

Dark Matter

from the bottom up

Bradley J Kavanagh (LPTHE, Paris 06)

in collaboration with Paolo Panci

GDR Terascale @ Grenoble - 23/11/2015



 bradley.kavanagh@lpthe.jussieu.fr

 @BradleyKavanagh

What can direct detection tell us about interactions between DM and the Standard Model?



EFT for Singlet Dirac fermion DM χ :

$$\mathcal{L}_{\text{SM}_\chi} = \mathcal{L}_{\text{SM}} + \bar{\chi} (i\not{\partial} - m_\chi) \chi + \sum_{d>4} \sum_{\alpha} \frac{c_\alpha^{(d)}}{\Lambda^{d-4}} \mathcal{O}_\alpha^{(d)}$$

...valid up to some cut-off scale Λ

Dimension 5: $\bar{\chi}\chi H^\dagger H$ $\bar{\chi}\sigma^{\mu\nu}\chi B_{\mu\nu}$
 $\bar{\chi}\gamma^5\chi H^\dagger H$ $\bar{\chi}\sigma^{\mu\nu}\chi \epsilon_{\mu\nu\rho\sigma} B^{\rho\sigma}$

e.g.
[arXiv:1007.5515](https://arxiv.org/abs/1007.5515)
[arXiv:1203.2064](https://arxiv.org/abs/1203.2064)

We'll be interested in dimension 6...

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

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

$$H^\dagger i \overleftrightarrow{D}_\mu H$$

$$H^\dagger i \overleftrightarrow{D}_\mu H$$

$$\bar{q}^{(3)}\gamma^\mu q^{(3)}$$

$$\bar{q}^{(3)}\gamma^\mu\gamma^5 q^{(3)}$$

$$\bar{q}^{(3)}\gamma^\mu q^{(3)}$$

$$\bar{q}^{(3)}\gamma^\mu\gamma^5 q^{(3)}$$

$$\bar{q}^{(2)}\gamma^\mu q^{(2)}$$

$$\bar{q}^{(2)}\gamma^\mu\gamma^5 q^{(2)}$$

$$\bar{q}^{(2)}\gamma^\mu q^{(2)}$$

$$\bar{q}^{(2)}\gamma^\mu\gamma^5 q^{(2)}$$

$$\bar{q}^{(1)}\gamma^\mu q^{(1)}$$

$$\bar{q}^{(1)}\gamma^\mu\gamma^5 q^{(1)}$$

$$\bar{q}^{(1)}\gamma^\mu q^{(1)}$$

$$\bar{q}^{(1)}\gamma^\mu\gamma^5 q^{(1)}$$

$$\bar{\tau}\gamma^\mu\tau$$

$$\bar{\tau}\gamma^\mu\gamma^5\tau$$

$$\bar{\tau}\gamma^\mu\tau$$

$$\bar{\tau}\gamma^\mu\gamma^5\tau$$

$$\bar{\mu}\gamma^\mu\mu$$

$$\bar{\mu}\gamma^\mu\gamma^5\mu$$

$$\bar{\mu}\gamma^\mu\mu$$

$$\bar{\mu}\gamma^\mu\gamma^5\mu$$

$$\bar{e}\gamma^\mu e$$

$$\bar{e}\gamma^\mu\gamma^5 e$$

$$\bar{e}\gamma^\mu e$$

$$\bar{e}\gamma^\mu\gamma^5 e$$

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

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

$$H^\dagger i \overleftrightarrow{D}_\mu H$$

$$H^\dagger i \overleftrightarrow{D}_\mu H$$

$$\bar{q}^{(3)}\gamma^\mu q^{(3)}$$

$$\bar{q}^{(3)}\gamma^\mu\gamma^5 q^{(3)}$$

$$\bar{q}^{(3)}\gamma^\mu\gamma^5 q^{(3)}$$

$$\bar{q}^{(3)}\gamma^\mu\gamma^5 q^{(3)}$$

$$\bar{q}^{(2)}\gamma^\mu q^{(2)}$$

$$\bar{q}^{(2)}\gamma^\mu\gamma^5 q^{(2)}$$

$$\bar{q}^{(1)}\gamma^\mu q^{(1)}$$

$$\bar{q}^{(1)}\gamma^\mu\gamma^5 q^{(1)}$$

$$\bar{\tau}\gamma^\mu\tau$$

$$\bar{\tau}\gamma^\mu\gamma^5\tau$$

$$\bar{\mu}\gamma^\mu\mu$$

$$\bar{\mu}\gamma^\mu\gamma^5\mu$$

$$\bar{e}\gamma^\mu e$$

$$\bar{e}\gamma^\mu\gamma^5 e$$

$$\bar{e}\gamma^\mu e$$

$$\bar{e}\gamma^\mu\gamma^5 e$$

Note:

$$\bar{\psi}\gamma^\mu\psi = \bar{\psi}_L\gamma^\mu\psi_L + \bar{\psi}_R\gamma^\mu\psi_R$$

$$\bar{\psi}\gamma^\mu\gamma^5\psi = \bar{\psi}_L\gamma^\mu\psi_L - \bar{\psi}_R\gamma^\mu\psi_R$$

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

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

$$H^\dagger i \overleftrightarrow{D}_\mu H$$

$$H^\dagger i \overleftrightarrow{D}_\mu H$$

$$\bar{q}^{(3)}\gamma^\mu q^{(3)}$$

$$\bar{q}^{(3)}\gamma^\mu\gamma^5 q^{(3)}$$

$$\bar{q}^{(3)}\gamma^\mu q^{(3)}$$

$$\bar{q}^{(3)}\gamma^\mu\gamma^5 q^{(3)}$$

$$\bar{q}^{(2)}\gamma^\mu q^{(2)}$$

$$\bar{q}^{(2)}\gamma^\mu\gamma^5 q^{(2)}$$

$$\bar{q}^{(2)}\gamma^\mu q^{(2)}$$

$$\bar{q}^{(2)}\gamma^\mu\gamma^5 q^{(2)}$$

$$\bar{q}^{(1)}\gamma^\mu q^{(1)}$$

$$\bar{q}^{(1)}\gamma^\mu\gamma^5 q^{(1)}$$

$$\bar{q}^{(1)}\gamma^\mu q^{(1)}$$

$$\bar{q}^{(1)}\gamma^\mu\gamma^5 q^{(1)}$$

$$\bar{\tau}\gamma^\mu\tau$$

$$\bar{\tau}\gamma^\mu\gamma^5\tau$$

$$\bar{\tau}\gamma^\mu\tau$$

$$\bar{\tau}\gamma^\mu\gamma^5\tau$$

$$\bar{\mu}\gamma^\mu\mu$$

$$\bar{\mu}\gamma^\mu\gamma^5\mu$$

$$\bar{\mu}\gamma^\mu\mu$$

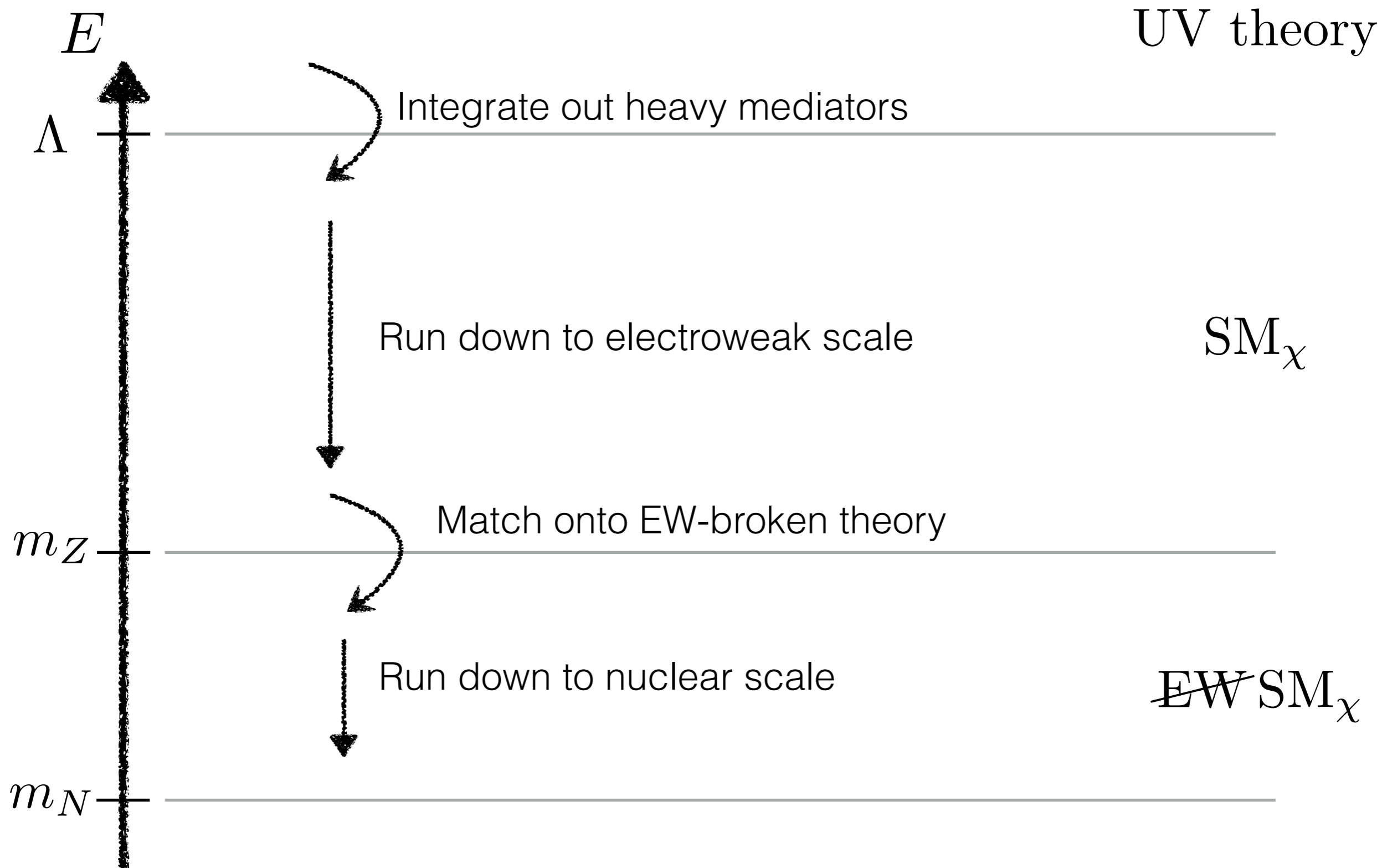
$$\bar{\mu}\gamma^\mu\gamma^5\mu$$

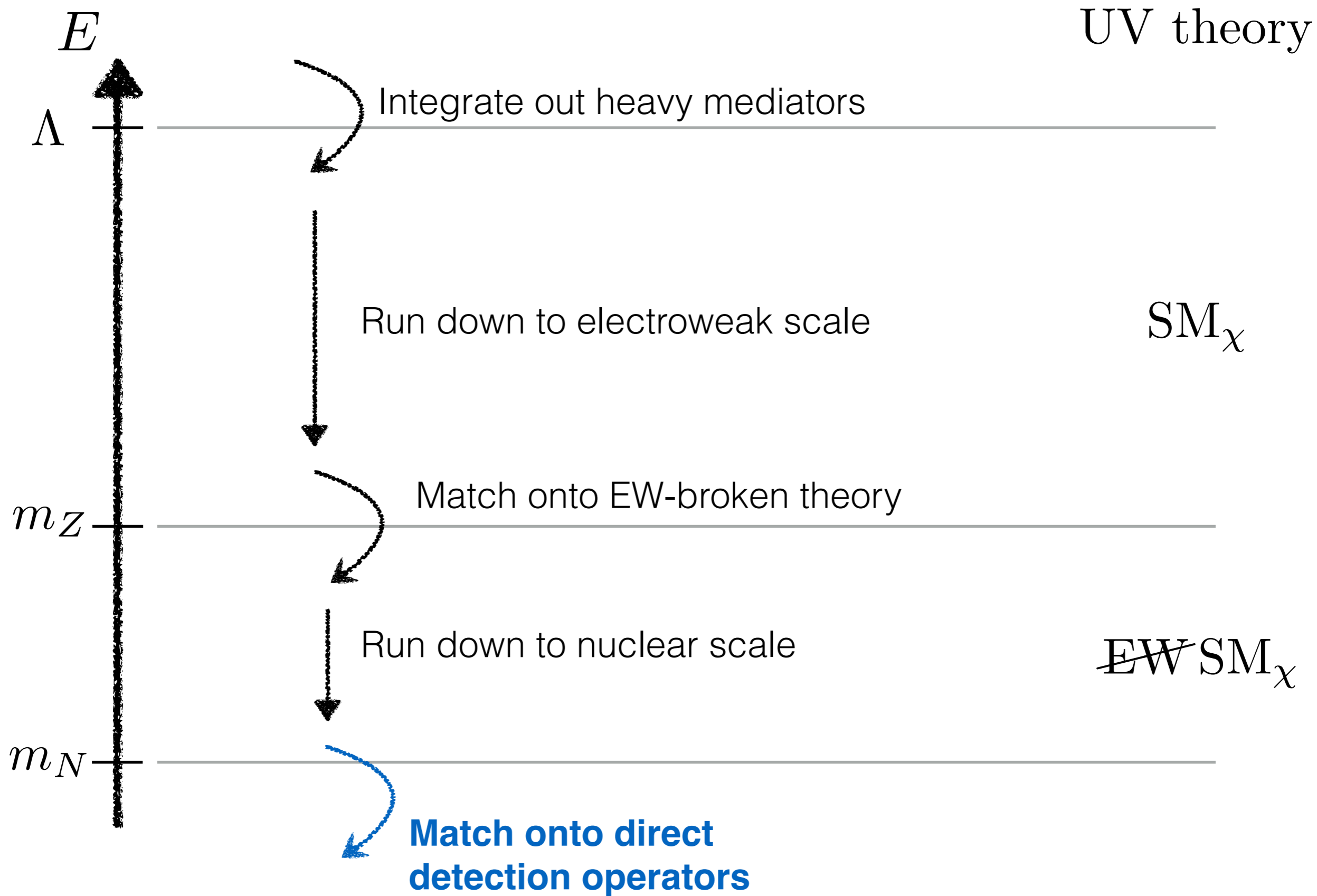
$$\bar{e}\gamma^\mu e$$

$$\bar{e}\gamma^\mu\gamma^5 e$$

$$\bar{e}\gamma^\mu e$$

$$\bar{e}\gamma^\mu\gamma^5 e$$





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

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

$$H^\dagger i \overleftrightarrow{D}_\mu H$$

$$H^\dagger i \overleftrightarrow{D}_\mu H$$

$$\bar{q}^{(3)}\gamma^\mu q^{(3)}$$

$$\bar{q}^{(3)}\gamma^\mu\gamma^5 q^{(3)}$$

$$\bar{q}^{(3)}\gamma^\mu q^{(3)}$$

$$\bar{q}^{(3)}\gamma^\mu\gamma^5 q^{(3)}$$

$$\bar{q}^{(2)}\gamma^\mu q^{(2)}$$

$$\bar{q}^{(2)}\gamma^\mu\gamma^5 q^{(2)}$$

$$\bar{q}^{(2)}\gamma^\mu q^{(2)}$$

$$\bar{q}^{(2)}\gamma^\mu\gamma^5 q^{(2)}$$

$$\bar{q}^{(1)}\gamma^\mu q^{(1)}$$

$$\bar{q}^{(1)}\gamma^\mu\gamma^5 q^{(1)}$$

$$\bar{q}^{(1)}\gamma^\mu q^{(1)}$$

$$\bar{q}^{(1)}\gamma^\mu\gamma^5 q^{(1)}$$

$$\bar{\tau}\gamma^\mu\tau$$

$$\bar{\tau}\gamma^\mu\gamma^5\tau$$

$$\bar{\tau}\gamma^\mu\tau$$

$$\bar{\tau}\gamma^\mu\gamma^5\tau$$

$$\bar{\mu}\gamma^\mu\mu$$

$$\bar{\mu}\gamma^\mu\gamma^5\mu$$

$$\bar{\mu}\gamma^\mu\mu$$

$$\bar{\mu}\gamma^\mu\gamma^5\mu$$

$$\bar{e}\gamma^\mu e$$

$$\bar{e}\gamma^\mu\gamma^5 e$$

$$\bar{e}\gamma^\mu e$$

$$\bar{e}\gamma^\mu\gamma^5 e$$

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

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

$$H^\dagger i \overleftrightarrow{D}_\mu H$$

$$H^\dagger i \overleftrightarrow{D}_\mu H$$

$$\bar{q}^{(3)}\gamma^\mu q^{(3)}$$

$$\bar{q}^{(3)}\gamma^\mu\gamma^5 q^{(3)}$$

$$\bar{q}^{(3)}\gamma^\mu q^{(3)}$$

$$\bar{q}^{(3)}\gamma^\mu\gamma^5 q^{(3)}$$

$$\bar{q}^{(2)}\gamma^\mu q^{(2)}$$

$$\bar{q}^{(2)}\gamma^\mu\gamma^5 q^{(2)}$$

$$\bar{q}^{(2)}\gamma^\mu q^{(2)}$$

$$\bar{q}^{(2)}\gamma^\mu\gamma^5 q^{(2)}$$

$$\bar{q}^{(1)}\gamma^\mu q^{(1)}$$

$$\bar{q}^{(1)}\gamma^\mu\gamma^5 q^{(1)}$$

$$\bar{q}^{(1)}\gamma^\mu q^{(1)}$$

$$\bar{q}^{(1)}\gamma^\mu\gamma^5 q^{(1)}$$

$$\bar{\tau}\gamma^\mu\tau$$

$$\bar{\tau}\gamma^\mu\gamma^5\tau$$

$$\bar{\tau}\gamma^\mu\tau$$

$$\bar{\tau}\gamma^\mu\gamma^5\tau$$

$$\bar{\mu}\gamma^\mu\mu$$

$$\bar{\mu}\gamma^\mu\gamma^5\mu$$

$$\bar{\mu}\gamma^\mu\mu$$

$$\bar{\mu}\gamma^\mu\gamma^5\mu$$

$$\bar{e}\gamma^\mu e$$

$$\bar{e}\gamma^\mu\gamma^5 e$$

$$\bar{e}\gamma^\mu e$$

$$\bar{e}\gamma^\mu\gamma^5 e$$

Relativistic quark operators

SI: $(\bar{\chi}\gamma^\mu\chi)(\bar{q}\gamma_\mu q) \rightarrow$

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

SD: $(\bar{\chi}\gamma^\mu\gamma^5\chi)(\bar{q}\gamma_\mu\gamma^5 q) \rightarrow$

