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

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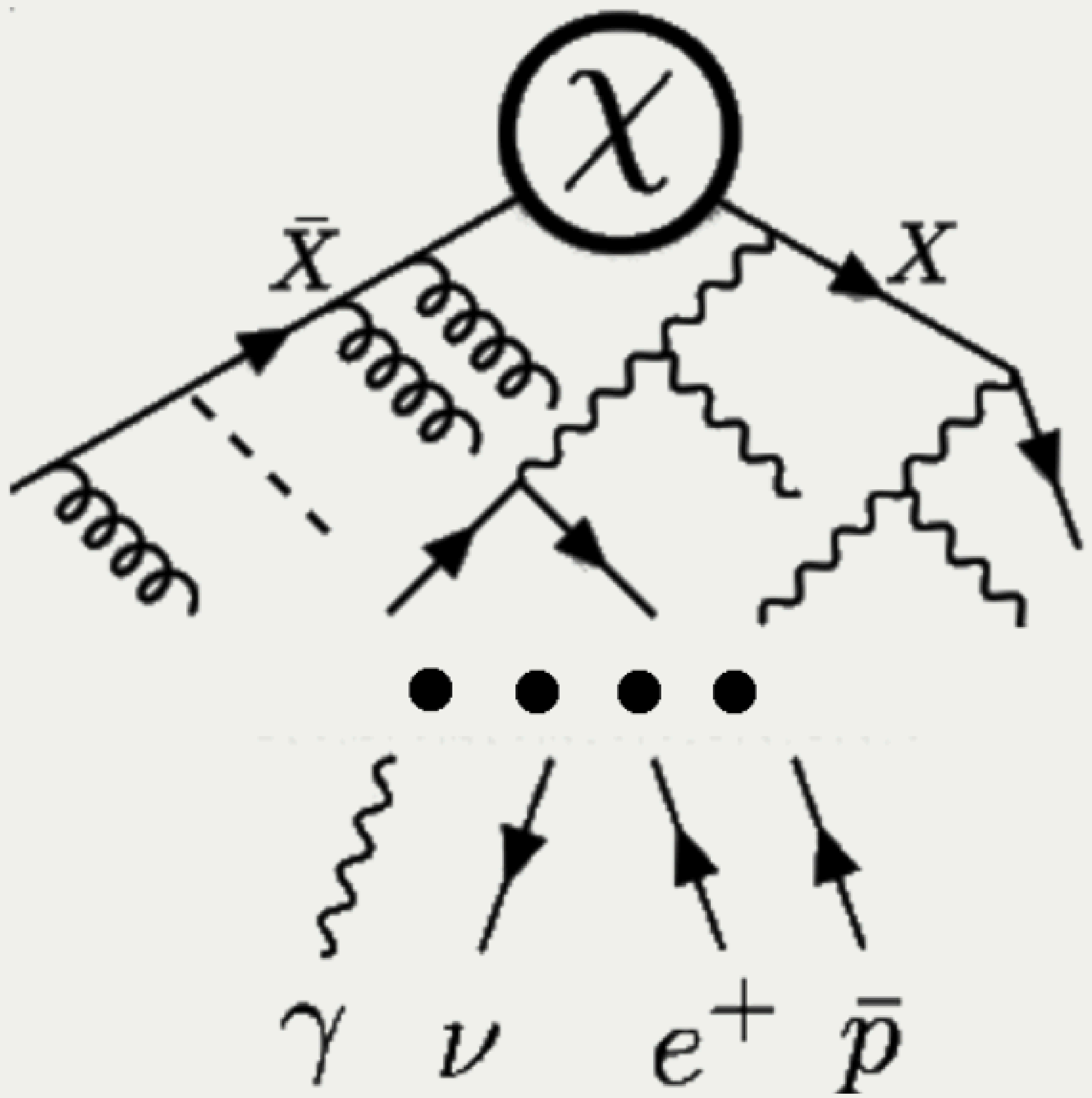
Andrew Cheek

In collaboration with C. Arina, K. Mimasu and L. Pagani

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 of 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-γ 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.

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

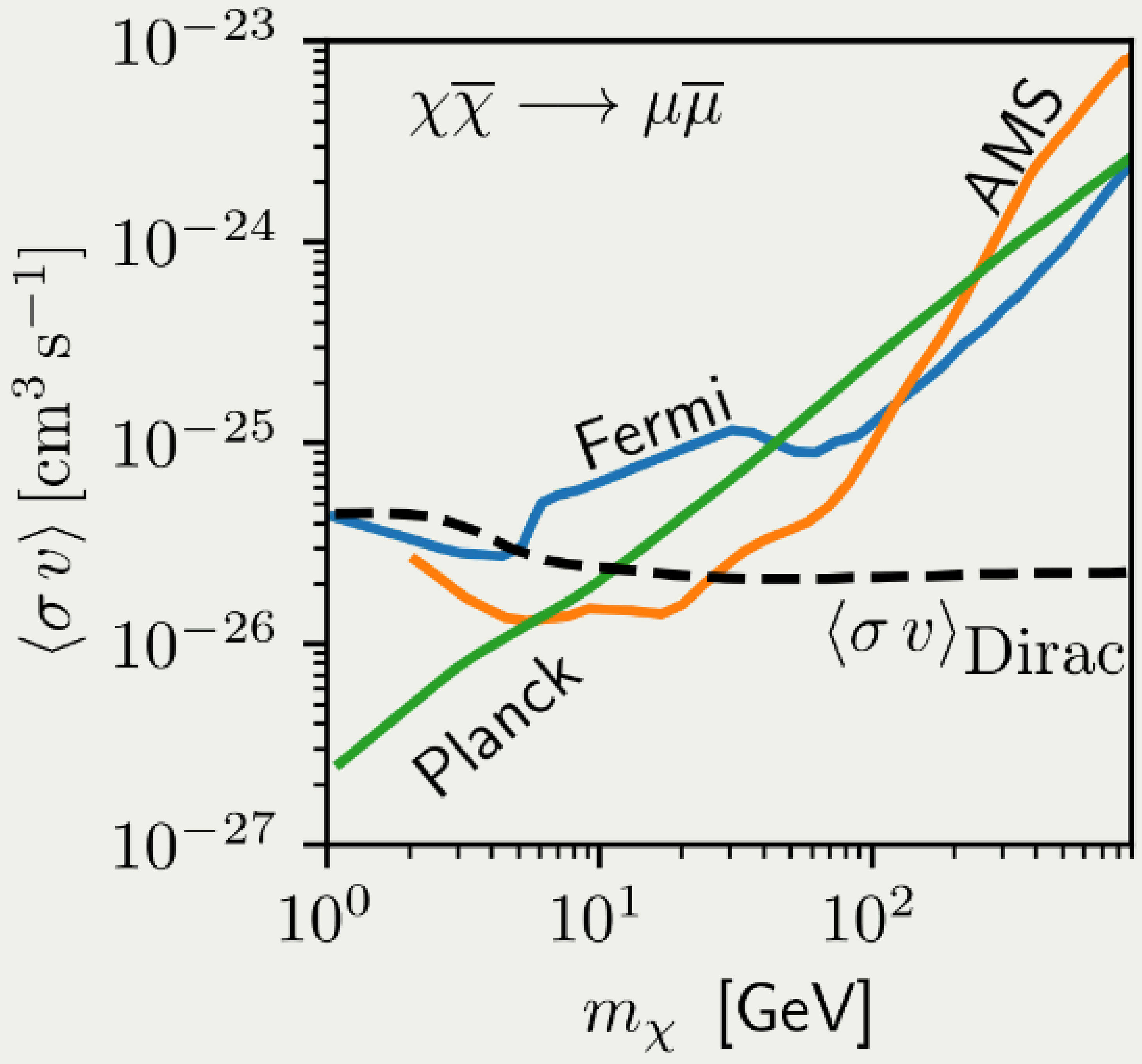
with

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

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

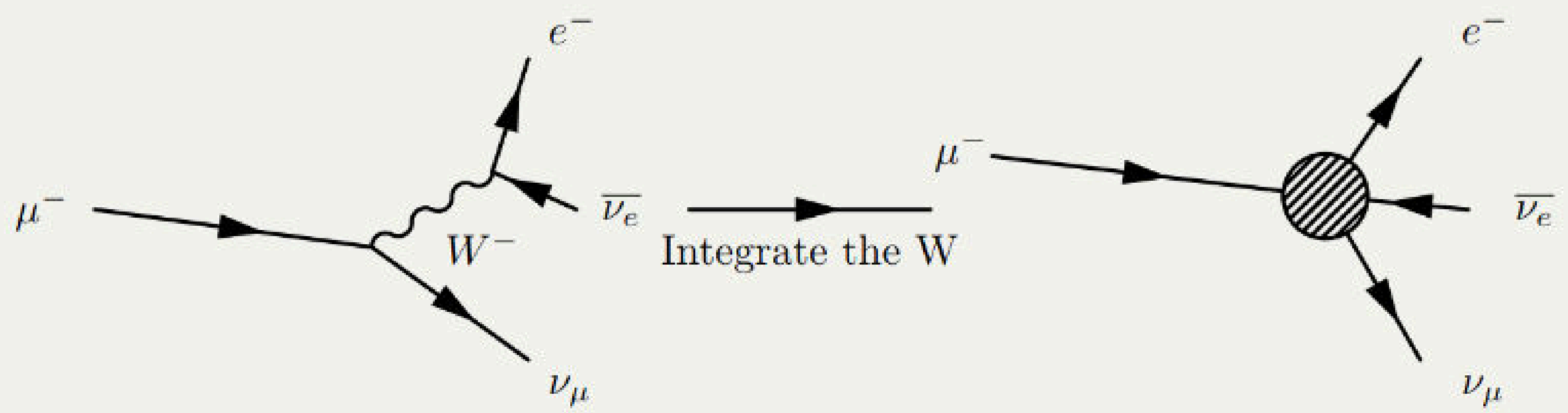
The toughest moment to constrain

- For majorana dark matter all are zero except the anapole.
- Also anapole is velocity surpressed so we potentially have an explaination for why we don't see it.
- These kinds of scenarios are particularly appealing for light dark matter models.



