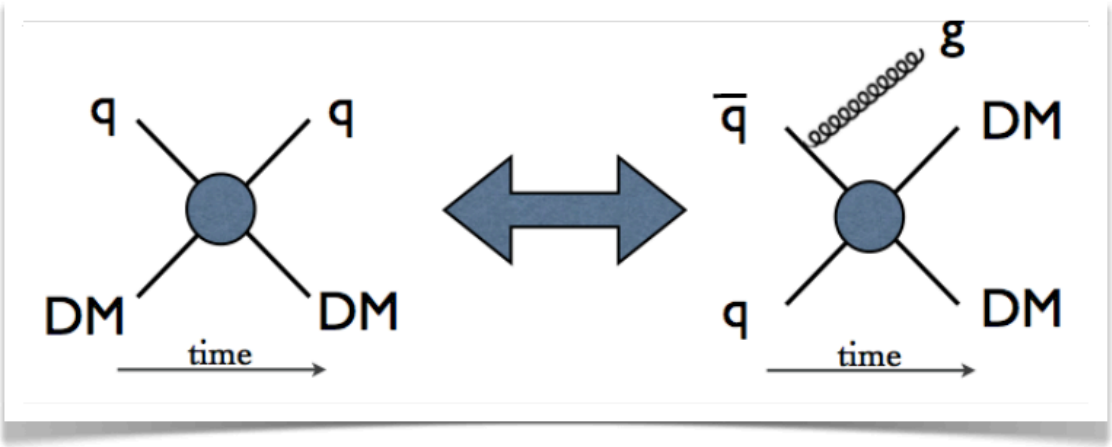
7th SYMPOSIUM ON LARGE TPCs FOR LOW-ENERGY RARE EVENT DETECTION



Oliver Buchmueller, Imperial College London

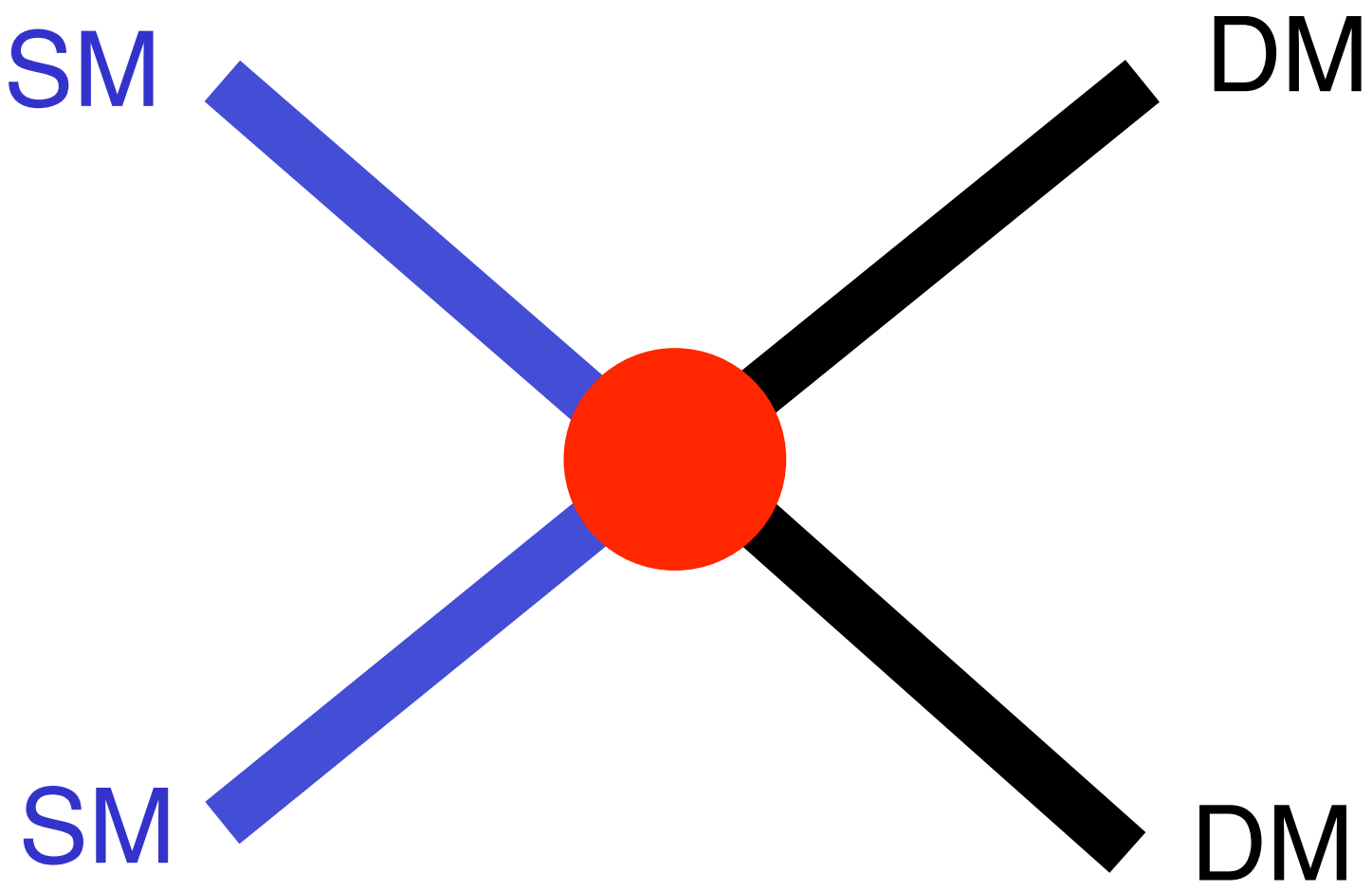
# DARK MATTER SEARCHES: COMPLEMENTARITY OF COLLIDER AND DIRECT DETECTION EXPERIMENTS



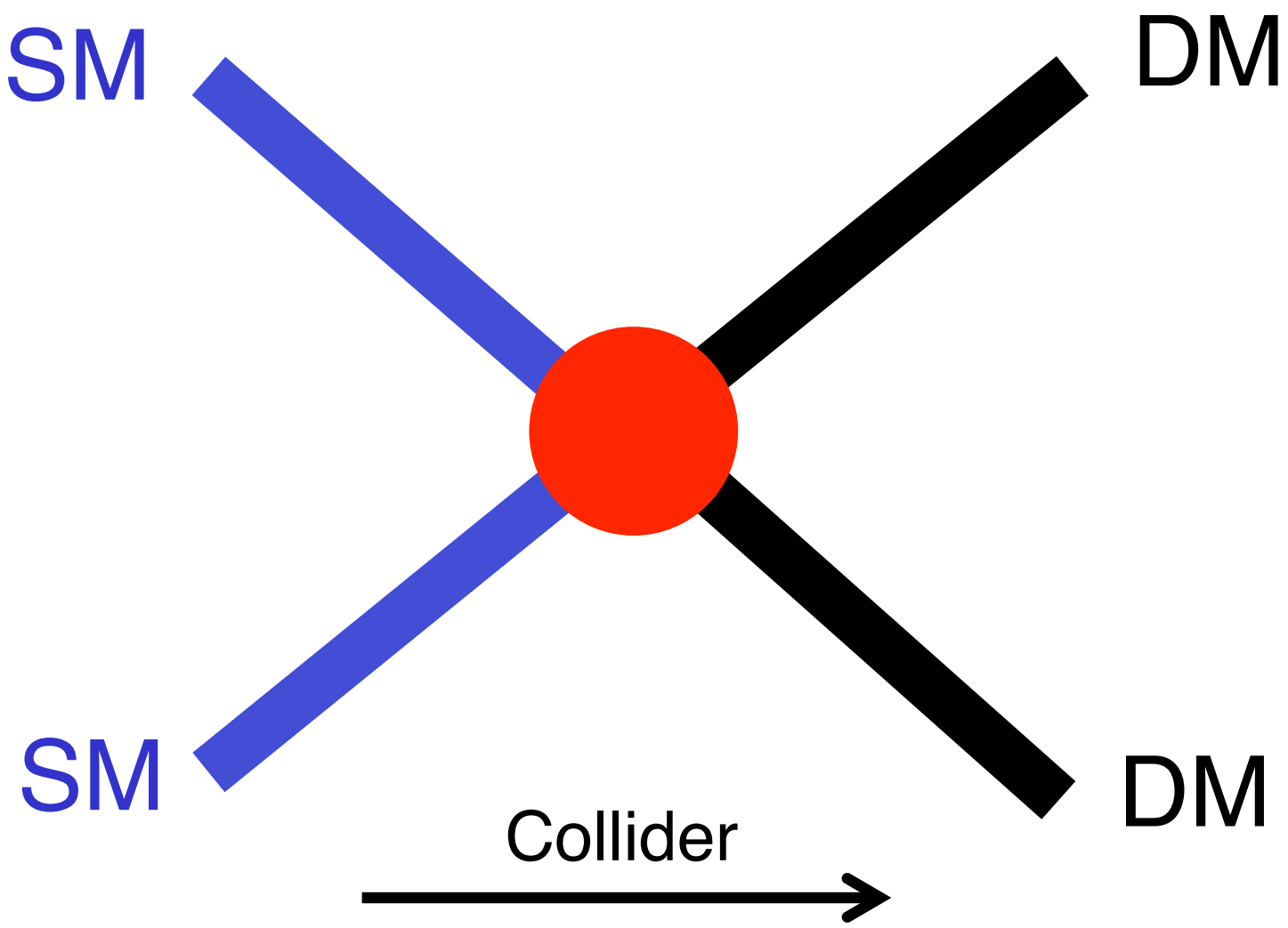
Imperial College London

# Landscape of Dark Matter Searches

# Dark Matter Searches



# Dark Matter Searches



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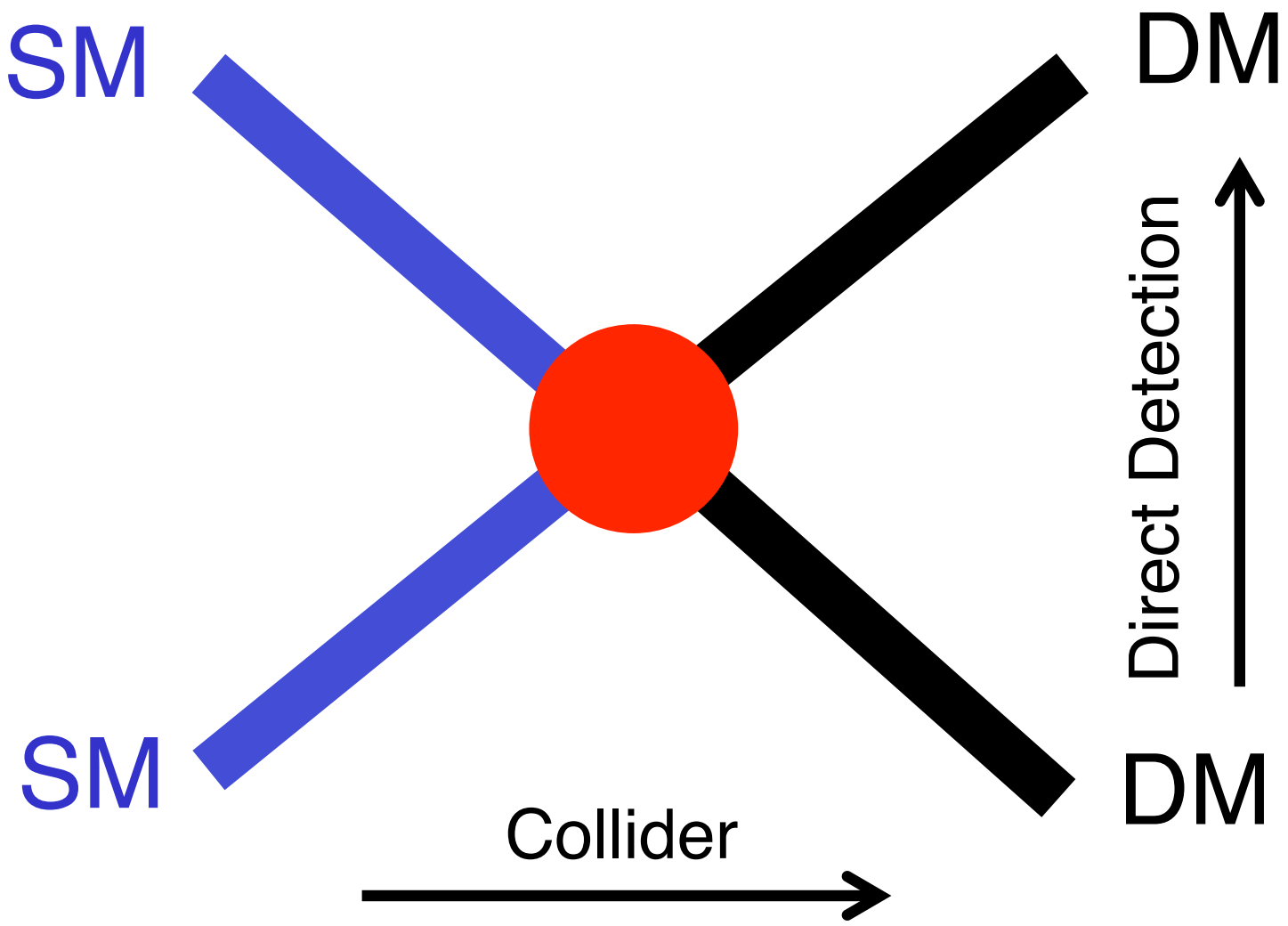

