You can hide but you have to run:

direct detection with vector mediators

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CERN Theory Institute - 28 July 2016

LHC vs Direct Detection

Energy Scale

LHC

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

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

Energy scales:
LHC ≫ Direct Detection

Direct Detection

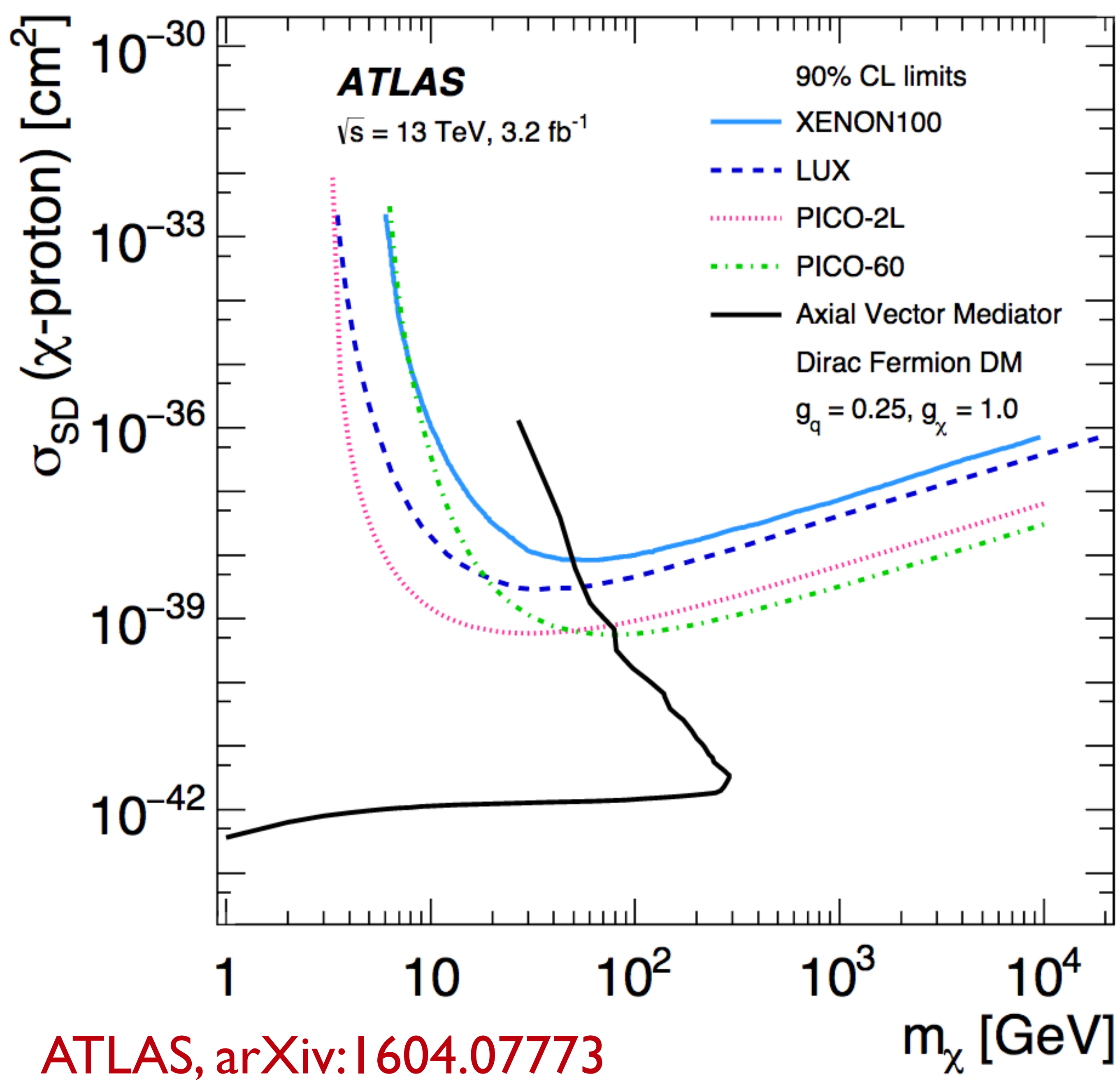
$$\chi \mathcal{N} \to \chi \mathcal{N}$$

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

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

LHC vs Direct Detection

$$\mathcal{L} = g_\chi \, A_\mu \, \overline{\chi}\gamma^\mu\gamma^5\chi + g_q \, A_\mu \, \overline{q}\gamma^\mu\gamma^5 q$$



ATLAS, arXiv:1604.07773

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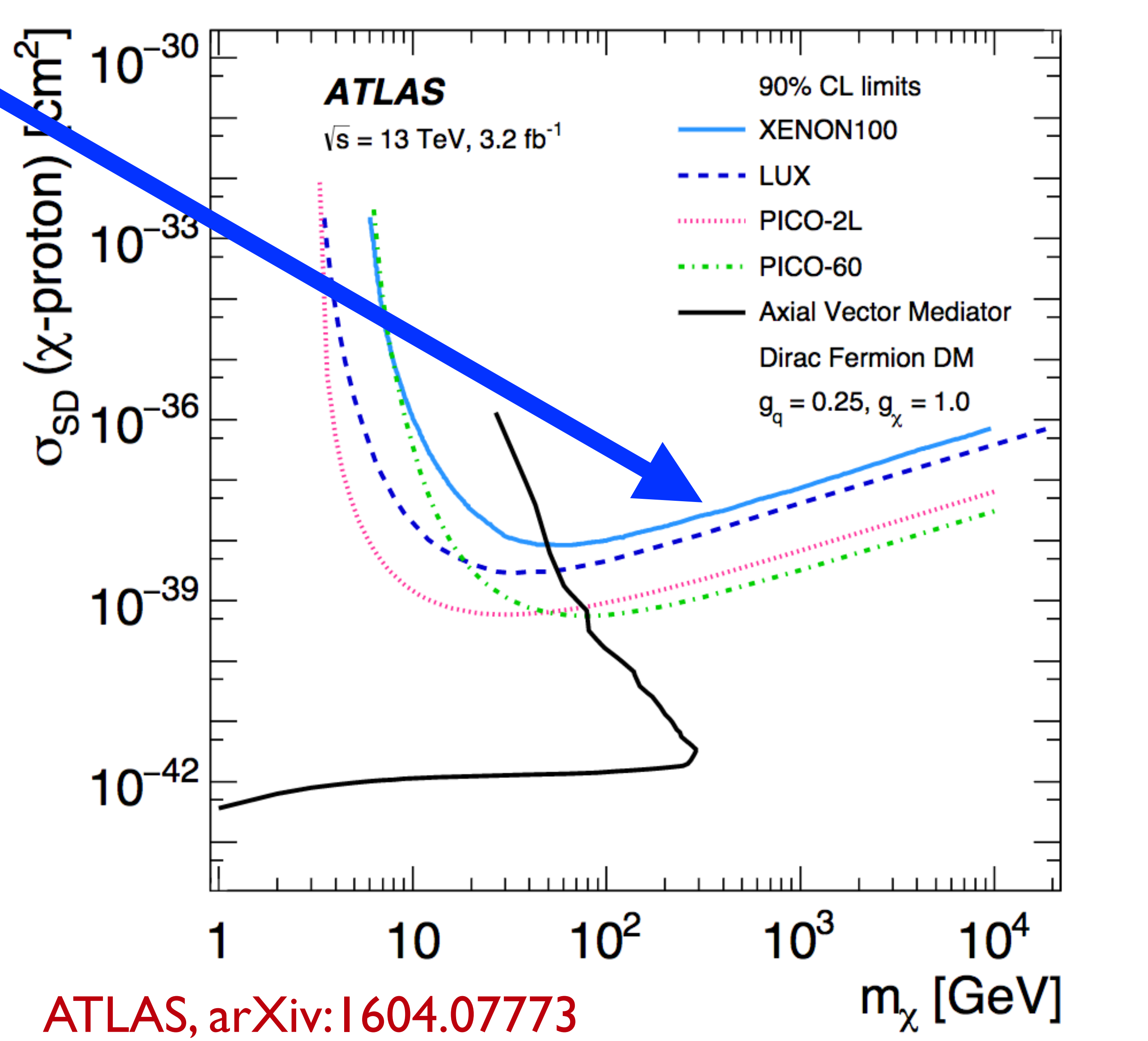

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LHC vs Direct Detection

Direct Detection

LHC (mono-jet)

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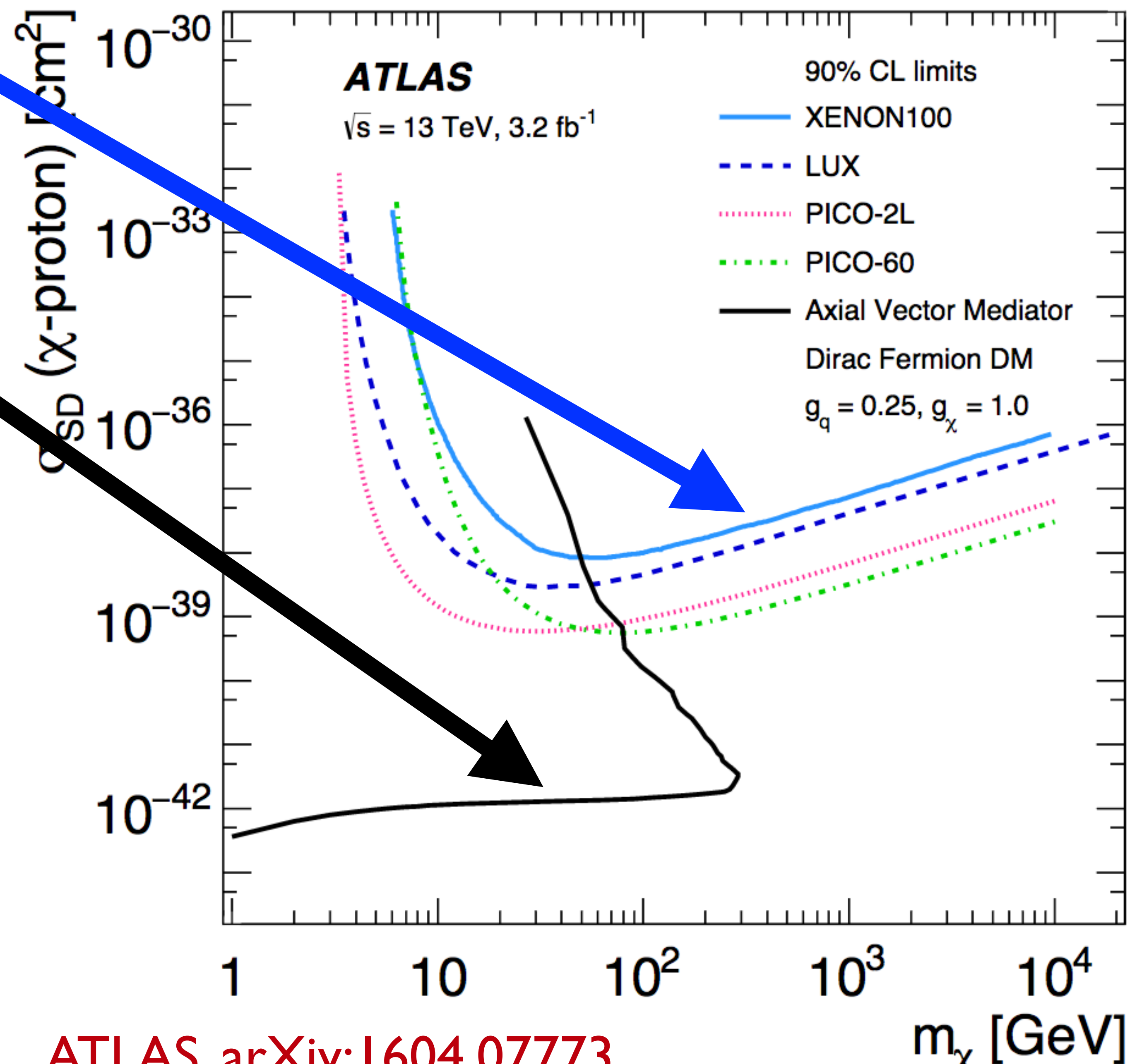

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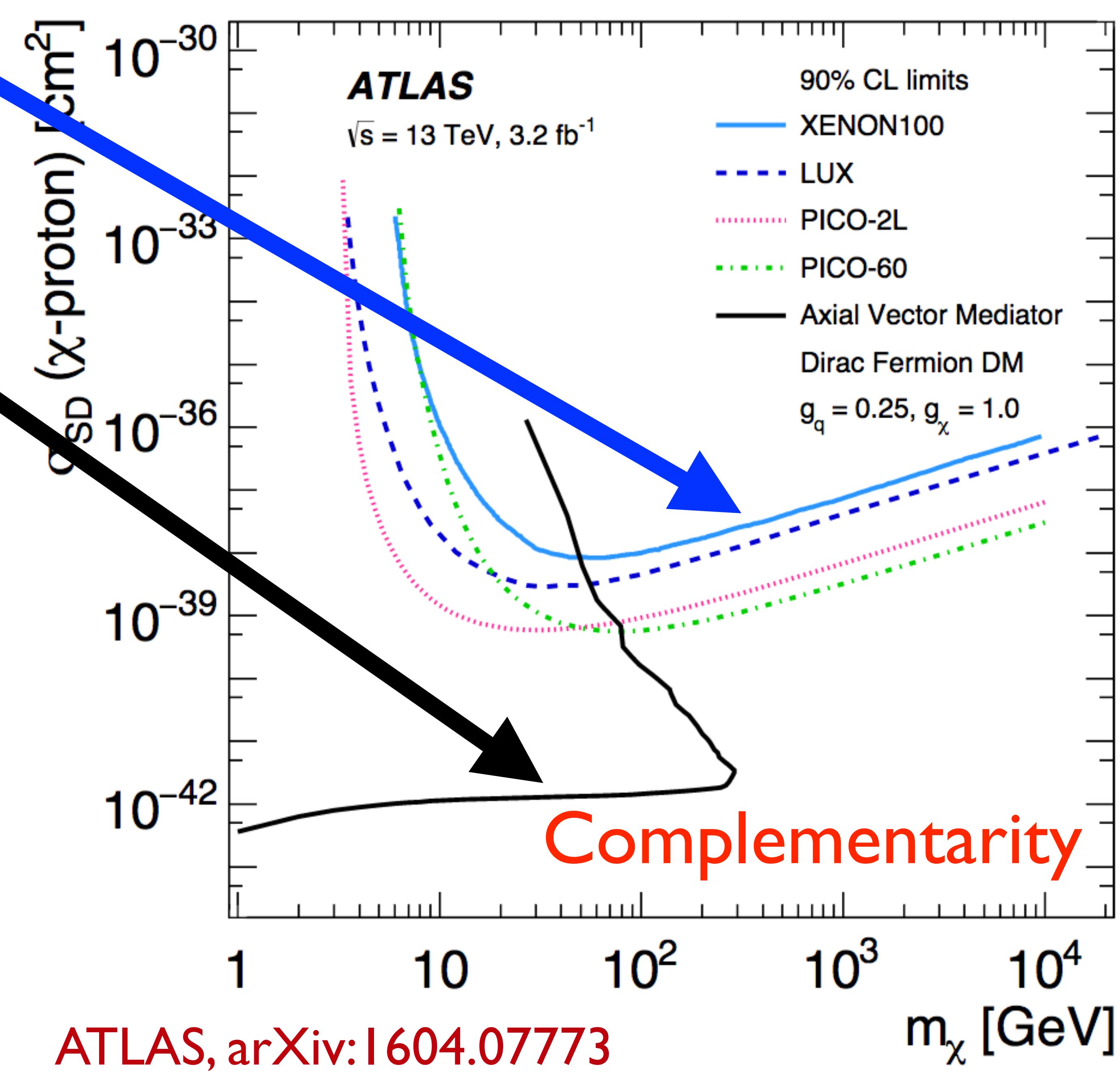

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LHC vs Direct Detection

How are LHC limits translated into the (m_{DM}, σ_{SD}) plane?

LHC bounds have to be evolved down to the direct detection scale

You have to run! (RGE)

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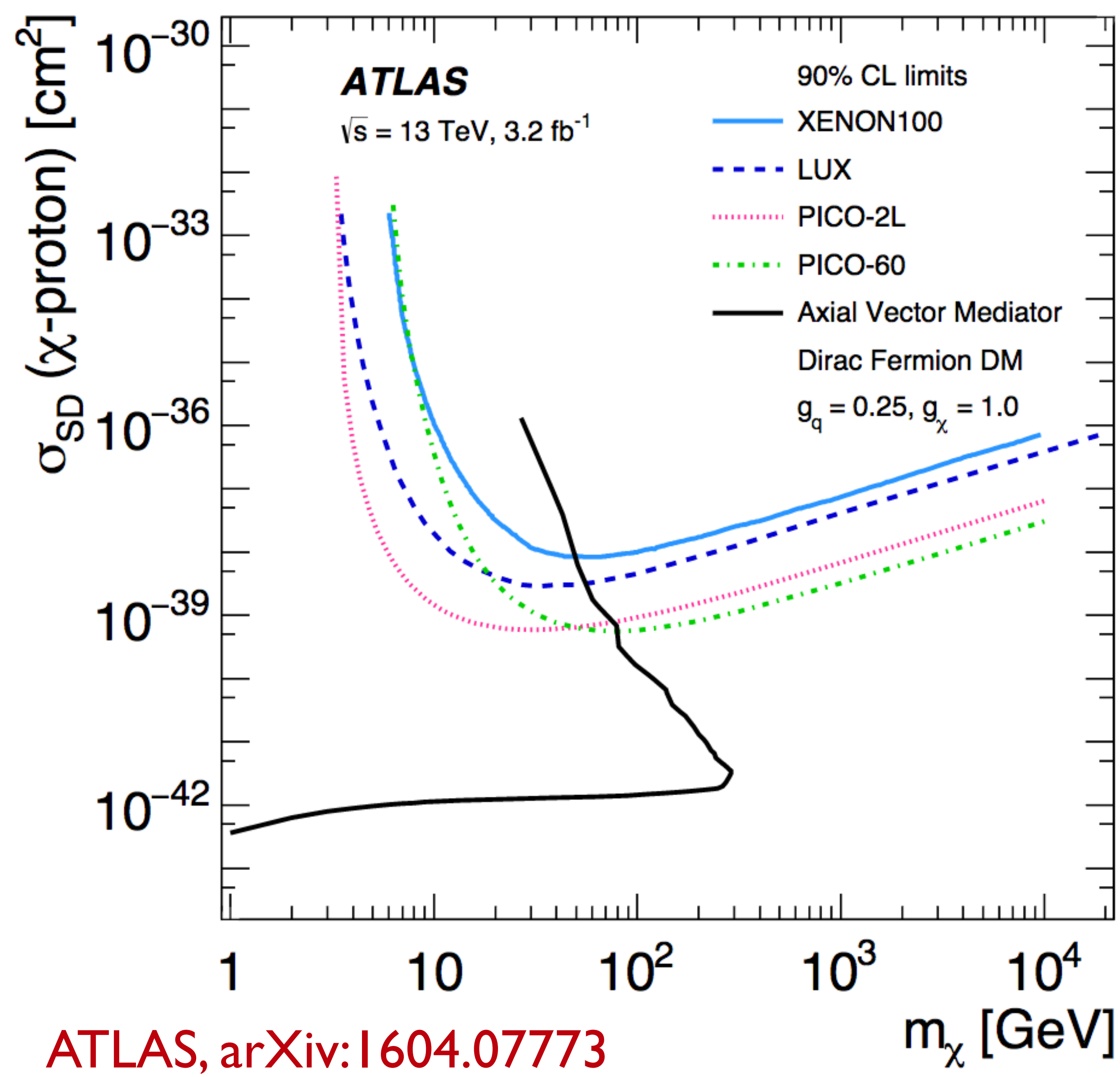

