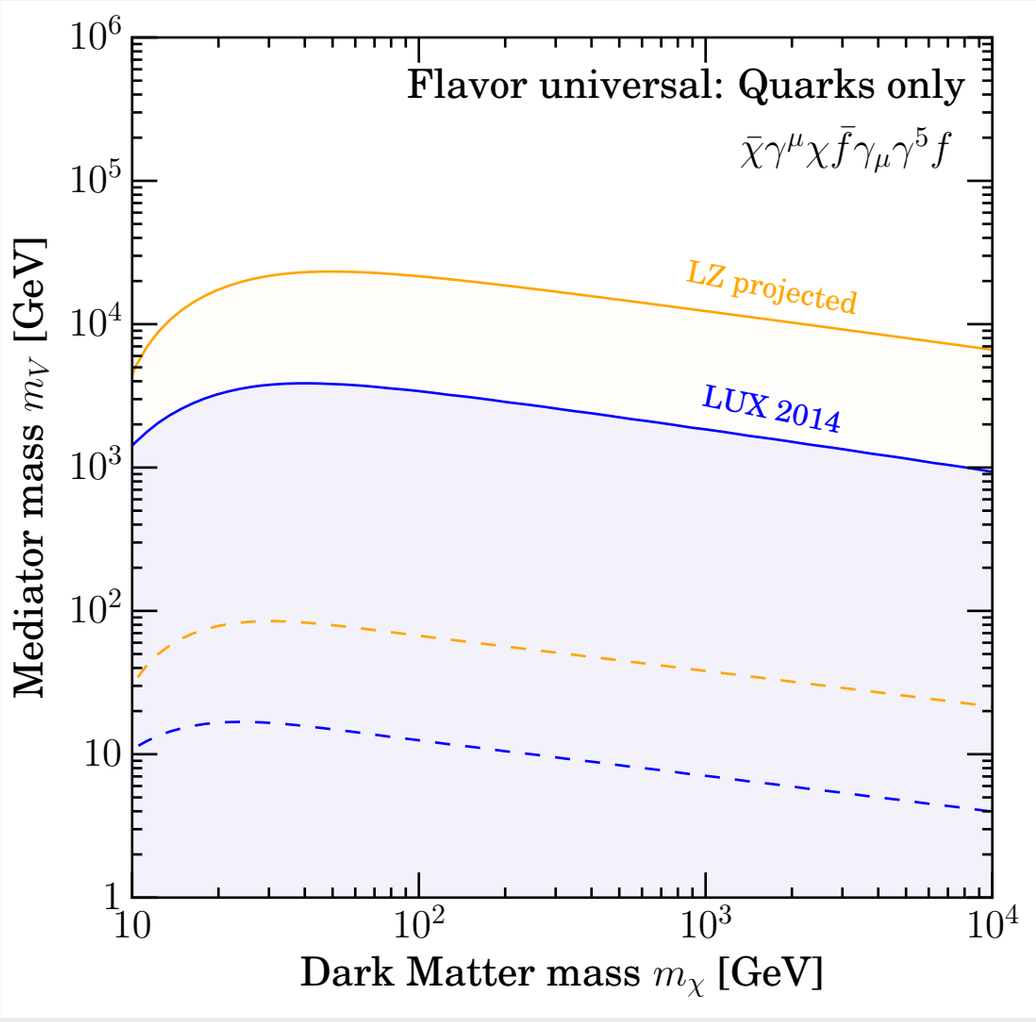


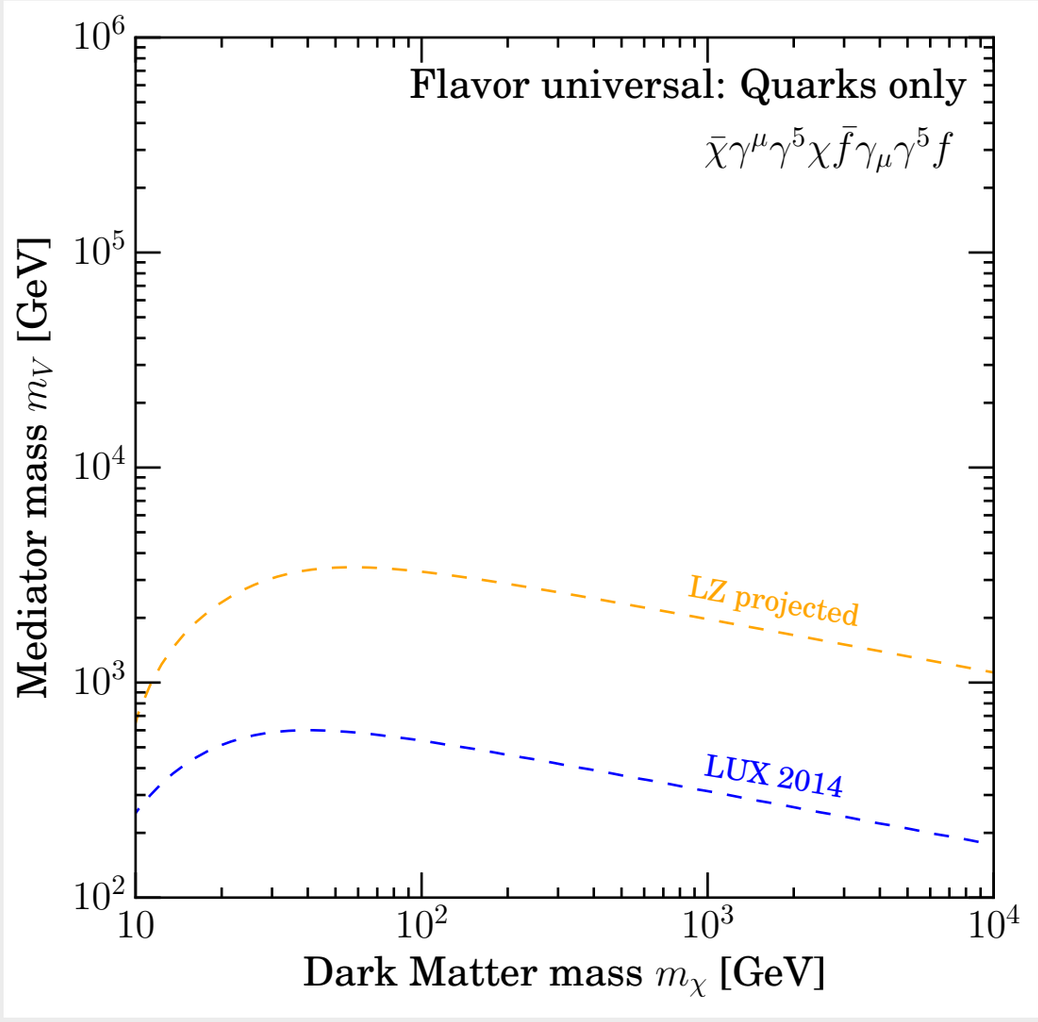


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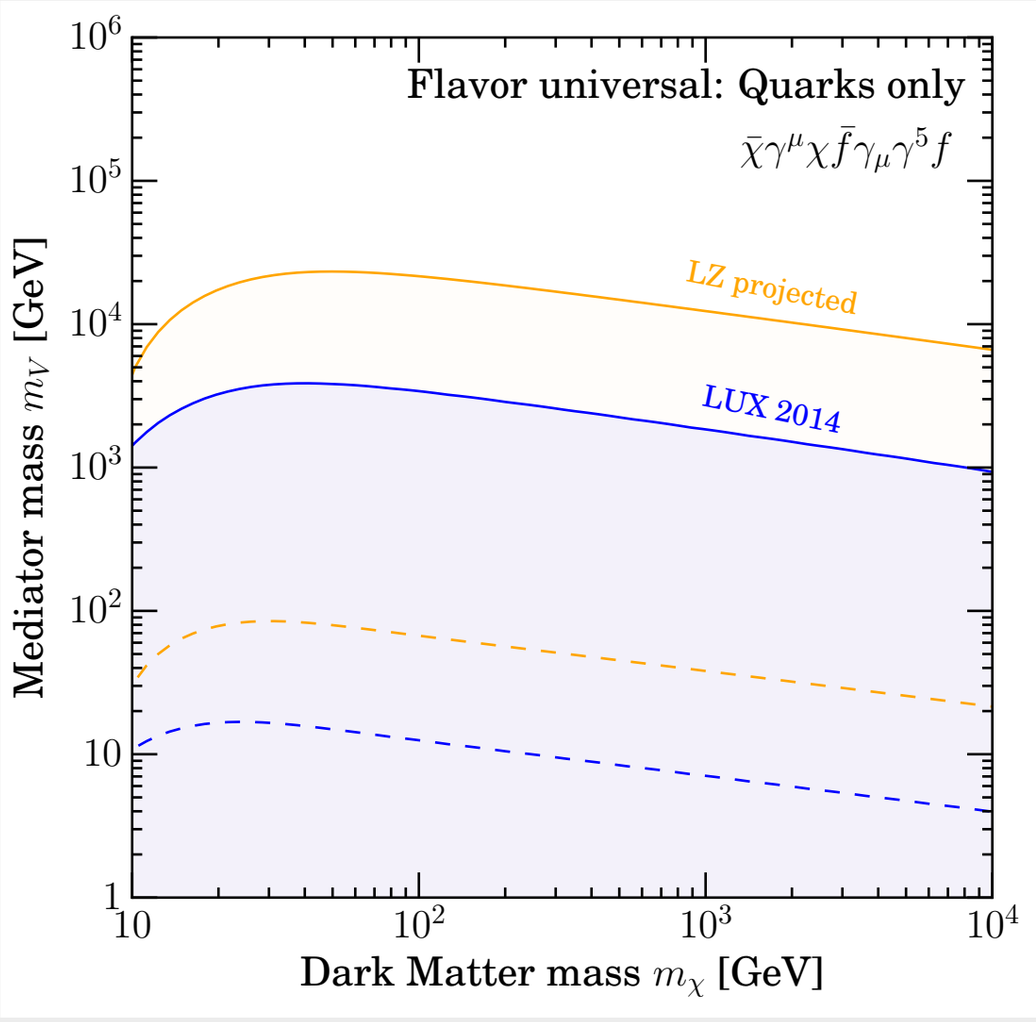
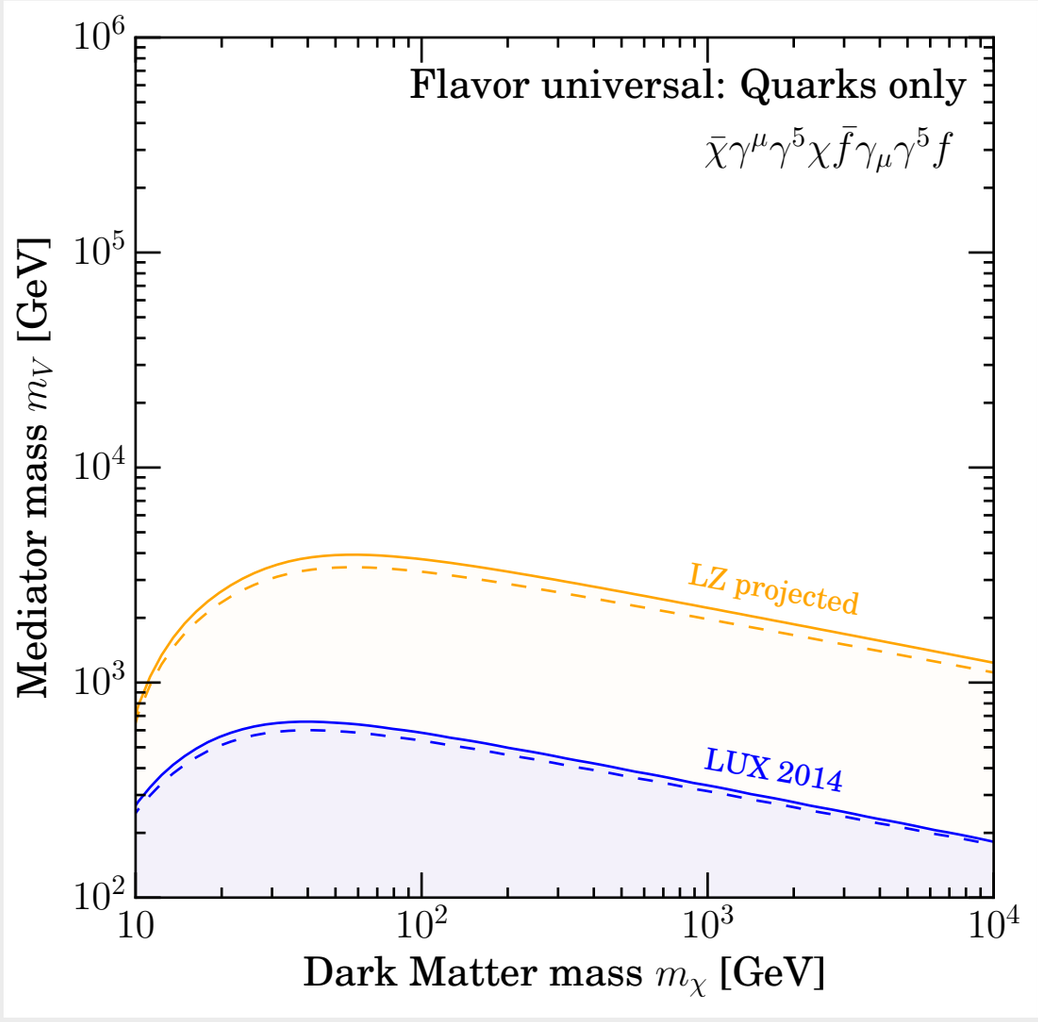