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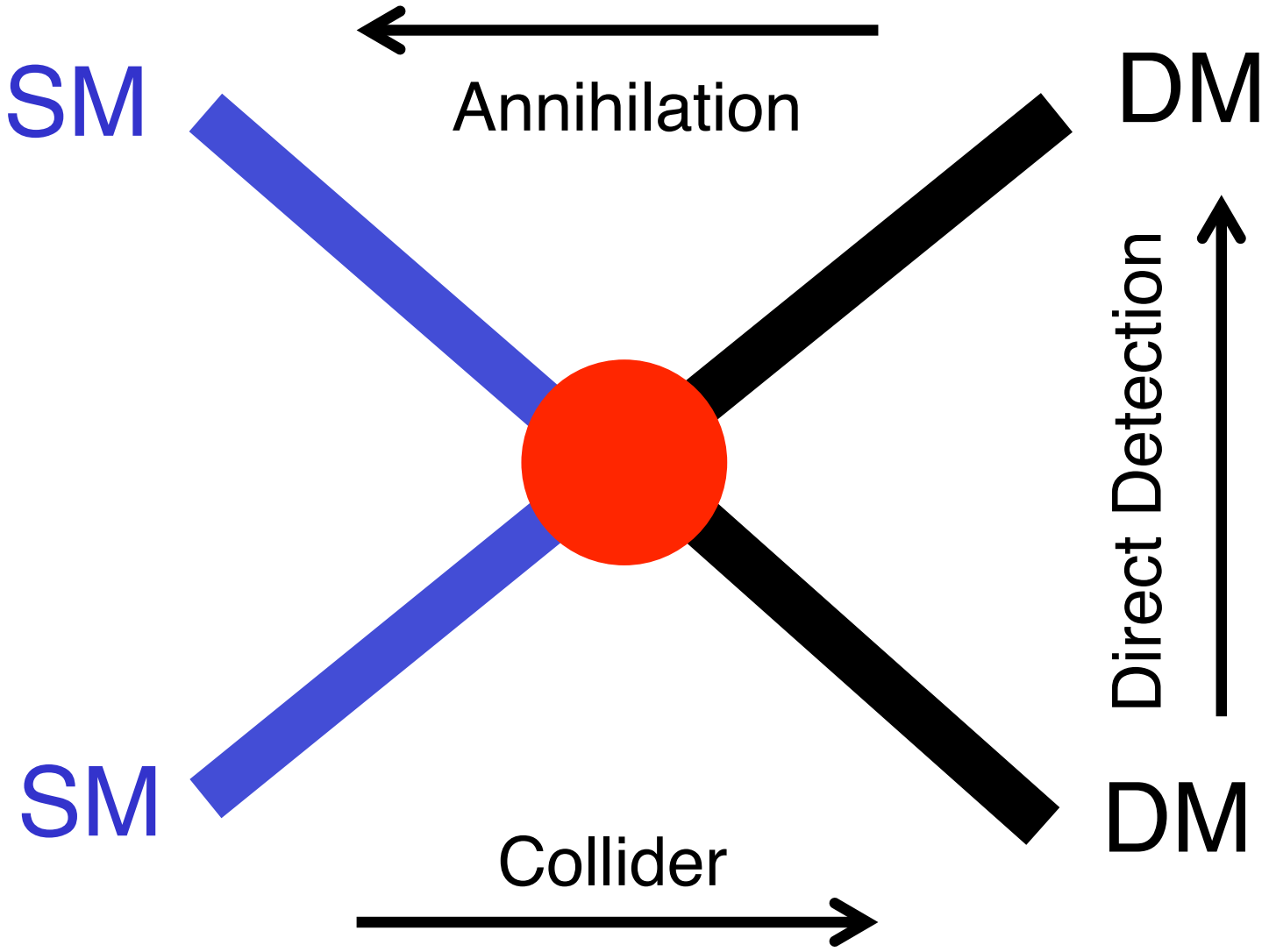
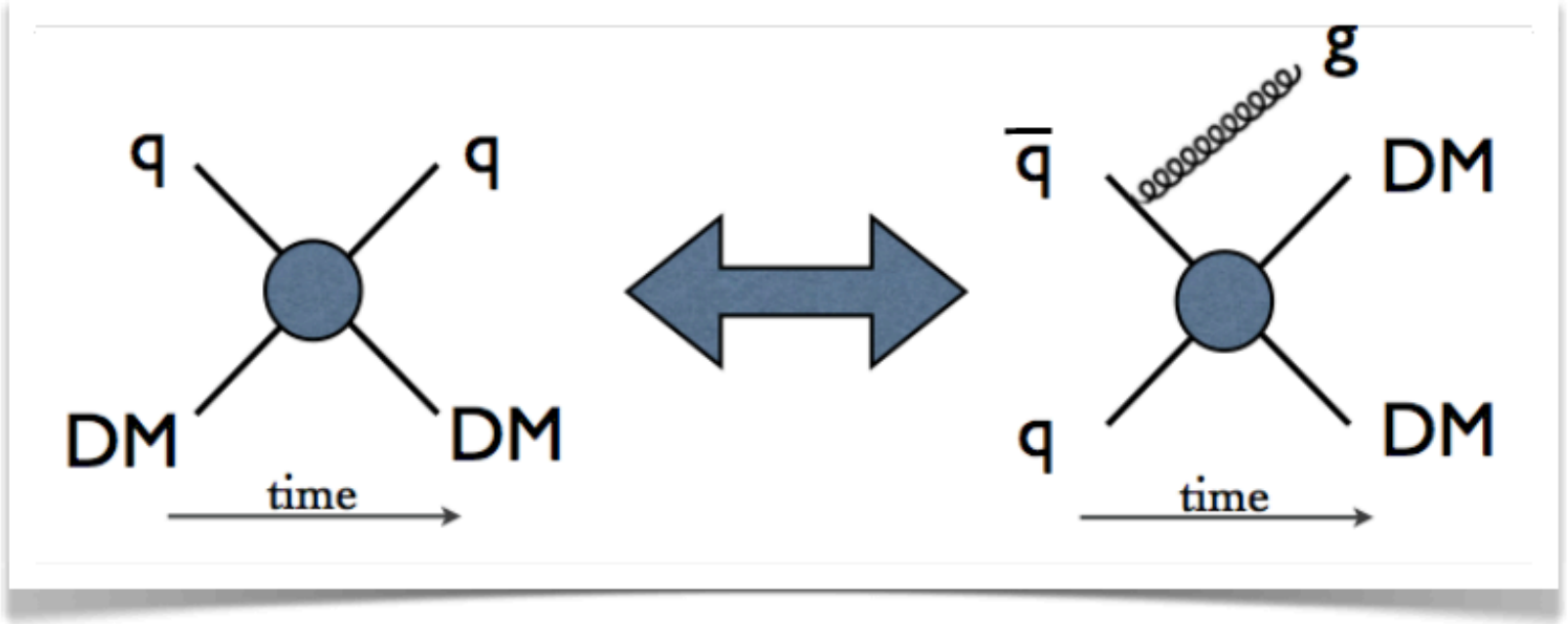
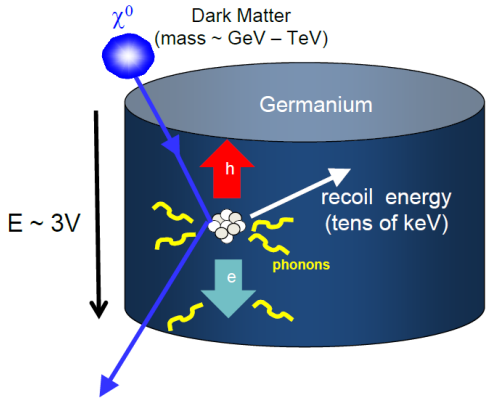