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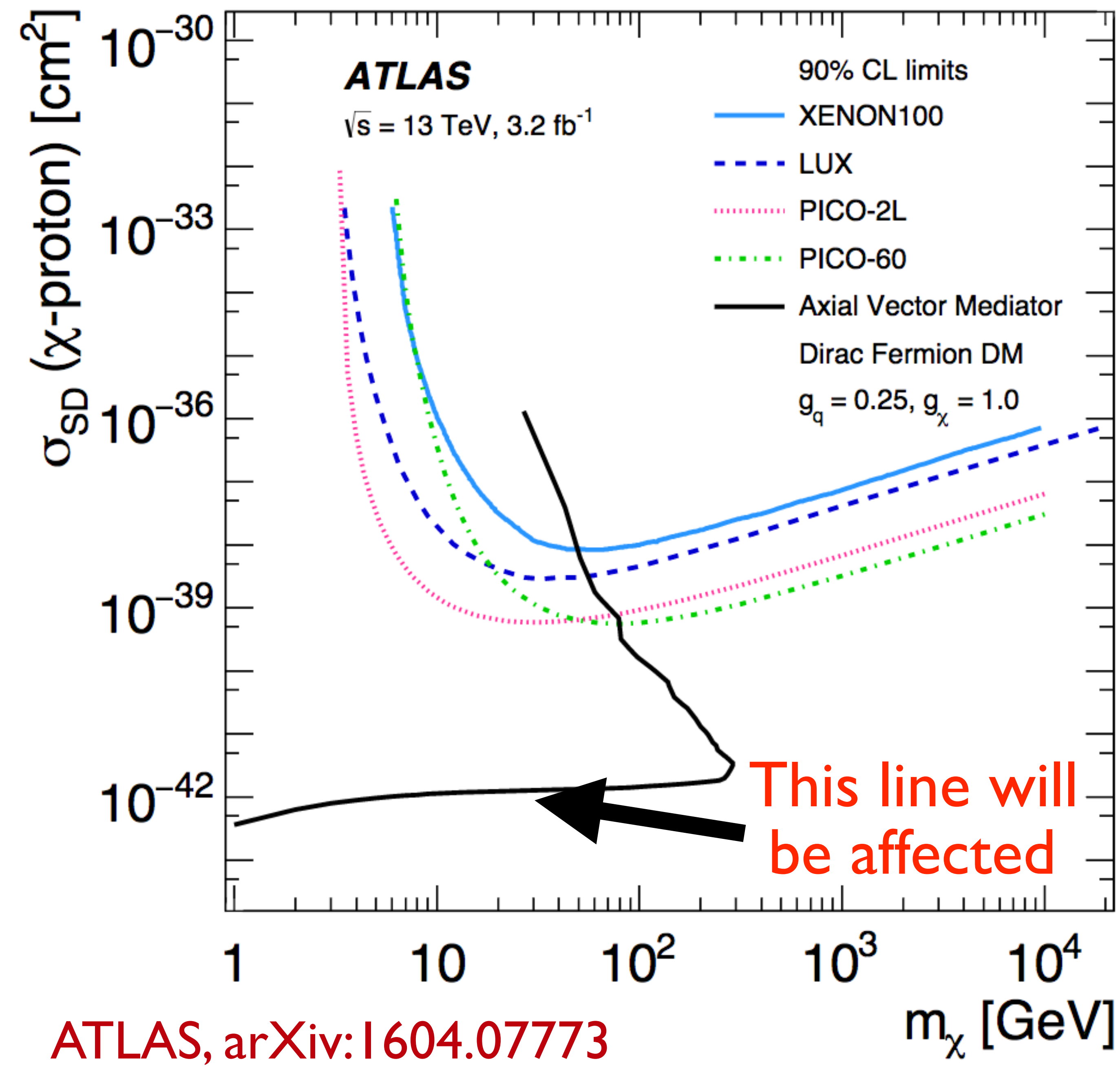
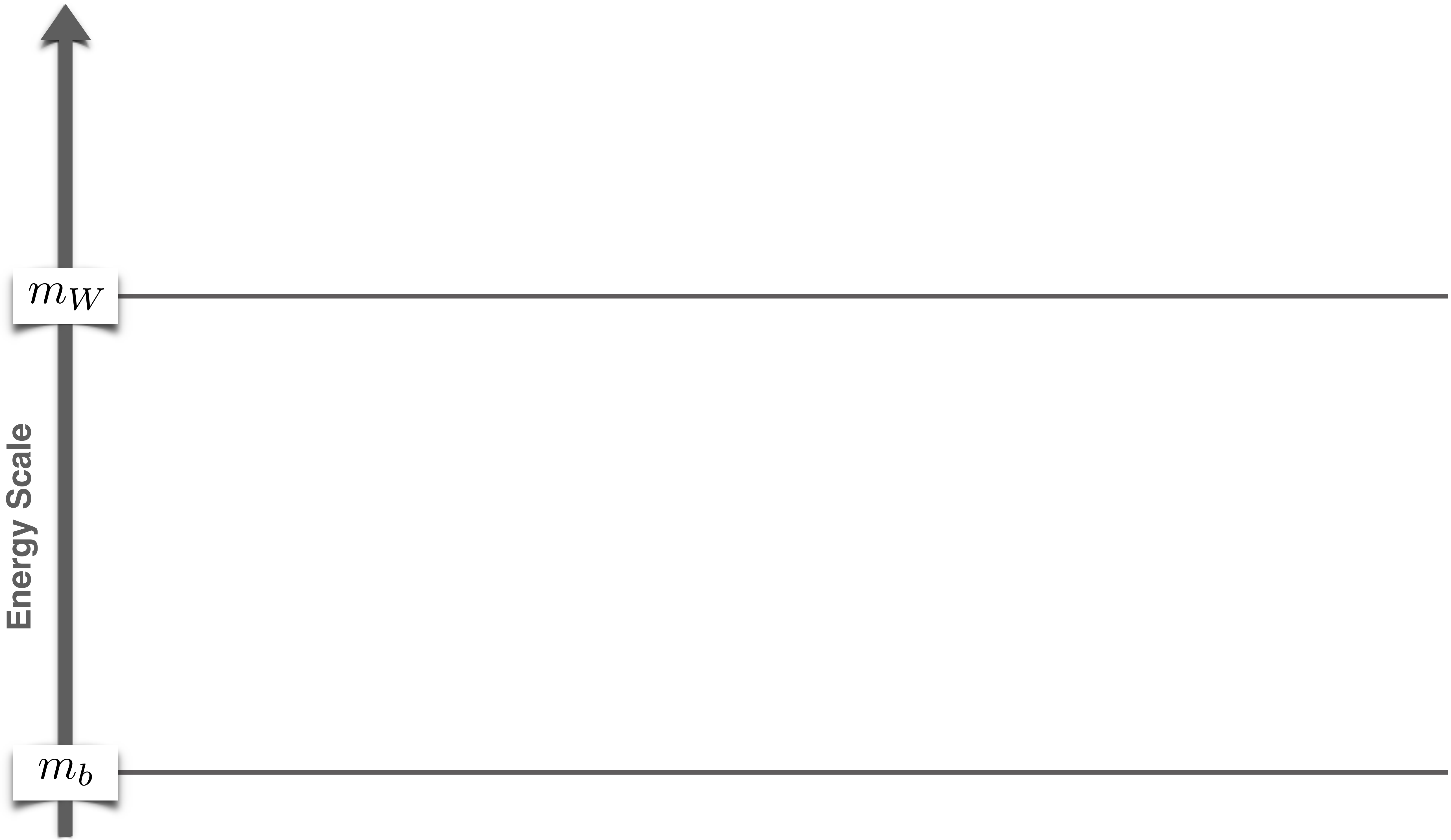


ATLAS, arXiv:1604.07773

A well know SM analogy

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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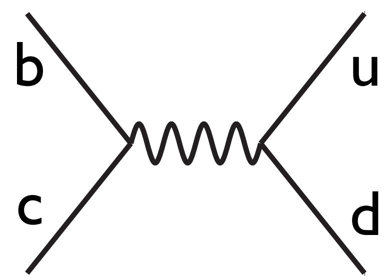
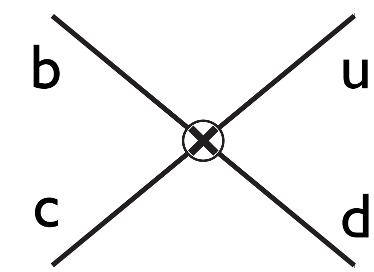


Integrate-out heavy SM states
(ElectroWeak Hamiltonian)
Buras, hep-ph/9806471



m_W

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

Energy Scale

m_b

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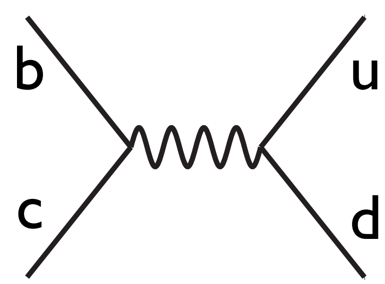

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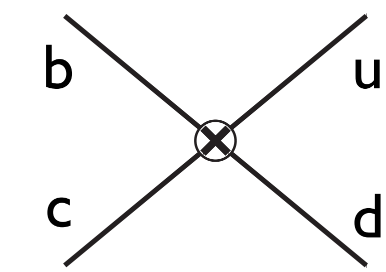

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$$\mathcal{H}_W \propto G_F \left[C_1\, \overline{c_\alpha} \gamma^\mu P_L b_\alpha\, \overline{d_\beta} \gamma_\mu P_L u_\beta + C_2\, \overline{c_\alpha} \gamma^\mu P_L b_\beta\, \overline{d_\beta} \gamma_\mu P_L u_\alpha \right]$$

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

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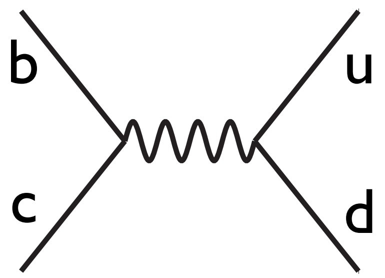

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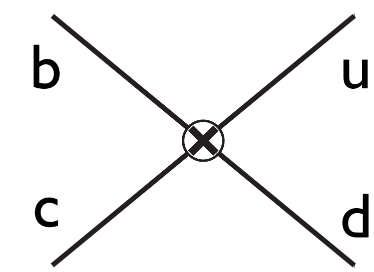

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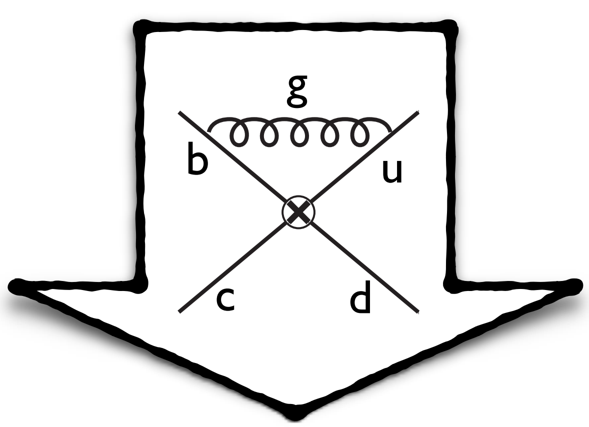

Renormalization
Group Evolution (RGE)

m_b

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

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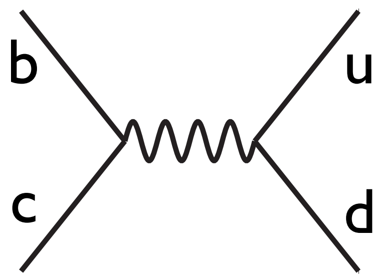

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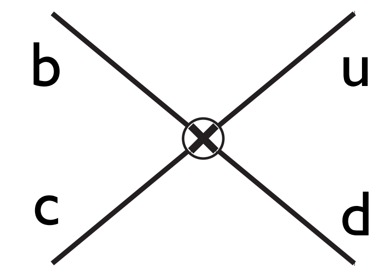

m_W

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

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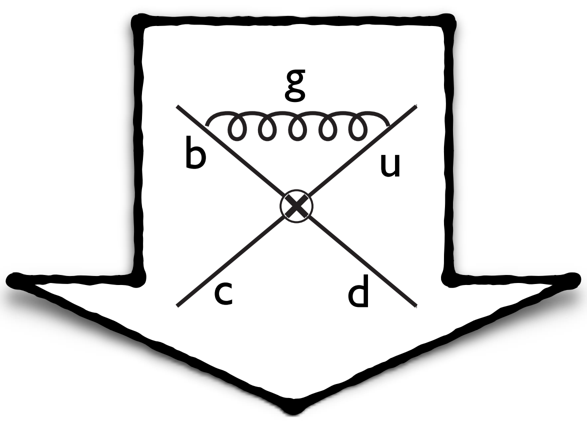

Renormalization
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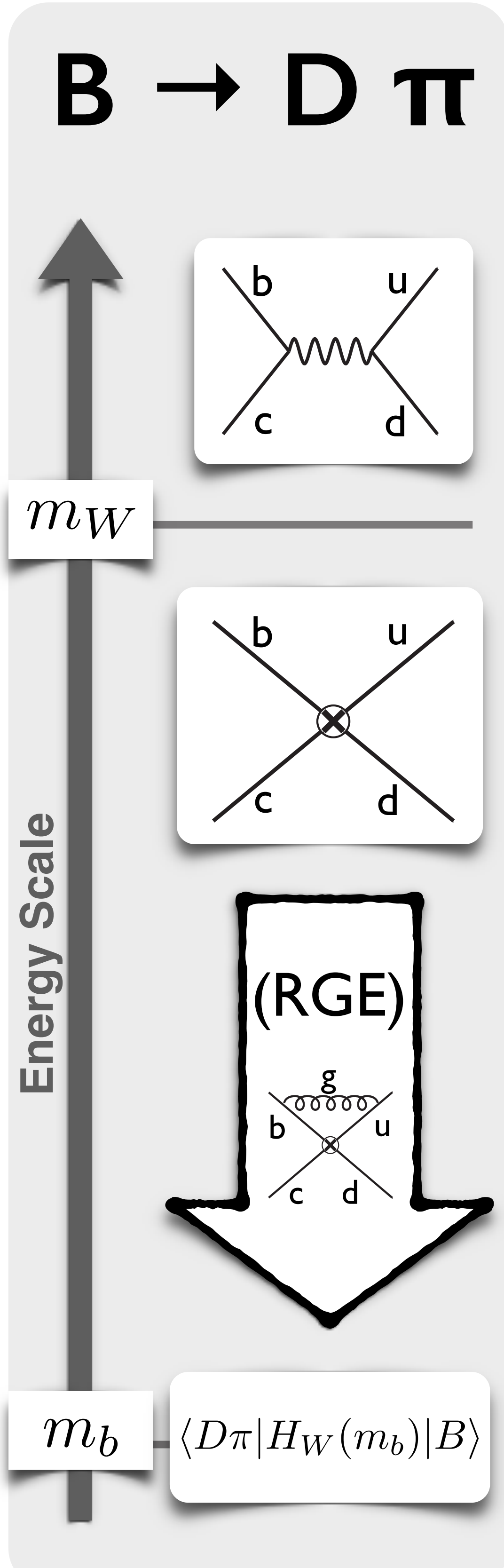
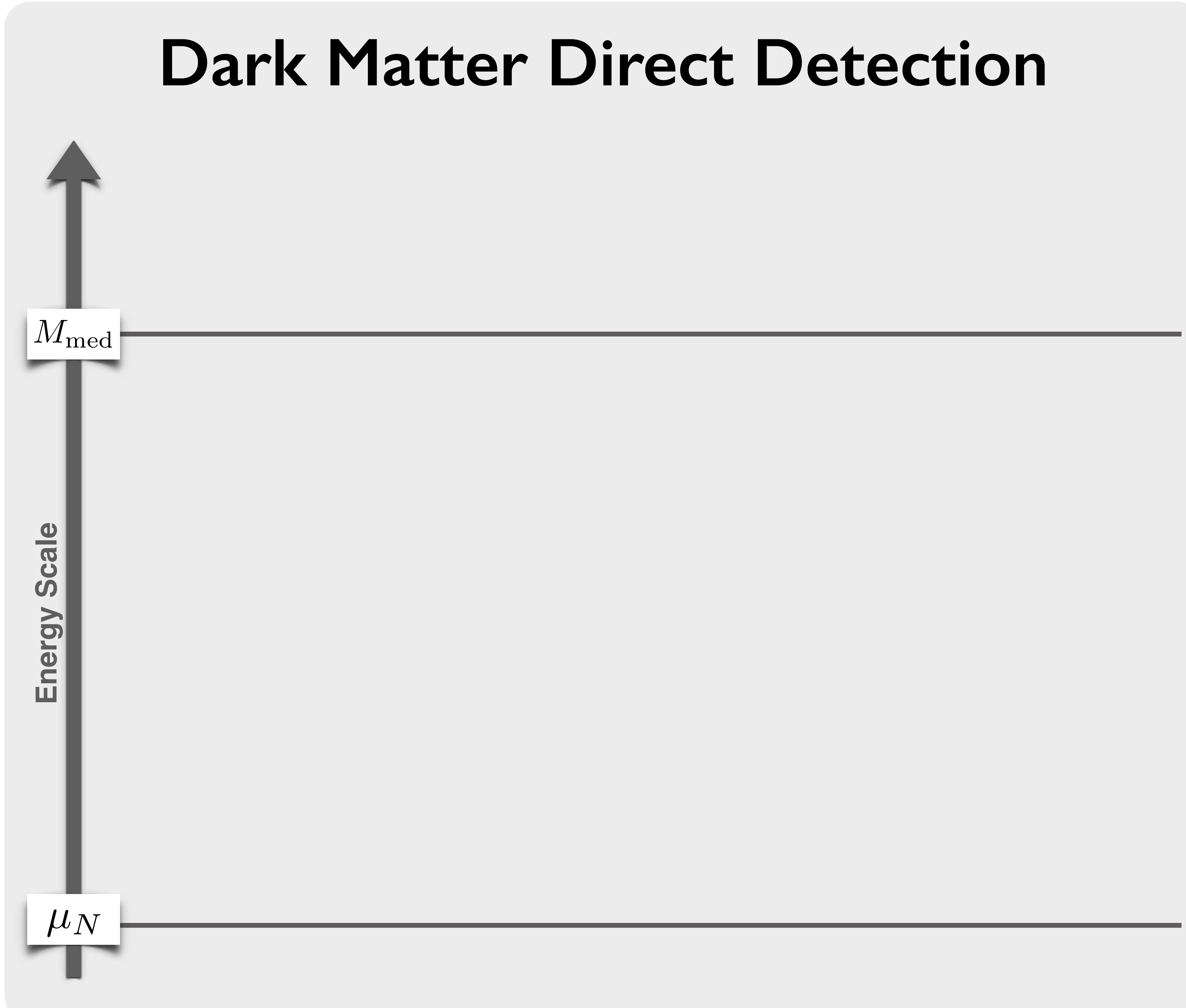
Effective couplings
at the scale m_b

