# New insights into dark matter from EFT basics

## Based on arXiv:2005.12789 (https://arxiv.org/abs/2005.12789)

### Andrew Cheek

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# New insights into dark matter from EFT basics

## Based on arXiv:2005.12789

**Andrew Cheek**

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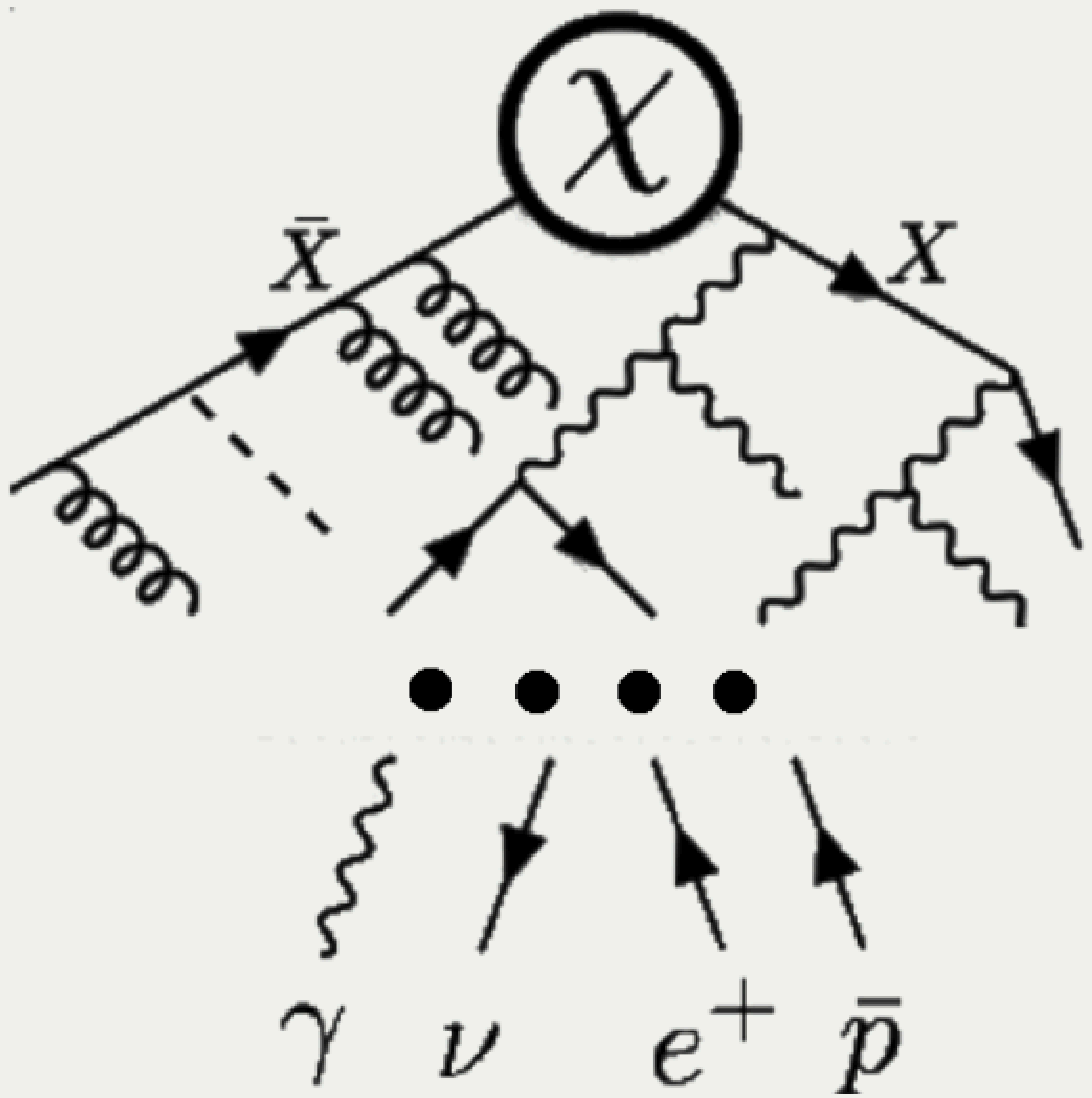
# Dark Matter and light

- Everything we know about dark matter says that its electromagnetically neutral, or at most millicharged.
- At the same time photons are a primary messenger for astrophysical and cosmological probes.
- Generically BSM scenarios with heavy charged particles will couple DM to photon via loops.
- These new charged particles, if they exist, are too heavy to be seen directly at the LHC, effective DM-$\gamma$ interactions may give us a better picture of the possibilities.



## Photon moments

- We consider the dimension 5 and 6 effective operators between the photon and a fermionic singlet.

$$\mathcal{L}^{\psi}_{\text{Dirac}} = 2\mathcal{L}^{\chi\to\psi}_{\text{Majorana}} + \left[\frac{\mathcal{C}_{\mathcal{M}}}{2\Lambda}\bar{\psi}\sigma^{\mu\nu}\psi\cdot F_{\mu\nu} + \frac{\mathcal{C}_{el}}{2\Lambda}i\bar{\psi}\sigma^{\mu\nu}\gamma^5\psi\cdot F_{\mu\nu} + \frac{\mathcal{C}_{cr}}{\Lambda^2}\bar{\psi}\gamma^{\mu}\psi\cdot\partial^{\nu}F_{\mu\nu}\right]$$

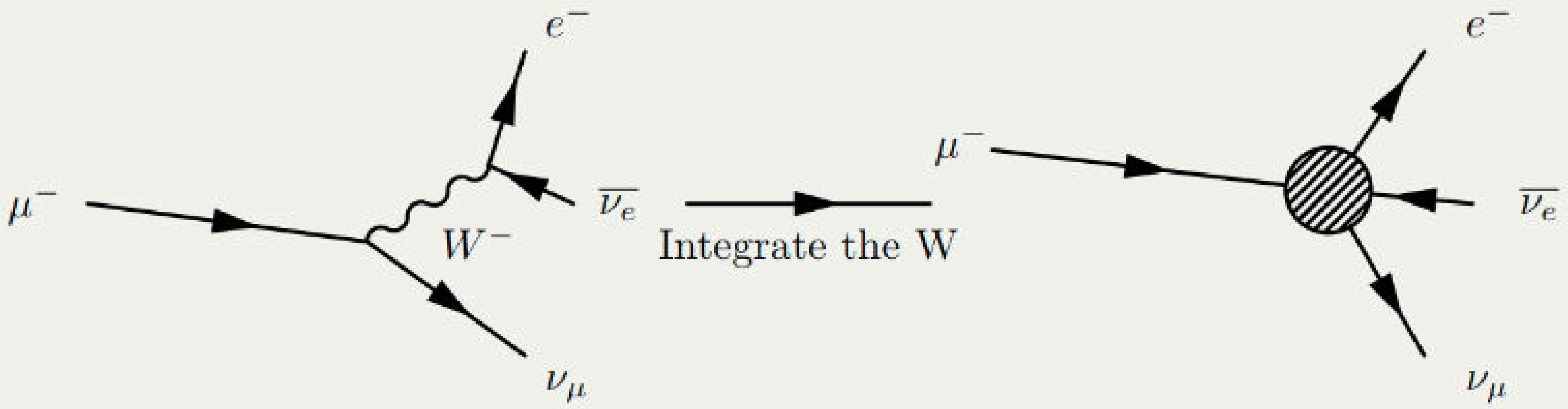
with

$$\mathcal{L}^{\chi}_{\text{Majorana}} = \frac{C_{\mathcal{A}}}{\Lambda^2}\frac{1}{2}\bar{\chi}\gamma^{\mu}\gamma^5\chi\cdot\partial^{\nu}F_{\mu\nu}$$

- $\chi$ is Majorana and $\psi$ is Dirac dark matter, but we choose the normalisation such that $\frac{C_{\mathcal{A}}}{\Lambda^2}$ constraints are the same for both.

# Effective Field Theory recap

- Effective field theories are incredibly useful everywhere in physics.
- Studying them helps you focus on just the relevent degrees of freedom.




- They provide a systematic prescription for searching for and constraining new physics.
- Build operators at higher dimensions, each dimension introduces a mass supression.

$$\mathcal{L}_{\text{EFT}} \approx \mathcal{L}_{\text{SM}} + \sum \frac{C_5}{\Lambda}\mathcal{O}_5 + \sum \frac{C_6}{\Lambda^2}\mathcal{O}_6 + \ldots$$

- This picture only works if processes studied are sufficiently below $\Lambda$.
- When building higher dimension operators, one uses the symmetries of the low-energy theories. At colliders we use the SM gauge symmetries, in direct detection its Galilean symmetry.

# To $F_{\mu\nu}$ or to $B_{\mu\nu}$...

- We know from the basic tenets of effective field theories that we should choose $B_{\mu\nu}$ since its invariant under the SM gauge group.
- This is related to $F_{\mu\nu}$ and $Z_{\mu\nu}$ simply by

$$\mathcal{O}^{\mu\nu} B_{\mu\nu} = c_{\rm W}\mathcal{O}^{\mu\nu} F_{\mu\nu} - s_{\rm W}\mathcal{O}^{\mu\nu} Z_{\mu\nu}$$

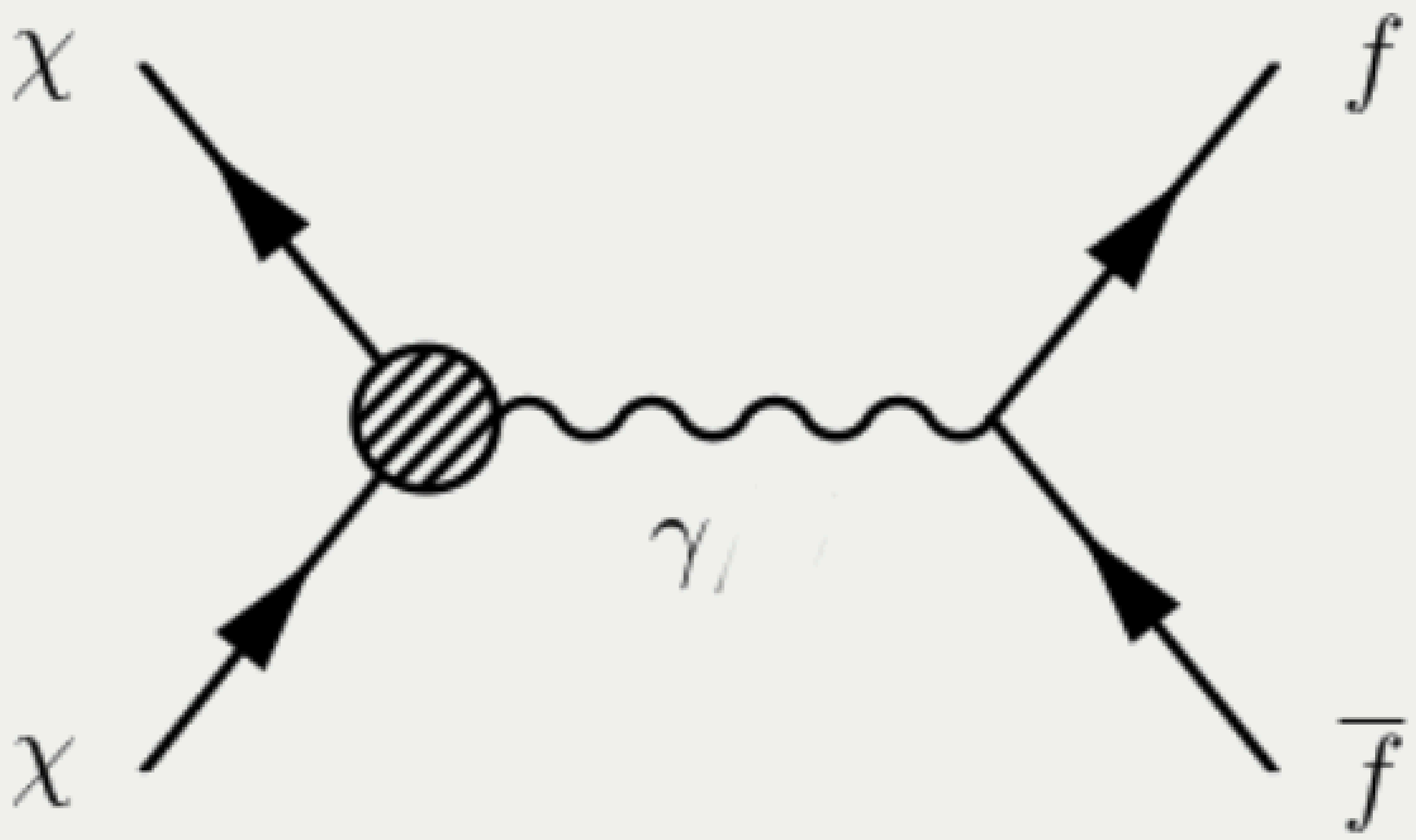
so at low energies (think direct detection)