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

Non-relativistic nucleon operators

1

$i\vec{S}_\chi \cdot (\vec{S}_N \times \vec{q}) - m_\chi \vec{S}_N \cdot \vec{v}^\perp$

$\vec{S}_\chi \cdot \vec{S}_N$

$m_N \vec{S}_N \cdot \vec{v}^\perp + i\vec{S}_\chi \cdot (\vec{S}_N \times \vec{q})$

Relativistic quark operators

SI: $(\bar{\chi}\gamma^\mu\chi)(\bar{q}\gamma_\mu q) \rightarrow$

~~$(\bar{\chi}\gamma^\mu\chi)(\bar{q}\gamma_\mu\gamma^5 q)$~~ \rightarrow

SD: $(\bar{\chi}\gamma^\mu\gamma^5\chi)(\bar{q}\gamma_\mu\gamma^5 q) \rightarrow$

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

Non-relativistic nucleon operators

1

$i\vec{S}_\chi \cdot (\vec{S}_N \times \vec{q}) - m_\chi \vec{S}_N \cdot \vec{v}^\perp$

$\vec{S}_\chi \cdot \vec{S}_N$

$m_N \vec{S}_N \cdot \vec{v}^\perp + i\vec{S}_\chi \cdot (\vec{S}_N \times \vec{q})$

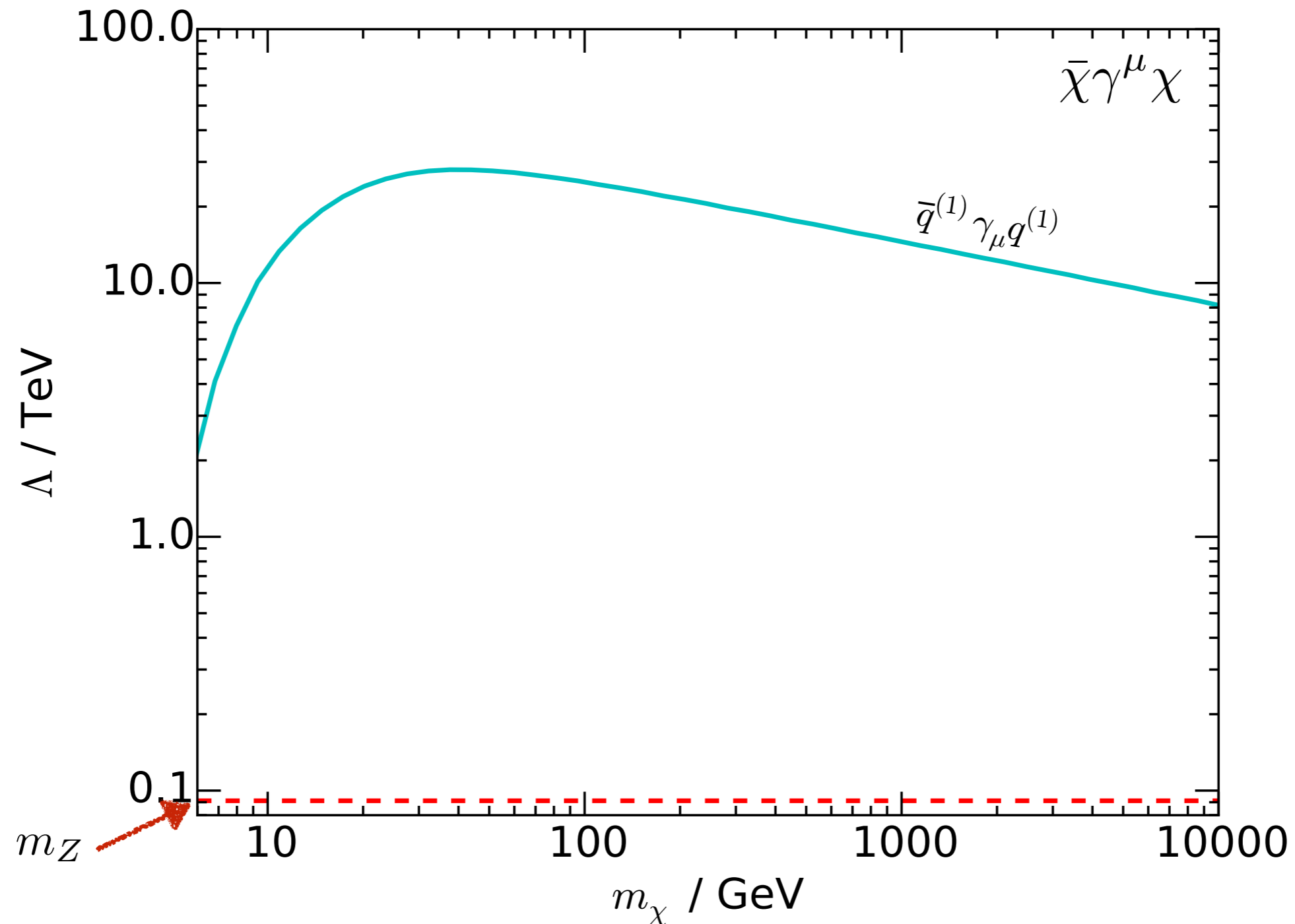
Constraints from Spin-Independent (SI) interactions



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

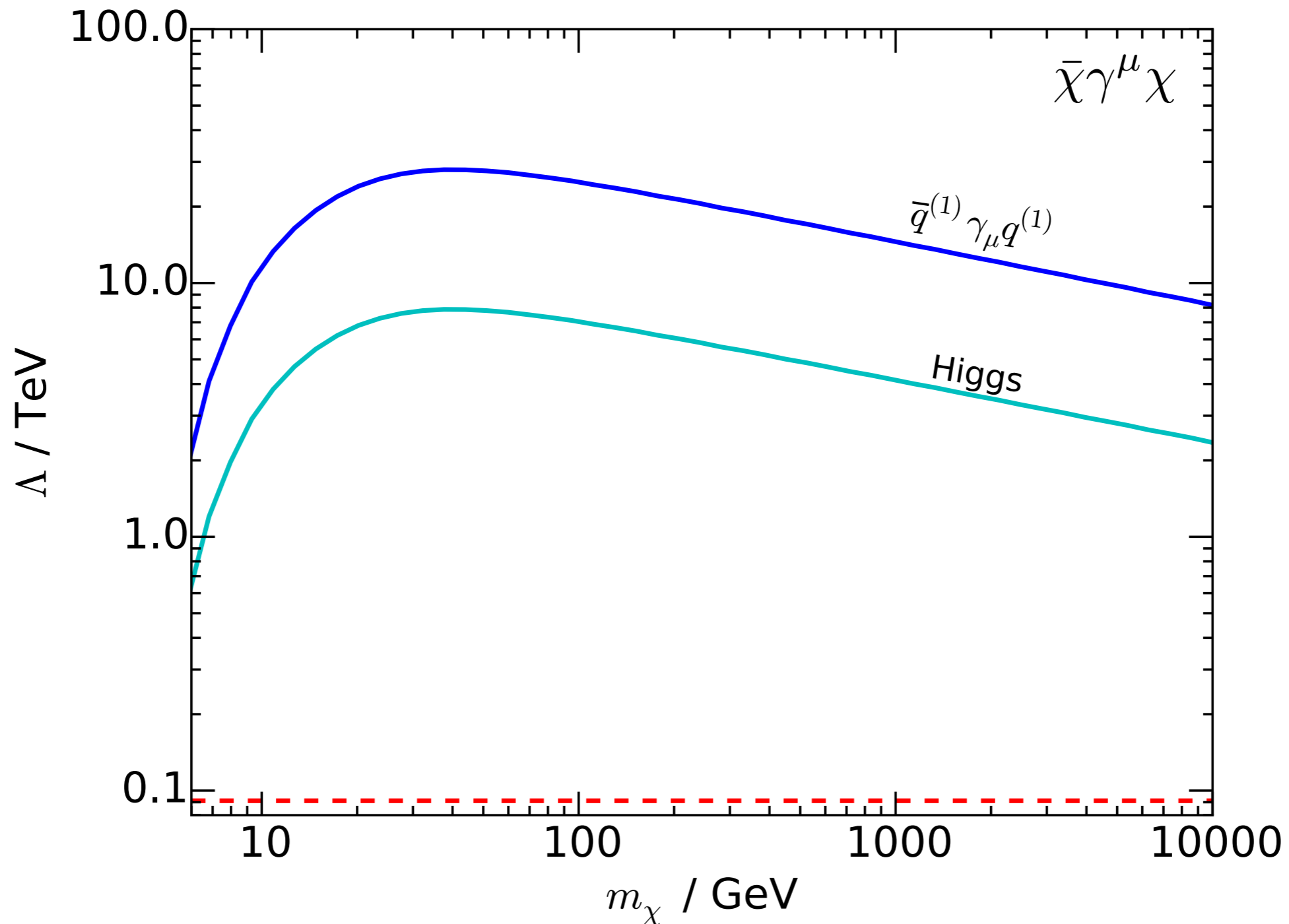
$$\bar{\chi}\gamma^{\mu}\chi\bar{d}\gamma_{\mu}d$$

Dim-6 SI interaction: $\frac{1}{\Lambda^2} \bar{\chi} \gamma^\mu \chi \bar{q}^{(1)} \gamma_\mu q^{(1)}$

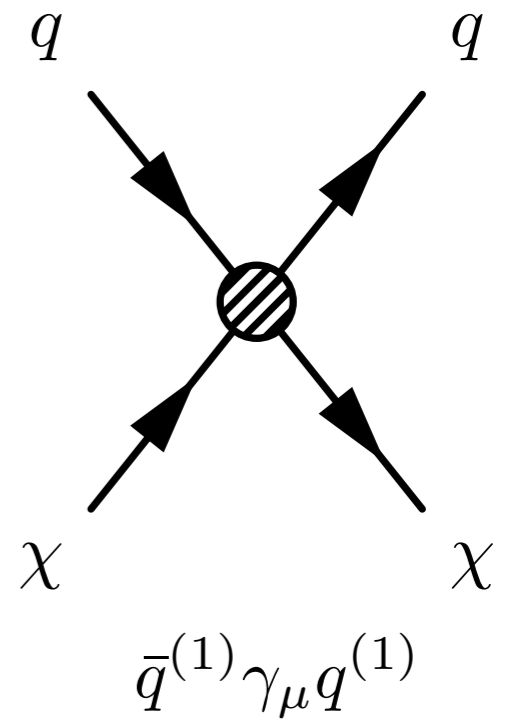
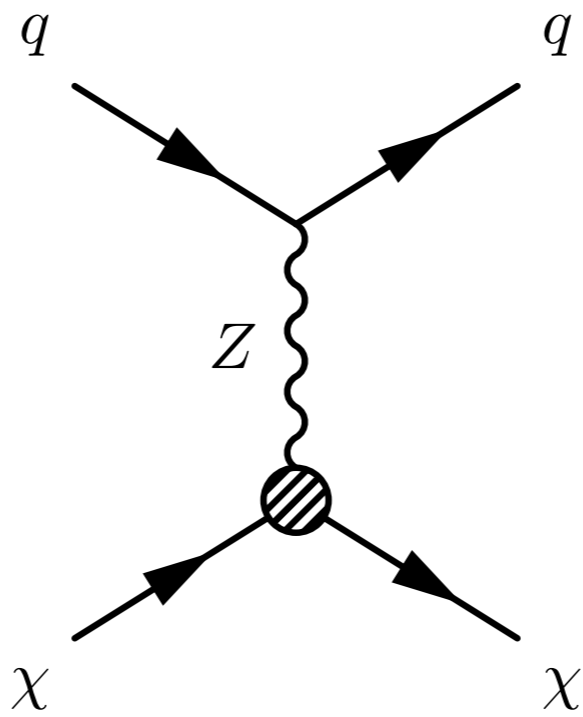
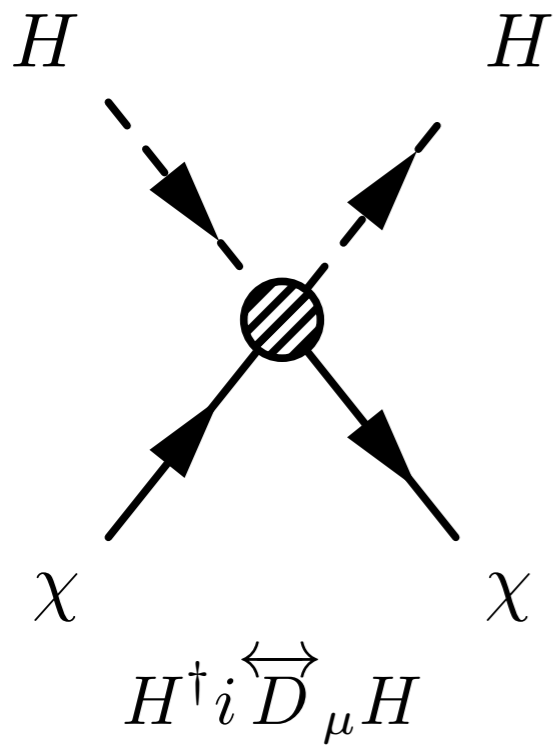


SI cross section limits from LUX [arXiv:1310.8214]

