

Interpreting dark matter searches *with contact interactions and simplified models*



Christopher McCabe

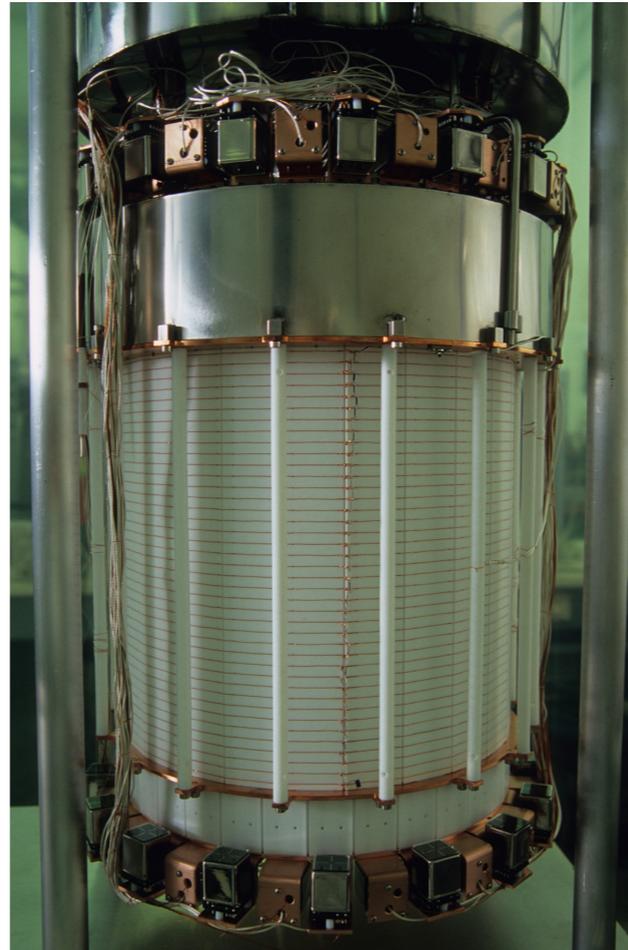


Searches for dark matter

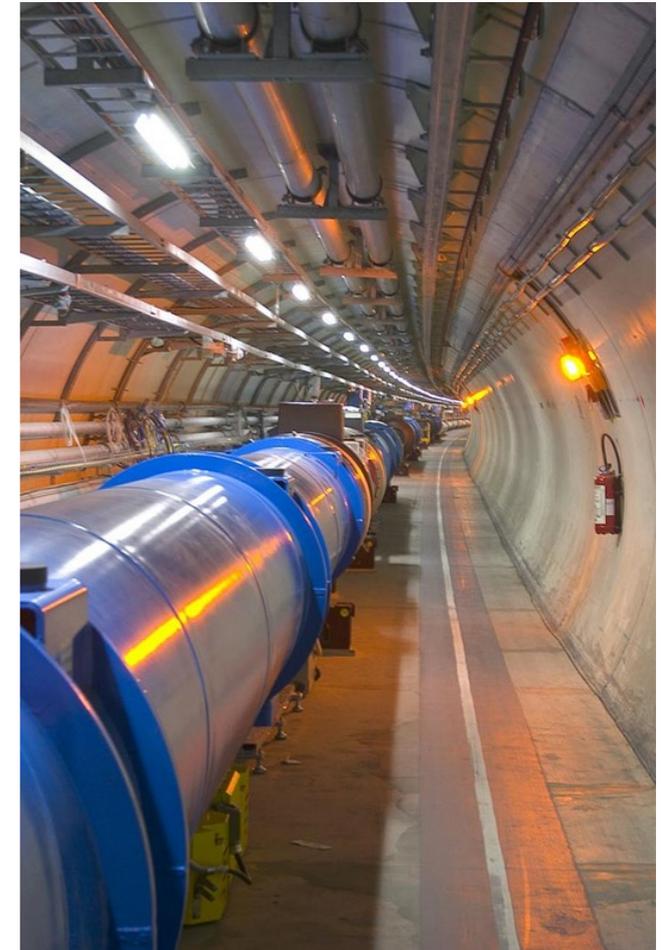
Indirect detection



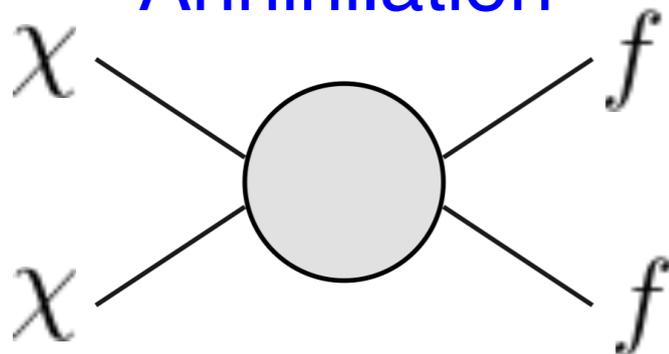
Direct detection



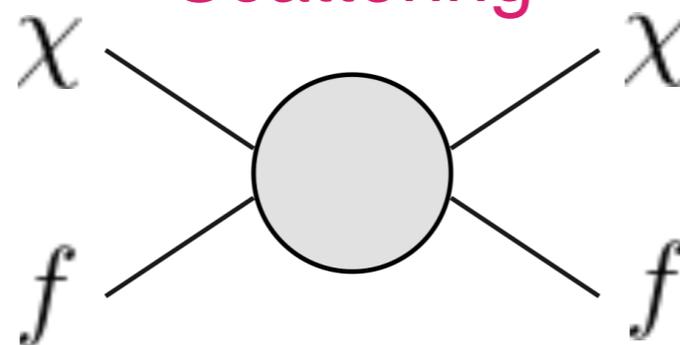