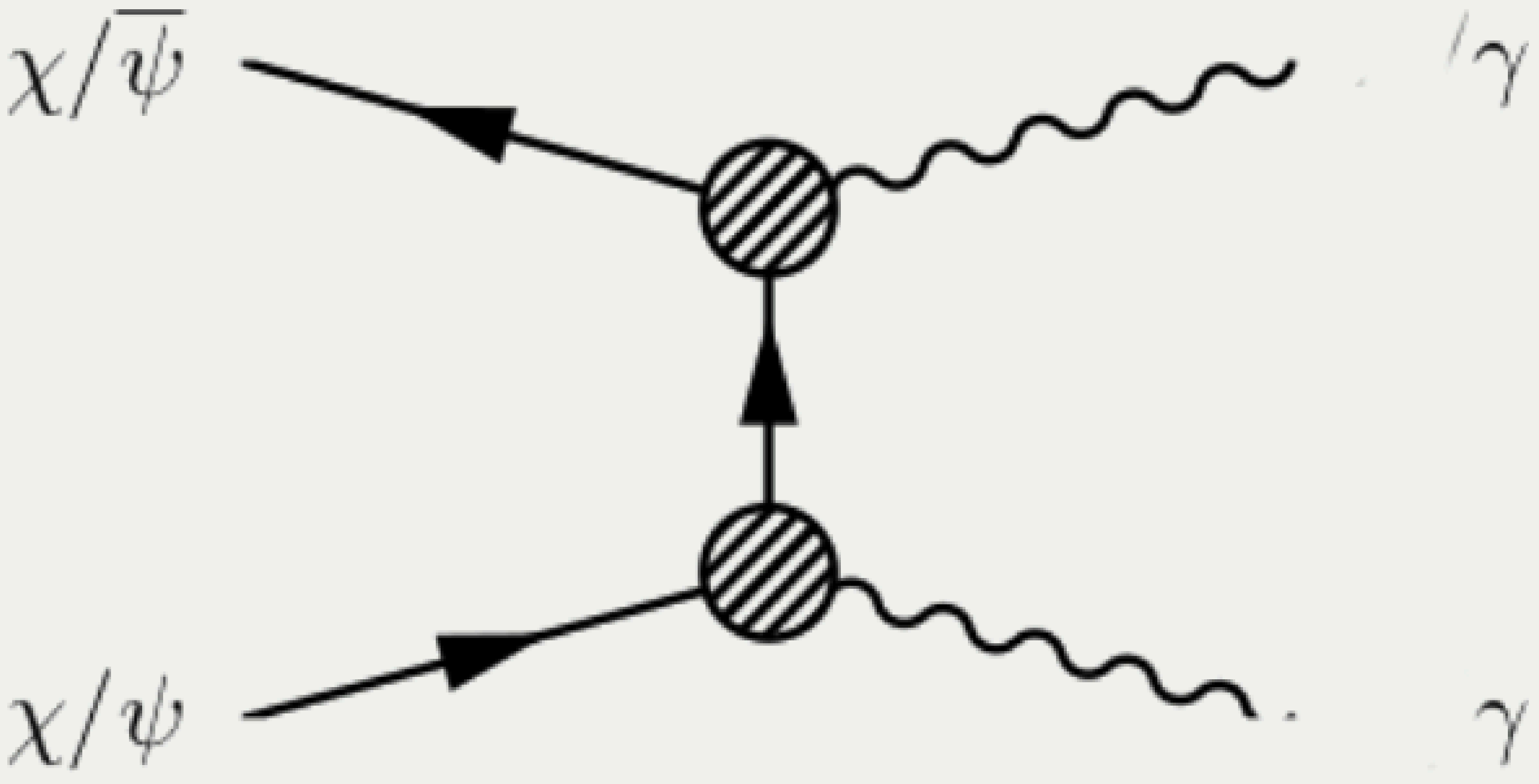
$$\mathcal{O}^{\mu\nu} B_{\mu\nu} \approx c_{\rm W}\mathcal{O}^{\mu\nu} F_{\mu\nu} + \mathcal{O}\left(\frac{q^2}{m_Z^2}\right)$$

- Therefore its often considered a choice. I'm here to show you that this it is not the case which has implications on the phenomenology.

# Early moment papers

- Pospelov and Veldhuis present the interactions in a 2000 paper and focus only on direct detection.
- Sigurdson et. al in 2004 have a very comprehensive study on the dark matter phenomology. With $m_\chi$ up to $10^4$ GeV