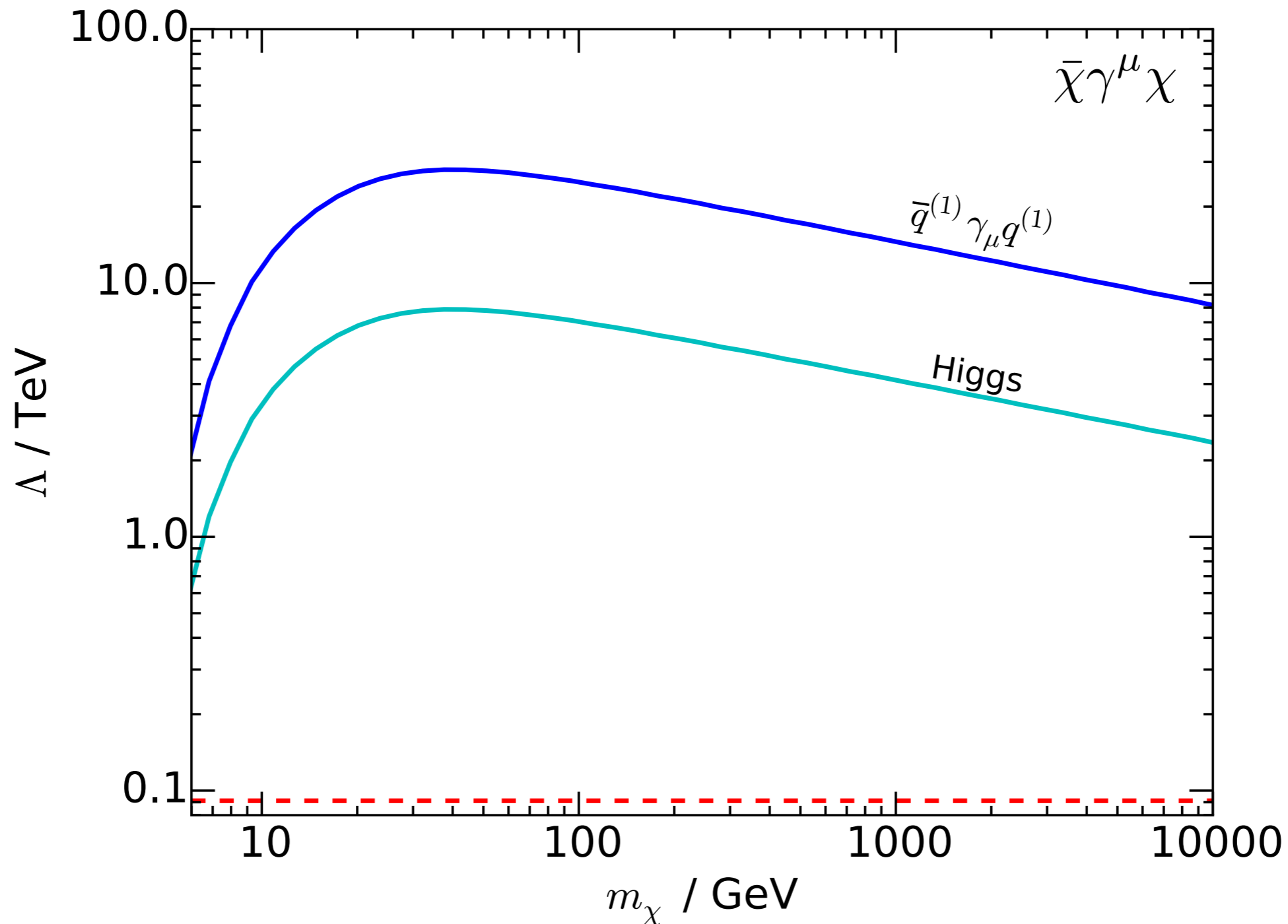
Higgs coupling: $\frac{1}{\Lambda^2} \bar{\chi} \gamma^\mu \chi H^\dagger i \overleftrightarrow{D}_\mu H$



SI cross section limits from LUX [arXiv:1310.8214]

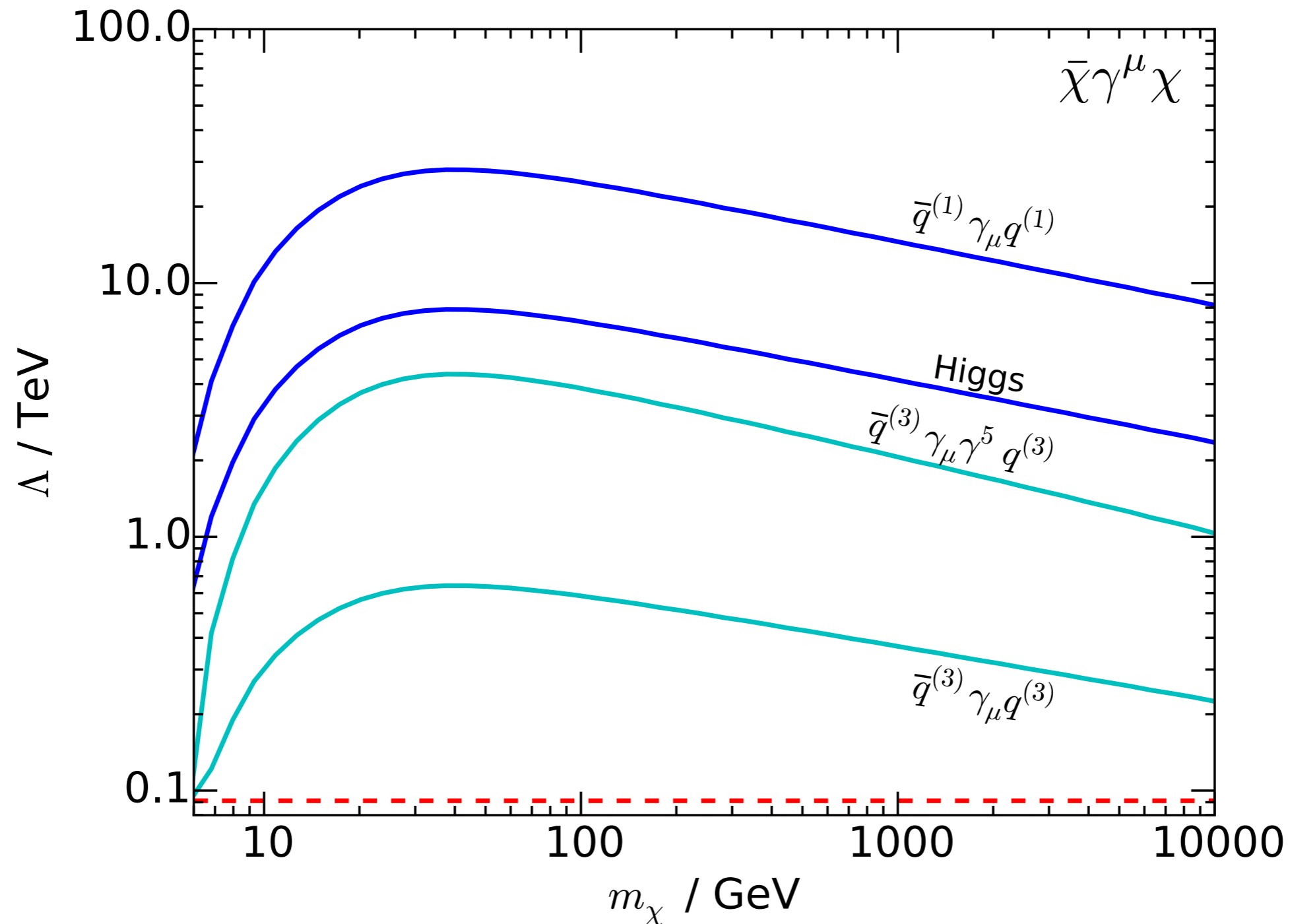


Higgs coupling: $\frac{1}{\Lambda^2} \bar{\chi} \gamma^\mu \chi H^\dagger i \overleftrightarrow{D}_\mu H$

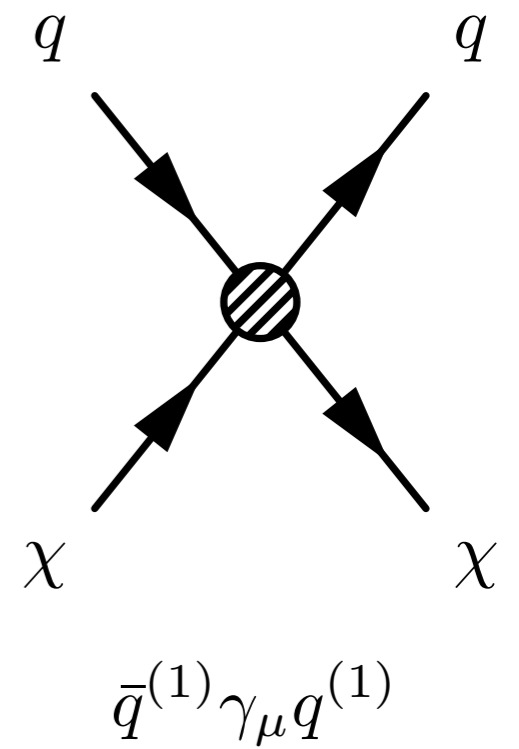
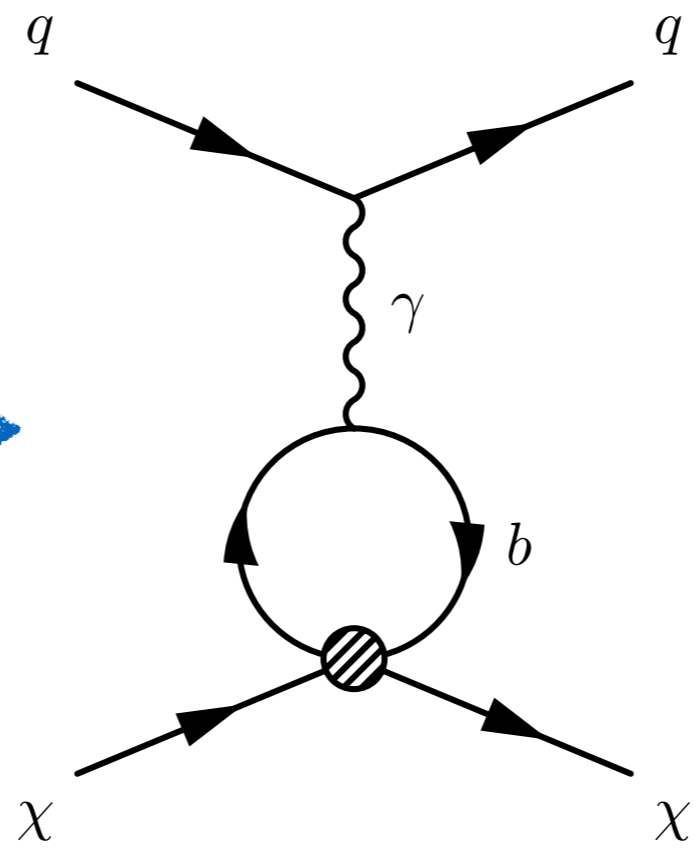
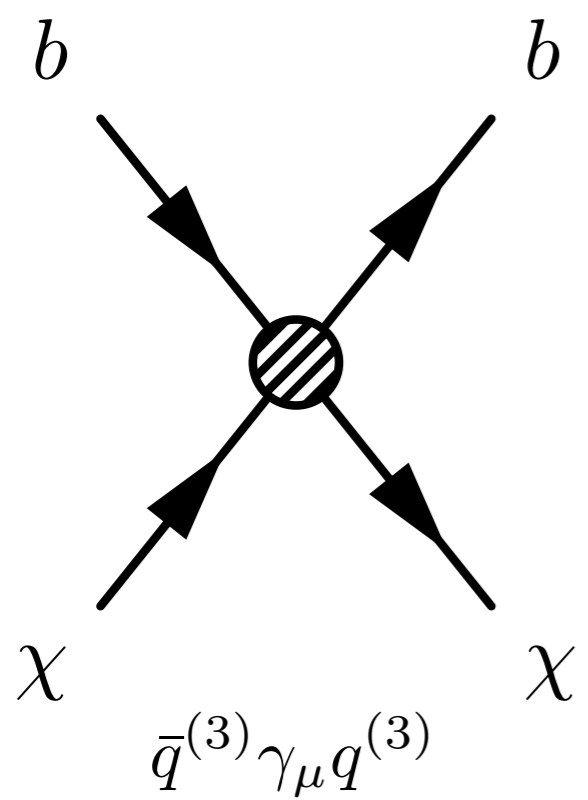
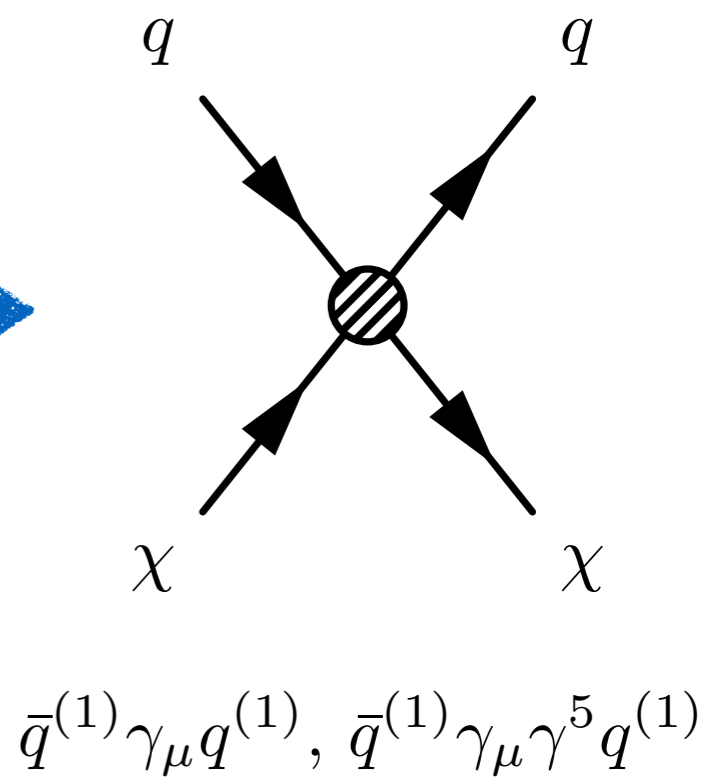
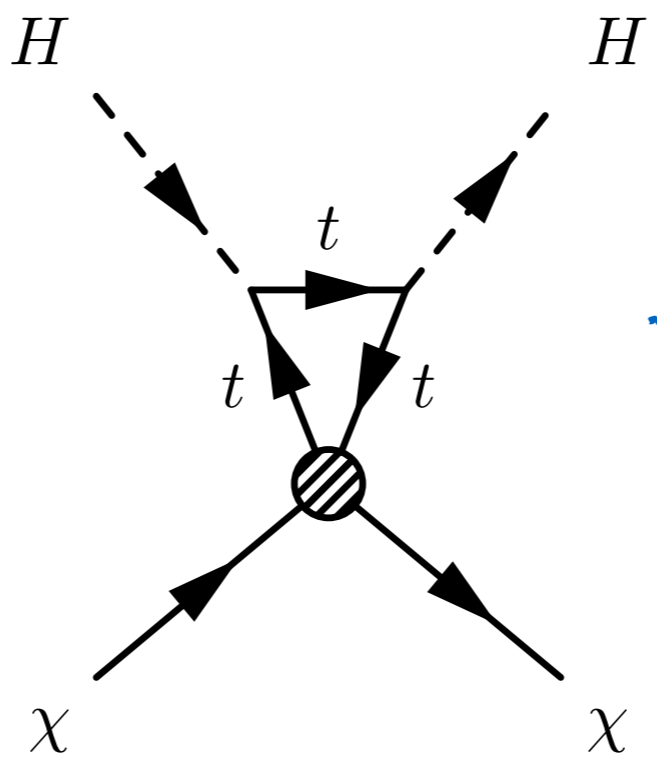
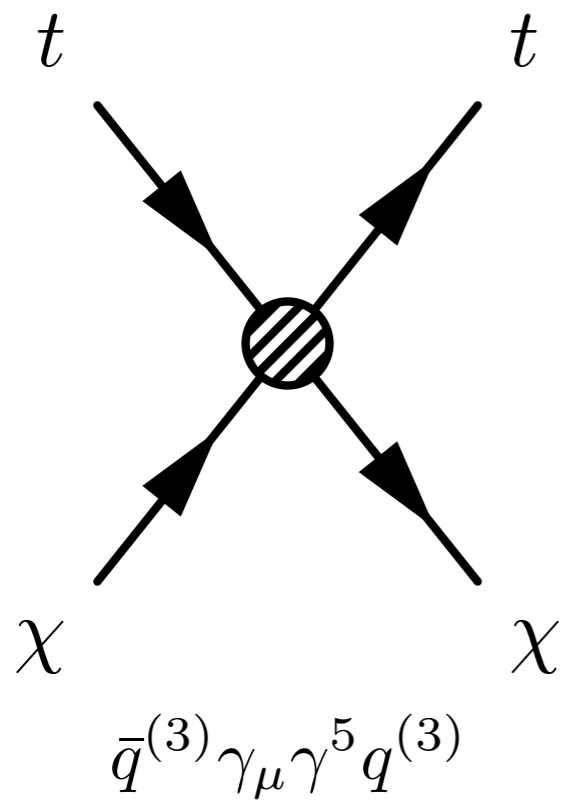


SI cross section limits from LUX [arXiv:1310.8214]