Collider



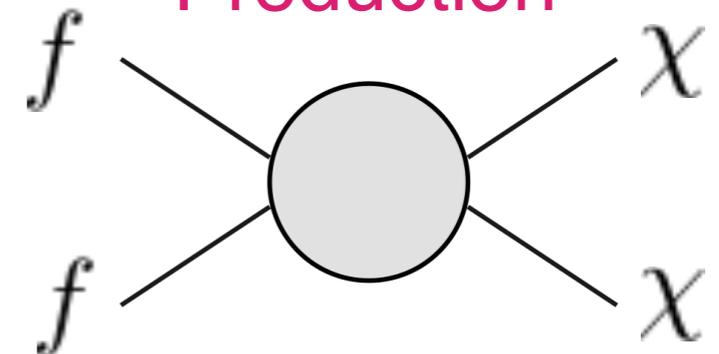
Annihilation



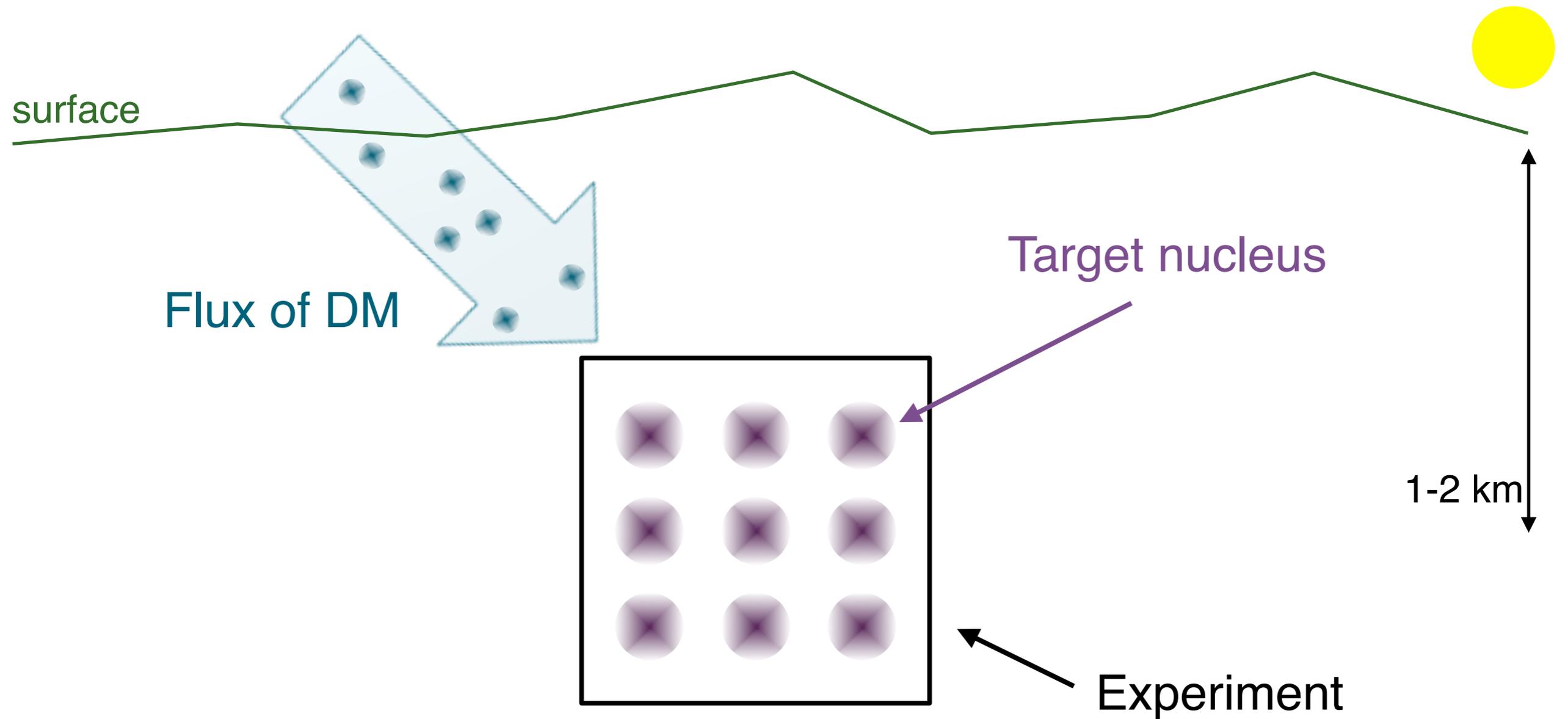
Scattering



Production

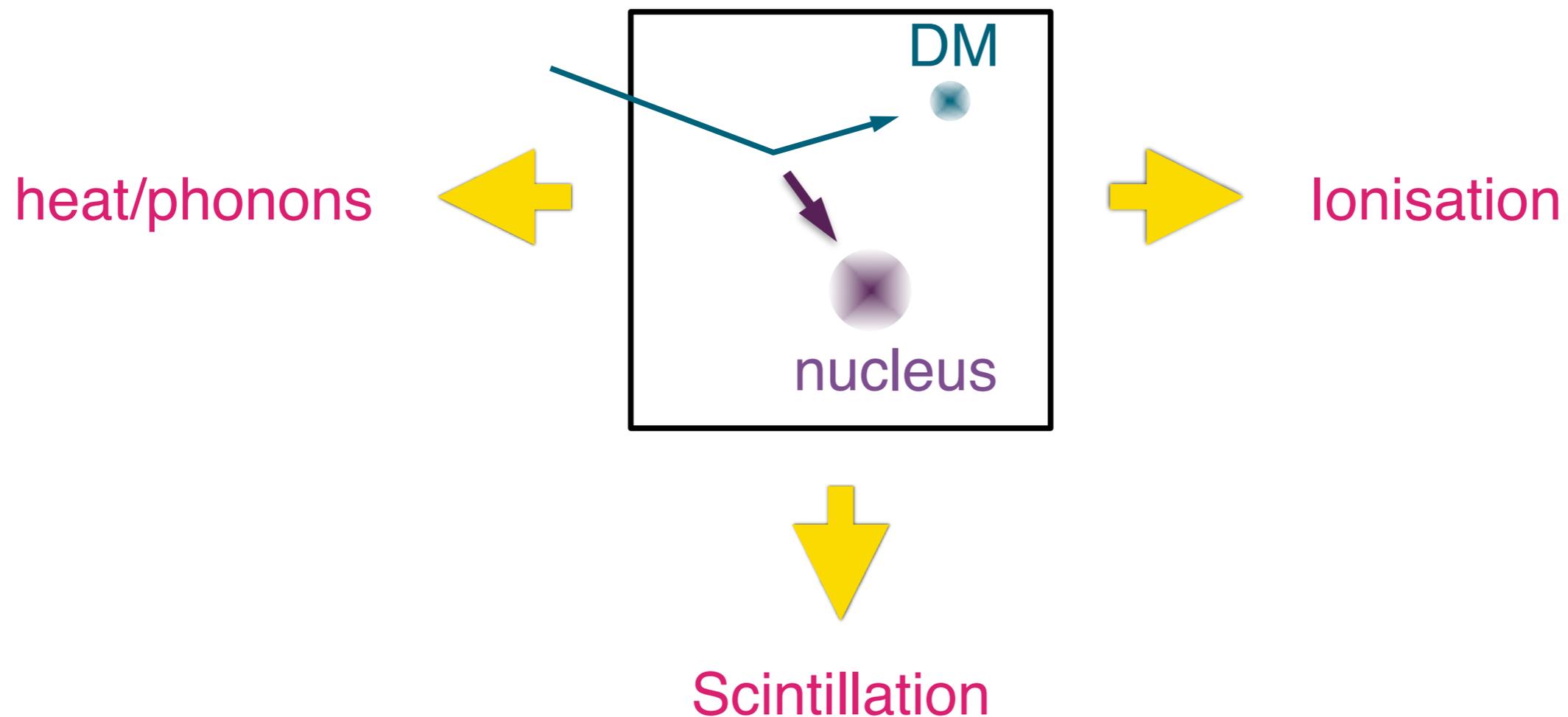


Direct detection: basics



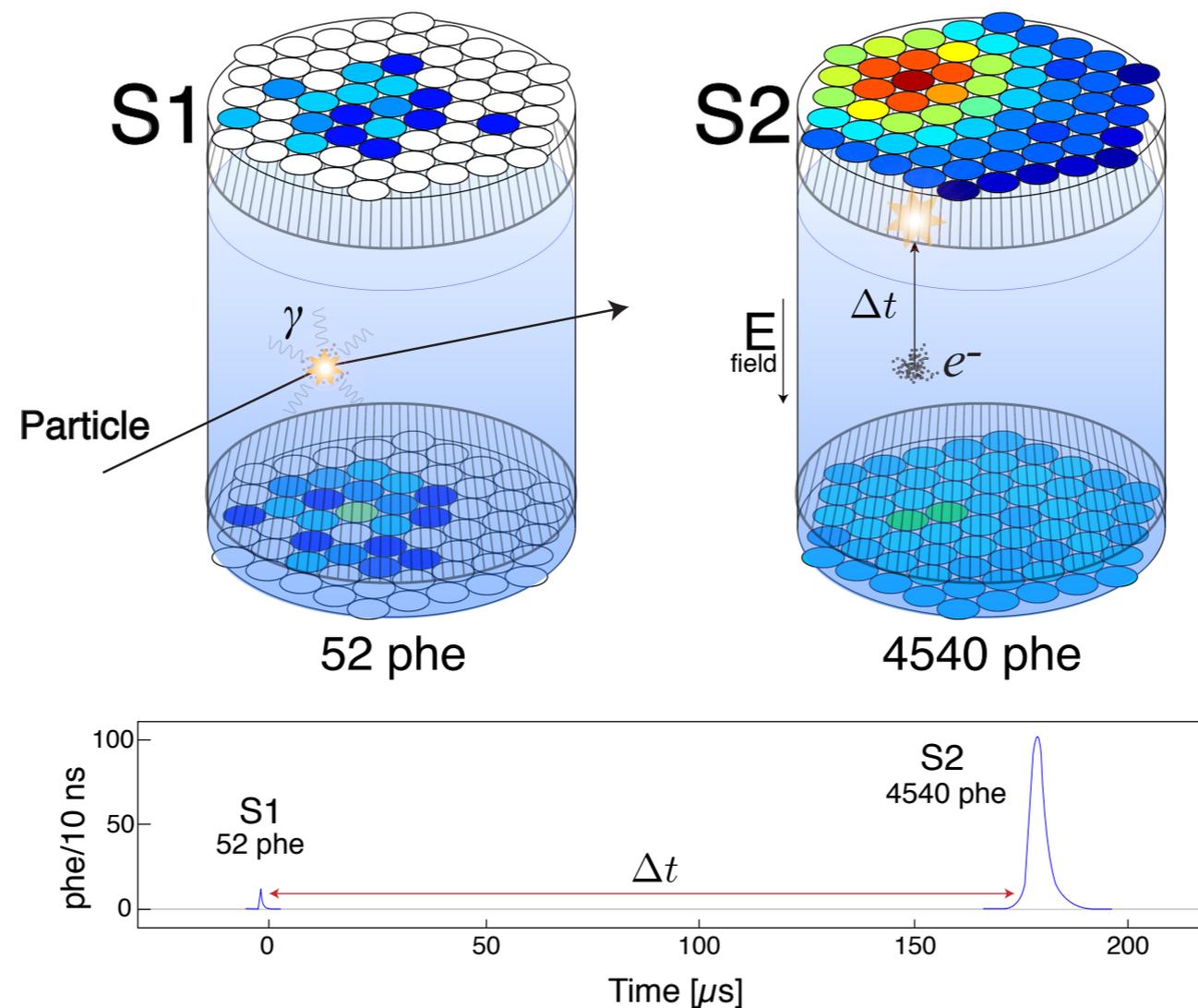
Direct detection: basics

Aim: Measure the energy deposited by the recoiling nucleus