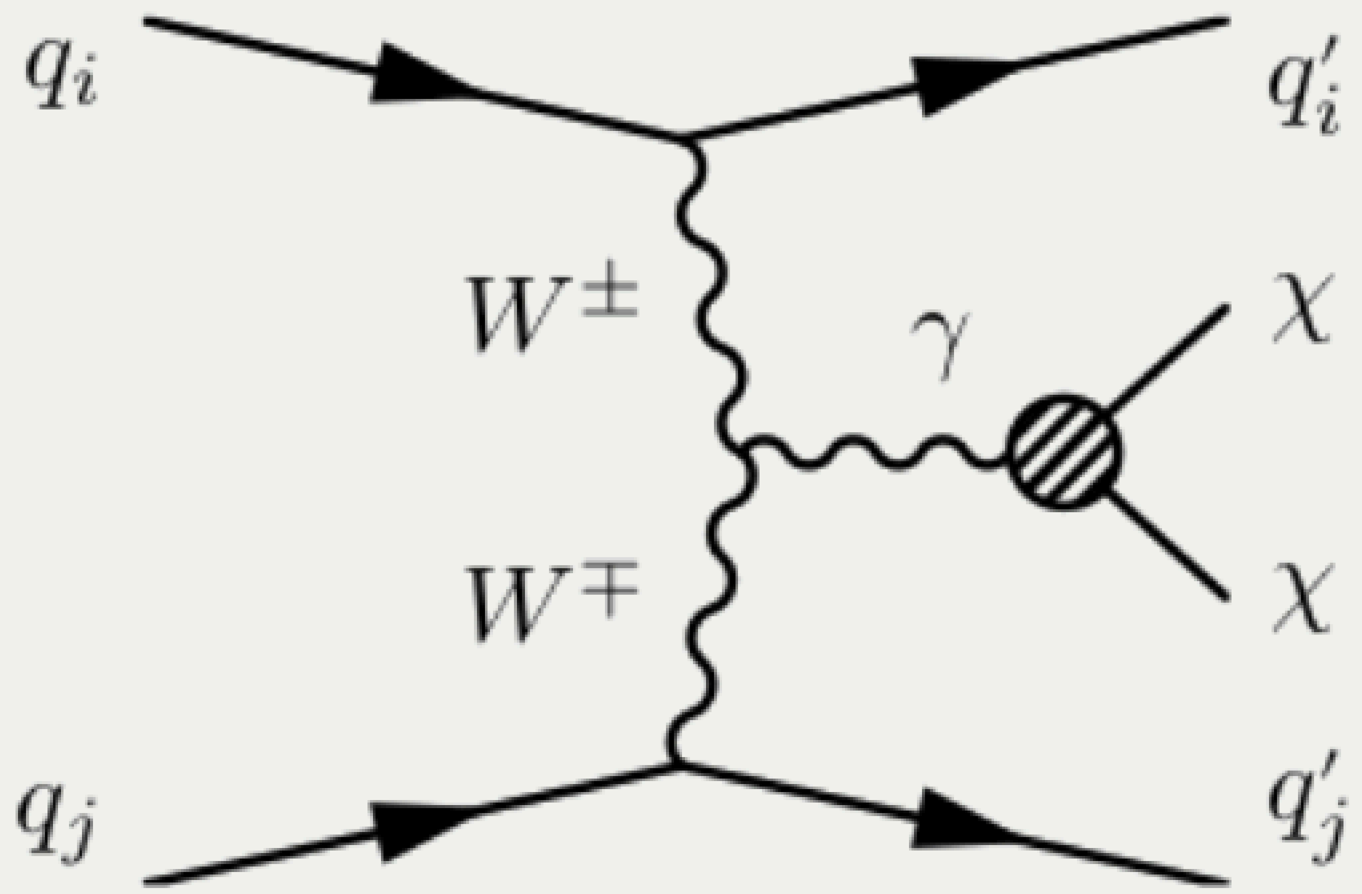


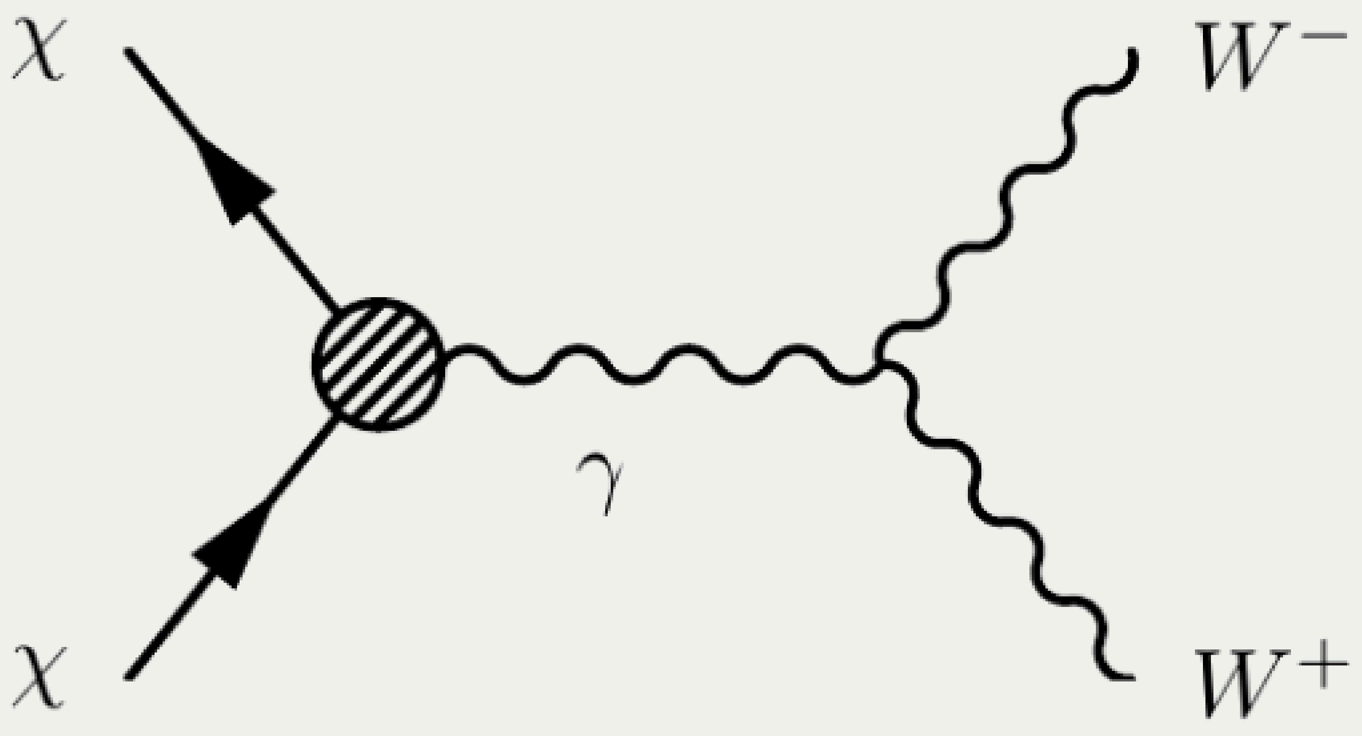

- Ho and Scherrer in the 2012 anapole dark matter paper were hesistant to explore $m_\chi \geq m_W$, we assume because they understood that care would have to be taken at the EW scale.

# More recent work

- In A. Florez et. al. (Phys.Rev.D 100 (2019)) studied the VBF signature coming from the triple vertex between two W's and a photon.
- Using the specific VBF topology, they were able to get impressive results for the anapole.



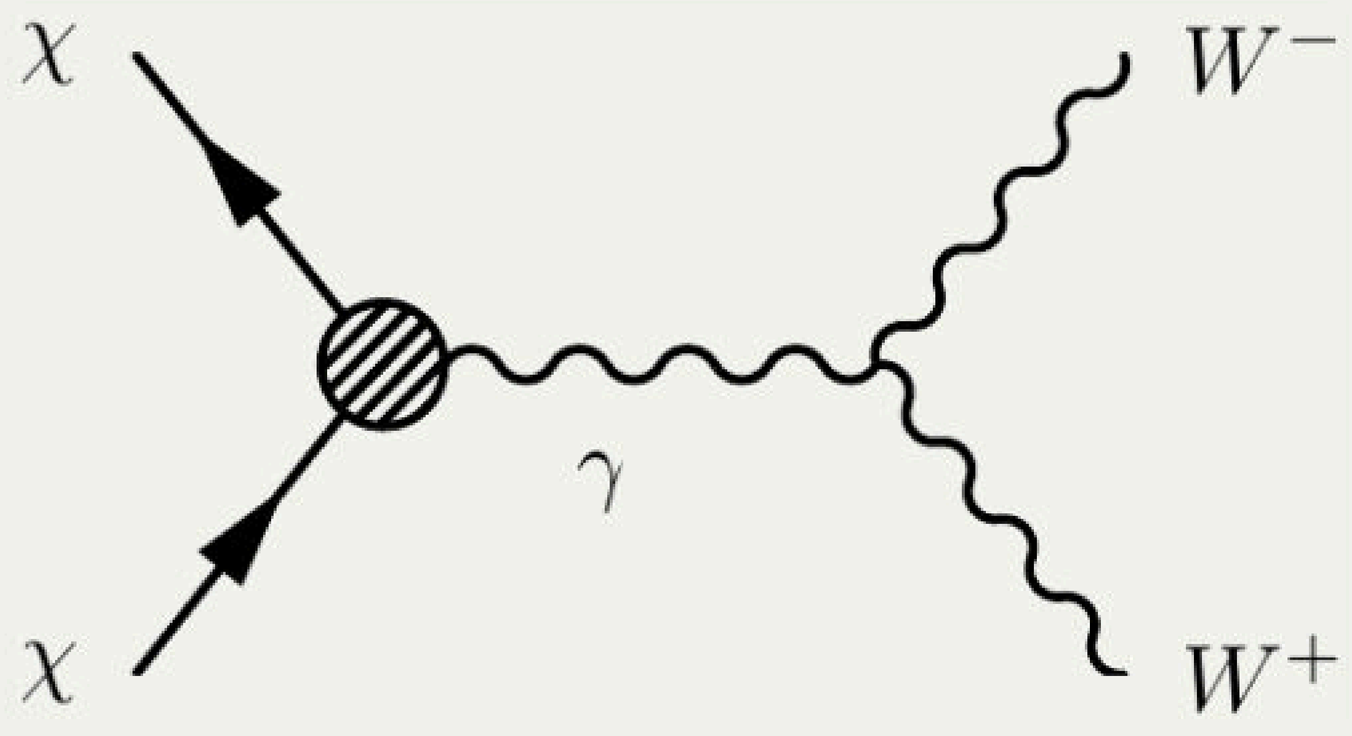

- This suggests that perhaps a diagram is missing in the relic density calculations




- B. Kavanagh et. al (JHEP 04 (2019)) assert that these interactions are subdominant compared to the photon operator. They only consider direct and indirect dark matter searches.

# Can we ignore $\chi\chi \to W^+ W^-$?

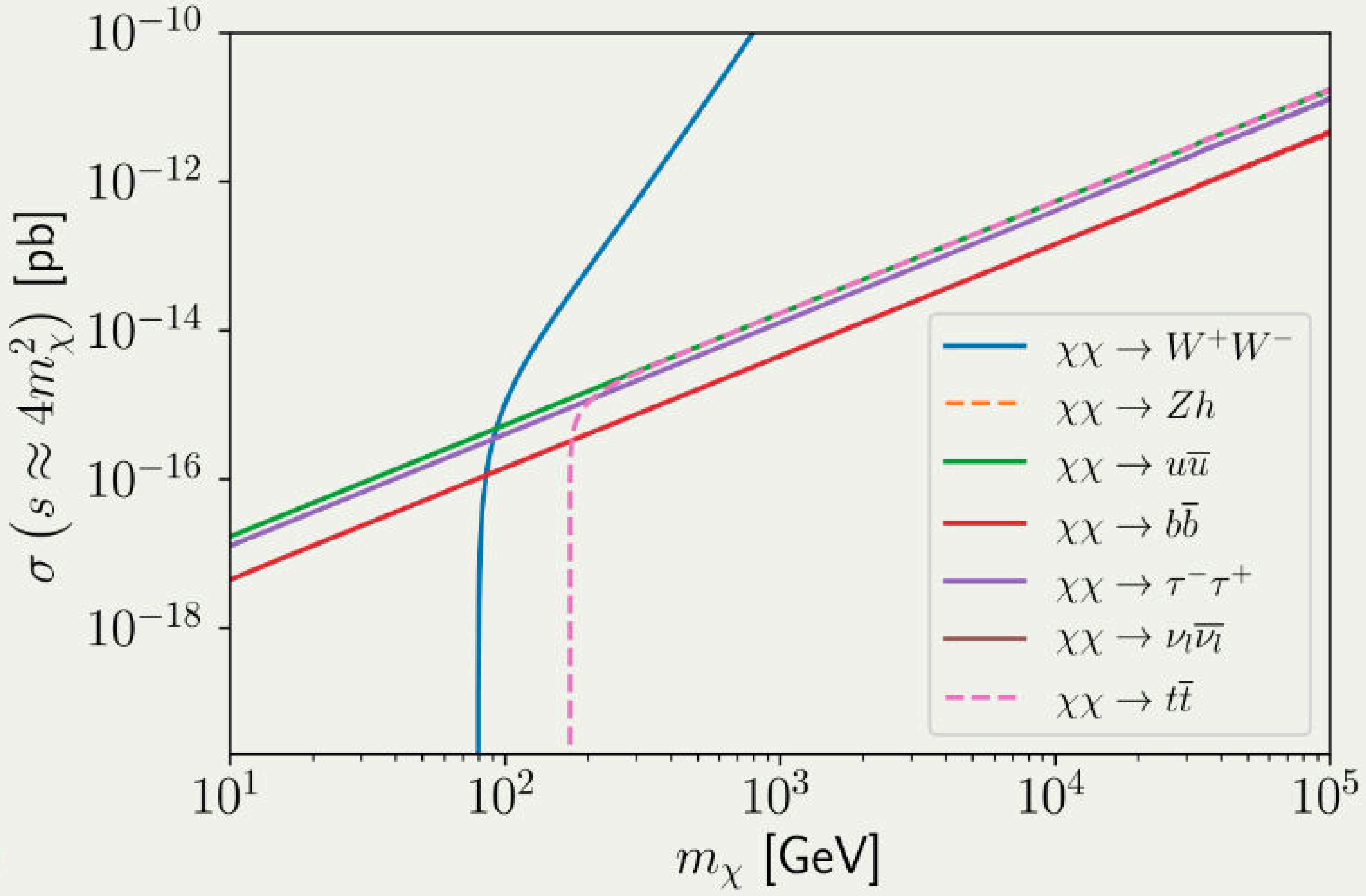
- Lets take the anapole, since the promising VBF results were for that.




$$|M^{\gamma}_{\mathcal{A}}|^2 \sim \frac{2\pi\alpha_{\rm EW}}{9M_W^4}\left(\frac{C^{\gamma}_{\mathcal{A}}}{\Lambda^2}\right)^2 s^4\ \sin^2\theta + \mathcal{O}(s^3)$$

for $M_W^2, M_\chi^2 \ll s < \Lambda^2$

- As we can see the amplitude grows as $s^4$, already a bad sign. At most dimension 6 should be $\propto s^2$.
- Using partial wave-analysis, unitarity is violated below the cutoff when $\Lambda \gtrsim \frac{1.7\text{TeV}}{\sqrt{C^{\gamma}_{\mathcal{A}}}}$.