# Dark Matter Searches: Direct Detection vs Colliders



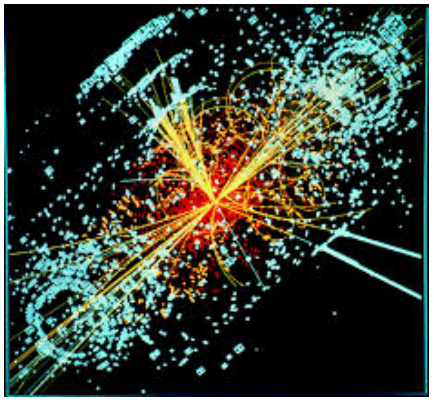

## *Direct Detection Experiments*

- DM-nucleus scattering



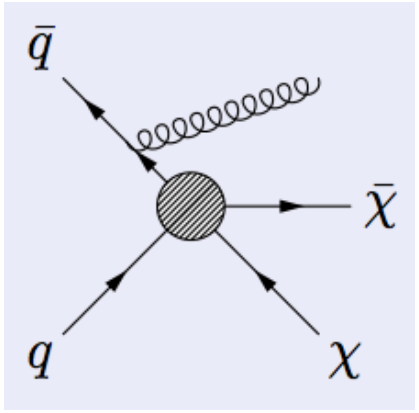

## *Collider Experiments*

- Pair-production of DM
- missing energy signature

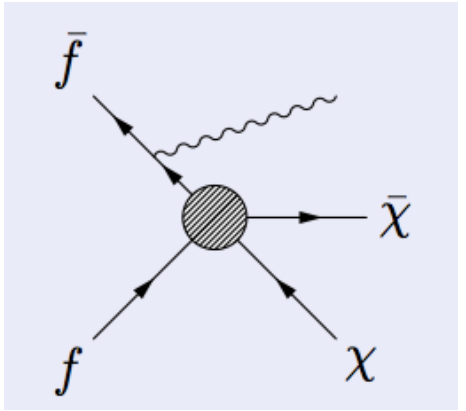


# Monojet and Monophoto (plus $E_T^{miss}$)

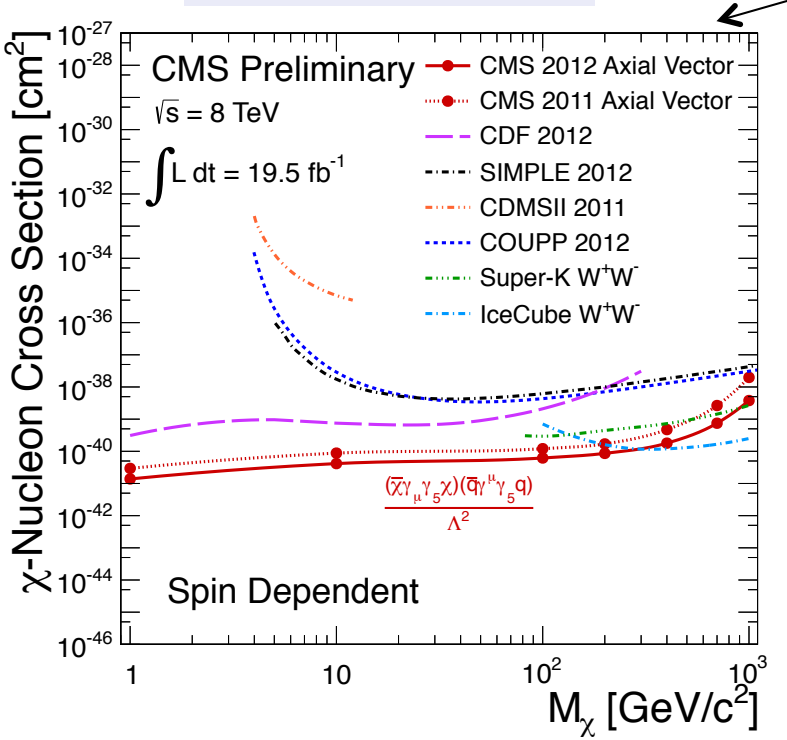
## Monojet: hard jet + $E_T^{miss}$

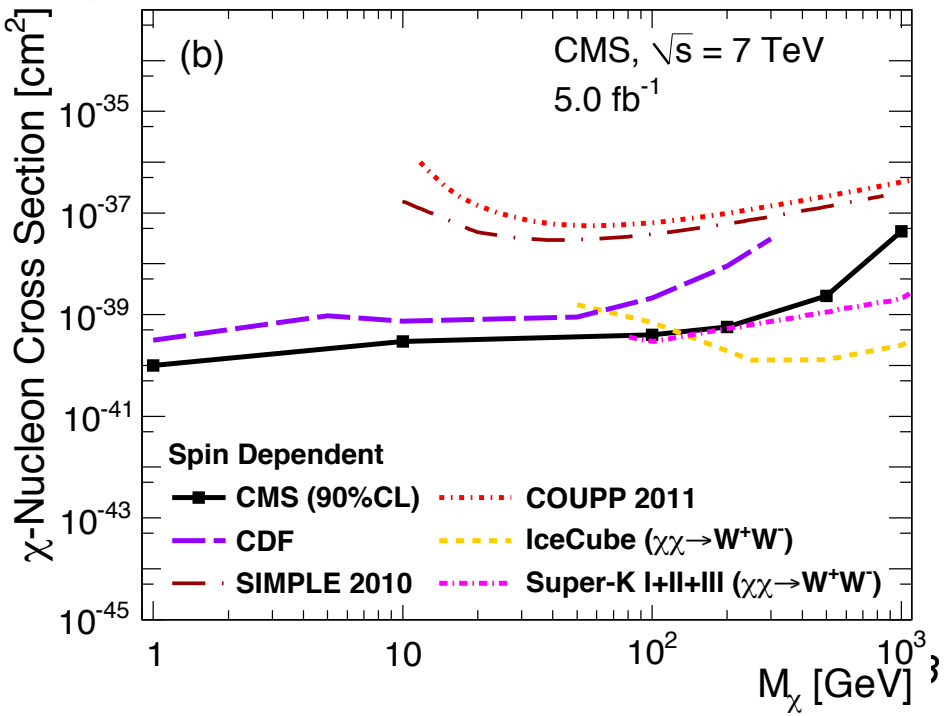



## Monphoton: hard photon + $E_T^{miss}$

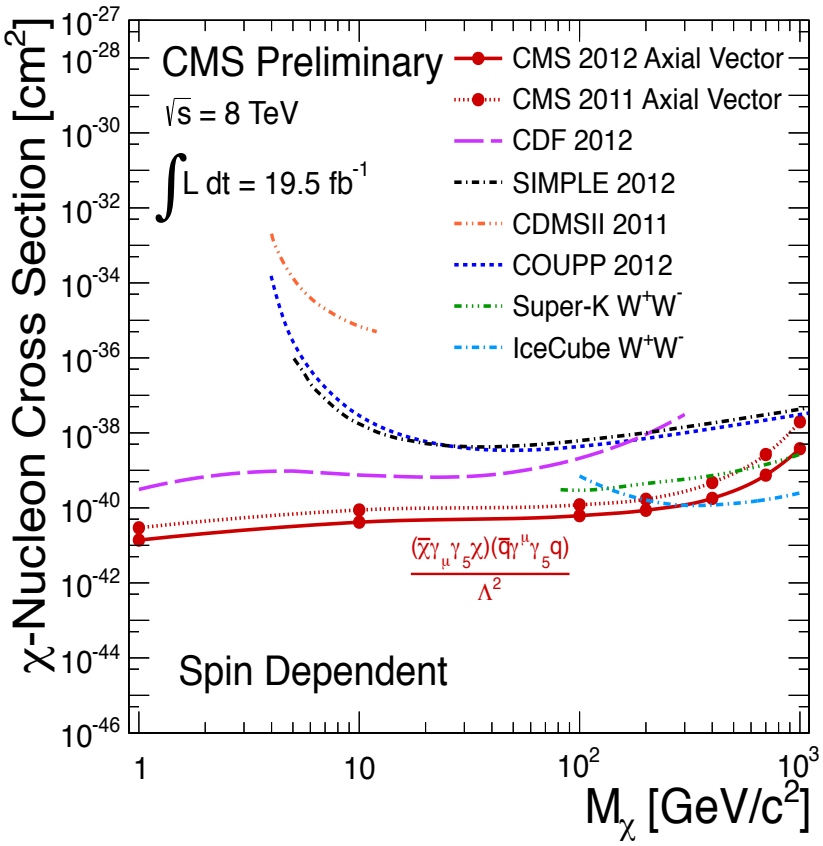


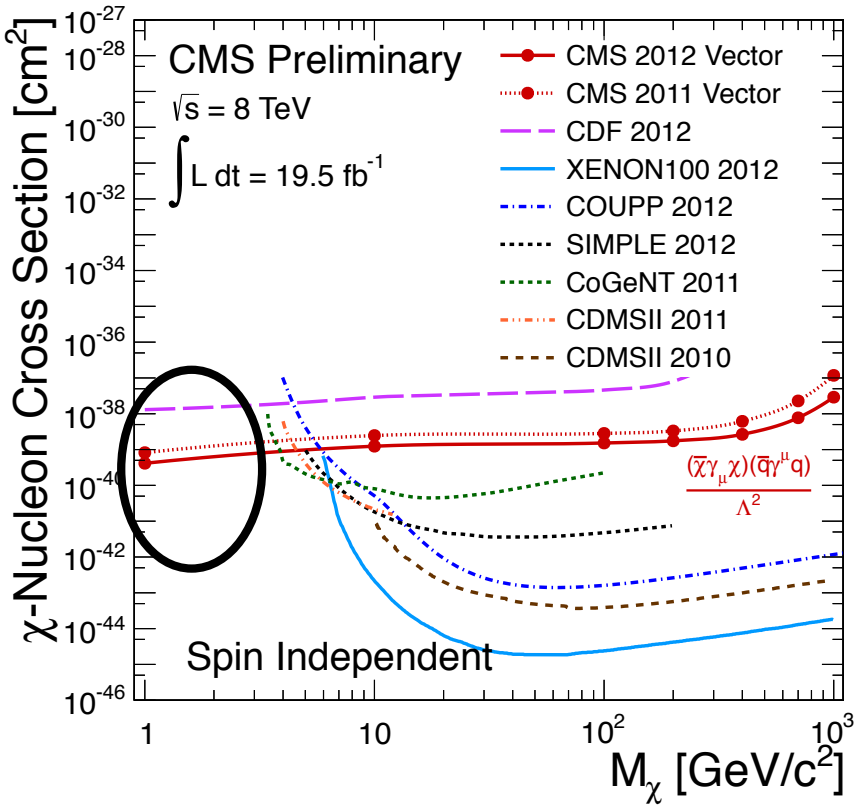

Note different y scale



# Monojet analyses better than direct detection?!



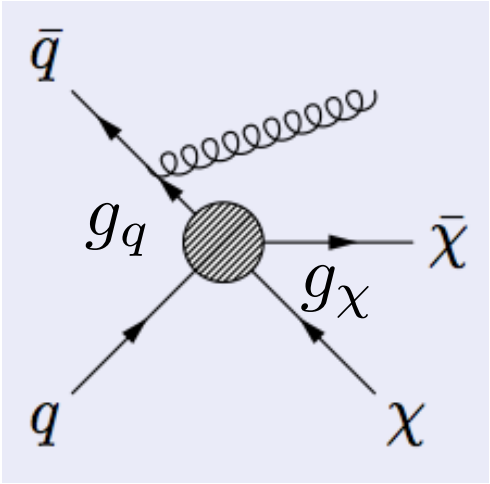




Claim [often made]:
For low mass and the entire spin-dependent case monojet limits are stronger than direct detection limits!

# Effective Field Theory (EFT) Interpretation

Example of considered operators:

$$O_V = \frac{(\bar{\chi}\gamma_\mu\chi)(\bar{q}\gamma_\mu q)}{\Lambda^2}$$ Vector operator, s-channel




$$O_{AV} = \frac{(\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{q}\gamma_\mu\gamma_5 q)}{\Lambda^2}$$ Axial vector operator, s-channel

**Assumption of EFT**

If the operator (e.g. V or AV) mediator is suitably(!!) heavy it can be integrated out to obtain the effective V or AV contact operator. In this case (and only this case), the contact interaction scale Λ is related to the parameters entering the Lagrangian:

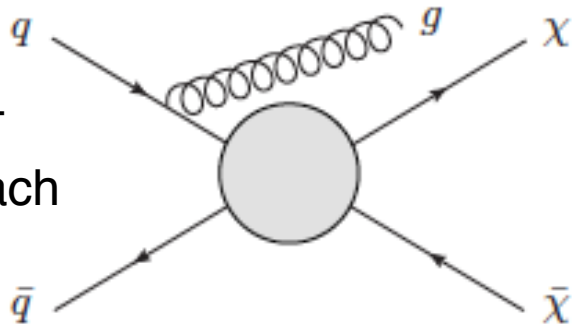
$$\Lambda = \frac{M_{mediator}}{\sqrt{g_q g_\chi}}$$ (relation in the full theory)

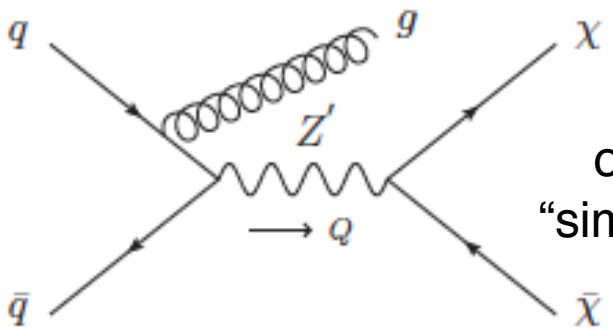
# Validity of Effective Field Theory Limits

Recent work from OB, M.Dolan,C.McCabe: arXiv:1308.6799

- Compare Effective Field Theory (EFT) with Full Theory (FT)

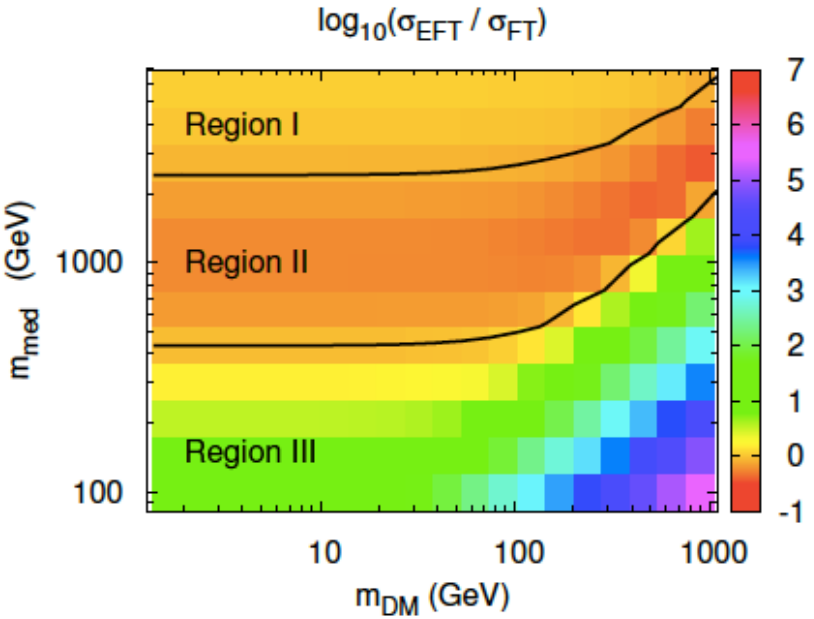
EFT approach




FT
one diagram
"simplified model"

Use vector and axial-vector mediators (e.g. Z' ) as example - scalar are similar in conclusion!




Compare prediction of FT with EFT in $m_{med}$ – $m_{DM}$ plane.
Three regions become visible:

Region I: EFT and FT agree better then 20%

- EFT is valid!

Region II: EFT yields significant weaker limits then FT

- EFT limits are too conservative!

Region III: EFT yields significant stronger limits then FT

- EFT limits are too aggressive!

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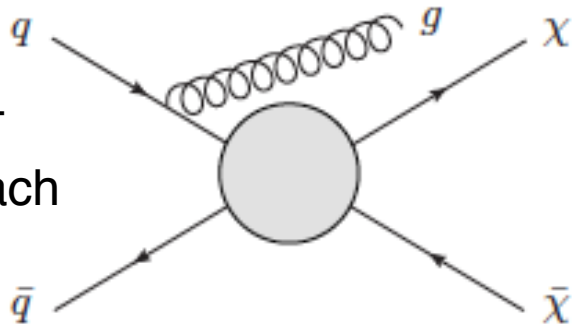


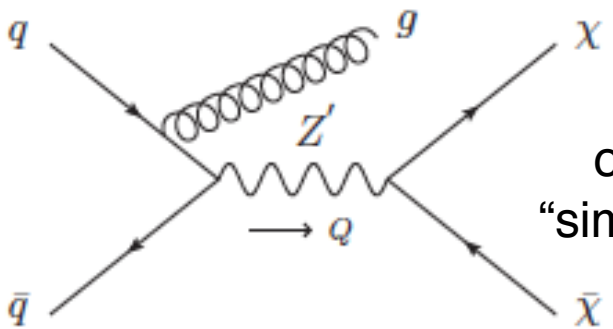


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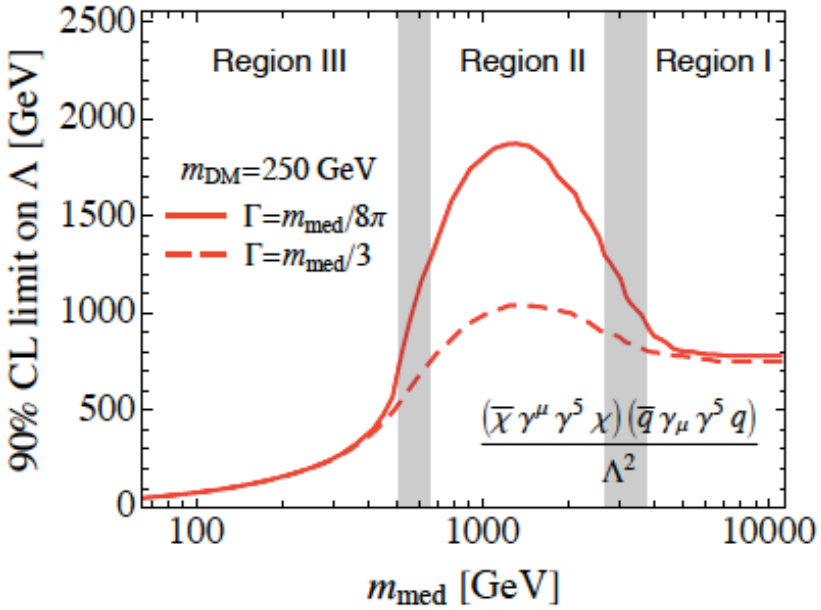


Three Regions as function of mediator mass:

Region I: Heavy $m_{med}$

- EFT is valid!

Region II: Medium $m_{med}$ – Resonant enhancement

- EFT limits are too conservative!

Region III: Low $m_{med}$

- EFT limits are too aggressive!

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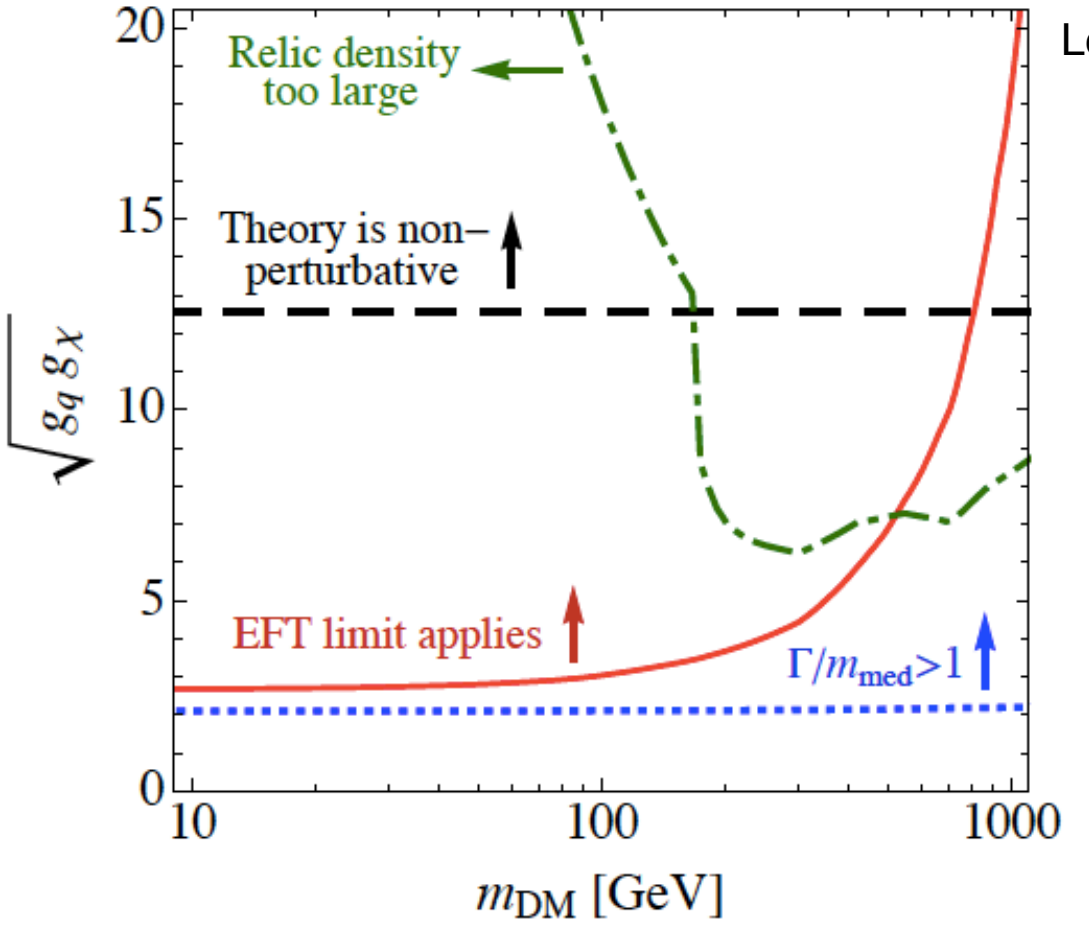
# What those this imply on model-dependences of EFT limits?




Look at EFT validity in $m_{DM}$ – coupling* plane!