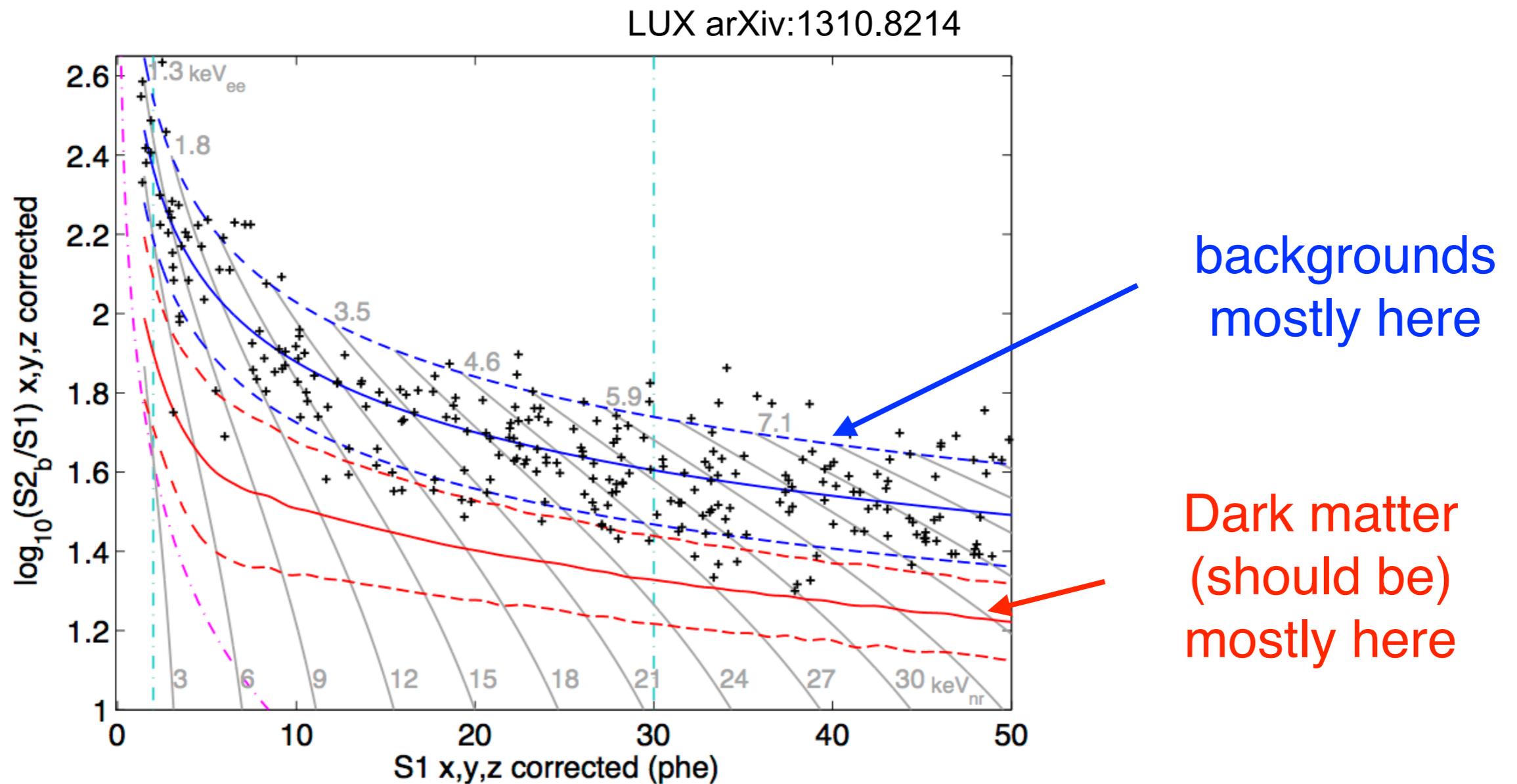
Xenon experiments

- Two-phase experiment (liquid and gas)
- Scattered particles create two pulses: S1 and S2



LUX results

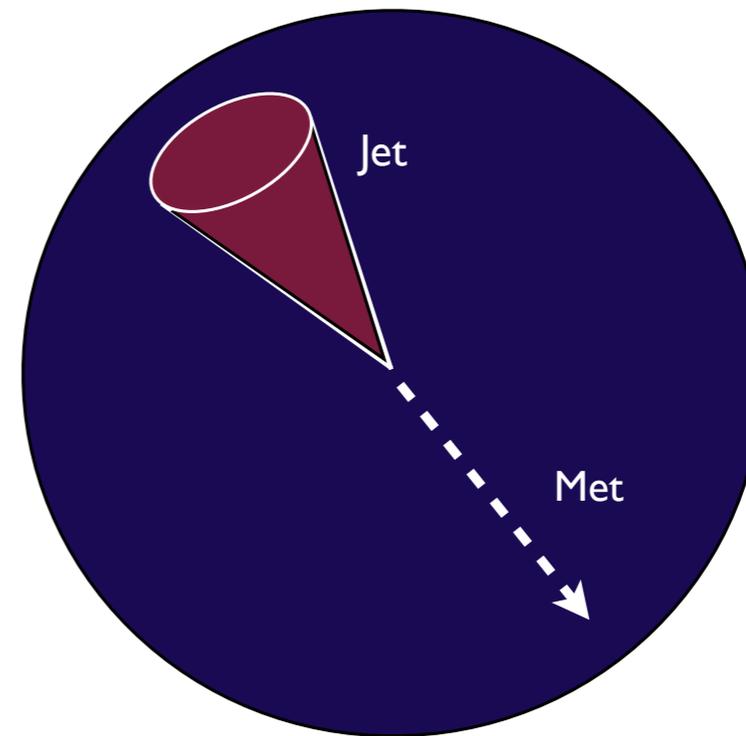
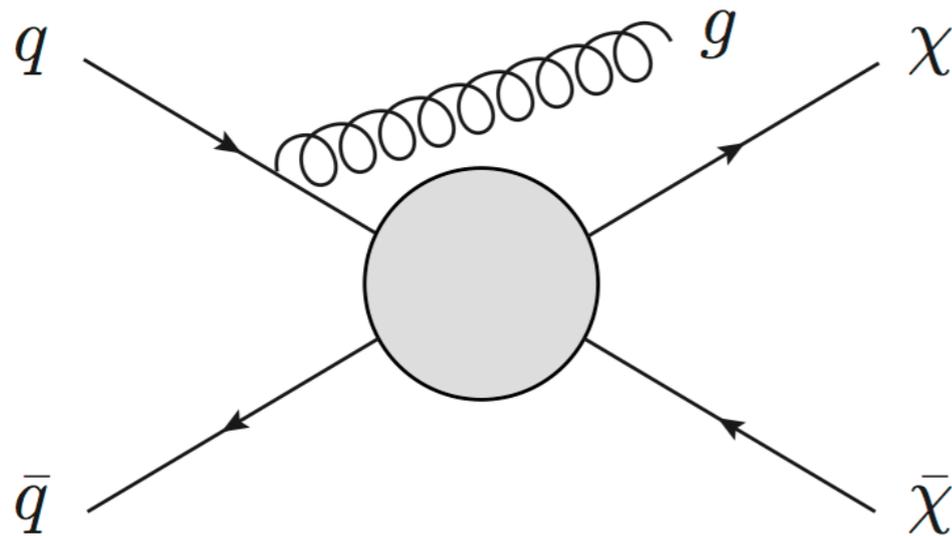
- Measurement consistent with background: No dark matter here