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

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

- This picture only works if processes studied are sufficiently below Λ.
- 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.
- In direct detection however

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

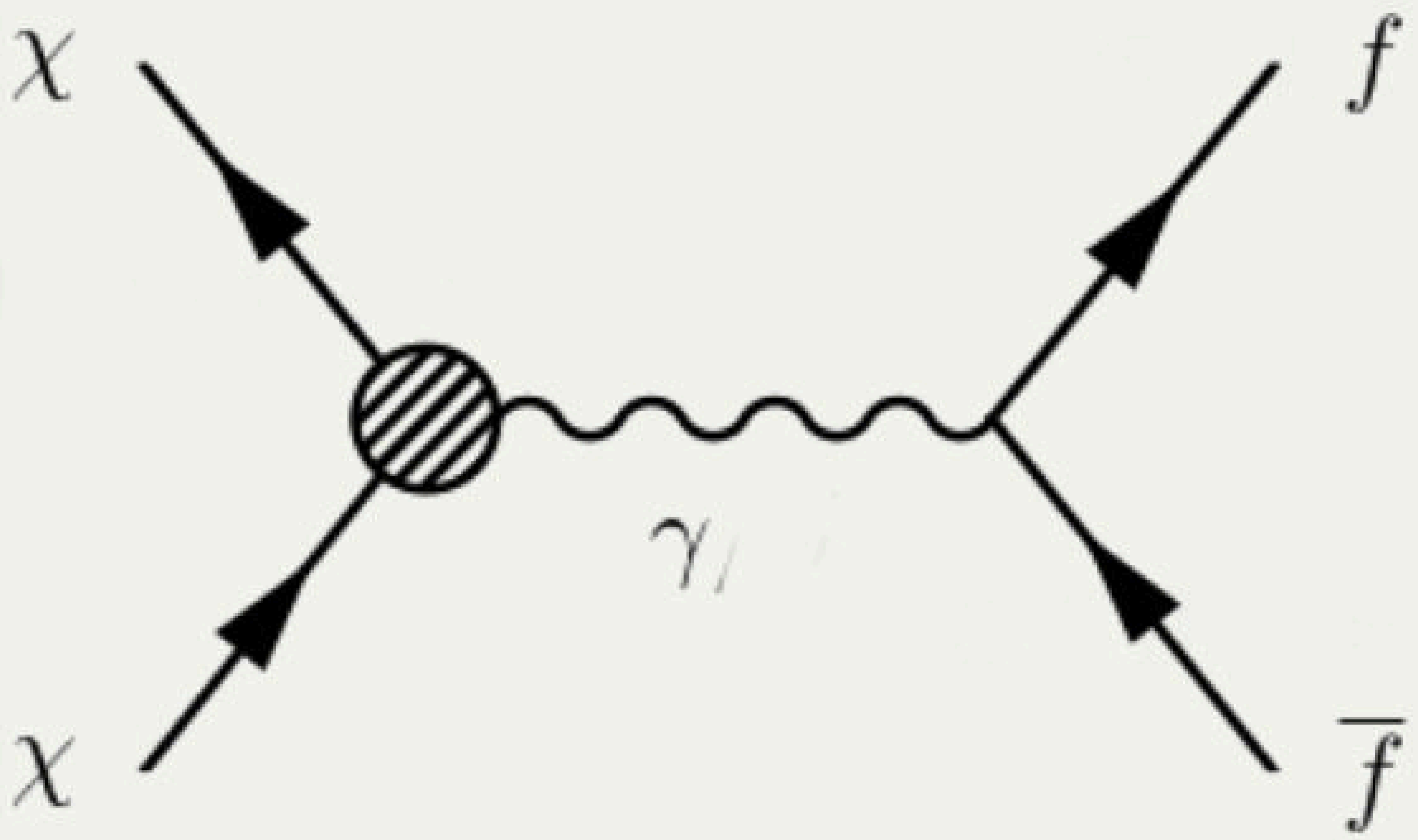
so at low energies

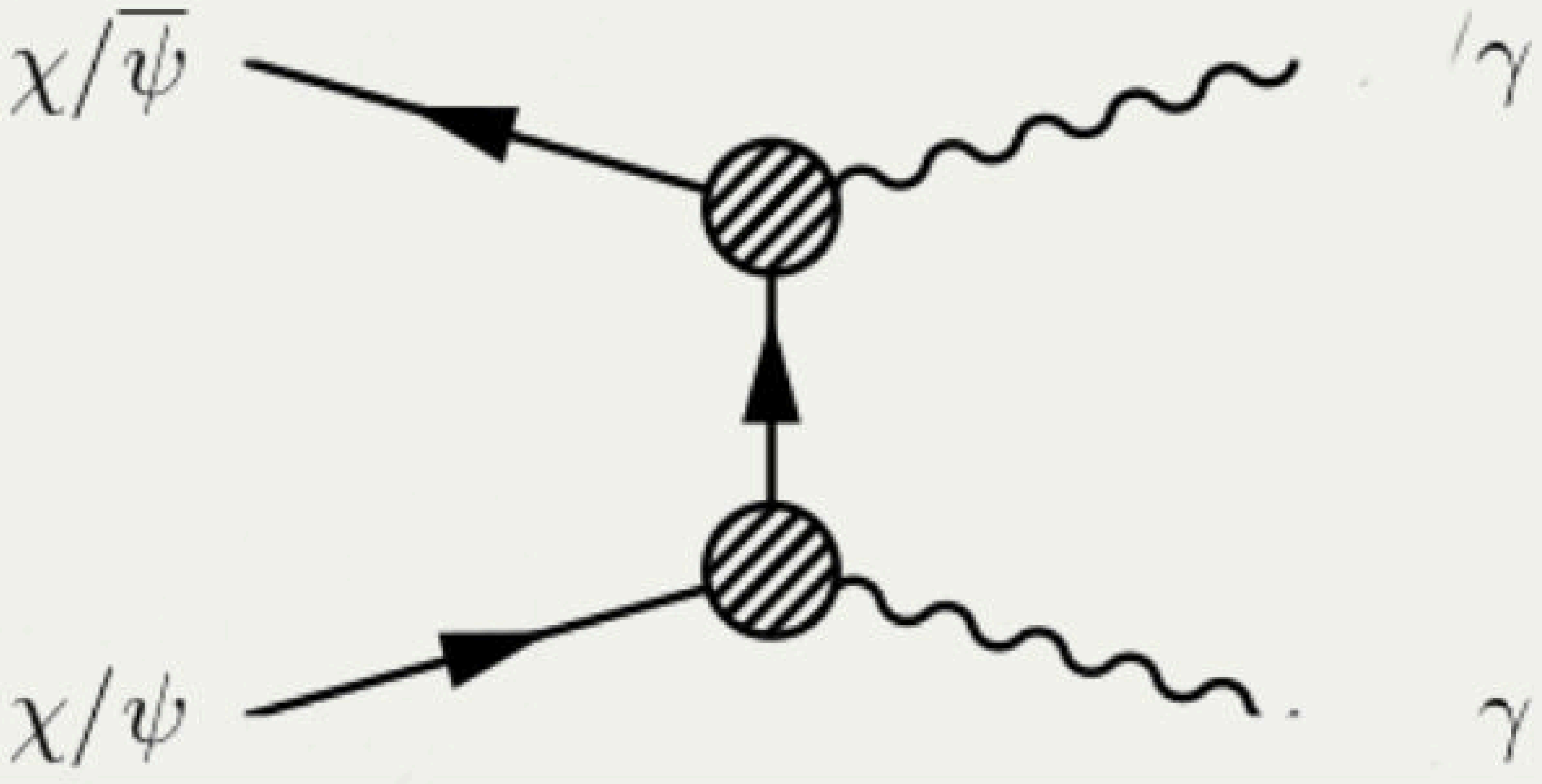
$$\mathcal{O}^{\mu\nu} B_{\mu\nu} \approx c_{\mathrm{W}} \mathcal{O}^{\mu\nu} F_{\mu\nu} + \mathcal{O}\left(\frac{q^2}{m_Z^2}\right)$$