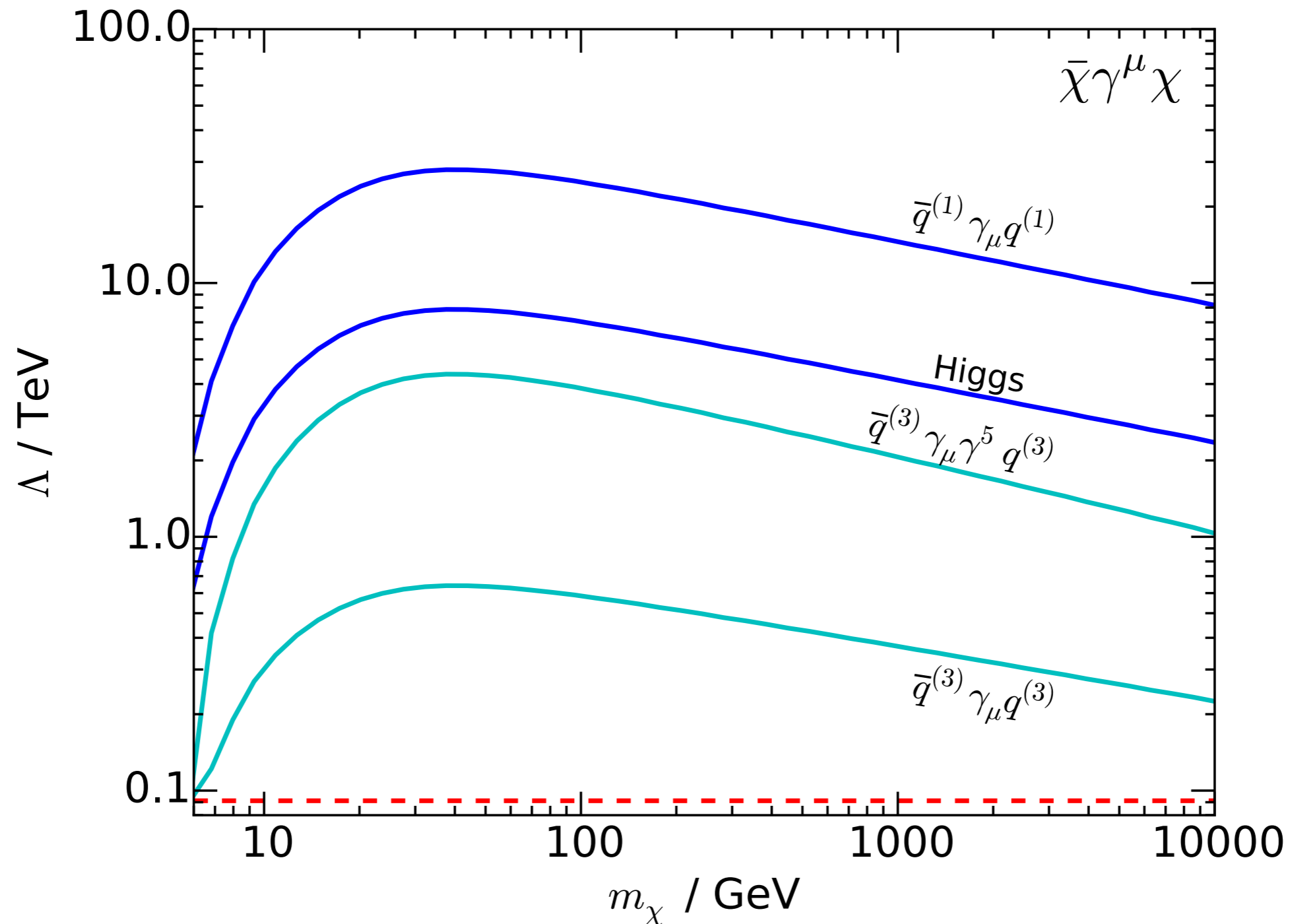
Heavy quarks: $\frac{1}{\Lambda^2} \bar{\chi} \gamma^\mu \chi \bar{q}^{(3)} \gamma_\mu q^{(3)}$, $\frac{1}{\Lambda^2} \bar{\chi} \gamma^\mu \chi \bar{q}^{(3)} \gamma_\mu \gamma^5 q^{(3)}$



SI cross section limits from LUX [arXiv:1310.8214]



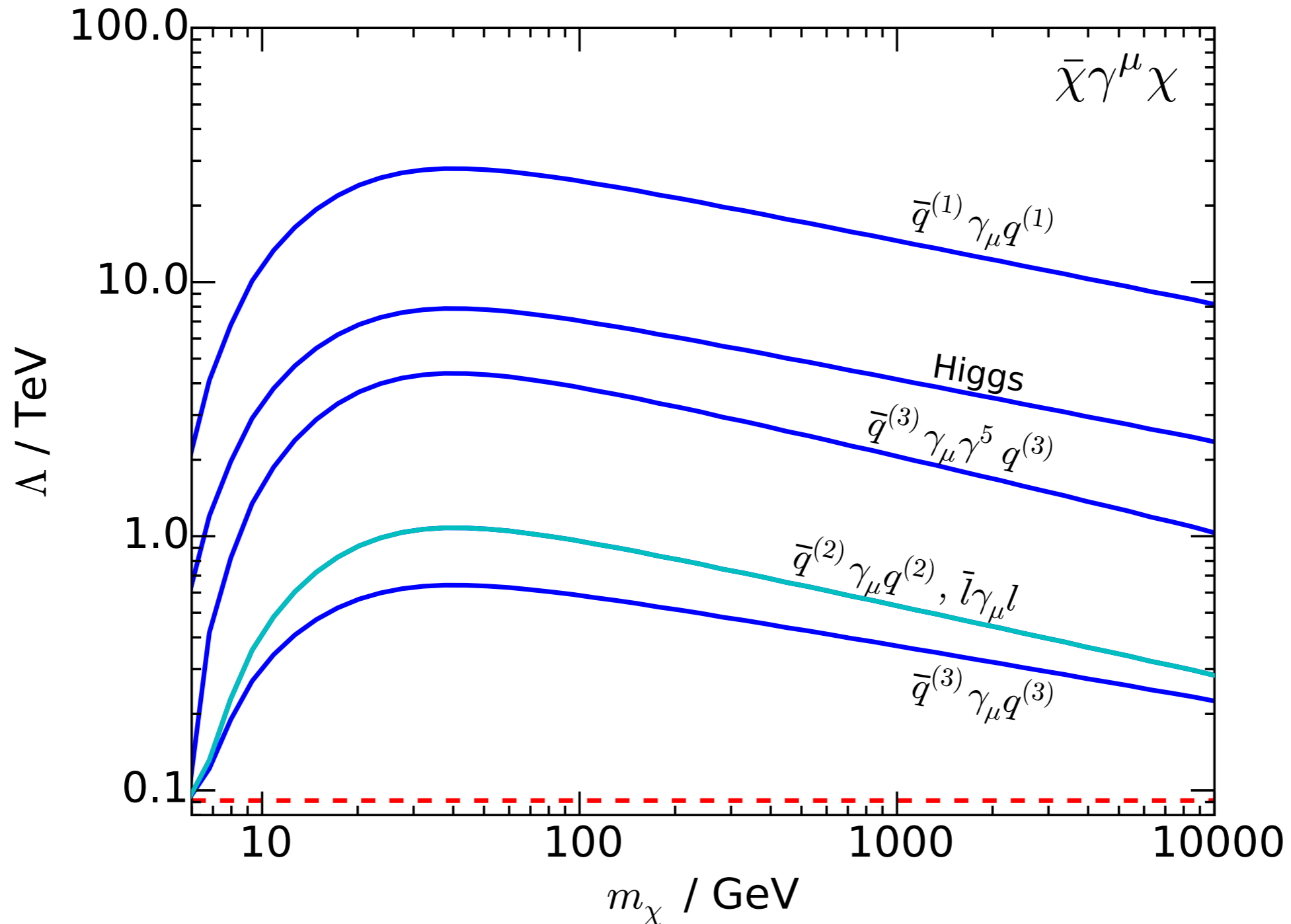
Heavy quarks: $\frac{1}{\Lambda^2} \bar{\chi} \gamma^\mu \chi \bar{q}^{(3)} \gamma_\mu q^{(3)}$, $\frac{1}{\Lambda^2} \bar{\chi} \gamma^\mu \chi \bar{q}^{(3)} \gamma_\mu \gamma^5 q^{(3)}$



SI cross section limits from LUX [arXiv:1310.8214]

Some more vector currents:

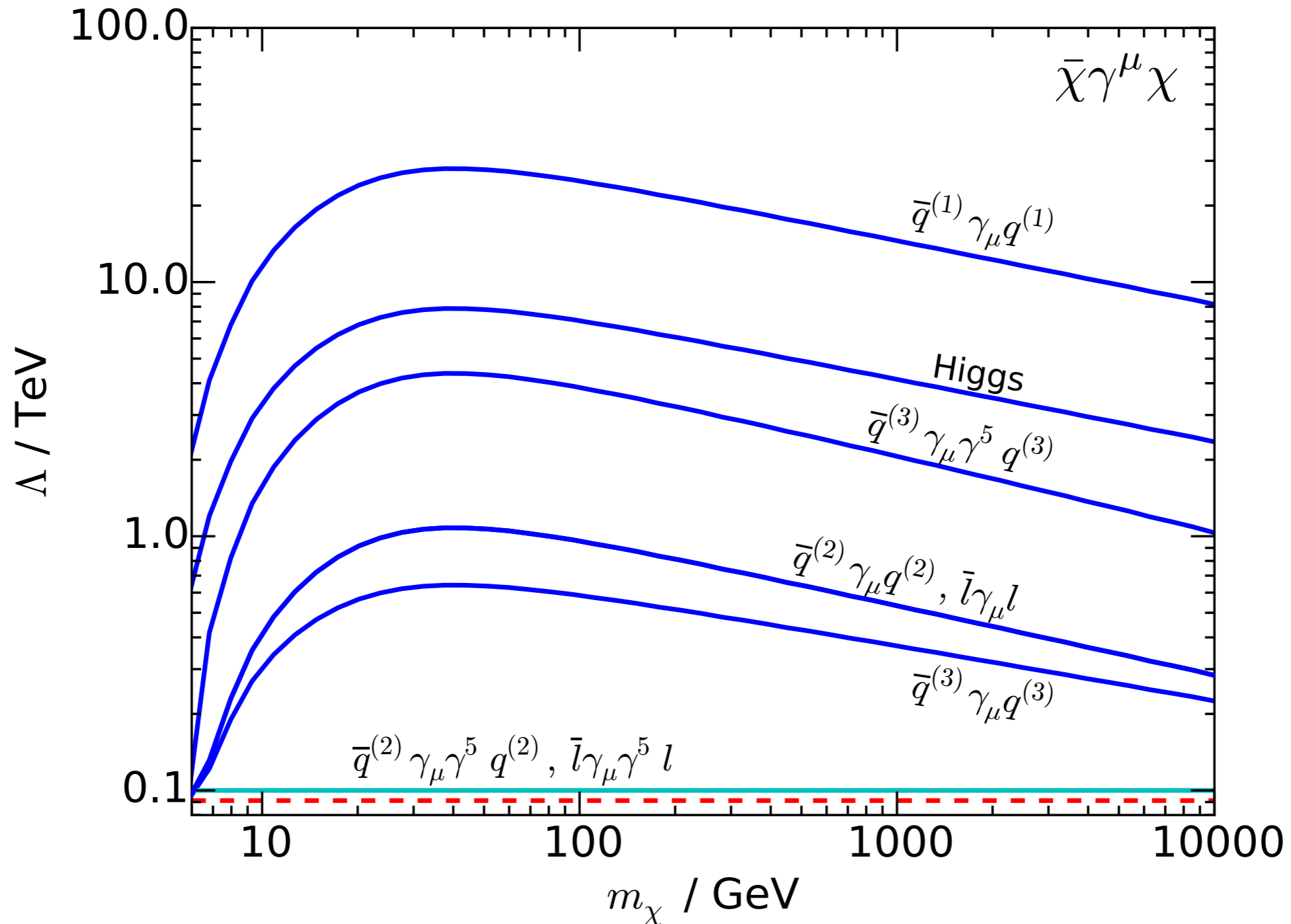
$$\frac{1}{\Lambda^2} \bar{\chi} \gamma^\mu \chi \bar{l} \gamma_\mu l, \quad \frac{1}{\Lambda^2} \bar{\chi} \gamma^\mu \chi \bar{q}^{(2)} \gamma_\mu q^{(2)}$$