Monojet signature

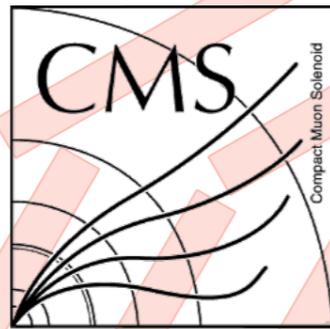
CMS: 1408.3583
ATLAS: 1502.01518

- ‘Classic’ pair production search
 - ➔ Simple and striking signature: hard jet and MET

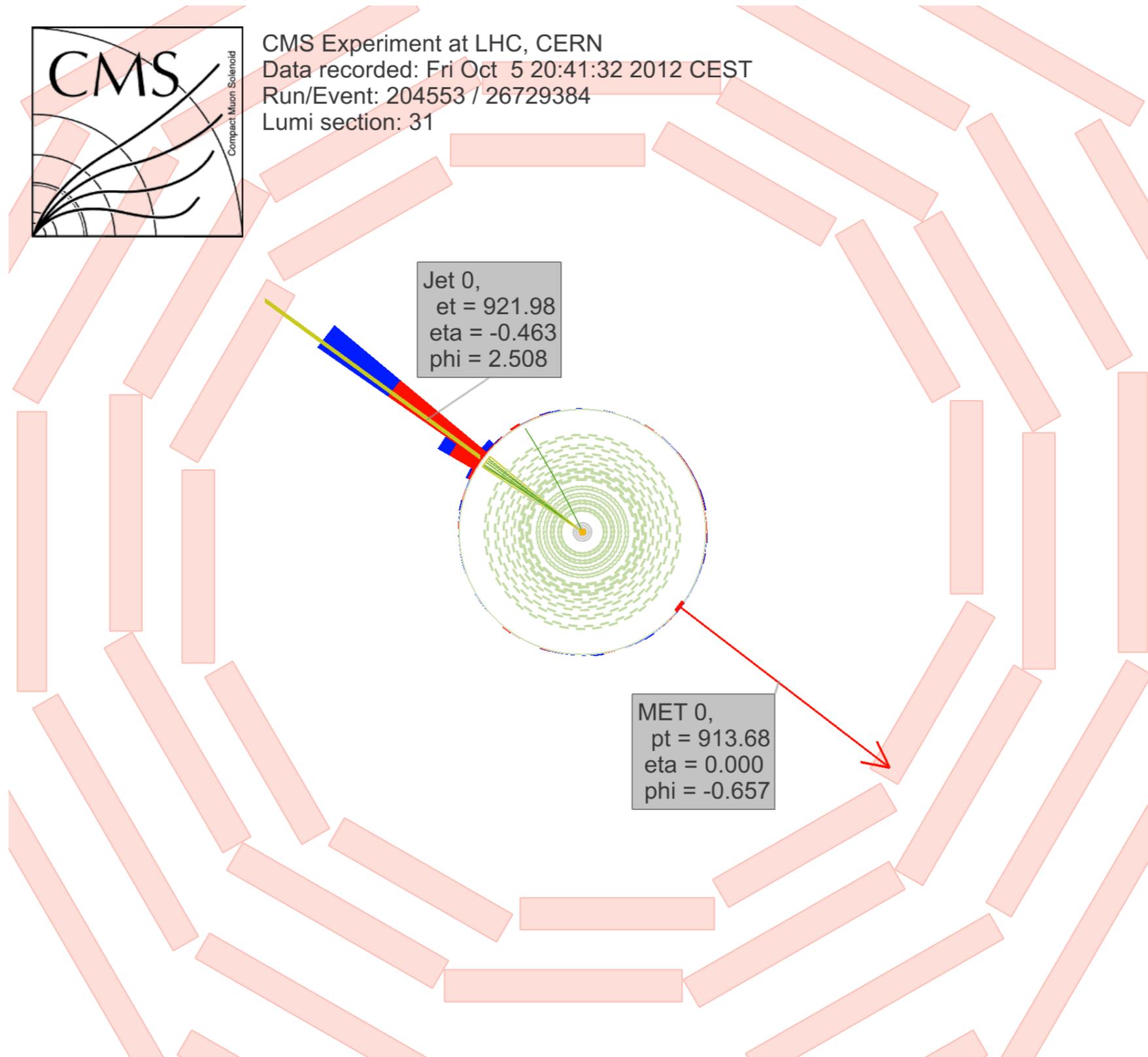


- Dark matter recoils against a QCD jet from initial state radiation (ISR)

Monojet: a real event



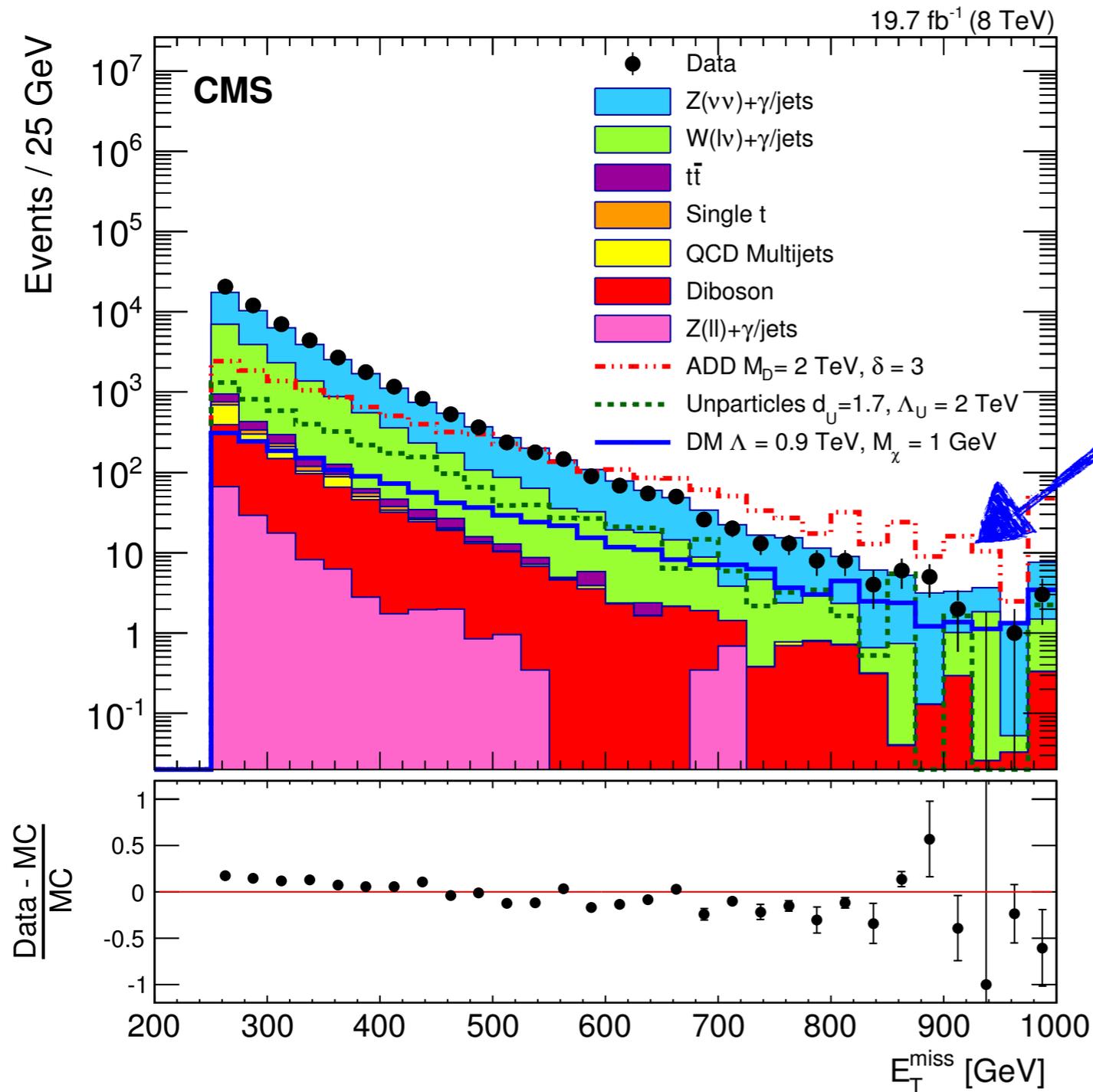
CMS Experiment at LHC, CERN
Data recorded: Fri Oct 5 20:41:32 2012 CEST
Run/Event: 204553 / 26729384
Lumi section: 31



