You can hide but you have to run: direct detection with vector mediators

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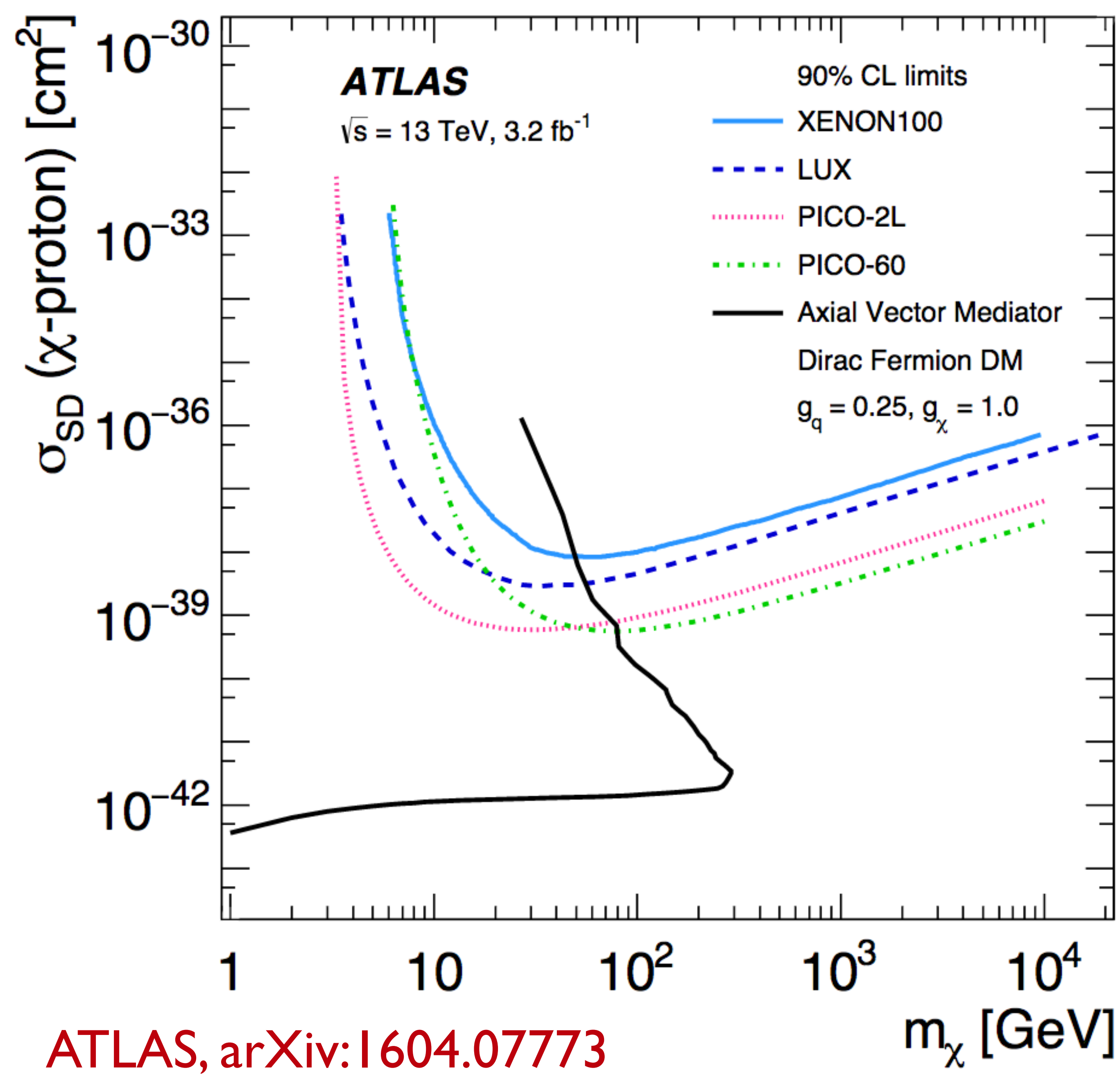
DMWG - 22 June 2016

LHC vs Direct Detection

Two probes of DM couplings at vastly different energies

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

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



ATLAS, arXiv:1604.07773

LHC vs Direct Detection

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

You have to run!

(Renormalization Group Evolution — RGE)

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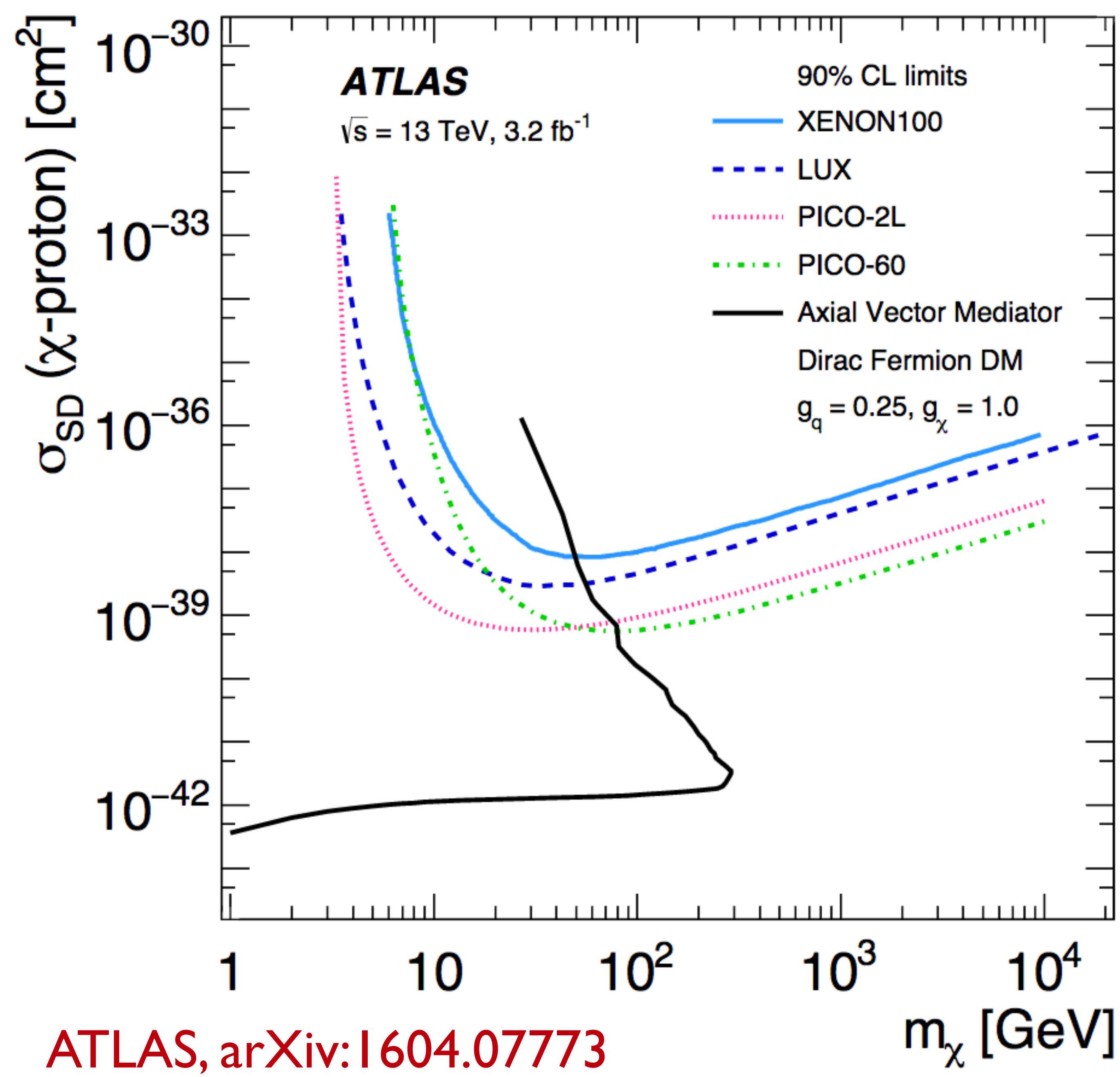

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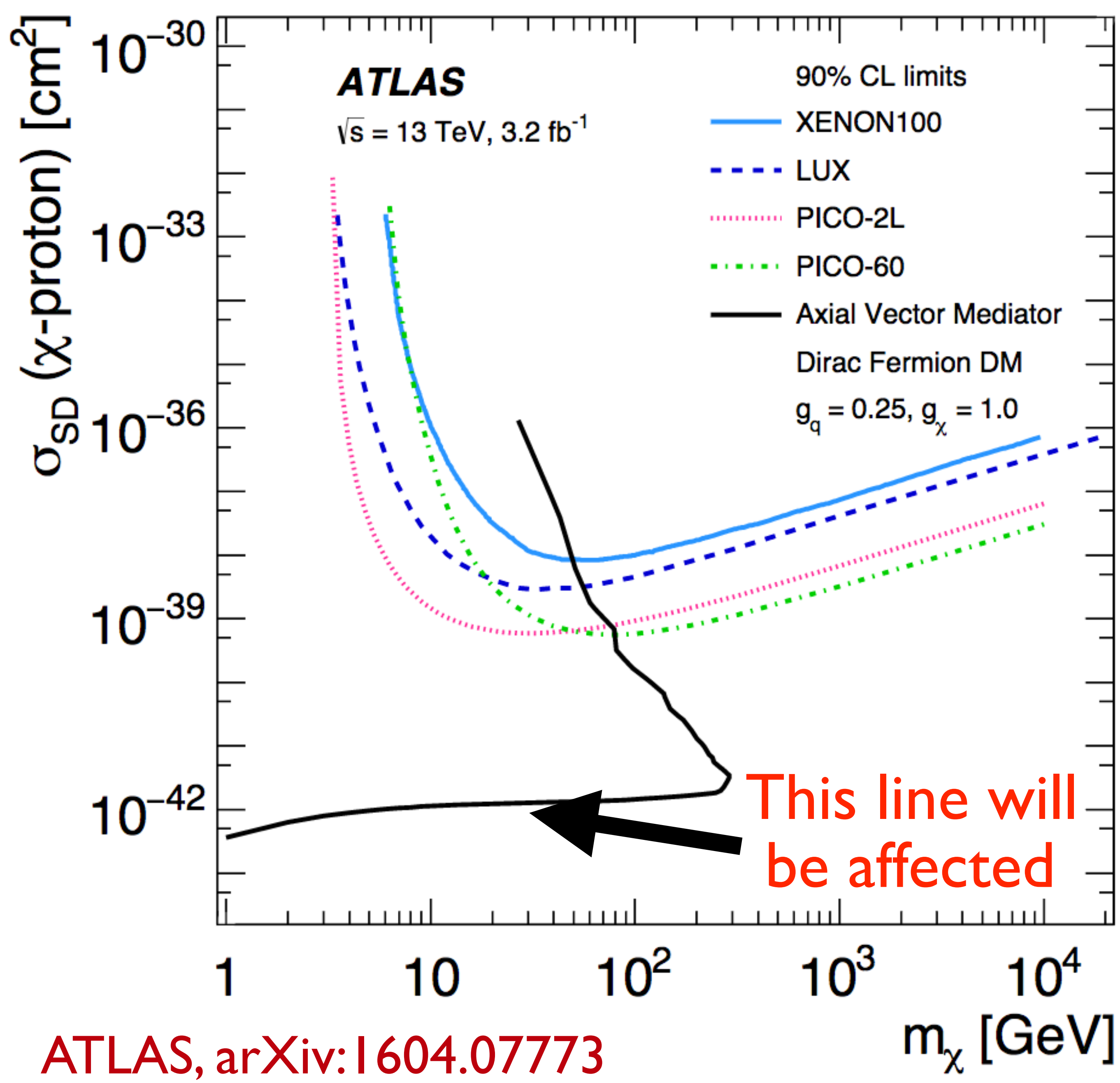

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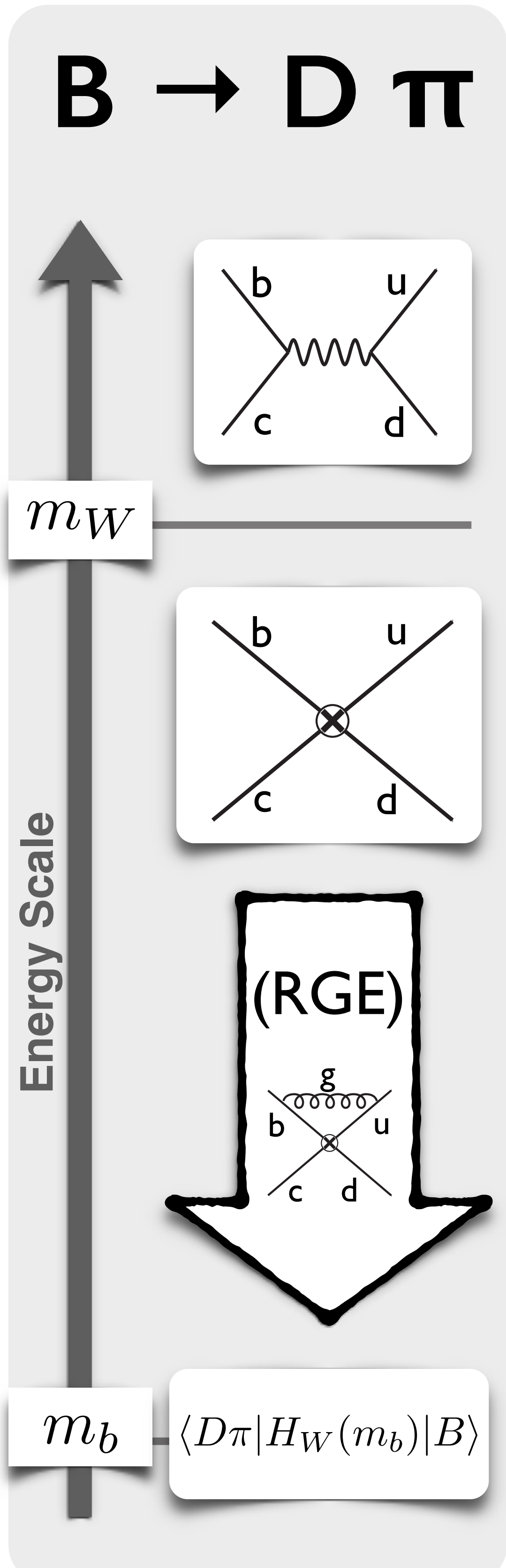
DM Direct Detection



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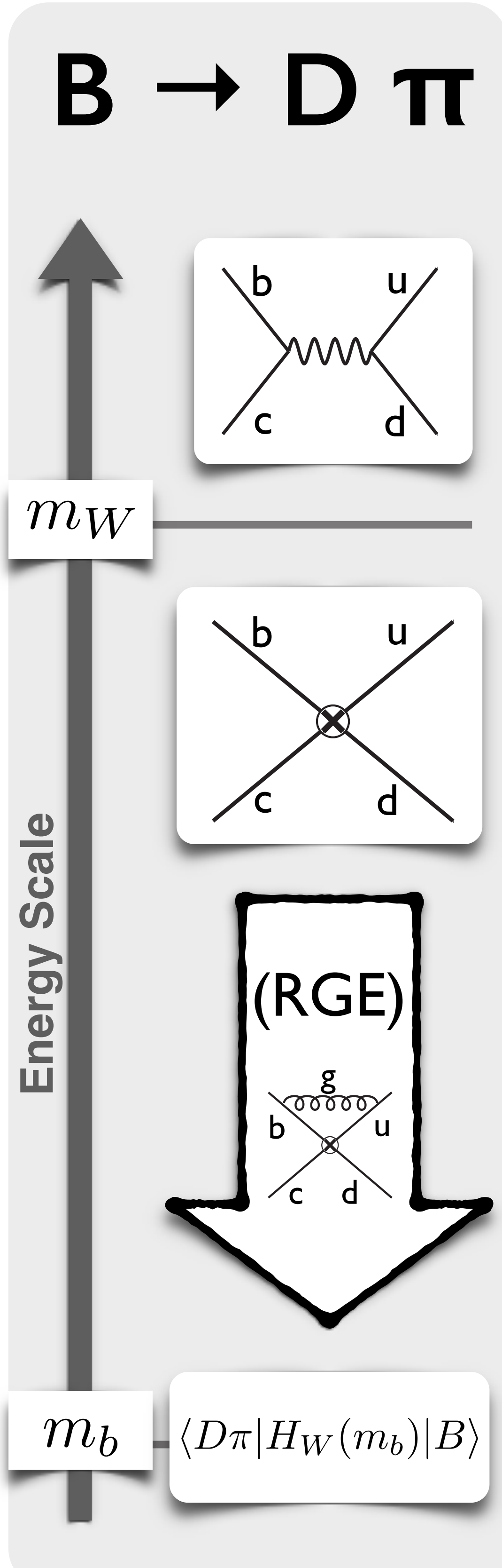