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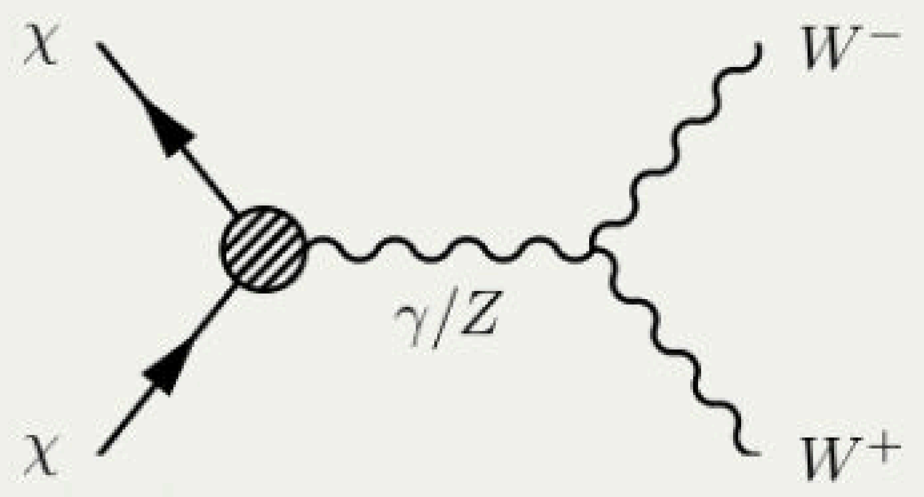
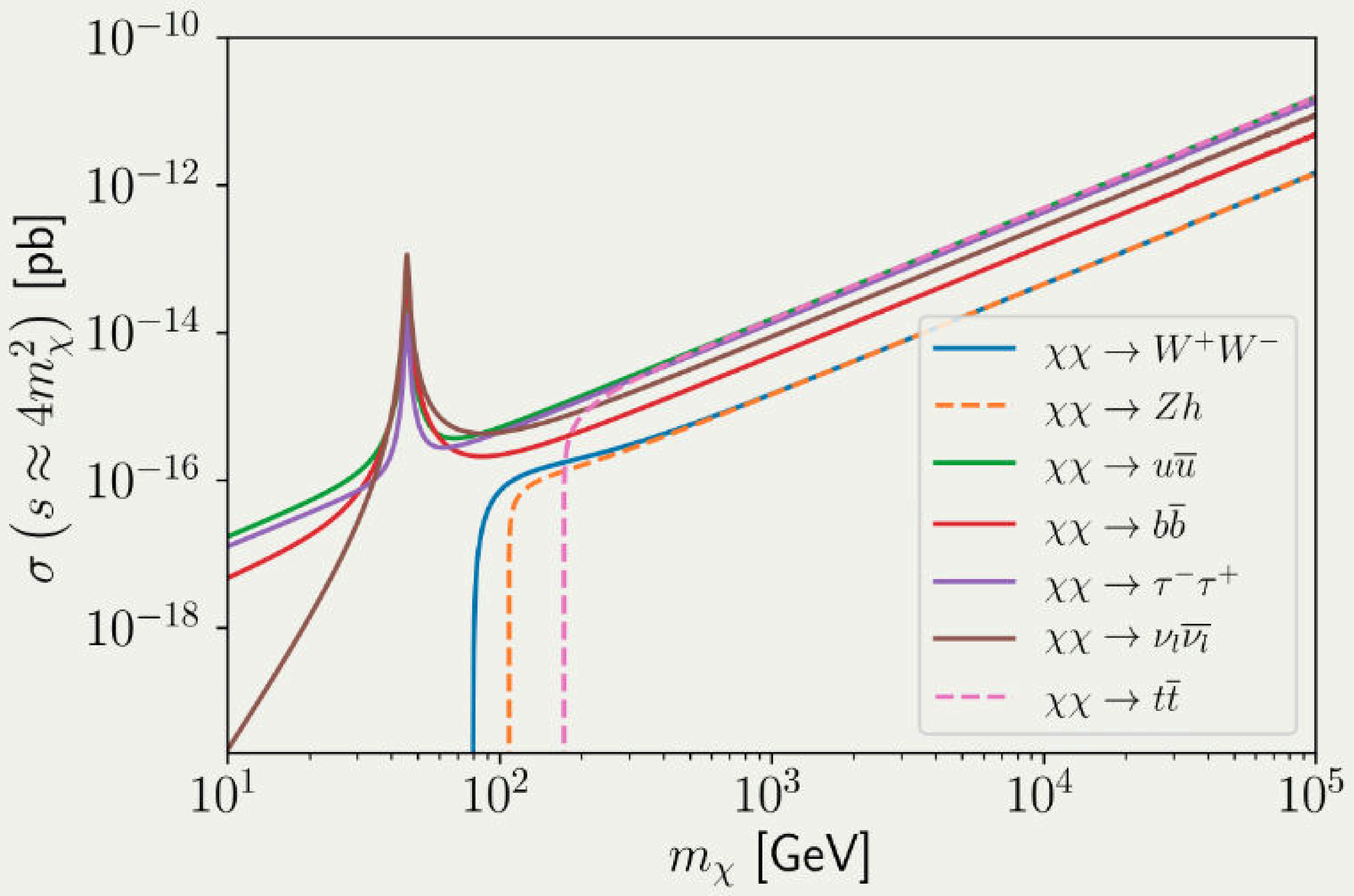
# The solution we already knew

- Using instead the SM gauge invariant field $B_{\mu\nu}$, you have the Z diagram interfering.
- Unsurprisingly this exactly cancels the $s^4$ growth in the amplitude squared

$$|M_A|^2 \sim \frac{2\pi\alpha_{EW}}{c_w^2}\left(\frac{C_\mathcal{A}}{\Lambda^2}\right)^2 s^2 \sin^2\theta + \mathcal{O}(s).$$

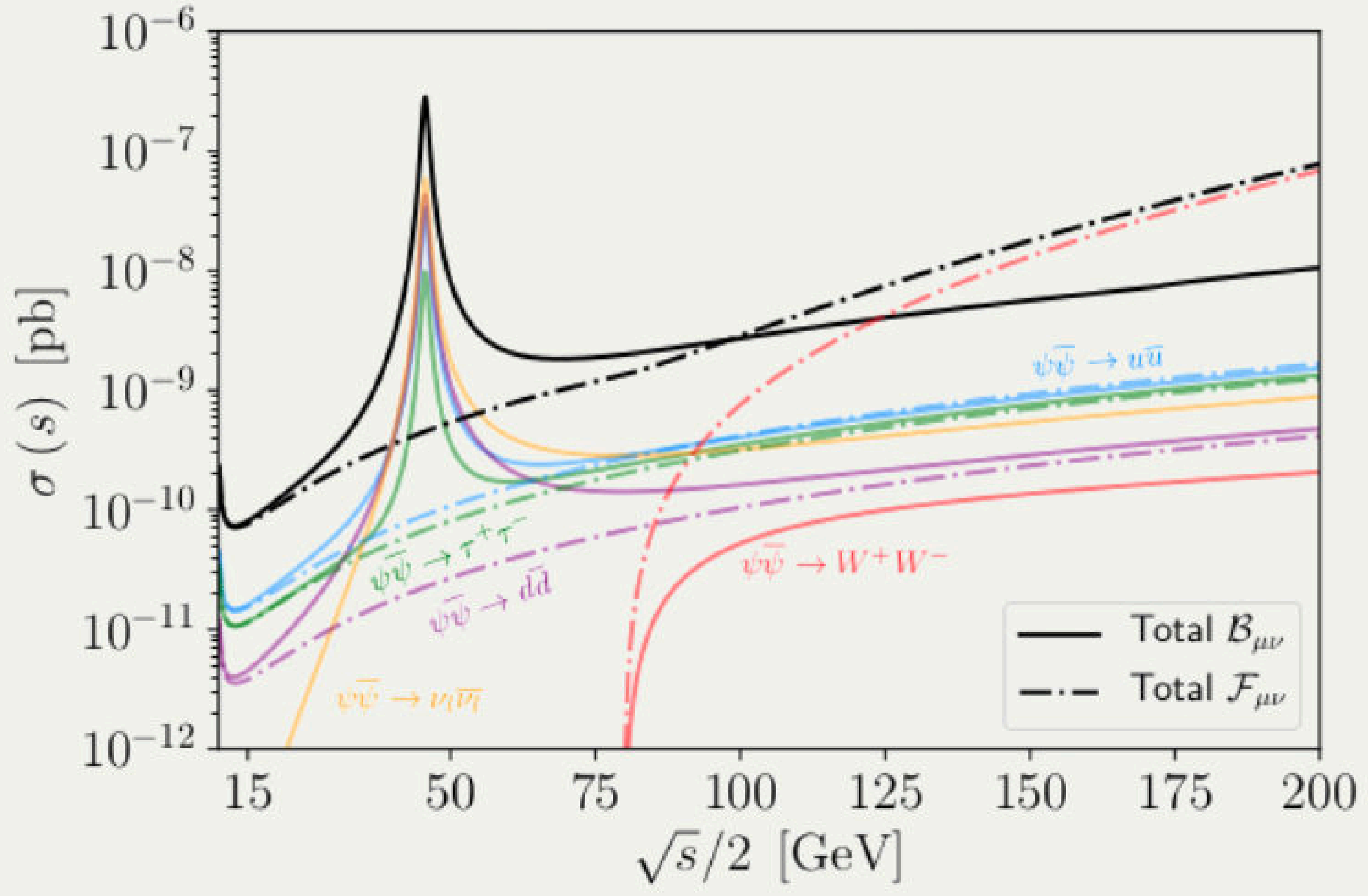
- So... can we ignore $\chi\chi \to W^+W^-$?



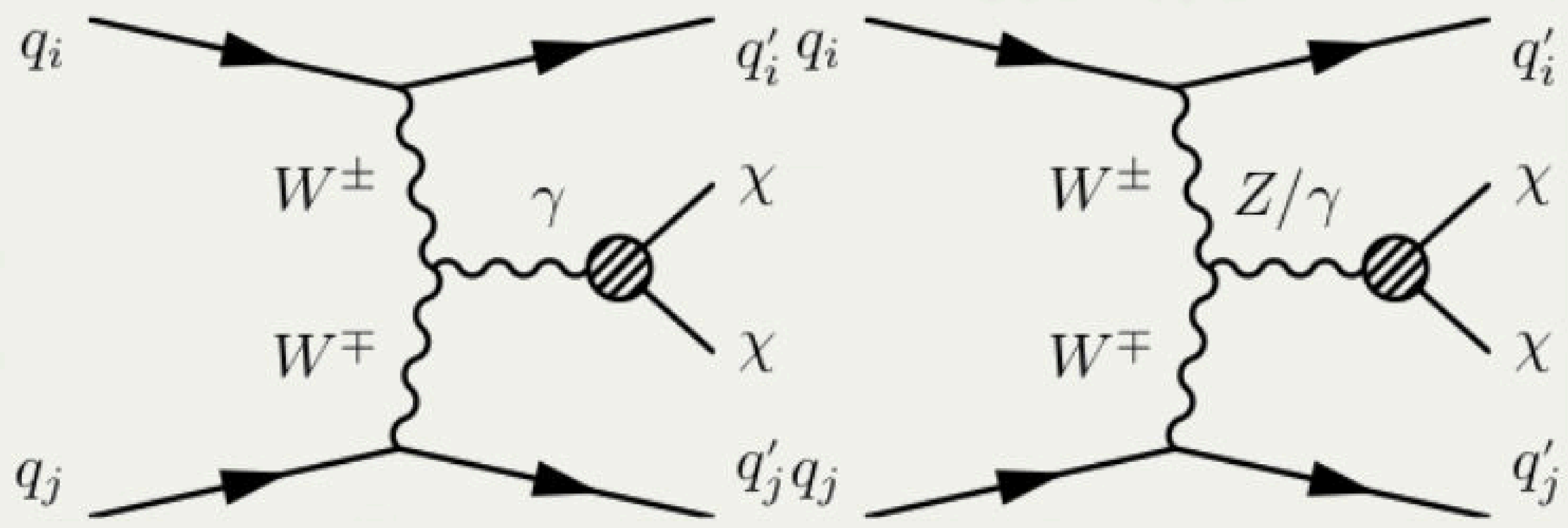
# Not really

- So in a sense you can ignore the $W^+W^-$ because its effects are not so dramatic for high DM masses.
- However, requiring the $Z$ boson has a phenomenological impact, $Z$-funnel, $Z$-width and neutrino interactions.
- The picture is for charge-radius, and is very similar for the other operators we consider.