Jet 0,
et = 921.98
eta = -0.463
phi = 2.508

MET 0,
pt = 913.68
eta = 0.000
phi = -0.657

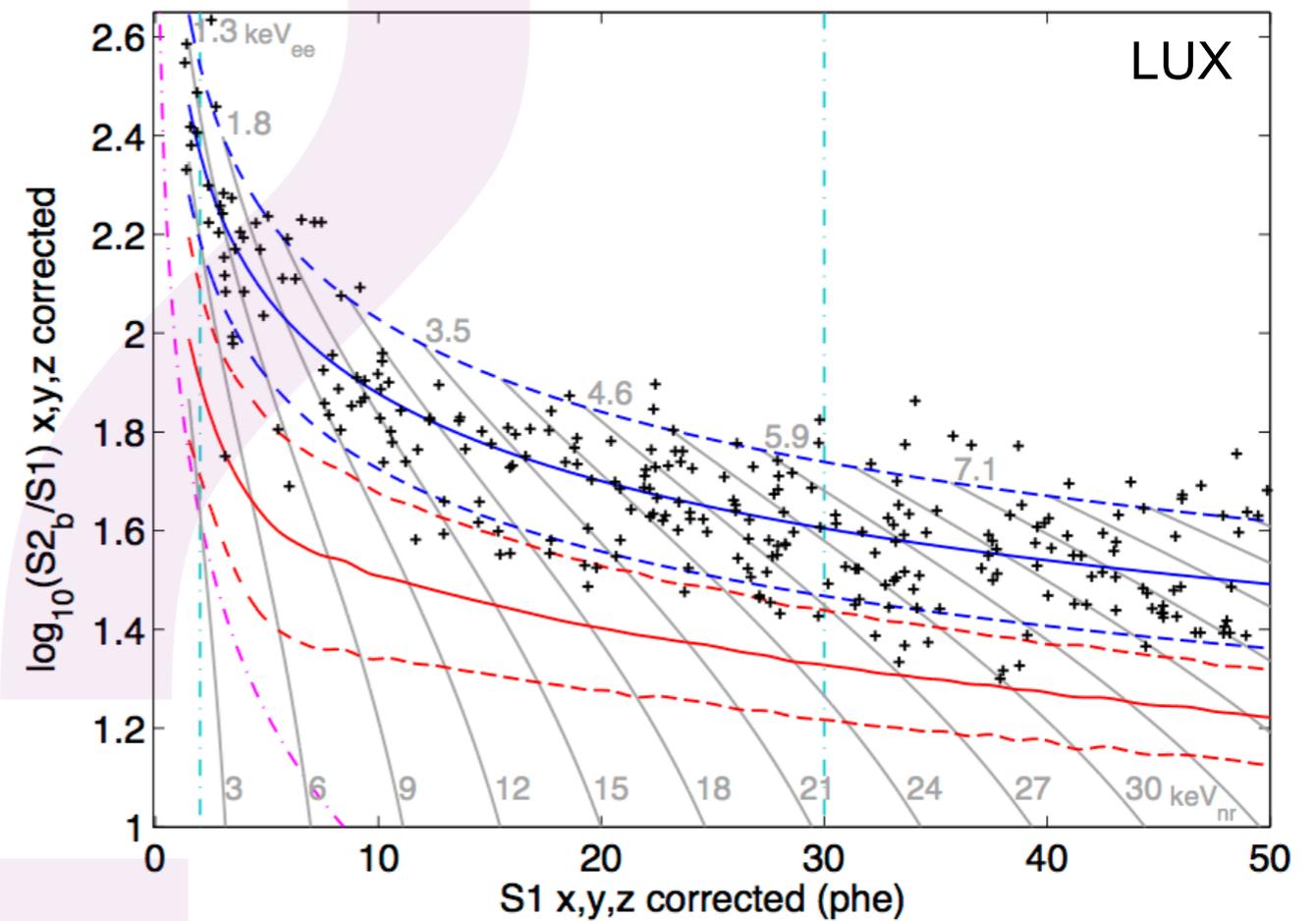
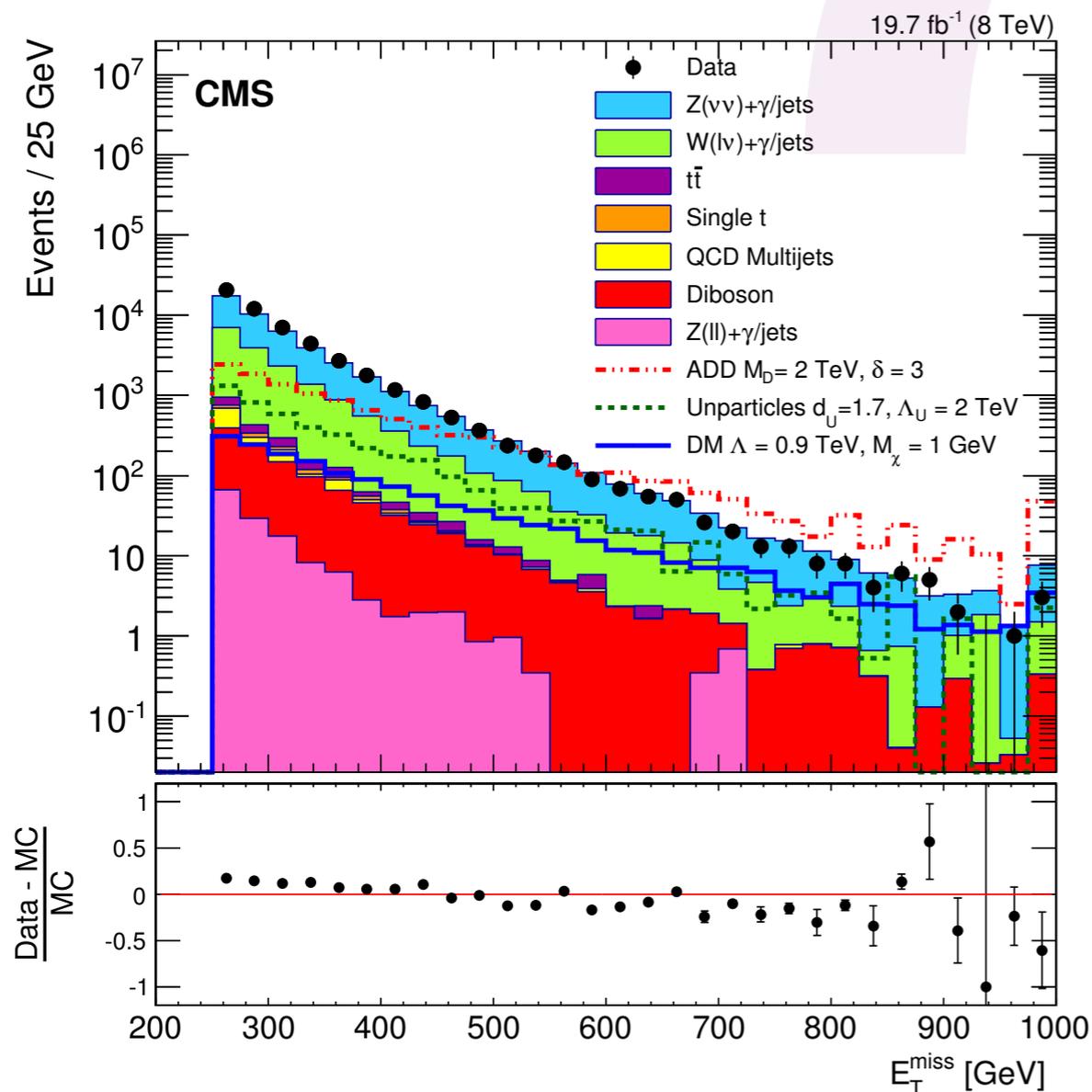
Monojet results