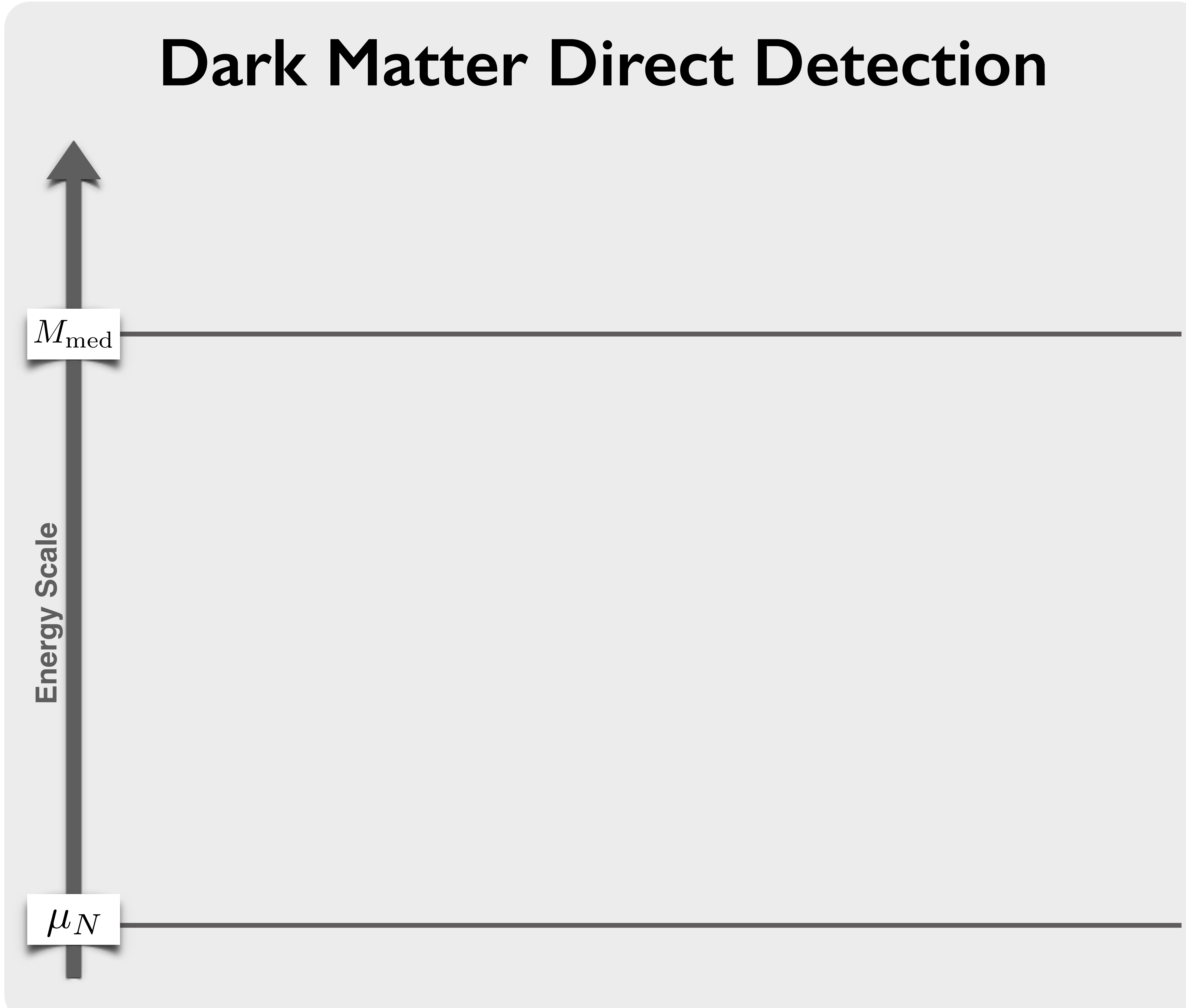

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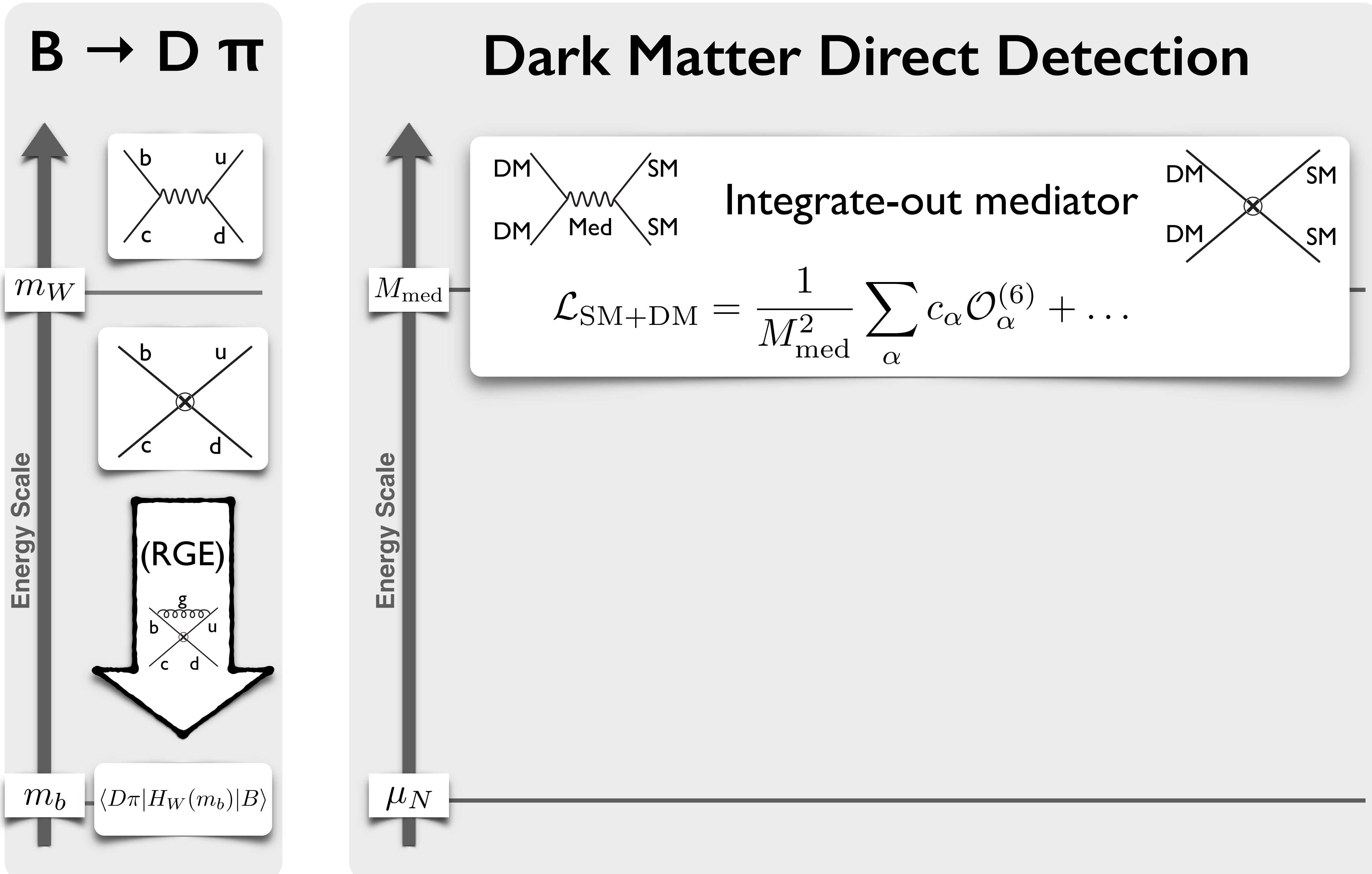

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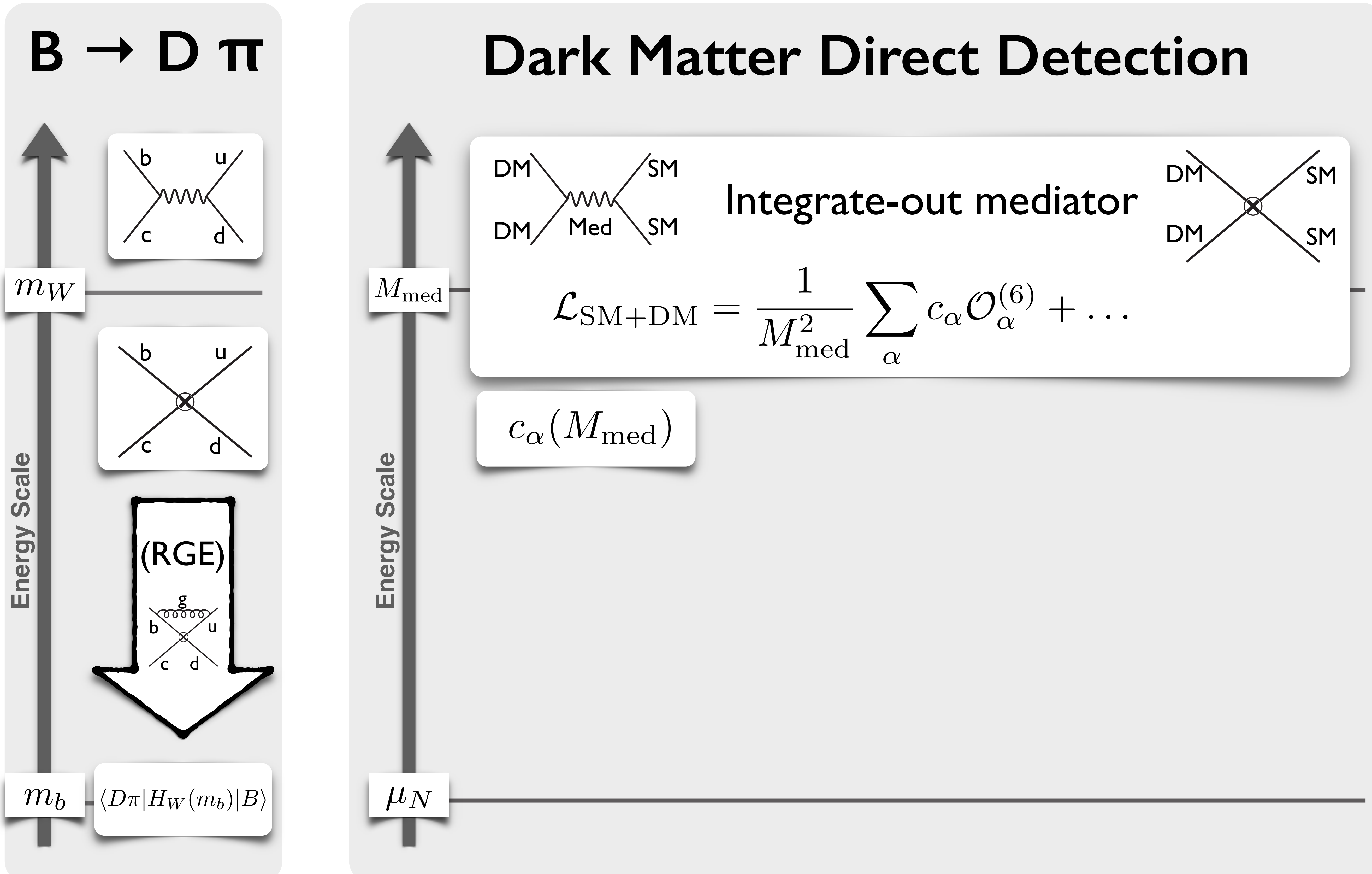

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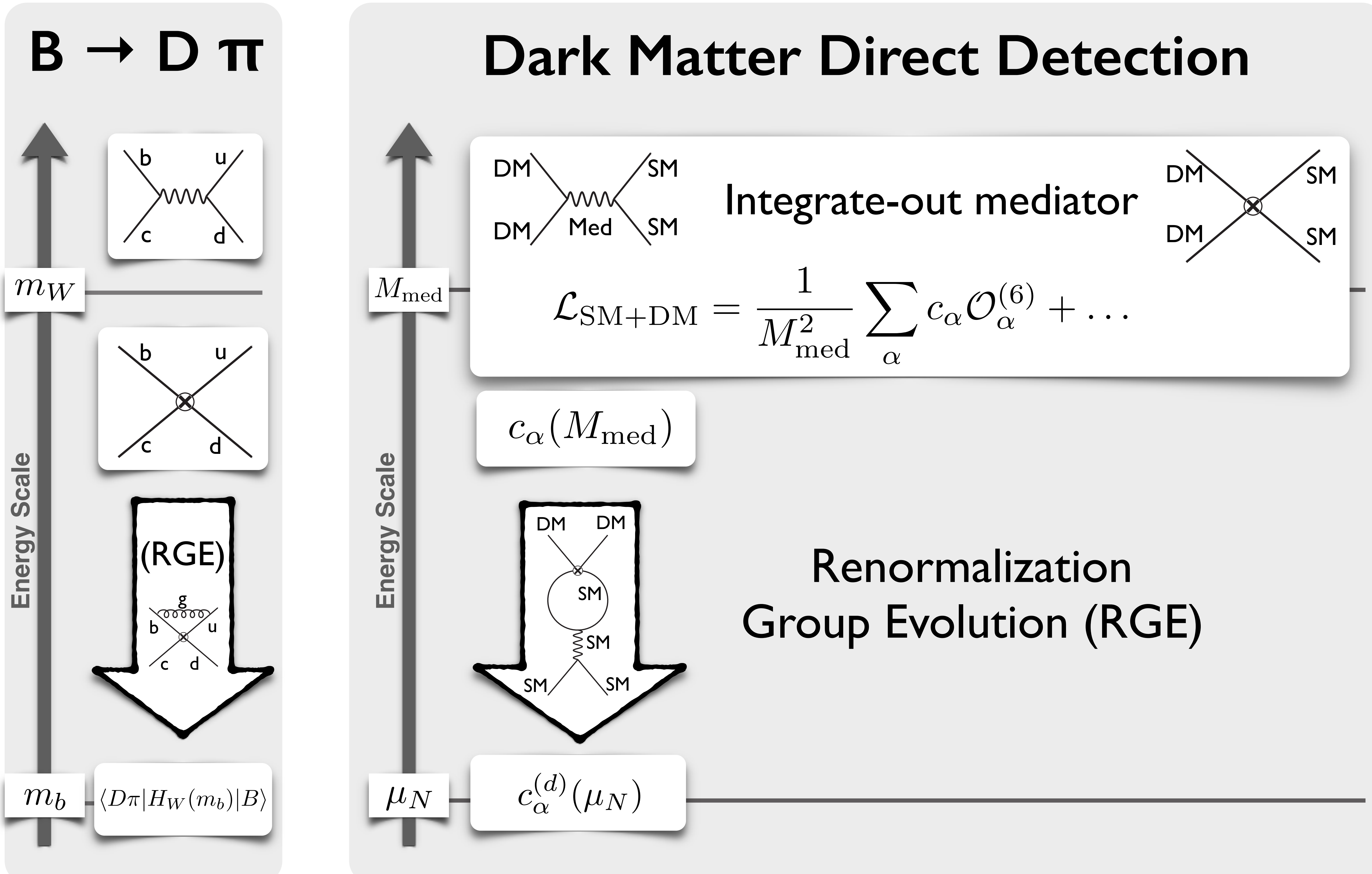

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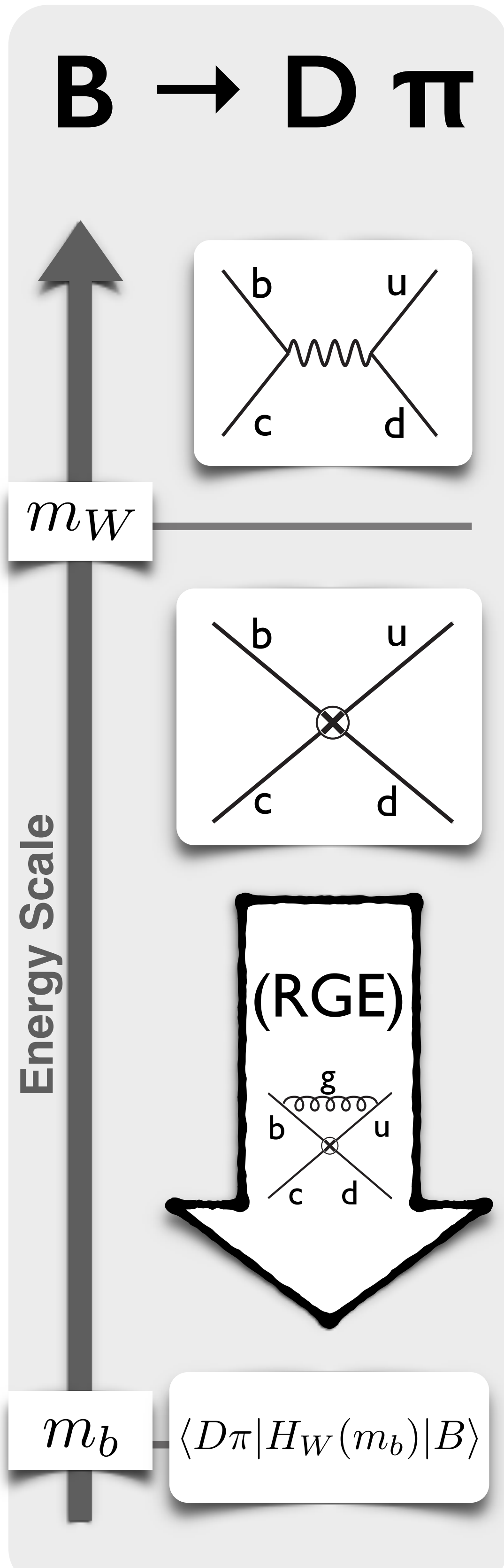
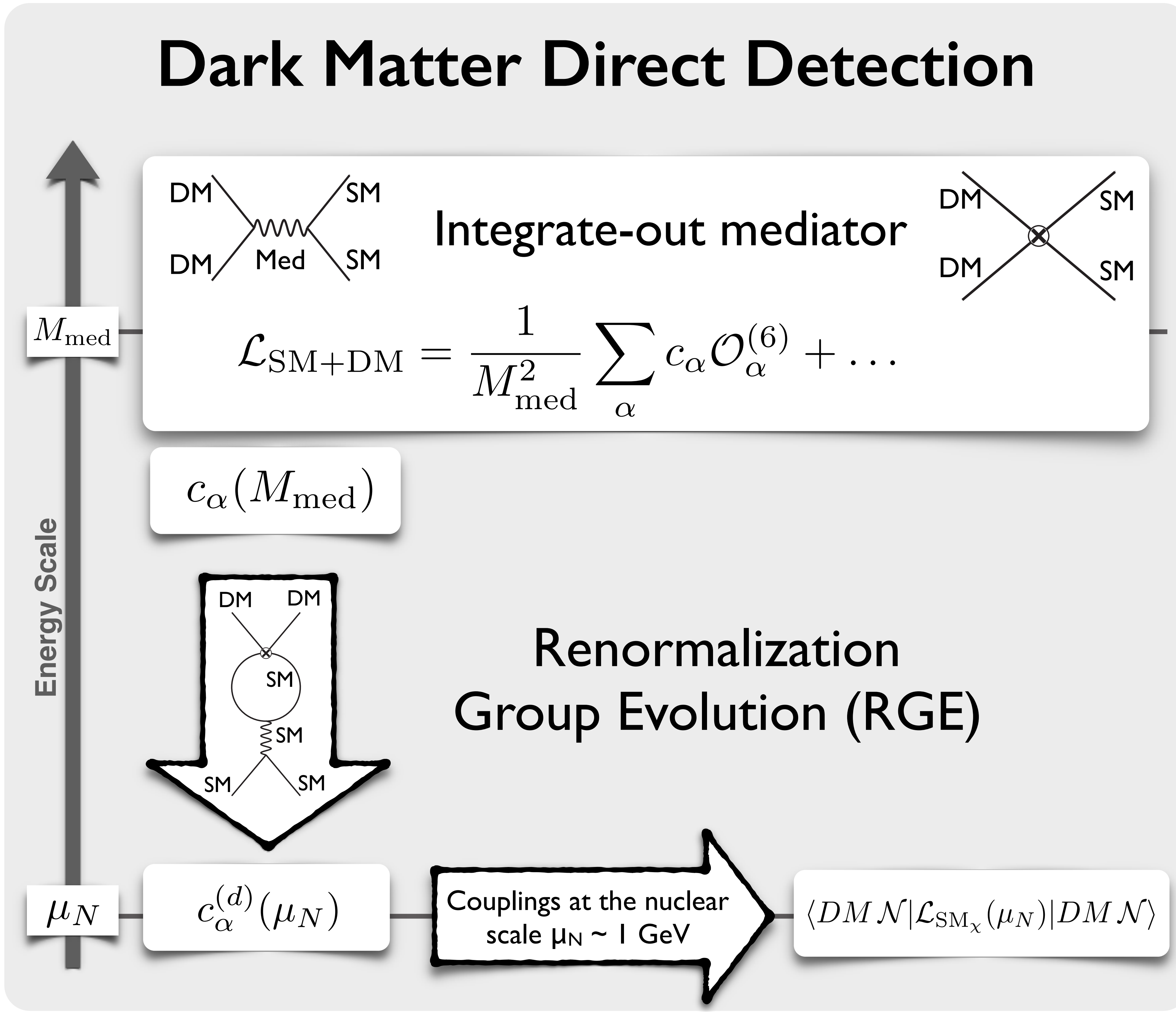
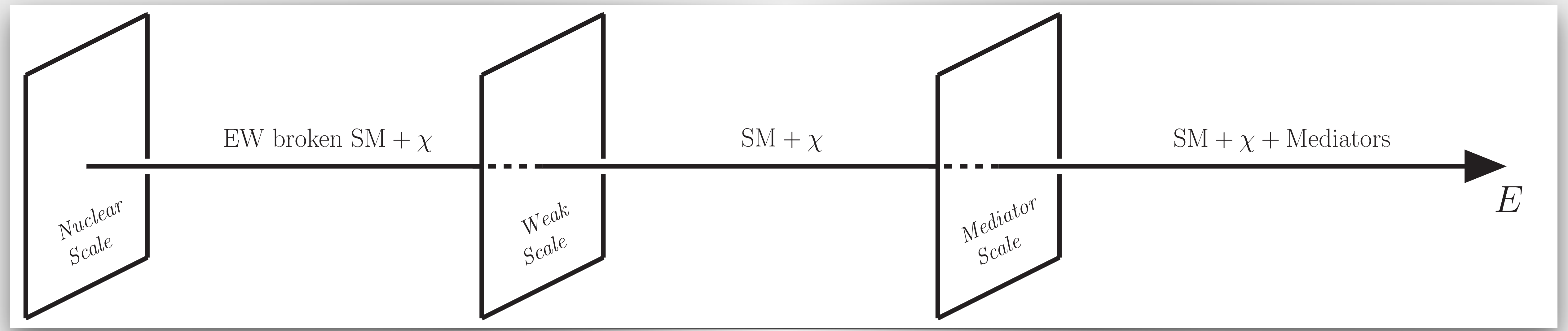