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

A well know SM analogy





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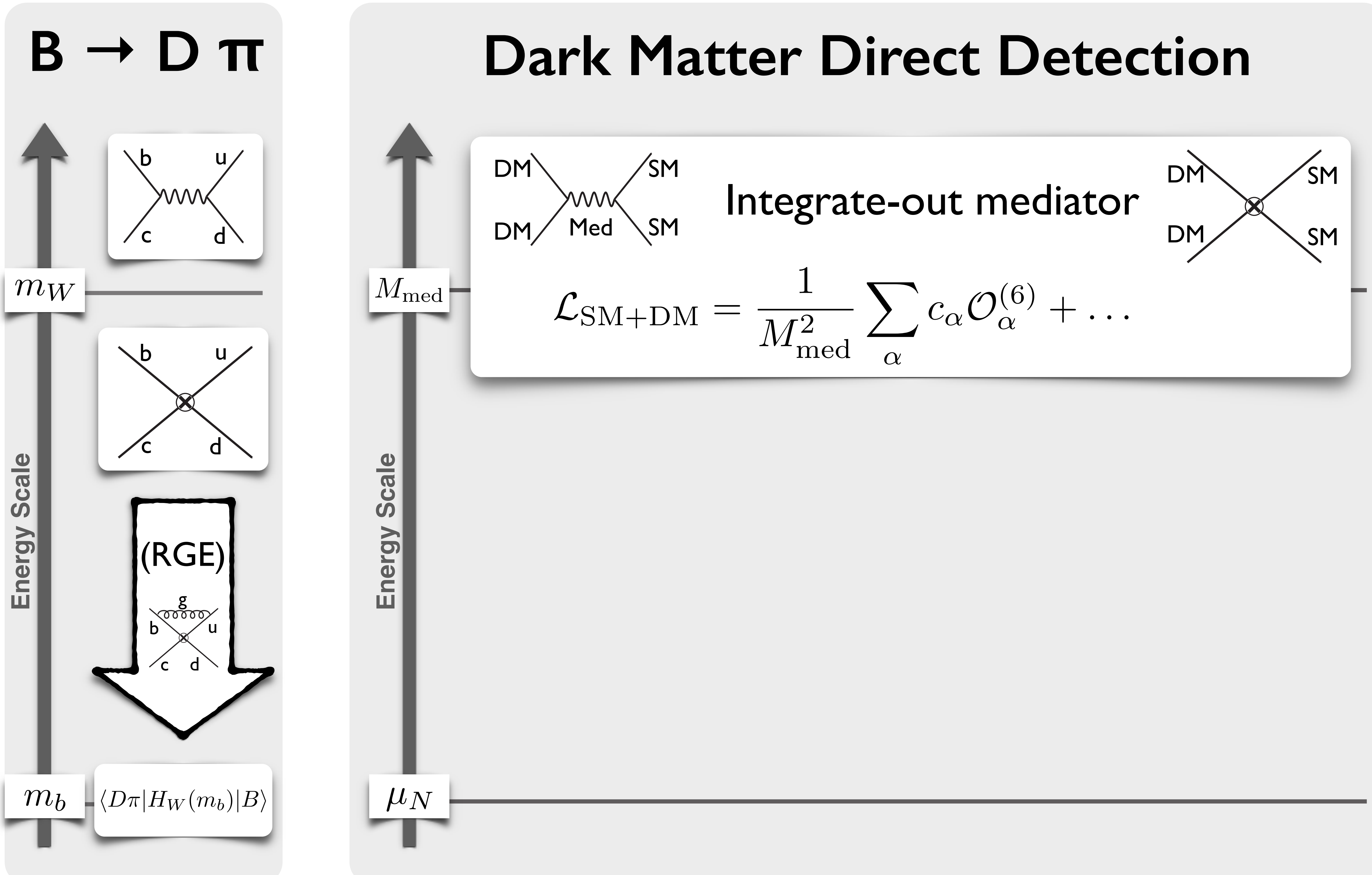

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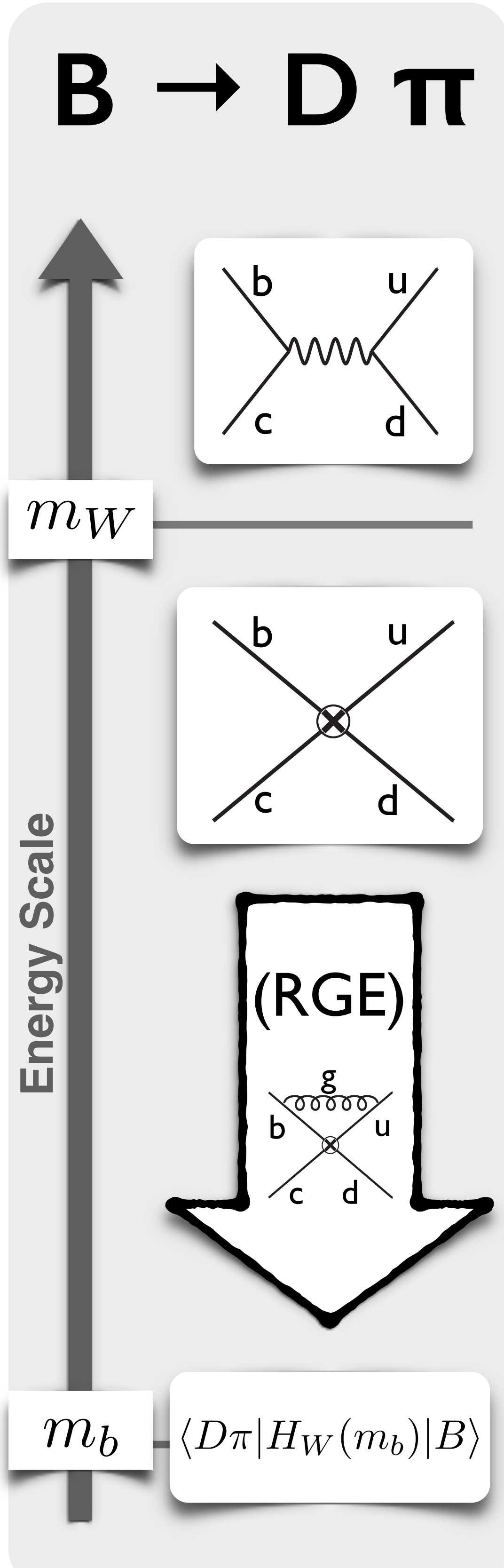

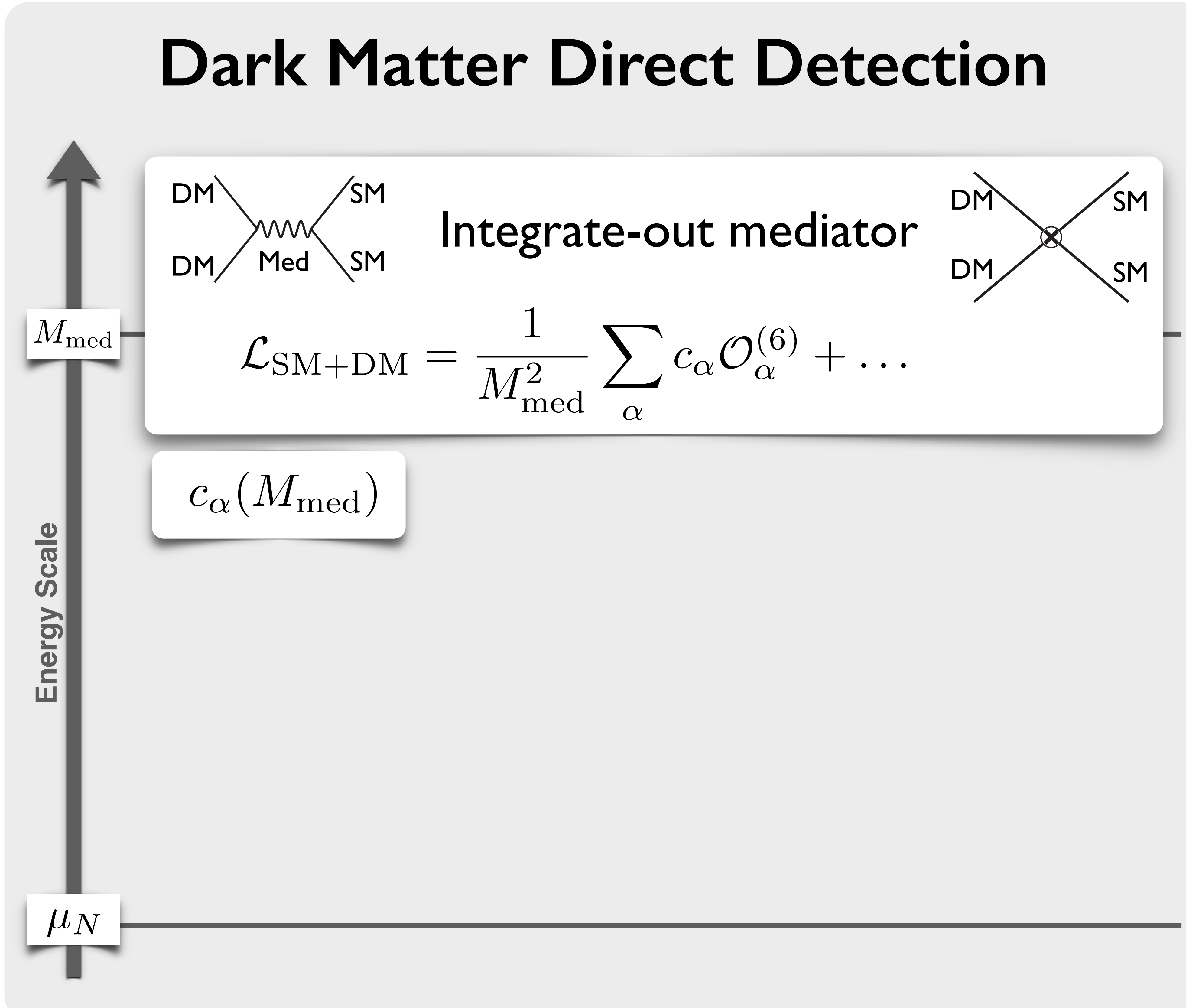

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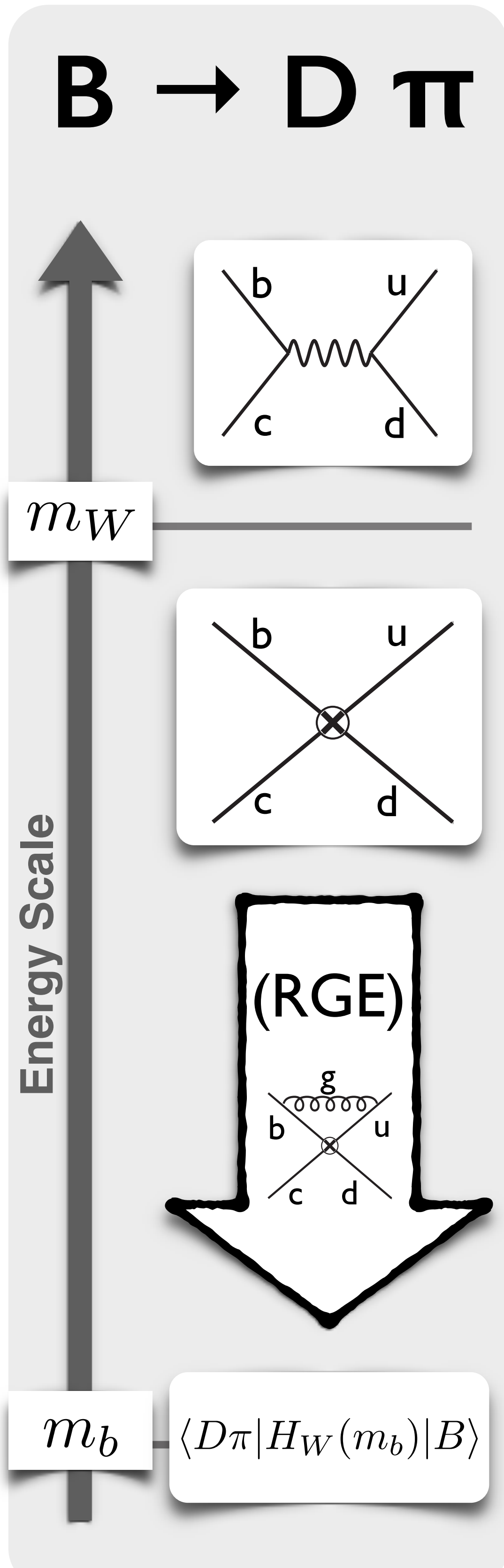

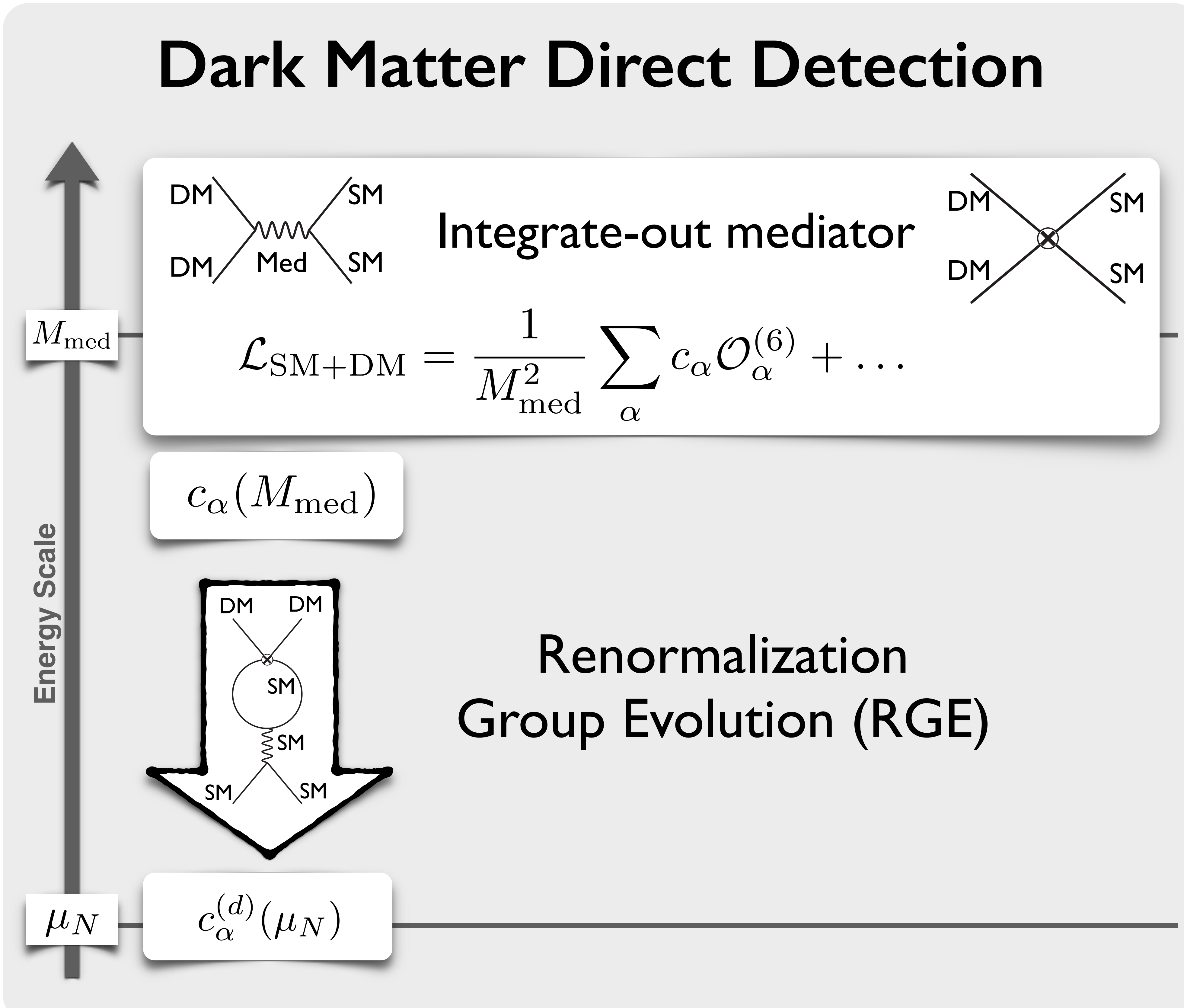

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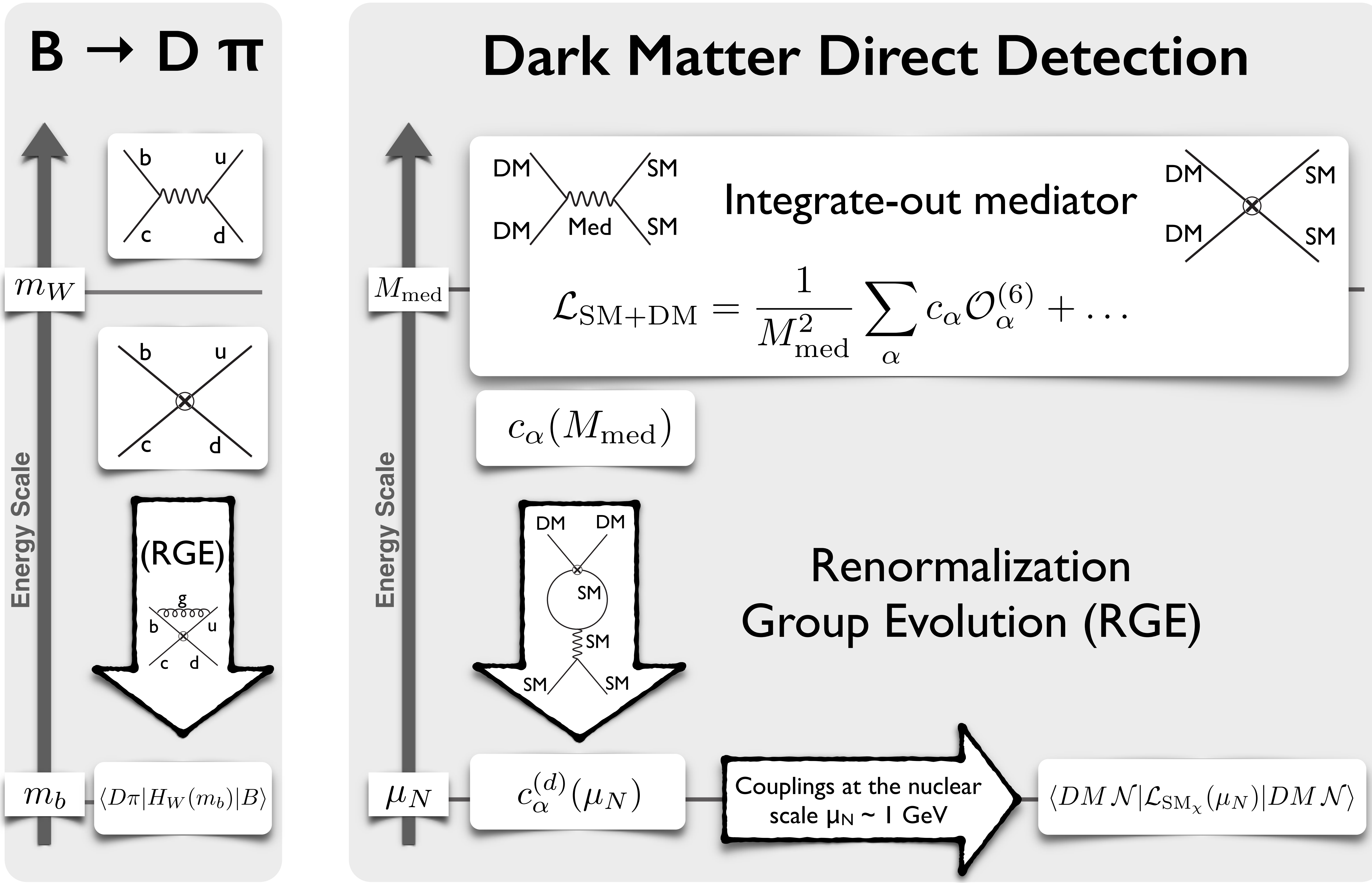

Why this matters?