- 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_χ up to 10^4 GeV

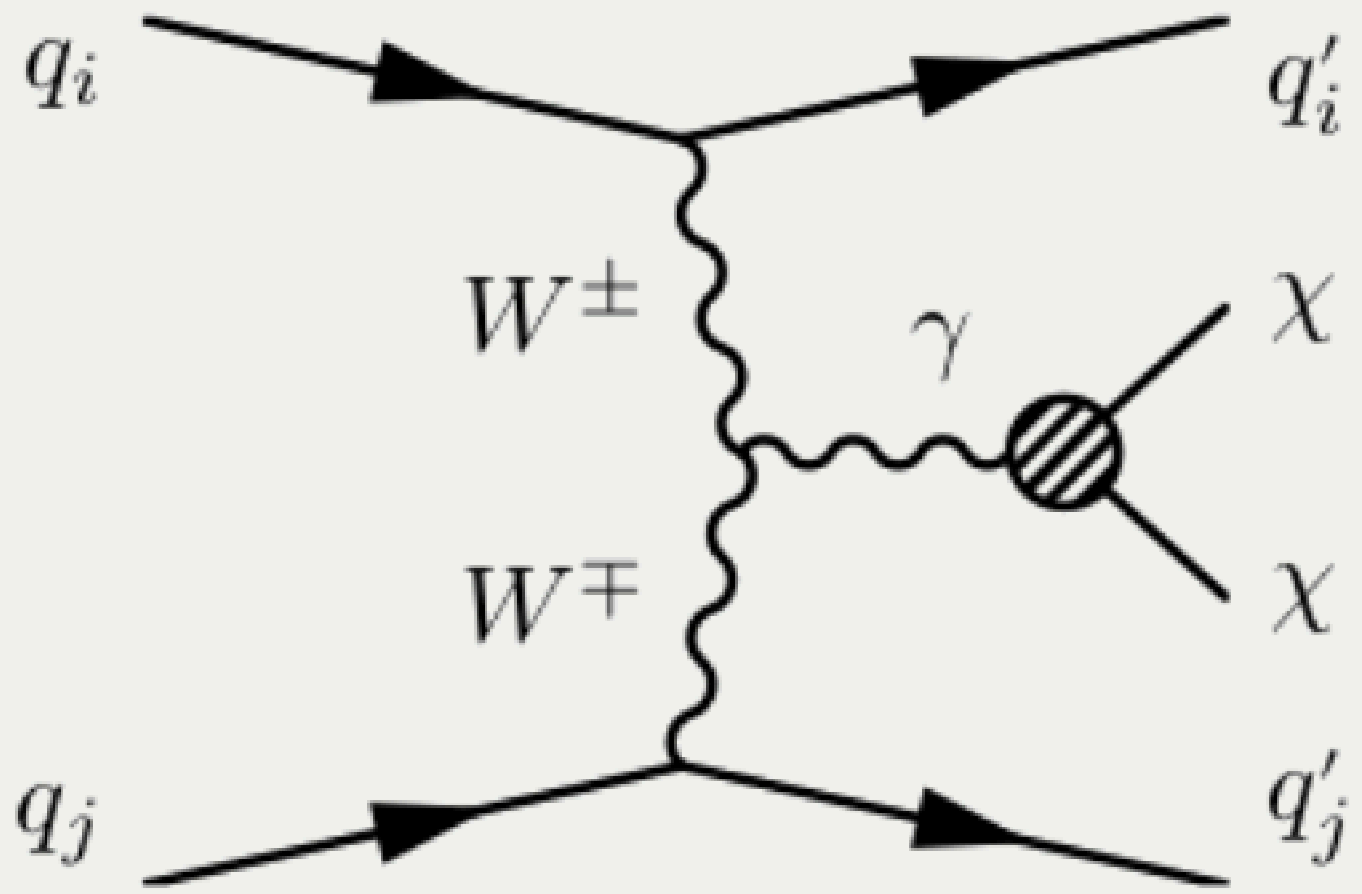




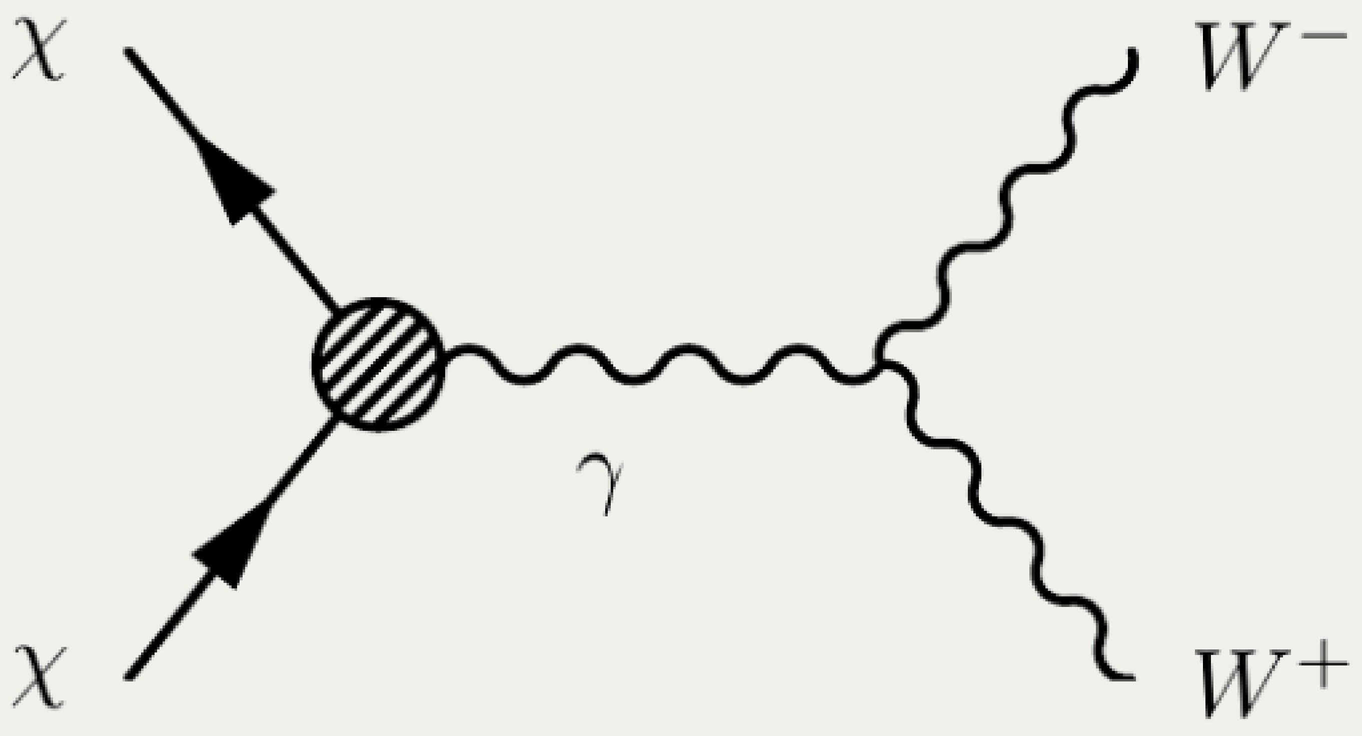
- Ho and Scherrer in the 2012 anapole dark matter paper were hesistant to explore $m_\chi \geq m_W$, we assume because they understood that care would have to be taken at the EW scale.

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.



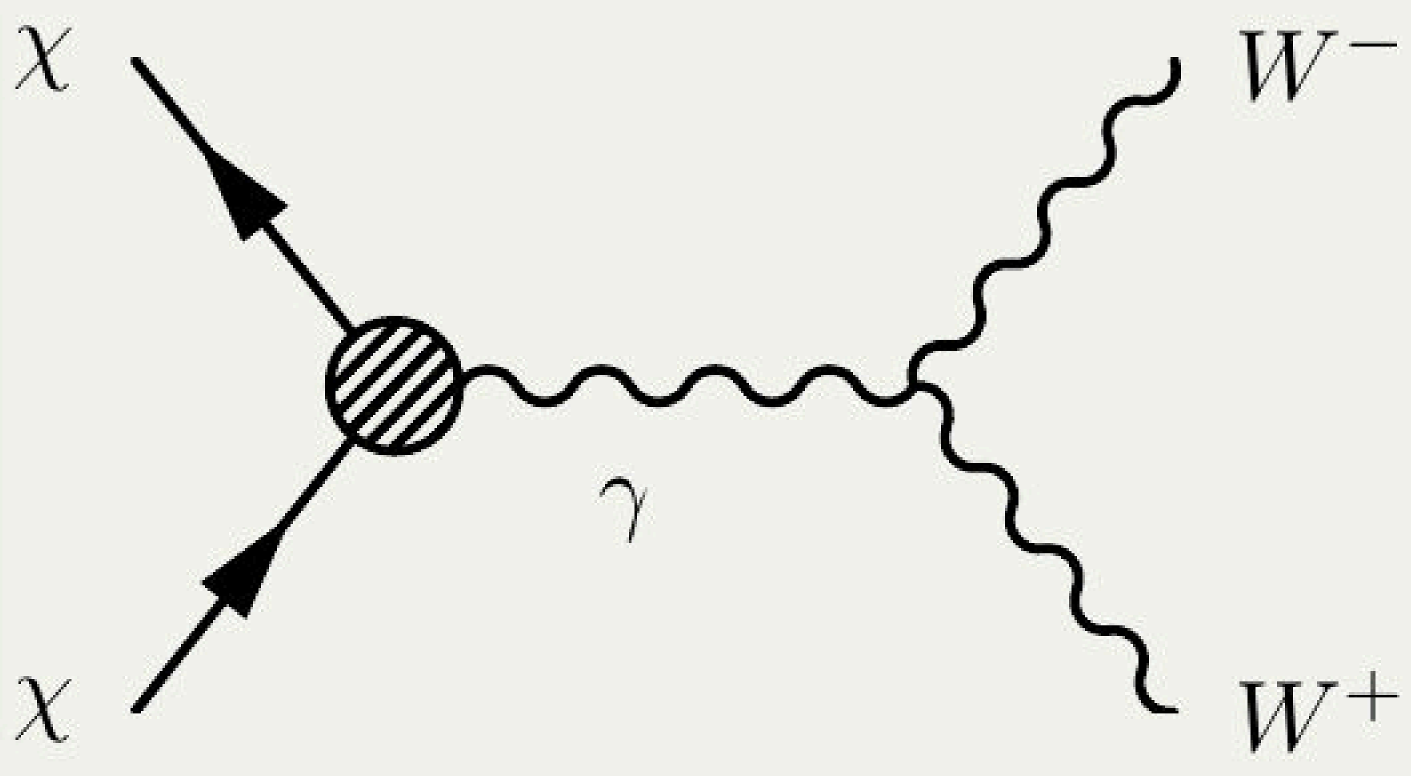
- This suggests that perhaps a diagram is missing in the relic density calculations



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

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

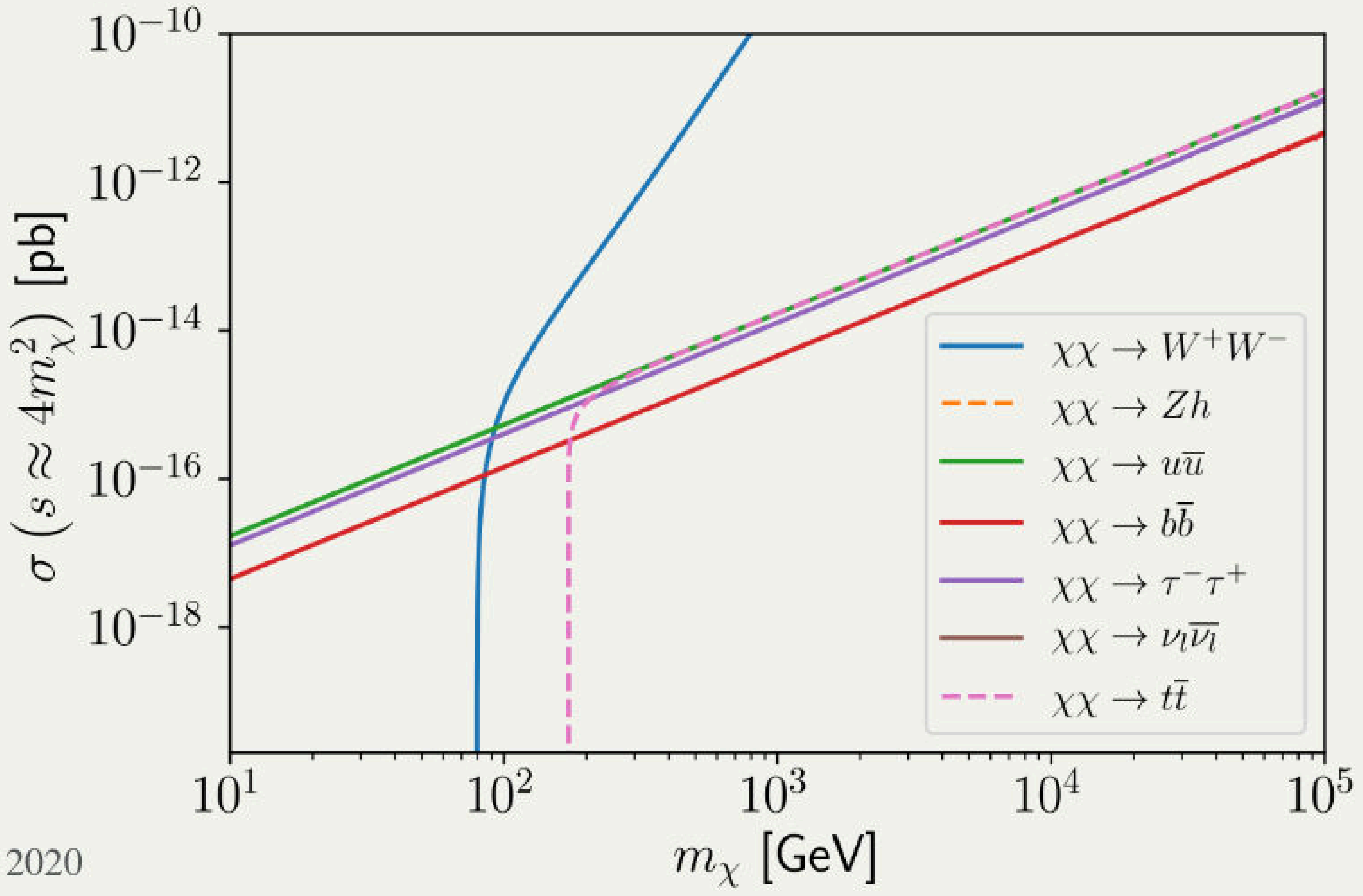
- Lets take the anapole, since the promising VBF results were for that.



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

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 $\propto s^2$.
- However, for $\langle \sigma v \rangle$ at freeze-out, $s \sim m_\chi^2$, lets see how this behaves.