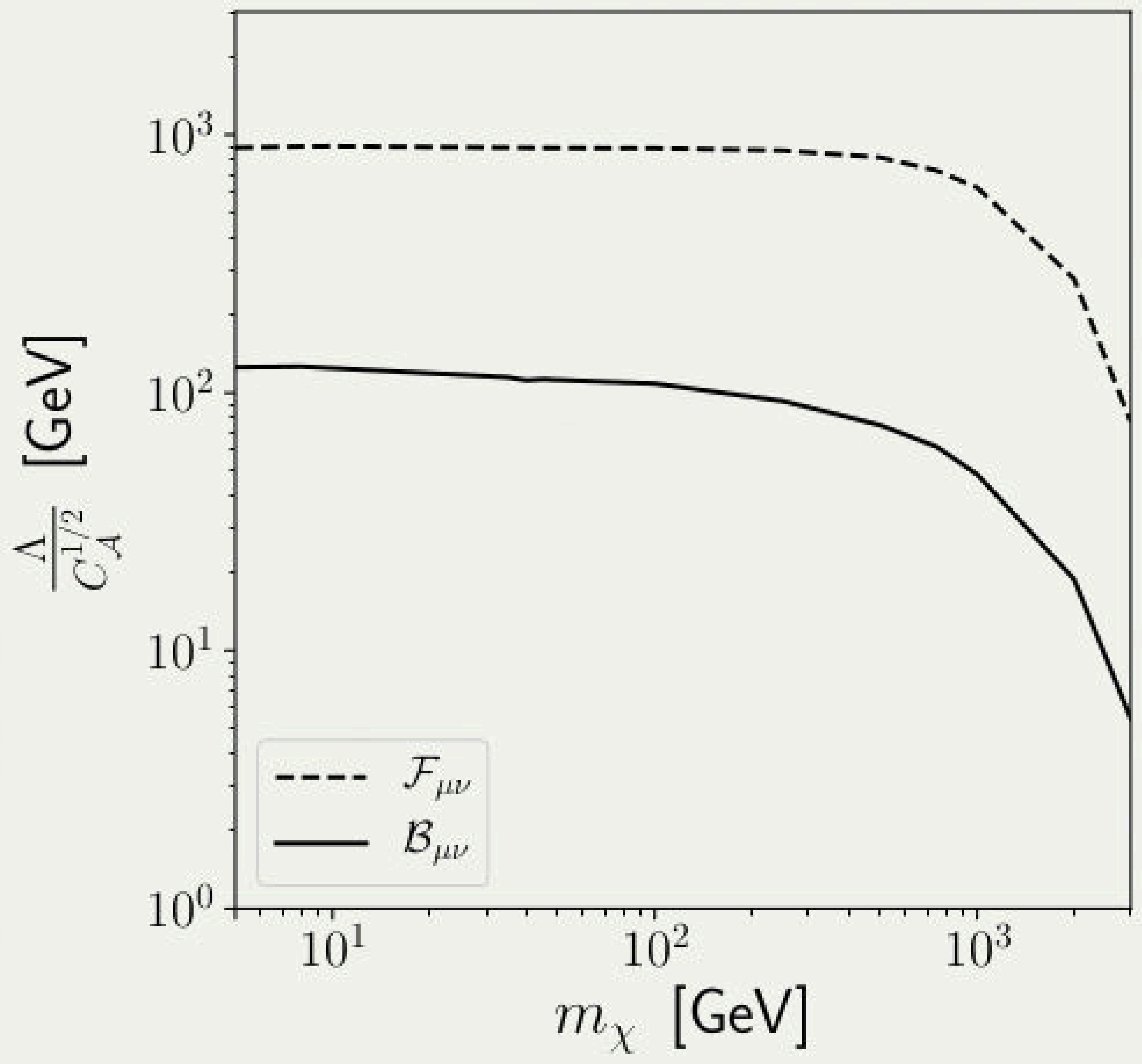


# VBF signals are once again sub-dominant

- We replicate the VBF search in A. Florez et. al. (Phys.Rev.D 100 (2019)) for both $F_{\mu\nu}$ and $B_{\mu\nu}$



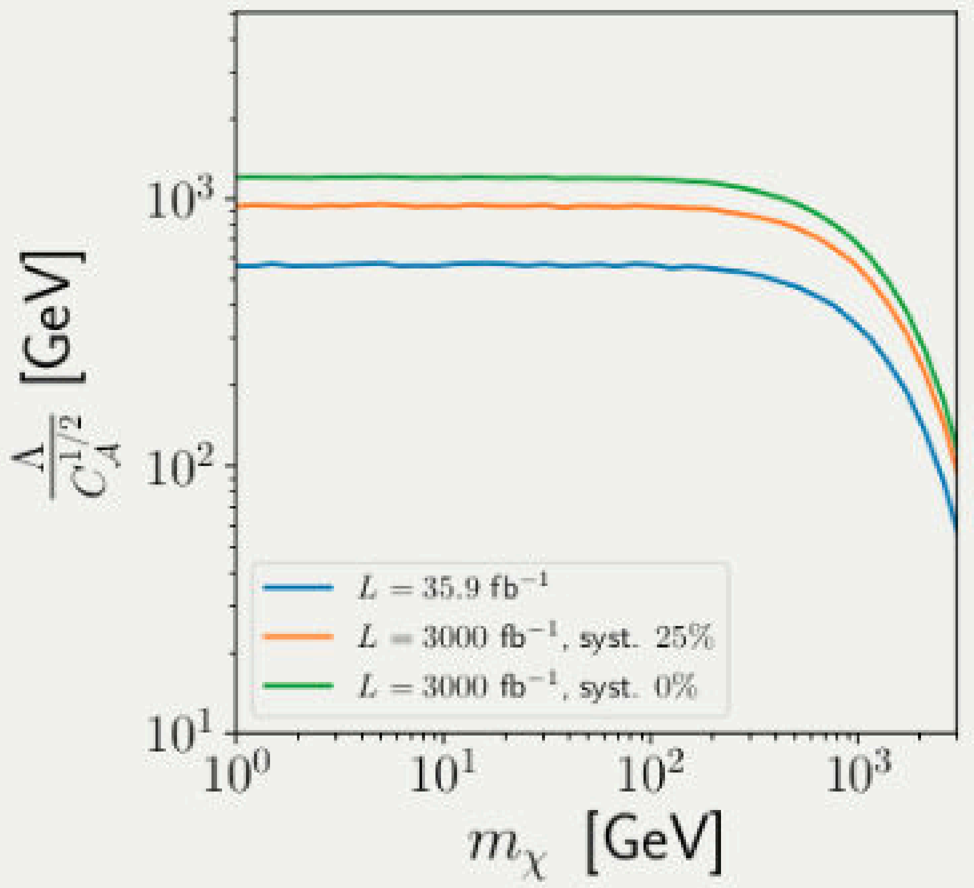

- Of course with the $Z$ included, the VBF constraints are much worse.



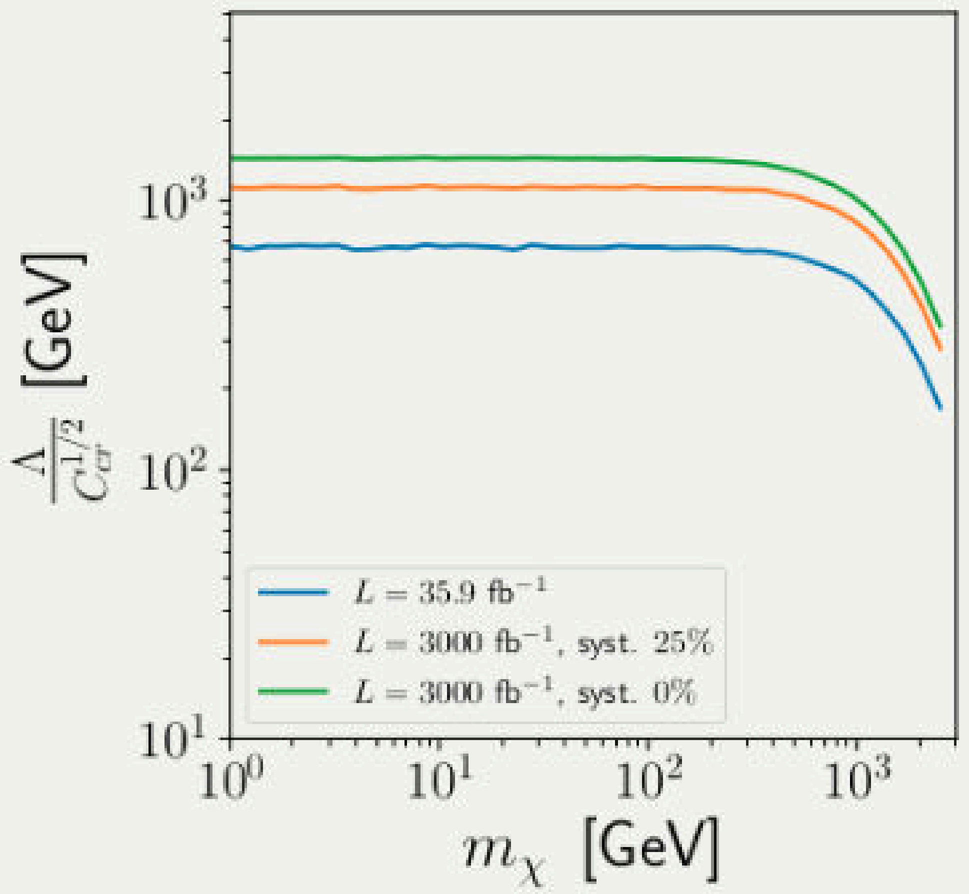

- So monojet plus MET is probably still the best signal to look for.