RGE effects

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

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DM-Nucleus scattering:

only through couplings to light SM degrees of freedom

and

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Goodman and Witten, PRD31 (1985)

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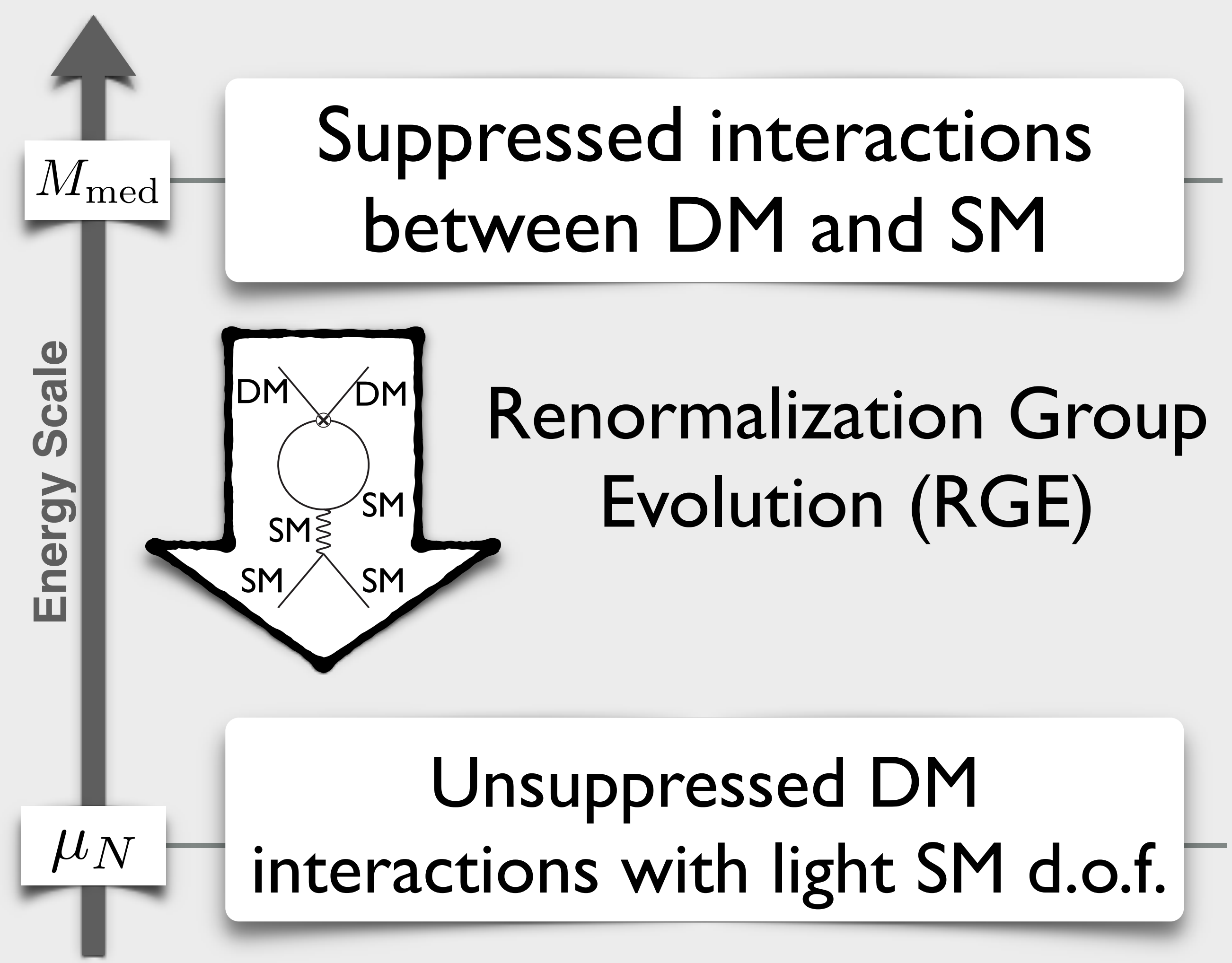

Why this matters?

RGE effects

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DM

on

light

very

ns

Group

E)

d.o.f.

Direct detection rates can be orders of magnitude larger than the ones computed without RGE effects

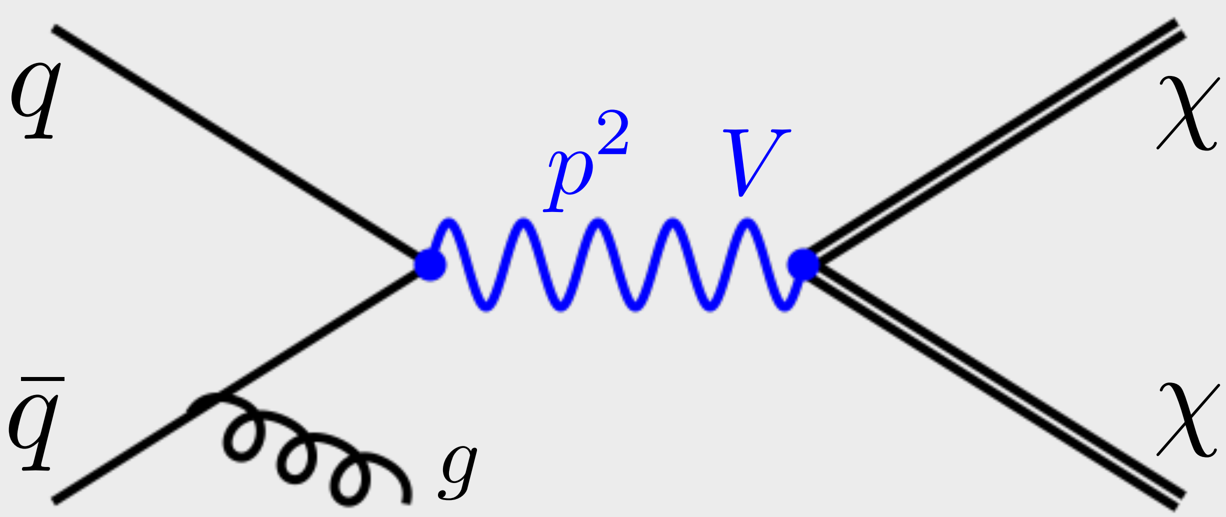
This was realized for specific interactions in:

Kopp, Niro, Schwetz, Zupan, PRD80 (2009), arXiv:0907.3159;
Freytsis, Ligeti, PRD83 (2011), arXiv:1012.5317
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, Haisch, PRD90 (2014), arXiv:1408.5046

Vector Mediators

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

Mediator effects fully accounted for



- $p^2 \lesssim m_V^2$
  Contact interaction
- $p^2 \simeq m_V^2$
  Resonant production
- $p^2 \gtrsim m_V^2$
  EFT badly breaks down

Vector Mediators

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

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

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

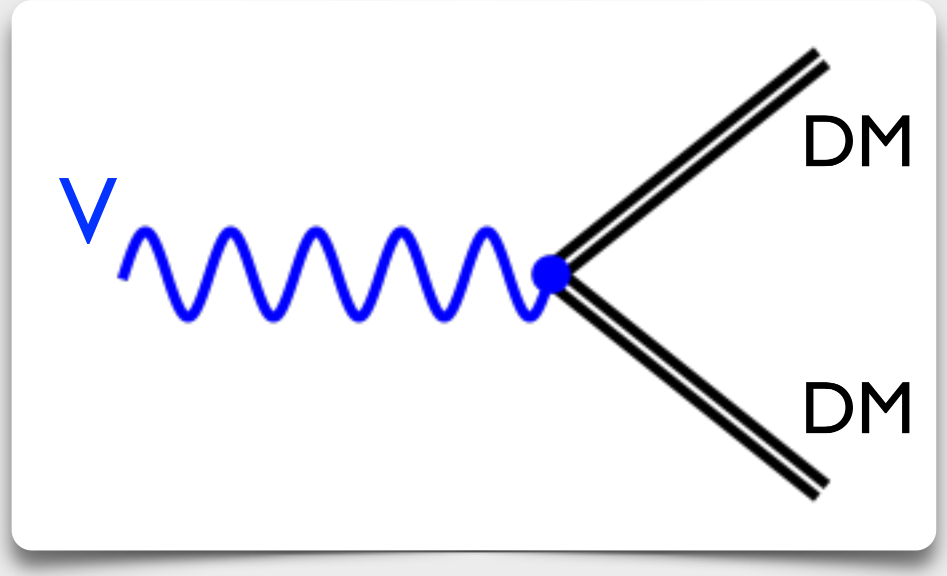
Spin-1 massive mediator

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

Vector Mediators

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

Mediator coupled to spin-1 DM currents



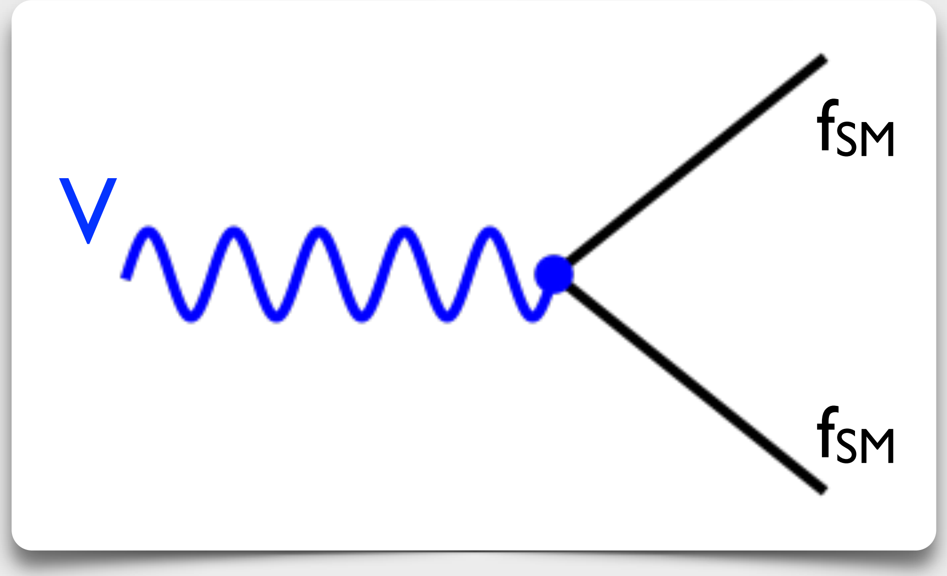
$$J^\mu_{\rm DM} = \begin{cases} c_\phi \, \phi^\dagger \overleftrightarrow{\partial}_\mu \phi & \text{scalar DM} \\ \mathcal{K}_\chi \left(c_{\chi V} \, \overline{\chi}\gamma^\mu\chi + c_{\chi A} \, \overline{\chi}\gamma^\mu\gamma^5\chi \right) & \text{fermion DM} \end{cases}$$

Vector Mediators

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

Mediator coupled to spin-1 currents of SM fermions

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



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

Vector Mediators

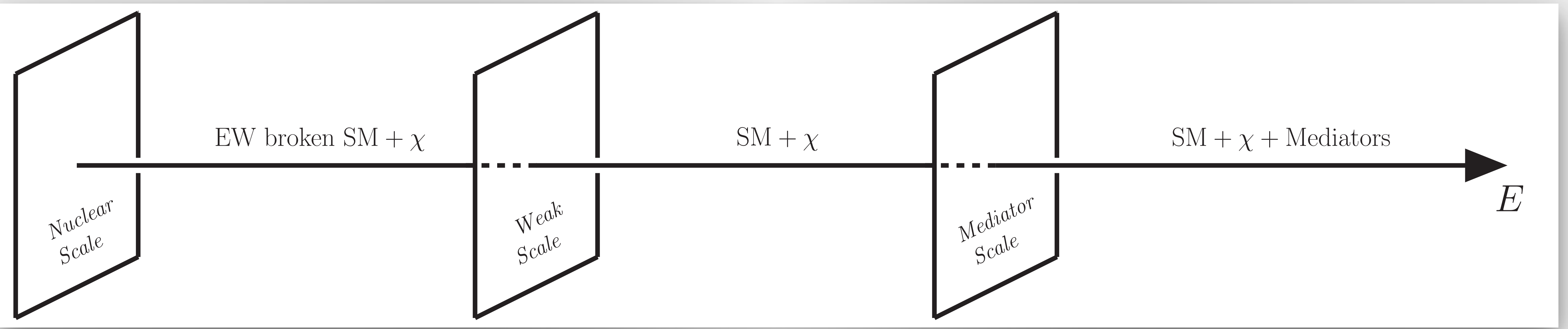
$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm DM} + \mathcal{L}_V + J^\mu_{\rm DM} V_\mu + J^\mu_{\rm SM} V_\mu$$

Apply EFT techniques:

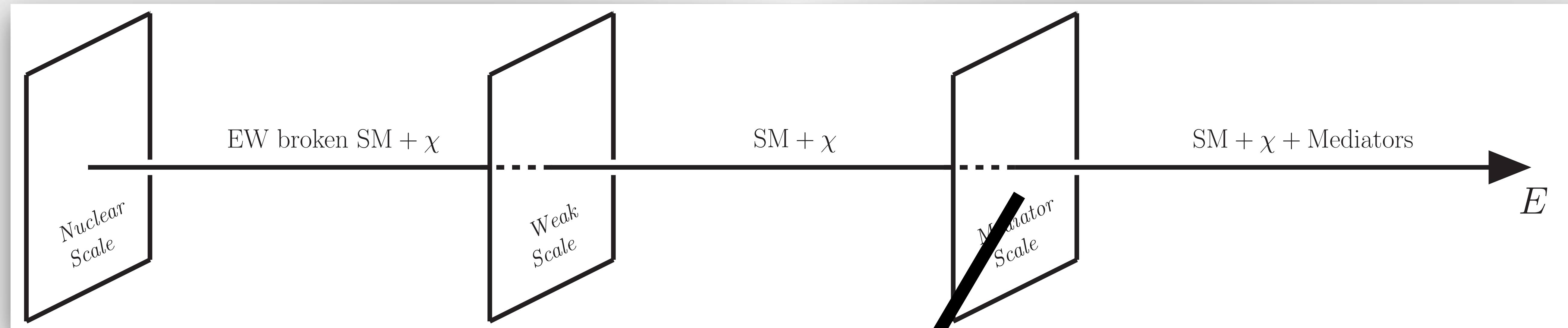
- evaluate direct detection rates
- compare LHC with direct detection

for this broad class of models

Connecting Scales



Connecting Scales



STEP 1:
Integrate-out mediator

$$\mathcal{L}_{\mathrm{EFT}}^{(m_V)} = -\frac{J_{\mathrm{DM}\,\mu}\, J^{\mu}_{\mathrm{SM}}}{m_V^2}$$

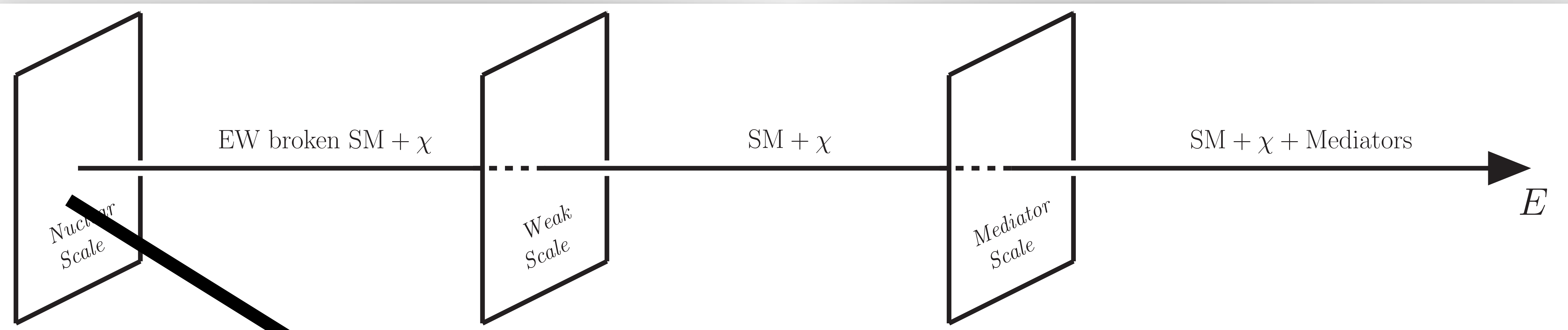
Connecting Scales

STEP II: Connecting Energy Scales

$$\frac{d\,c}{d\ln\mu} = \gamma_{\mathrm{SM}_\chi}\, c$$

Crivellin, FD, Procura, Phys.Rev.Lett.112 (2014), arXiv:1402.1173
FD, Procura, JHEP1504 (2015), arXiv:1411.3342

Connecting Scales



STEP III:
Nuclear Matrix Elements

$$\langle DM\,\mathcal{N}|\mathcal{L}_{\mathrm{SM}_\chi}(\mu_N)|DM\,\mathcal{N}\rangle$$

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

runDM: code for RGE

Inclusion of RGE effects automatic

FD, Kavanagh, Panci, arXiv:1605.04917

INPUT:

Effective couplings at an arbitrary energy scale

runDM-examples.nb

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 for more details.

Initialisation

Let's start by loading in the runDM code.

In[1]:=
```
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.

In[2]:=
```
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., 1., 1., -1., 1., 0.}
Vector coupling to all SM leptons: {0., 0., 0., 1., 1., 0., 0., 0., 1., 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.