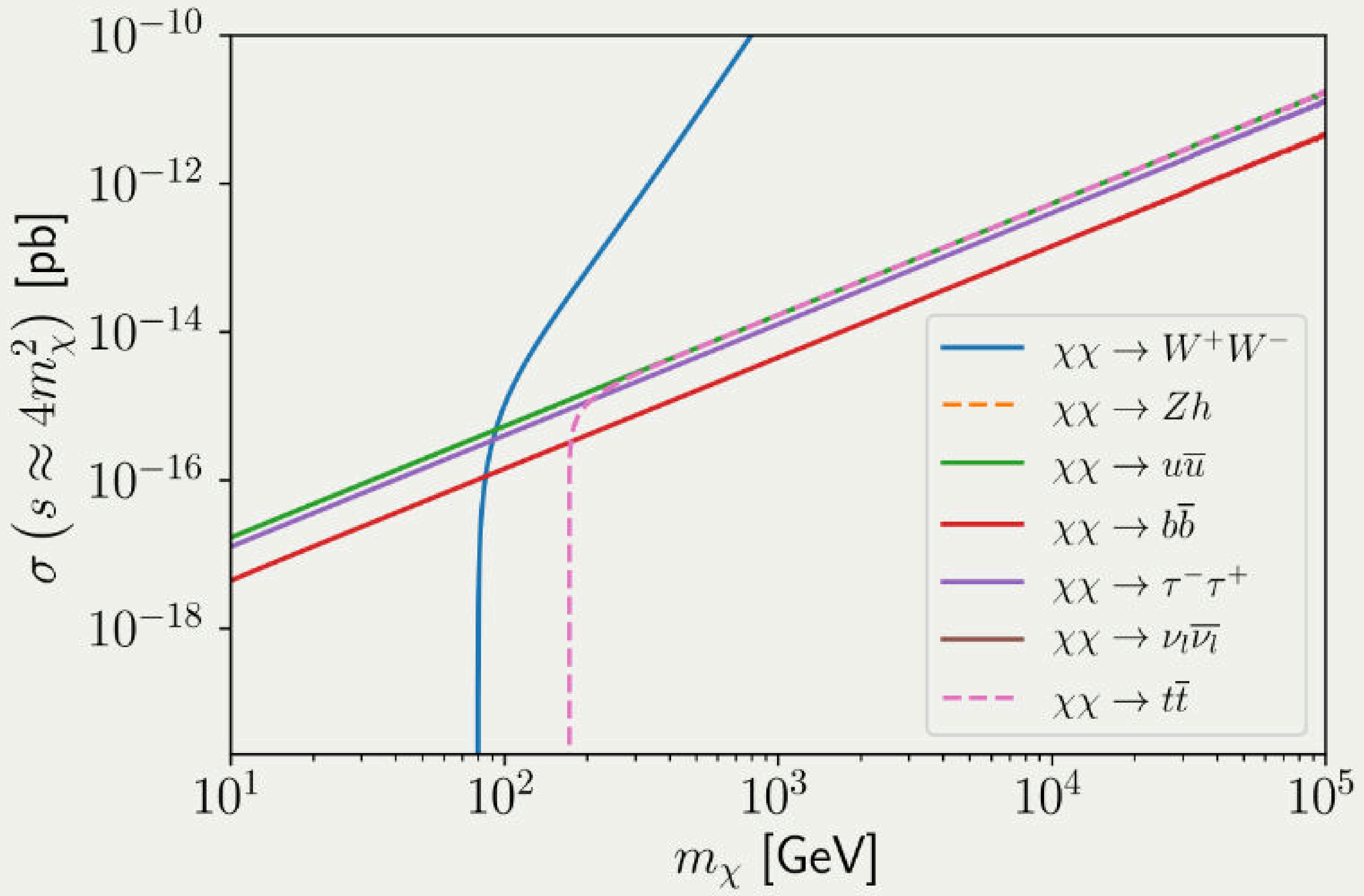


Can we ignore $\chi\chi \to W^+ W^-$?

- Taking the lowest partial wave of the amplitude, we see unitarity violation at

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

- Now since EFTs make use of non-local operators, unitarity isn't preserved for all s.
- For the electromagnetic anapole unitarity violation occurs below the cutoff at failry low values.



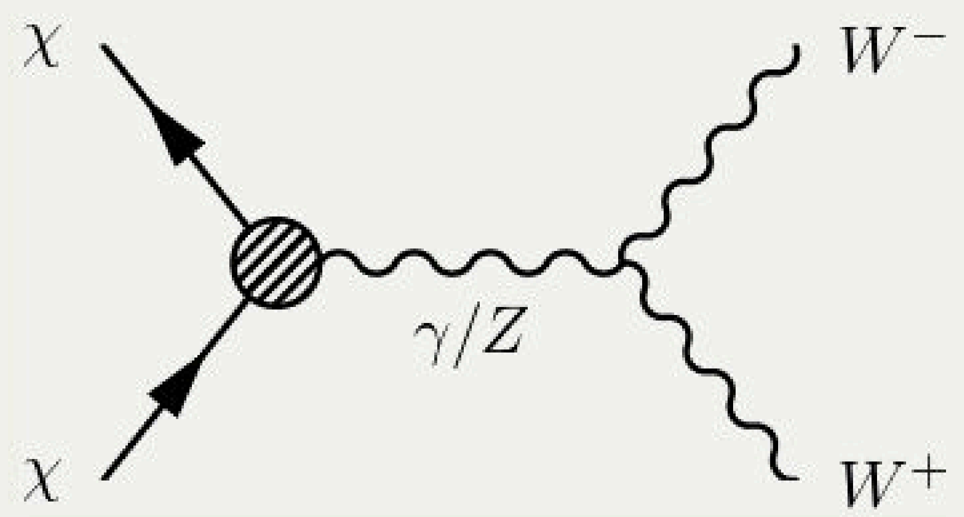
$$\Lambda \gtrsim \frac{1.7\text{TeV}}{\sqrt{C_{\mathcal{A}}^{\gamma}}}$$

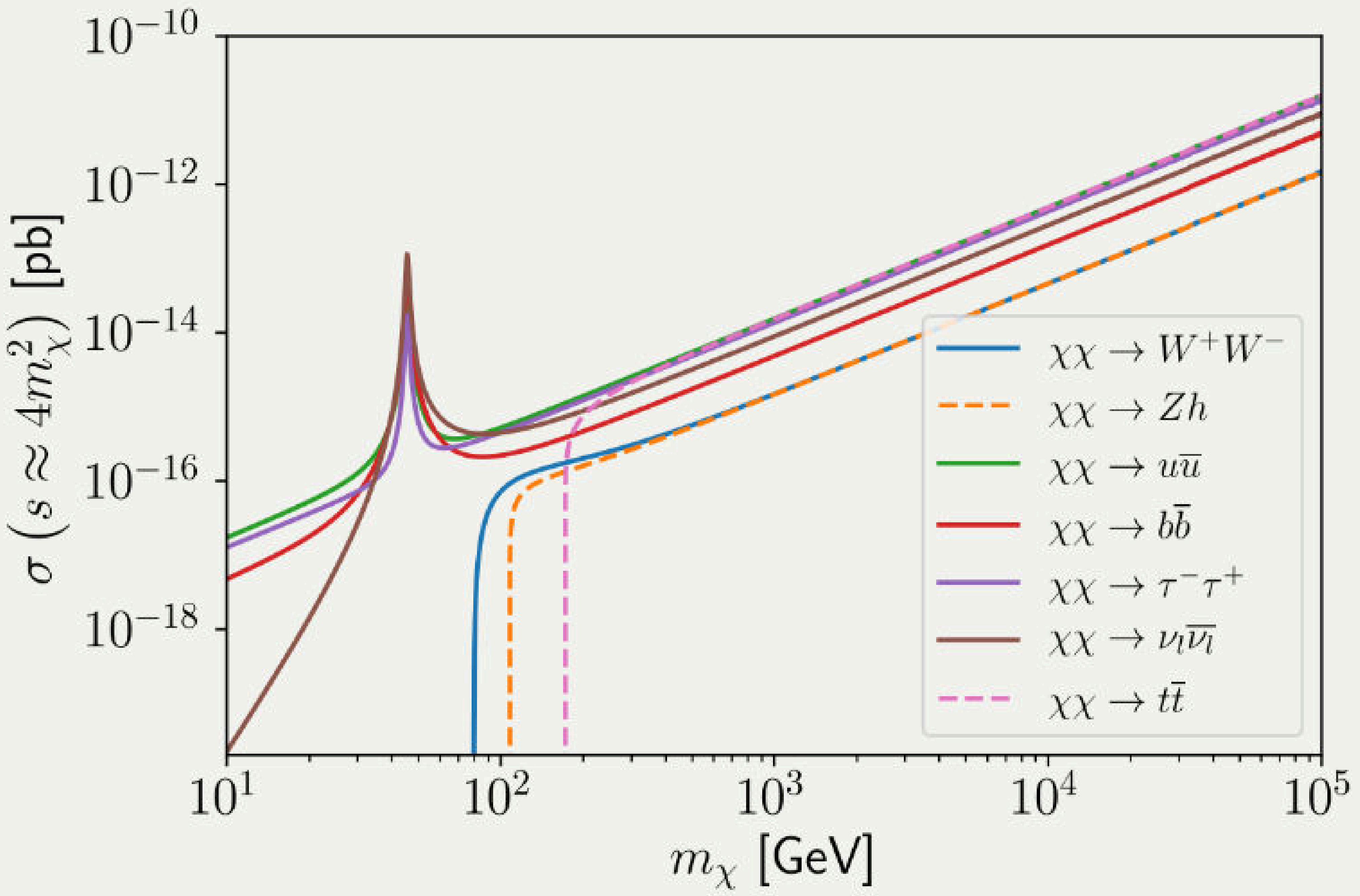
The solution we already knew

- 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

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

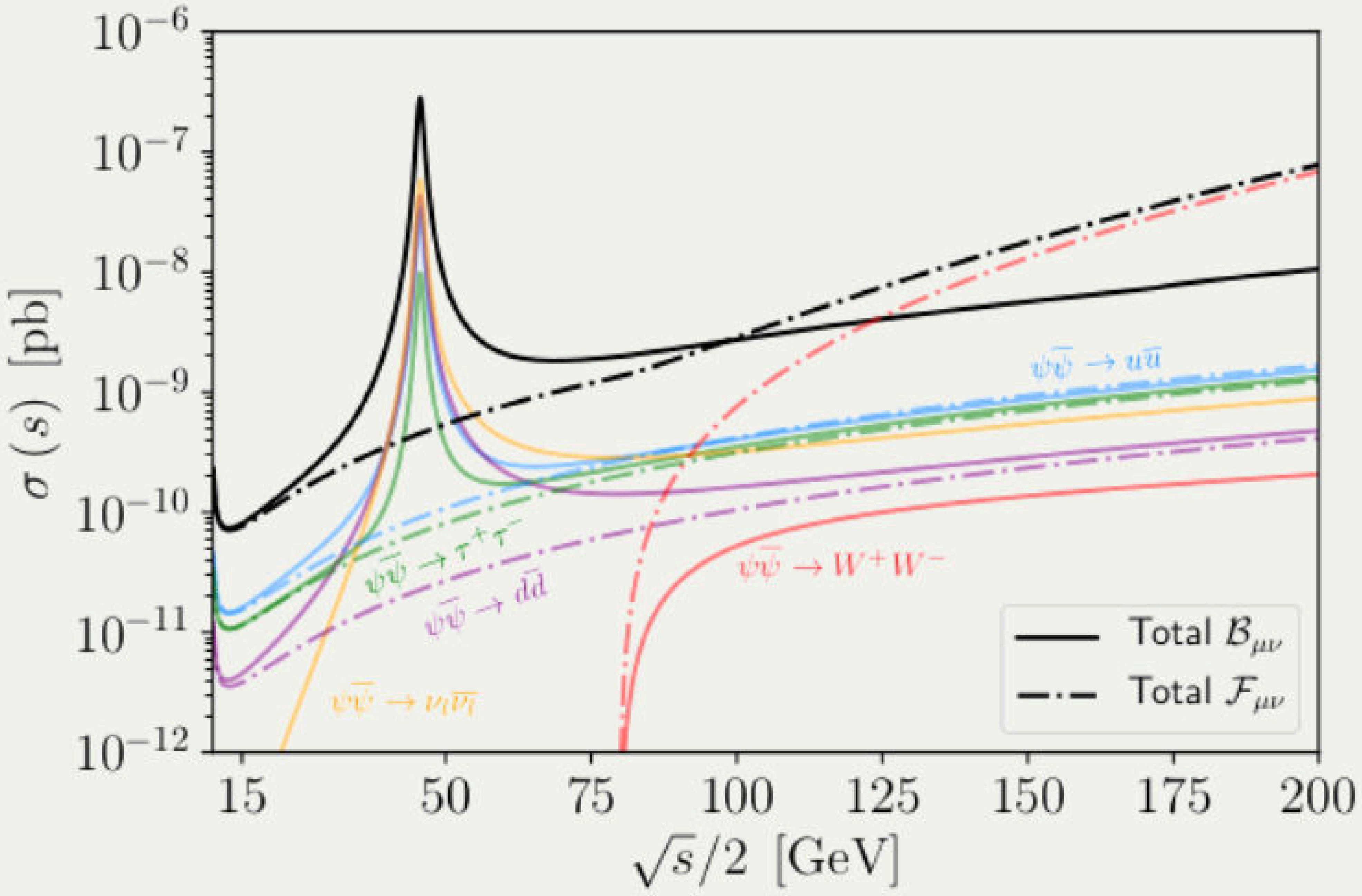
- So... can we ignore $\chi\chi \to W^+W^-$?