Vector Mediators RGE



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

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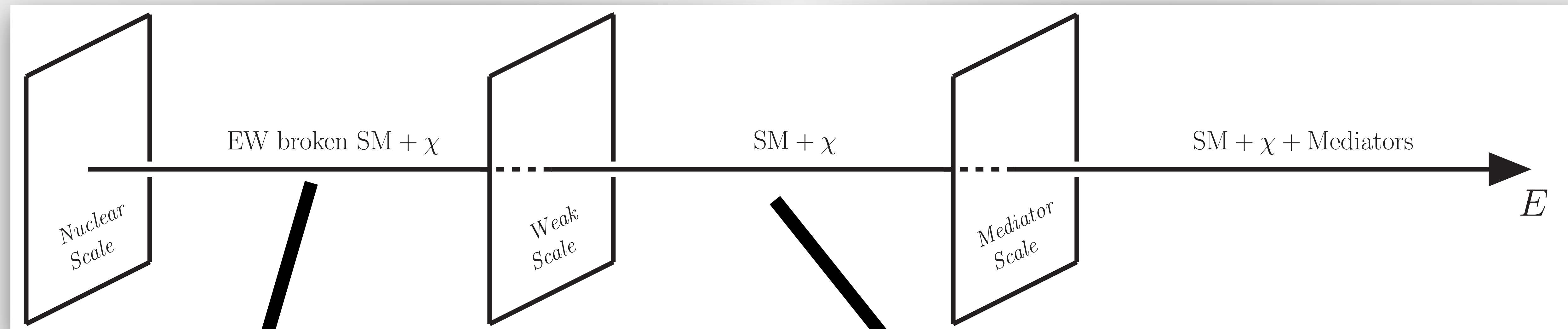

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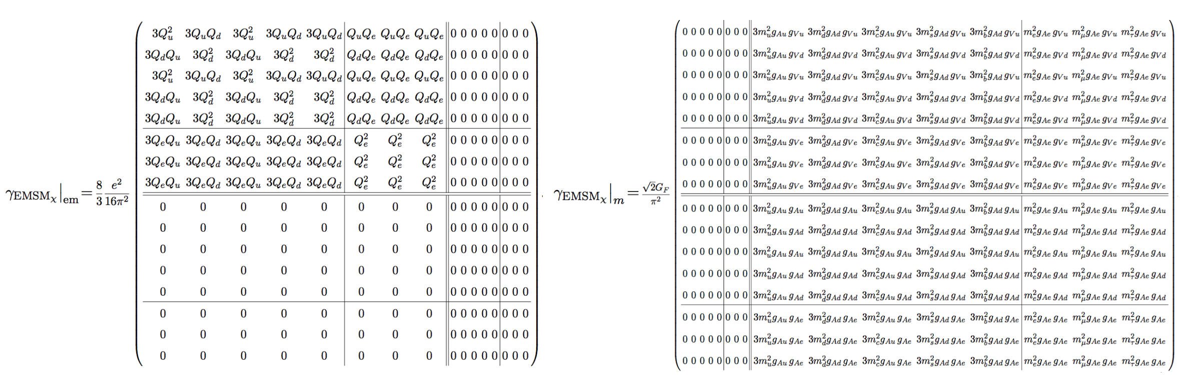
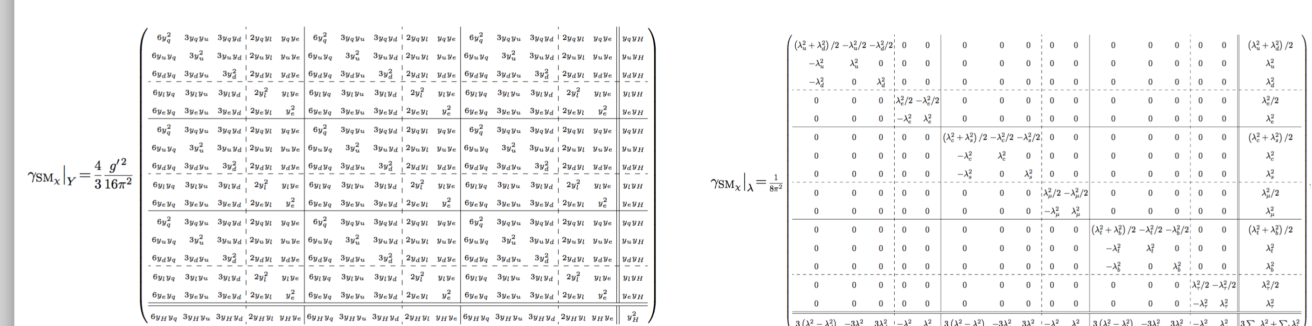


$$\frac{d\,c}{d\ln\mu} = \gamma_{\mathrm{SM}_\chi}\,c$$



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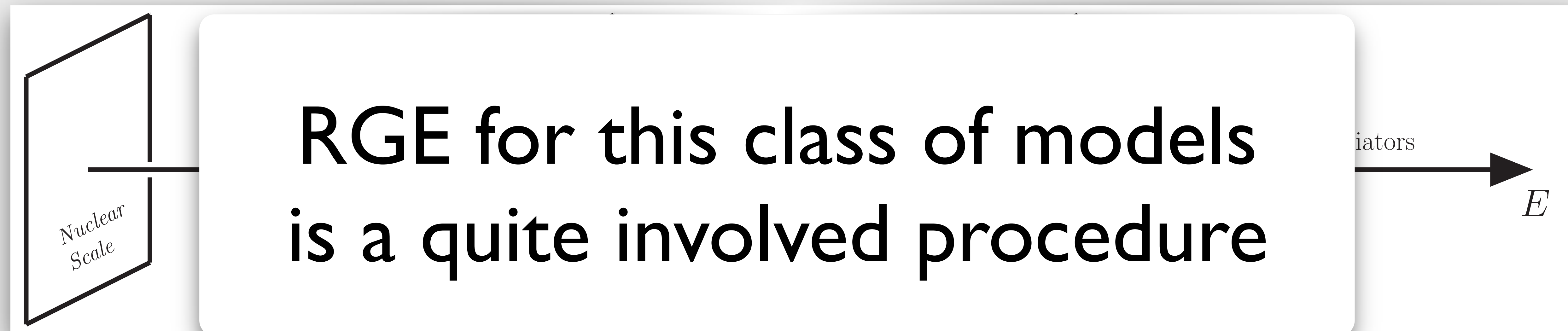

RGE for this class of models is a quite involved procedure

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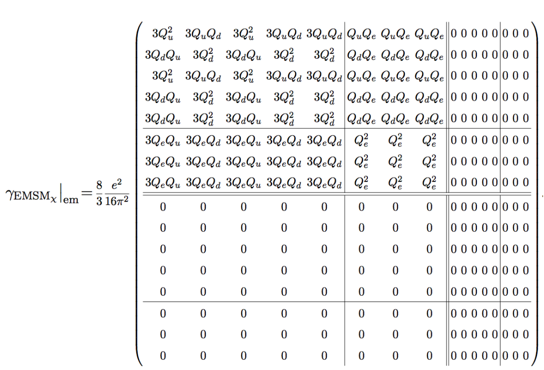

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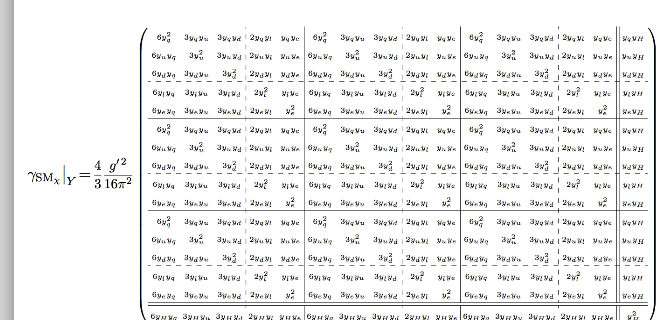
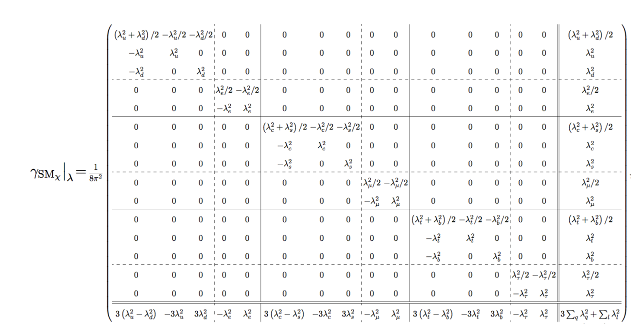