In[7]:=
```
chigh = initCouplings[];
chigh[[3]] = 1.0;
chigh[[7]] = -1.0;
Print["User-defined couplings: " <> ToString[chigh]];
```

```
User-defined couplings: {0, 0, 1., 0, 0, 0, -1., 0, 0, 0, 0, 0, 0, 0, 0, 0}
```

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

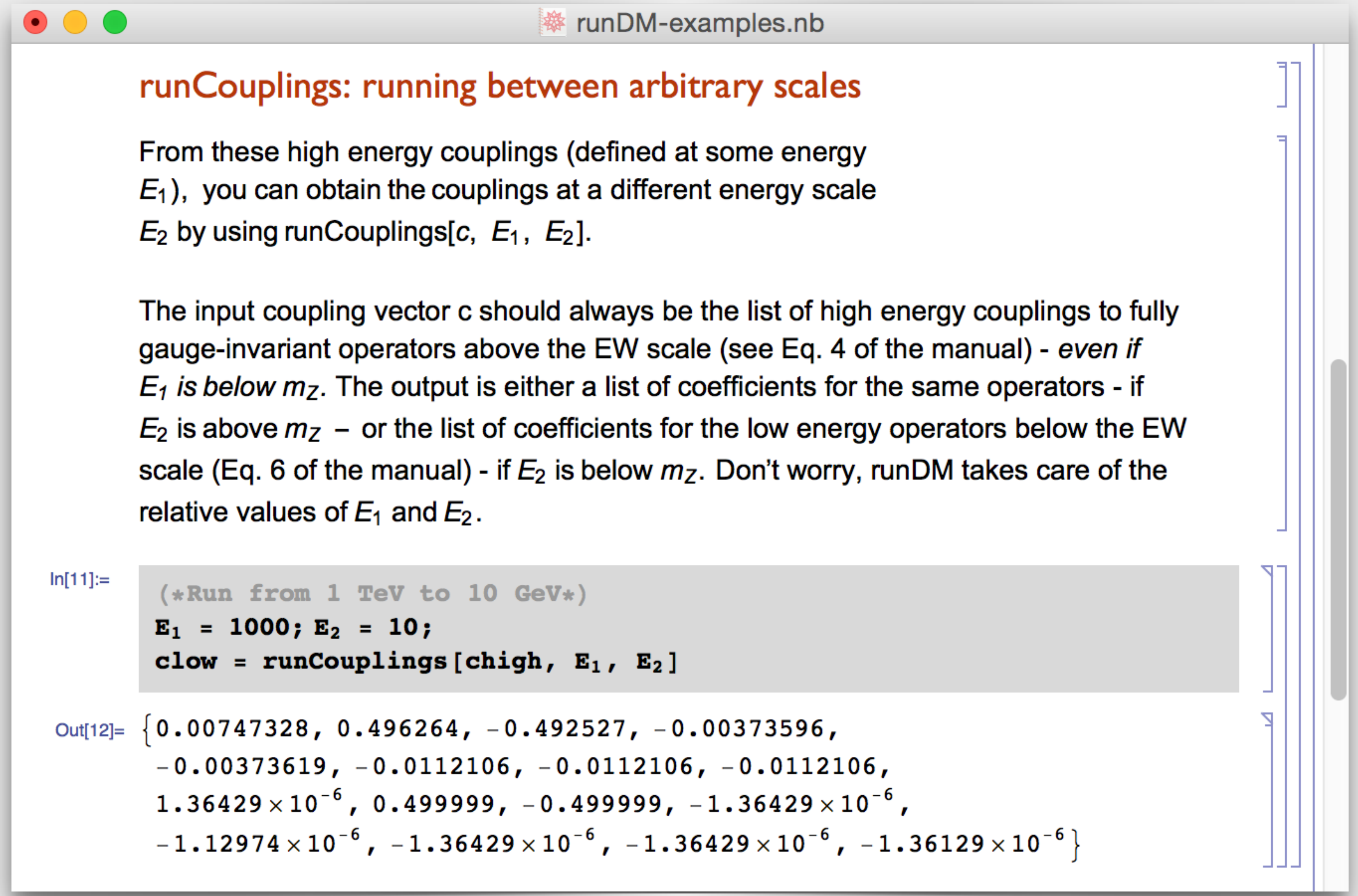
runDM: code for RGE

Inclusion of RGE effects automatic

FD, Kavanagh, Panci, arXiv:1605.04917

OUTPUT I:

RG evolved couplings at a second arbitrary energy scale (useful for future ID studies)


runDM-examples.nb

runCouplings: running between arbitrary scales

From these high energy couplings (defined at some energy E_1), you can obtain the couplings at a different energy scale E_2 by using runCouplings[c, E_1, E_2].

The input coupling vector c should always be the list of high energy couplings to fully gauge-invariant operators above the EW scale (see Eq. 4 of the manual) - *even if E_1 is below m_Z*. The output is either a list of coefficients for the same operators - if E_2 is above m_Z – or the list of coefficients for the low energy operators below the EW scale (Eq. 6 of the manual) - if E_2 is below m_Z. Don't worry, runDM takes care of the relative values of E_1 and E_2.

In[11]:=

```
(*Run from 1 TeV to 10 GeV*)
E1 = 1000; E2 = 10;
clow = runCouplings[chigh, E1, E2]
```

Out[12]=

{0.00747328, 0.496264, −0.492527, −0.00373596, −0.00373619, −0.0112106, −0.0112106, −0.0112106, 1.36429×10^{-6}, 0.499999, −0.499999, -1.36429×10^{-6}, -1.12974×10^{-6}, -1.36429×10^{-6}, -1.36429×10^{-6}, -1.36129×10^{-6}}

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

runDM: code for RGE

Inclusion of RGE effects automatic

FD, Kavanagh, Panci, arXiv:1605.04917

OUTPUT II:

RG evolved couplings for direct detection

runDM-examples.nb

DDCouplingsQuarks: calculating low-energy DM-quark couplings

If we're only interested in direct detection experiments, we can use the function DDCouplingsQuarks[c, E_1] to extract the couplings to light quarks. In this case, the code evolves the couplings from energy E_1, down to the nuclear energy scale ~ 1 GeV. The output is an array with 5 elements, the vector and axial-vector couplings to light quarks: $c_q = (c_V{}^{(u)}, c_V{}^{(d)}, c_A{}^{(u)}, c_A{}^{(d)}, c_A{}^{(s)})$. Let's calculate them and print them out.

In[13]:=

```
(*Run from 10 TeV to 1 GeV*)
E1 = 10 000;
cq = DDCouplingsQuarks[chigh, E1];

clabels = {"cV(u)", "cV(d)", "cA(u)", "cA(d)", "cA(s)"};
Grid[Transpose[{clabels, cq}]]
```

Out[16]=

$c_V{}^{(u)}$	0.0145847
$c_V{}^{(d)}$	0.492712
$c_A{}^{(u)}$	8.56843×10^{-6}
$c_A{}^{(d)}$	0.499991
$c_A{}^{(s)}$	-8.56843×10^{-6}

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

RGE Handbook

Interested in the RGE-induced currents with light quarks

$M_{\rm med}$

$V_\mu \, \overline{f_{\rm SM}} \gamma^\mu \, f_{\rm SM}$

$V_\mu \, \overline{f_{\rm SM}} \gamma^\mu \gamma^5 \, f_{\rm SM}$

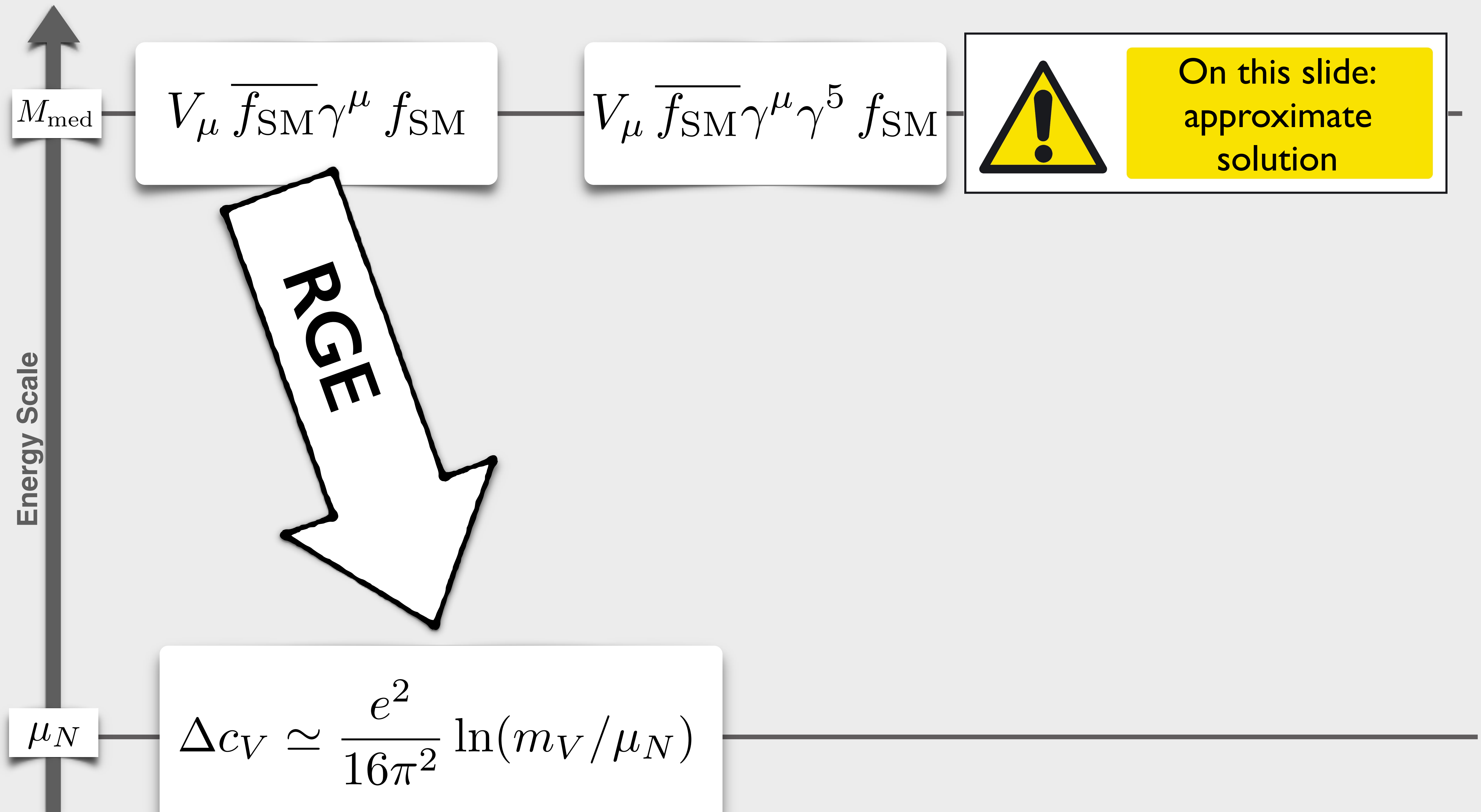
On this slide: approximate solution

Energy Scale

μ_N

RGE Handbook

Interested in the RGE-induced currents with light quarks



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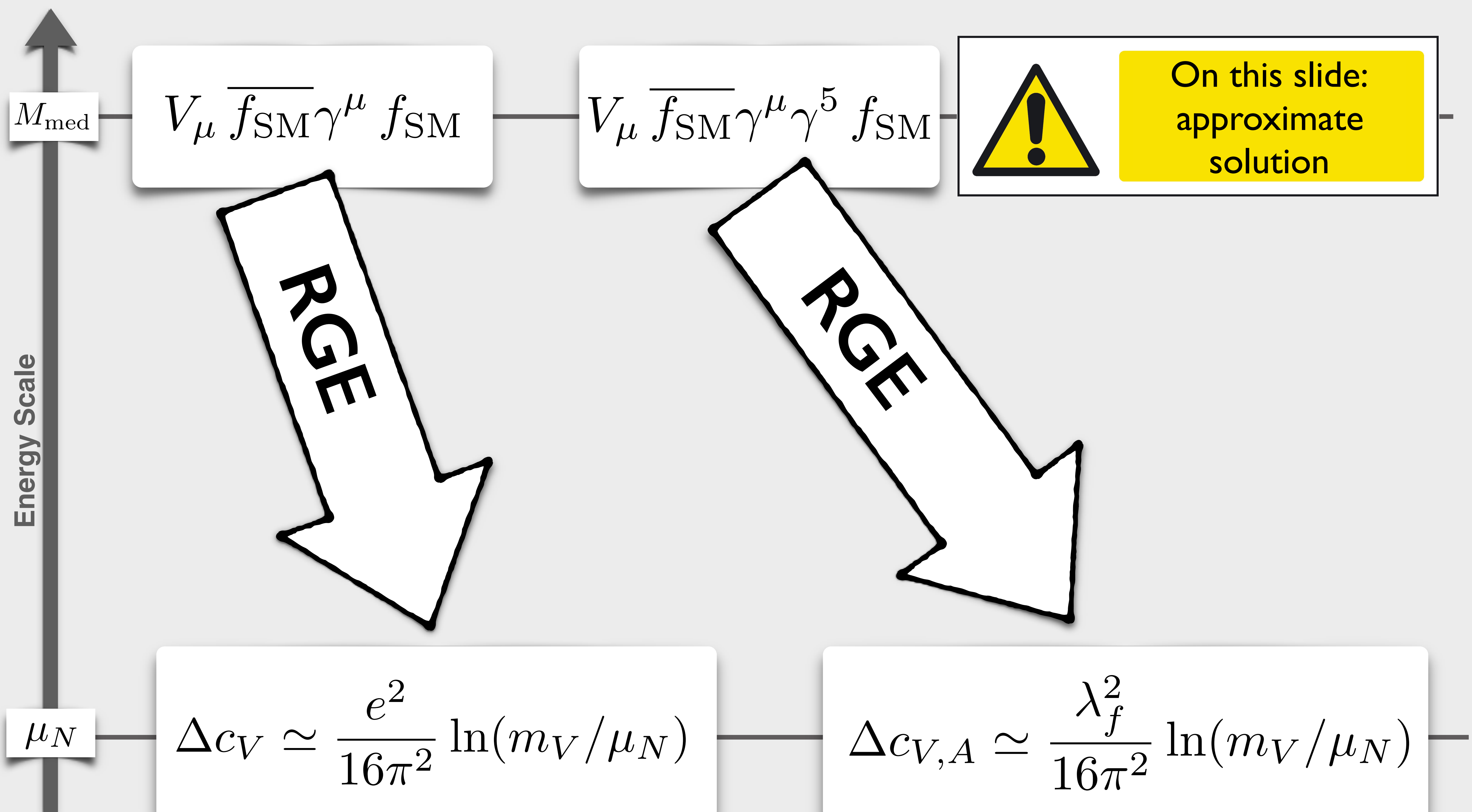

Results I: quarks vector

Flavor universal couplings to quark vector currents

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

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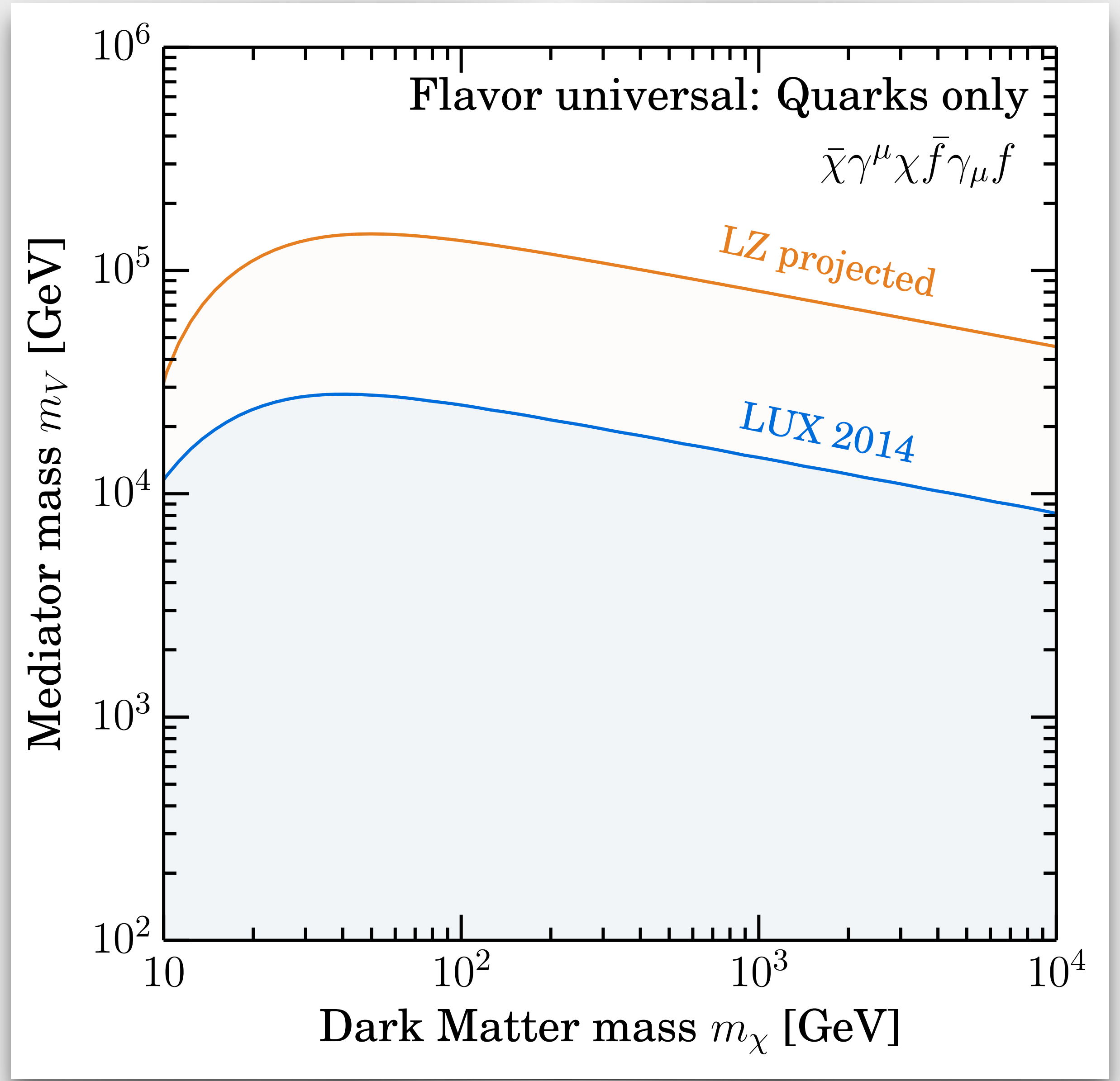