* Coupling chose such that CMS EFT limit on Λ applies to FT

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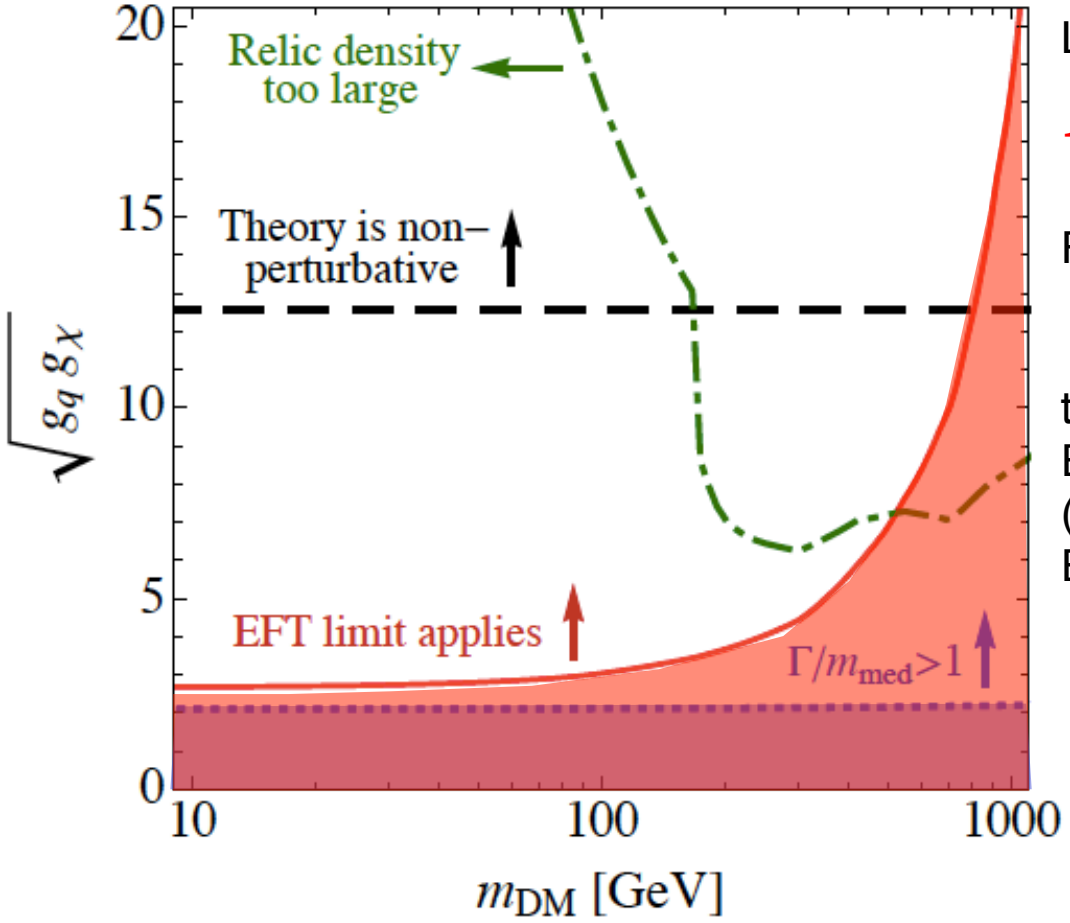
# Model-dependences of EFT limits




Look at EFT validity in $m_{DM}$ – coupling* plane!

1. Region in which EFT is **NOT** valid

For this we calculate the minimum coupling

$$\sqrt{g_q g_\chi} = m_{med}/\Lambda_{CMS}$$

that the simplified model must have for the EFT limits to apply. This is defined by region I (i.e. better then 20% agreement of FT and EFT).

* Coupling chose such that CMS EFT limit on Λ applies to FT

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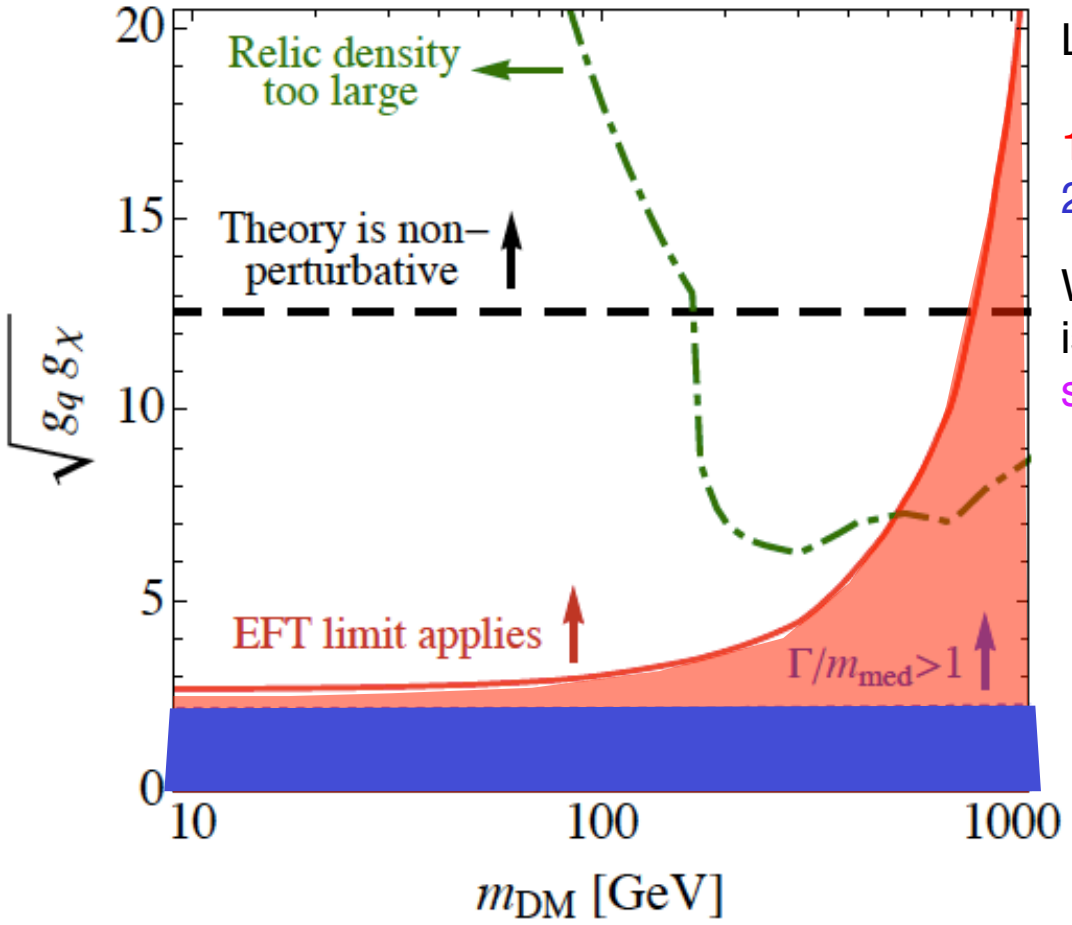
# Model-dependences of EFT limits




Look at EFT validity in $m_{DM}$ – coupling* plane!

1. Region in which EFT is **NOT** valid
2. $M_{med} > \Gamma_{med}$ ALWAYS!

We also find that for all DM models the EFT is valid only IF the mass of the mediator is smaller than its width!

In the reaming part of the plot:

$$\sqrt{g_q g_\chi} > 2$$

a particle-like interpretation of the mediator is doubtful because of $\mathbf{M_{med} < \Gamma_{med}}$ !

See discussion about equation 3.5 in arXiv:1308.6799 for further details.

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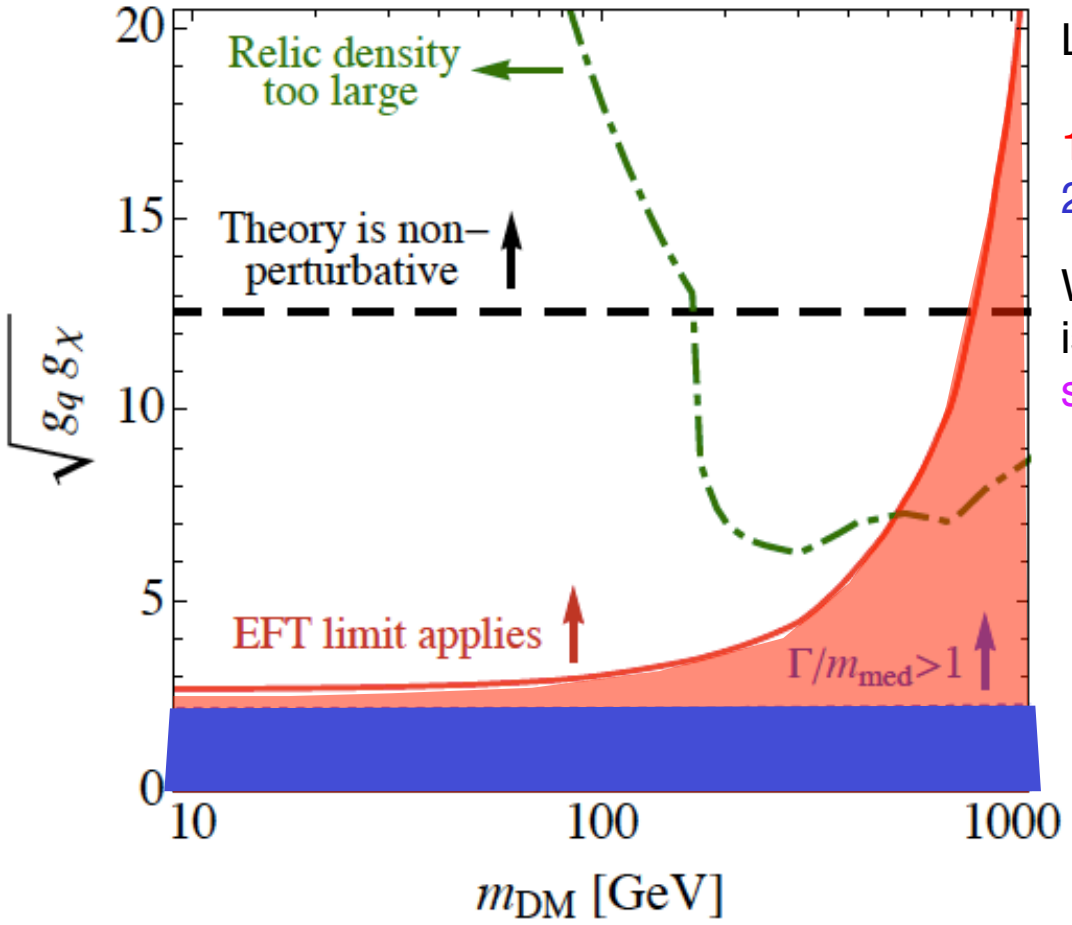
# Model-dependences of EFT limits

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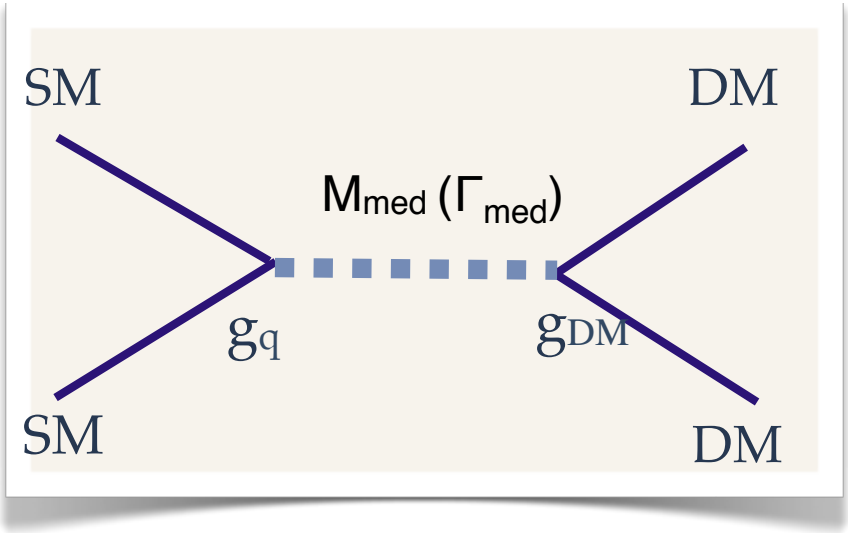
The observation that all DM theories for which the EFT is valid must have $\mathbf{m_{med} < \Gamma_{med}}$ and the small class of models it applies in any case leads to the conclusion that the EFT only applies to a very (as in VERY) small class of DM models.

**EFT limits of monojet searches are therefore highly model-depended!**

# GOING BEYOND THE EFT!

# Minimal Simplified Dark Matter Model

Based on work from :
OB, S. Malik,
M.Dolan,C.McCabe
arXiV:1407.8257




s-channel

| Define simplified model with (minimum) 4 parameters | |
|---|---|
| Mediator mass ($M_{med}$) | DM mass ($M_{DM}$) |
| $g_q$ | $g_{DM}$ |

| DM | |
|---|---|
| Dirac fermion | Scalar - real |
| Majorana fermion | Scalar - complex |

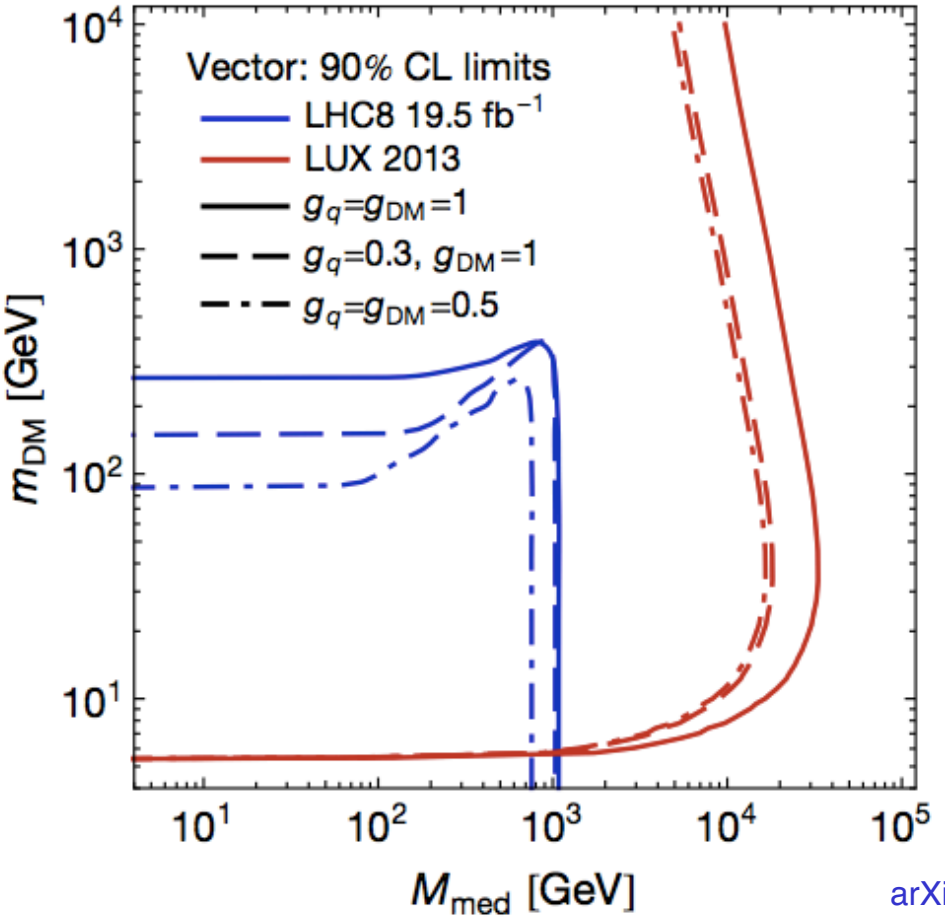
| Consider comprehensive set of diagrams for mediator | |
|---|---|
| Vector | Axial-vector |
| Scalar | Pseudoscalar |