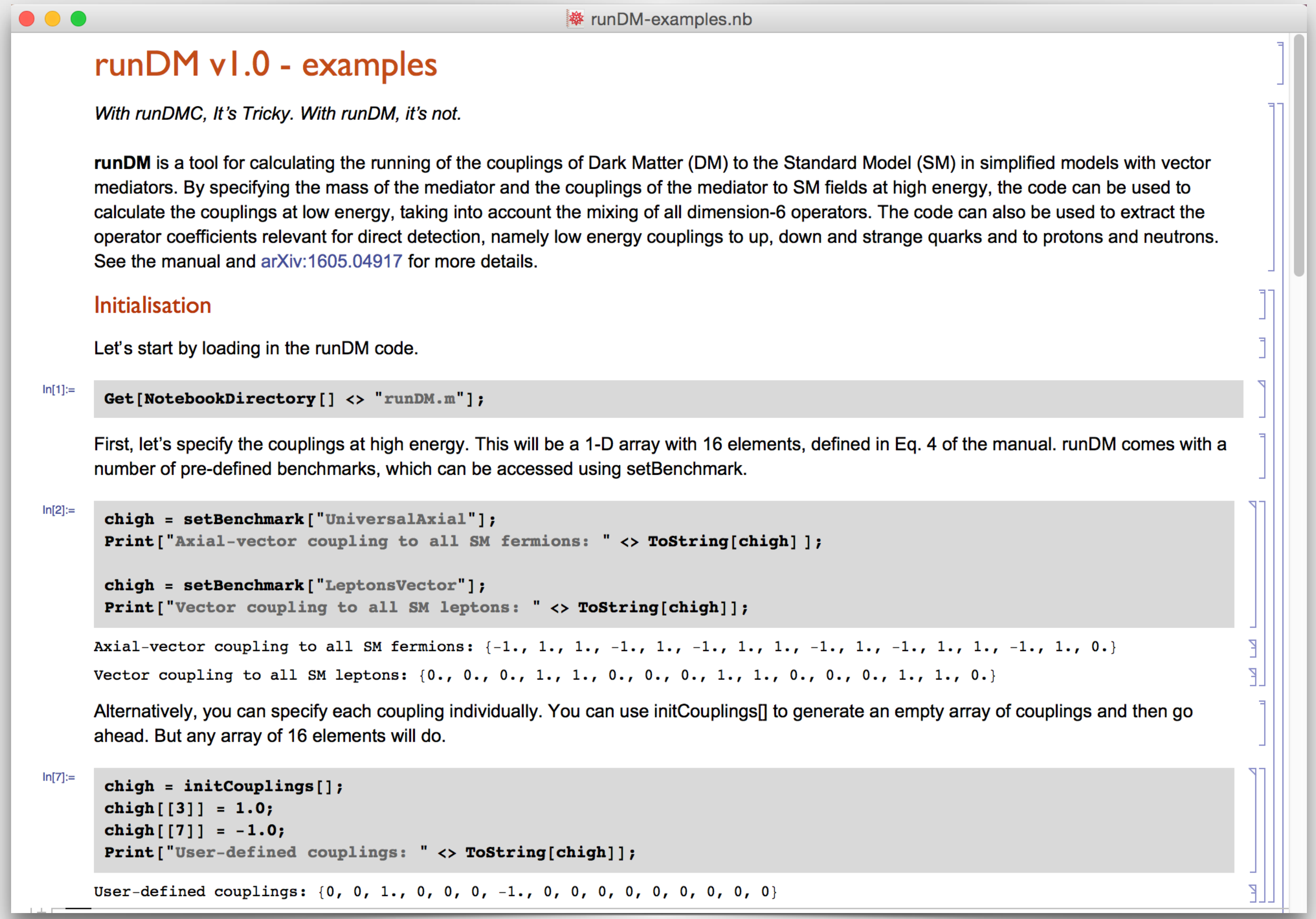


runDM: code for RGE

Inclusion of RGE effects automatic

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}
```

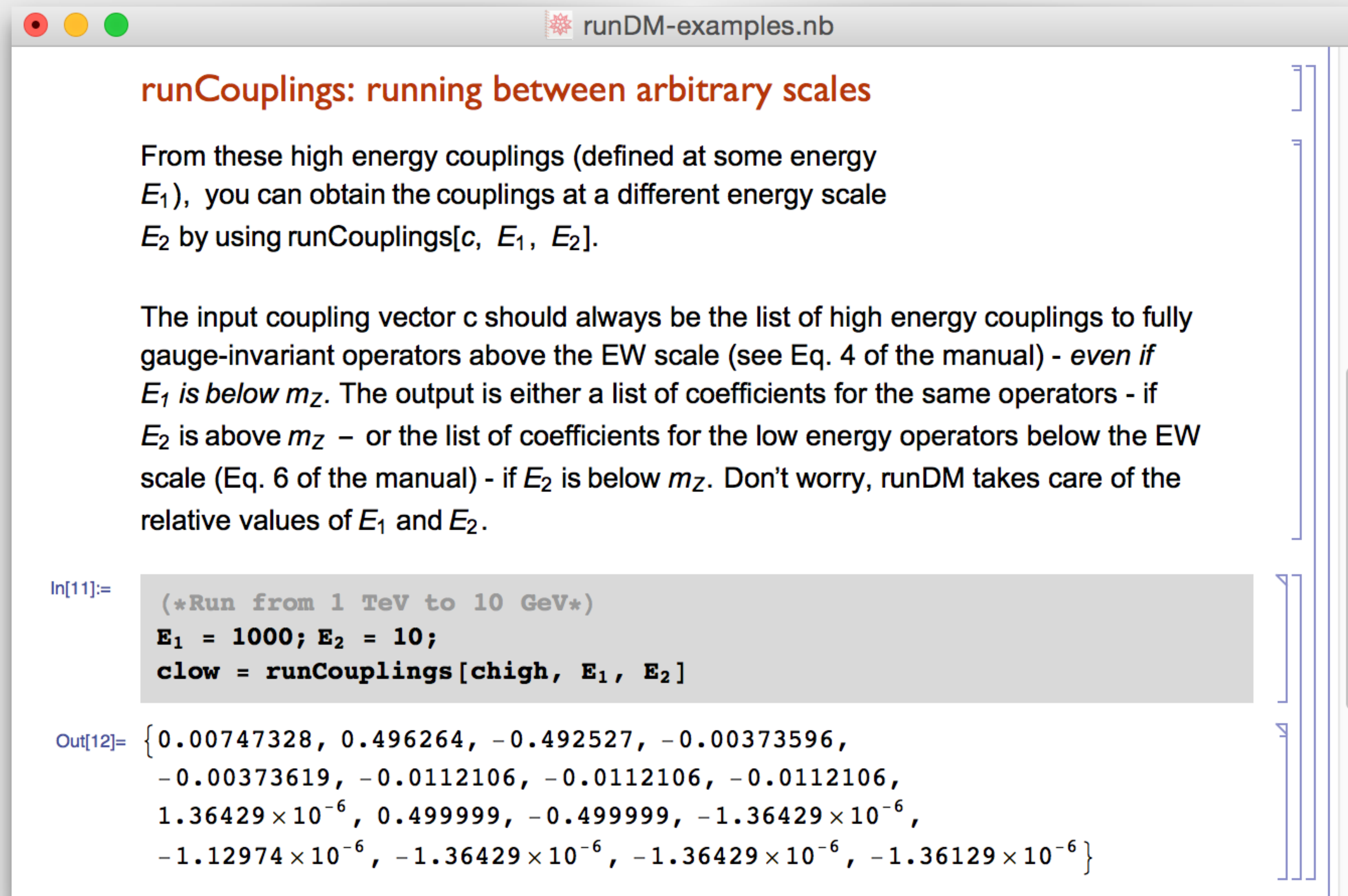
Mathematica and Python versions available at: https://github.com/bradkav/runDM/

runDM: code for RGE

Inclusion of RGE effects automatic

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]= $\{0.00747328, 0.496264, -0.492527, -0.00373596, -0.00373619, -0.0112106, -0.0112106, -0.0112106, 1.36429\times10^{-6}, 0.499999, -0.499999, -1.36429\times10^{-6}, -1.12974\times10^{-6}, -1.36429\times10^{-6}, -1.36429\times10^{-6}, -1.36129\times10^{-6}\}$

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runDM: code for RGE

Inclusion of RGE effects automatic

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/

Results: 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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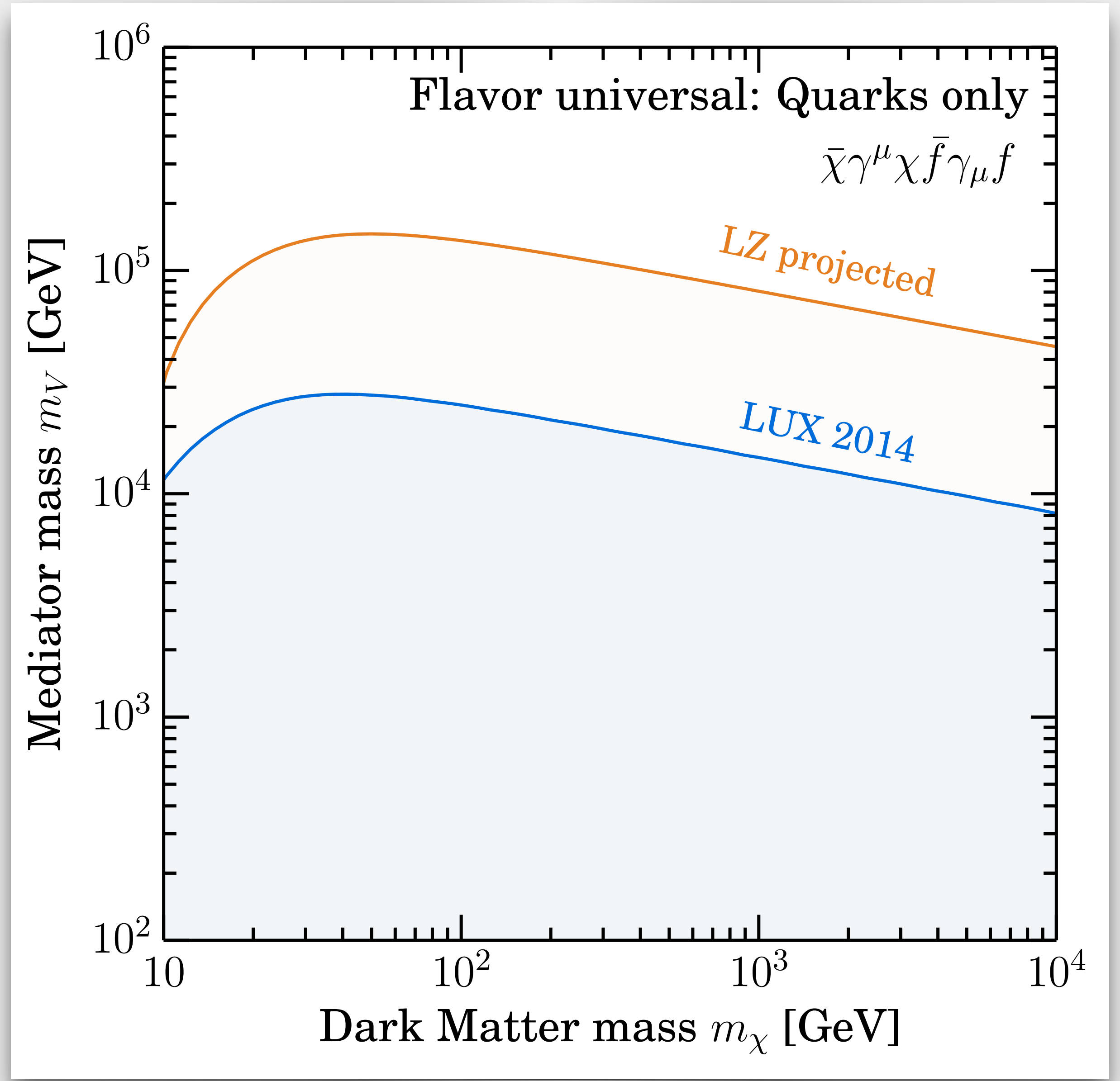