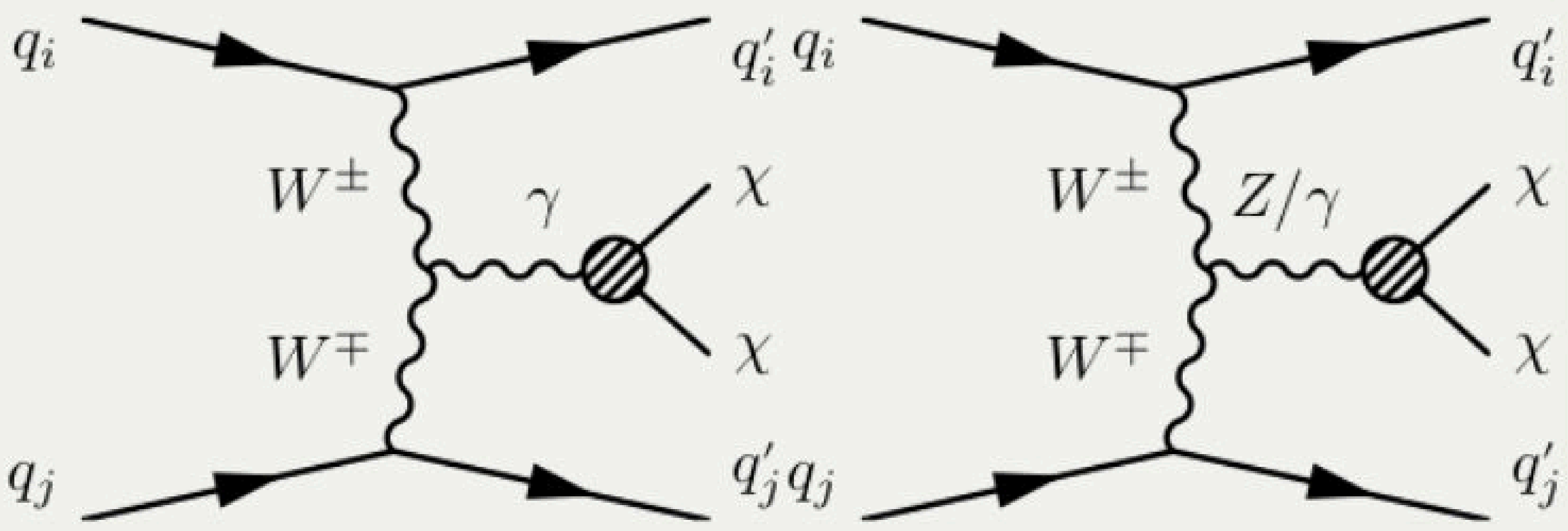
Not really

- So in a sense to ignore the W^+W^- effects isn't so dramatic for high DM masses.
- However, the necessity for the Z has 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.

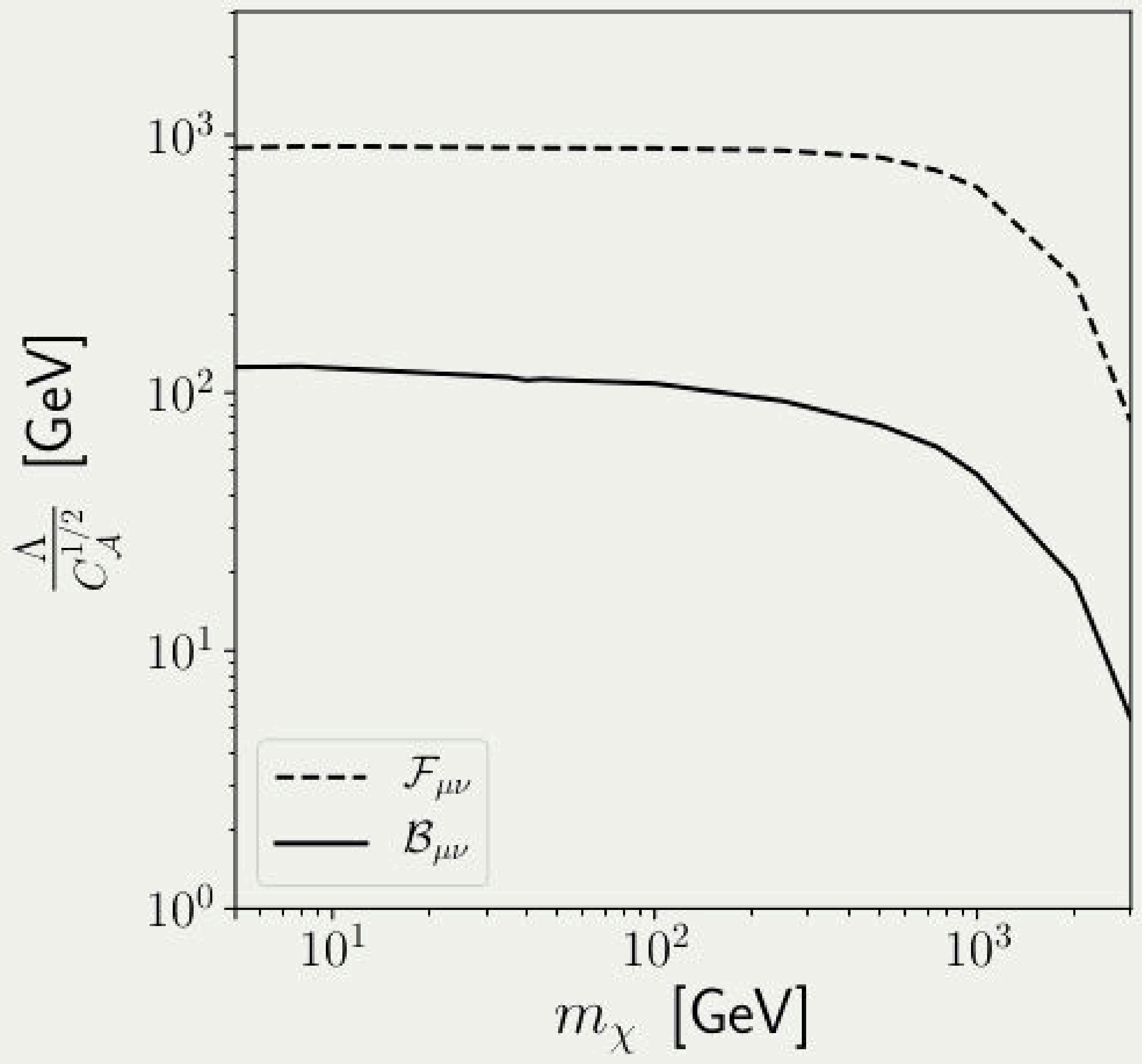


VBF signals are once again sub-dominant

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



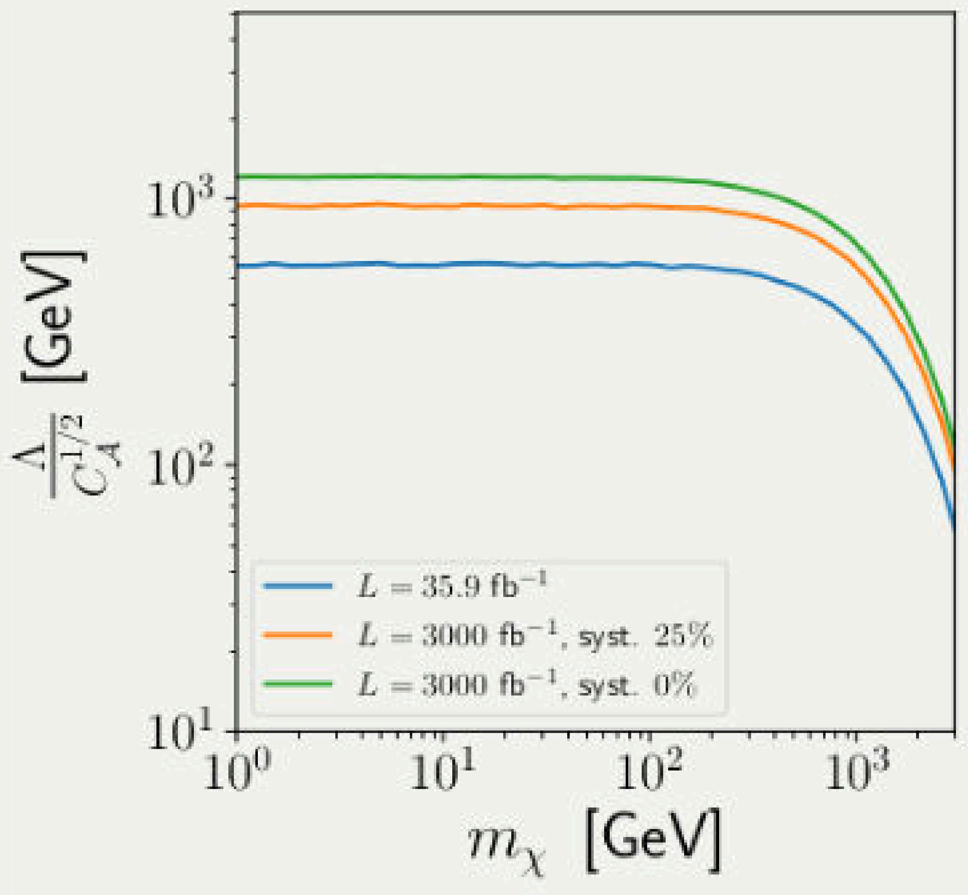
- Of course with the Z included, the VBF constraints are much worse.



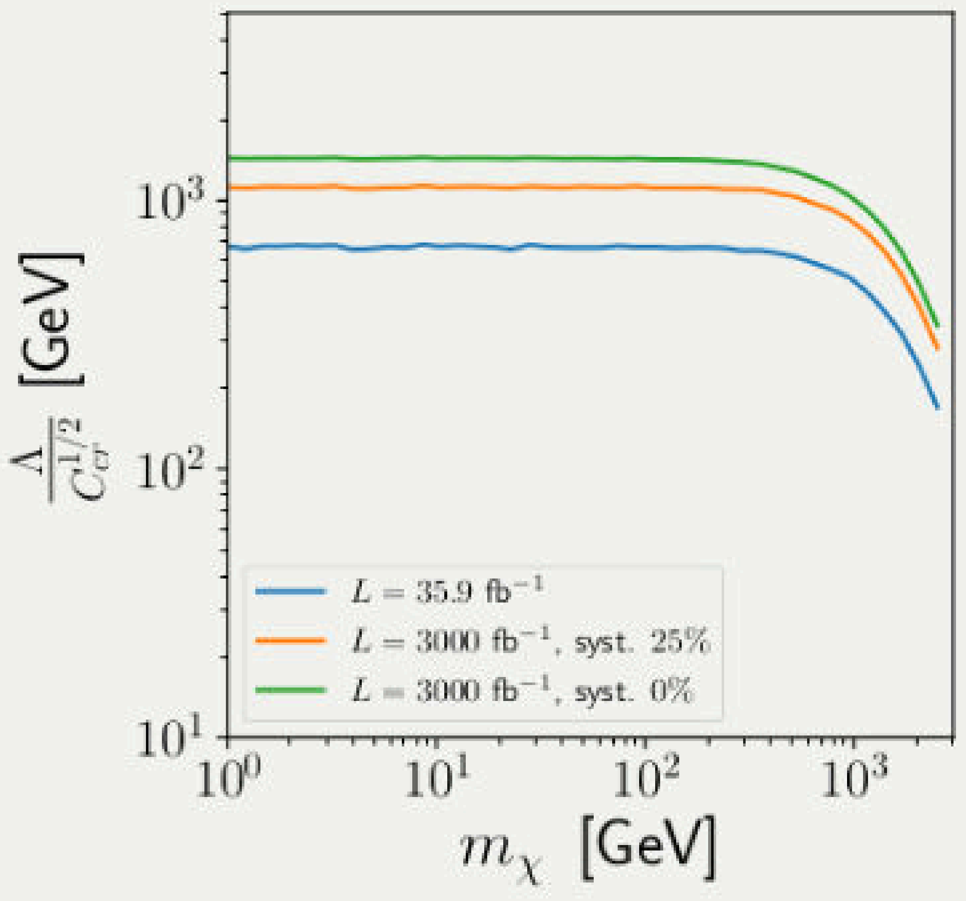
- So monojet MET is probably still the best signal to look for.