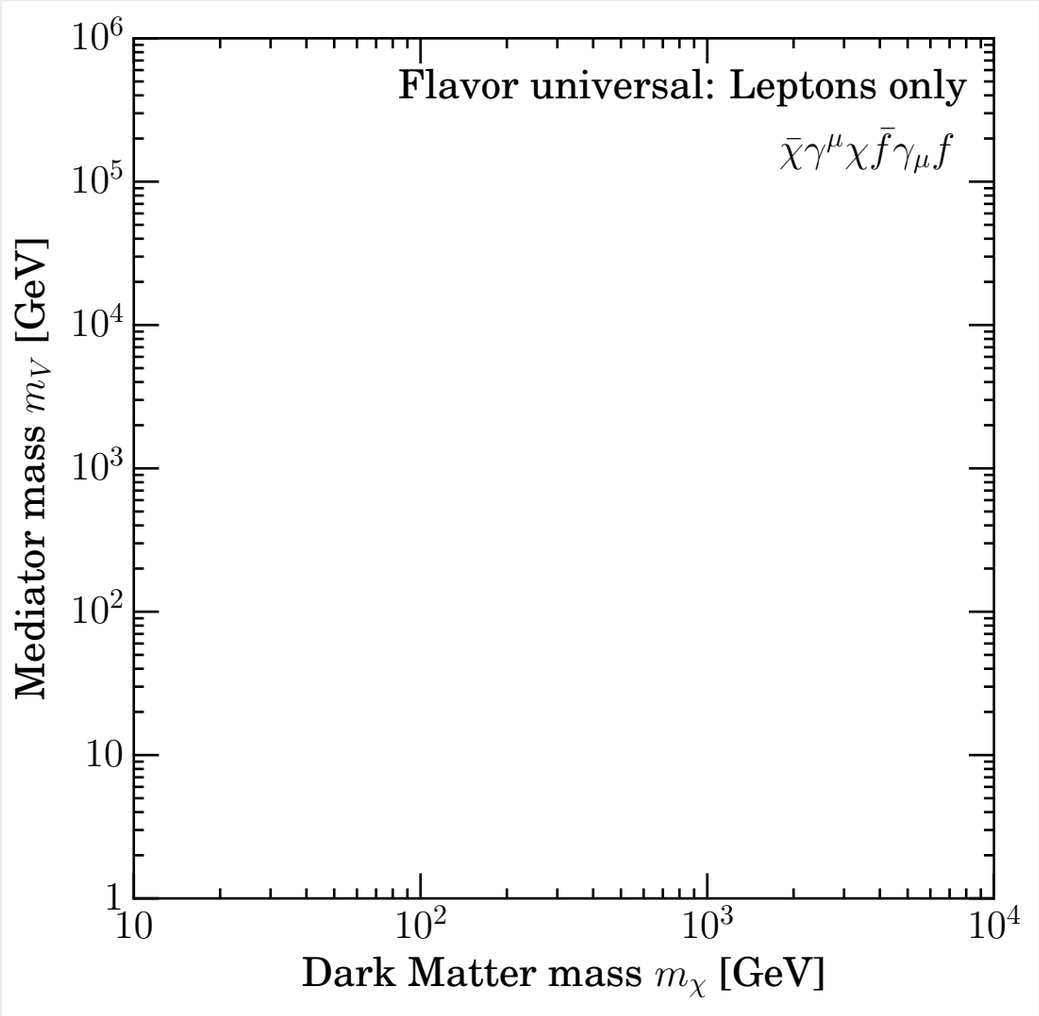



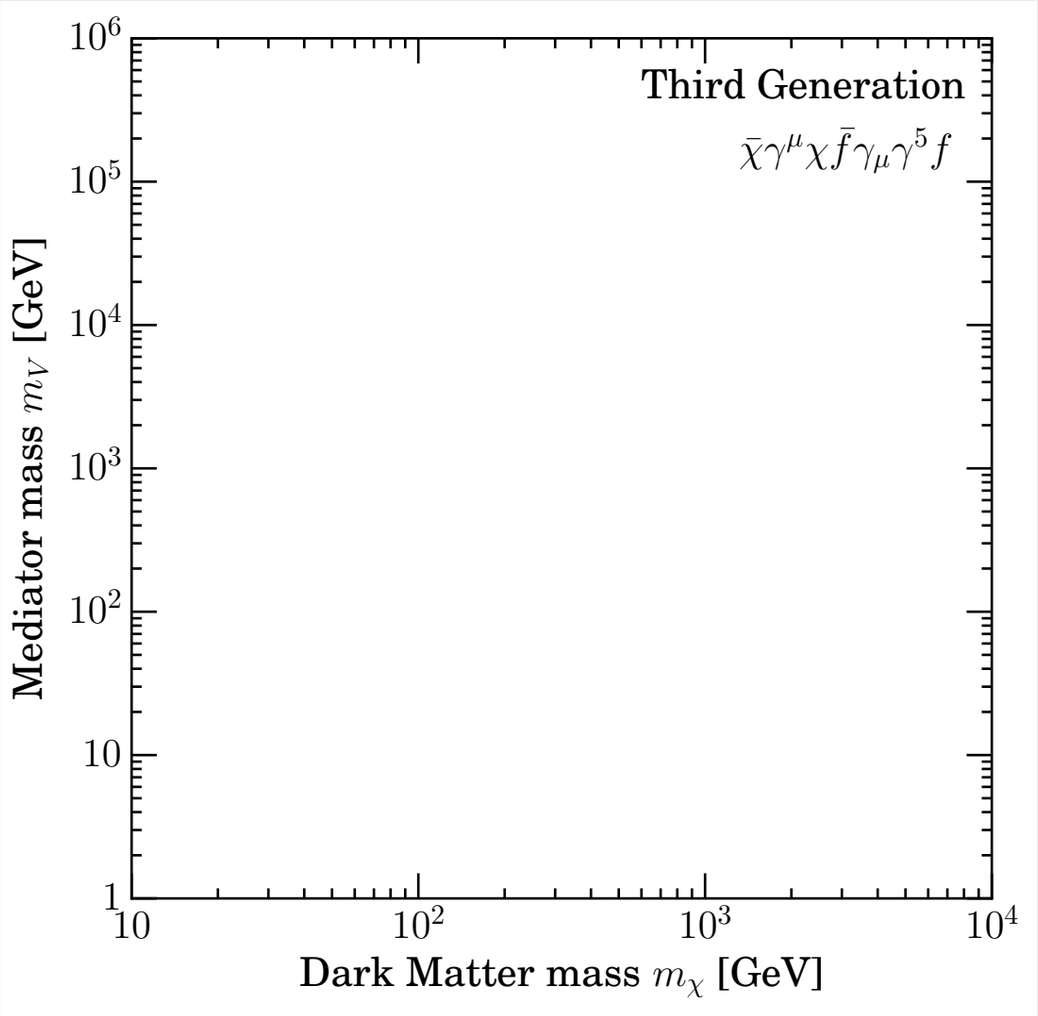

RGE effects drive by Yukawa couplings alter the rates

FD, Kavanagh, Panci, in preparation

# Results III: other cases

## Our analysis valid also if V not coupled to light quarks




Exhaustive study of different cases (including scalar DM) in upcoming paper

FD, Kavanagh, Panci, in preparation

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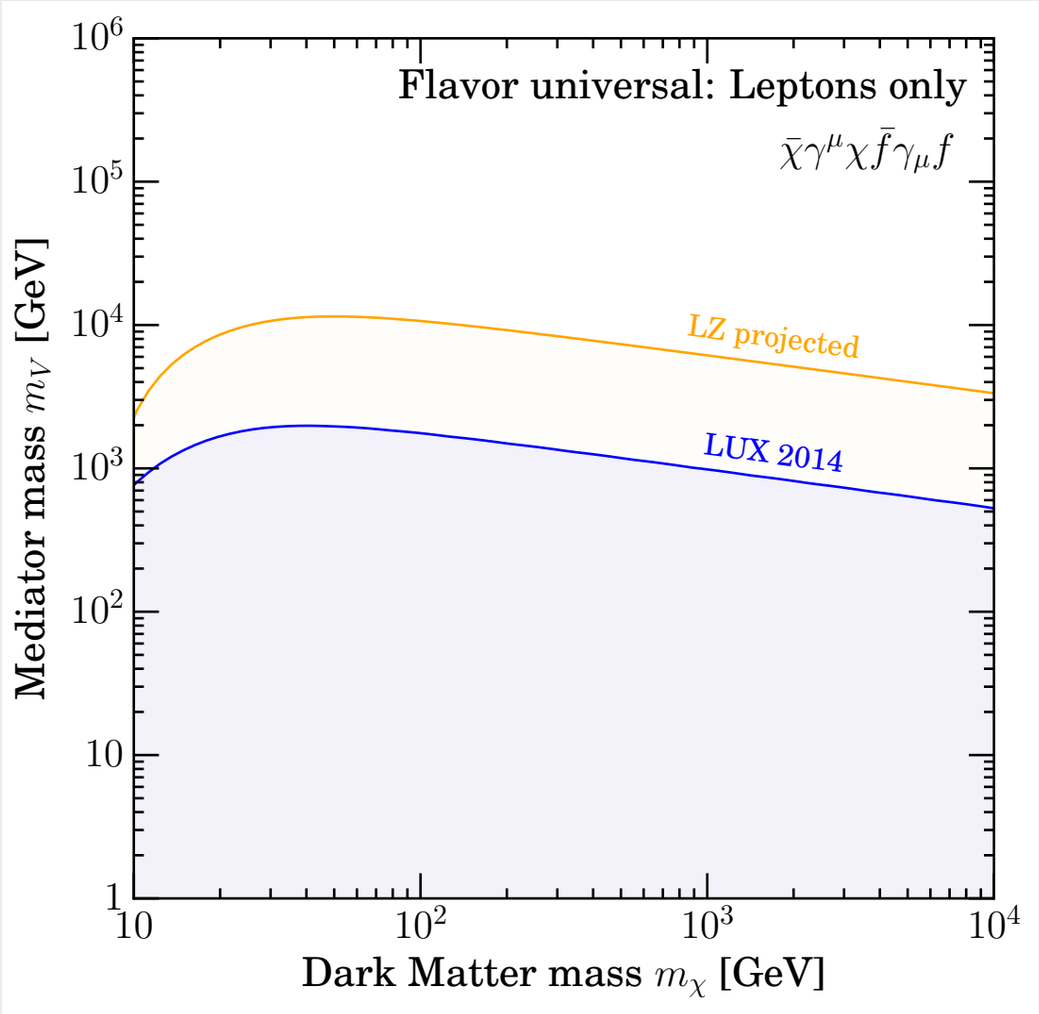


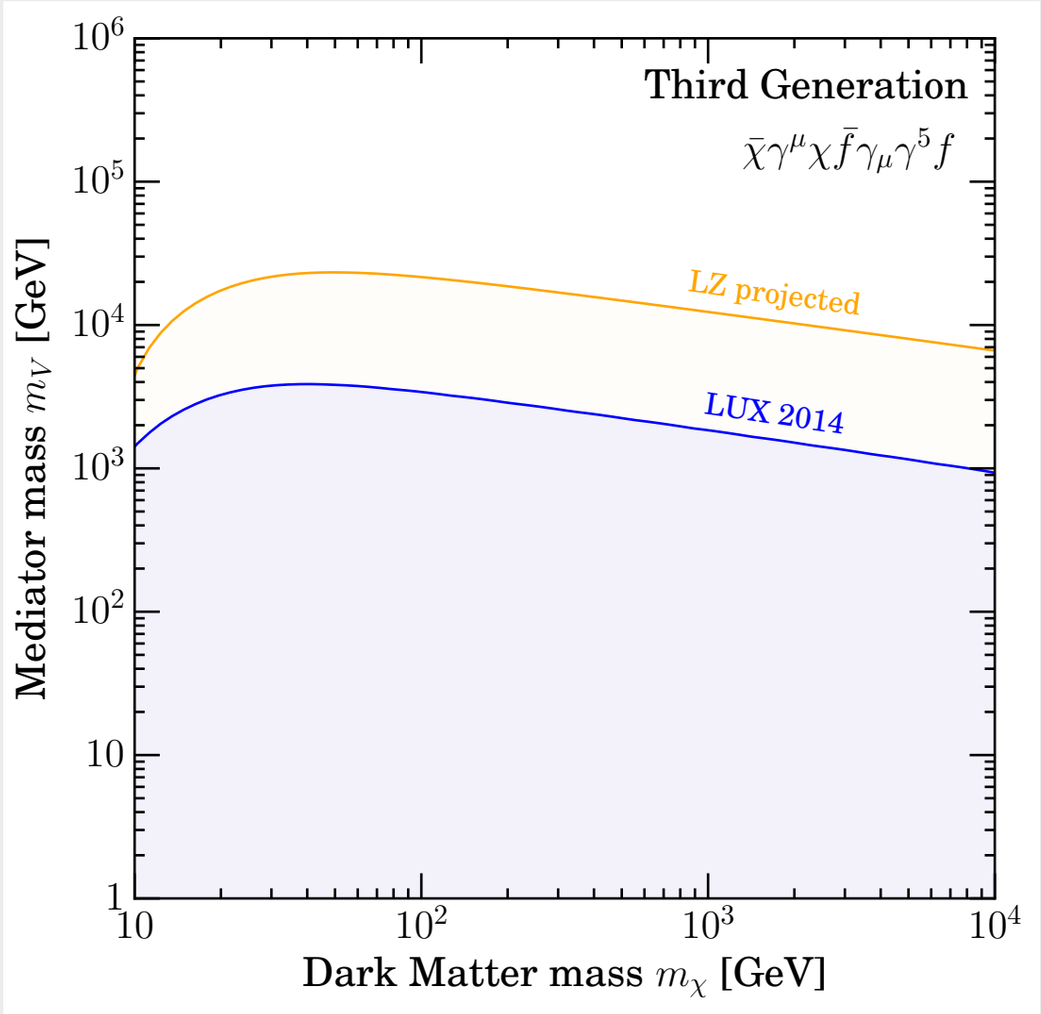


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# Plan for Today's Talk

## DD for Vector Mediators

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FD, Kavanagh, Panci, in preparation