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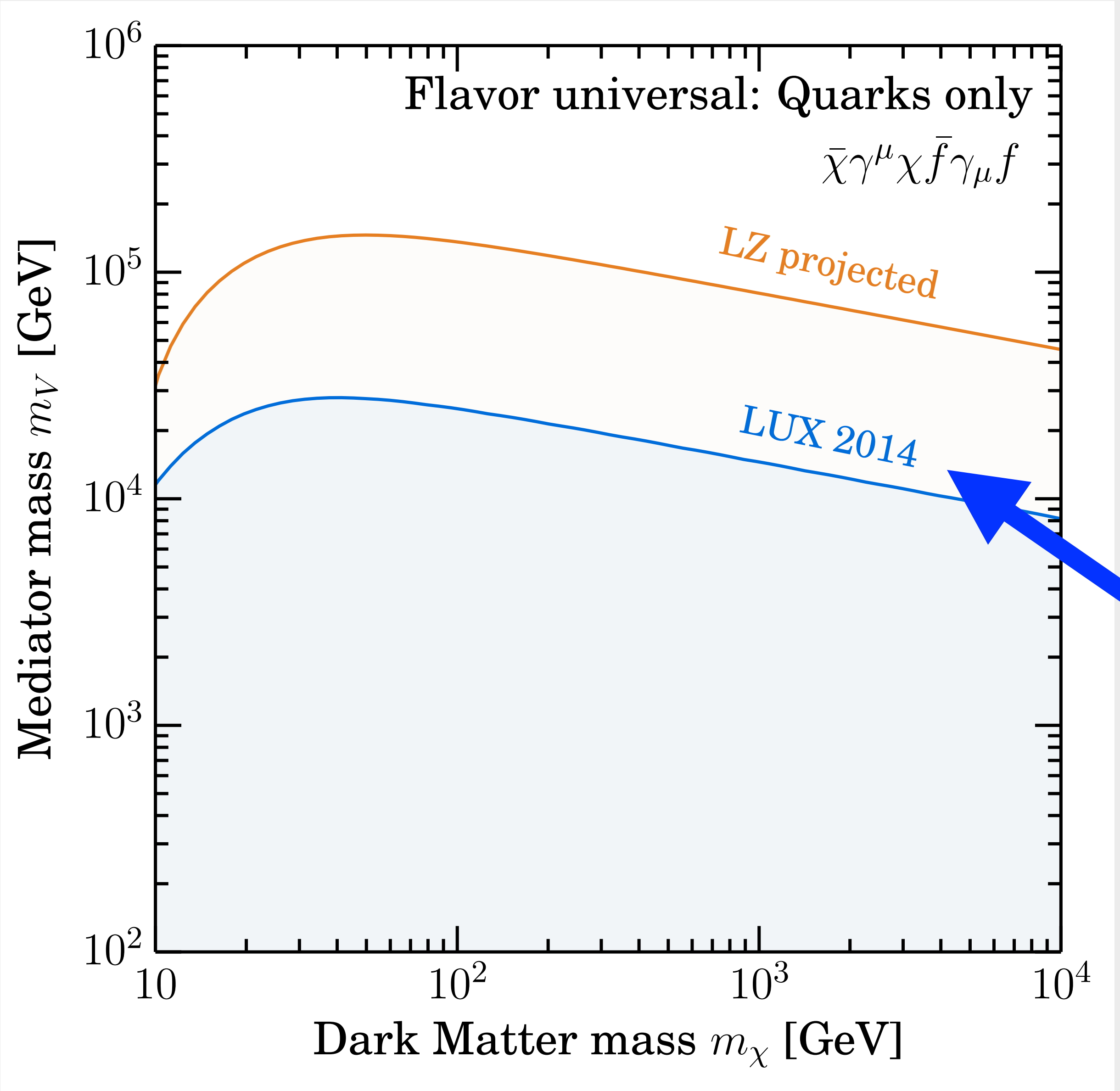

RGE:
O(1%) correction to EFT couplings

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

FD, Kavanagh, Panci, arXiv:1605.04917

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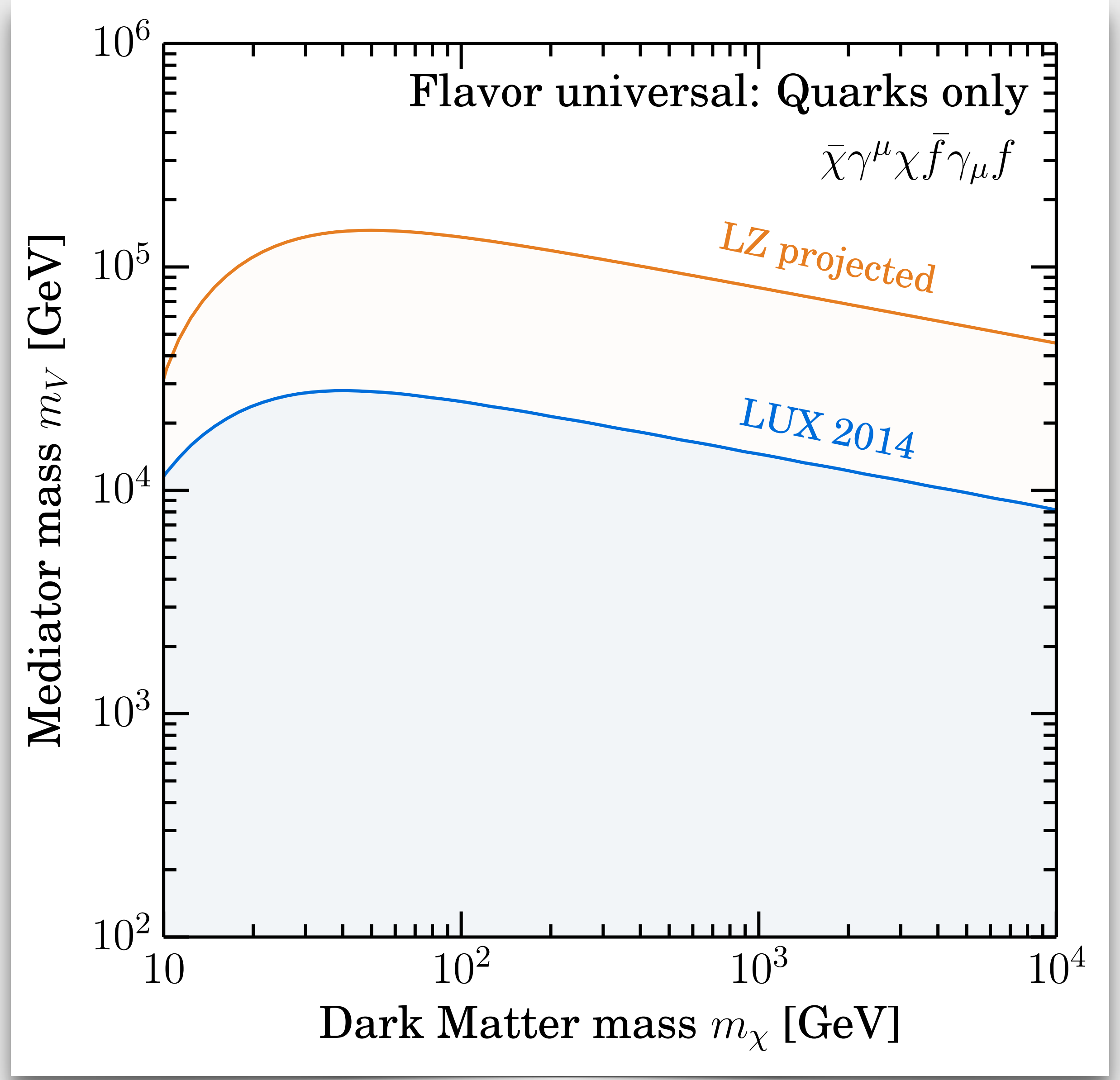

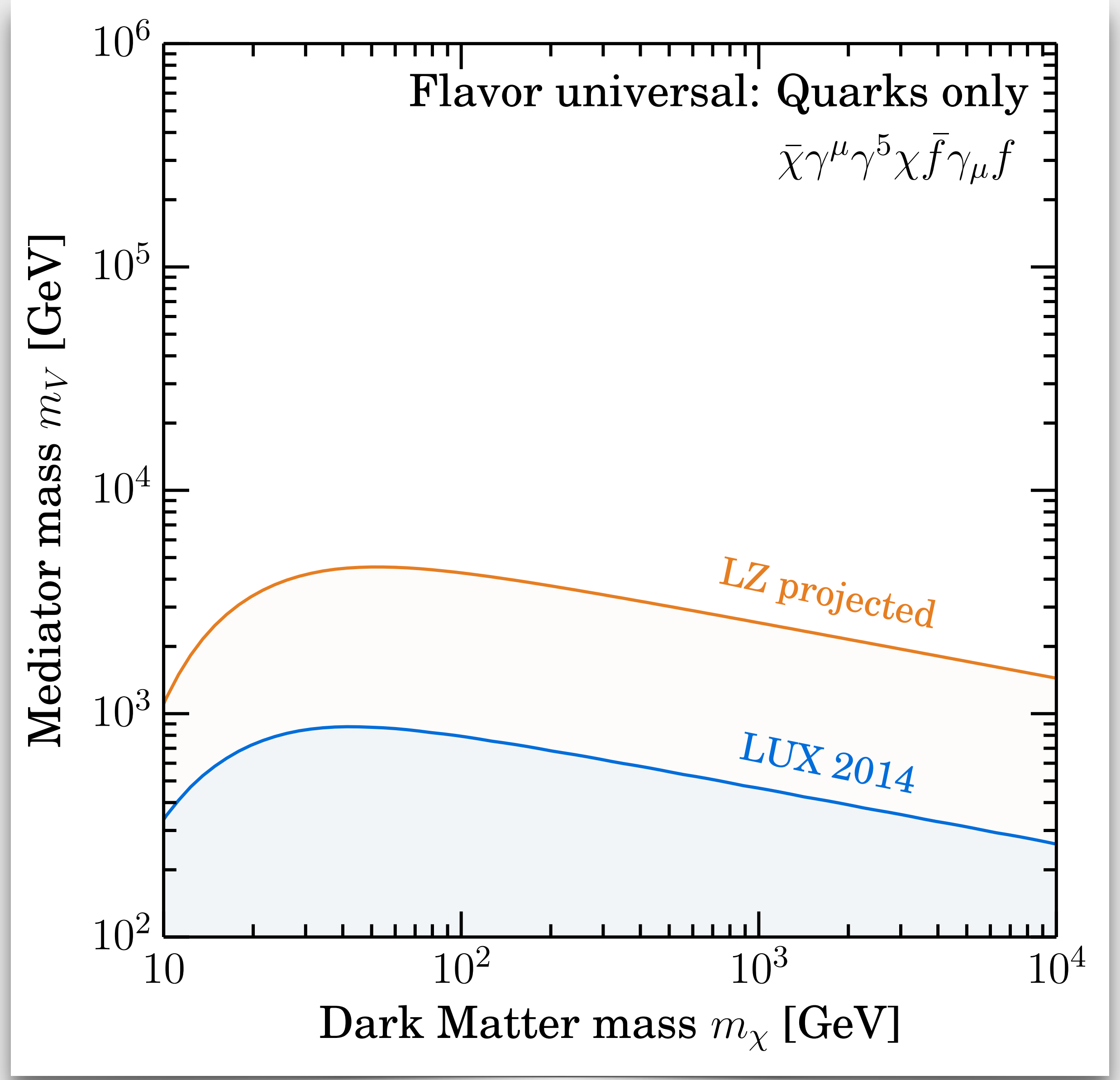

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Results: quarks axial

Flavor universal couplings to quark axial currents

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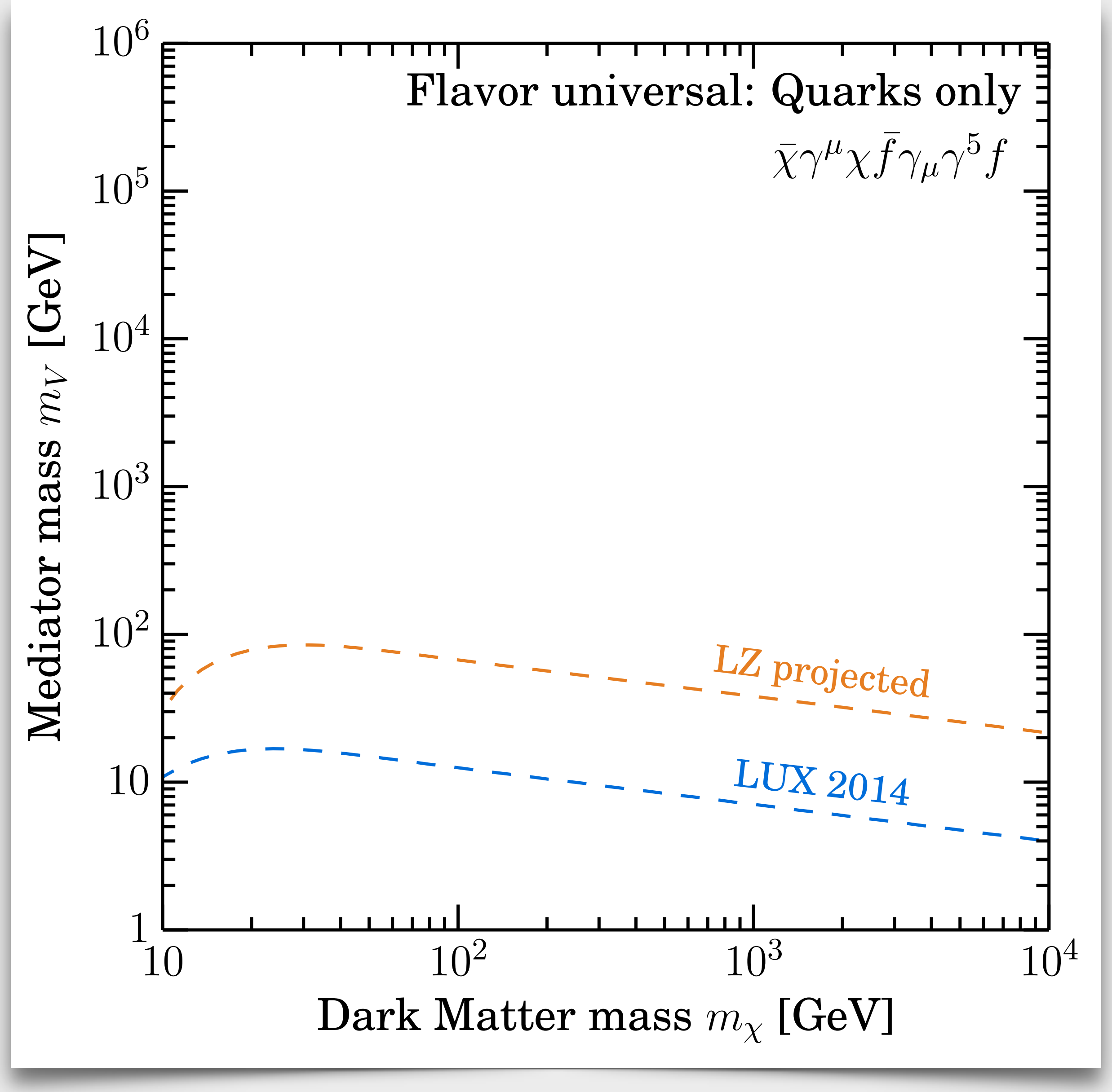

without RGE

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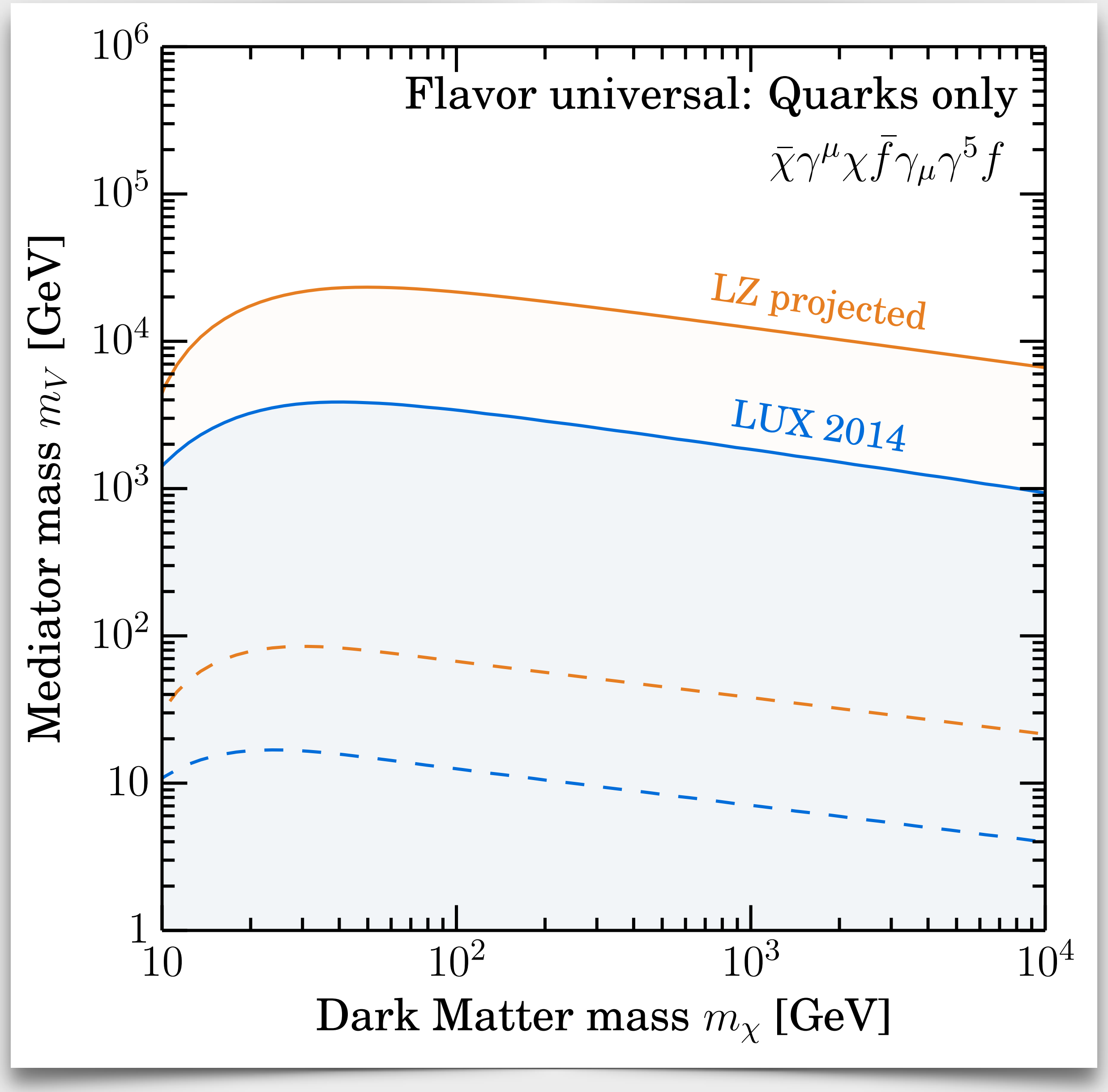

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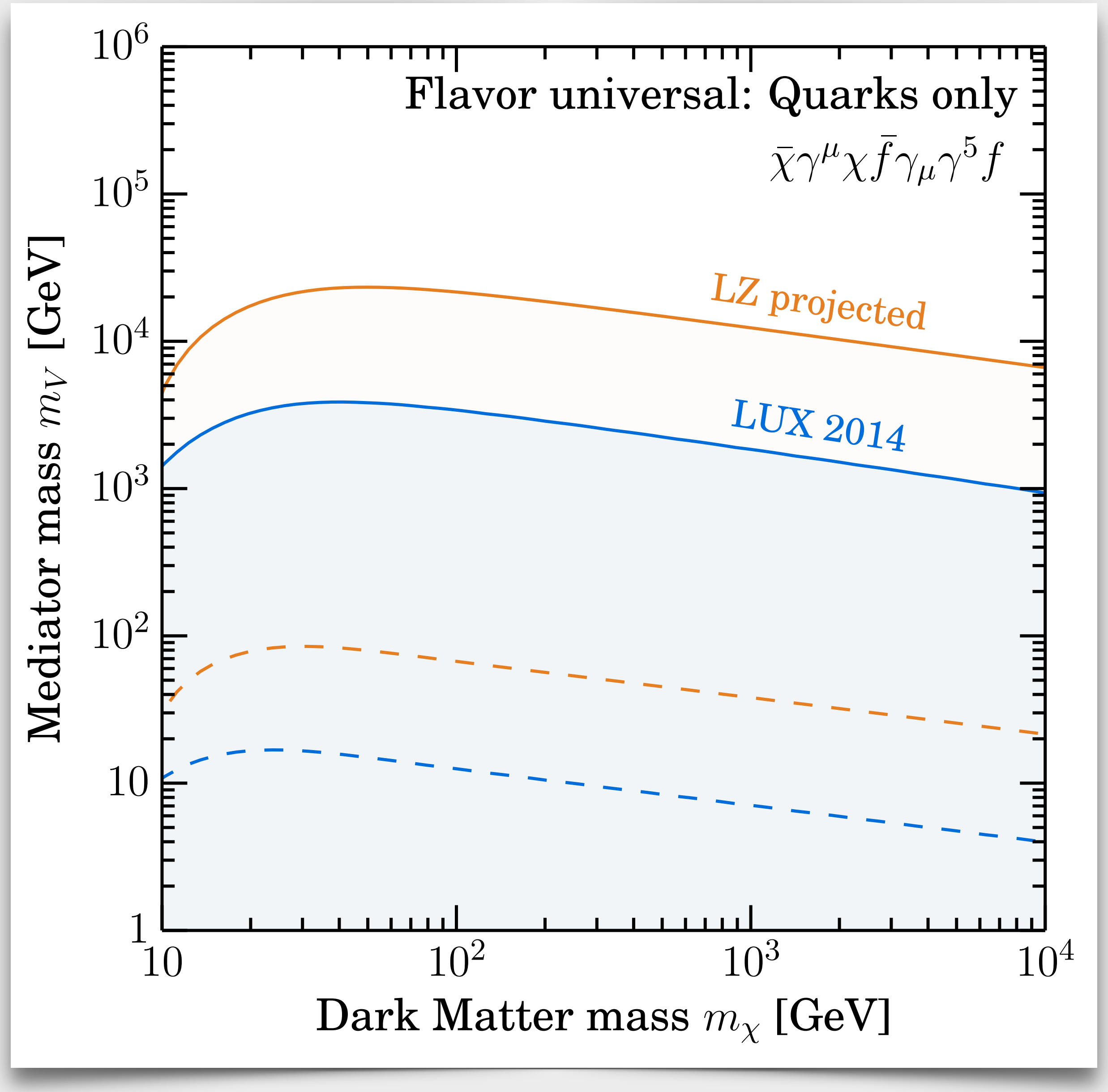

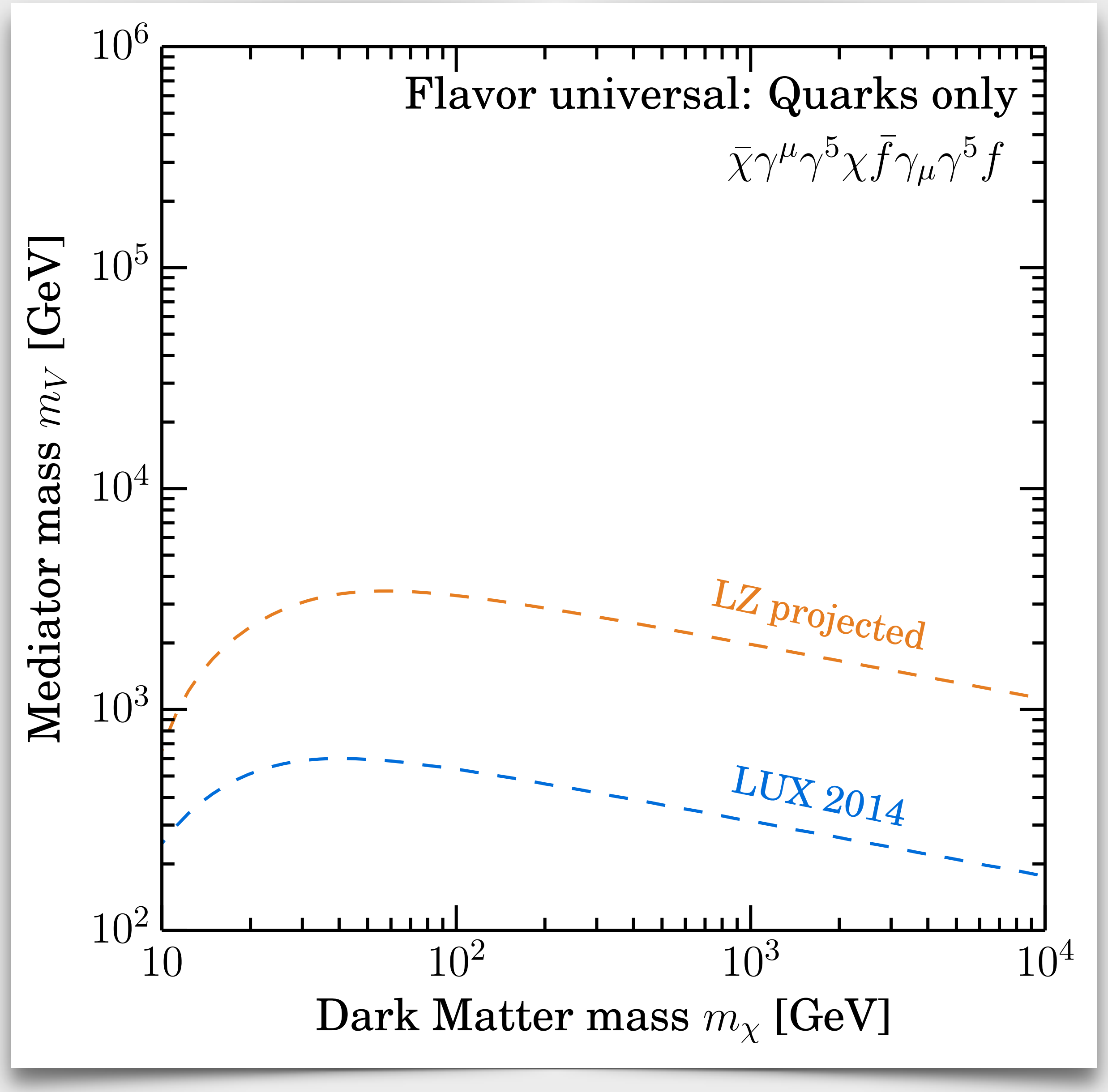

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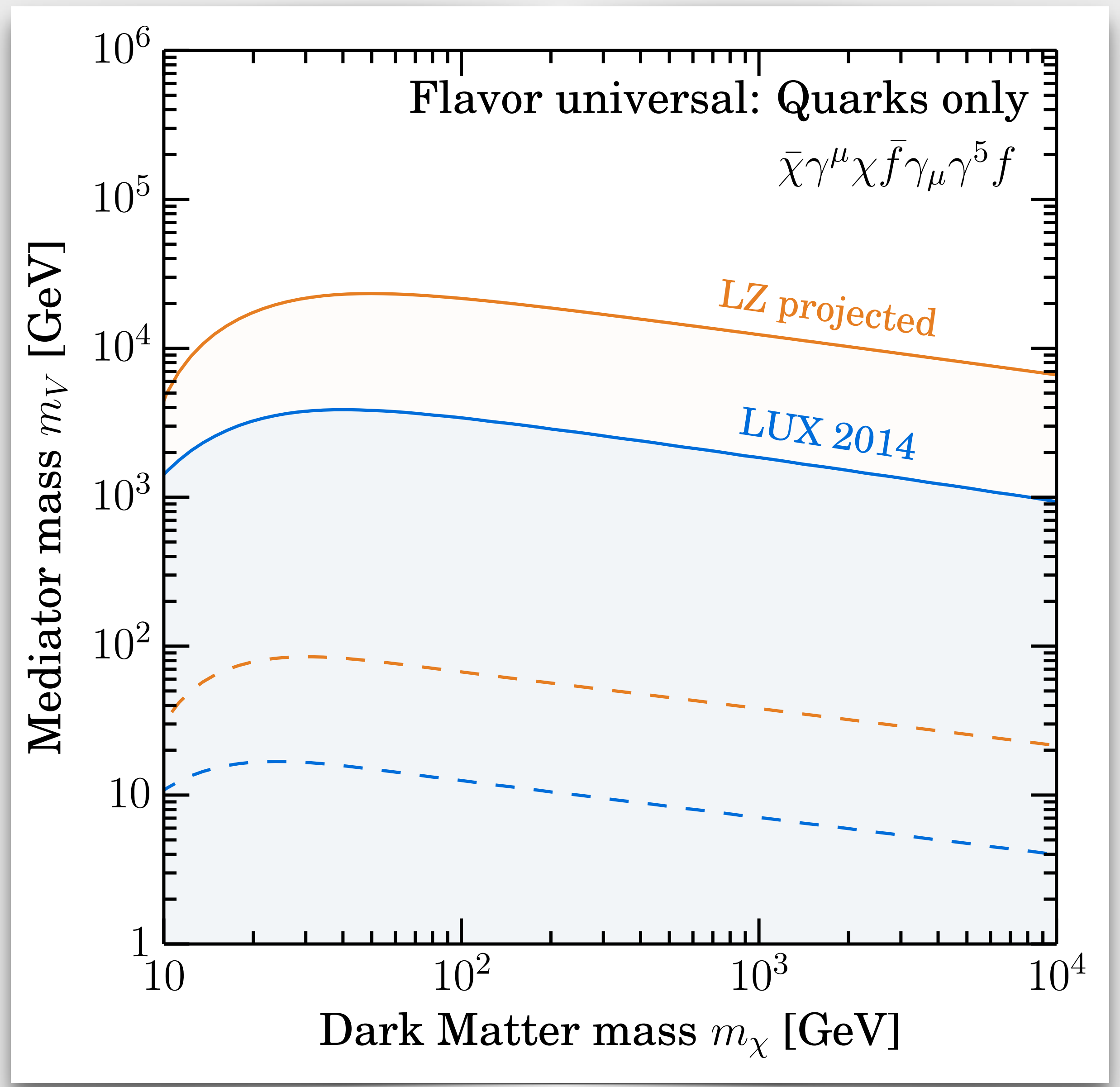

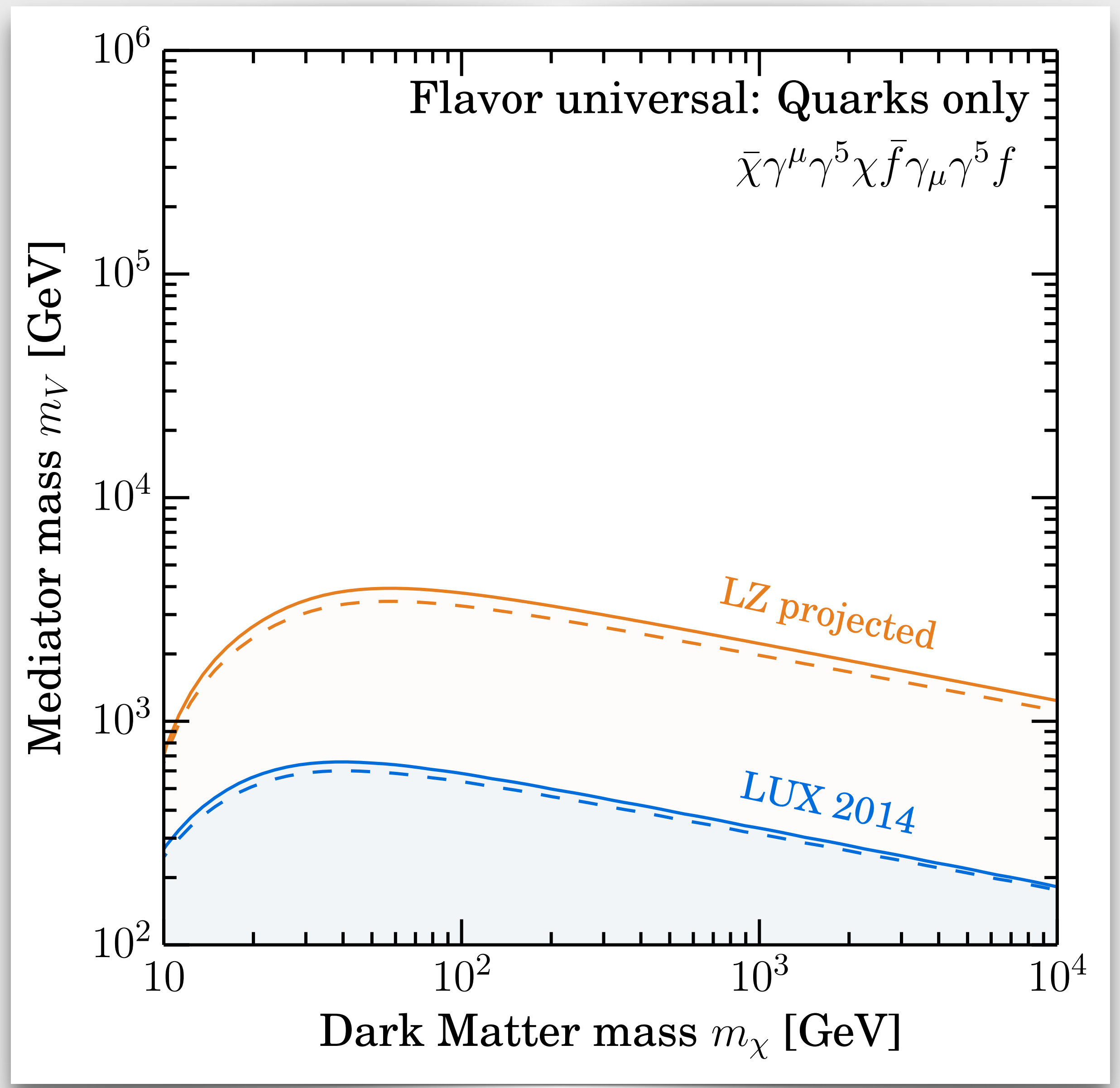

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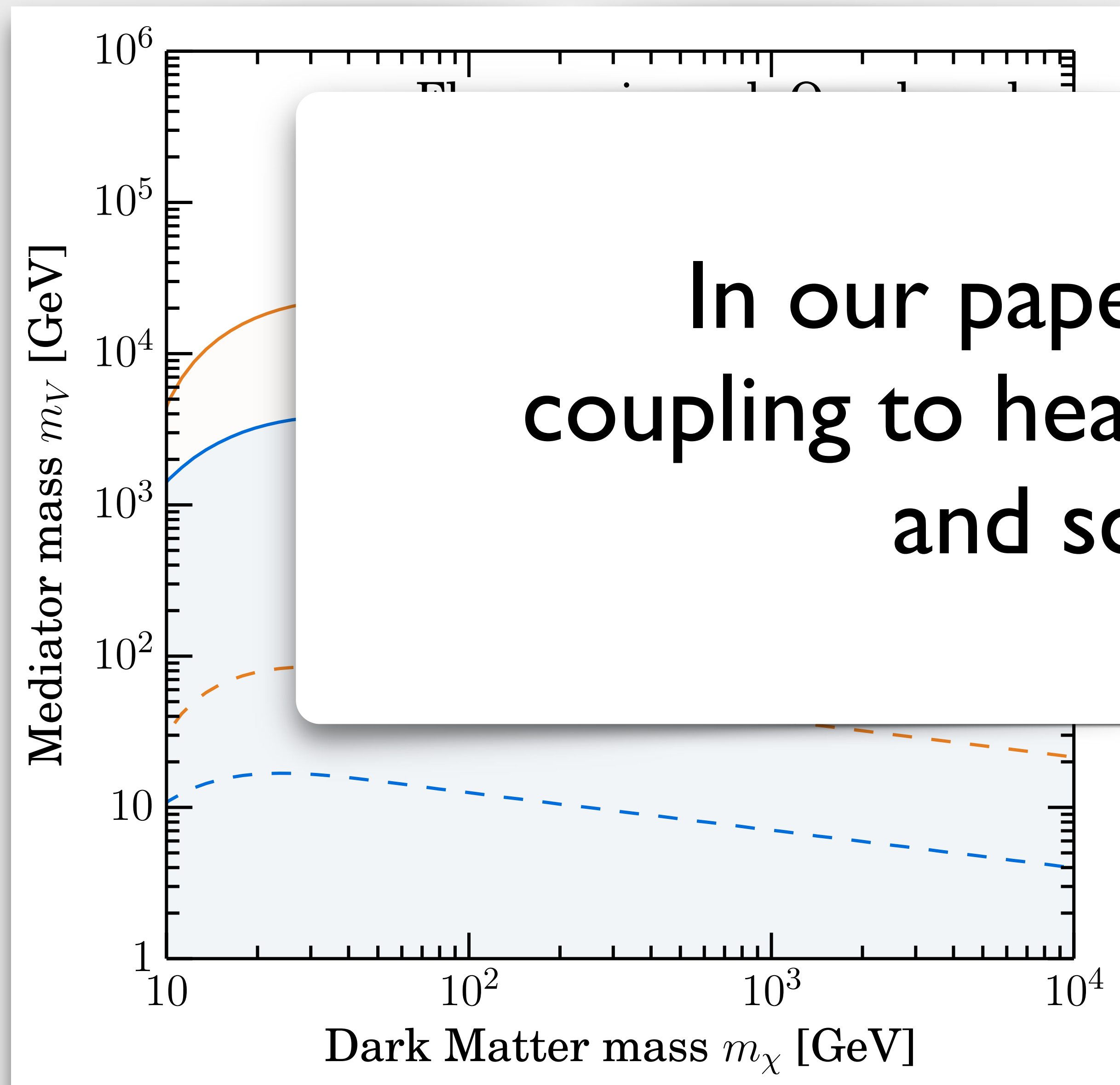