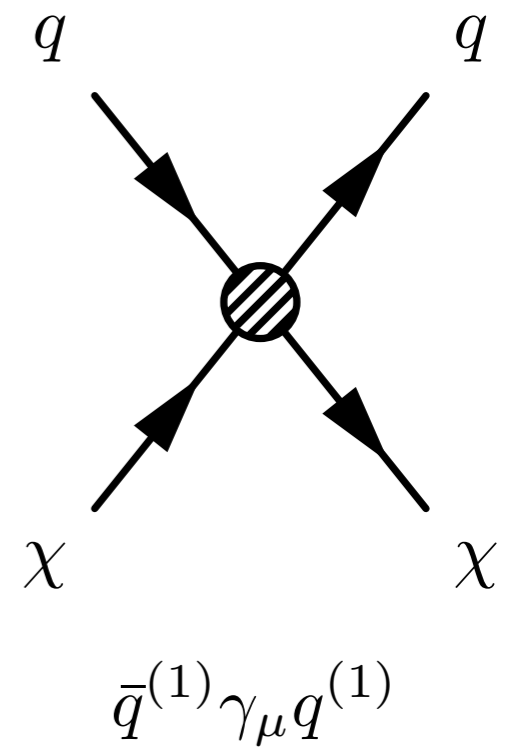
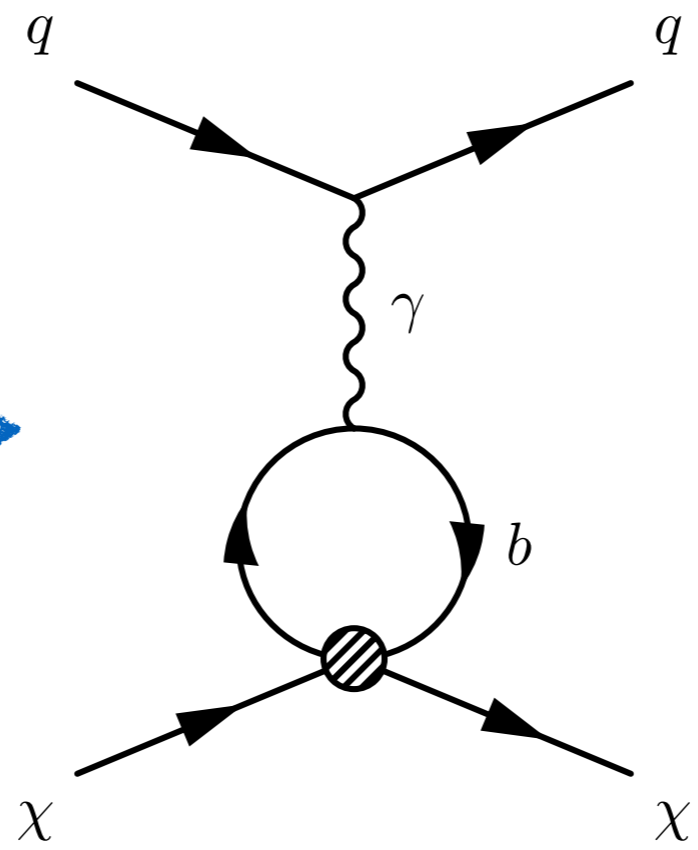
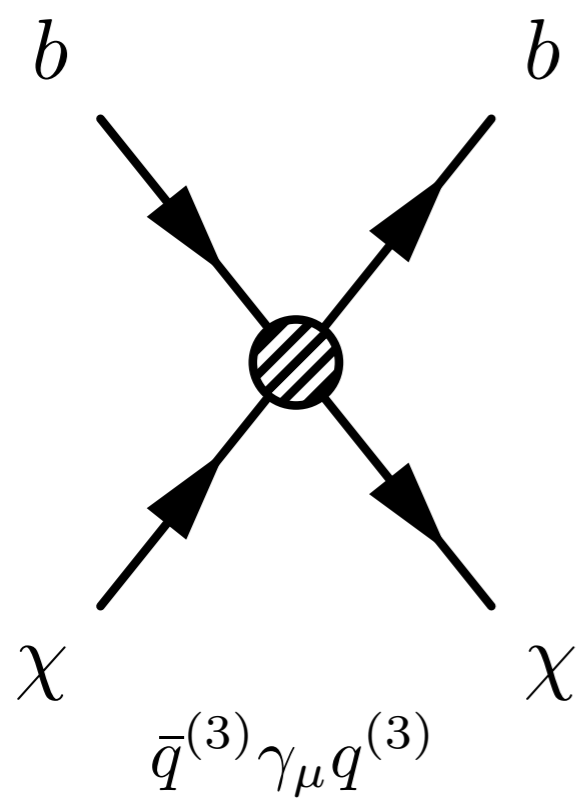
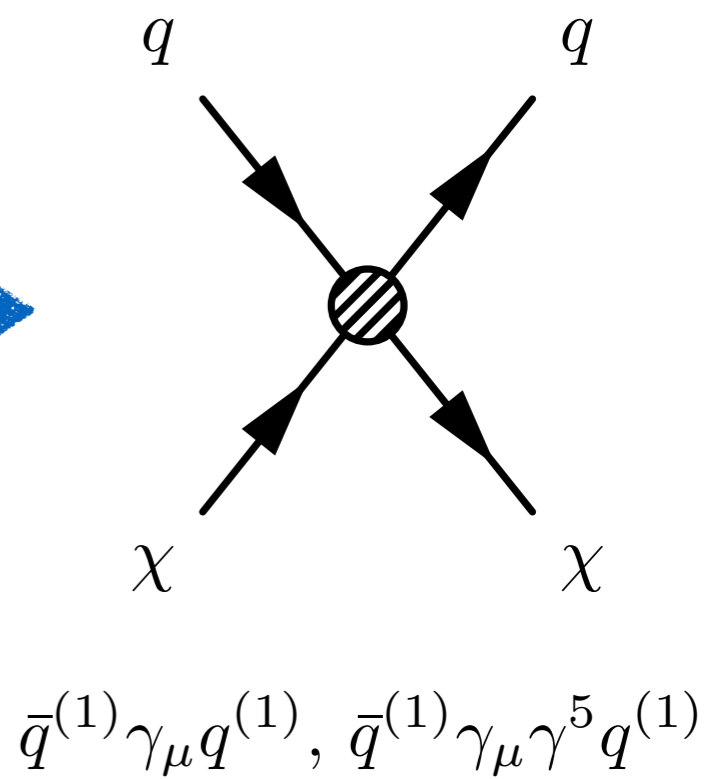
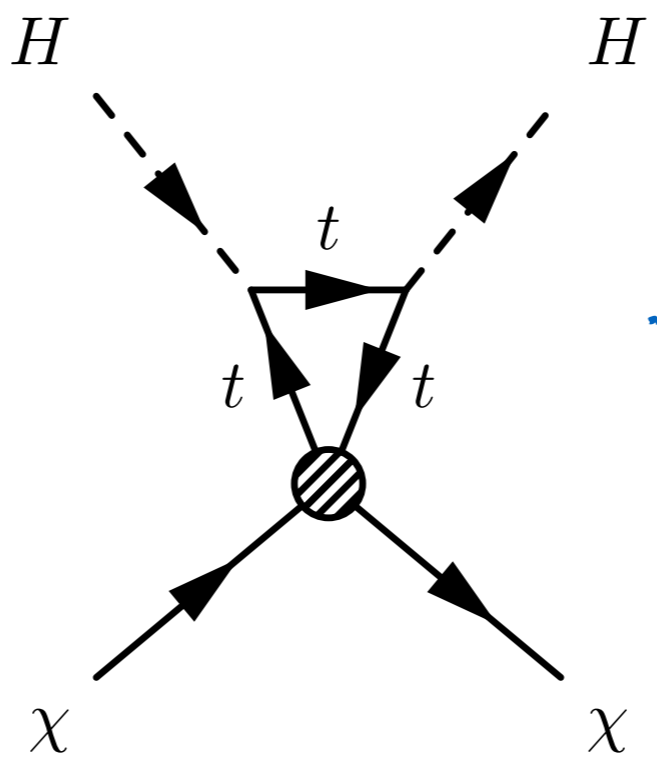
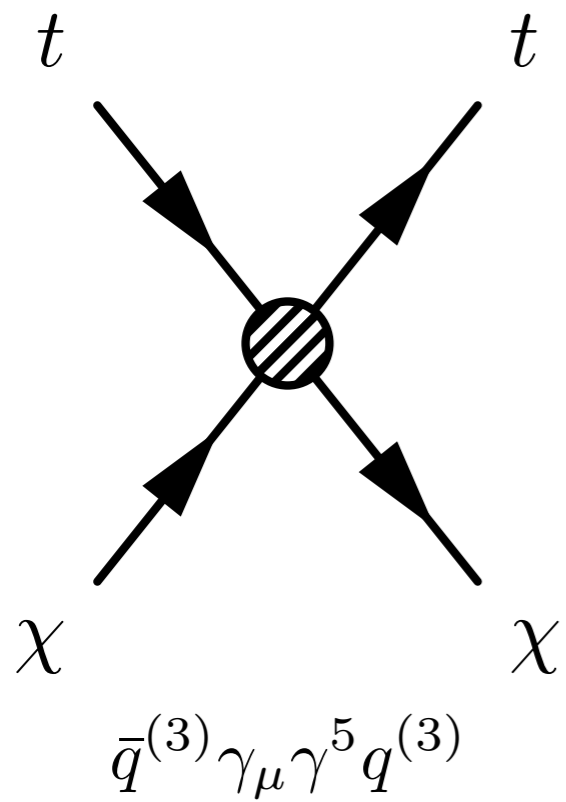
SI cross section limits from LUX [arXiv:1310.8214]

And axial-vector currents:

$$\frac{1}{\Lambda^2} \bar{\chi} \gamma^\mu \chi \bar{l} \gamma_\mu \gamma^5 l, \quad \frac{1}{\Lambda^2} \bar{\chi} \gamma^\mu \chi \bar{q}^{(2)} \gamma_\mu \gamma^5 q^{(2)}$$

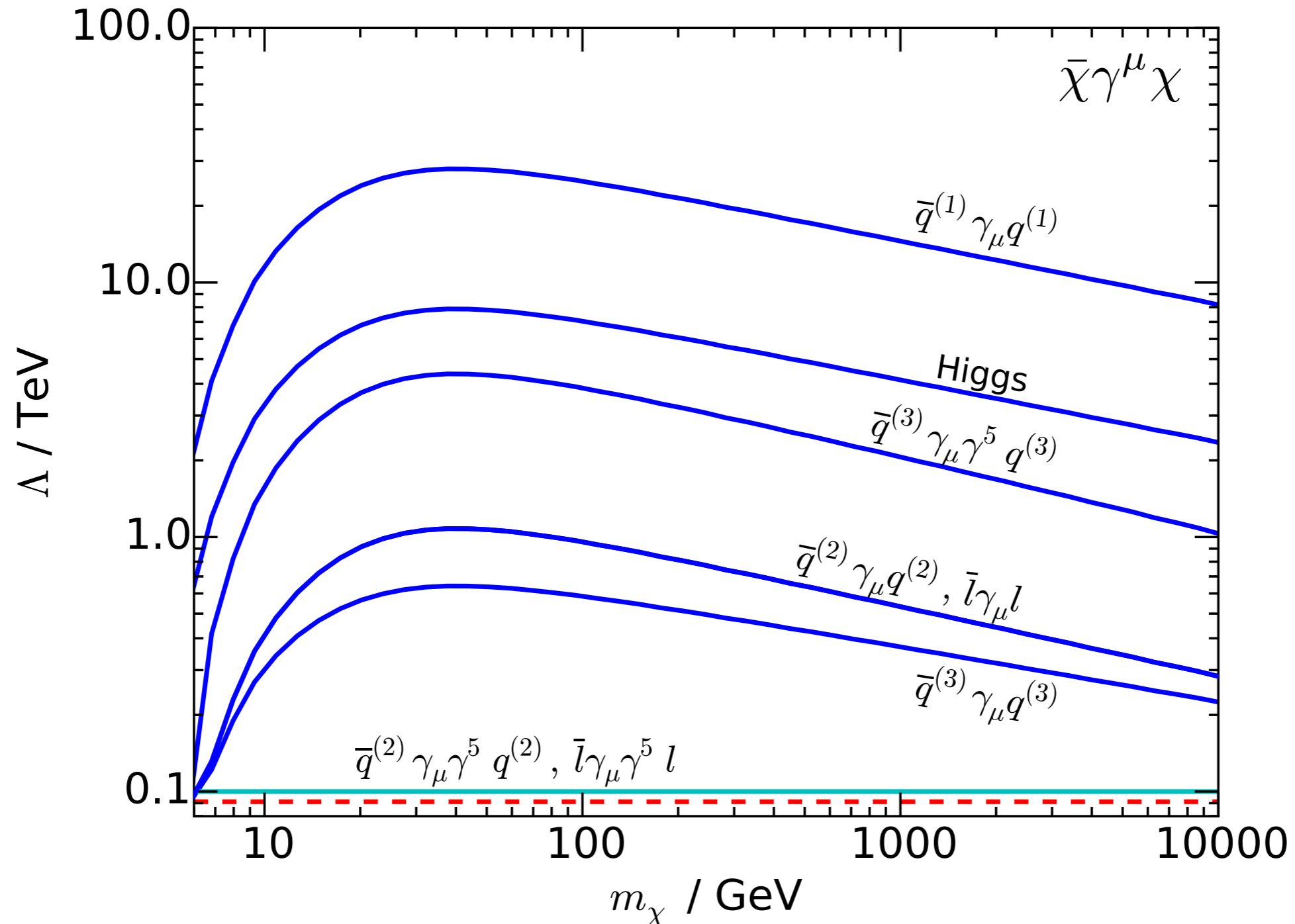


SI cross section limits from LUX [arXiv:1310.8214]



And axial-vector currents:

$$\frac{1}{\Lambda^2} \bar{\chi} \gamma^\mu \chi \bar{l} \gamma_\mu \gamma^5 l, \quad \frac{1}{\Lambda^2} \bar{\chi} \gamma^\mu \chi \bar{q}^{(2)} \gamma_\mu \gamma^5 q^{(2)}$$



SI cross section limits from LUX [arXiv:1310.8214]

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

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

$$H^\dagger i \overleftrightarrow{D}_\mu H$$

$$H^\dagger i \overleftrightarrow{D}_\mu H$$

$$\bar{q}^{(3)}\gamma^\mu q^{(3)}$$

$$\bar{q}^{(3)}\gamma^\mu\gamma^5 q^{(3)}$$

$$\bar{q}^{(3)}\gamma^\mu q^{(3)}$$

$$\bar{q}^{(3)}\gamma^\mu\gamma^5 q^{(3)}$$

$$\bar{q}^{(2)}\gamma^\mu q^{(2)}$$

$$\bar{q}^{(2)}\gamma^\mu\gamma^5 q^{(2)}$$

$$\bar{q}^{(2)}\gamma^\mu q^{(2)}$$

$$\bar{q}^{(2)}\gamma^\mu\gamma^5 q^{(2)}$$

$$\bar{q}^{(1)}\gamma^\mu q^{(1)}$$

$$\bar{q}^{(1)}\gamma^\mu\gamma^5 q^{(1)}$$

$$\bar{q}^{(1)}\gamma^\mu q^{(1)}$$

$$\bar{q}^{(1)}\gamma^\mu\gamma^5 q^{(1)}$$

$$\bar{\tau}\gamma^\mu\tau$$

$$\bar{\tau}\gamma^\mu\gamma^5\tau$$

$$\bar{\tau}\gamma^\mu\tau$$

$$\bar{\tau}\gamma^\mu\gamma^5\tau$$

$$\bar{\mu}\gamma^\mu\mu$$

$$\bar{\mu}\gamma^\mu\gamma^5\mu$$

$$\bar{\mu}\gamma^\mu\mu$$

$$\bar{\mu}\gamma^\mu\gamma^5\mu$$


$$\bar{e}\gamma^\mu e$$

$$\bar{e}\gamma^\mu\gamma^5 e$$

$$\bar{e}\gamma^\mu e$$

$$\bar{e}\gamma^\mu\gamma^5 e$$

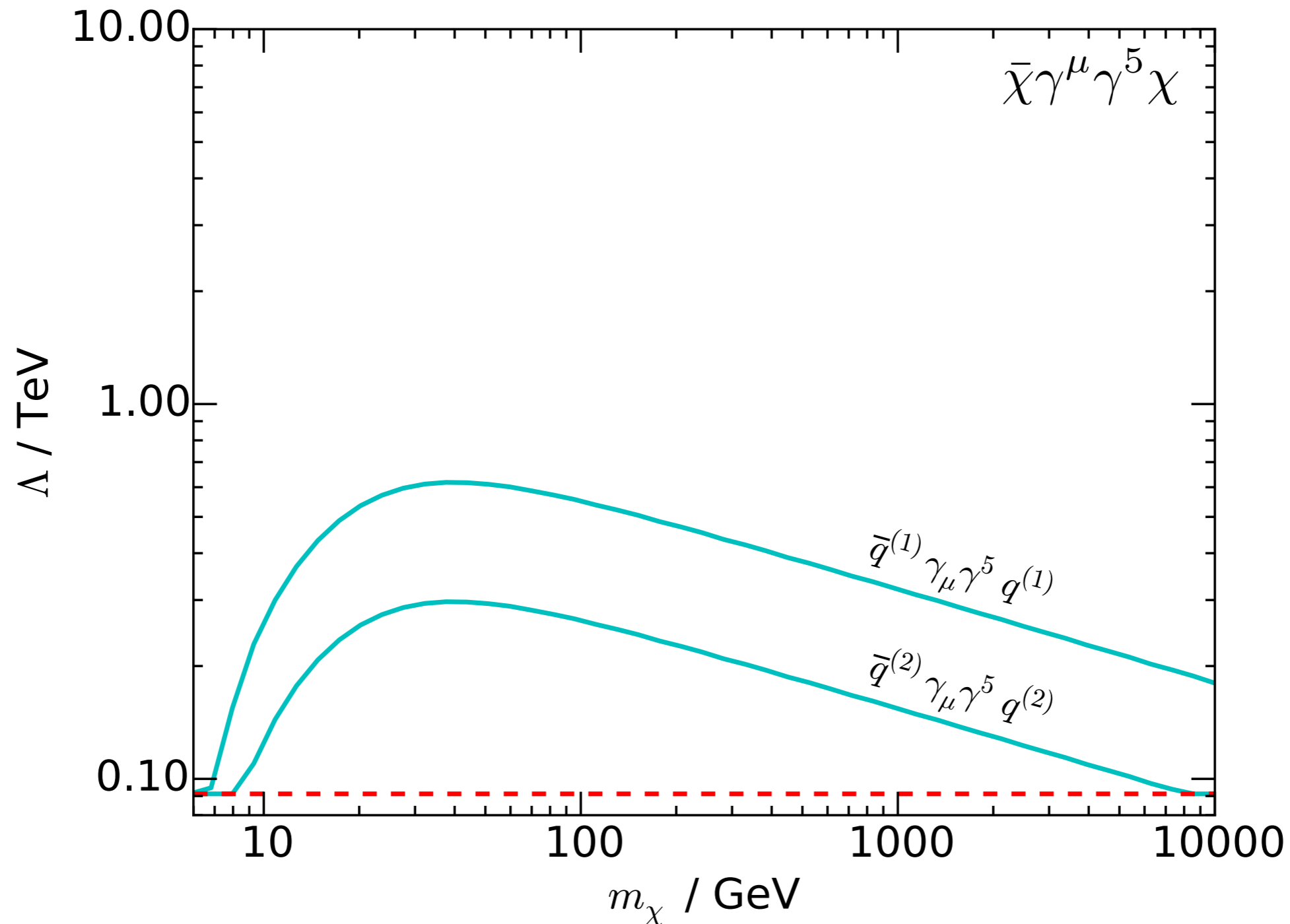
Constraints from Spin-dependent (SD) interactions



$$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{u}\gamma_\mu\gamma^5u \quad \bar{\chi}\gamma^\mu\gamma^5\chi\bar{d}\gamma_\mu\gamma^5d$$