Monojet result

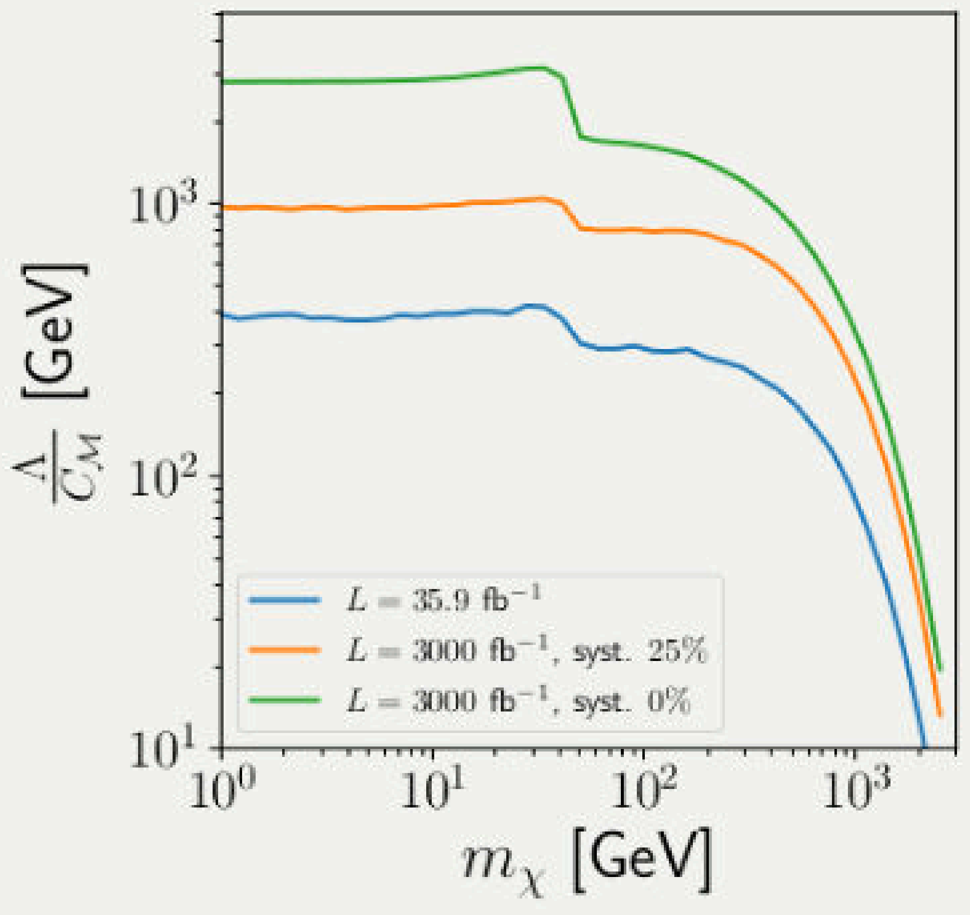
B Anapole



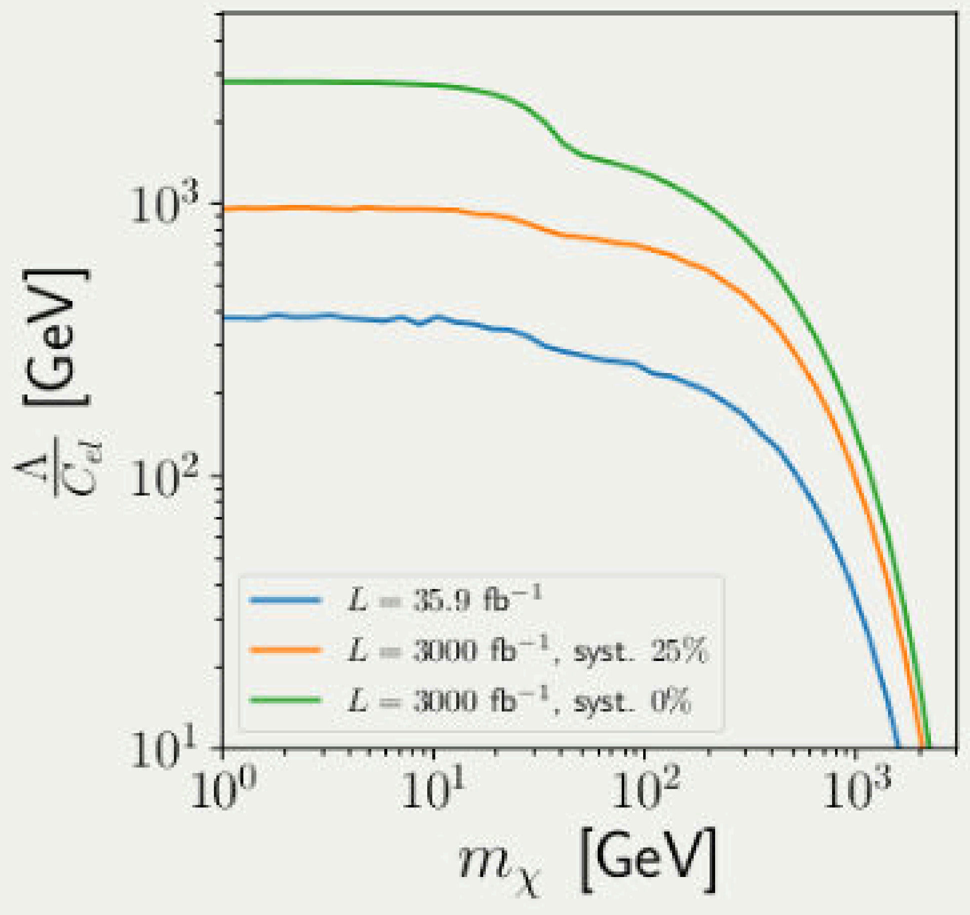
B Charge-radius



B Magnetic dipole



B electric dipole



EFT validity is something to be careful of

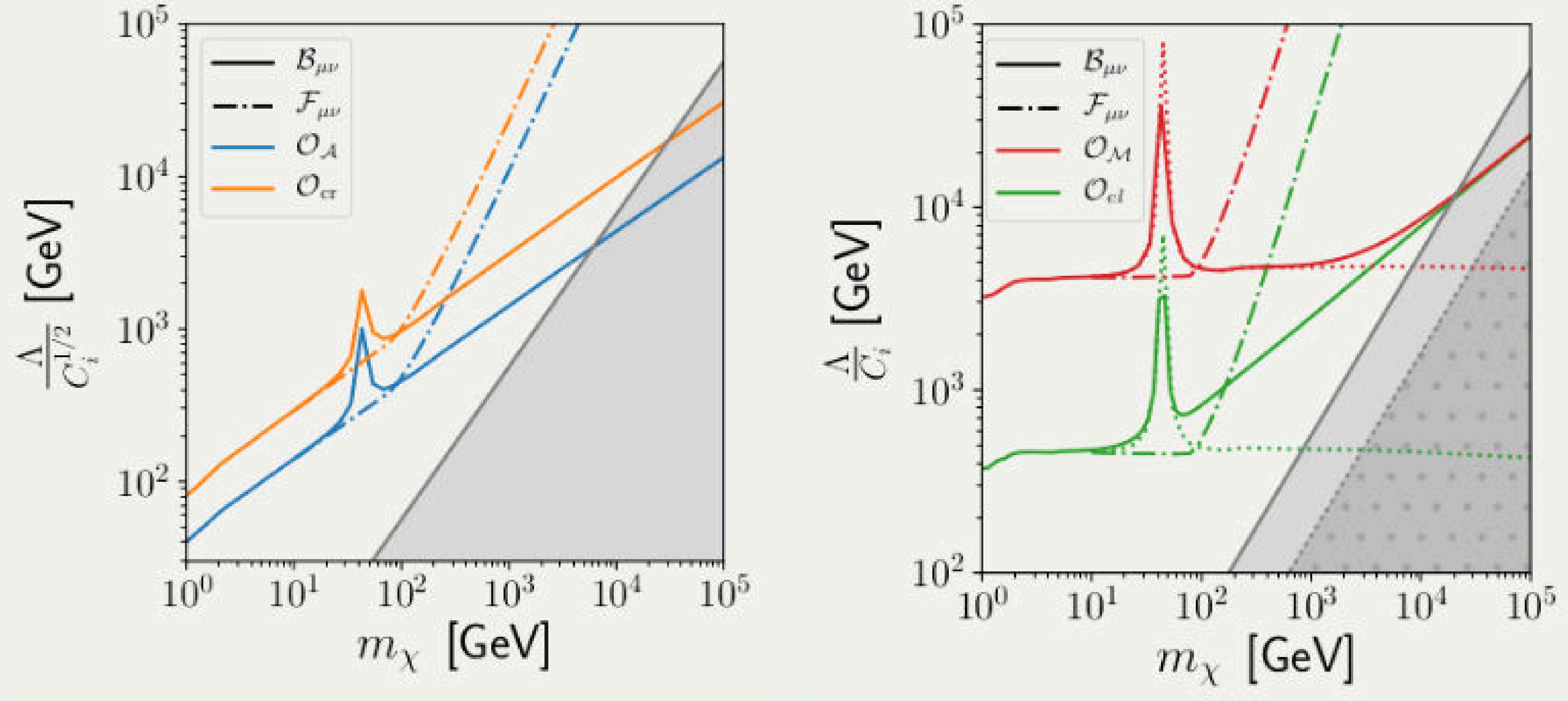
- We need to be sure that our proccess is sufficiently below Λ.
- Since constraints only apply to C/Λ^n, you are technically safe up to a point.
- Naively we can require $\Lambda > p_{\mathrm{T}}^{\max}$ and recast $C/\Lambda^n <$ limit, to get

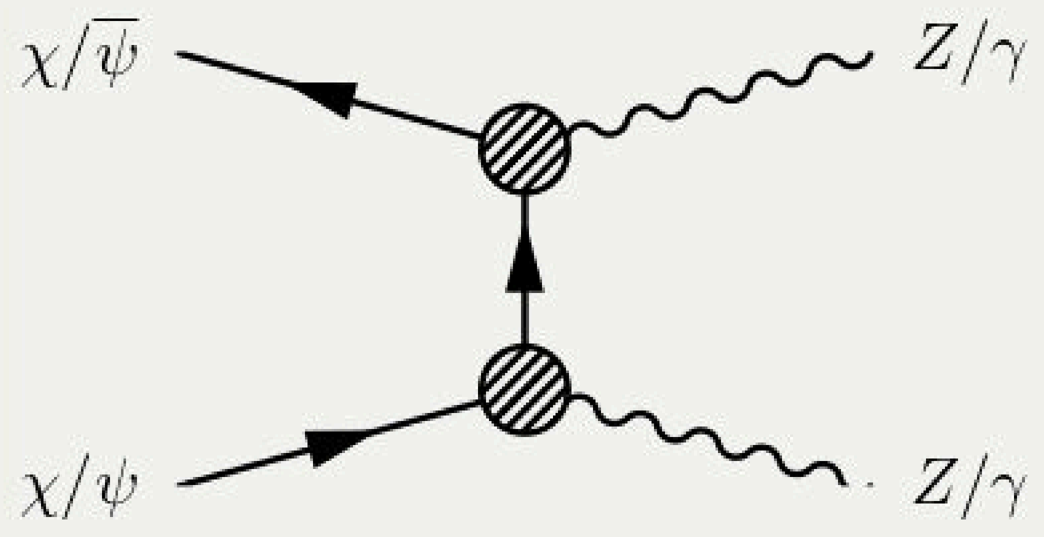
$$C_j > \left(\frac{\text{max bin}}{\text{limit}}\right) \quad \text{and} \quad C_j > \left(\frac{\text{max bin}}{\text{limit}}\right)^2$$

- Roughly this gives $C > \mathcal{O}(1)$ for the current monojet constraints.
- But perhaps one could push this down by analysing the signal a little bit.