FD, Kavanagh, Panci, arXiv:1605.04917

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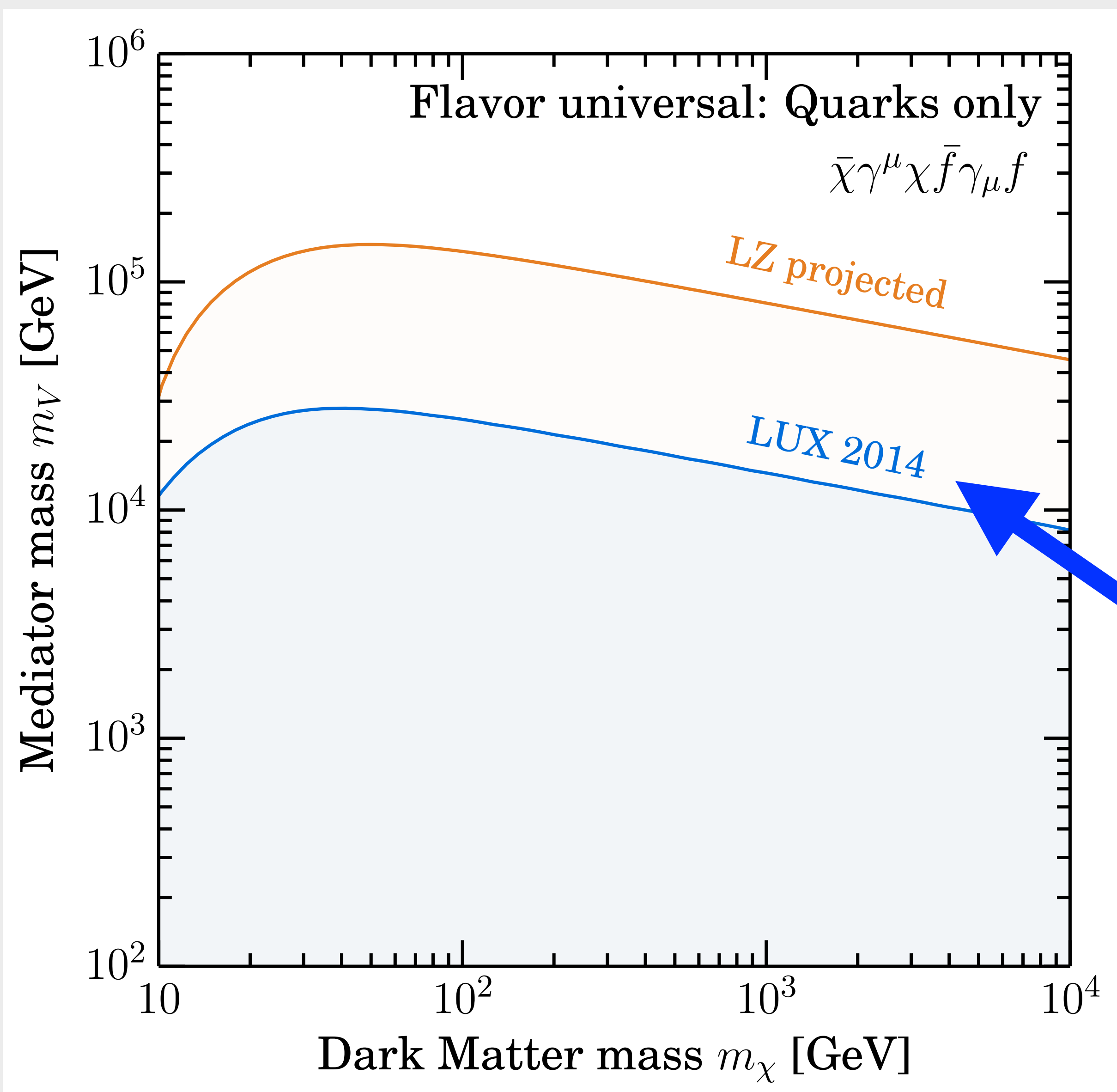

RGE:
O(1%) correction to EFT couplings

Very strong bounds, meaningful results also for loop-induced rates

FD, Kavanagh, Panci, arXiv:1605.04917

Results II: quarks axial

Flavor universal couplings to quark axial currents

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

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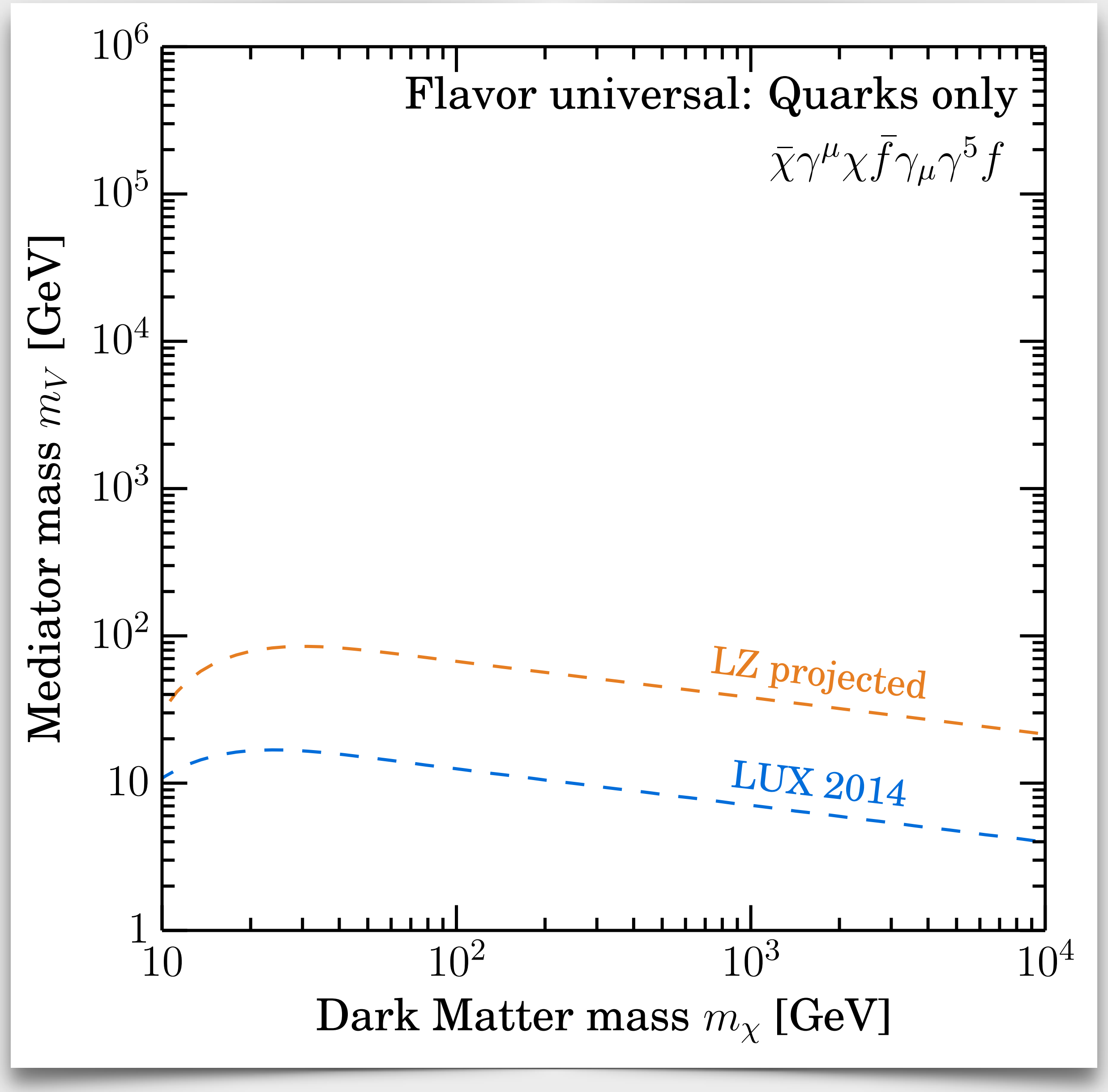

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Flavor universal couplings to quark axial currents

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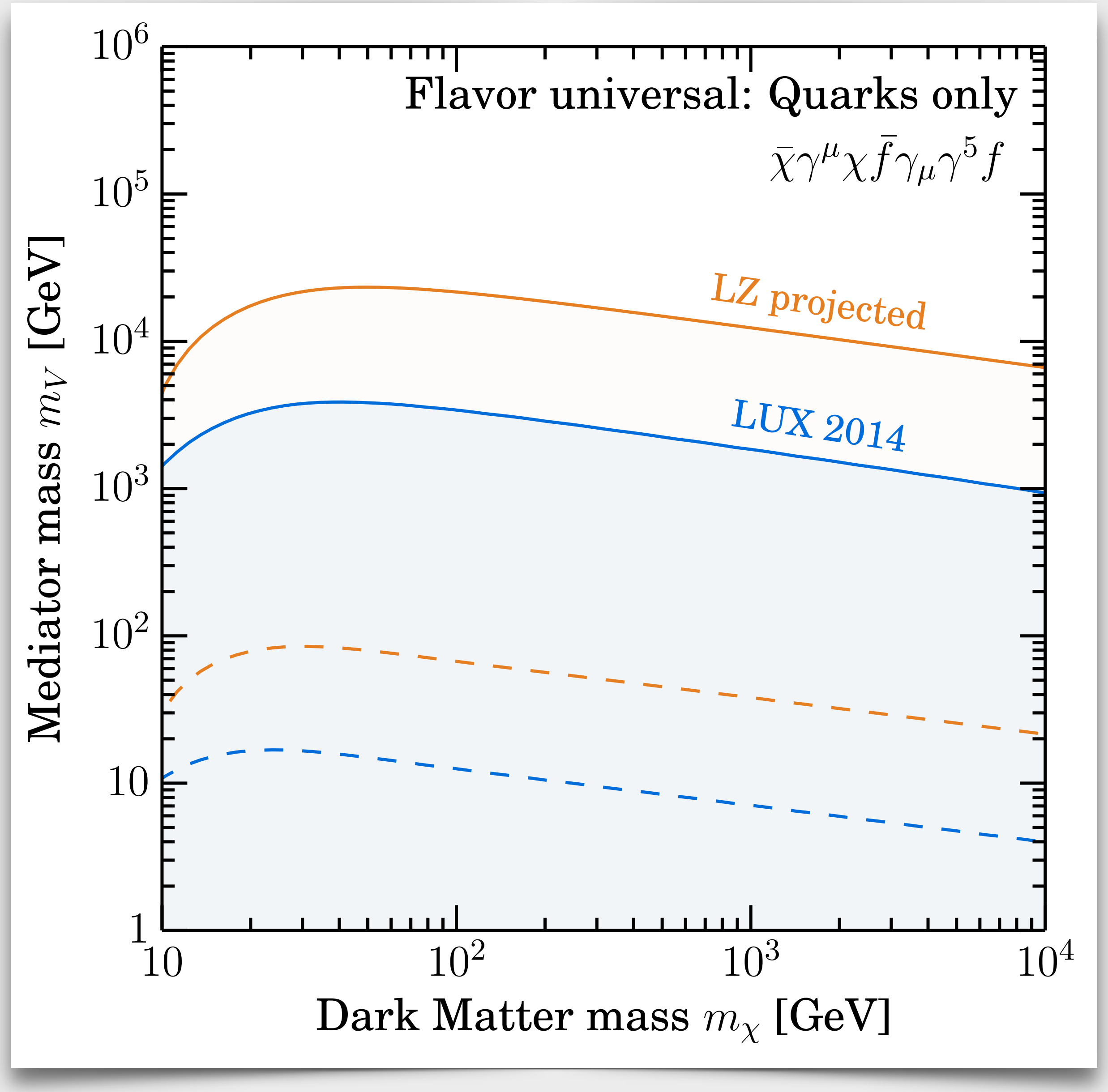

without RGE

with RGE

FD, Kavanagh, Panci, arXiv:1605.04917

Results II: quarks axial

Flavor universal couplings to quark axial currents

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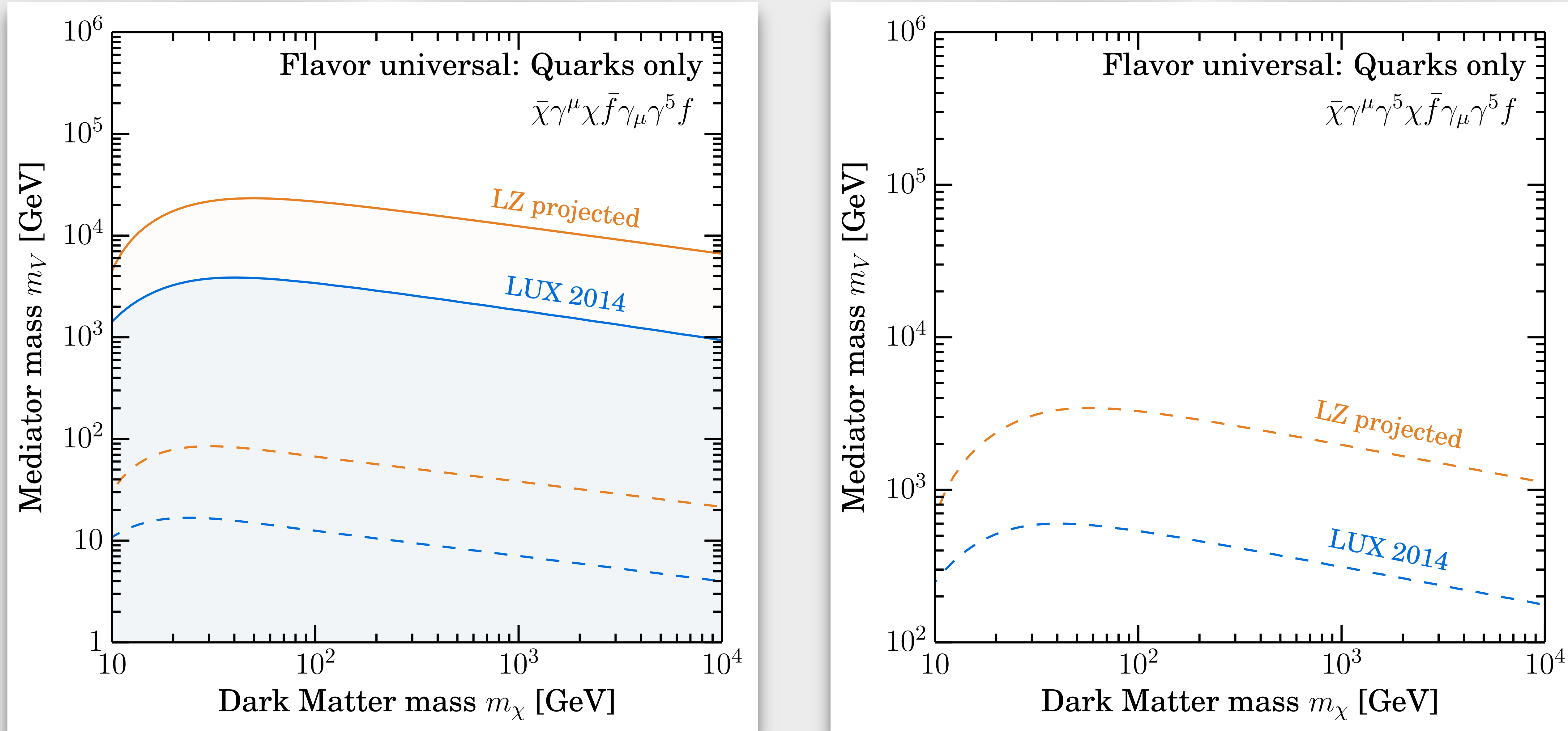