- Signal is a slight increase in the tail of the distribution
- **Difficult to observe**
- So far, no excess

Interpretation

How should we interpret these results so that we learn more about dark matter



Interpretation

How should we interpret these results so that we learn more about dark matter

One approach (unnamed experimentalist):

“Who cares!”

“We should only care about positive detections; why worry about interpreting no signal.”

Still useful to know what dark matter candidates we are excluding

Complementarity: Null searches still help us to understand positive detections (eg Fermi excess)

Interpretation

How should we interpret these results so that we learn more about dark matter

Problem: In which framework should we interpret the search?

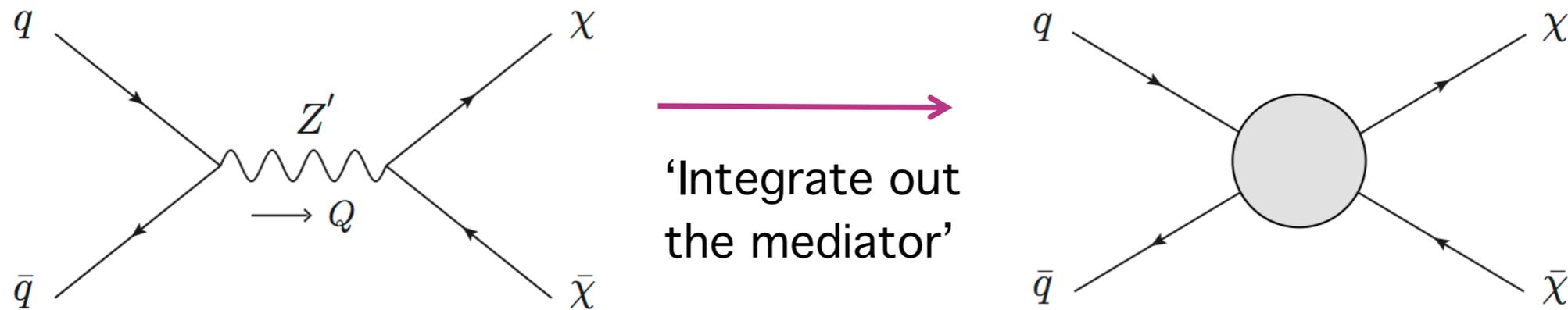
→ There is no canonical dark matter model (outside SUSY...)

Different approaches taken:

1. Contact interaction/Effective field theory
2. Simplified models

1. Effective field theory (EFT)

- Treat the interaction as a contact (point-like) interaction



$$\begin{aligned}\mathcal{L} &\sim g_\chi Z'_\mu \bar{\chi} \gamma^\mu \chi \\ &+ g_q Z'_\mu \bar{q} \gamma^\mu q \\ &+ \frac{1}{2} m_{Z'}^2 Z'_\mu Z'^\mu + \dots\end{aligned}$$

$$\mathcal{L} \sim \frac{1}{\Lambda^2} \bar{q} \gamma_\mu q \bar{\chi} \gamma^\mu \chi$$

- Parameter of interest is the contact interaction scale Λ

- Related to parameters in the full theory: $\Lambda = \frac{m_{Z'}}{\sqrt{g_q g_\chi}}$

This is not a new idea

- Fermi could describe β -decay without knowing the microscopic details:

$$\mathcal{L} = \frac{G_F}{\sqrt{2}} [\bar{\psi}\gamma^\mu(1 - \gamma^5)\psi] [\bar{\psi}\gamma_\mu(1 - \gamma^5)\psi] \quad \text{where } G_F \propto \frac{g_{\text{weak}}^2}{M_W^2}$$

- It is a very useful idea
- we don't need to know all details of the full theory
- Can (in principle) constrain many different theories:

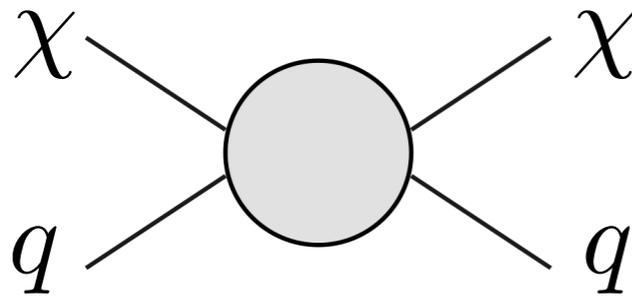
| Name | Operator | Coefficient |
|------|---|--------------------|
| D1 | $\bar{\chi}\chi\bar{q}q$ | m_q/M_*^3 |
| D2 | $\bar{\chi}\gamma^5\chi\bar{q}q$ | im_q/M_*^3 |
| D3 | $\bar{\chi}\chi\bar{q}\gamma^5q$ | im_q/M_*^3 |
| D4 | $\bar{\chi}\gamma^5\chi\bar{q}\gamma^5q$ | m_q/M_*^3 |
| D5 | $\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$ | $1/M_*^2$ |
| D6 | $\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$ | $1/M_*^2$ |
| D7 | $\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5q$ | $1/M_*^2$ |
| D8 | $\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5q$ | $1/M_*^2$ |
| D9 | $\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$ | $1/M_*^2$ |
| D10 | $\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi\bar{q}\sigma_{\alpha\beta}q$ | i/M_*^2 |
| D11 | $\bar{\chi}\chi G_{\mu\nu}G^{\mu\nu}$ | $\alpha_s/4M_*^3$ |
| D12 | $\bar{\chi}\gamma^5\chi G_{\mu\nu}G^{\mu\nu}$ | $i\alpha_s/4M_*^3$ |
| D13 | $\bar{\chi}\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$ | $i\alpha_s/4M_*^3$ |
| D14 | $\bar{\chi}\gamma^5\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$ | $\alpha_s/4M_*^3$ |

| Name | Operator | Coefficient |
|------|--|--------------------|
| C1 | $\chi^\dagger\chi\bar{q}q$ | m_q/M_*^2 |
| C2 | $\chi^\dagger\chi\bar{q}\gamma^5q$ | im_q/M_*^2 |
| C3 | $\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu q$ | $1/M_*^2$ |
| C4 | $\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu\gamma^5q$ | $1/M_*^2$ |
| C5 | $\chi^\dagger\chi G_{\mu\nu}G^{\mu\nu}$ | $\alpha_s/4M_*^2$ |
| C6 | $\chi^\dagger\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$ | $i\alpha_s/4M_*^2$ |
| R1 | $\chi^2\bar{q}q$ | $m_q/2M_*^2$ |
| R2 | $\chi^2\bar{q}\gamma^5q$ | $im_q/2M_*^2$ |
| R3 | $\chi^2 G_{\mu\nu}G^{\mu\nu}$ | $\alpha_s/8M_*^2$ |
| R4 | $\chi^2 G_{\mu\nu}\tilde{G}^{\mu\nu}$ | $i\alpha_s/8M_*^2$ |