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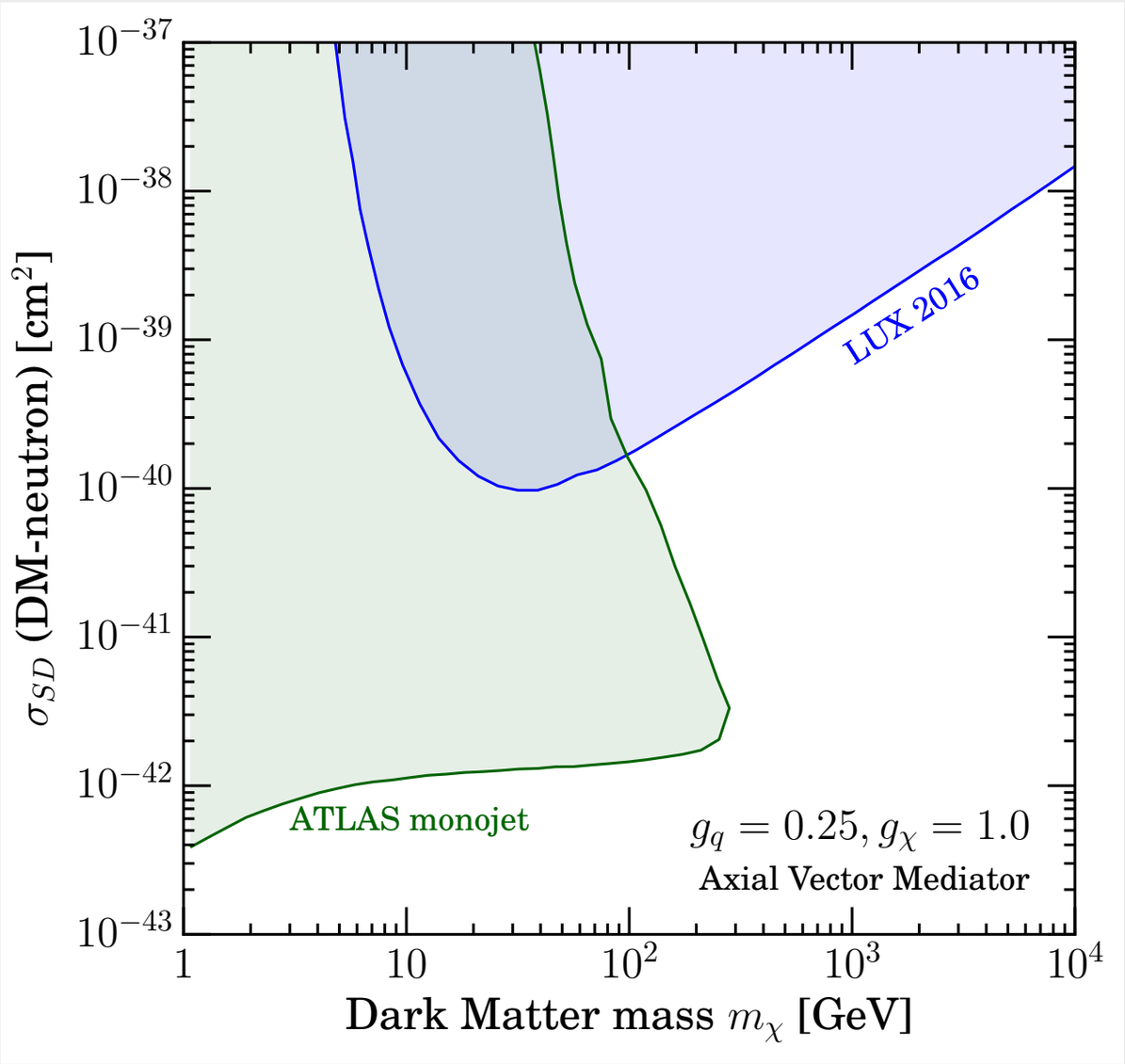
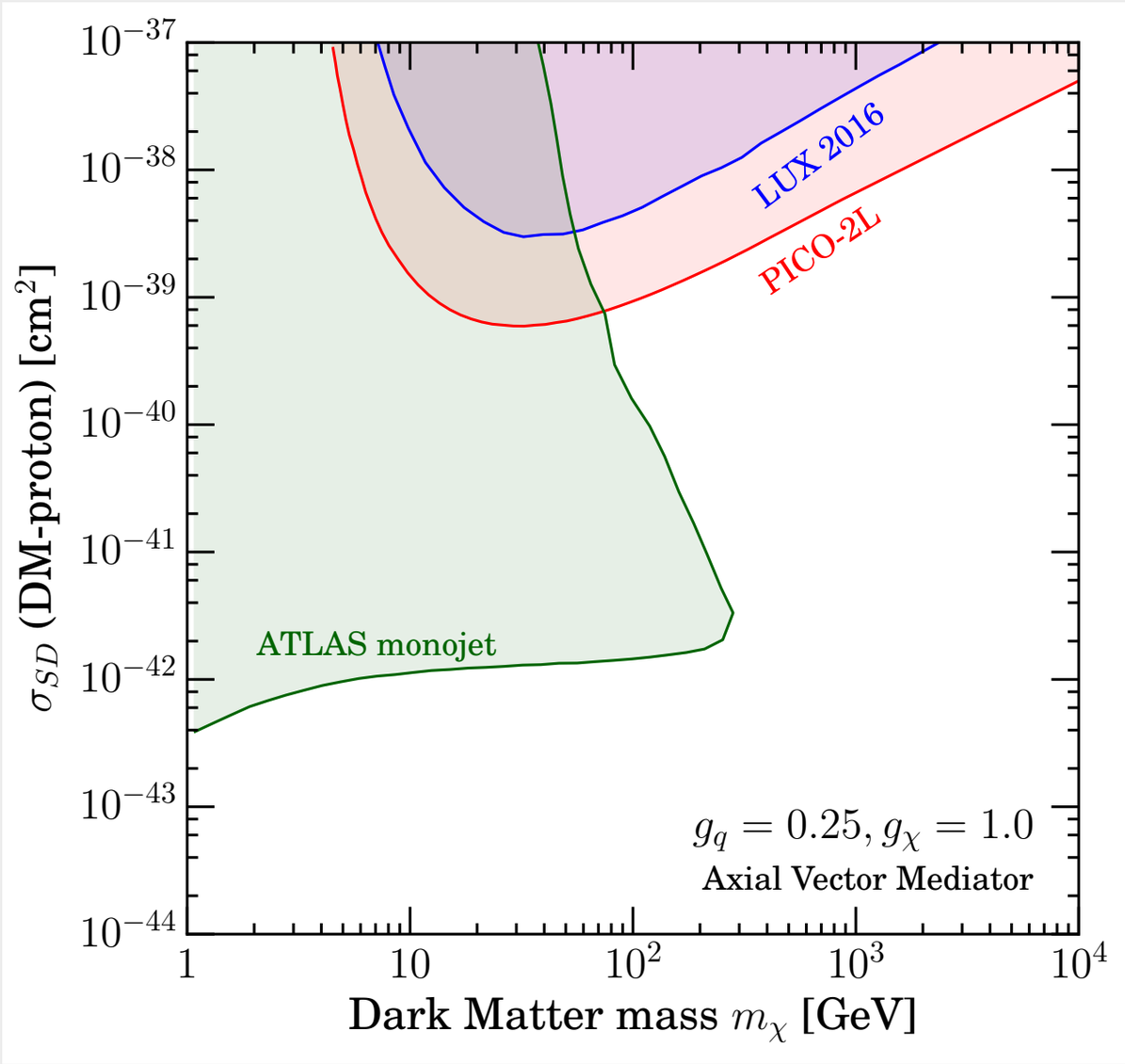
FD, de Vries, Panci, arXiv:

# Axial-axial operator




LUX, arXiv:1602.03489

PICO-2L, arXiv:1601.03729

ATLAS monojet, talk by Andreas Korn at this workshop

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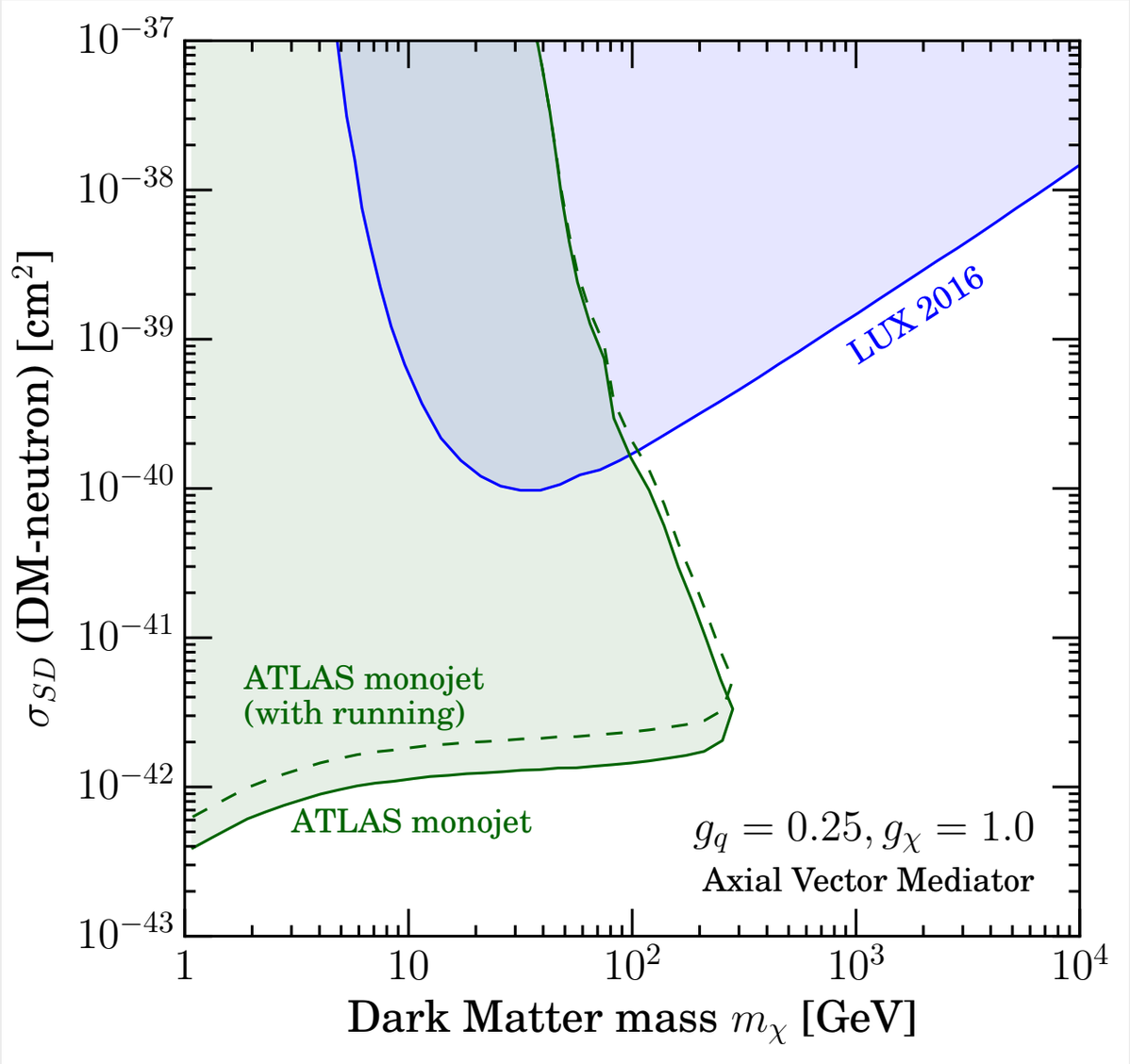