# Monojet result

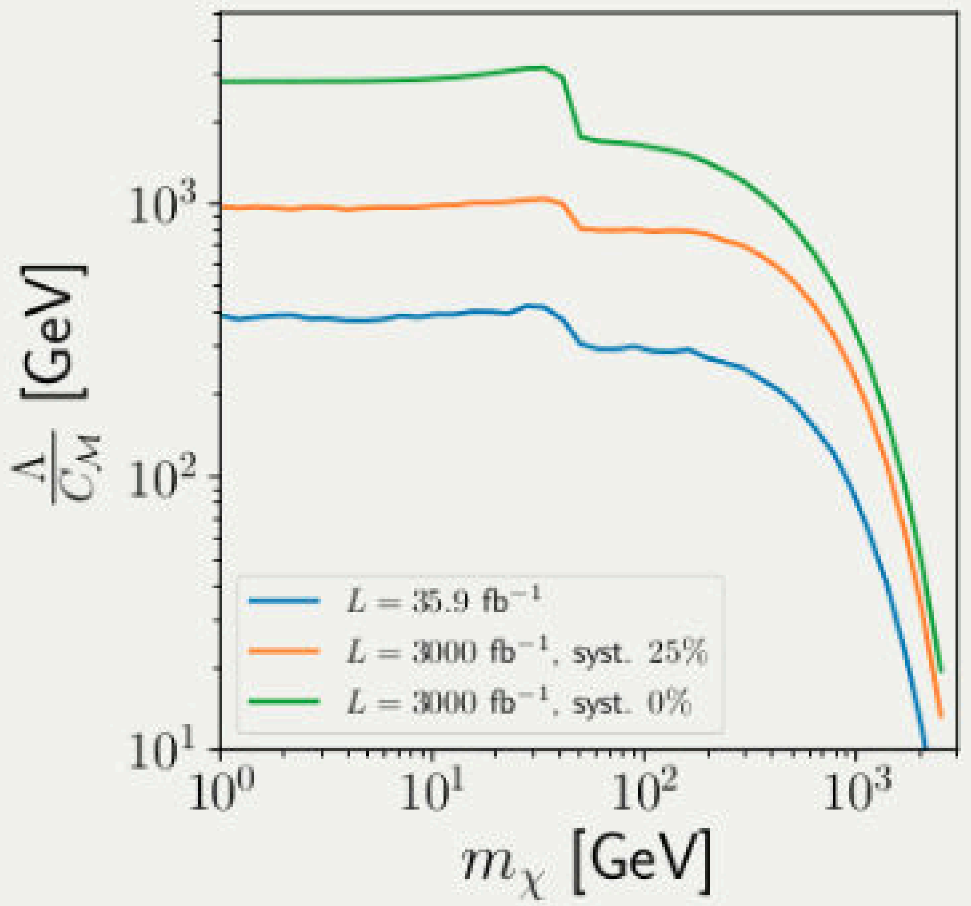
$B$ Anapole



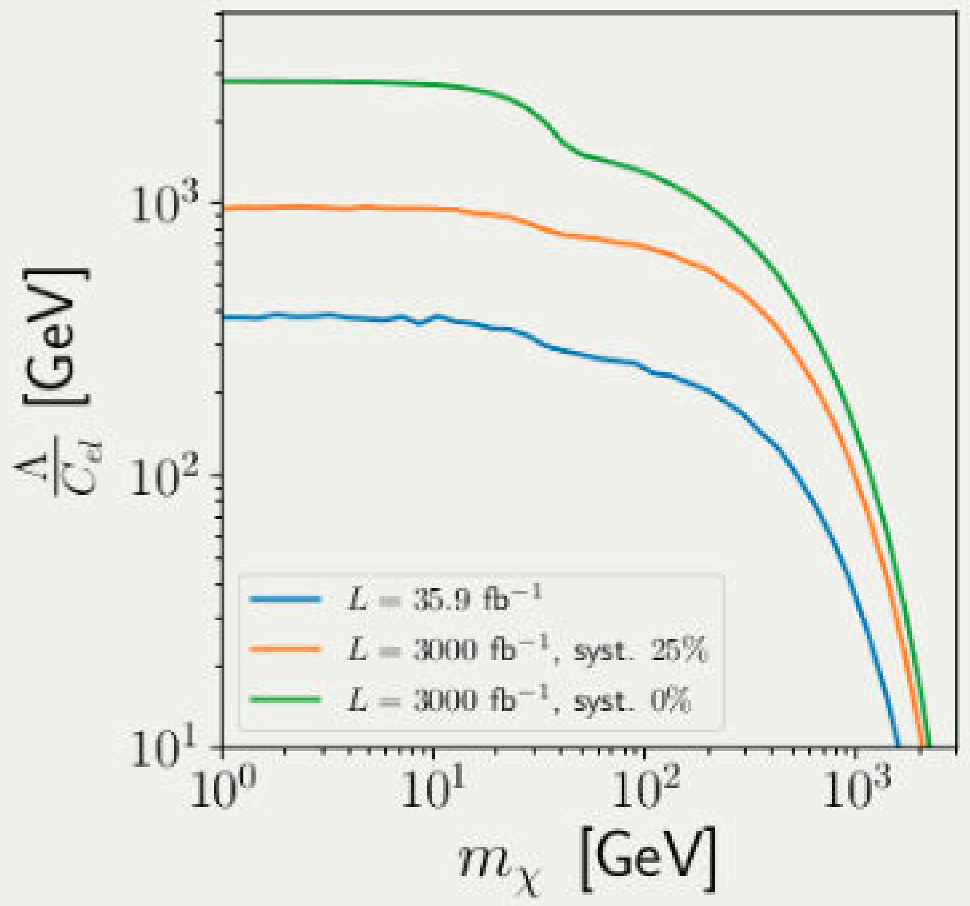

$B$ Charge-radius




$B$ Magnetic dipole




$B$ electric dipole



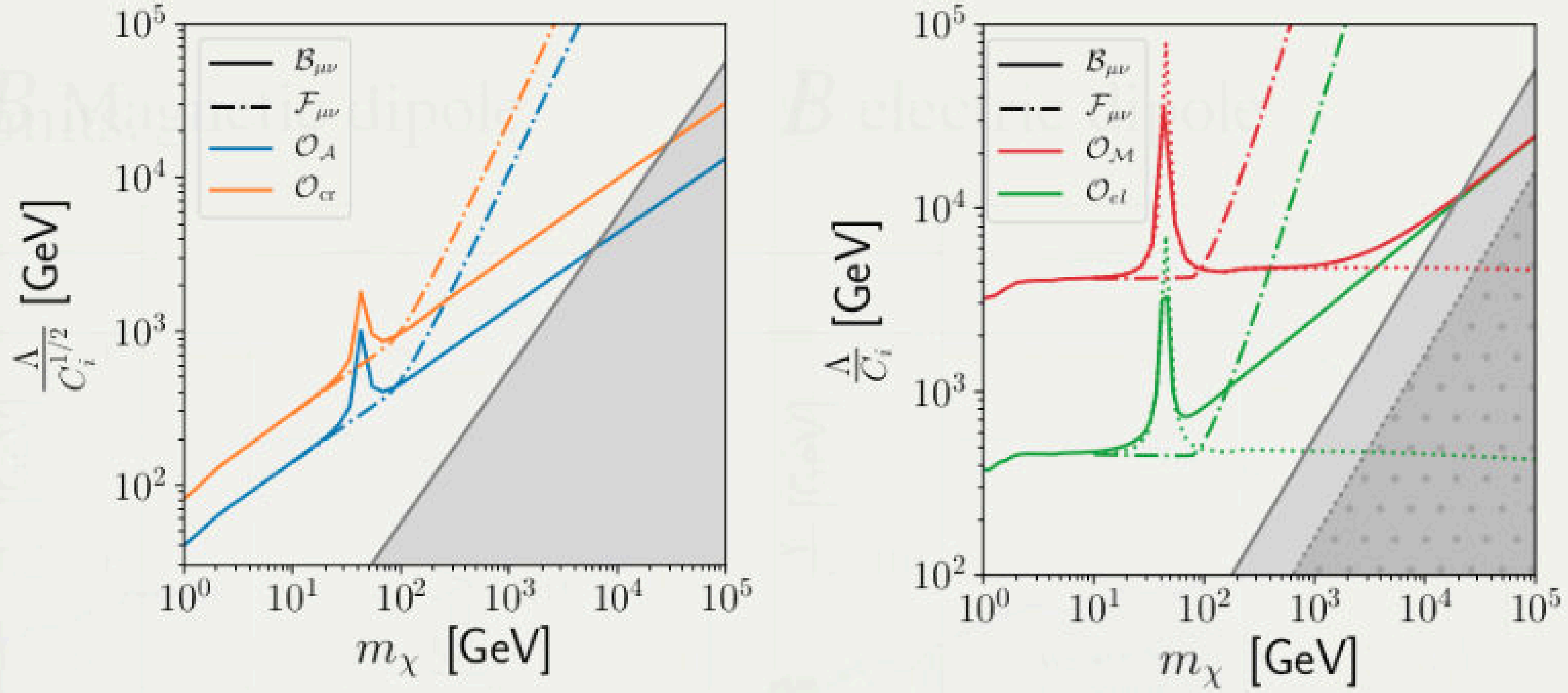

- Discussion of EFT validity can be read in our paper.

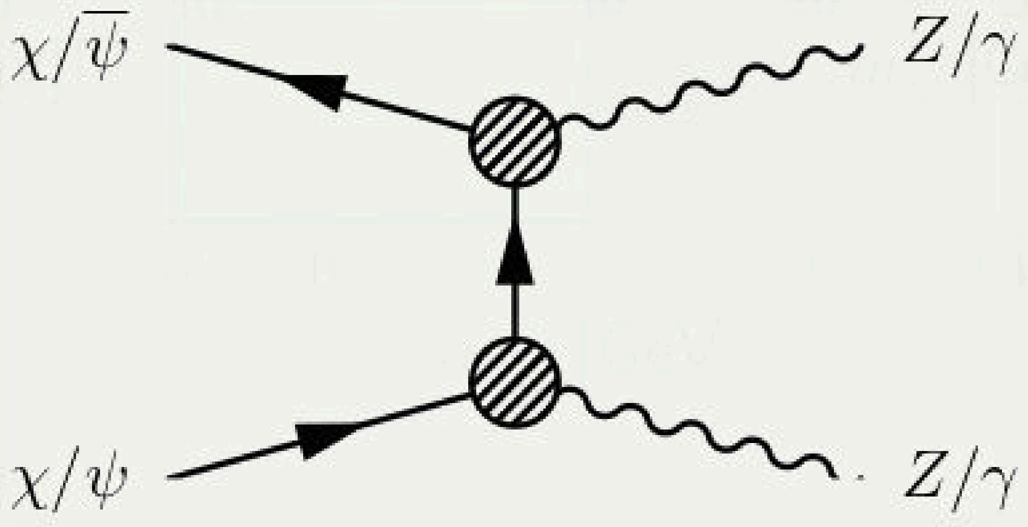
# Astroparticle constraints

- In keeping with dark matter tradition, we check what happens with freeze-out.
- Naive perturbative unitarity

$$\frac{\mathcal{C}_5}{\Lambda}\sqrt{s} \leq 4\pi, \quad \text{and} \quad \frac{\mathcal{C}_6}{\Lambda^2} s \leq 4\pi.$$

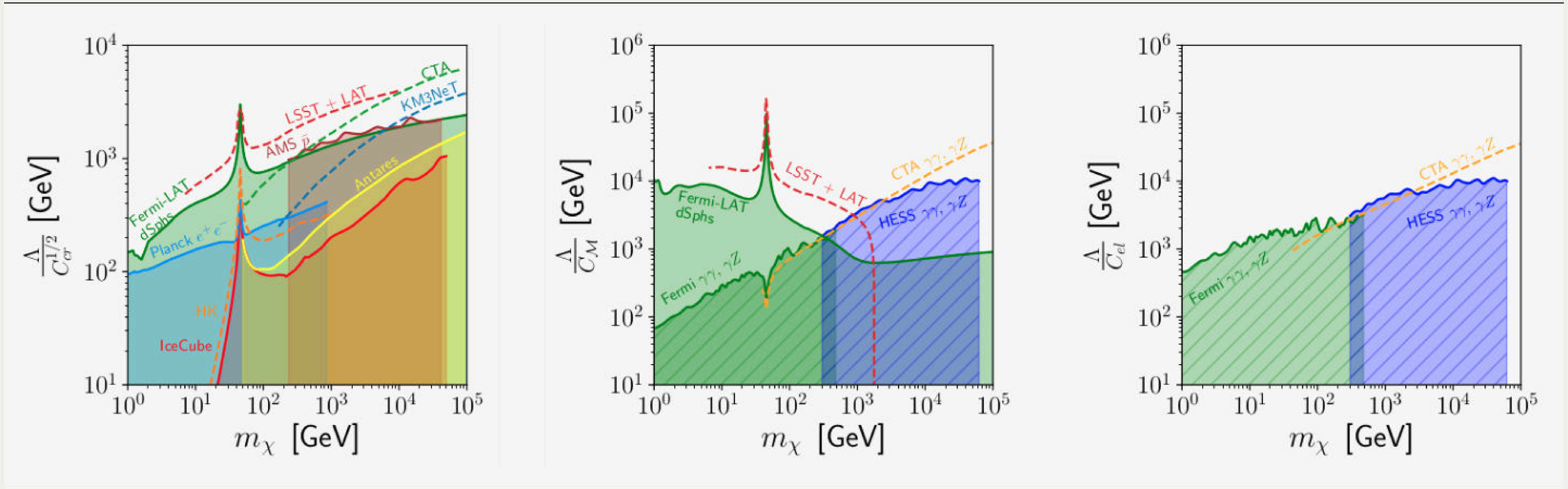
- We're actually considering the dimension 5 interaction up to dimension 6 though!