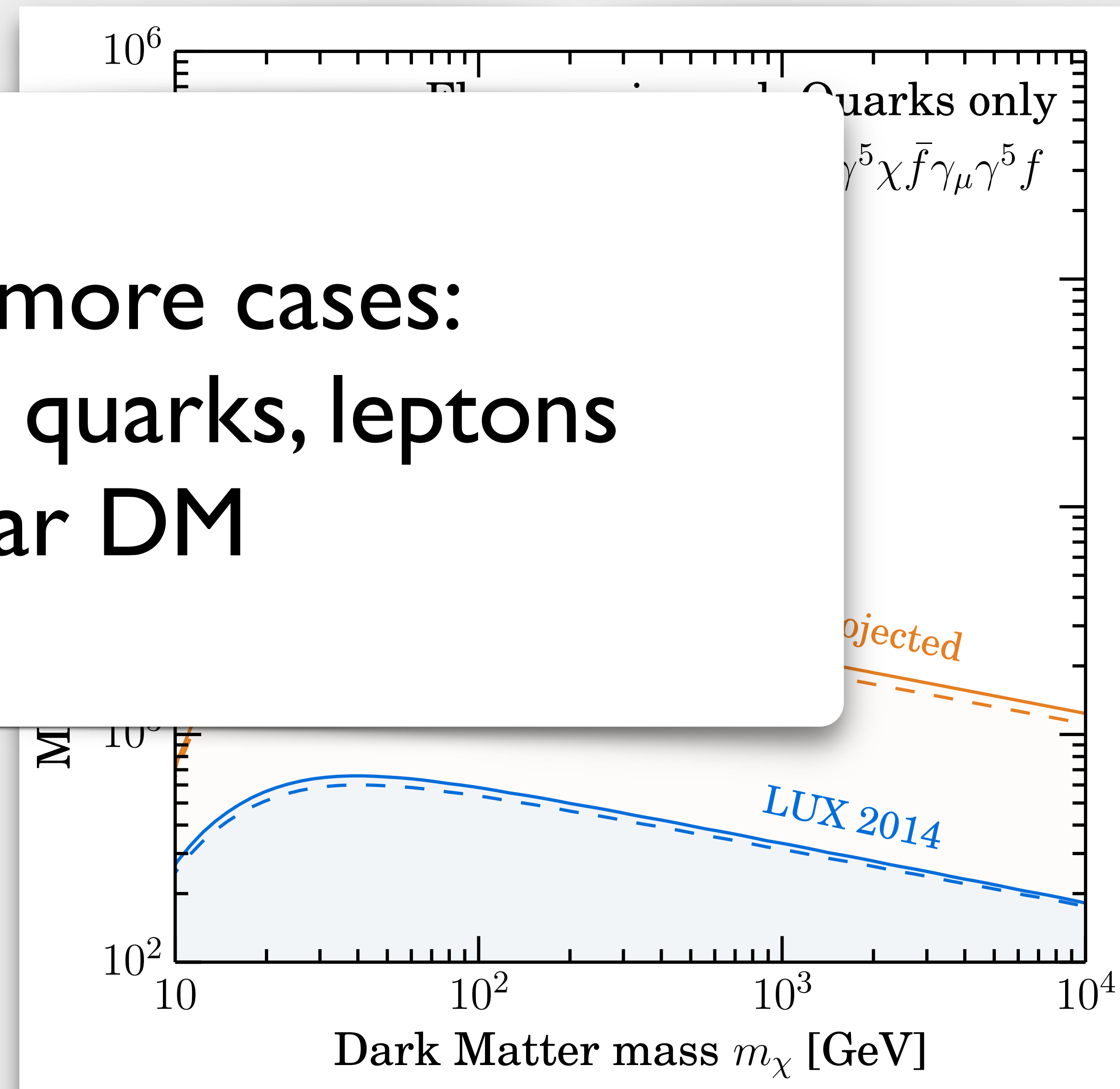


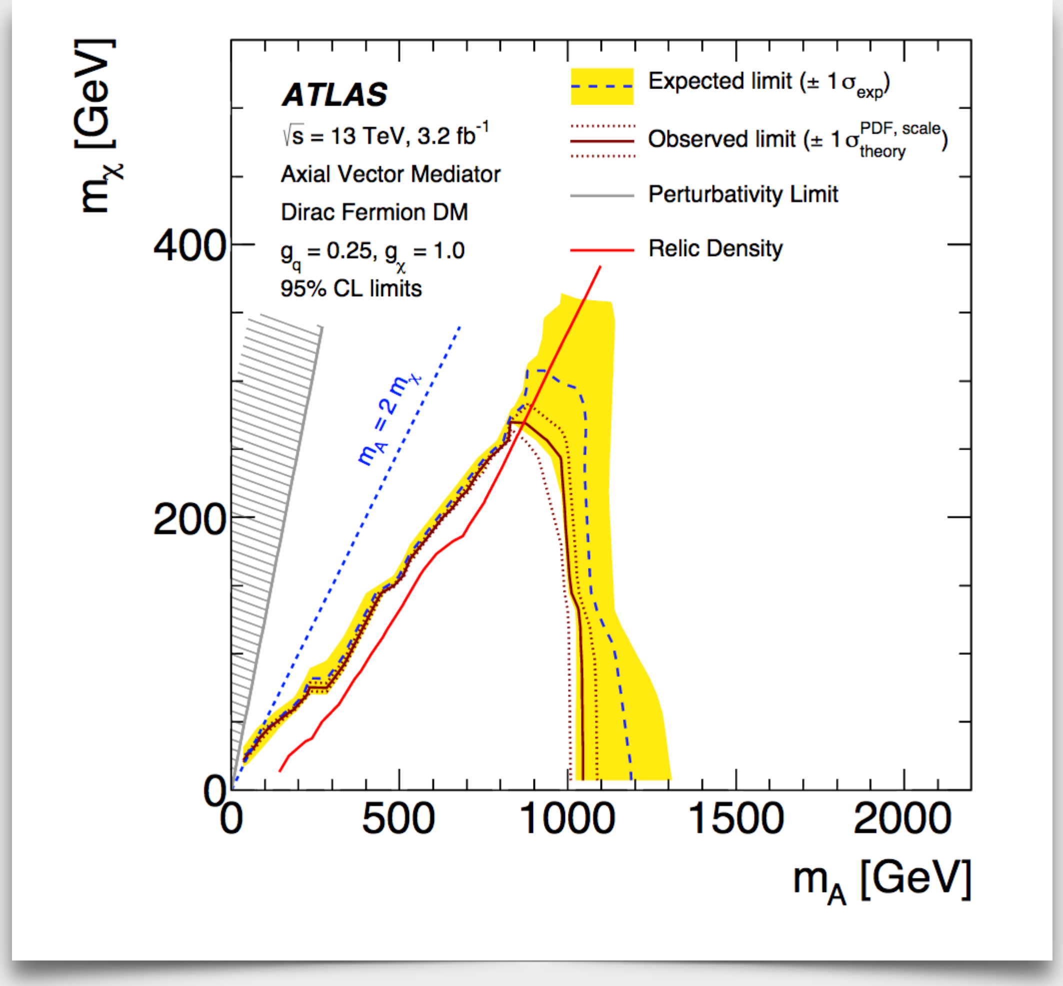


In our paper more cases:
coupling to heavy quarks, leptons
and scalar DM

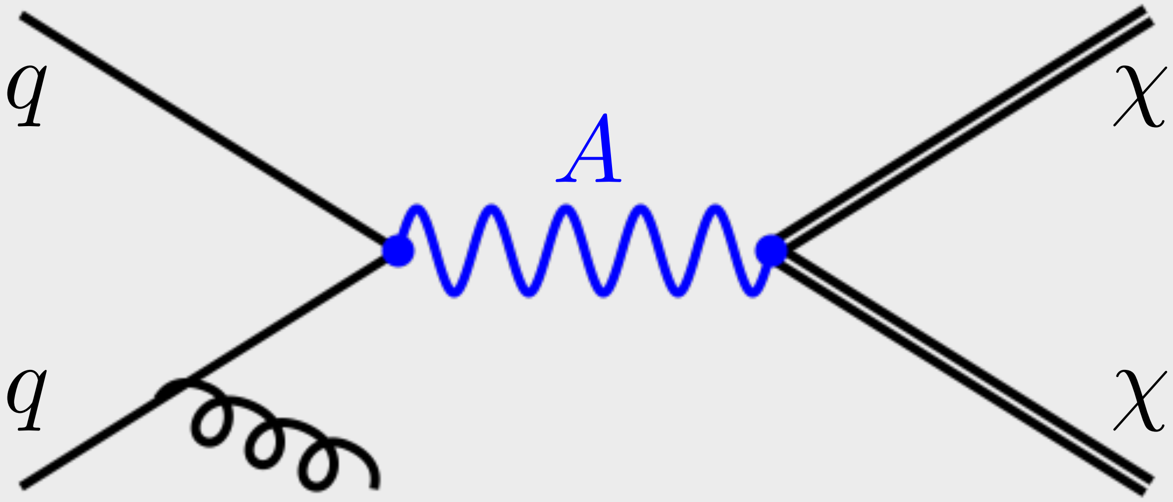
FD, Kavanagh, Panci, arXiv:1605.04917

Comparison with LHC

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



$$\mathcal{L}_{\mathrm{Axial-Vector}} = g_\chi\, A_\mu\, \overline{\chi}\gamma^\mu\gamma^5\chi + g_q\, A_\mu\, \overline{q}\gamma^\mu\gamma^5 q$$

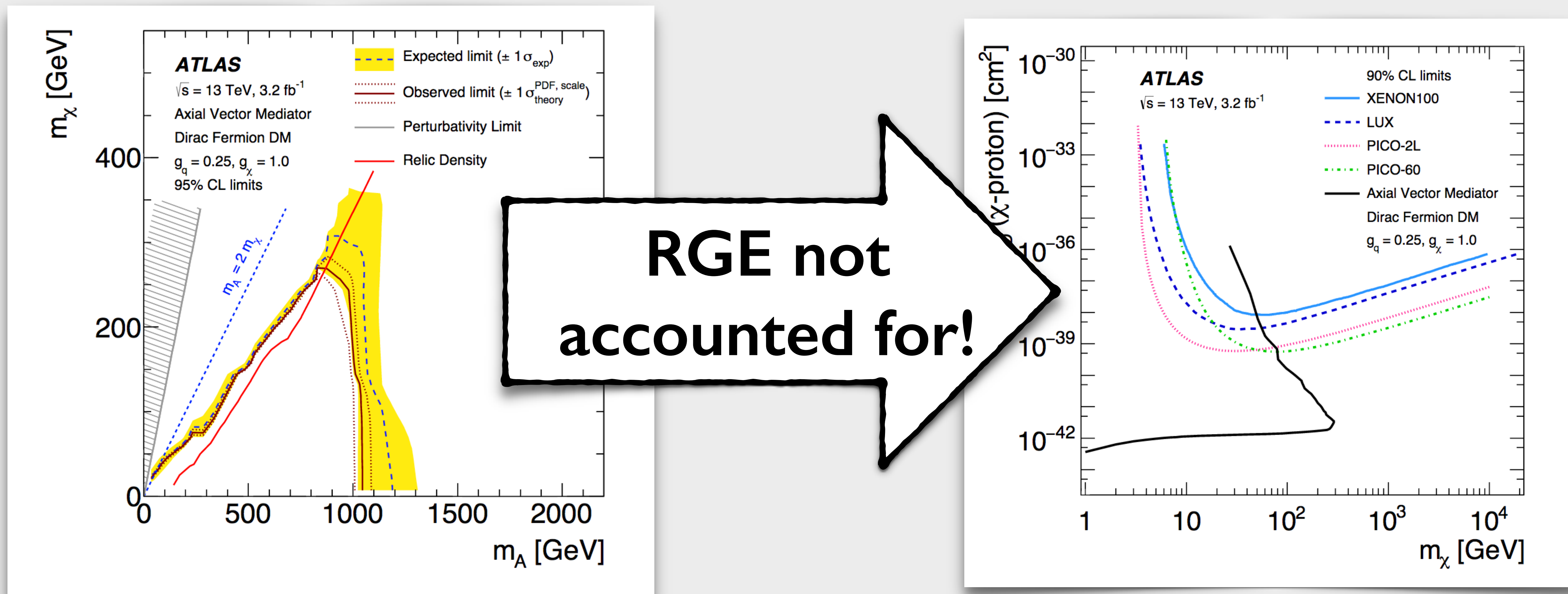


LUX, arXiv:1602.03489 and PICO-2L, arXiv:1601.03729

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

Comparison with LHC

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



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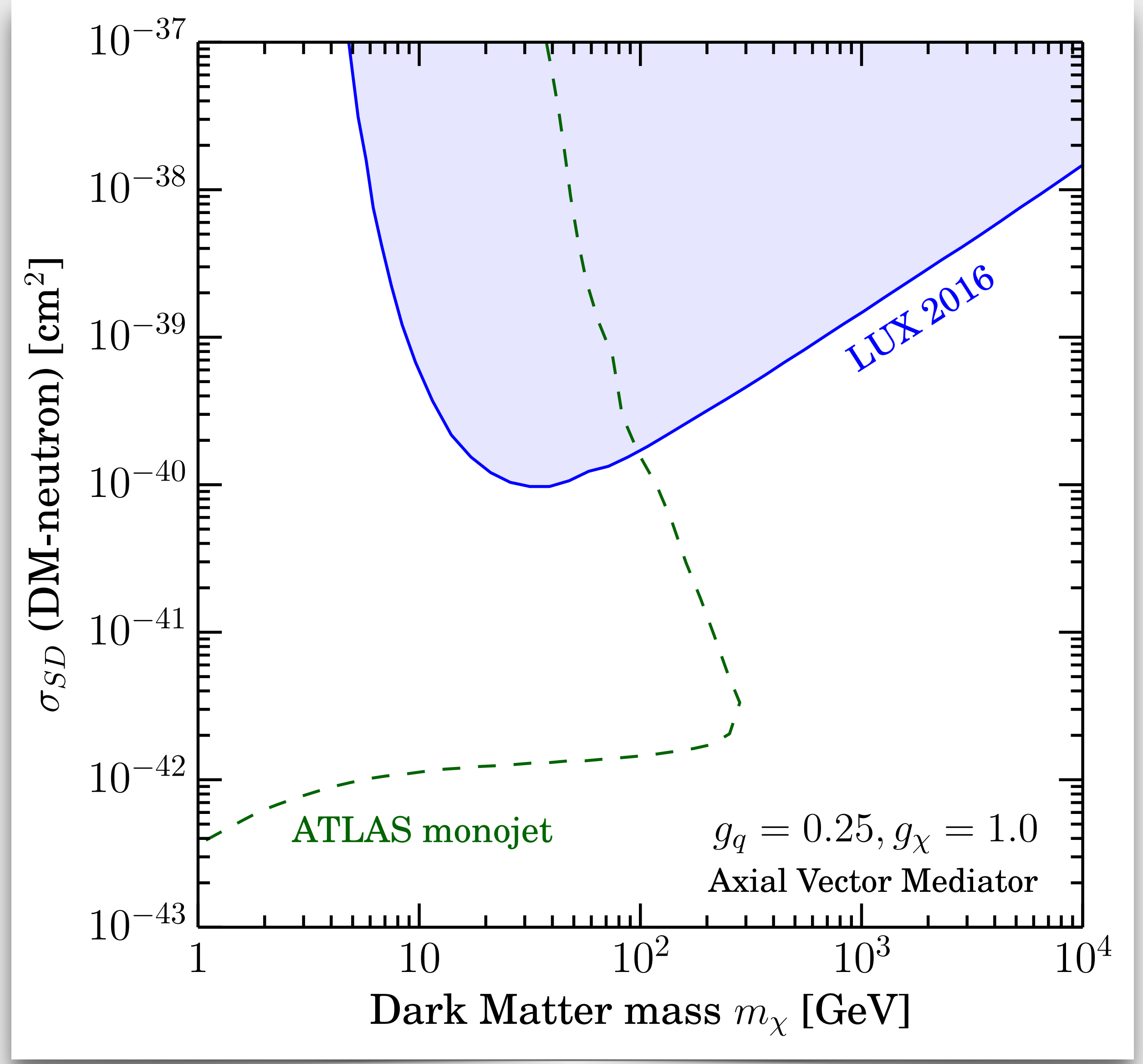
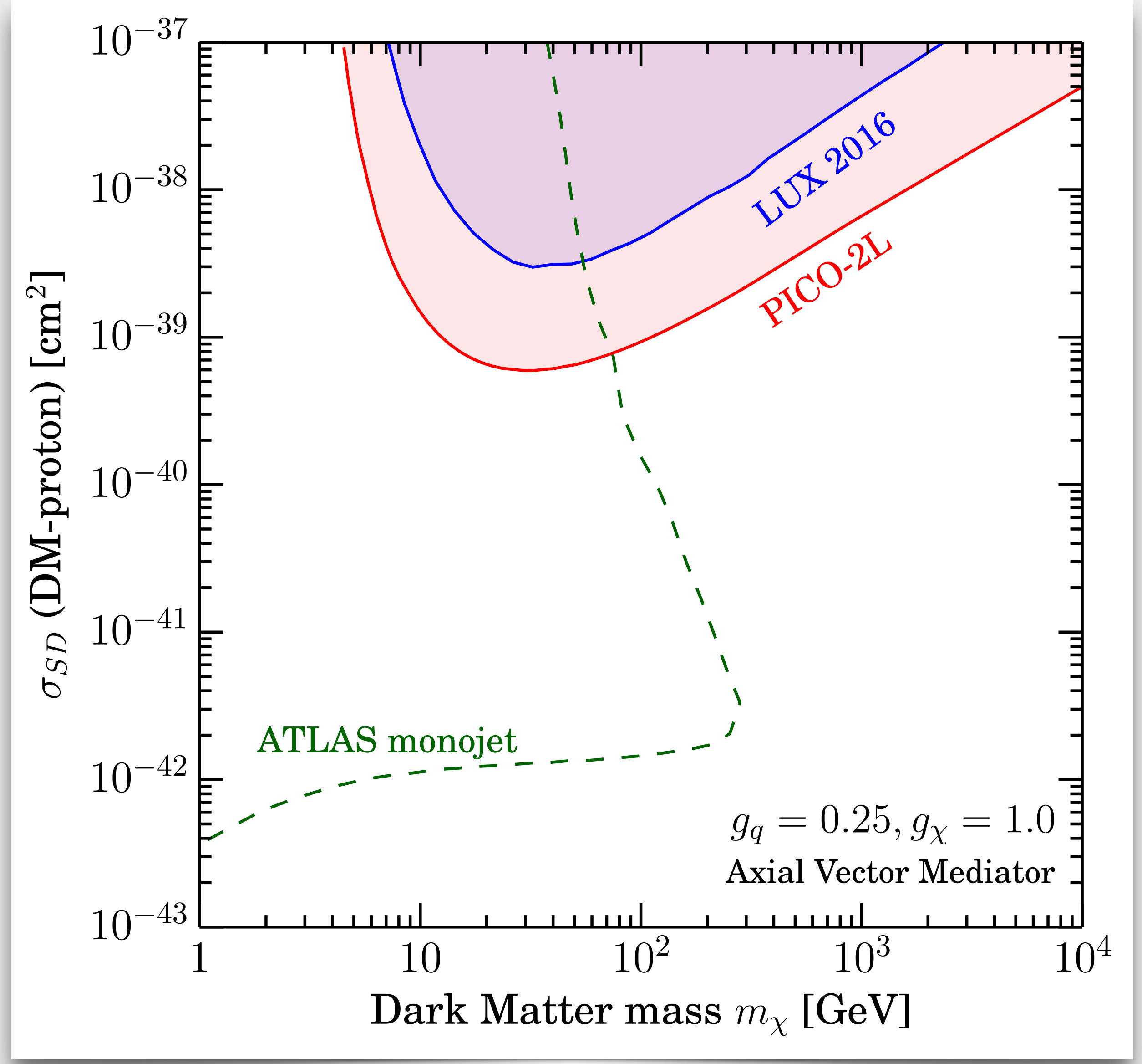
Mono–jet Searches





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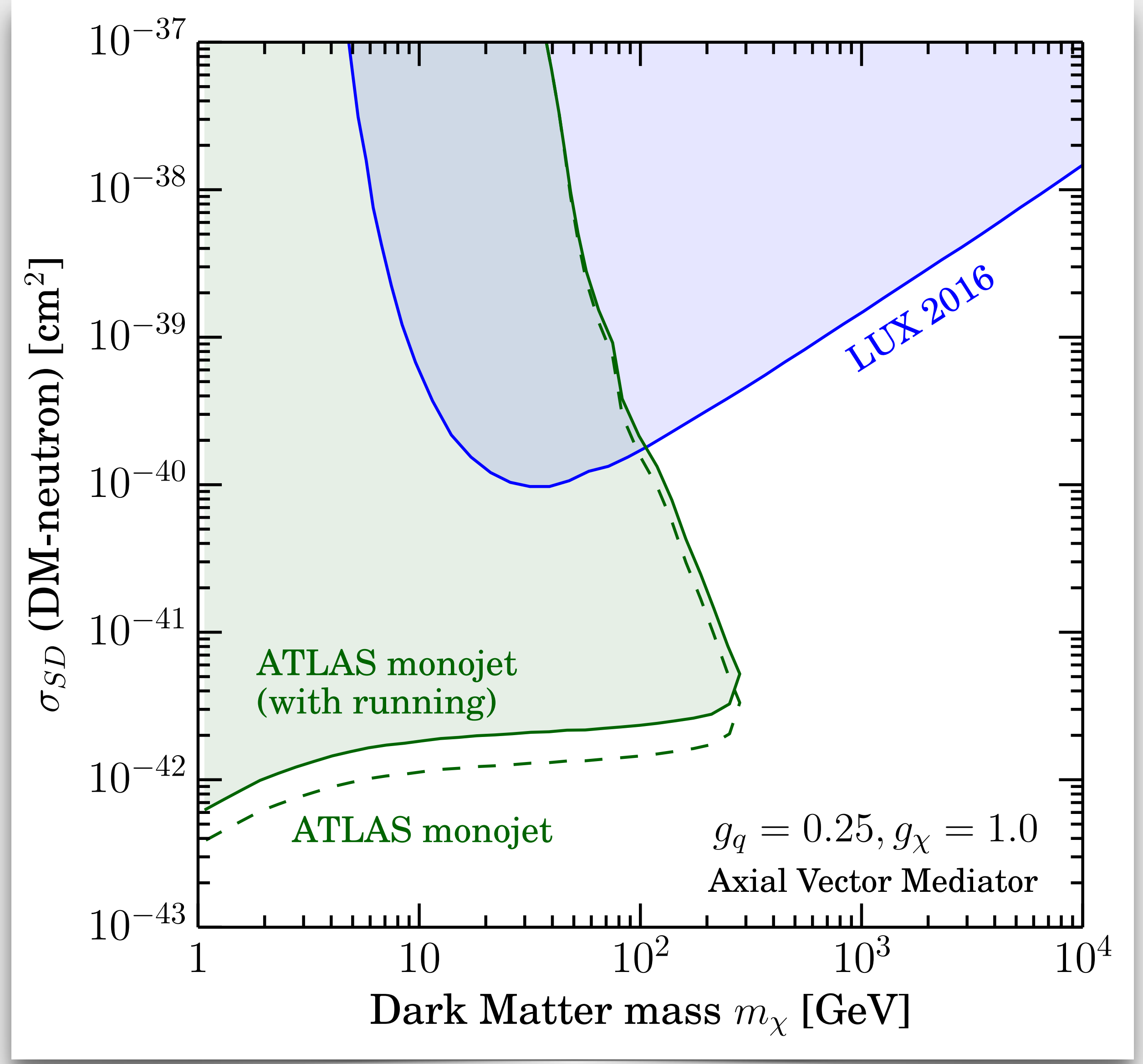

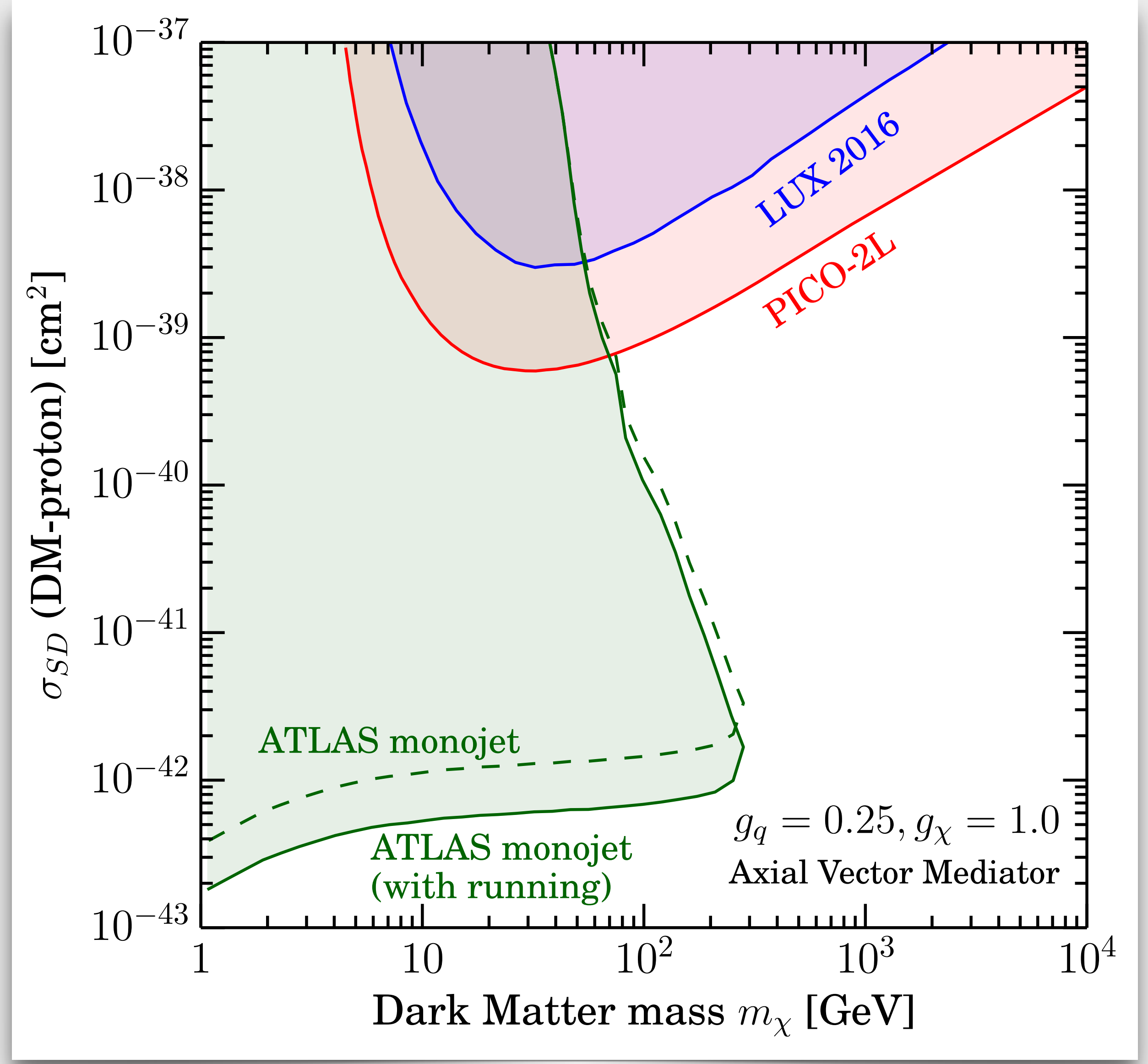