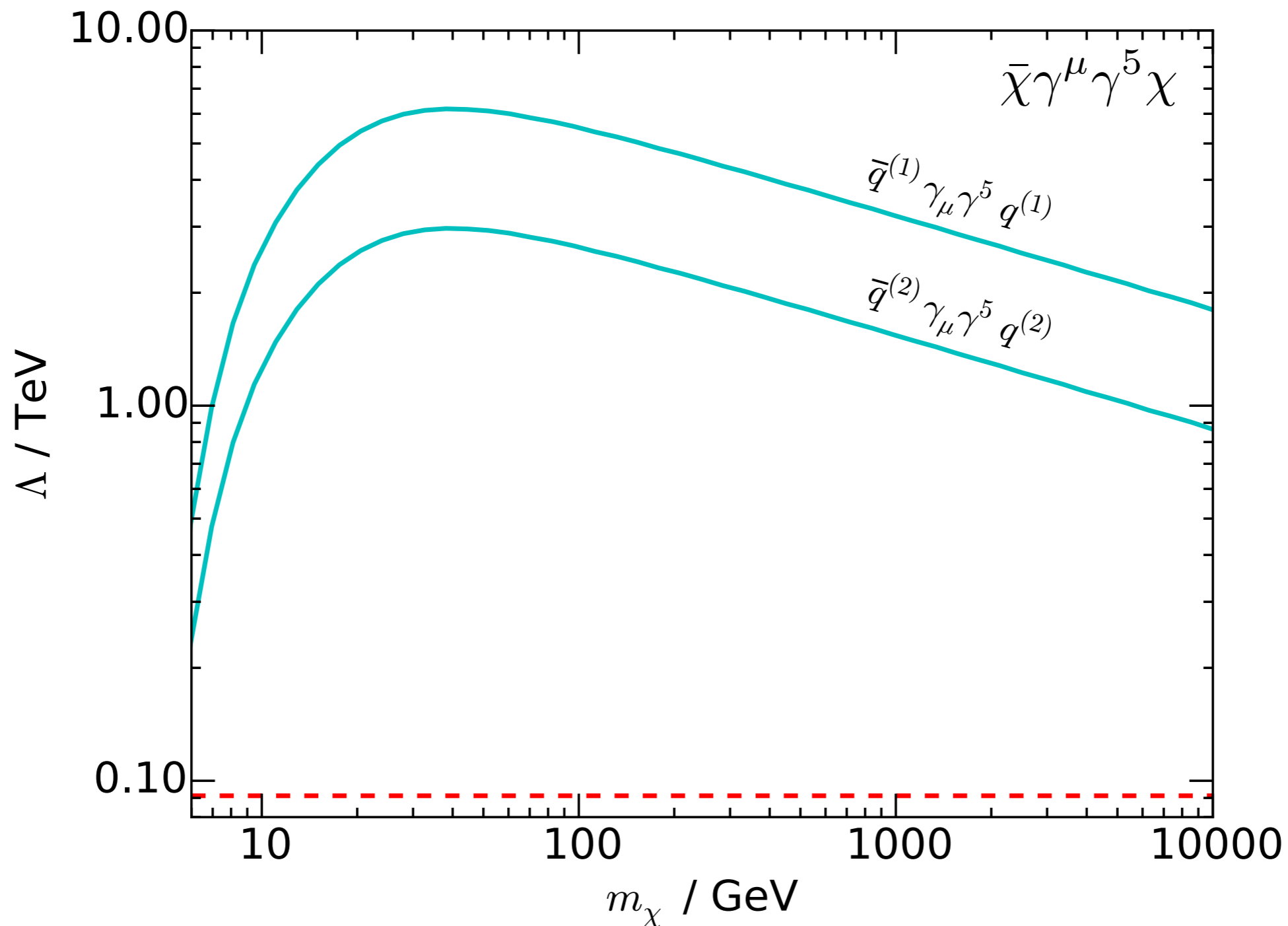
$$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{s}\gamma_\mu\gamma^5s$$

SD interaction: $\frac{1}{\Lambda^2} \bar{\chi} \gamma^5 \gamma^\mu \chi \bar{q}^{(1,2)} \gamma_\mu \gamma^5 q^{(1,2)}$



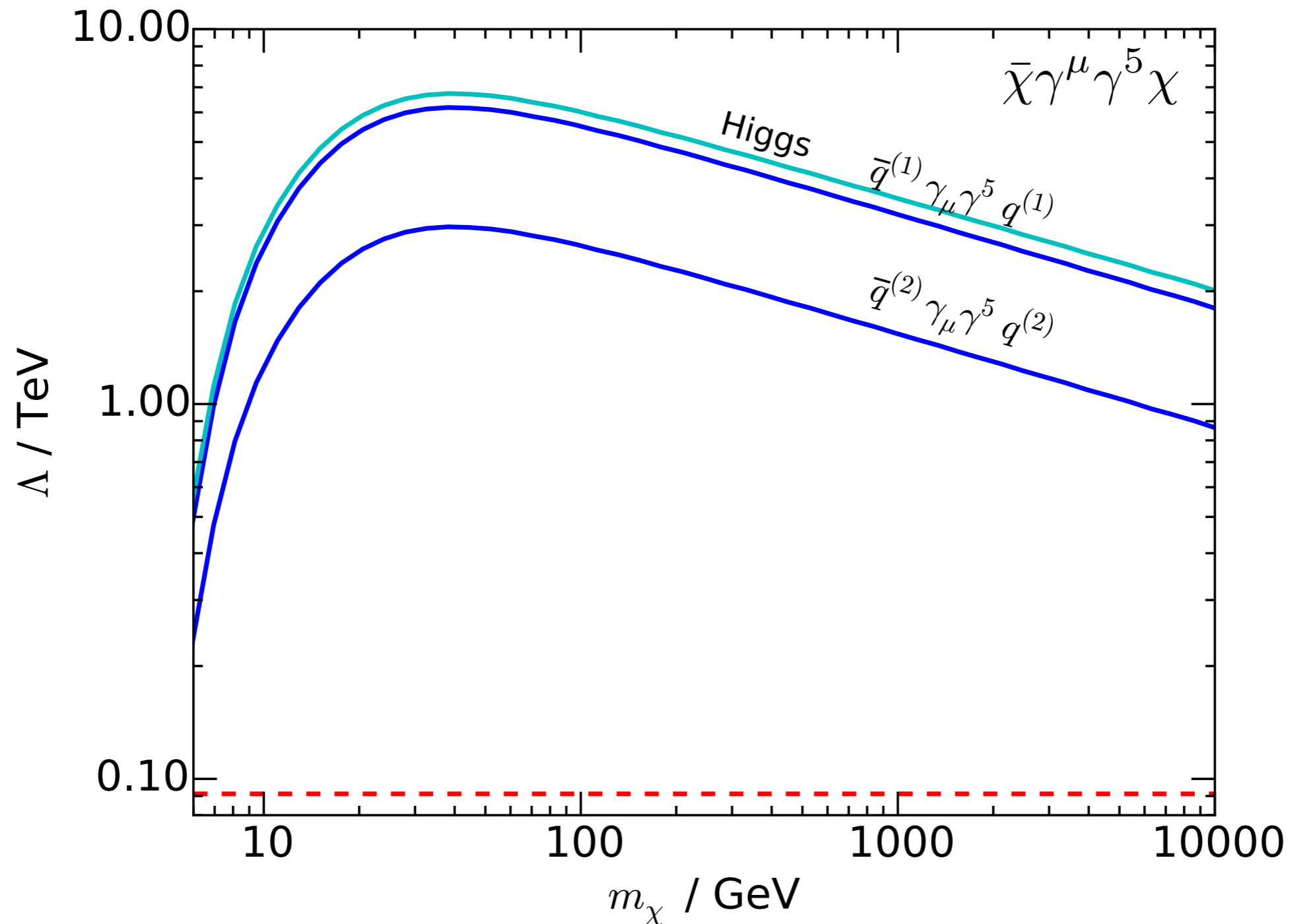
SD cross section limits from LUX [arXiv:1310.8214]

SD interaction: $\frac{1}{\Lambda^2} \bar{\chi} \gamma^5 \gamma^\mu \chi \bar{q}^{(1,2)} \gamma_\mu \gamma^5 q^{(1,2)}$



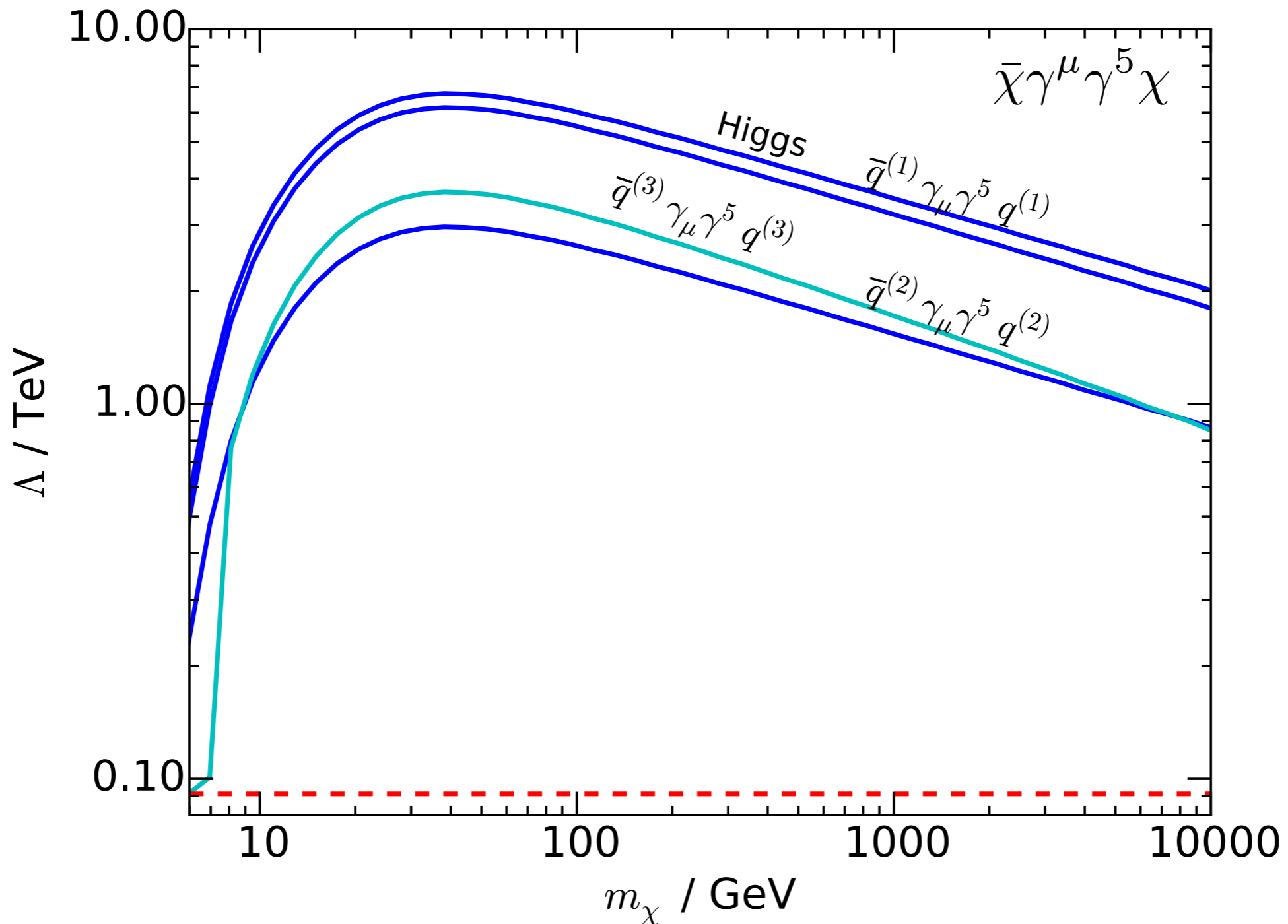
Projected SD cross section limits from **LZ** [arXiv:1509.02910]

Higgs coupling: $\frac{1}{\Lambda^2} \bar{\chi} \gamma^\mu \chi H^\dagger i \overleftrightarrow{D}_\mu H$



Projected SD cross section limits from **LZ** [arXiv:1509.02910]

Heavy quarks: $\frac{1}{\Lambda^2} \bar{\chi} \gamma^5 \gamma^\mu \chi \bar{q}^{(3)} \gamma_\mu \gamma^5 q^{(3)}$



Projected SD cross section limits from **LZ** [arXiv:1509.02910]