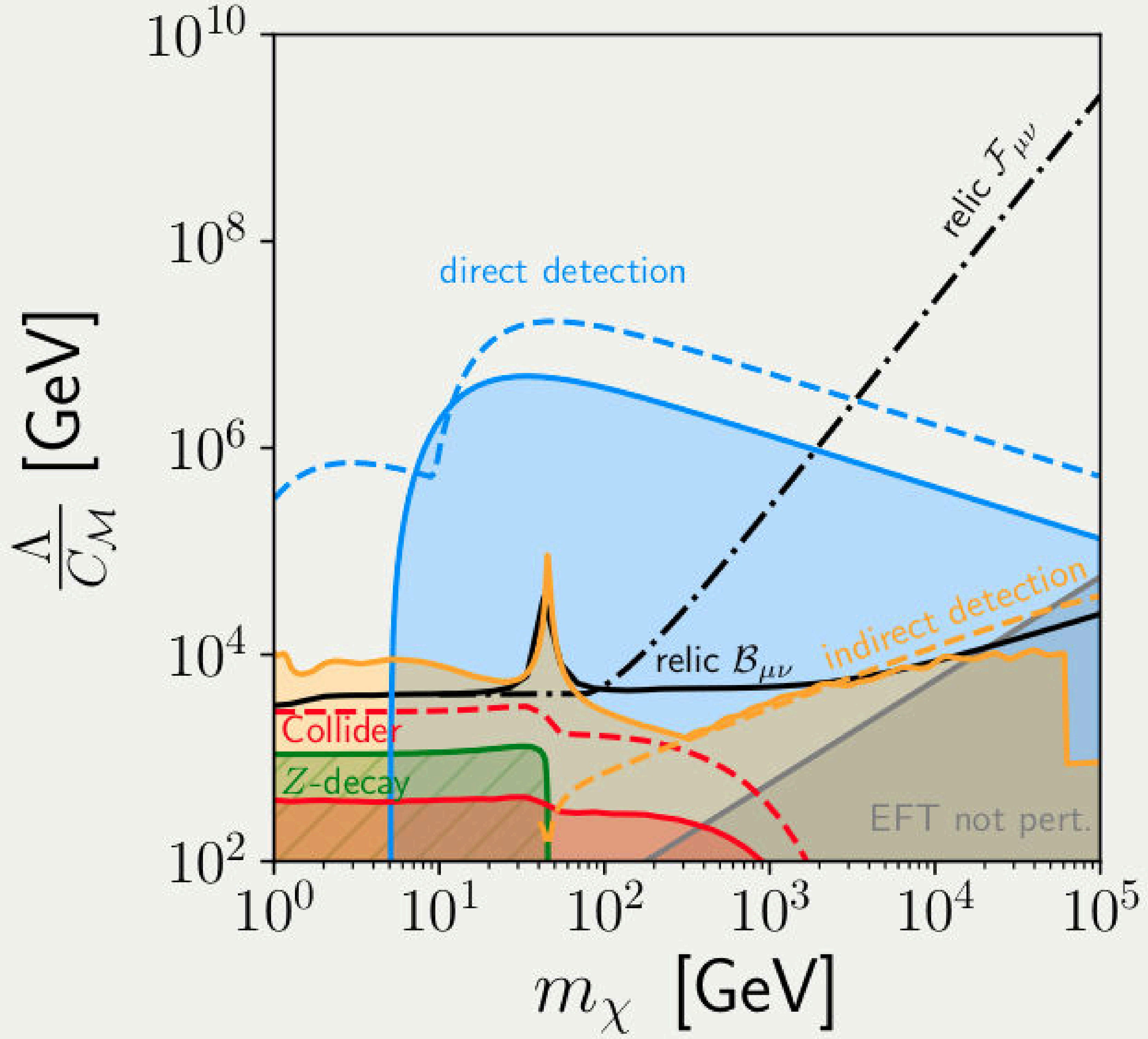
# Indirect limits

- We performed a up-to-date recast of current and future limits.

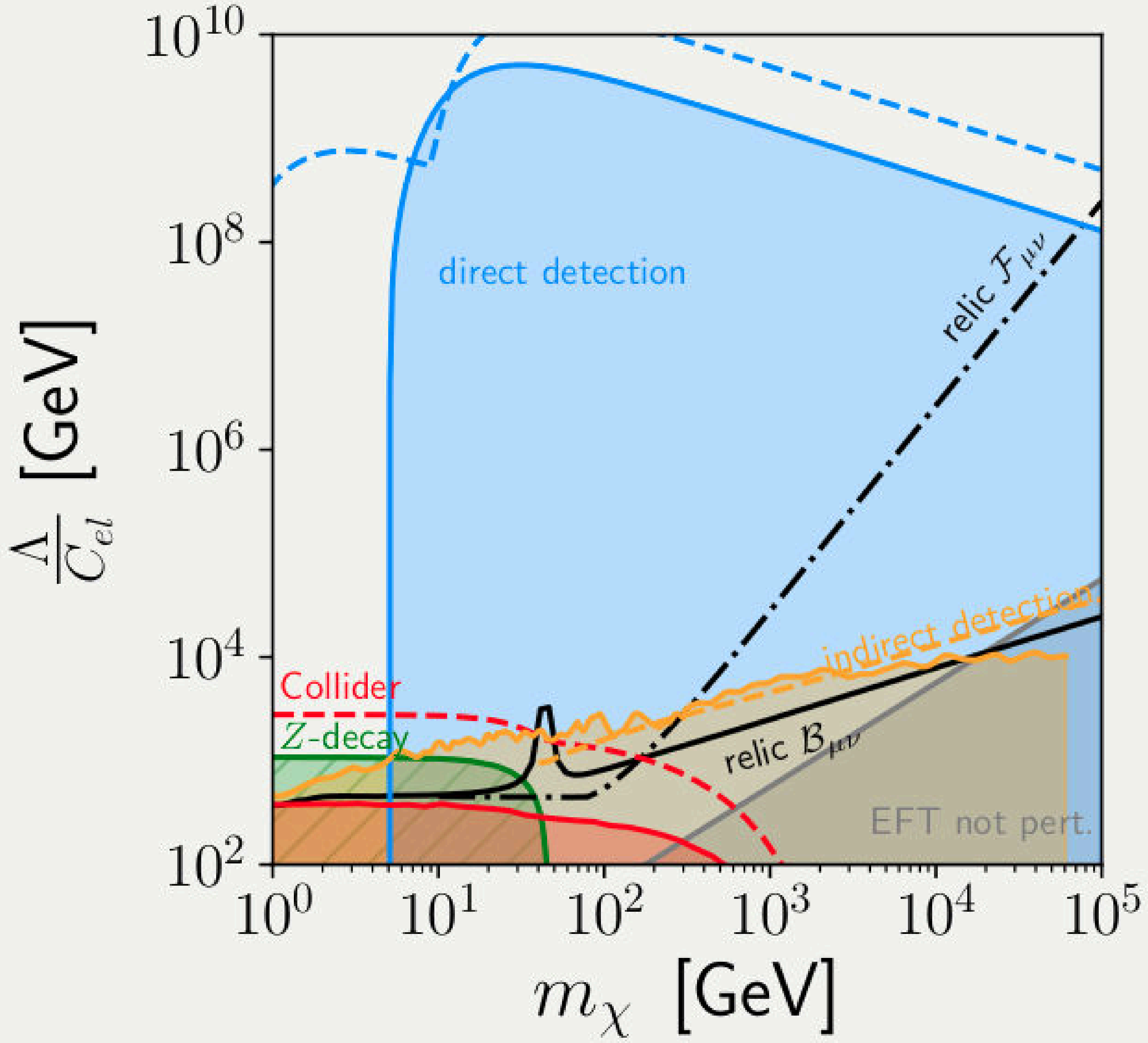


# Global Results

$$\frac{C_{\mathcal{M}}}{2\Lambda}\bar{\psi}\sigma^{\mu\nu}\psi \cdot B_{\mu\nu}$$