Astroparticle constraints

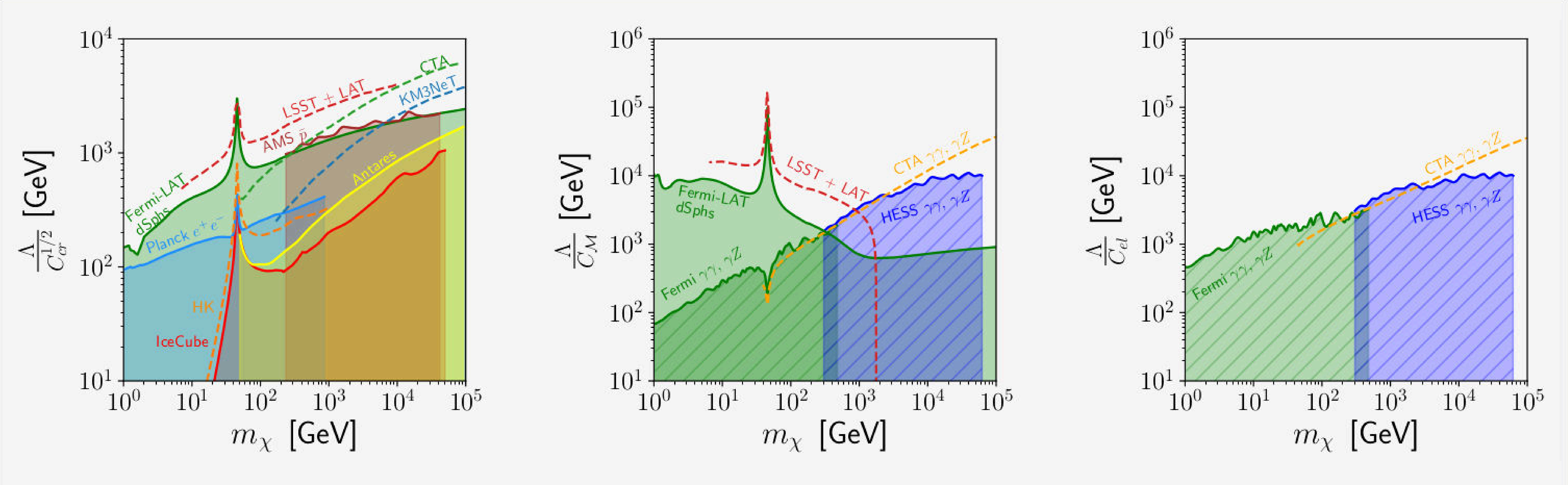
- A customary first calculation for any dark matter study is to check whether it was ever in thermal equilibrium and what happens with freeze-out.
- We were no different.
- Naive perturbative unitarity
$$\frac{C_5}{\Lambda}\sqrt{s} \leq 4\pi, \quad \text{and} \quad \frac{C_6}{\Lambda^2} s \leq 4\pi.$$
- Actually considering the dimension 5 interaction up to dimension 6 though!