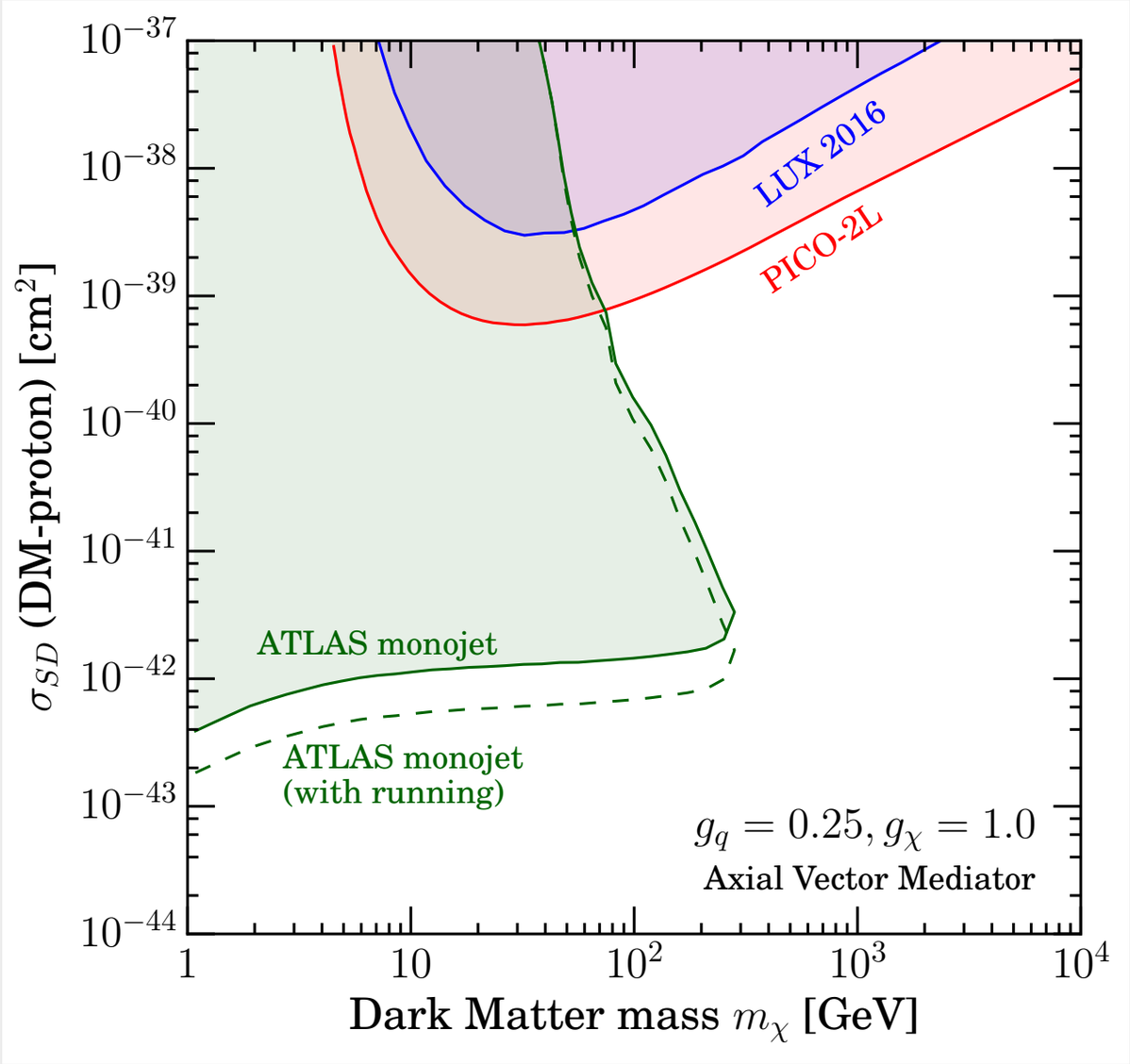


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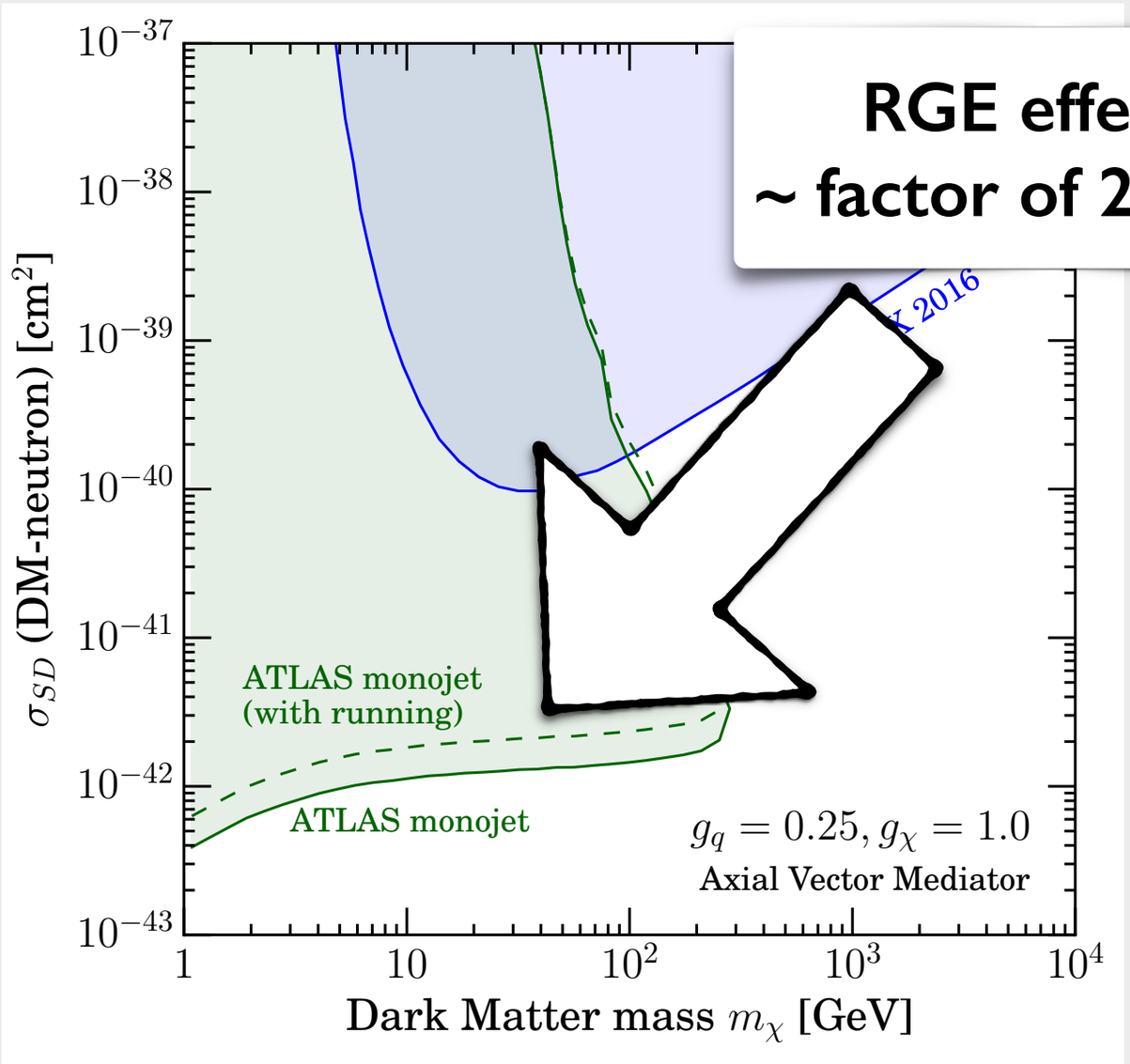