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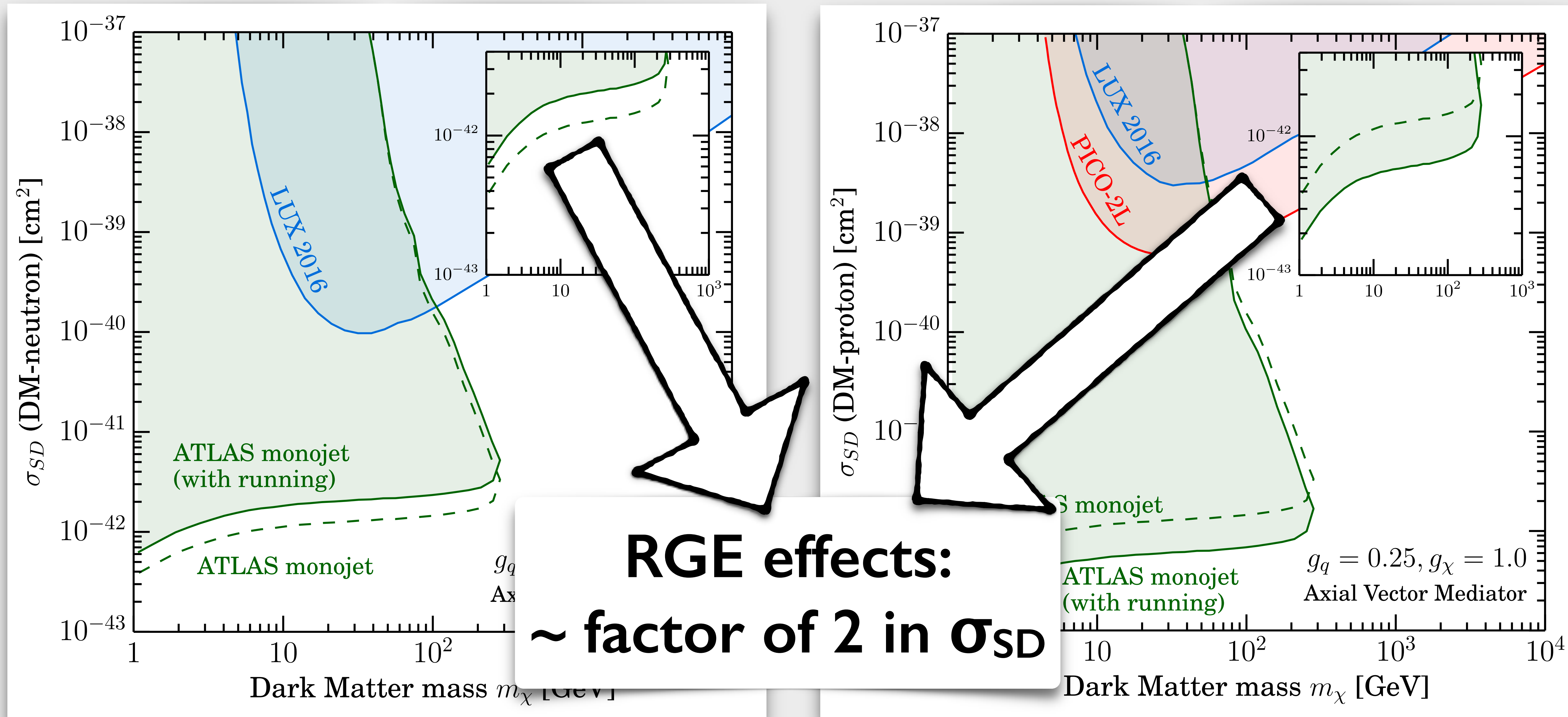

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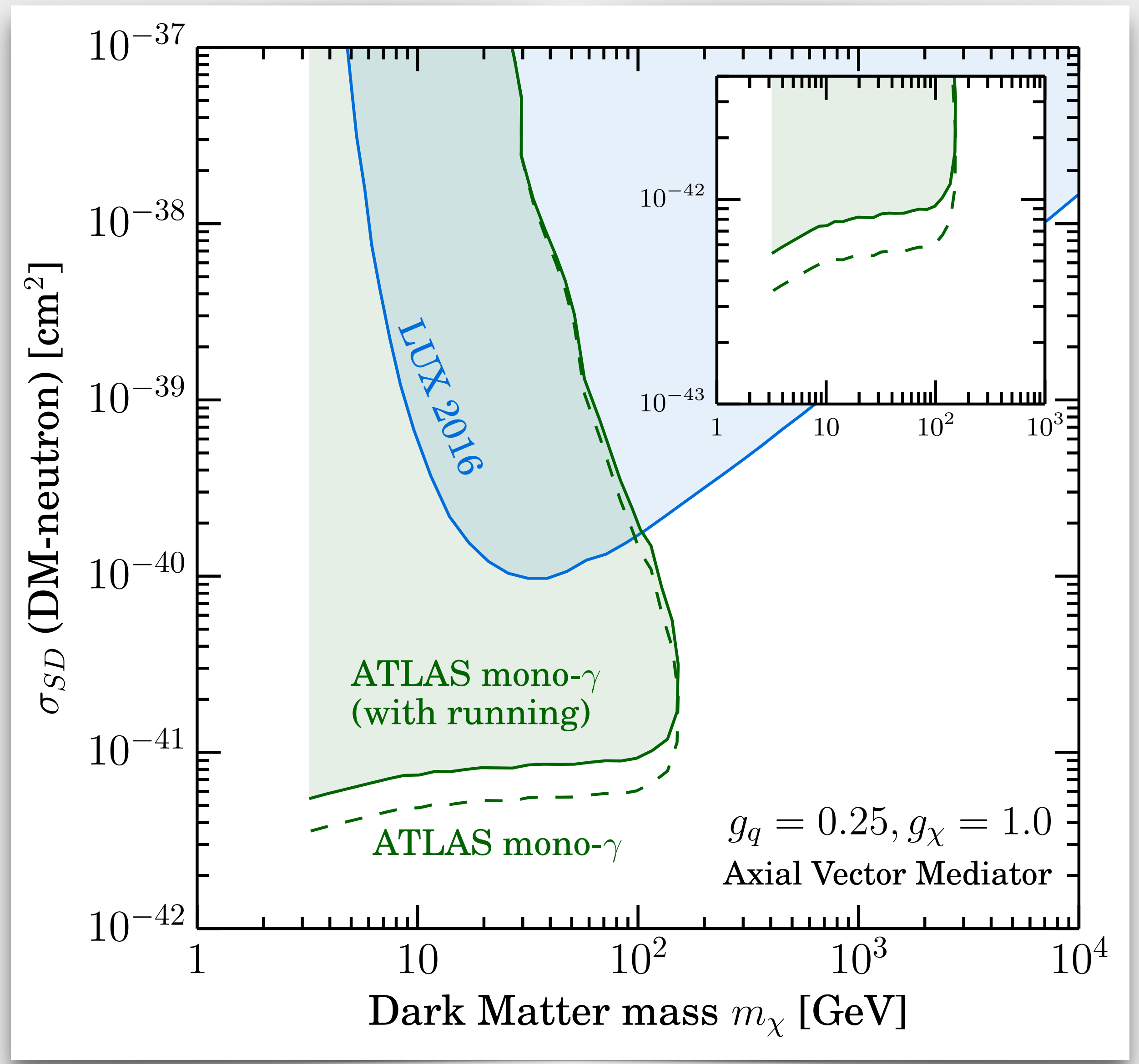
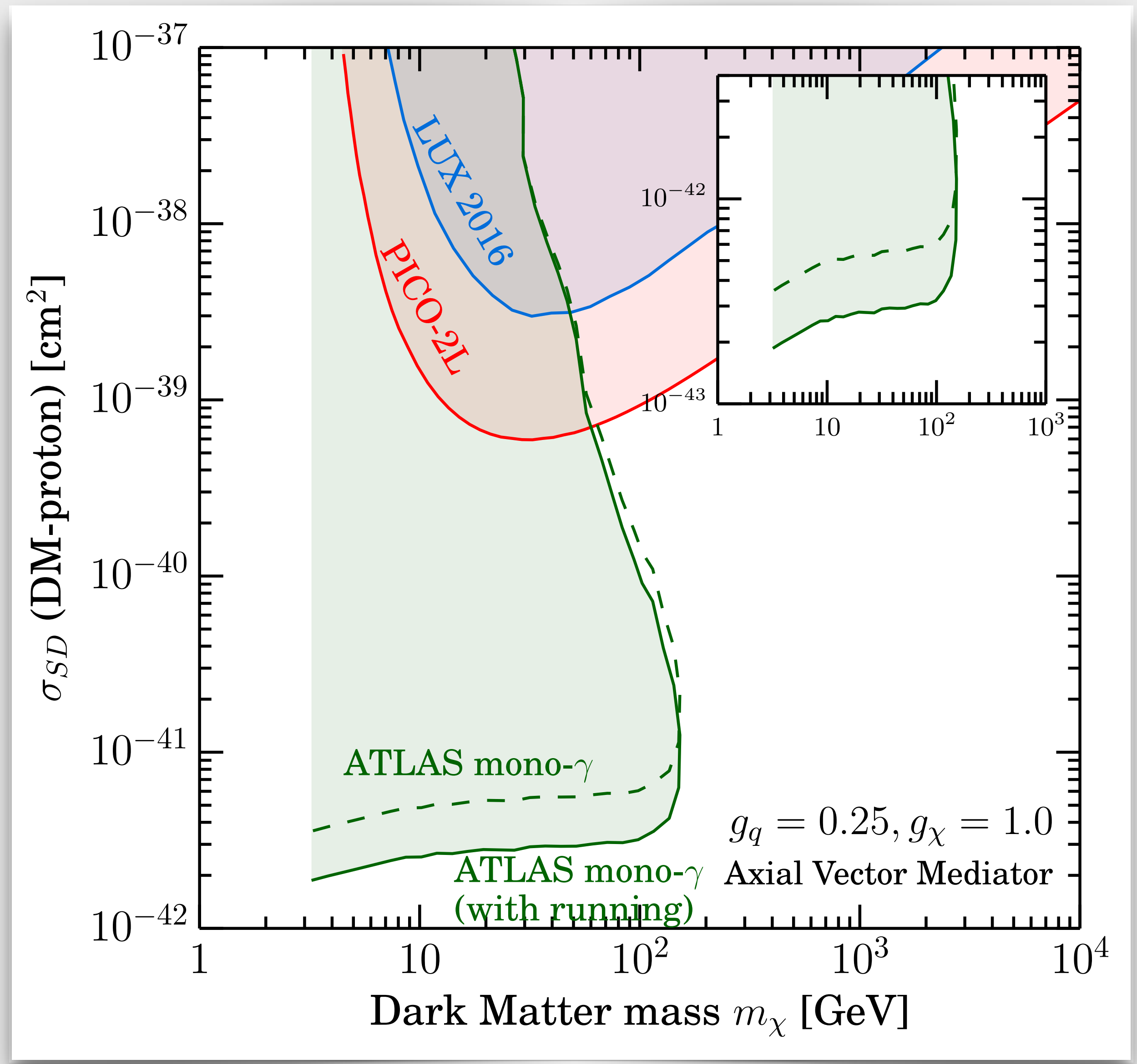
Mono-photon Searches





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

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

More Complementarity

How well can be constrained by collider and direct detection?

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

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

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

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

More Complementarity

How well can be constrained by collider and direct detection?

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

~ same as the others

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

~ same as the others

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

~ same as the others

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