($\Gamma_{med}$ can also be free as long As $\Gamma_{med} < M_{med}$)

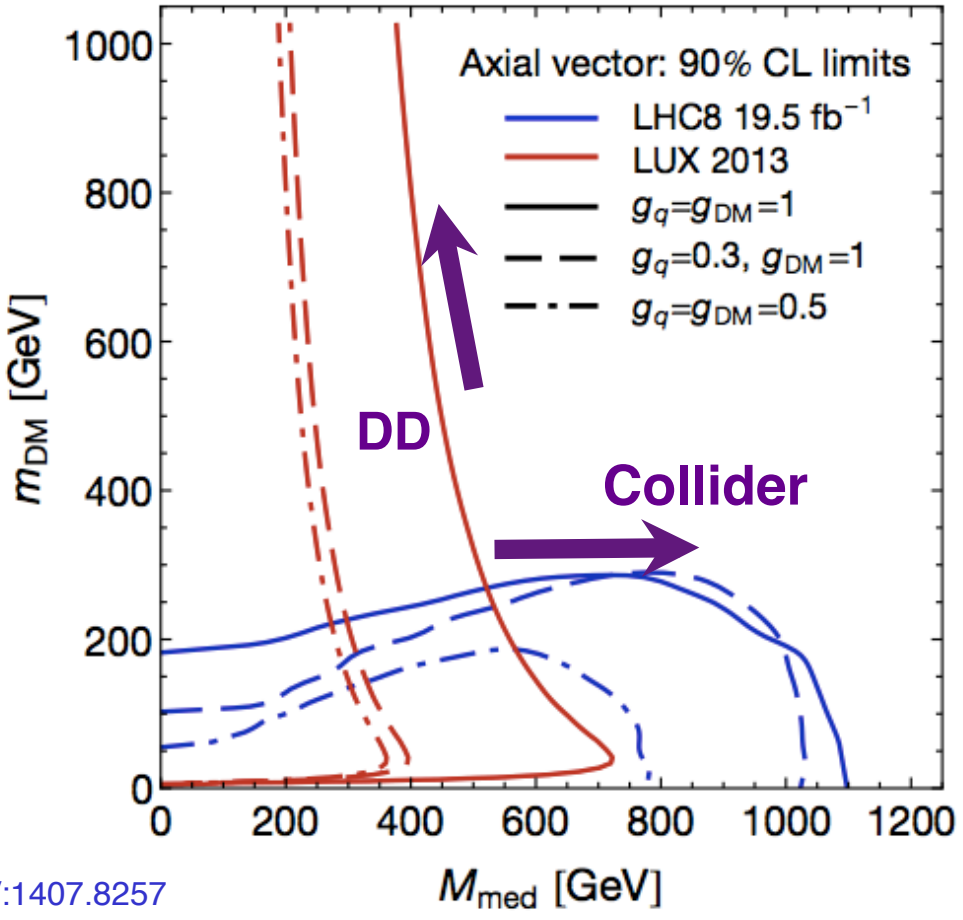
# Collider vs Direct Detection

| $M_{DM}$ | $M_{med}$ |
|---|---|
| $g_q$ | $g_{DM}$ |

Vector




Axial vector

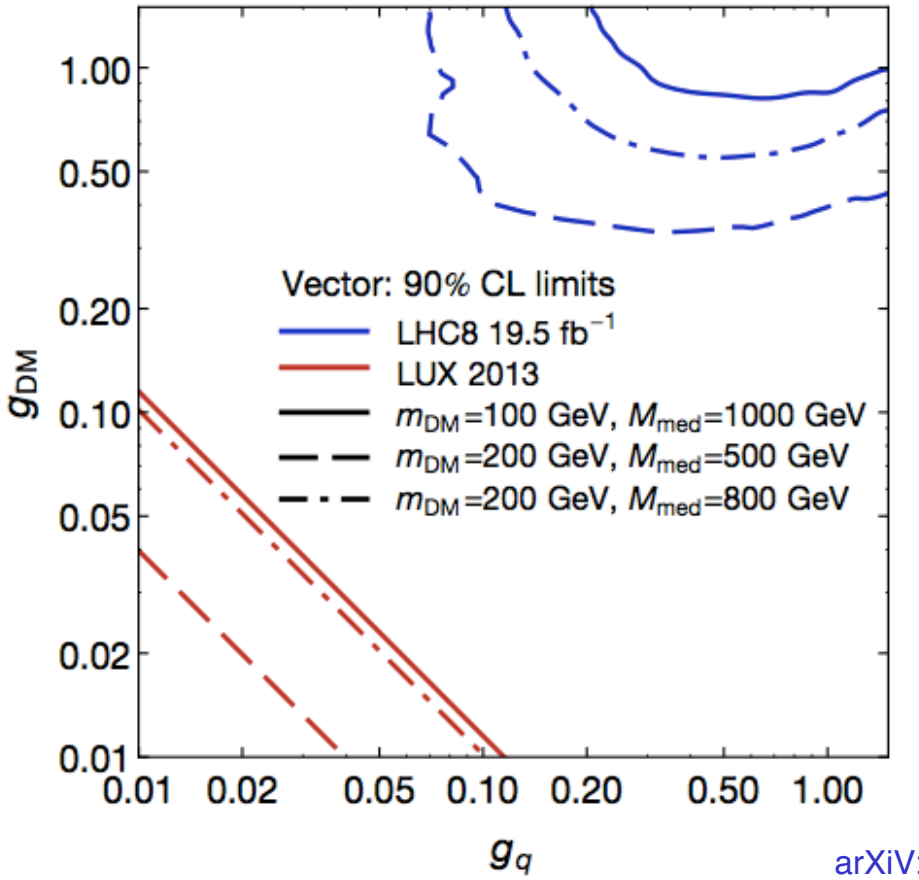



arXiV:1407.8257

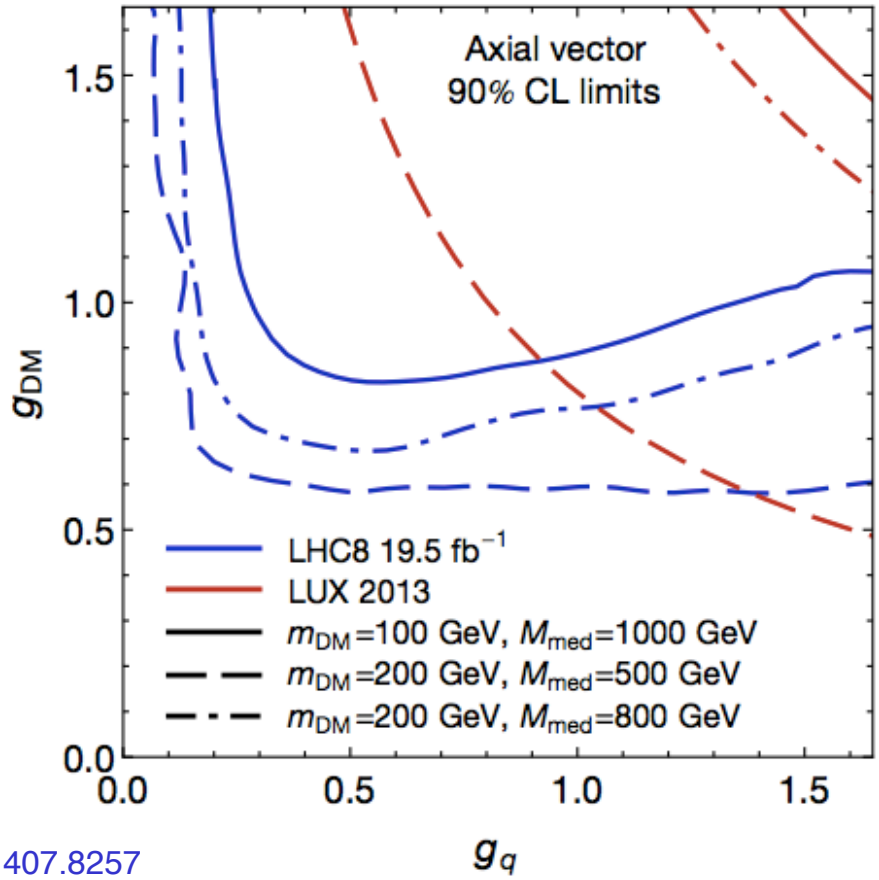
# Collider vs Direct Detection

| $M_{DM}$ | $M_{med}$ |
|---|---|
| $g_q$ | $g_{DM}$ |

## Vector




## Axial vector




arXiV:1407.8257

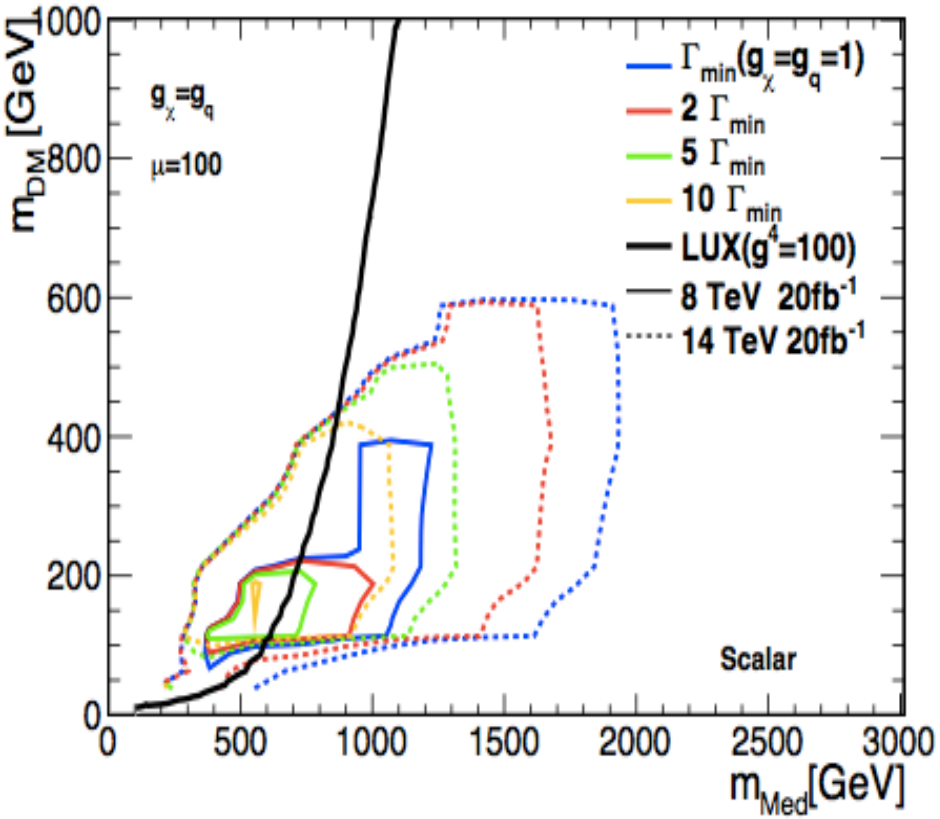
# Scalar and Pseudoscalar

Philip Harris, Valentin V. Khoze,
Michael Spannowsky, Ciaran Williams

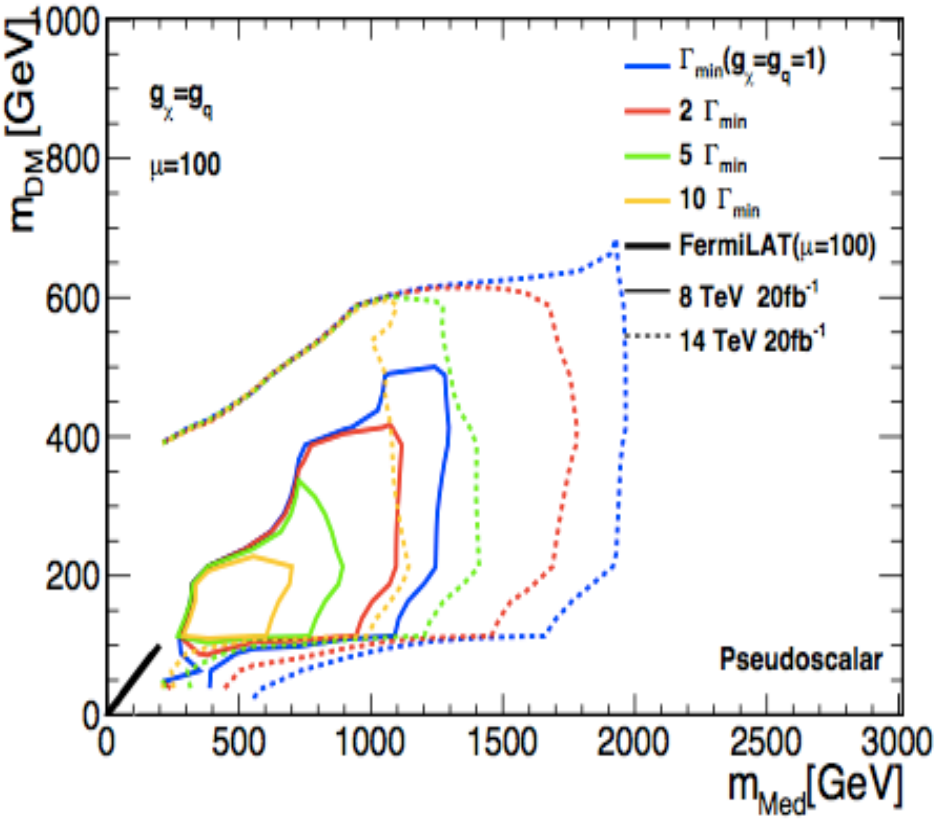
arXiv:1411.0535

See also Buckley et al
arXiv:1410.6497

Scalar




Pseudoscalar



# Projections for Future Experiments: $M_{med}$ vs $M_{DM}$

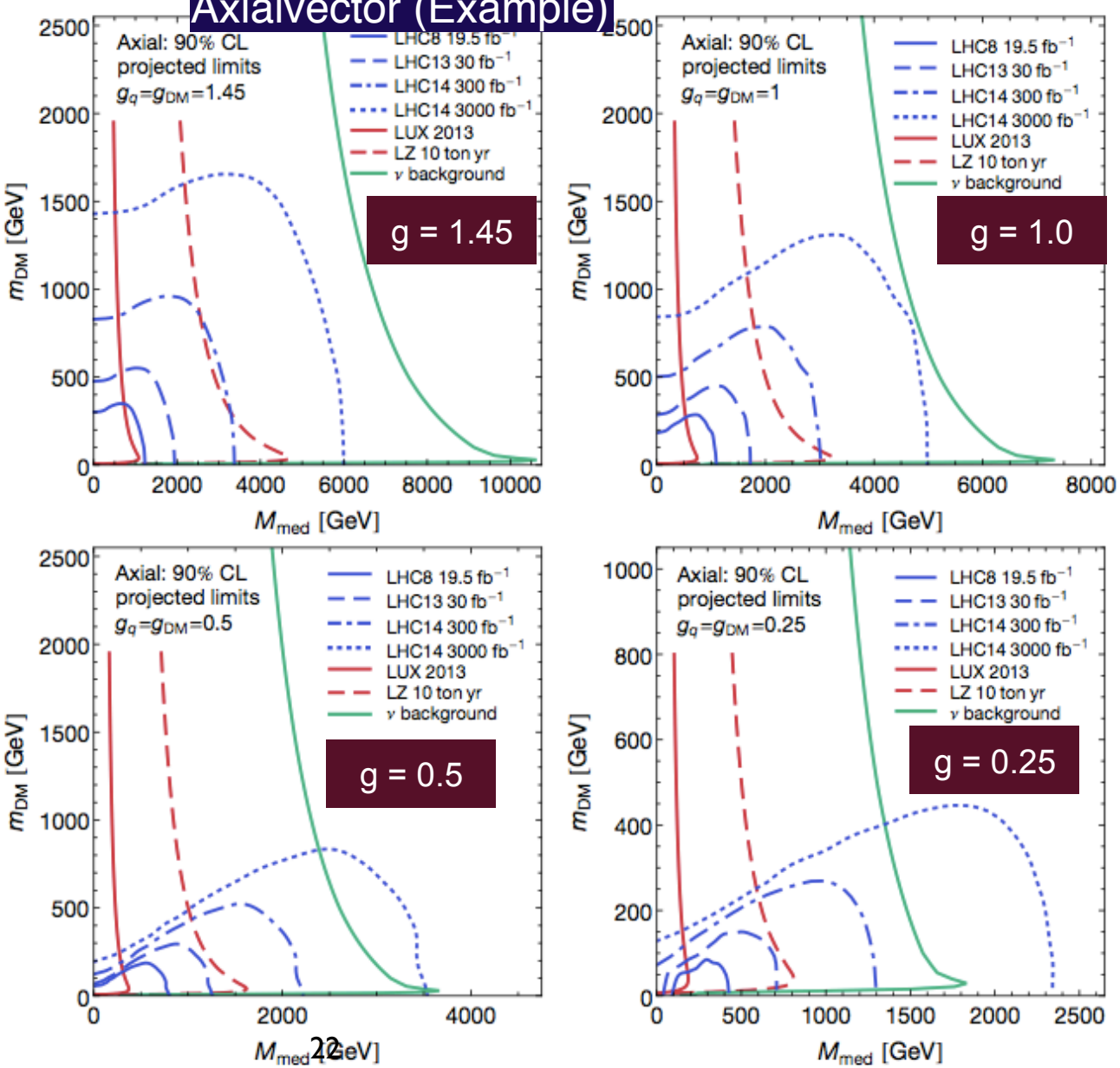
Based on work from :
S. Malik, OB, M.Dolan, C.McCabe et al
arXiV:1409.4075

Limits from 8 TeV monojet search and projected limits for 3 LHC scenarios:
- 13 TeV 30 fb$^{-1}$
- 14 TeV, 300 fb$^{-1}$
- 14 TeV, 3000 fb$^{-1}$

LUX 2013 limits and projected limits for LZ assuming 10 tonne-year exposure

Discovery reach accounting for coherent neutrino scattering

Axialvector (Example)



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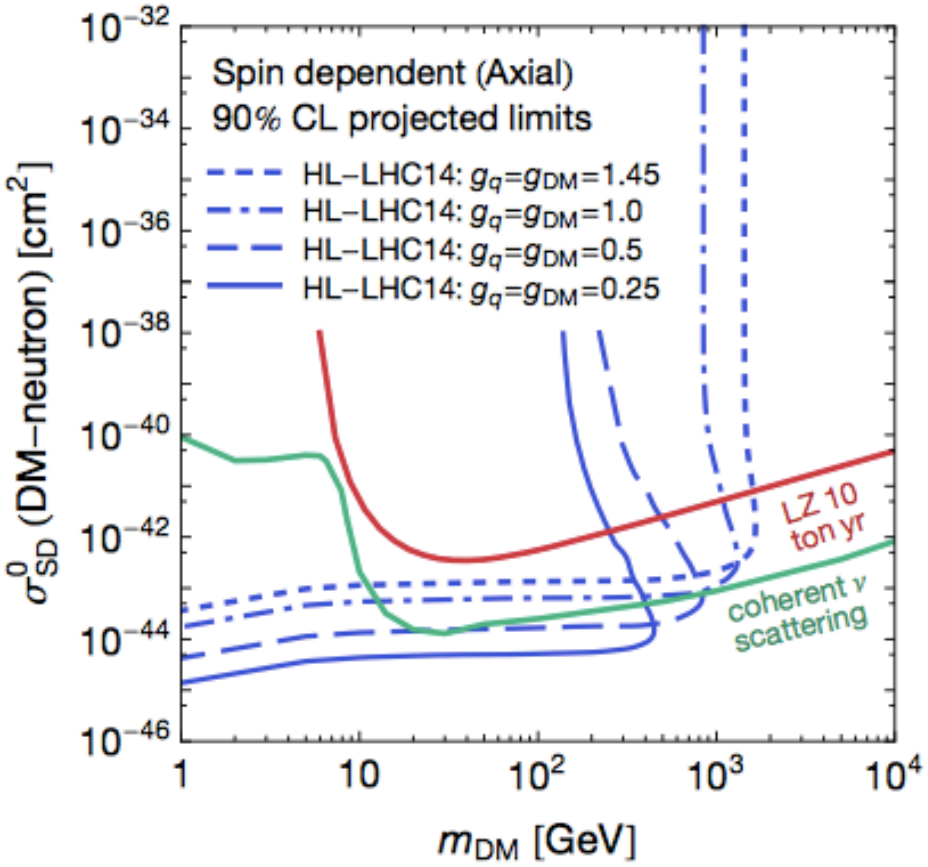
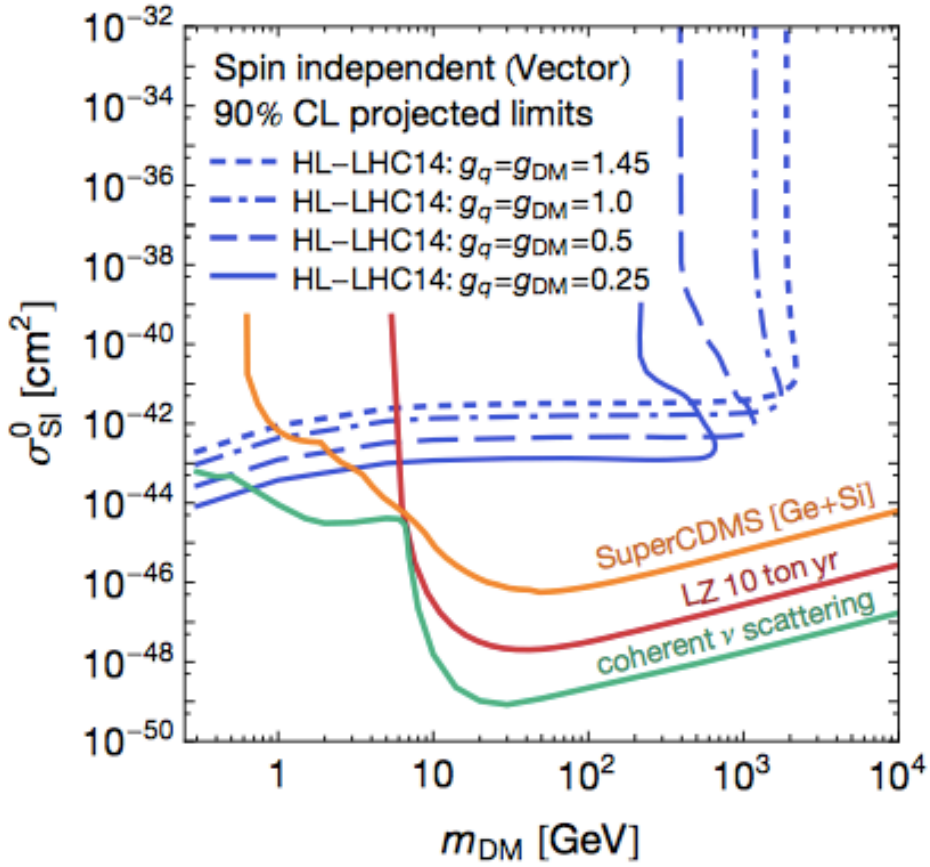
# Projections for Future Experiments: σ vs $M_{DM}$

Can be also shown in the σ vs $M_{DM}$ plane …




**Direct Detection experiments and collider are complementary!**
**They are probing different regions of the relevant parameter space!**

# Summary for most basic Mediator Interactions

… in a nutshell!

| Basic Mediators | |
|---|---|
| **Vector**<br>EWK like coupling<br>(assumed equal to all leptons).<br>*Besides very low DM masses DD wins clearly over collider!* | **Axial-vector**<br>EWK like coupling<br>(assumed equal to all leptons).<br>*DD and collider are equal in overall sensitivity but probe different regions of parameter space!* |