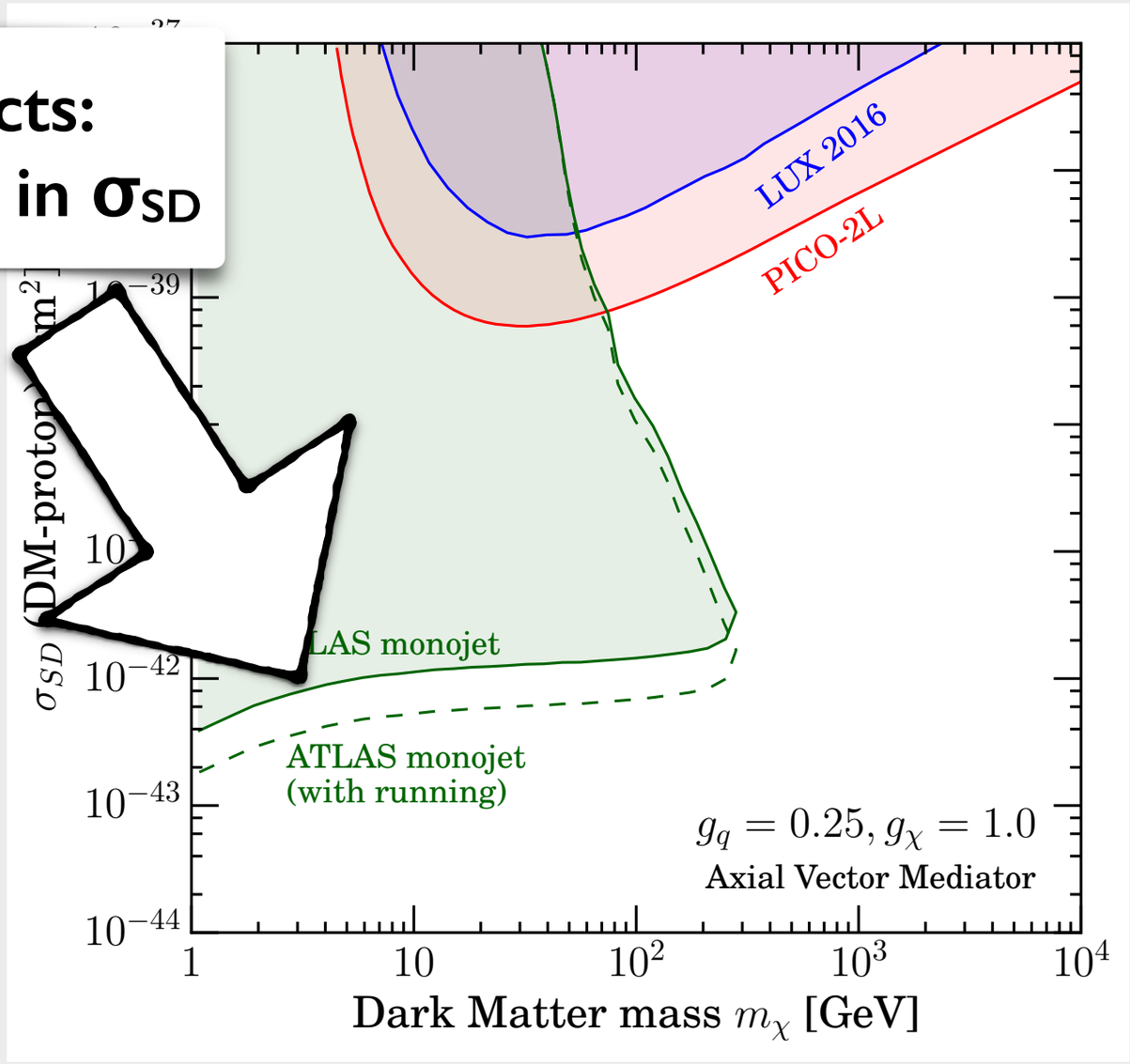


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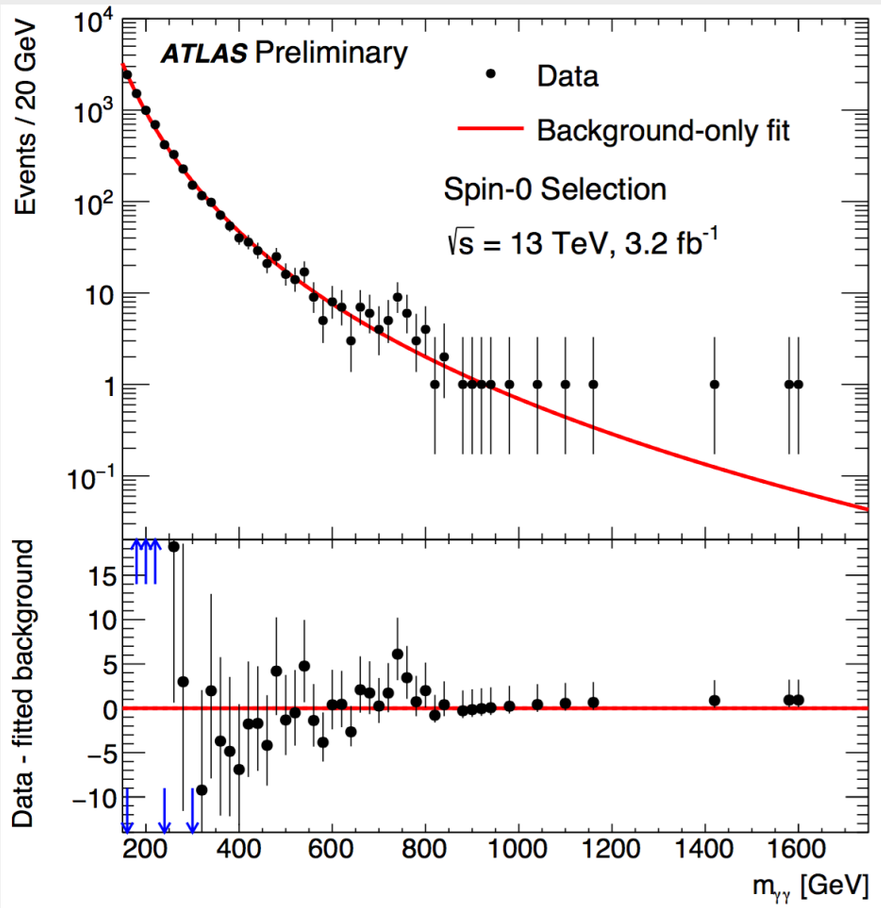
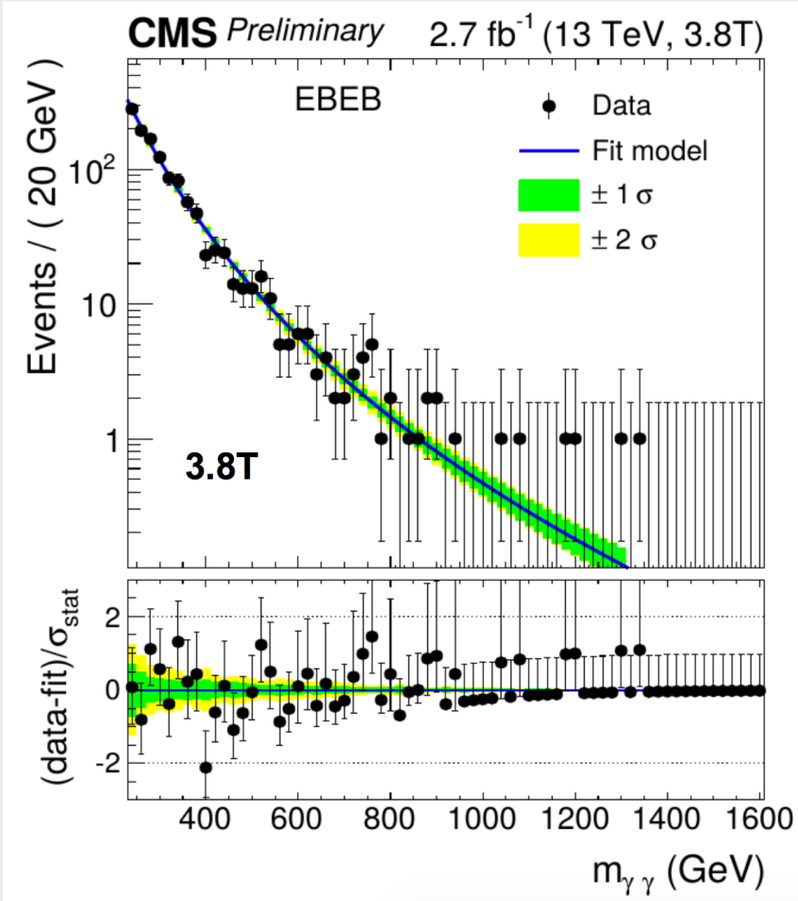
# A 750 GeV Portal?

Delmastro's Talk @ Moriond2016




Could this new hypothetical particle be the mediator between DM and SM?