Goodman et al
arXiv:1008.1783

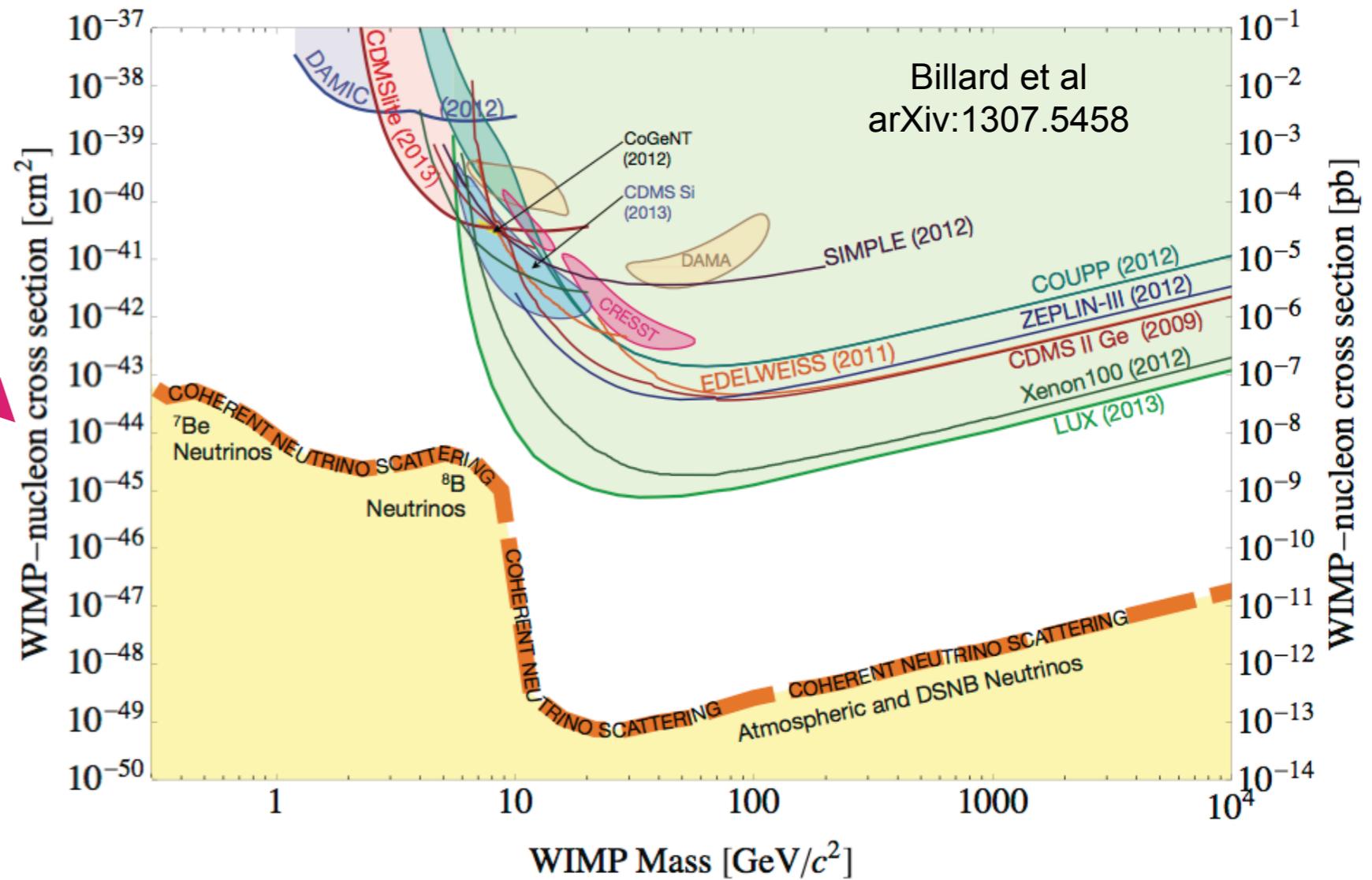
EFT in action: direct detection

$$\sigma \propto \frac{\text{GeV}^2}{\Lambda^4}$$



$$\mathcal{L} \sim \frac{1}{\Lambda^2} \bar{q} q \bar{\chi} \chi$$

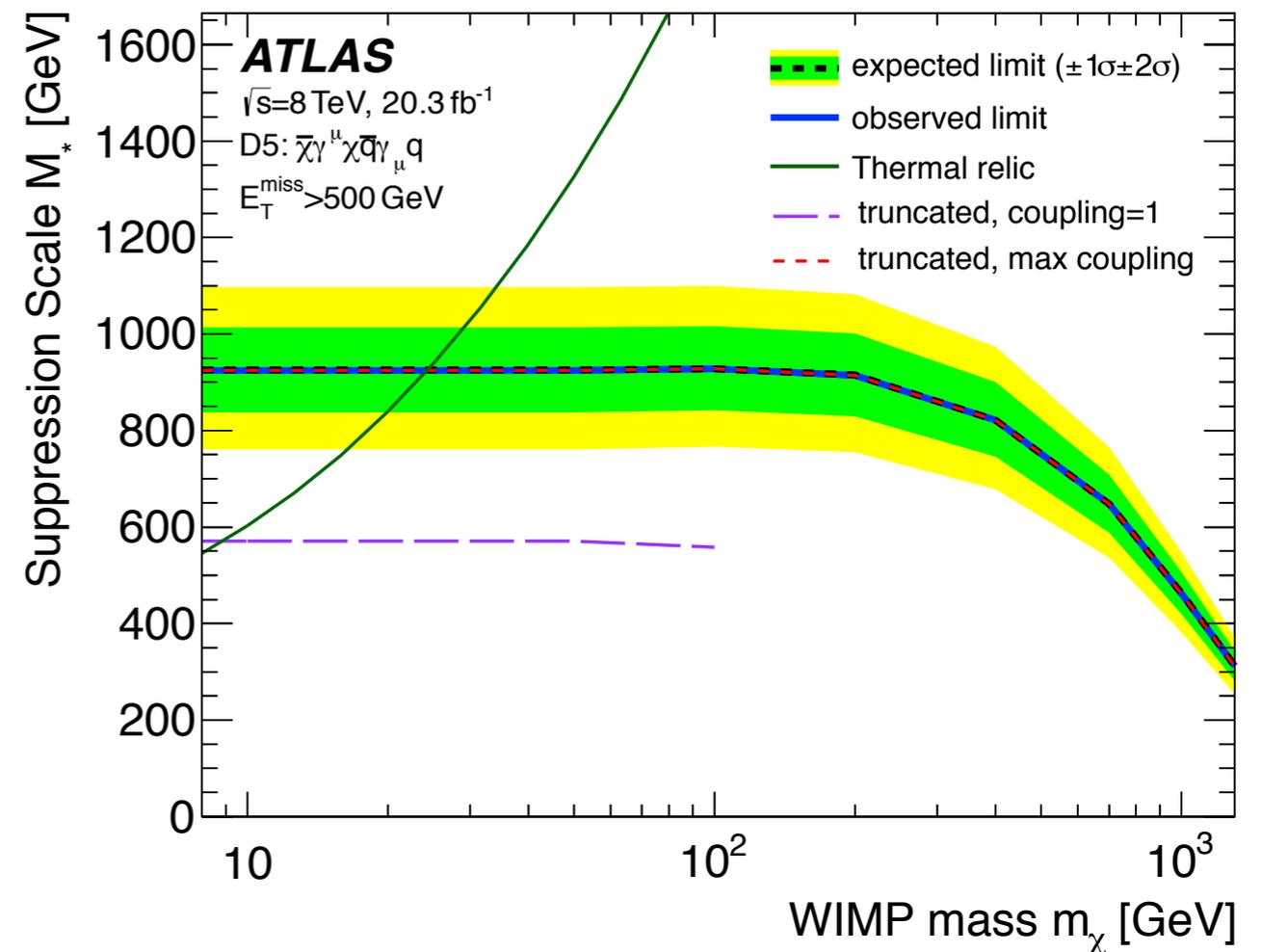
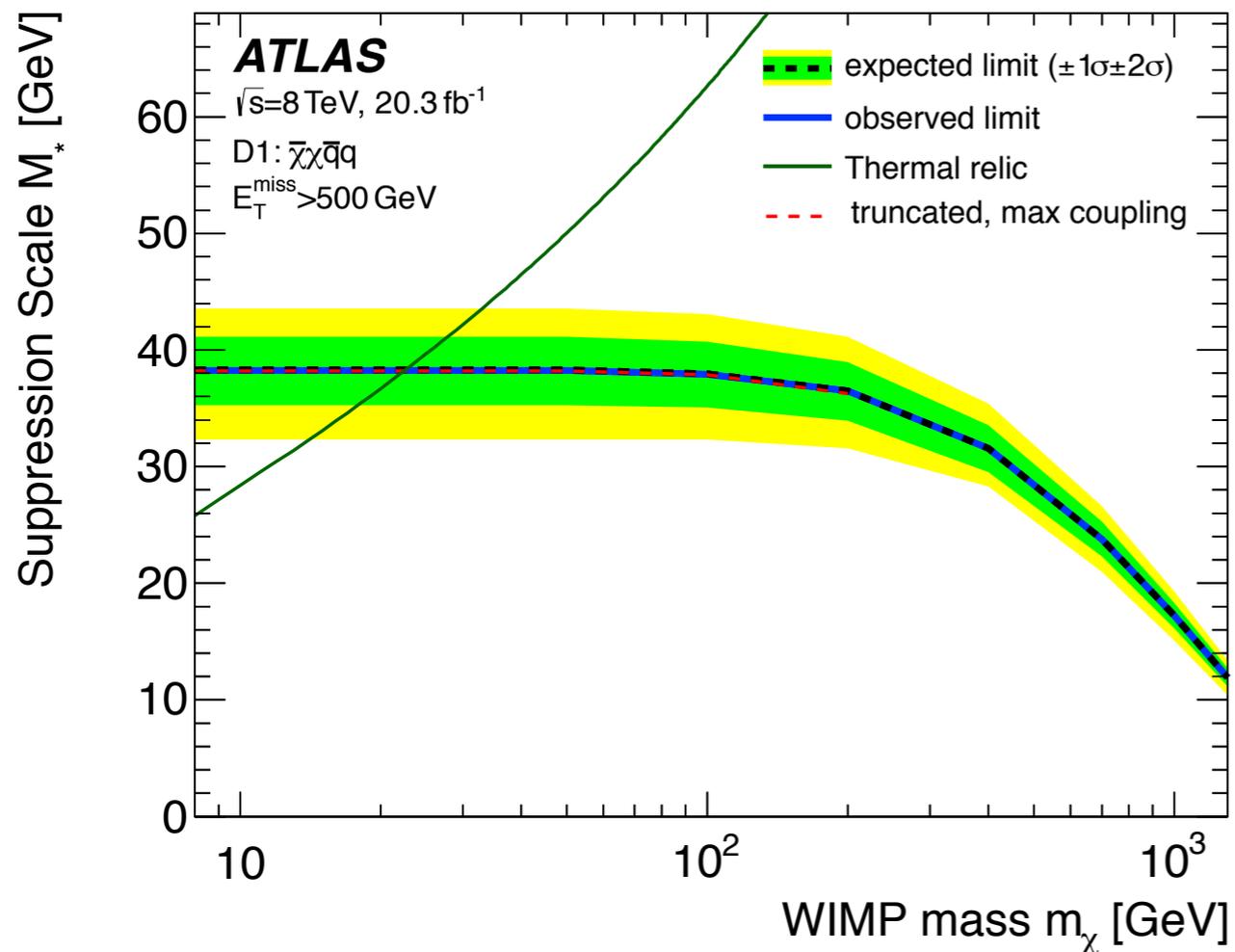
$$\mathcal{L} \sim \frac{1}{\Lambda^2} \bar{q} \gamma^\mu q \bar{\chi} \gamma_\mu \chi$$