~ same as the others

More Complementarity

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

More Complementarity

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 RGE corrections)

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

~ same as the others

Spin-Independent (SI) via RGE

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

Outlook

Direct detection rates and comparison with LHC: not always straightforward

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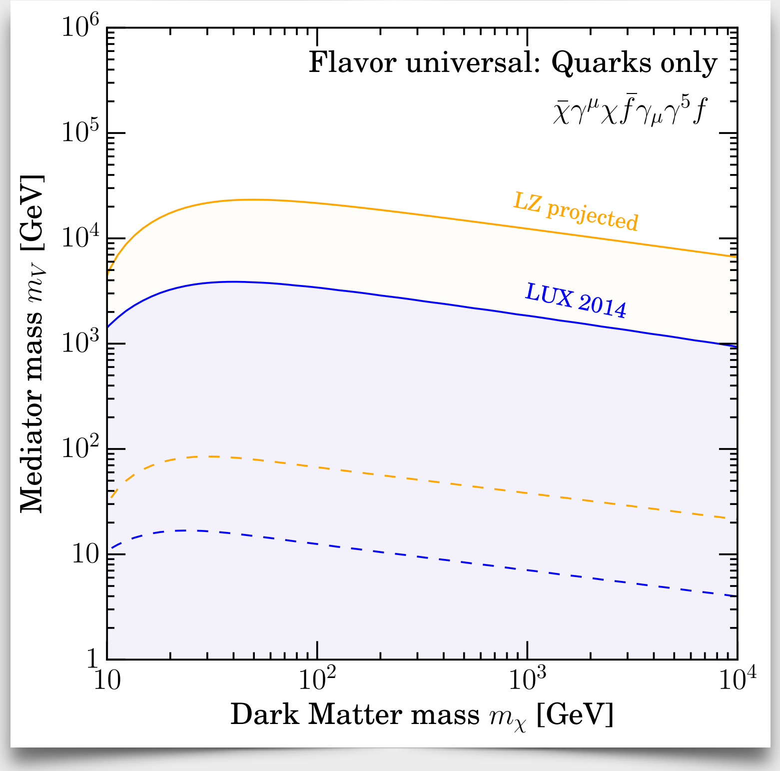
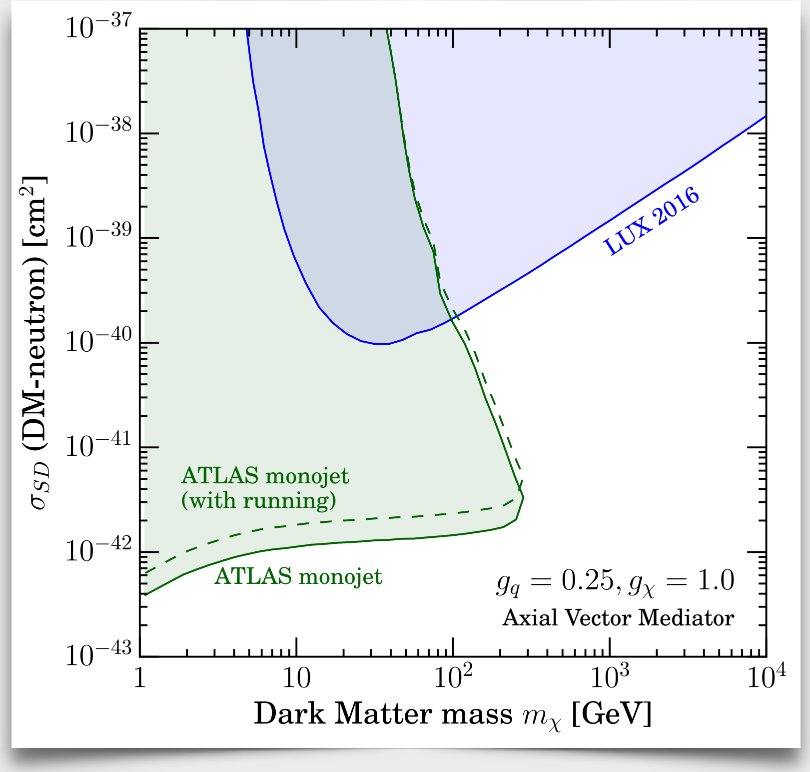
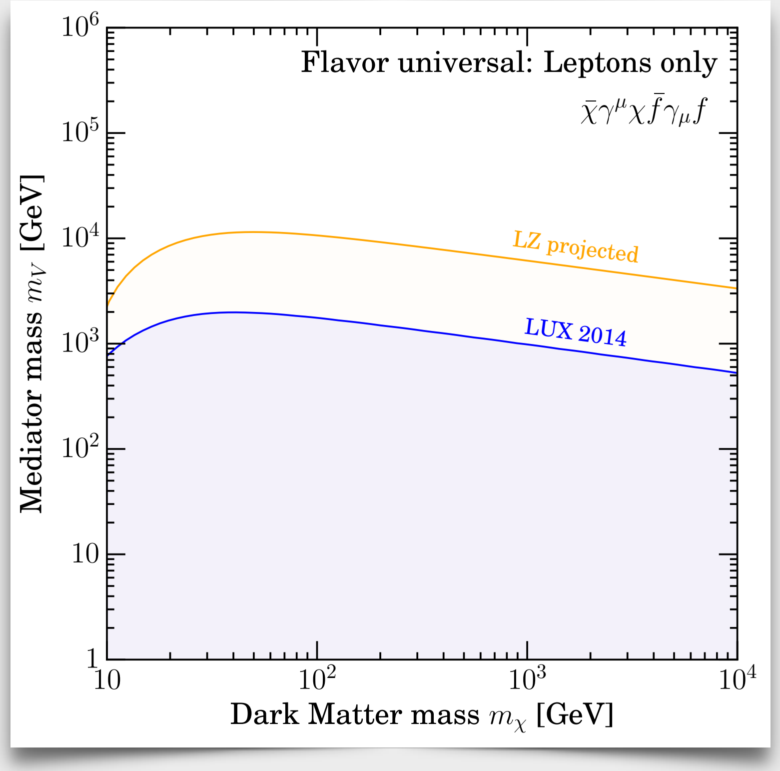
Direct detection rates and comparison with LHC: not always straightforward



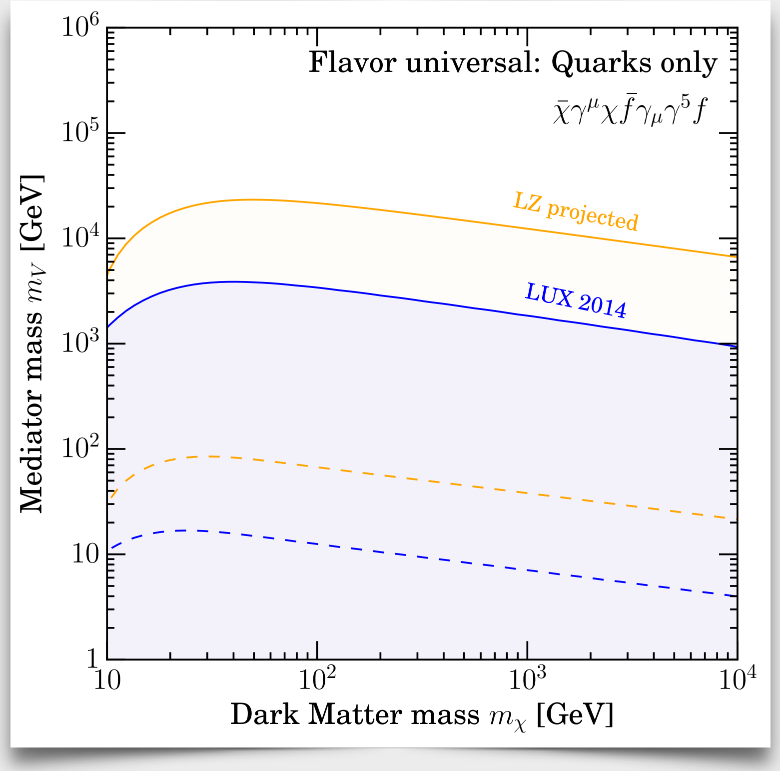


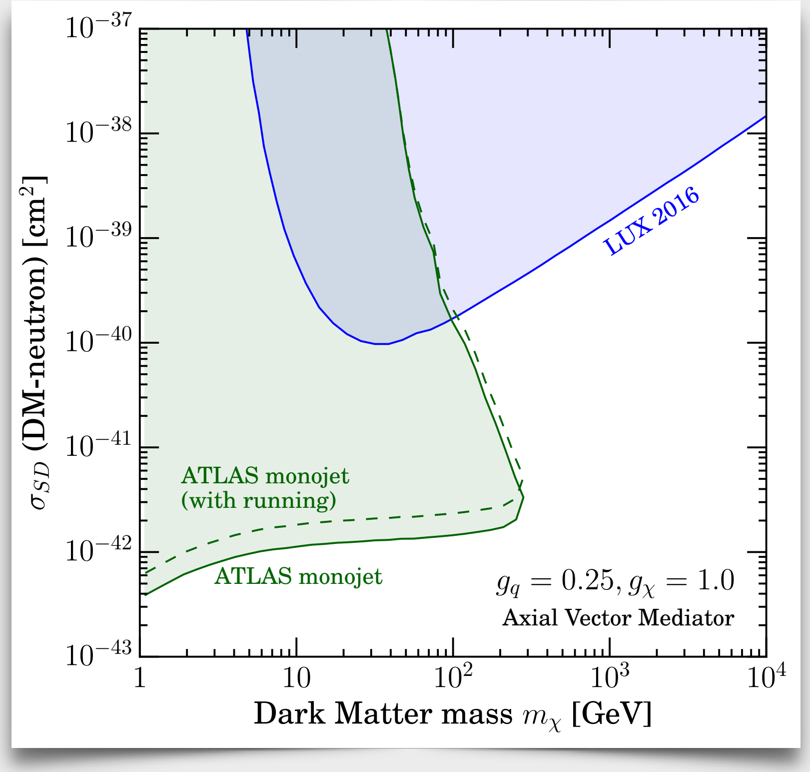


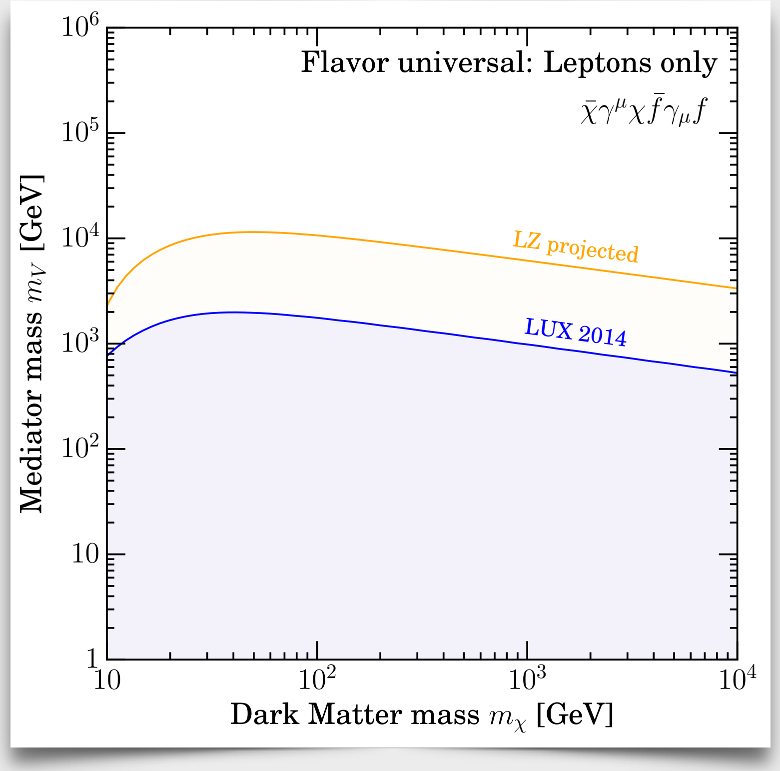
FD, Kavanagh, Panci, arXiv:1605.04917

Outlook

Direct detection rates and comparison with LHC: not always straightforward







FD, Kavanagh, Panci, arXiv:1605.04917

Thank You!