| **Scalar**<br>Yukawa like coupling on SM side<br>(mass based on SM side)<br>*DD and collider are equal in overall sensitivity but probe different regions of parameter space!* | **Pseudoscalar**<br>Yukawa like coupling on SM side<br>(mass based on SM side)<br>*No limits from DD (only from indirect detection). Collider provides limits similar in sensitivity to scalar limits* |

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**True complementarity between DD and collider!**

# Summary

- Interpretation of collider based DM searches in the framework of EFT have limitations!
  - EFT limits are only applicable to a small class od DM models. Furthermore, these models must all have $\Gamma_{med} > M_{med}$ which makes an particle ansatz doubtful.
  - A comparison of EFT limits with results of direct detection experiments in the SI/SD – $M_{DM}$ plane is NOT an equal-footing comparison.
  - IF(!) this form of comparison is used in the future the caveats that come along with EFT limits must be explicitly stated!
- Interpretation of DM searches in simplified models overcome many of the EFT shortcomings!
  - Characterizing monojet results with using $m_{med}$, $m_{DM,}$ $g$, $\Gamma_{med}$ captures all of the important properties relevant for collider searches.
  - The approach is similar to what has been successfully utilized for SUSY searches.
- This approach also provides a fair comparison with results of direct detection experiments!
  - Establishing the complementarity of the two type of searches becomes much easier!

# BACKUP

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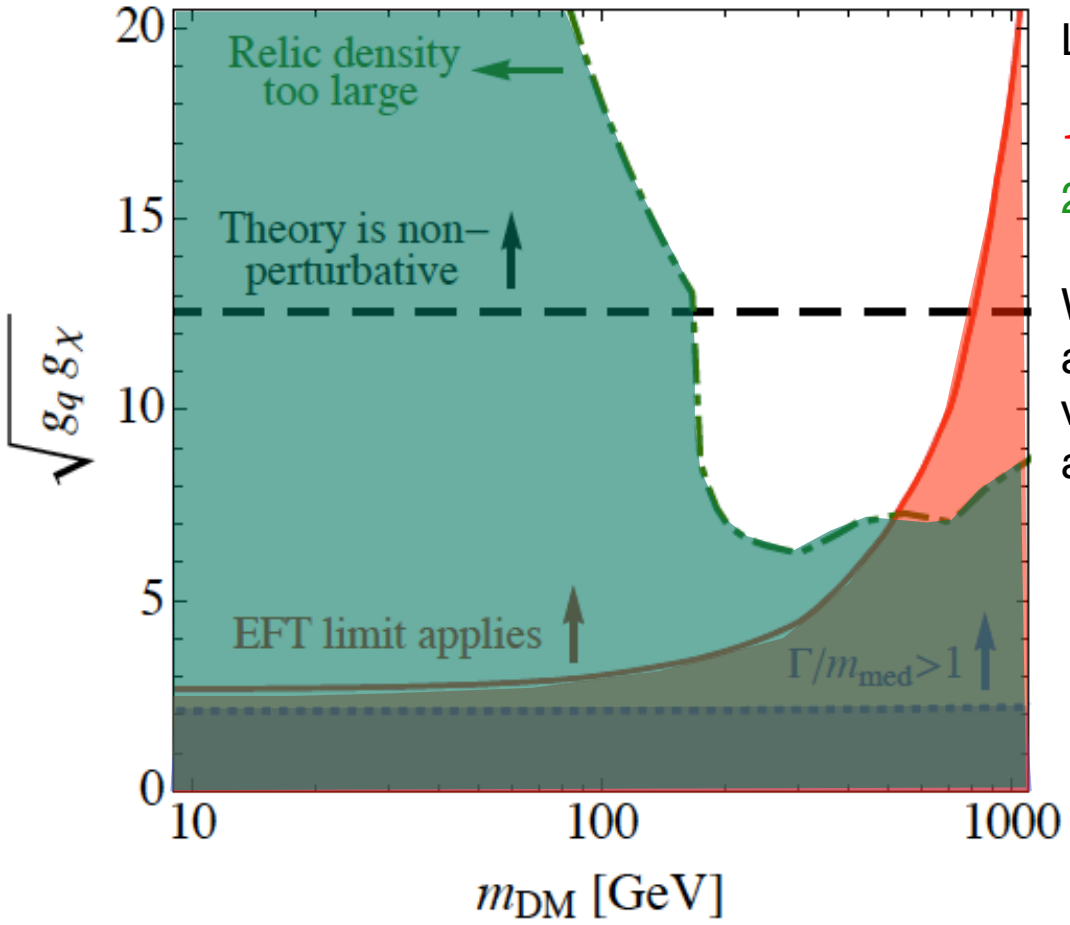
# Model-dependences of EFT limits




Look at EFT validity in $m_{DM}$ – coupling* plane!