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

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

$$H^\dagger i \overleftrightarrow{D}_\mu H$$

$$H^\dagger i \overleftrightarrow{D}_\mu H$$

$$\bar{q}^{(3)}\gamma^\mu q^{(3)}$$

$$\bar{q}^{(3)}\gamma^\mu\gamma^5 q^{(3)}$$

$$\bar{q}^{(3)}\gamma^\mu q^{(3)}$$

$$\bar{q}^{(3)}\gamma^\mu\gamma^5 q^{(3)}$$

$$\bar{q}^{(2)}\gamma^\mu q^{(2)}$$

$$\bar{q}^{(2)}\gamma^\mu\gamma^5 q^{(2)}$$

$$\bar{q}^{(2)}\gamma^\mu q^{(2)}$$

$$\bar{q}^{(2)}\gamma^\mu\gamma^5 q^{(2)}$$

$$\bar{q}^{(1)}\gamma^\mu q^{(1)}$$

$$\bar{q}^{(1)}\gamma^\mu\gamma^5 q^{(1)}$$

$$\bar{q}^{(1)}\gamma^\mu q^{(1)}$$

$$\bar{q}^{(1)}\gamma^\mu\gamma^5 q^{(1)}$$

$$\bar{\tau}\gamma^\mu\tau$$

$$\bar{\tau}\gamma^\mu\gamma^5\tau$$

$$\bar{\tau}\gamma^\mu\tau$$

$$\bar{\tau}\gamma^\mu\gamma^5\tau$$

$$\bar{\mu}\gamma^\mu\mu$$

$$\bar{\mu}\gamma^\mu\gamma^5\mu$$

$$\bar{\mu}\gamma^\mu\mu$$

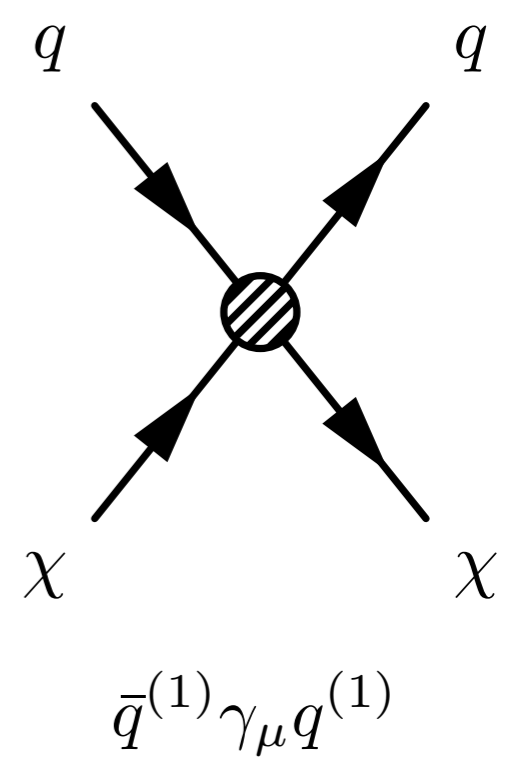
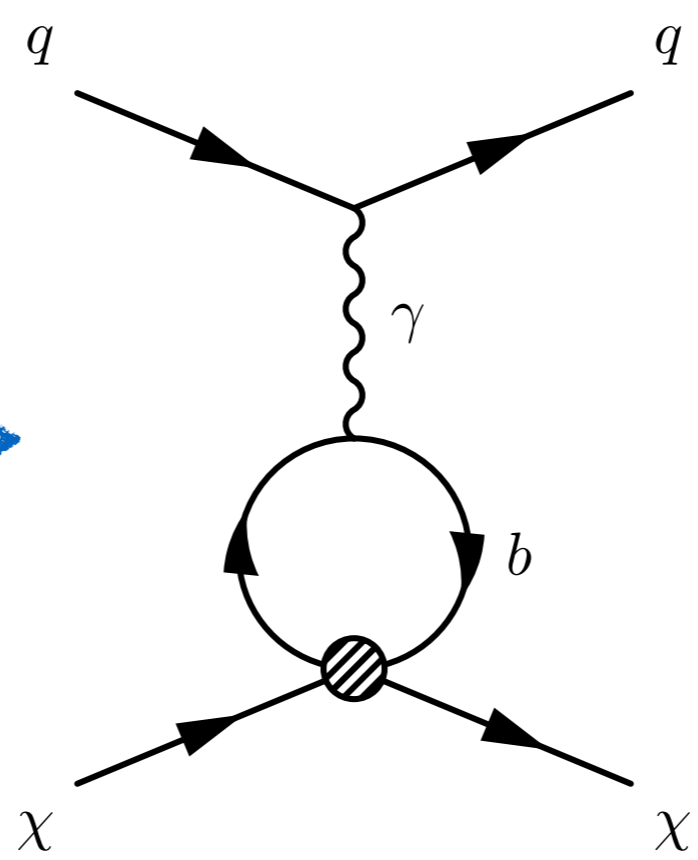
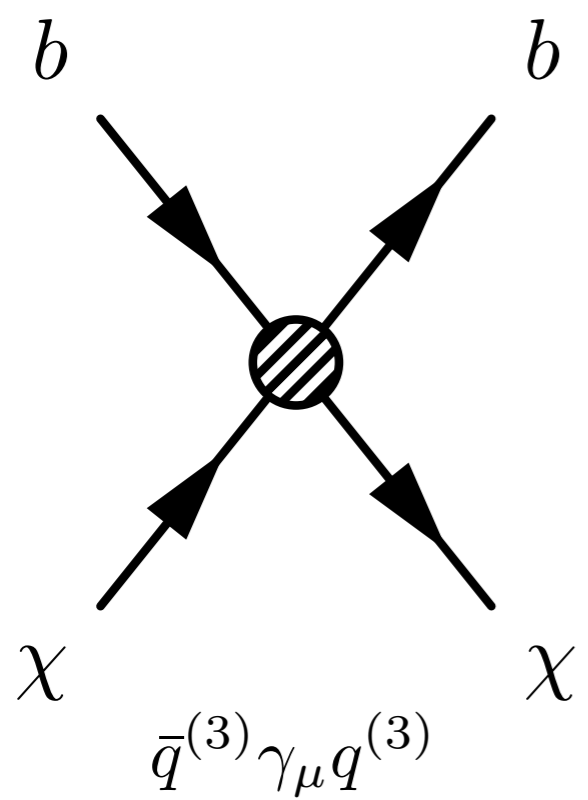
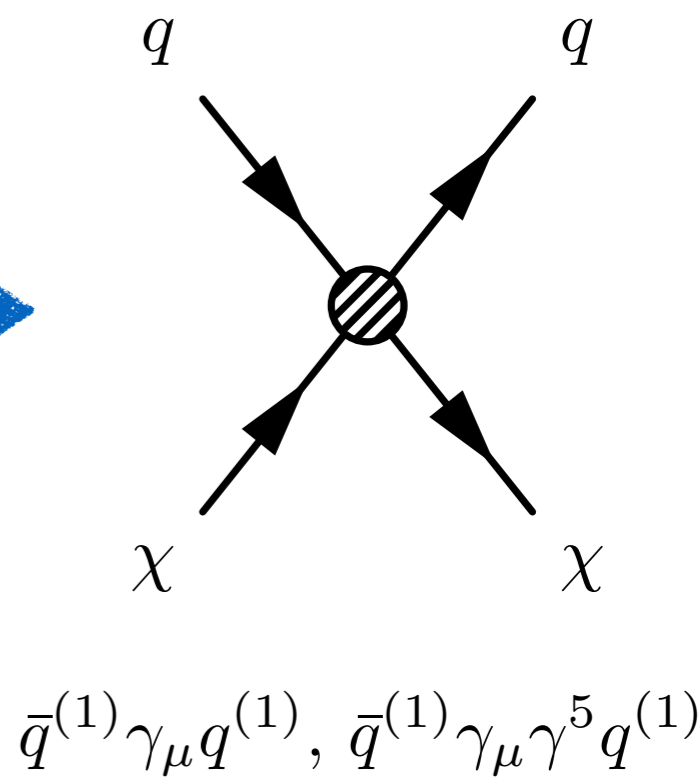
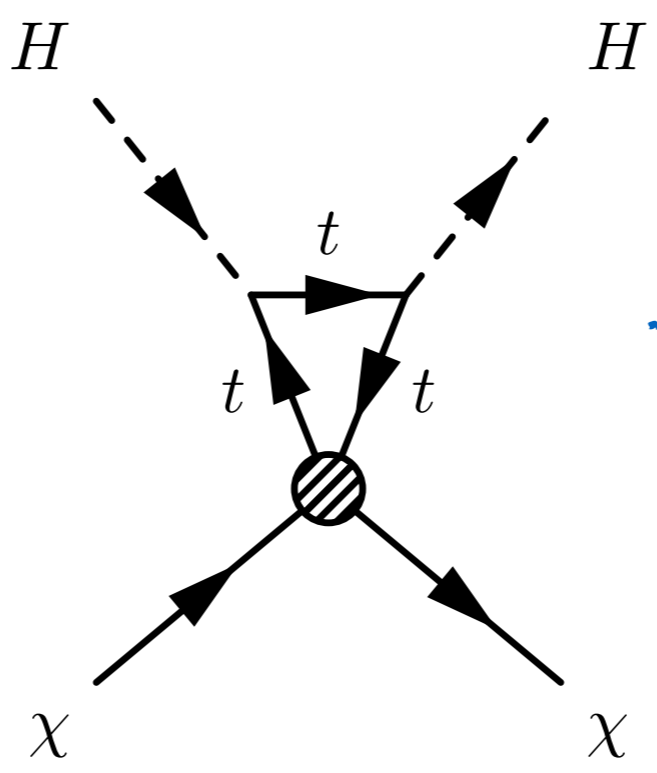
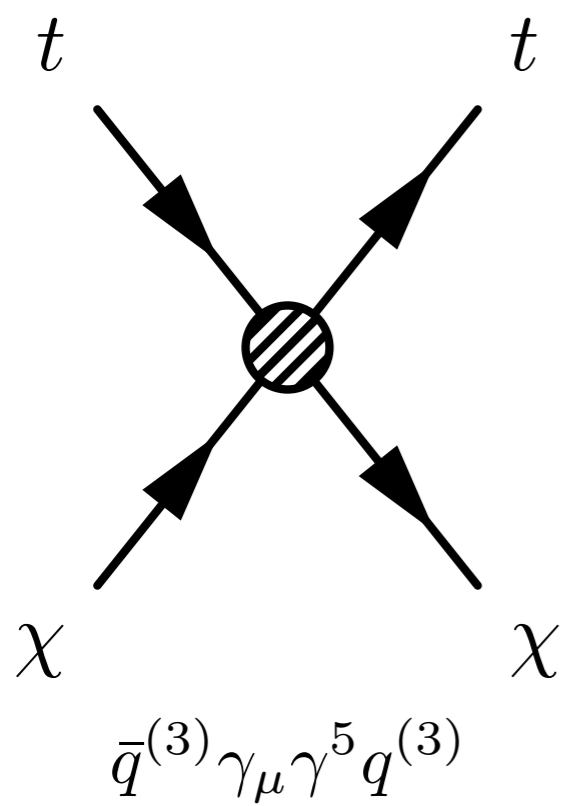
$$\bar{\mu}\gamma^\mu\gamma^5\mu$$

$$\bar{e}\gamma^\mu e$$

$$\bar{e}\gamma^\mu\gamma^5 e$$

$$\bar{e}\gamma^\mu e$$

$$\bar{e}\gamma^\mu\gamma^5 e$$



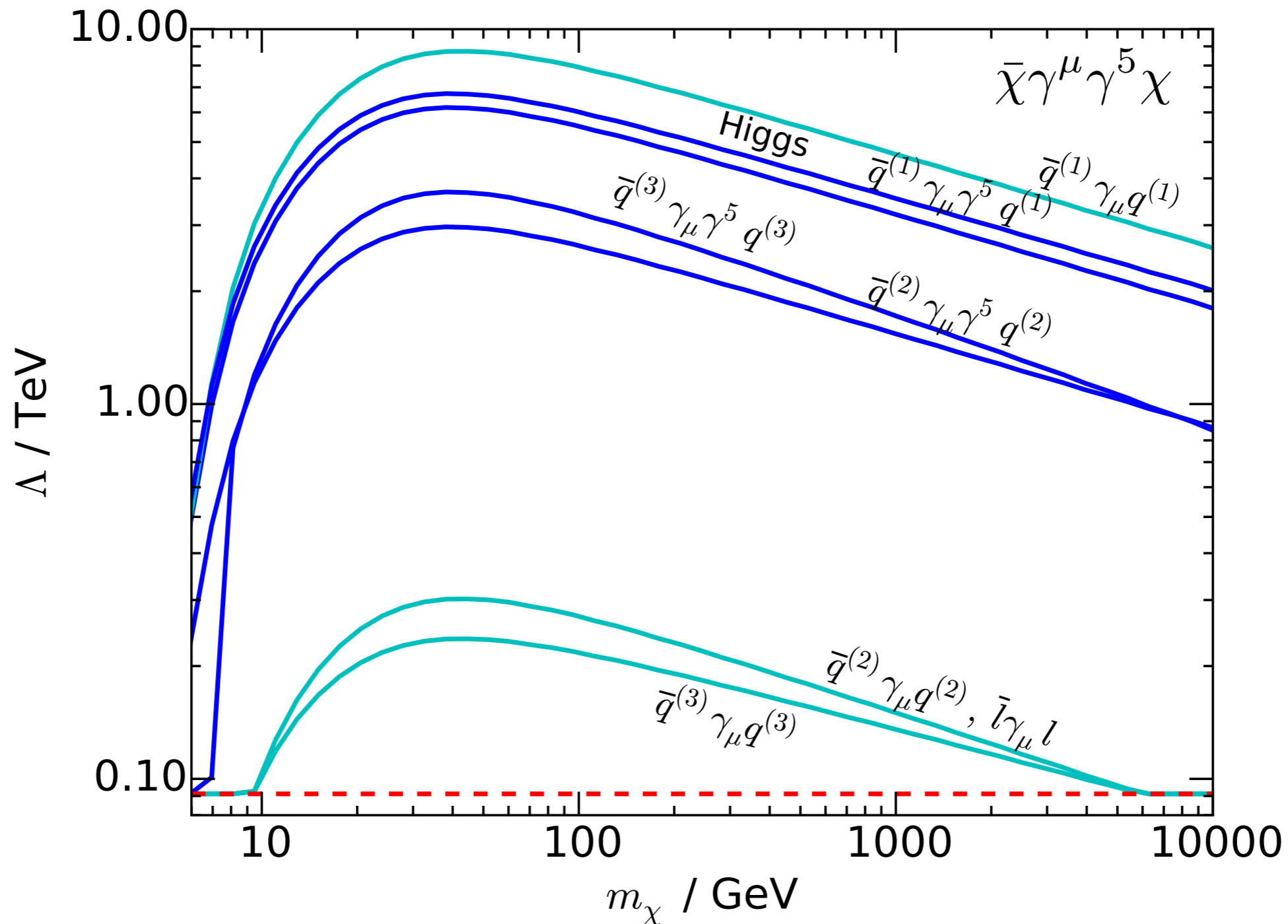
Constraints from SD and non-standard interactions



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

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

Vector currents: $\frac{1}{\Lambda^2} \bar{\chi} \gamma^\mu \gamma^5 \chi \bar{f} \gamma_\mu f$



Projected **total** cross section limits from **LZ** [arXiv:1509.02910]

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

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

$$H^\dagger i \overleftrightarrow{D}_\mu H$$

$$H^\dagger i \overleftrightarrow{D}_\mu H$$

$$\bar{q}^{(3)}\gamma^\mu q^{(3)}$$

$$\bar{q}^{(3)}\gamma^\mu\gamma^5 q^{(3)}$$

$$\bar{q}^{(3)}\gamma^\mu q^{(3)}$$

$$\bar{q}^{(3)}\gamma^\mu\gamma^5 q^{(3)}$$

$$\bar{q}^{(2)}\gamma^\mu q^{(2)}$$

$$\bar{q}^{(2)}\gamma^\mu\gamma^5 q^{(2)}$$

$$\bar{q}^{(2)}\gamma^\mu q^{(2)}$$

$$\bar{q}^{(2)}\gamma^\mu\gamma^5 q^{(2)}$$

$$\bar{q}^{(1)}\gamma^\mu q^{(1)}$$

$$\bar{q}^{(1)}\gamma^\mu\gamma^5 q^{(1)}$$

$$\bar{q}^{(1)}\gamma^\mu q^{(1)}$$

$$\bar{q}^{(1)}\gamma^\mu\gamma^5 q^{(1)}$$

$$\bar{\tau}\gamma^\mu\tau$$

$$\bar{\tau}\gamma^\mu\gamma^5\tau$$

$$\bar{\tau}\gamma^\mu\tau$$

$$\bar{\tau}\gamma^\mu\gamma^5\tau$$

$$\bar{\mu}\gamma^\mu\mu$$

$$\bar{\mu}\gamma^\mu\gamma^5\mu$$

$$\bar{\mu}\gamma^\mu\mu$$

$$\bar{\mu}\gamma^\mu\gamma^5\mu$$

$$\bar{e}\gamma^\mu e$$

$$\bar{e}\gamma^\mu\gamma^5 e$$

$$\bar{e}\gamma^\mu e$$

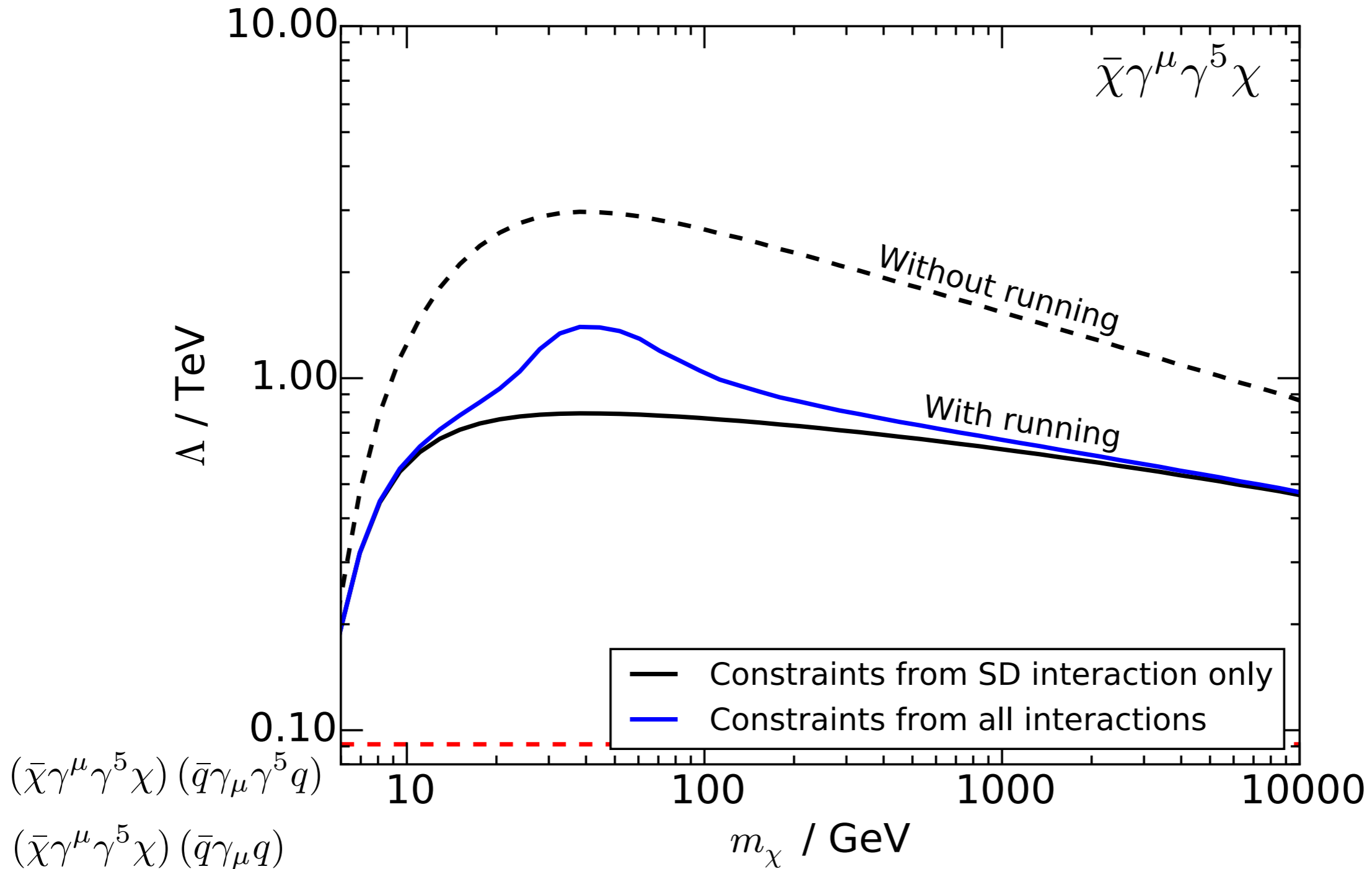
$$\bar{e}\gamma^\mu\gamma^5 e$$

An interesting example



Gen. 2 & 3 quarks:

$$\frac{1}{\Lambda^2} \bar{\chi} \gamma^5 \gamma^\mu \chi \left(\bar{q}^{(2)} \gamma_\mu \gamma^5 q^{(2)} + \bar{q}^{(3)} \gamma_\mu \gamma^5 q^{(3)} \right)$$