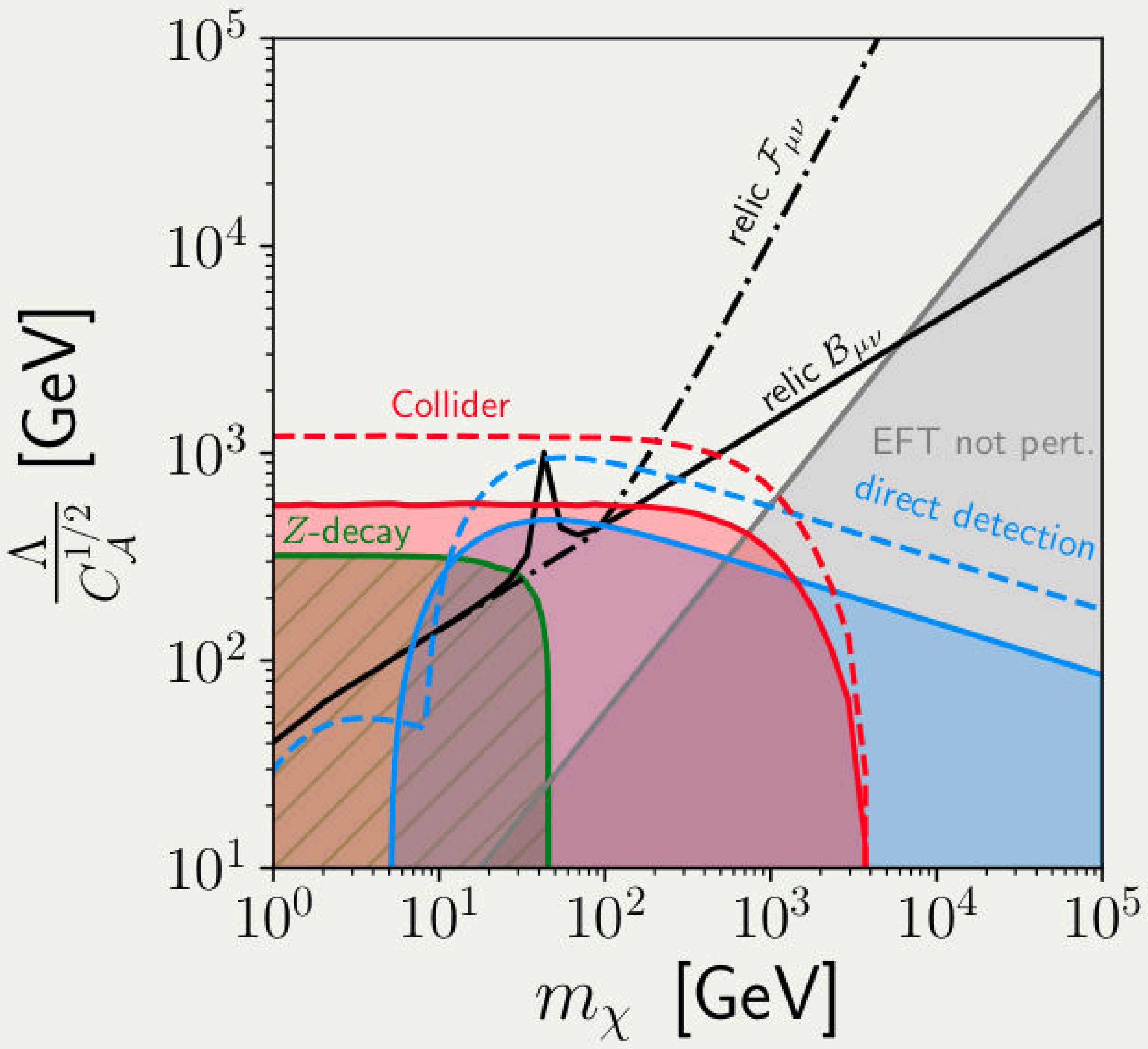



$$\frac{C_{el}}{2\Lambda}i\bar{\psi}\sigma^{\mu\nu}\gamma^5\psi \cdot B_{\mu\nu}$$

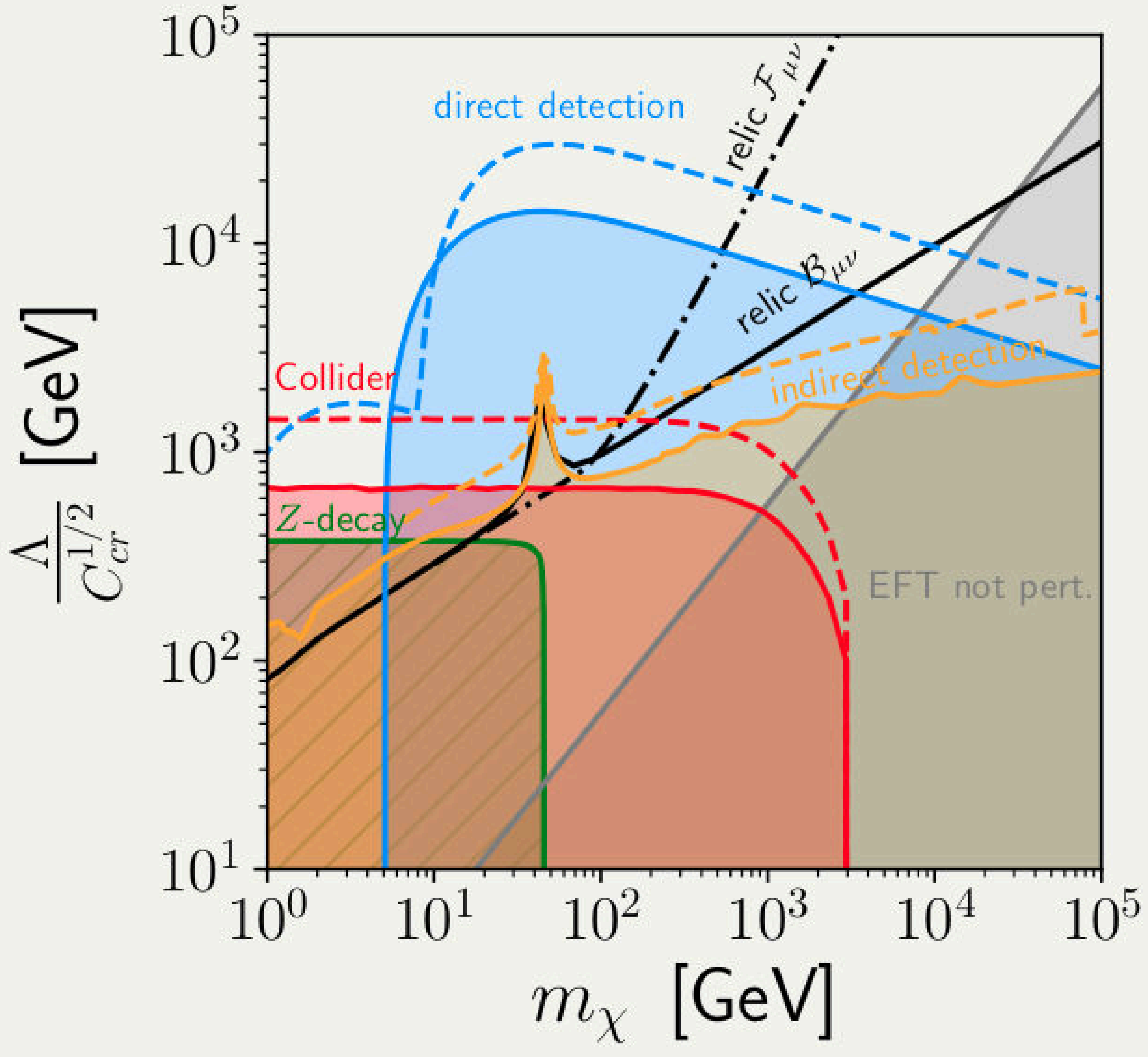


# Global Results

$$\frac{C_{\mathcal{A}}}{\Lambda^2}\frac{1}{2}\bar{\chi}\gamma^\mu\gamma^5\chi\cdot\partial^\nu B_{\mu\nu}$$



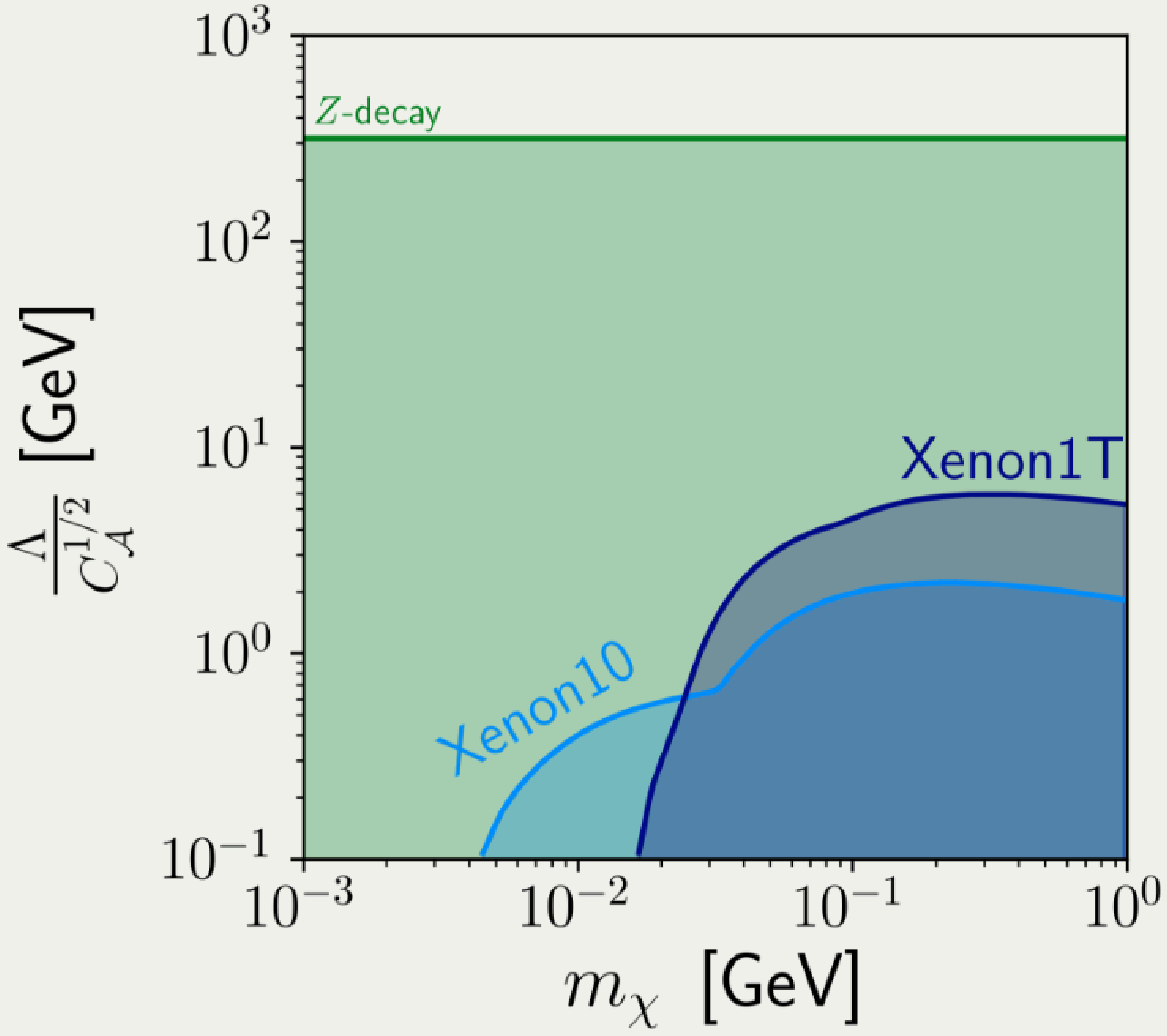

$$\frac{C_{cr}}{\Lambda^2}\bar{\psi}\gamma^\mu\psi\cdot\partial^\nu B_{\mu\nu}$$



# Implications for light DM

- Insisting on using the $B$ field provides a very strong constraint for light dark matter, lets see how it compares with electron recoil analysis as presented in arXiv:1912.08204.
- This is most relevant for anapole dark matter.
- $Z$-width is orders of magnitude more constraining.
- If you want to avoid this constraint, you have to fix unitarity violation before

$$\sqrt{s} \gtrsim 4.3 \sqrt{m_Z \frac{\Lambda}{\sqrt{C^{\gamma}_{\mathcal{A}}}}}$$



# Conclusions

- There isn't a choice between $B_{\mu\nu}$ and $F_{\mu\nu}$!
- Sadly, it means that promising VBF results are no longer promising.
- Other phenomelogical constraints are opened up though, mainly from $Z$ physics.
- The simple freeze-out scenario is still allowed for dimension 6 interactions.
- Light dark matter experimental collaborations should be aware that $Z$-width constraints can be particularly strong for certain models.