Musella's Talk @ Moriond2016



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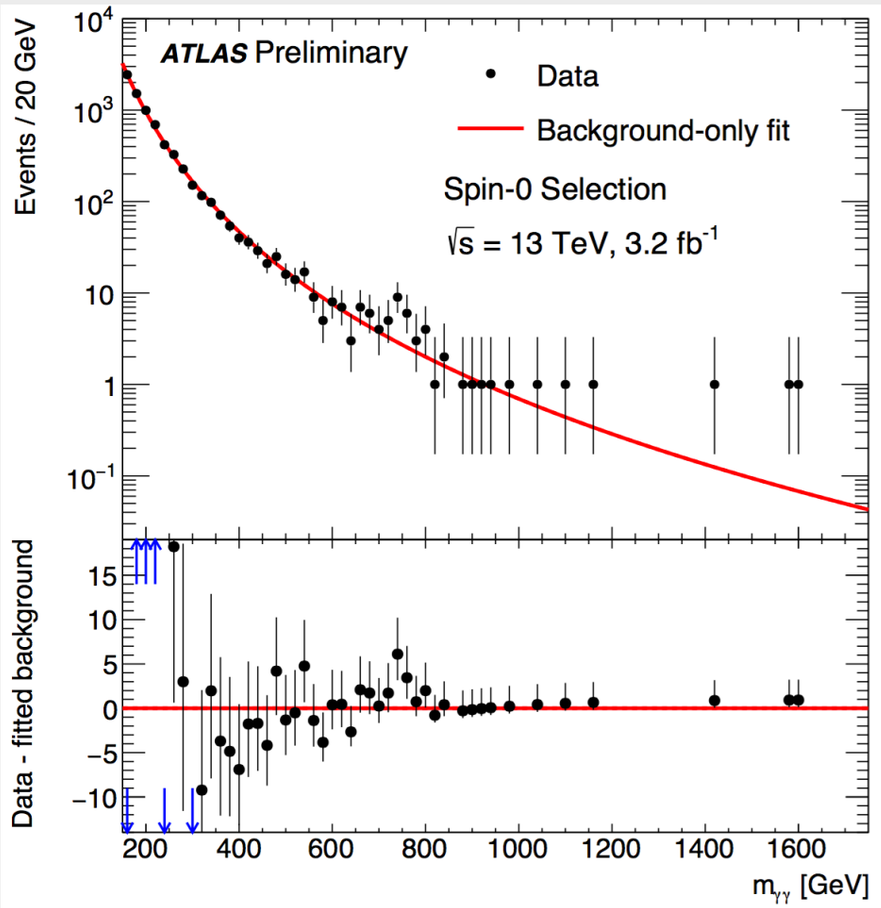


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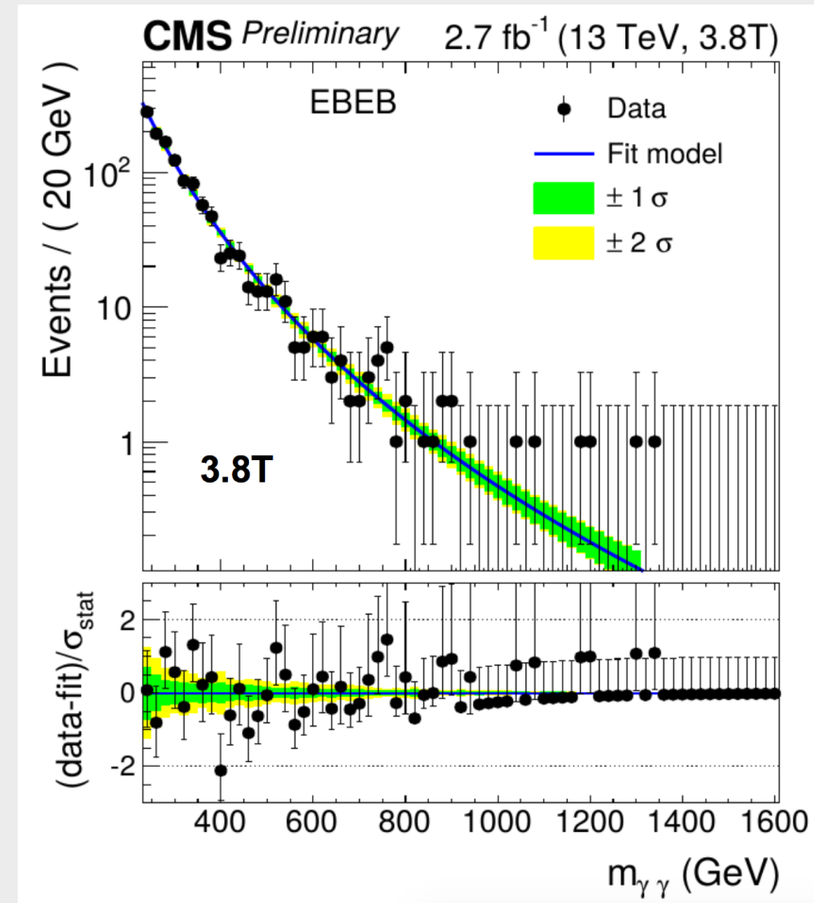
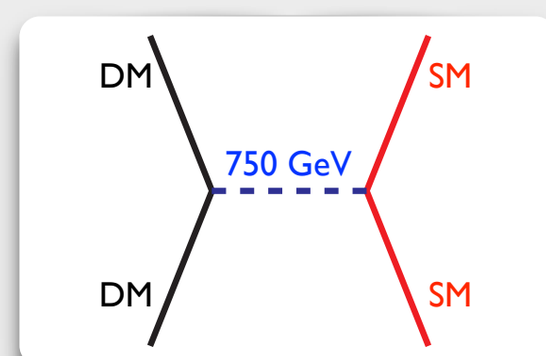