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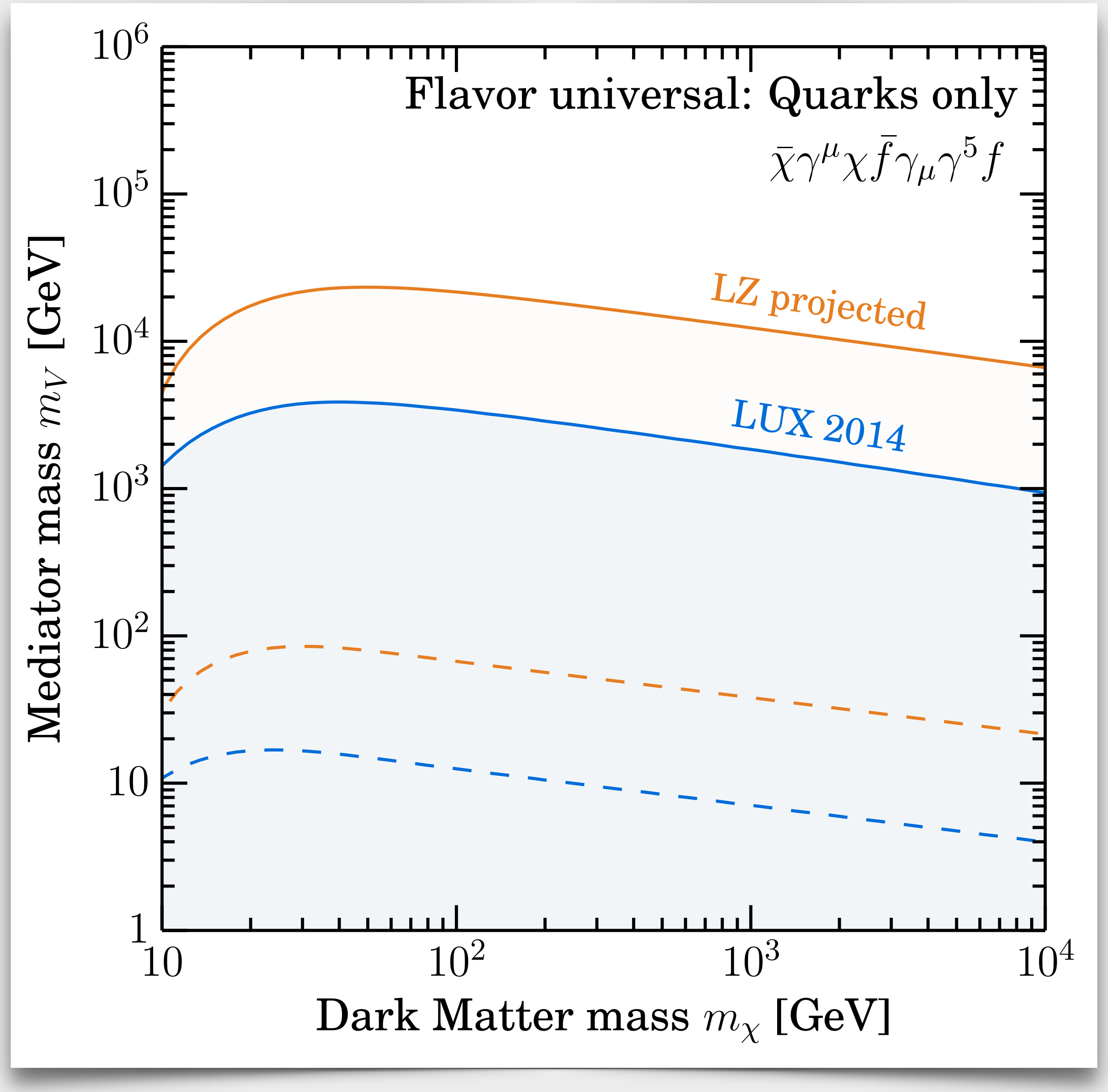
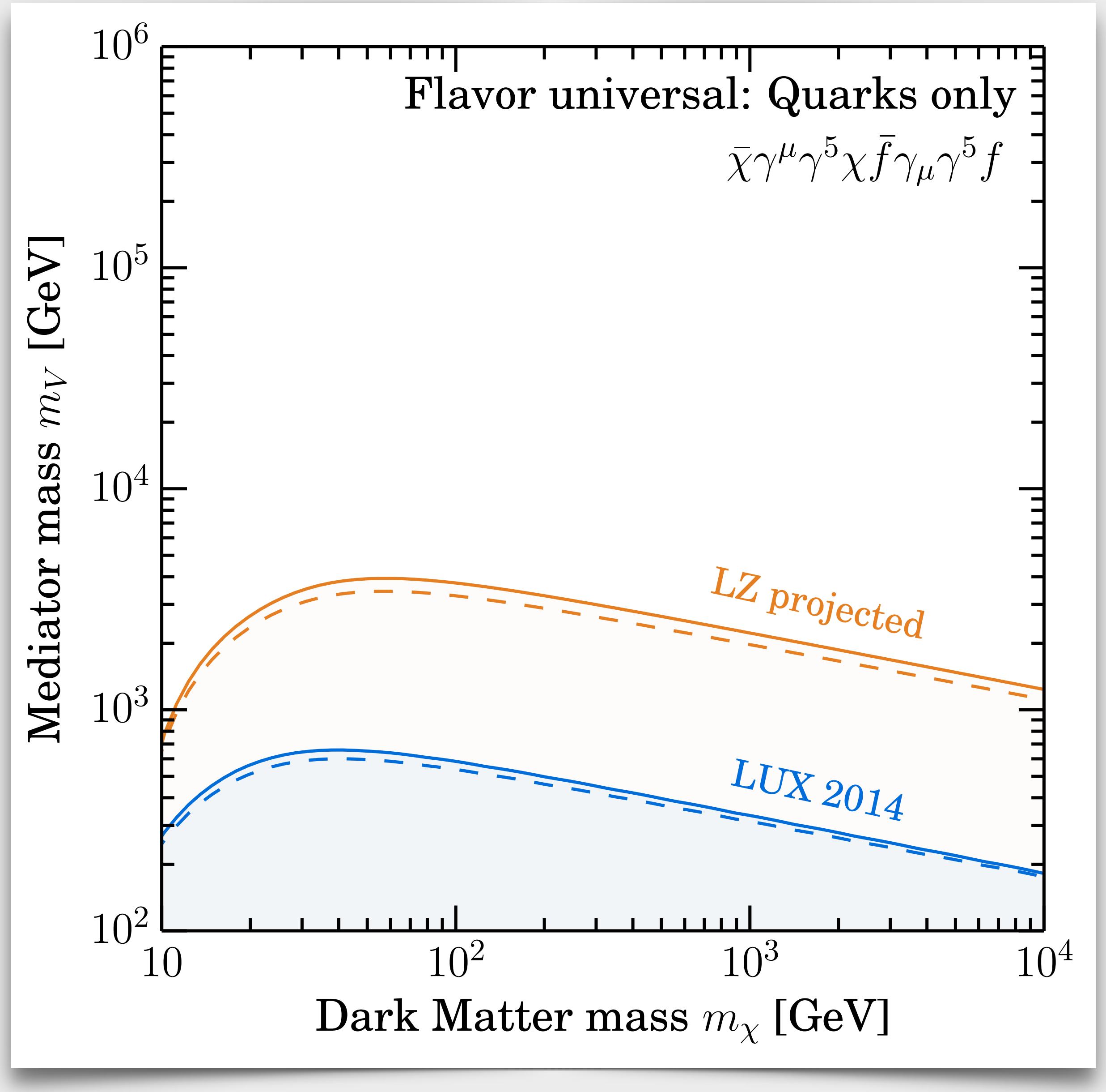
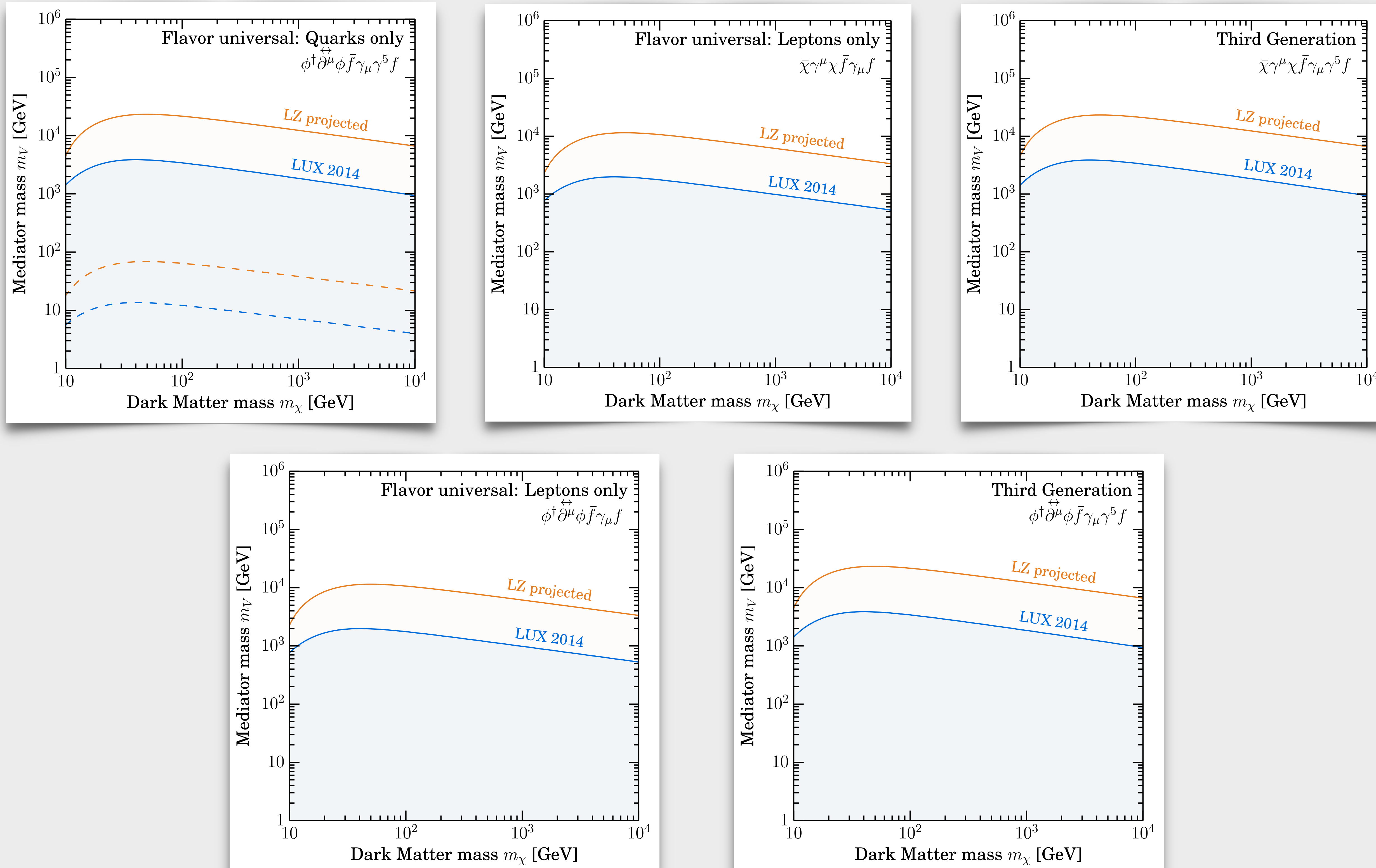




FD, Kavanagh, Panci, arXiv:1605.04917

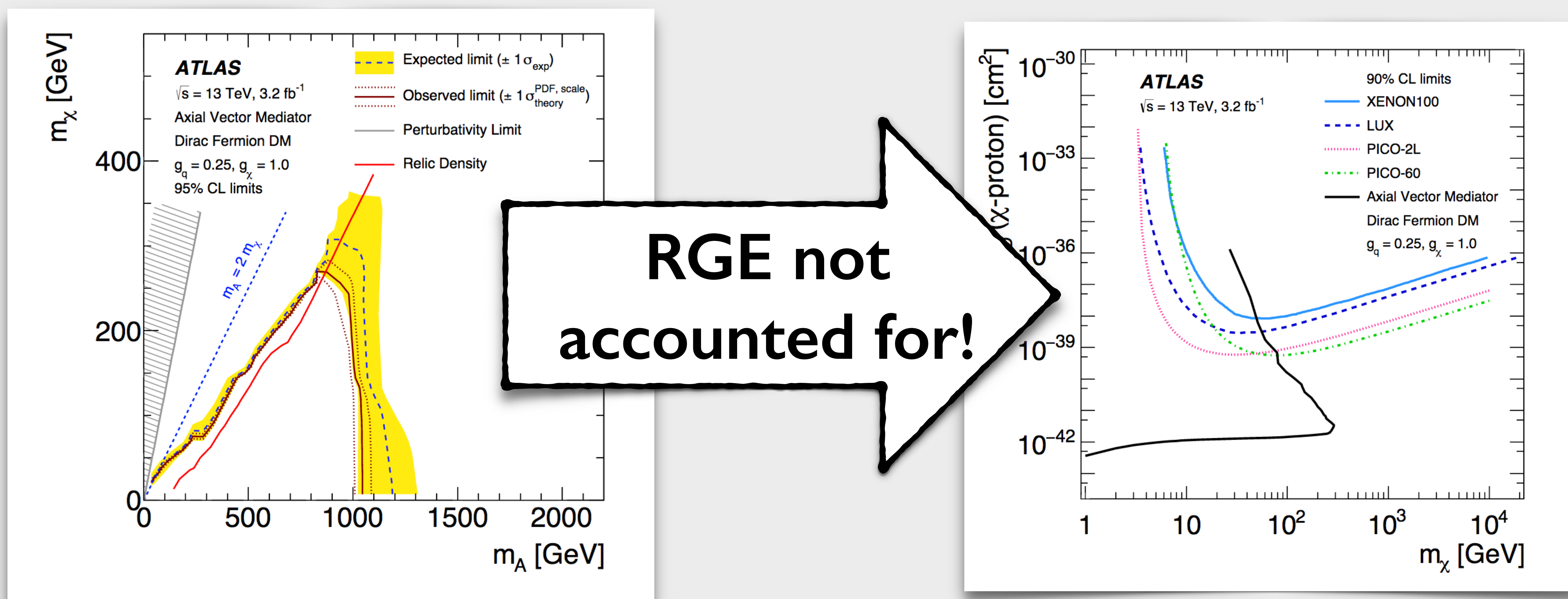
Results III: other cases



FD, Kavanagh, Panci, arXiv:1605.04917

Comparison with LHC

LHC limits on mediator mass translated into limits on direct detection cross section



LUX, arXiv:1602.03489 and PICO-2L, arXiv:1601.03729

ATLAS, arXiv:1604.07773 (mono-jet) and arXiv:1604.01306 (mono-photon)

Impact of the running

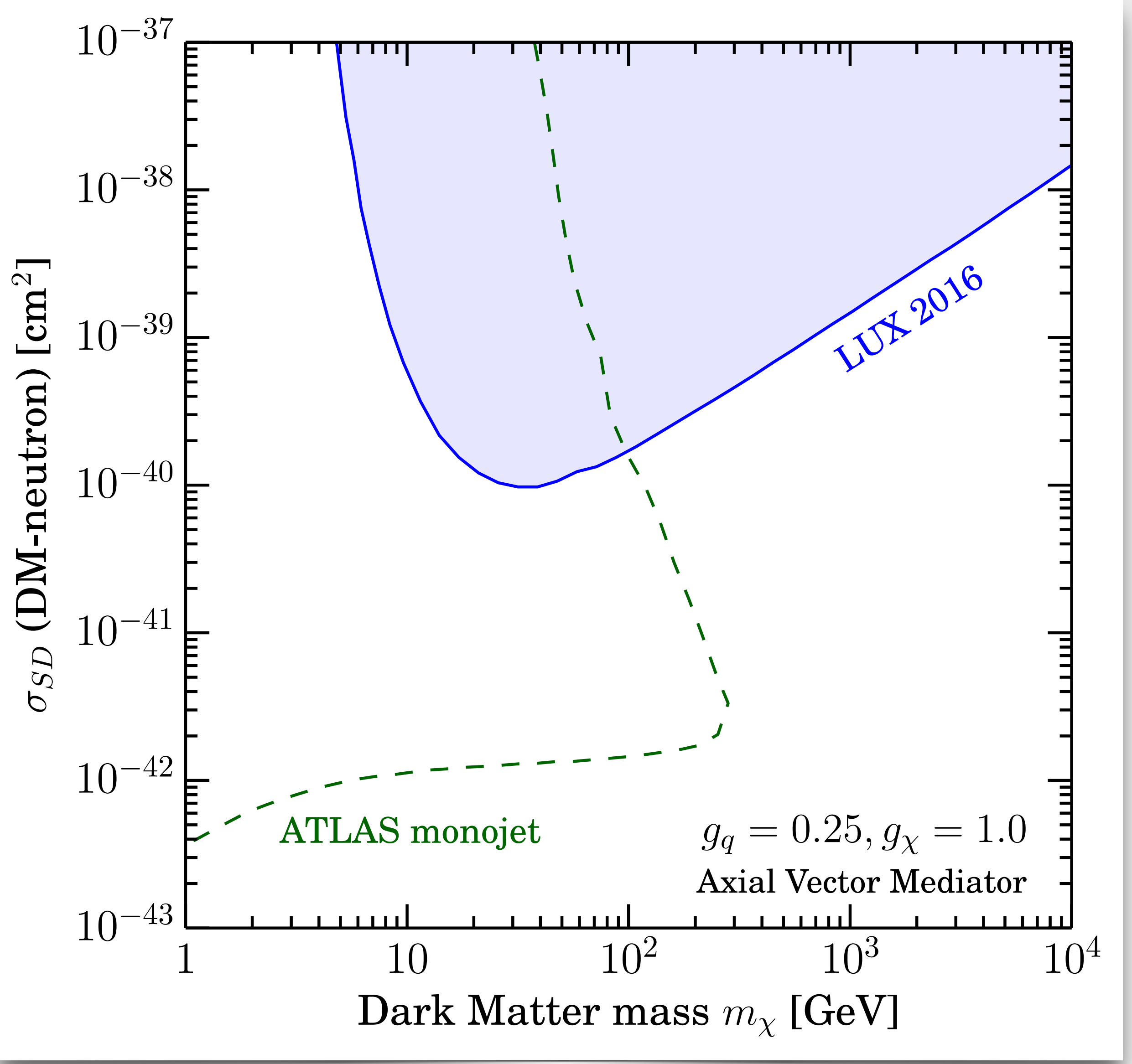
$$\sigma_{\rm SD}^{N} = \frac{3\mu_N^2}{\pi} \frac{\left(c_{\chi A}\mathcal{C}_A^{(N)}\right)^2}{m_V^4}$$

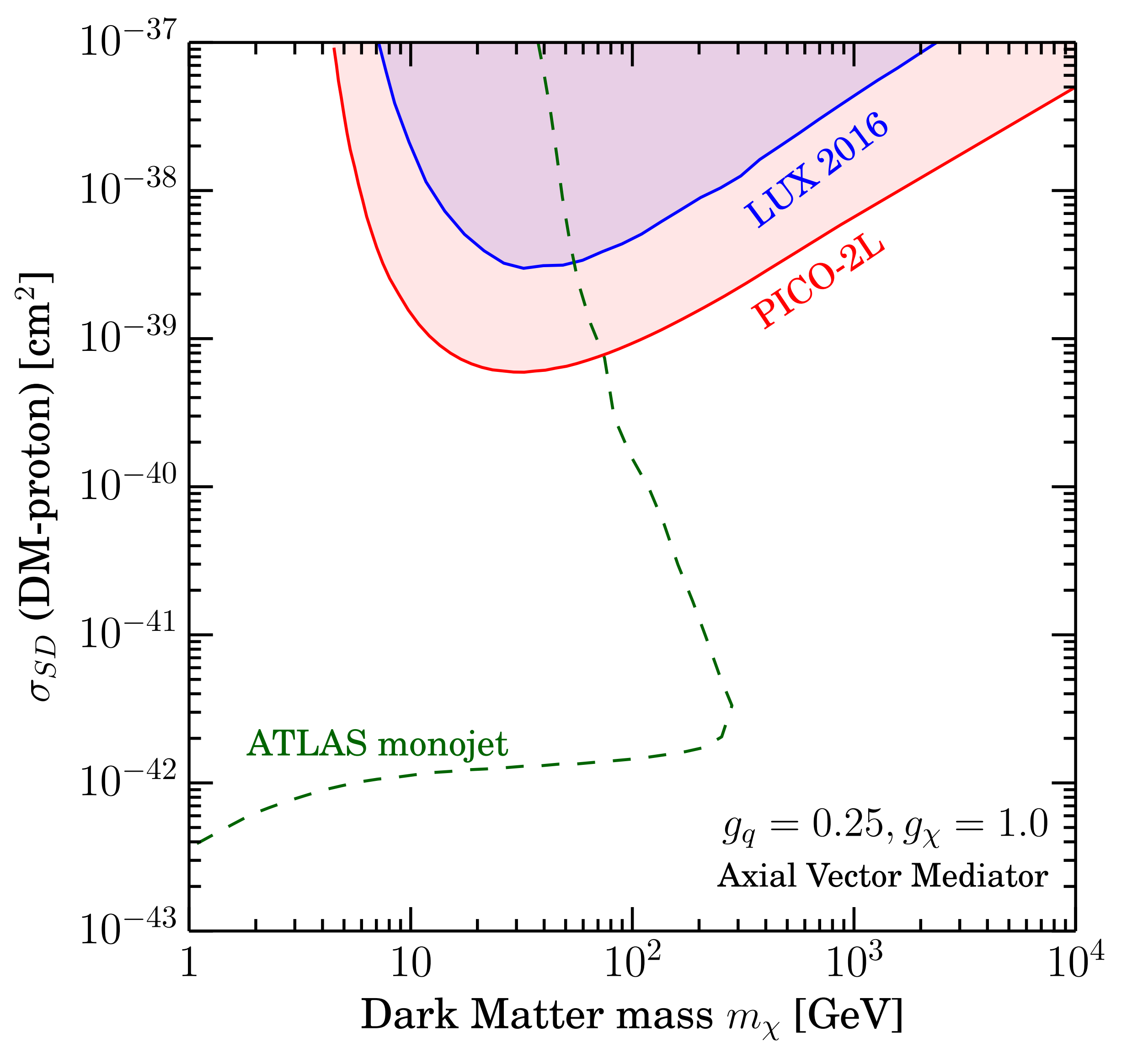
$$\mathcal{C}_A^{(N)} \simeq g_q \left[\sum_{q=u,d,s} \Delta_q^{(N)}\right] + g_q \frac{3\alpha_t}{2\pi}\left(\Delta_d^{(N)} + \Delta_s^{(N)} - \Delta_u^{(N)}\right) \ln(m_V/m_Z)$$