1. Region in which EFT is valid (20%)
2. Require compatibility with relic density

When exclude the region in which relic abundance is larger then the observed value of $\Omega_{\chi\chi}h^2 = 0.119$ only mediator masses above a few hundred GeV fulfill this.

* Coupling chose such that CMS EFT limit on Λ applies to FT

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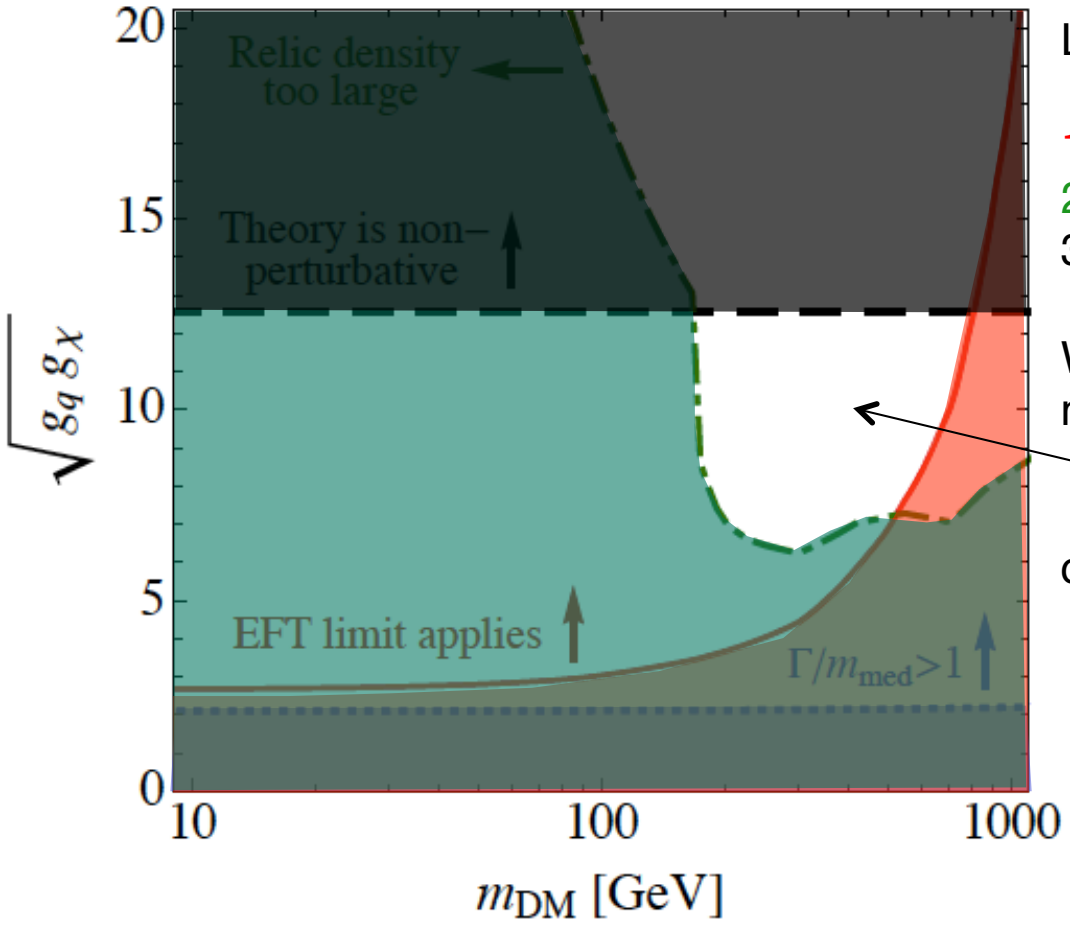
# Model-dependences of EFT limits




Look at EFT validity in $m_{DM}$ – coupling* plane!

1. Region in which EFT is valid (20%)
2. Require compatibility with relic density
3. Require theory to be perturbative (<4π )

When we also require that the region/theory must be perturbative:

$$\sqrt{g_q g_\chi} < 4\pi$$

only a very small region is left!

EFT limits of monojet searches only apply to a very (as in VERY) small class of DM models!

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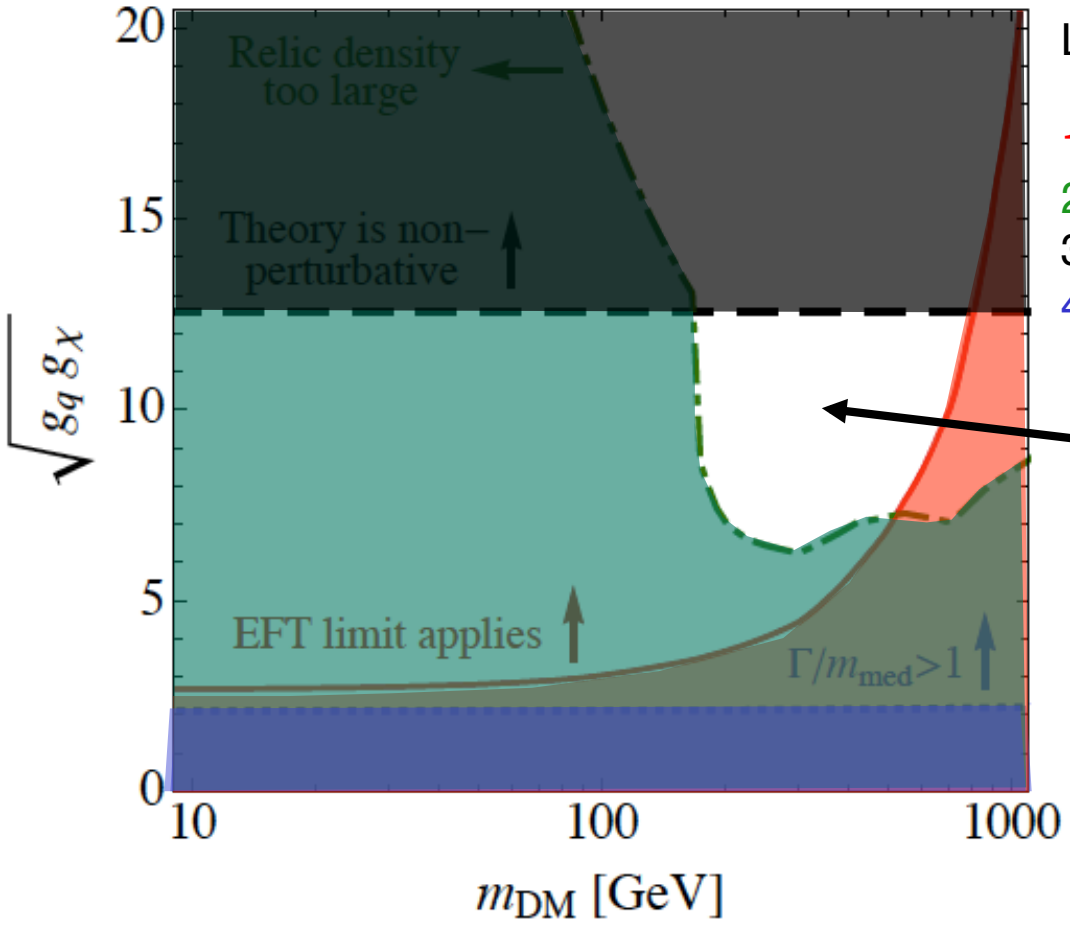
# What those this imply on model-dependences of EFT limits?




Look at EFT validity in $m_{DM}$ – coupling* plane!

1. Region in which EFT is valid (20%)
2. Require compatibility with relic density
3. Require theory to be perturbative (<4π )
4. $m_{med} < \Gamma_{med}$ ALWAYS!

Region of “EFT validity”

The observation that all DM theories for which the EFT is valid must have $m_{med} < \Gamma_{med}$ and the small class to models it applies in any case leads to the conclusion the EFT only applies to a very small class of DM models.
EFT limits of monojet searches are therefore highly model-depended!

# Model-dependences of EFT limits

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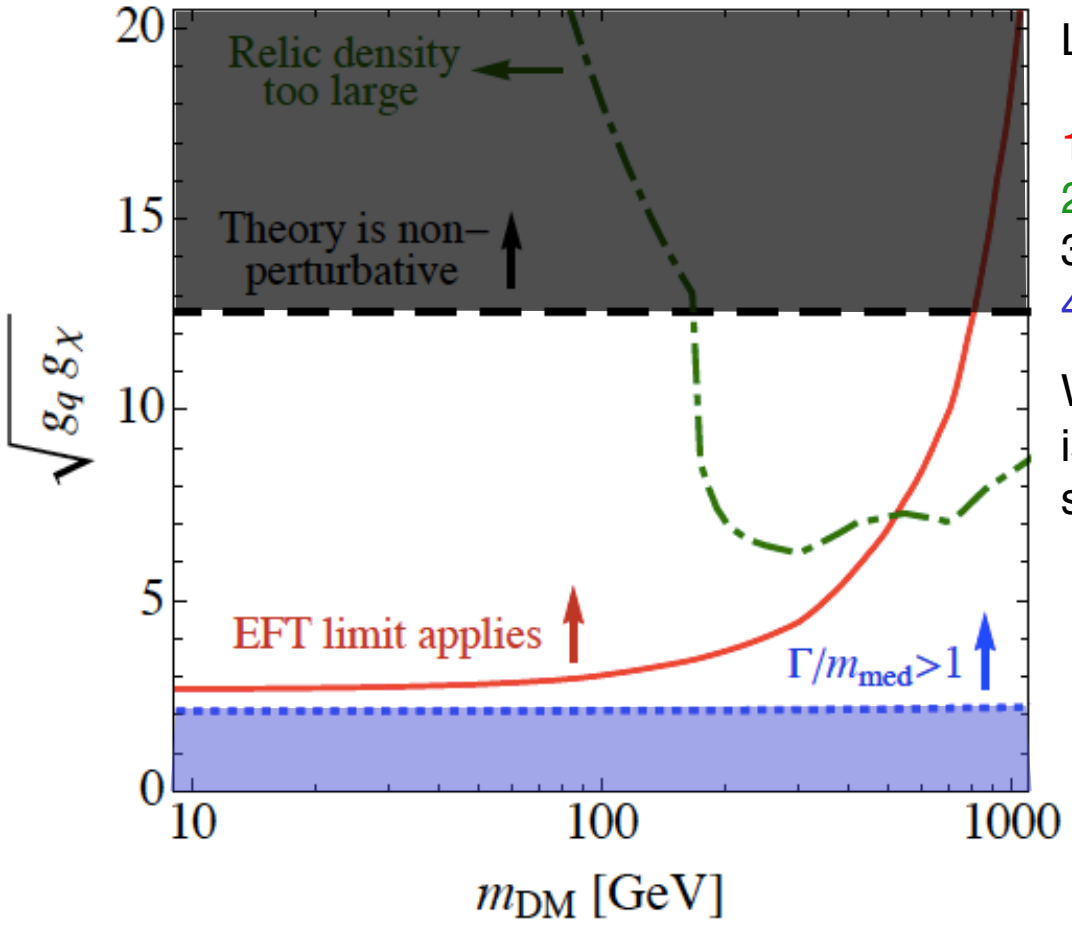



Look at EFT validity in $m_{DM}$ – coupling* plane!

1. Region in which EFT is valid (20%)
2. Require compatibility with relic density
3. Require theory to be perturbative (<4π )
4. $m_{med} < \Gamma_{med}$ ALWAYS!

We also find that for all DM models the EFT is valid only IF the mass of the mediator is smaller than its width !

In the reaming part of the plot:

$$\sqrt{g_q g_\chi} > 2$$

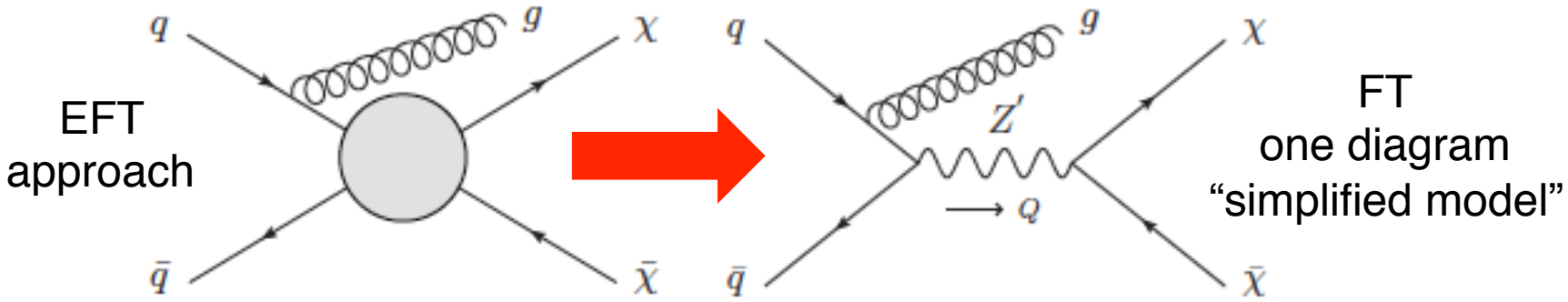
a particle-like interpretation of the mediator is doubtful because of $m_{med} < \Gamma_{med}$ !

See discussion about equation 3.5 in arXiv:1308.6799 for further details.