## Scalar Mediator

- LHC (invisible decays)
- Direct Detection




## Pseudo-Scalar Mediator

- LHC (invisible decays)
- Indirect Detection

FD, de Vries, Panci, arXiv:1601.01571

# A 750 Scalar Portal

Simple EFT for a 750 GeV scalar portal (S) and fermion DM (χ)

$$\mathcal{L}_{\rm EFT} = \frac{S}{\Lambda}\left[c_{GG}\, G^{A\,\mu\nu} G^A_{\mu\nu} + c_{WW}\, W^{I\,\mu\nu} W^I_{\mu\nu} + c_{BB}\, B^{\mu\nu} B_{\mu\nu}\right] + c_{\chi S}\, S\, \overline{\chi}\chi$$

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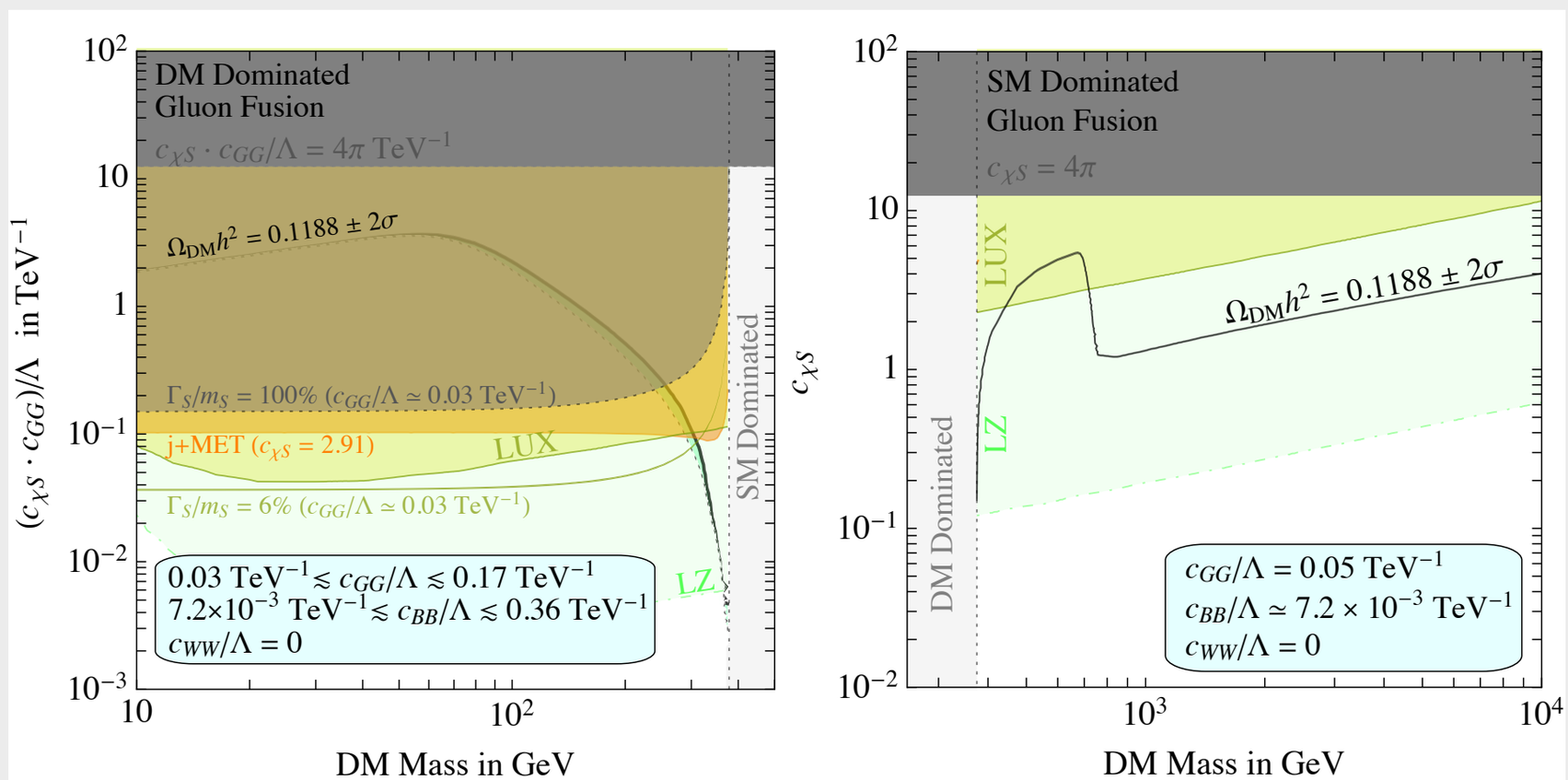
**Excess initiated by gluon fusion**

$$\mathcal{L}^{\rm DD}_{\rm EFT} = \mathcal{C}_G \overline{\chi}\chi\, G^{A\,\mu\nu} G^A_{\mu\nu}$$

$$\mathcal{C}_{GG}(\mu_N) \simeq 4.01\, \frac{c_{\chi S}}{\Lambda m_S^2} c_{GG}(m_S)$$

**RGE change DD rates by a factor of 16!**




FD, de Vries, Panci, arXiv:1601.01571

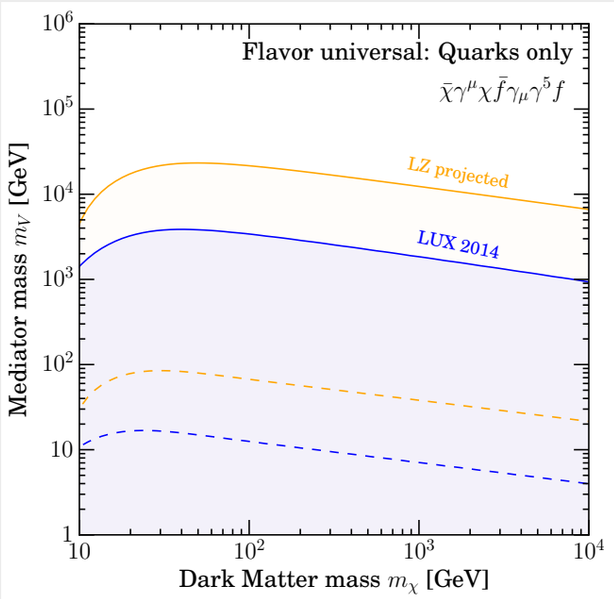
# Outlook

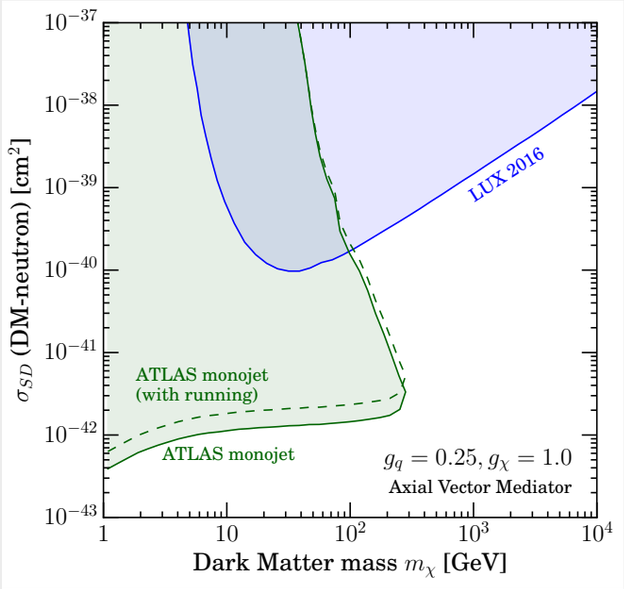
Comparing LHC with DD not always straightforward