Tree-level

Loop-induced

Mono-jet Searches





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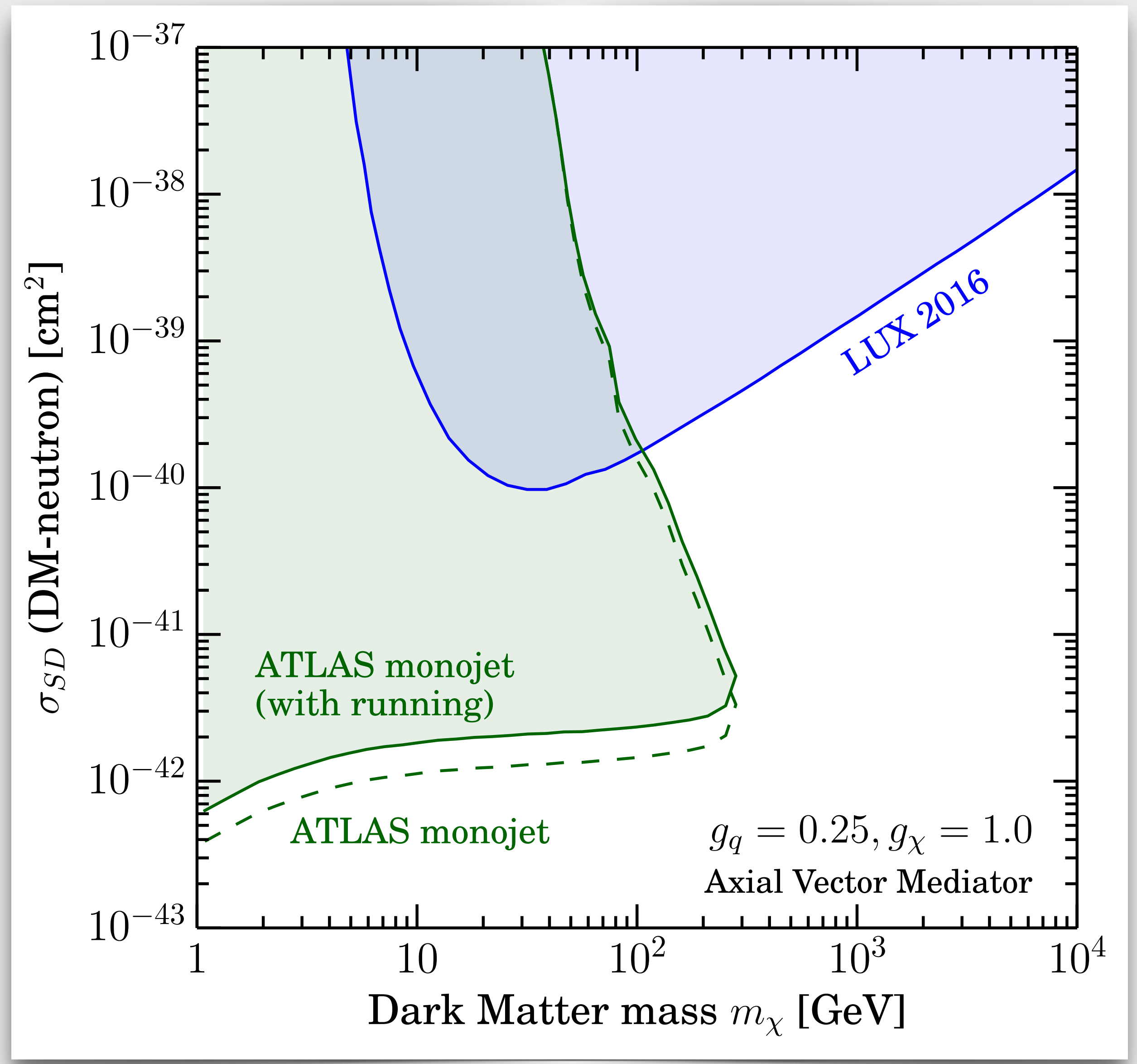

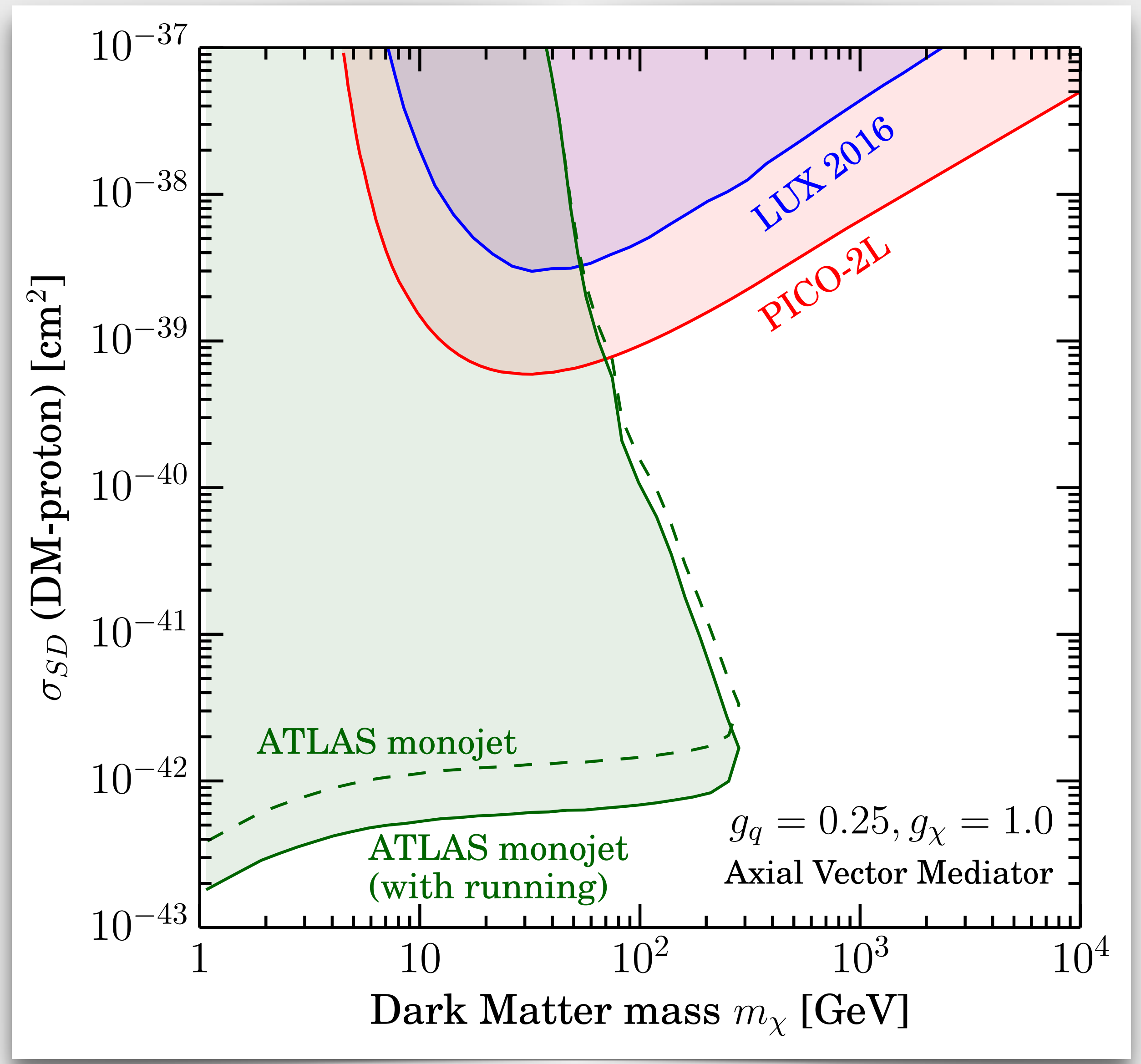

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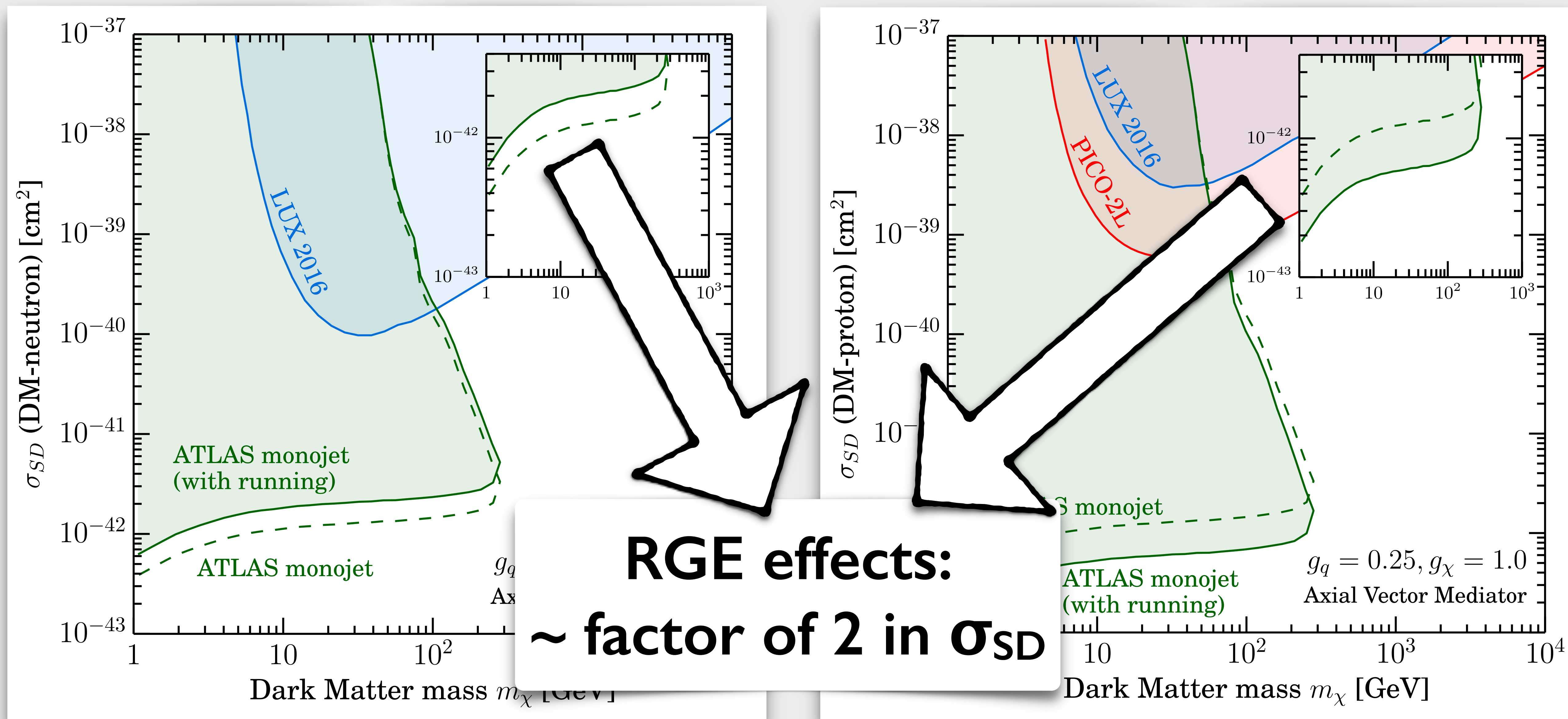

LUX, arXiv:1602.03489 and PICO-2L, arXiv:1601.03729

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Outlook

How well can be constrained by collider and direct detection?

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

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

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How well can be constrained by collider and direct detection?

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

~ same as the others

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Outlook

How well can be constrained by collider and direct detection?

Standard Lore

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

~ same as the others

Spin-Independent (SI), no suppression

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

~ same as the others

Spin-Dependent (SD), no suppression

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

~ same as the others

SD with v

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

~ same as the others

SI with v

Outlook

How well can be constrained by collider and direct detection?

Standard Lore

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

~ same as the others

Spin-Independent (SI), no suppression

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

~ same as the others

Spin-Dependent (SD), no suppression (large corrections)

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

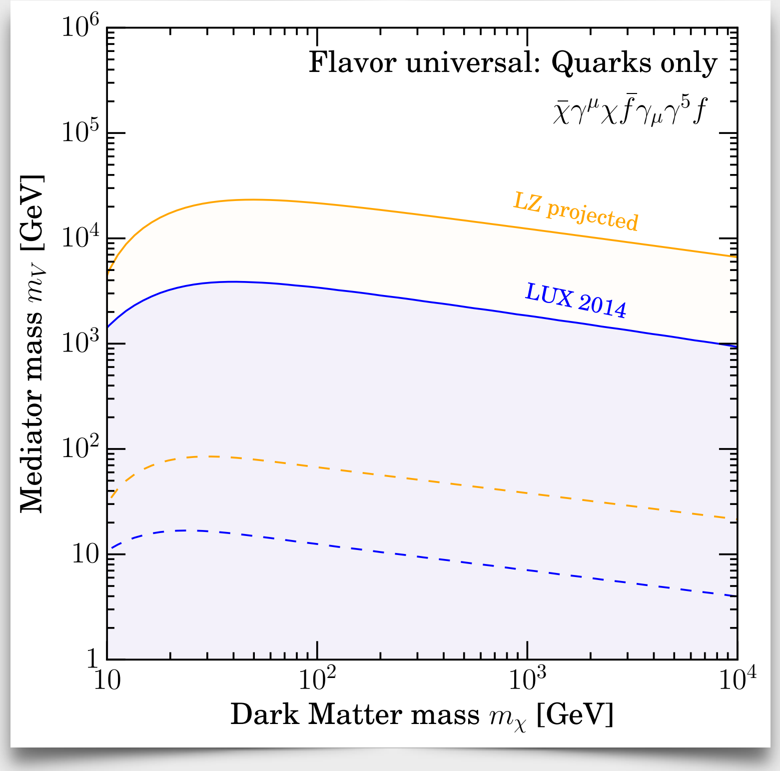
~ same as the others

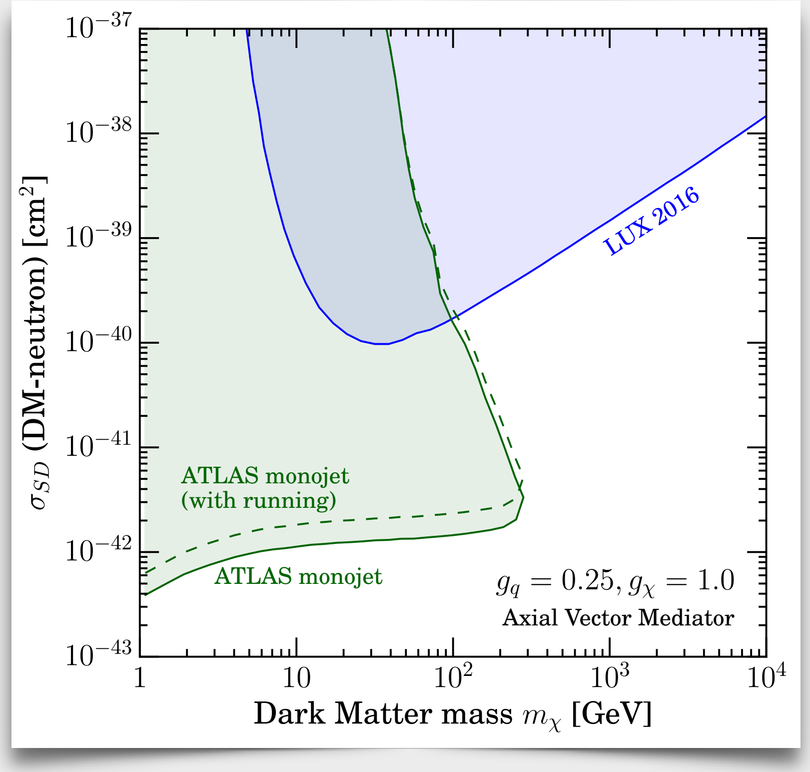
Spin-Independent (SI) at one-loop

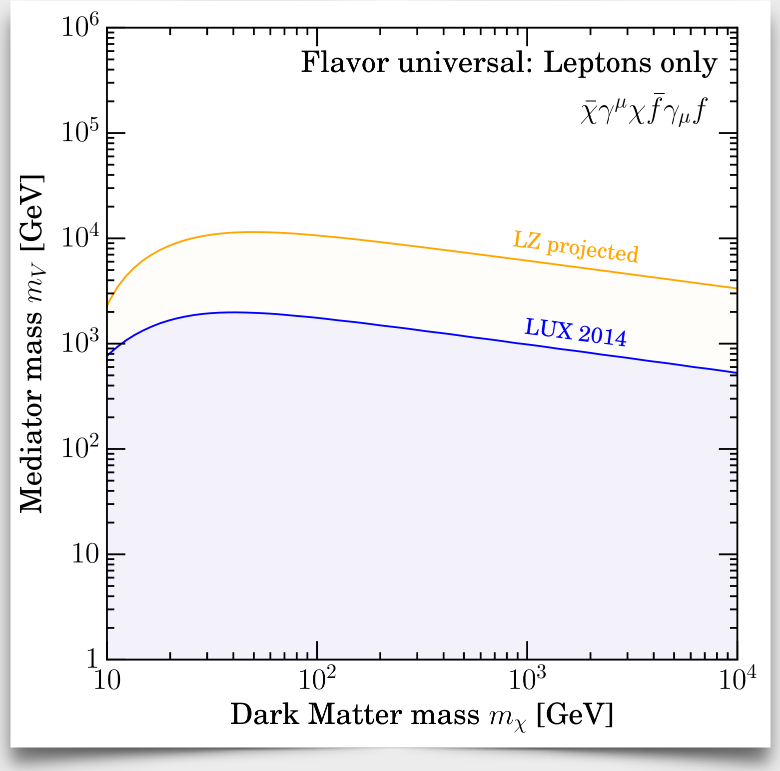
But if you run...
(and you have to run!)

Outlook

Direct detection rates and comparison with LHC: not always straightforward







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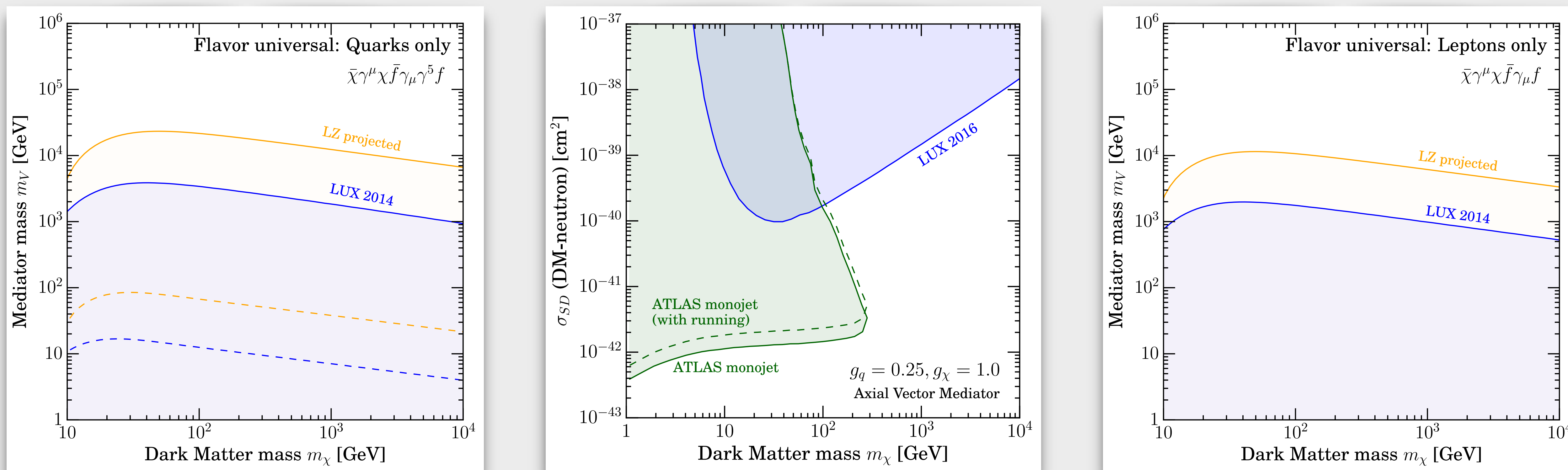
Still need to quantify RGE effects for other simplified models

Outlook

Direct detection rates and comparison with LHC: not always straightforward



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Thank You!