Projected **total** cross section limits from **LZ** [arXiv:1509.02910]

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

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

$$H^\dagger i \overleftrightarrow{D}_\mu H$$

$$H^\dagger i \overleftrightarrow{D}_\mu H$$

$$\bar{q}^{(3)}\gamma^\mu q^{(3)}$$

$$\bar{q}^{(3)}\gamma^\mu\gamma^5 q^{(3)}$$

$$\bar{q}^{(3)}\gamma^\mu q^{(3)}$$

$$\bar{q}^{(3)}\gamma^\mu\gamma^5 q^{(3)}$$

$$\bar{q}^{(2)}\gamma^\mu q^{(2)}$$

$$\bar{q}^{(2)}\gamma^\mu\gamma^5 q^{(2)}$$

$$\bar{q}^{(2)}\gamma^\mu q^{(2)}$$

$$\bar{q}^{(2)}\gamma^\mu\gamma^5 q^{(2)}$$

$$\bar{q}^{(1)}\gamma^\mu q^{(1)}$$

$$\bar{q}^{(1)}\gamma^\mu\gamma^5 q^{(1)}$$

$$\bar{q}^{(1)}\gamma^\mu q^{(1)}$$

$$\bar{q}^{(1)}\gamma^\mu\gamma^5 q^{(1)}$$

$$\bar{\tau}\gamma^\mu\tau$$

$$\bar{\tau}\gamma^\mu\gamma^5\tau$$

$$\bar{\tau}\gamma^\mu\tau$$

$$\bar{\tau}\gamma^\mu\gamma^5\tau$$

$$\bar{\mu}\gamma^\mu\mu$$

$$\bar{\mu}\gamma^\mu\gamma^5\mu$$

$$\bar{\mu}\gamma^\mu\mu$$

$$\bar{\mu}\gamma^\mu\gamma^5\mu$$

$$\bar{e}\gamma^\mu e$$

$$\bar{e}\gamma^\mu\gamma^5 e$$

$$\bar{e}\gamma^\mu e$$

$$\bar{e}\gamma^\mu\gamma^5 e$$

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

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

$$H^\dagger i \overleftrightarrow{D}_\mu H$$

$$H^\dagger i \overleftrightarrow{D}_\mu H$$

$$\bar{q}^{(3)}\gamma^\mu q^{(3)}$$

$$\bar{q}^{(3)}\gamma^\mu\gamma^5 q^{(3)}$$

$$\bar{q}^{(3)}\gamma^\mu q^{(3)}$$

$$\bar{q}^{(3)}\gamma^\mu\gamma^5 q^{(3)}$$

$$\bar{q}^{(2)}\gamma^\mu q^{(2)}$$

$$\bar{q}^{(2)}\gamma^\mu\gamma^5 q^{(2)}$$

$$\bar{q}^{(2)}\gamma^\mu q^{(2)}$$

$$\bar{q}^{(2)}\gamma^\mu\gamma^5 q^{(2)}$$

$$\bar{q}^{(1)}\gamma^\mu q^{(1)}$$

$$\bar{q}^{(1)}\gamma^\mu\gamma^5 q^{(1)}$$

$$\bar{q}^{(1)}\gamma^\mu q^{(1)}$$

$$\bar{q}^{(1)}\gamma^\mu\gamma^5 q^{(1)}$$

$$\bar{\tau}\gamma^\mu\tau$$

$$\bar{\tau}\gamma^\mu\gamma^5\tau$$

$$\bar{\tau}\gamma^\mu\tau$$

$$\bar{\tau}\gamma^\mu\gamma^5\tau$$

$$\bar{\mu}\gamma^\mu\mu$$

$$\bar{\mu}\gamma^\mu\gamma^5\mu$$

$$\bar{\mu}\gamma^\mu\mu$$

$$\bar{\mu}\gamma^\mu\gamma^5\mu$$

$$\bar{e}\gamma^\mu e$$

$$\bar{e}\gamma^\mu\gamma^5 e$$

$$\bar{e}\gamma^\mu e$$

$$\bar{e}\gamma^\mu\gamma^5 e$$

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

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

$$H^\dagger i \overleftrightarrow{D}_\mu H$$

$$H^\dagger i \overleftrightarrow{D}_\mu H$$

$$\bar{q}^{(3)}\gamma^\mu q^{(3)}$$

$$\bar{q}^{(3)}\gamma^\mu\gamma^5 q^{(3)}$$

$$\bar{q}^{(3)}\gamma^\mu q^{(3)}$$

$$\bar{q}^{(3)}\gamma^\mu\gamma^5 q^{(3)}$$

$$\bar{q}^{(2)}\gamma^\mu q^{(2)}$$

$$\bar{q}^{(2)}\gamma^\mu\gamma^5 q^{(2)}$$

$$\bar{q}^{(2)}\gamma^\mu q^{(2)}$$

$$\bar{q}^{(2)}\gamma^\mu\gamma^5 q^{(2)}$$

$$\bar{q}^{(1)}\gamma^\mu q^{(1)}$$

$$\bar{q}^{(1)}\gamma^\mu\gamma^5 q^{(1)}$$

$$\bar{q}^{(1)}\gamma^\mu q^{(1)}$$

$$\bar{q}^{(1)}\gamma^\mu\gamma^5 q^{(1)}$$

$$\bar{\tau}\gamma^\mu\tau$$

$$\bar{\tau}\gamma^\mu\gamma^5\tau$$

$$\bar{\tau}\gamma^\mu\tau$$

$$\bar{\tau}\gamma^\mu\gamma^5\tau$$

$$\bar{\mu}\gamma^\mu\mu$$

$$\bar{\mu}\gamma^\mu\gamma^5\mu$$

$$\bar{\mu}\gamma^\mu\mu$$

$$\bar{\mu}\gamma^\mu\gamma^5\mu$$

$$\bar{e}\gamma^\mu e$$

$$\bar{e}\gamma^\mu\gamma^5 e$$

$$\bar{e}\gamma^\mu e$$

$$\bar{e}\gamma^\mu\gamma^5 e$$

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

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

$$H^\dagger i \overleftrightarrow{D}_\mu H$$

$$H^\dagger i \overleftrightarrow{D}_\mu H$$

$$\bar{q}^{(3)}\gamma^\mu q^{(3)}$$

$$\bar{q}^{(3)}\gamma^\mu\gamma^5 q^{(3)}$$

$$\bar{q}^{(3)}\gamma^\mu q^{(3)}$$

$$\bar{q}^{(3)}\gamma^\mu\gamma^5 q^{(3)}$$

$$\bar{q}^{(2)}\gamma^\mu q^{(2)}$$

$$\bar{q}^{(2)}\gamma^\mu\gamma^5 q^{(2)}$$

$$\bar{q}^{(2)}\gamma^\mu q^{(2)}$$

$$\bar{q}^{(2)}\gamma^\mu\gamma^5 q^{(2)}$$

$$\bar{q}^{(1)}\gamma^\mu q^{(1)}$$

$$\bar{q}^{(1)}\gamma^\mu\gamma^5 q^{(1)}$$

$$\bar{q}^{(1)}\gamma^\mu q^{(1)}$$

$$\bar{q}^{(1)}\gamma^\mu\gamma^5 q^{(1)}$$

$$\bar{\tau}\gamma^\mu\tau$$

$$\bar{\tau}\gamma^\mu\gamma^5\tau$$

$$\bar{\tau}\gamma^\mu\tau$$

$$\bar{\tau}\gamma^\mu\gamma^5\tau$$

$$\bar{\mu}\gamma^\mu\mu$$

$$\bar{\mu}\gamma^\mu\gamma^5\mu$$

$$\bar{\mu}\gamma^\mu\mu$$

$$\bar{\mu}\gamma^\mu\gamma^5\mu$$

$$\bar{e}\gamma^\mu e$$

$$\bar{e}\gamma^\mu\gamma^5 e$$

$$\bar{e}\gamma^\mu e$$

$$\bar{e}\gamma^\mu\gamma^5 e$$

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

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

$$H^\dagger i \overleftrightarrow{D}_\mu H$$

$$H^\dagger i \overleftrightarrow{D}_\mu H$$

$$\bar{q}^{(3)}\gamma^\mu q^{(3)}$$

$$\bar{q}^{(3)}\gamma^\mu\gamma^5 q^{(3)}$$

$$\bar{q}^{(3)}\gamma^\mu q^{(3)}$$

$$\bar{q}^{(3)}\gamma^\mu\gamma^5 q^{(3)}$$

$$\bar{q}^{(2)}\gamma^\mu q^{(2)}$$

$$\bar{q}^{(2)}\gamma^\mu\gamma^5 q^{(2)}$$

$$\bar{q}^{(2)}\gamma^\mu q^{(2)}$$

$$\bar{q}^{(2)}\gamma^\mu\gamma^5 q^{(2)}$$

$$\bar{q}^{(1)}\gamma^\mu q^{(1)}$$

$$\bar{q}^{(1)}\gamma^\mu\gamma^5 q^{(1)}$$

$$\bar{q}^{(1)}\gamma^\mu q^{(1)}$$

$$\bar{q}^{(1)}\gamma^\mu\gamma^5 q^{(1)}$$

$$\bar{\tau}\gamma^\mu\tau$$

$$\bar{\tau}\gamma^\mu\gamma^5\tau$$

$$\bar{\tau}\gamma^\mu\tau$$

$$\bar{\tau}\gamma^\mu\gamma^5\tau$$

$$\bar{\mu}\gamma^\mu\mu$$

$$\bar{\mu}\gamma^\mu\gamma^5\mu$$

$$\bar{\mu}\gamma^\mu\mu$$

$$\bar{\mu}\gamma^\mu\gamma^5\mu$$

$$\bar{e}\gamma^\mu e$$

$$\bar{e}\gamma^\mu\gamma^5 e$$

$$\bar{e}\gamma^\mu e$$

$$\bar{e}\gamma^\mu\gamma^5 e$$

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

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

$$H^\dagger i \overleftrightarrow{D}_\mu H$$

$$H^\dagger i \overleftrightarrow{D}_\mu H$$

$$\bar{q}^{(3)}\gamma^\mu q^{(3)}$$

$$\bar{q}^{(3)}\gamma^\mu\gamma^5 q^{(3)}$$

$$\bar{q}^{(3)}\gamma^\mu q^{(3)}$$

$$\bar{q}^{(3)}\gamma^\mu\gamma^5 q^{(3)}$$

$$\bar{q}^{(2)}\gamma^\mu q^{(2)}$$

$$\bar{q}^{(2)}\gamma^\mu\gamma^5 q^{(2)}$$

$$\bar{q}^{(2)}\gamma^\mu q^{(2)}$$

$$\bar{q}^{(2)}\gamma^\mu\gamma^5 q^{(2)}$$

$$\bar{q}^{(1)}\gamma^\mu q^{(1)}$$

$$\bar{q}^{(1)}\gamma^\mu\gamma^5 q^{(1)}$$

$$\bar{q}^{(1)}\gamma^\mu q^{(1)}$$

$$\bar{q}^{(1)}\gamma^\mu\gamma^5 q^{(1)}$$

$$\bar{\tau}\gamma^\mu\tau$$

$$\bar{\tau}\gamma^\mu\gamma^5\tau$$

$$\bar{\tau}\gamma^\mu\tau$$

$$\bar{\tau}\gamma^\mu\gamma^5\tau$$

$$\bar{\mu}\gamma^\mu\mu$$

$$\bar{\mu}\gamma^\mu\gamma^5\mu$$

$$\bar{\mu}\gamma^\mu\mu$$

$$\bar{\mu}\gamma^\mu\gamma^5\mu$$

$$\bar{e}\gamma^\mu e$$

$$\bar{e}\gamma^\mu\gamma^5 e$$

$$\bar{e}\gamma^\mu e$$

$$\bar{e}\gamma^\mu\gamma^5 e$$

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

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

$$H^\dagger i \overleftrightarrow{D}_\mu H$$

$$H^\dagger i \overleftrightarrow{D}_\mu H$$

$$\bar{q}^{(3)}\gamma^\mu q^{(3)}$$

$$\bar{q}^{(3)}\gamma^\mu\gamma^5 q^{(3)}$$

$$\bar{q}^{(3)}\gamma^\mu q^{(3)}$$

$$\bar{q}^{(3)}\gamma^\mu\gamma^5 q^{(3)}$$

$$\bar{q}^{(2)}\gamma^\mu q^{(2)}$$

$$\bar{q}^{(2)}\gamma^\mu\gamma^5 q^{(2)}$$

$$\bar{q}^{(2)}\gamma^\mu q^{(2)}$$

$$\bar{q}^{(2)}\gamma^\mu\gamma^5 q^{(2)}$$

$$\bar{q}^{(1)}\gamma^\mu q^{(1)}$$

$$\bar{q}^{(1)}\gamma^\mu\gamma^5 q^{(1)}$$

$$\bar{q}^{(1)}\gamma^\mu q^{(1)}$$

$$\bar{q}^{(1)}\gamma^\mu\gamma^5 q^{(1)}$$

$$\bar{\tau}\gamma^\mu\tau$$

$$\bar{\tau}\gamma^\mu\gamma^5\tau$$

$$\bar{\tau}\gamma^\mu\tau$$

$$\bar{\tau}\gamma^\mu\gamma^5\tau$$

$$\bar{\mu}\gamma^\mu\mu$$

$$\bar{\mu}\gamma^\mu\gamma^5\mu$$

$$\bar{\mu}\gamma^\mu\mu$$

$$\bar{\mu}\gamma^\mu\gamma^5\mu$$

$$\bar{e}\gamma^\mu e$$

$$\bar{e}\gamma^\mu\gamma^5 e$$

$$\bar{e}\gamma^\mu e$$

$$\bar{e}\gamma^\mu\gamma^5 e$$

Essig et al.
arXiv:1509.01598

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

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

Thank you!

$$H^\dagger i \overleftrightarrow{D}_\mu H$$

$$H^\dagger i \overleftrightarrow{D}_\mu H$$

$$\bar{q}^{(3)}\gamma^\mu q^{(3)}$$

$$\bar{q}^{(3)}\gamma^\mu\gamma^5 q^{(3)}$$

$$\bar{q}^{(3)}\gamma^\mu q^{(3)}$$

$$\bar{q}^{(3)}\gamma^\mu\gamma^5 q^{(3)}$$

$$\bar{q}^{(2)}\gamma^\mu q^{(2)}$$

$$\bar{q}^{(2)}\gamma^\mu\gamma^5 q^{(2)}$$

$$\bar{q}^{(2)}\gamma^\mu q^{(2)}$$

$$\bar{q}^{(2)}\gamma^\mu\gamma^5 q^{(2)}$$

$$\bar{q}^{(1)}\gamma^\mu q^{(1)}$$

$$\bar{q}^{(1)}\gamma^\mu\gamma^5 q^{(1)}$$

$$\bar{q}^{(1)}\gamma^\mu q^{(1)}$$

$$\bar{q}^{(1)}\gamma^\mu\gamma^5 q^{(1)}$$

$$\bar{\tau}\gamma^\mu\tau$$

$$\bar{\tau}\gamma^\mu\gamma^5\tau$$

$$\bar{\tau}\gamma^\mu\tau$$

$$\bar{\tau}\gamma^\mu\gamma^5\tau$$

$$\bar{\mu}\gamma^\mu\mu$$

$$\bar{\mu}\gamma^\mu\gamma^5\mu$$

$$\bar{\mu}\gamma^\mu\mu$$

$$\bar{\mu}\gamma^\mu\gamma^5\mu$$

$$\bar{e}\gamma^\mu e$$

$$\bar{e}\gamma^\mu\gamma^5 e$$

$$\bar{e}\gamma^\mu e$$

$$\bar{e}\gamma^\mu\gamma^5 e$$