# Outlook

## Comparing LHC with DD not always straightforward

### Vector Mediator



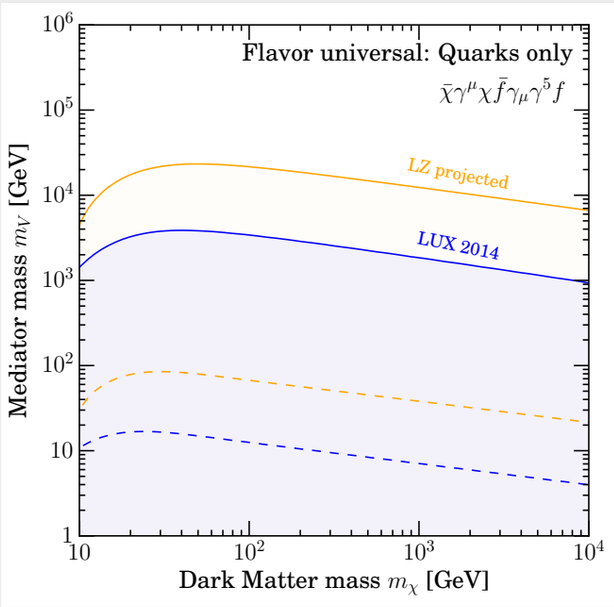



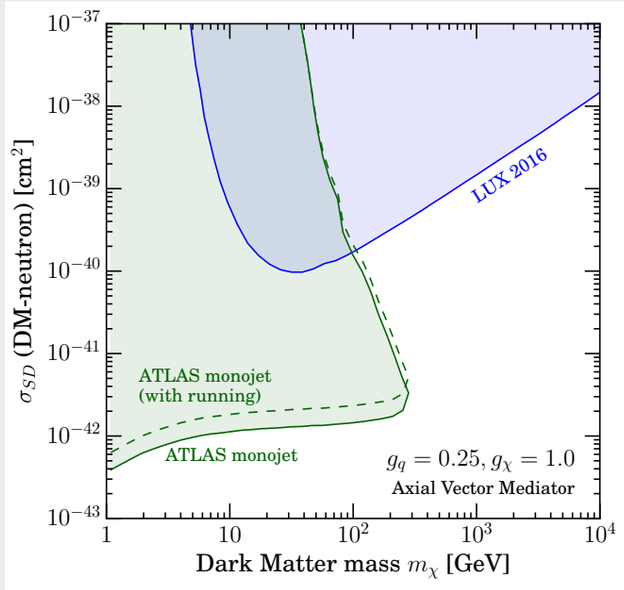

FD, Kavanagh, Panci, in preparation

# Outlook

## Comparing LHC with DD not always straightforward

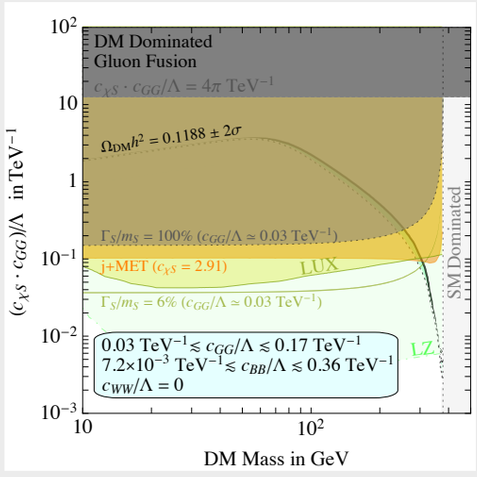
### Vector Mediator

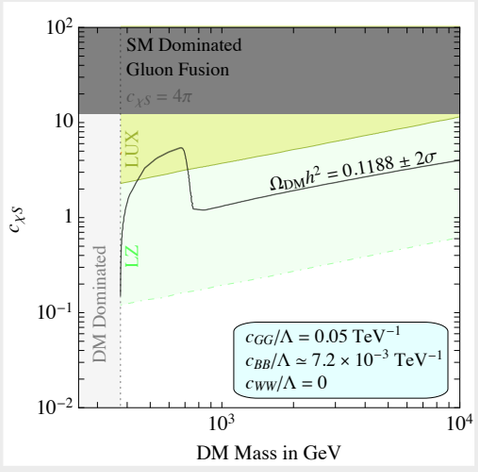



FD, Kavanagh, Panci, in preparation

### 750 GeV Scalar Mediator



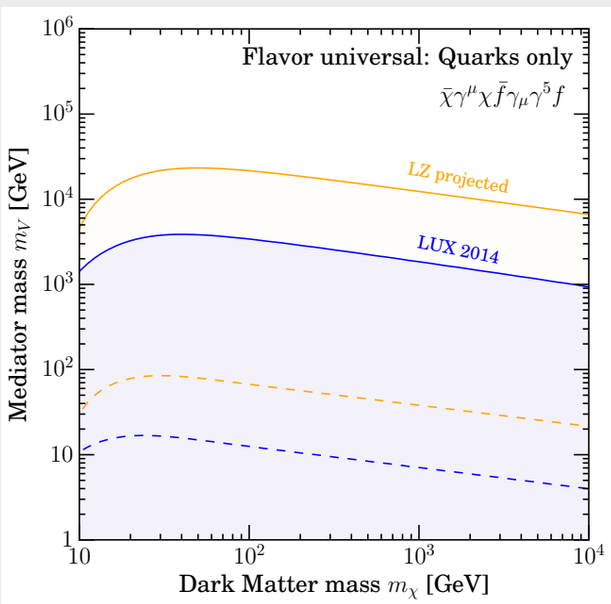



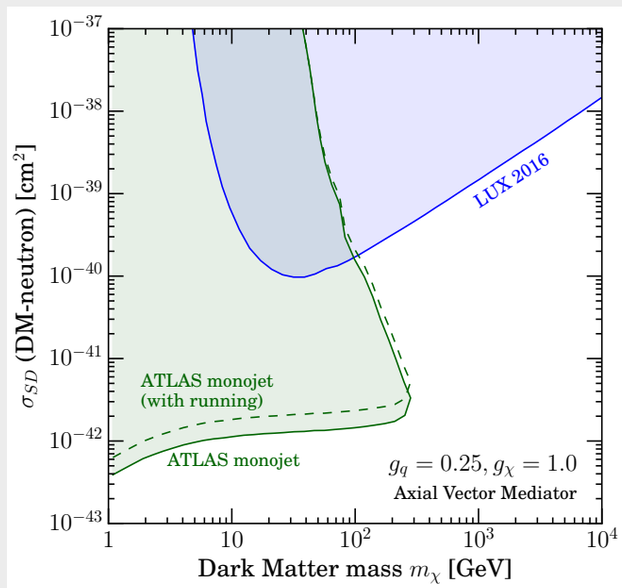

FD, de Vries, Panci, arXiv:1601.01571

# Outlook

## Comparing LHC with DD not always straightforward

### Vector Mediator

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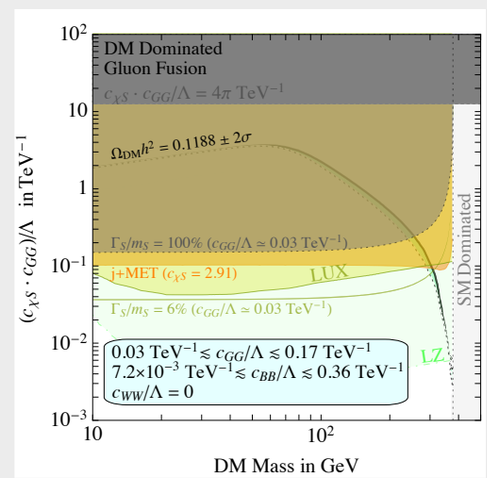


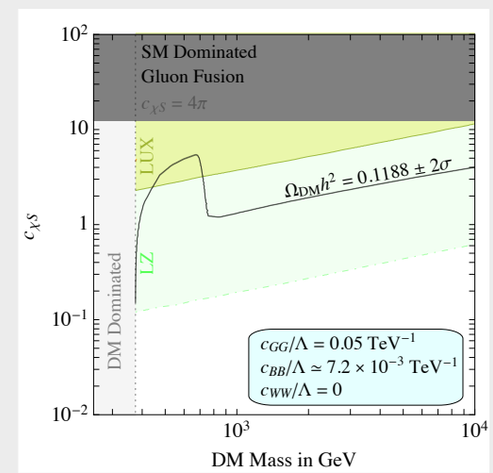


FD, de Vries, Panci, arXiv:1601.01571

**Still need to quantify RGE effects for other simplified models!**

# Outlook

## Comparing LHC with DD not always straightforward

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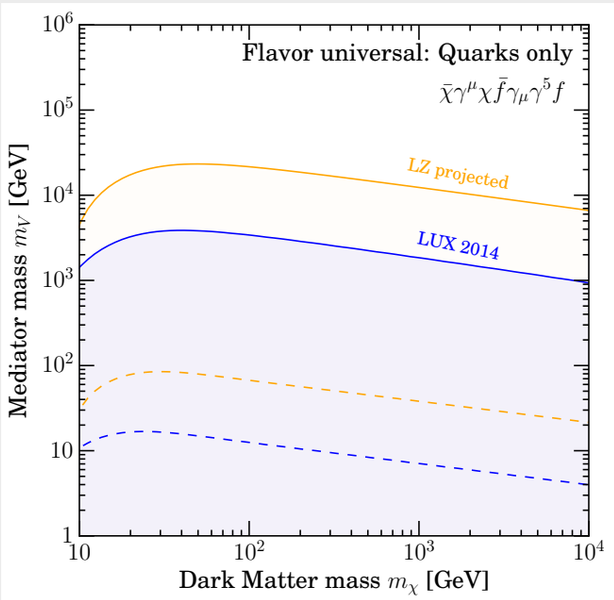


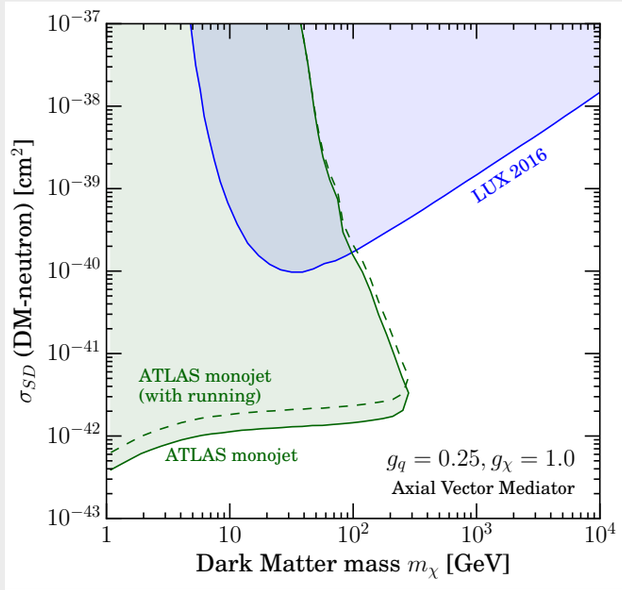


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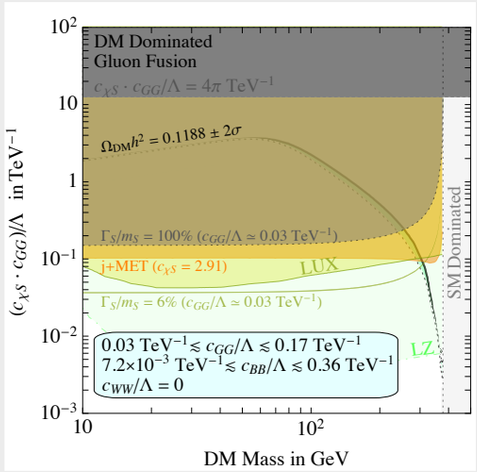


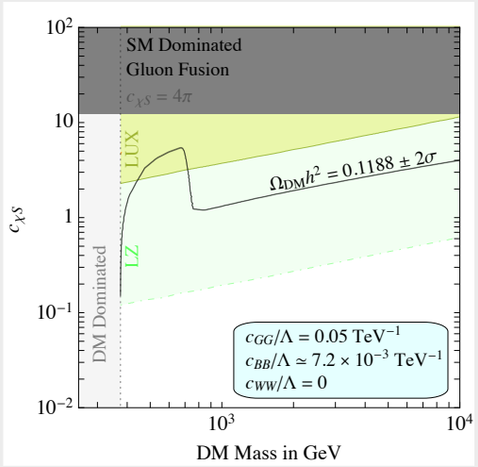


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Thank You!