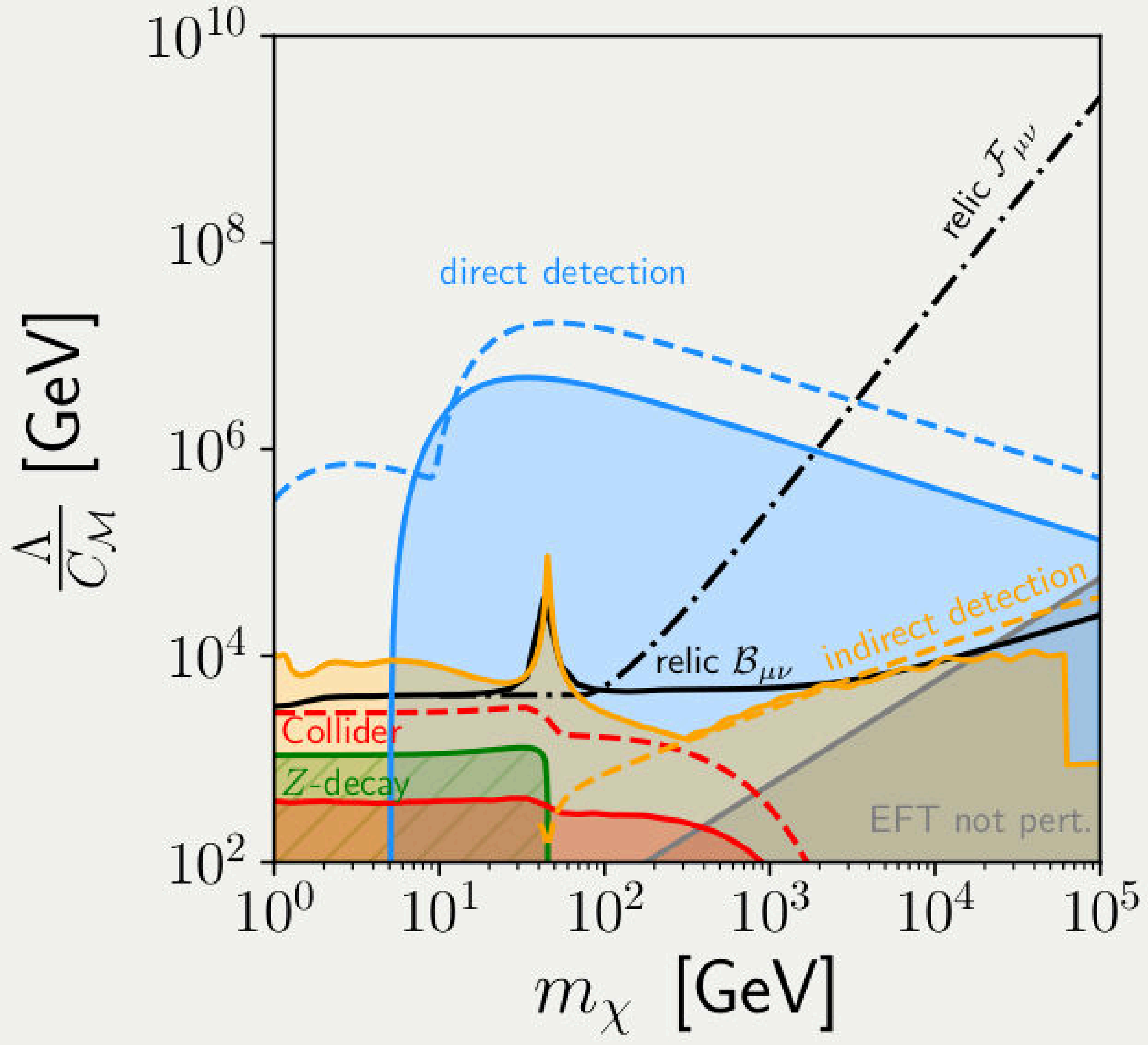
Indirect limits

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

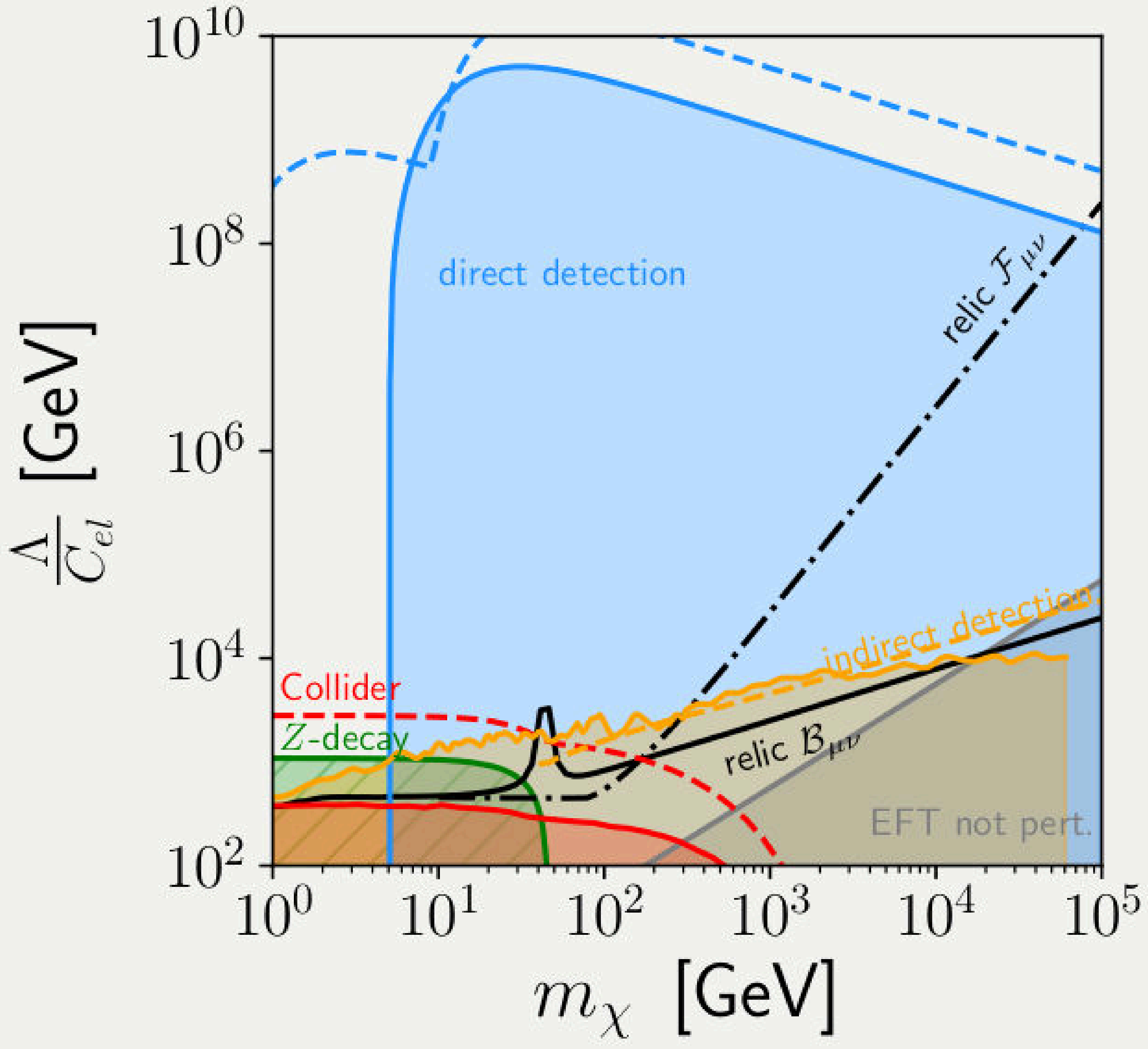


Global Results

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

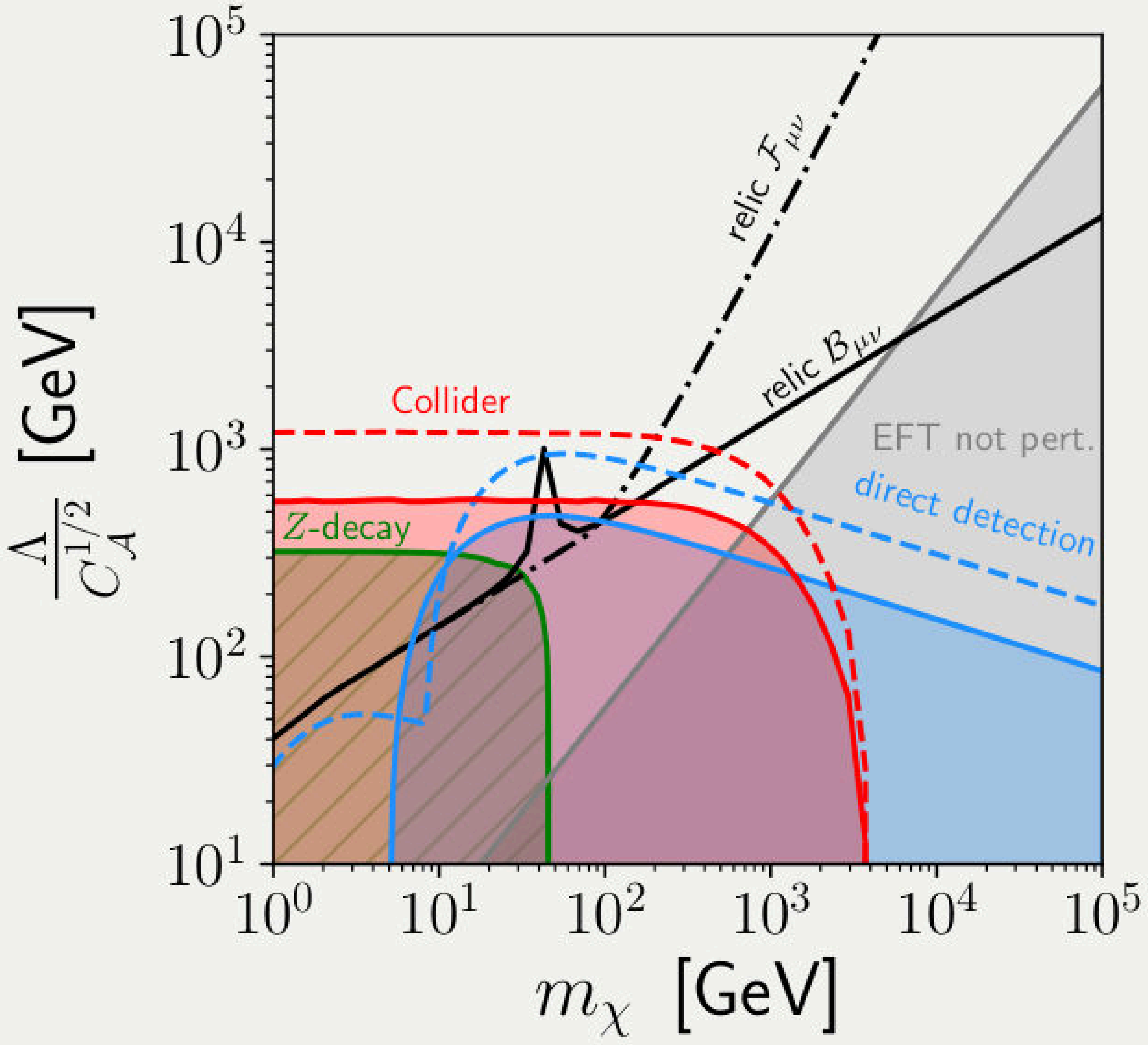


$$\frac{\mathcal{C}_{el}}{2\Lambda}i\bar{\psi}\sigma^{\mu\nu}\gamma^5\psi \cdot B_{\mu\nu}$$

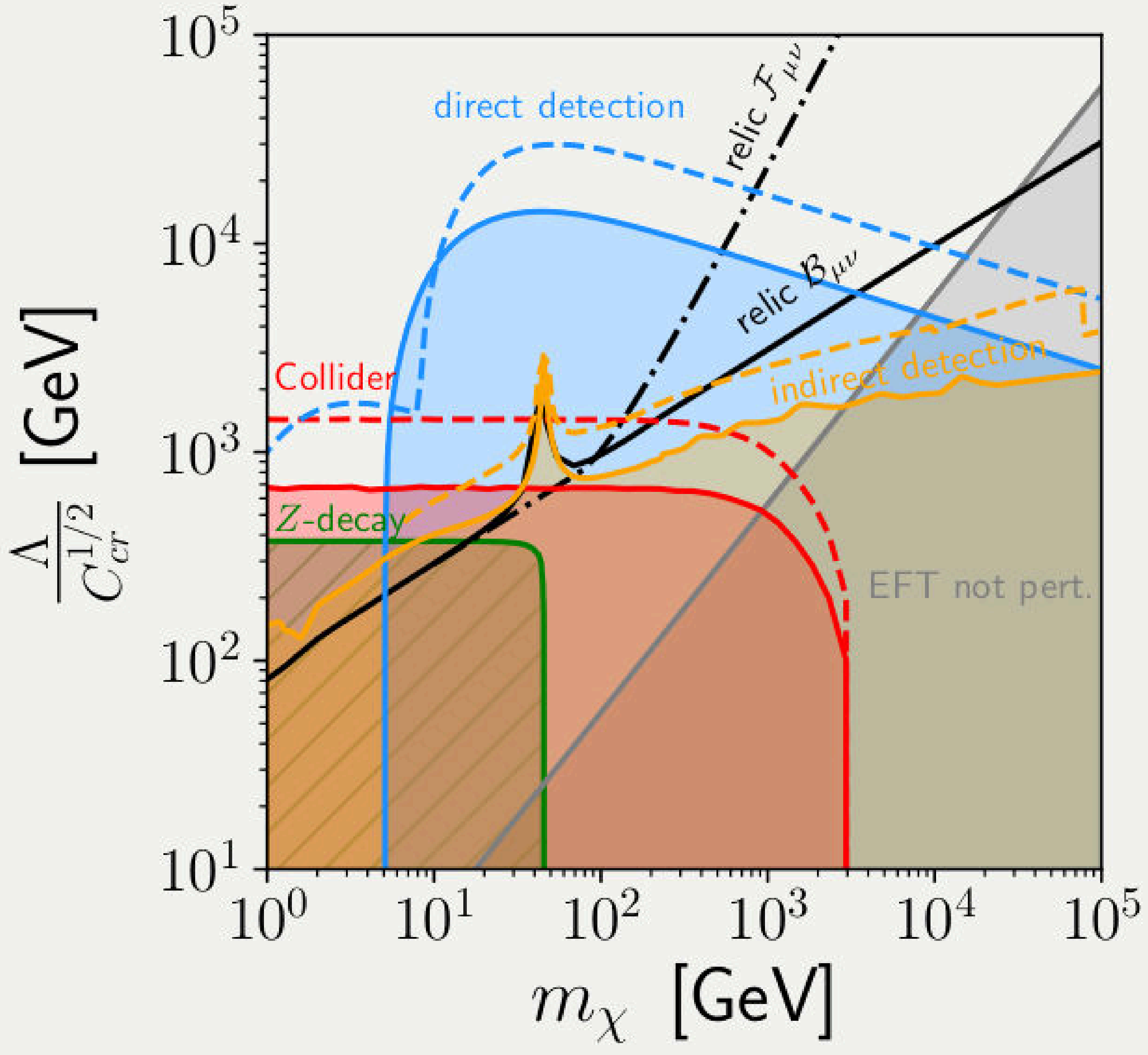


Global Results

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



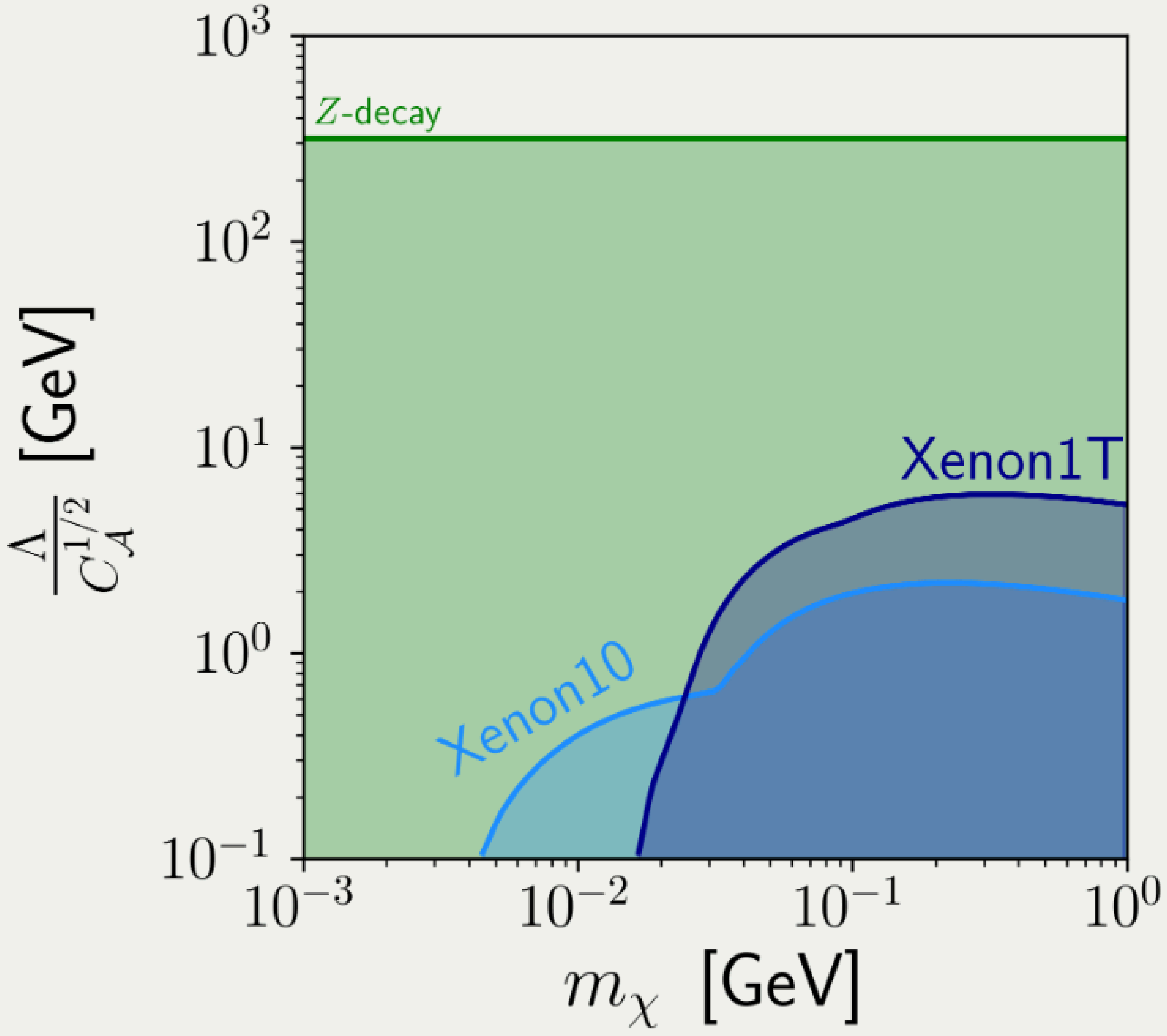
$$\frac{C_{cr}}{\Lambda^2}\bar{\psi}\gamma^{\mu}\psi\cdot\partial^{\nu}B_{\mu\nu}$$



Implications for light DM mass

- 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

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



Conclusions

- Hopefully I've convinced you that there isn't really 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, so we need to check there.
- Light dark matter experimental collaborations should be aware of these constraints since Z-width can be particularly strong.