# Alternative Interpretation Ansatz: Simplified models

Recent work from OB, M.Dolan,C.McCabe: arXiv:1308.6799

- Compare Effective Field Theory (EFT) with Full Theory (FT)




After three years of operation at the LHC the landscape for interpretation of searches has changed dramatically – new superior & modern approaches have replaced in many areas longstanding traditional ones (e.g. SUSY searches)

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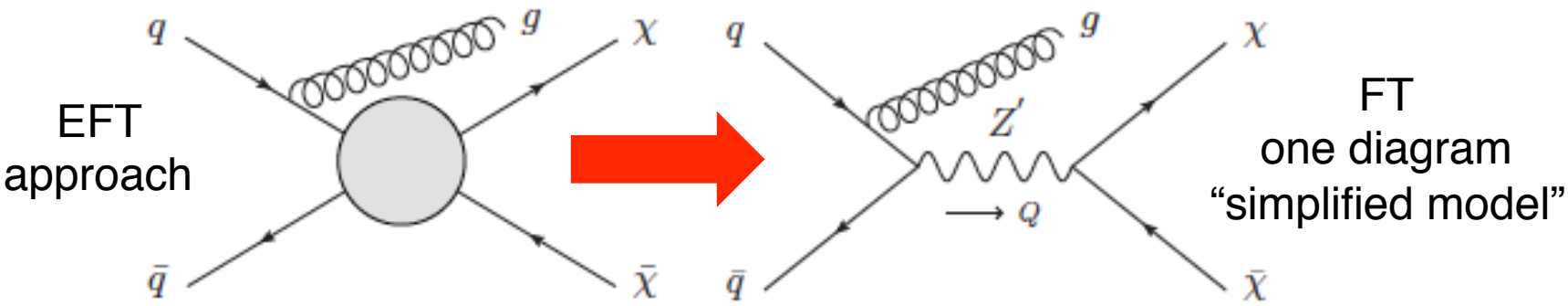
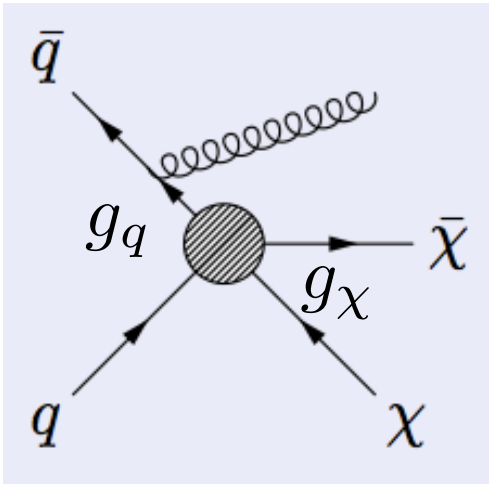


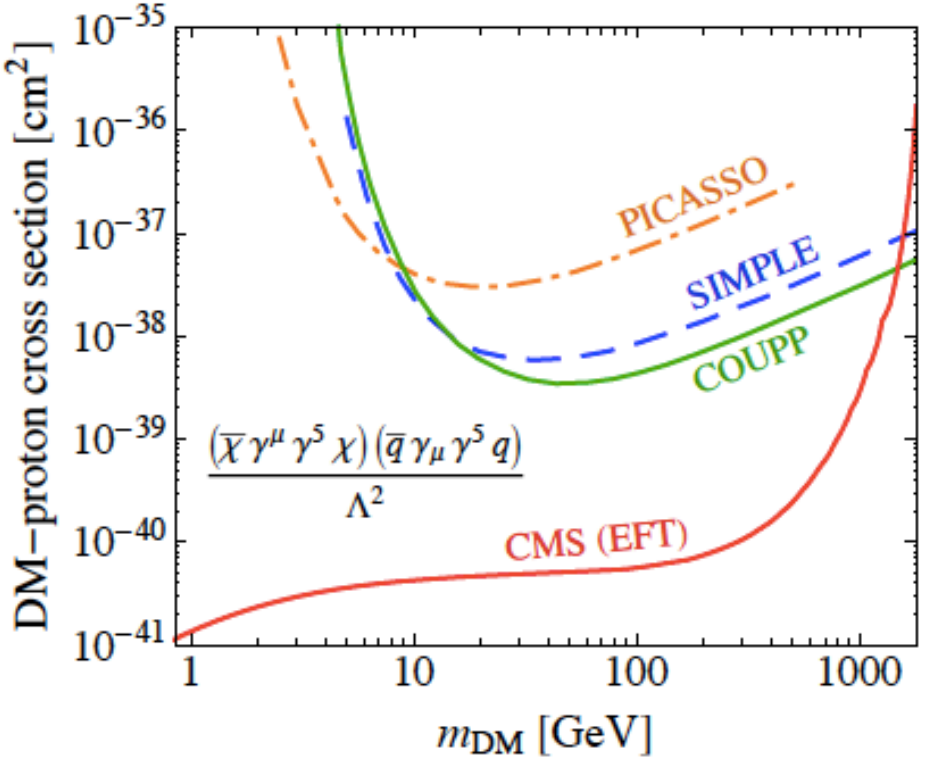




**The problem is governed by five variables:**

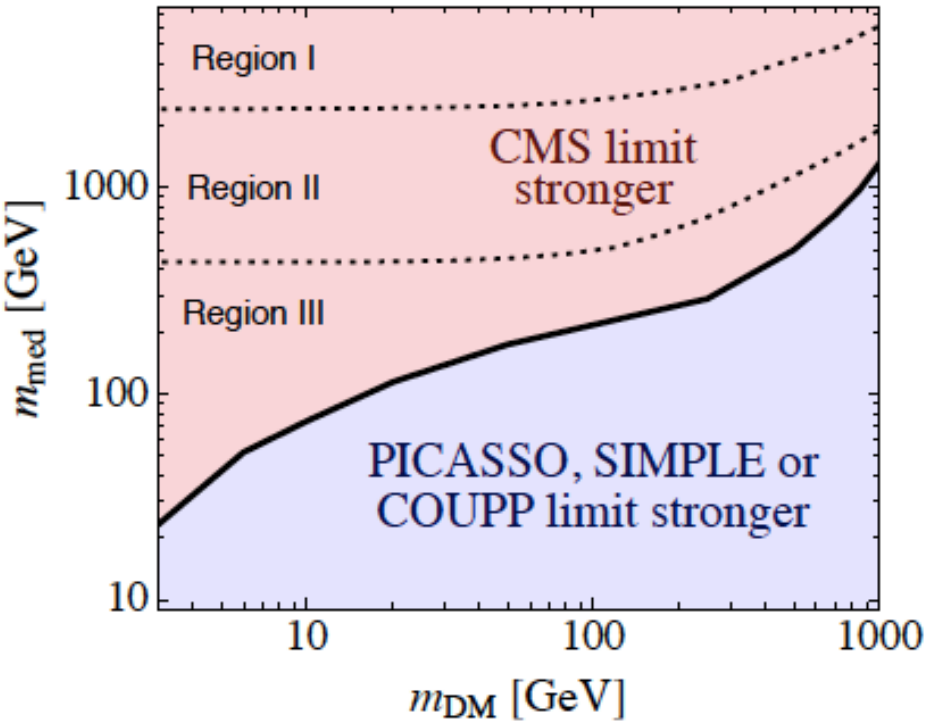
- Couplings $g_q$ and $g_\chi$
- Mediator mass $m_{med}$ and mediator width $\Gamma_{med}$
- Dark matter candidate mass $m_{DM}$

# Beyond EFT limits: Simplified models

Working out the complementarity between direct DM detection experiments and collider based DM searches!




EFT limits give the impression that monsjet searches outperform direct detection BUT EFT only applies a VERY small class of DM models.




Simplified model limits give a much better Account of the REAL complementarity and thus seem superior for a comparison.

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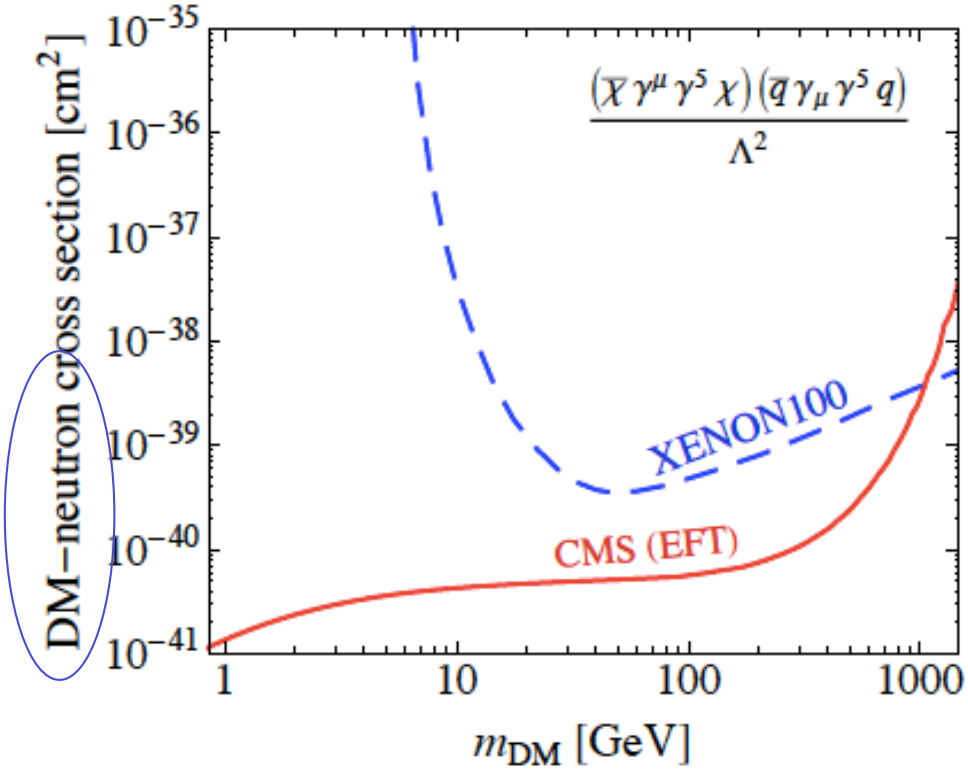


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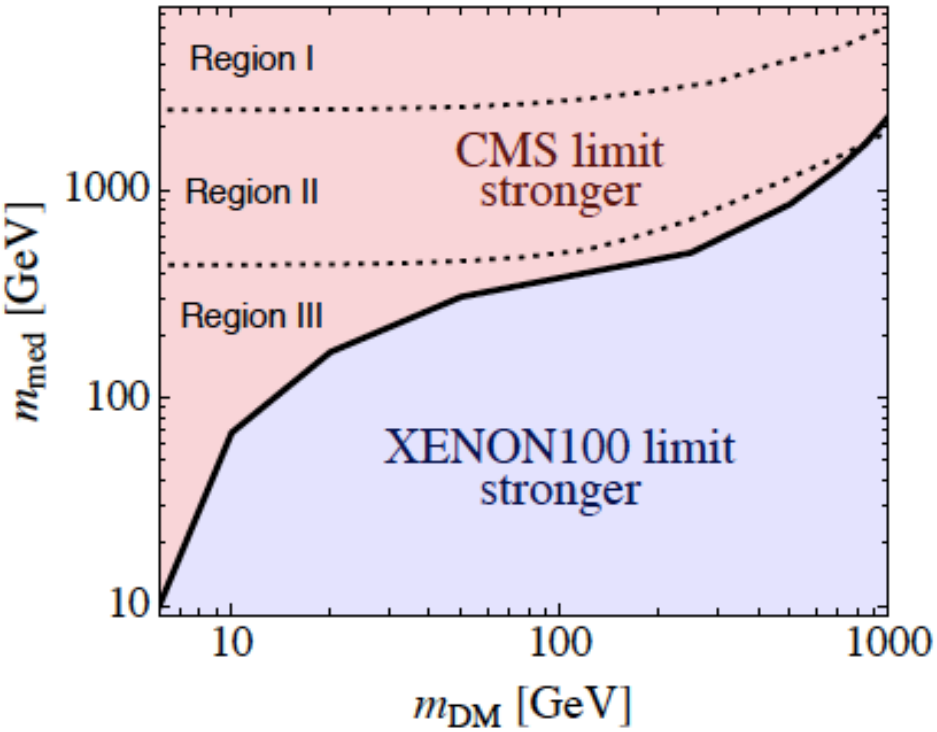


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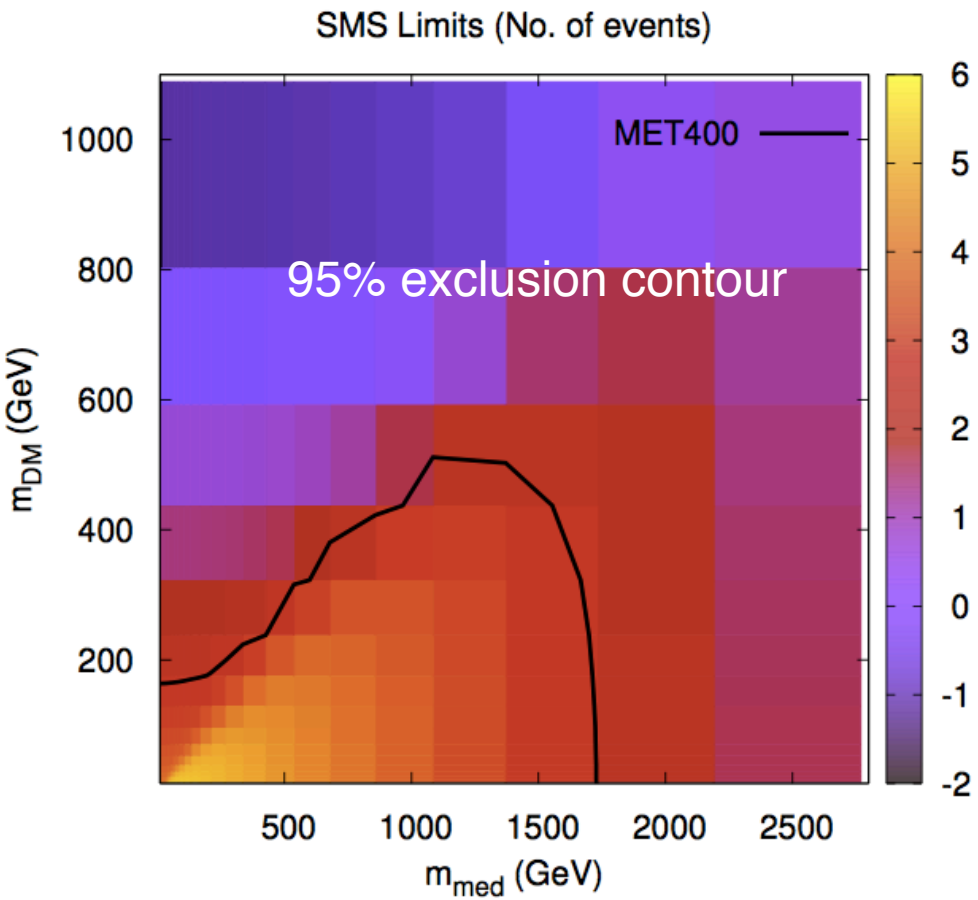
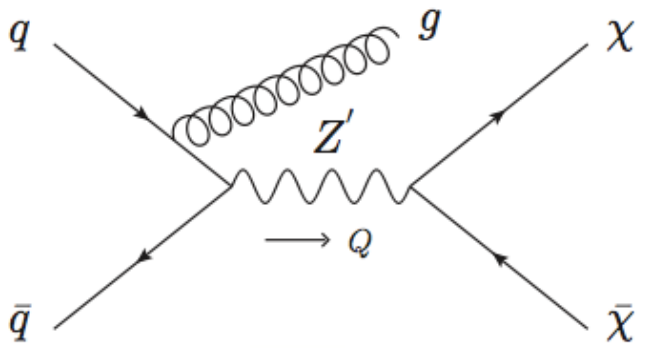
# Absolute Limits in simplified models

Example: CMS monojet search




Assumes:

$$g_q = g_\chi = 1$$

$$\Gamma_{med} = \frac{m_{med}}{8\pi}$$

Would need to also characterize dependence on $\Gamma_{med}$ and couplings. This could e.g. be done by defining some benchmark scenarios.

Would also need to look at other operators (of course).