One limit valid for multiple operators

EFT in action: monojet

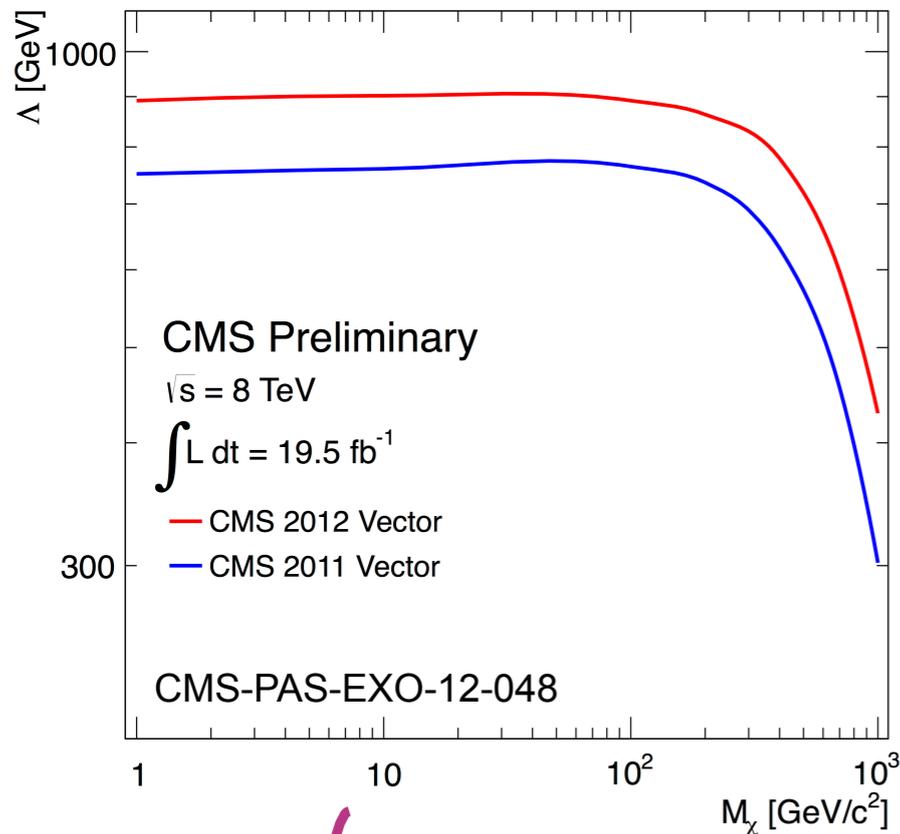
- Directly constrain Λ (or M_\star) for various operators



Separate limit for each operator

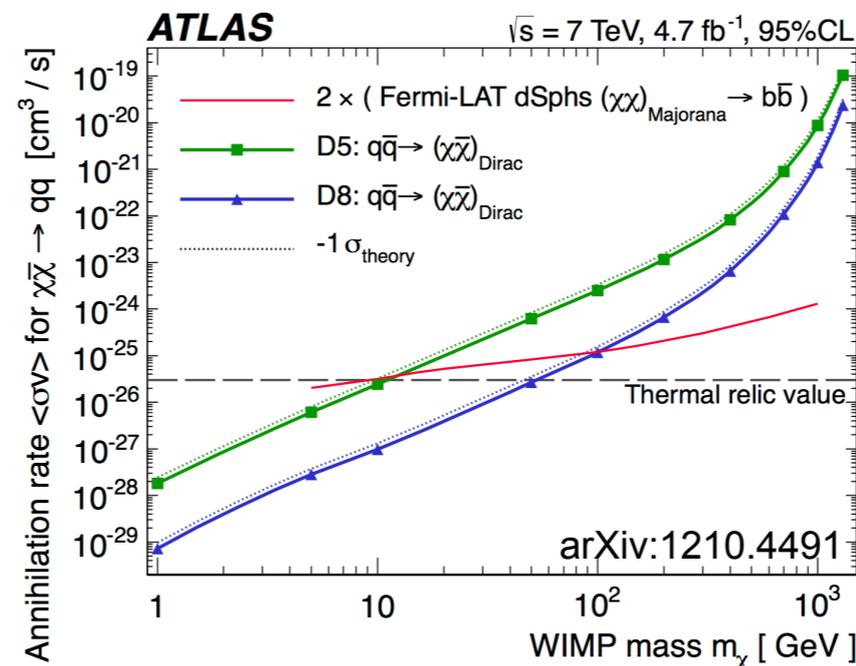
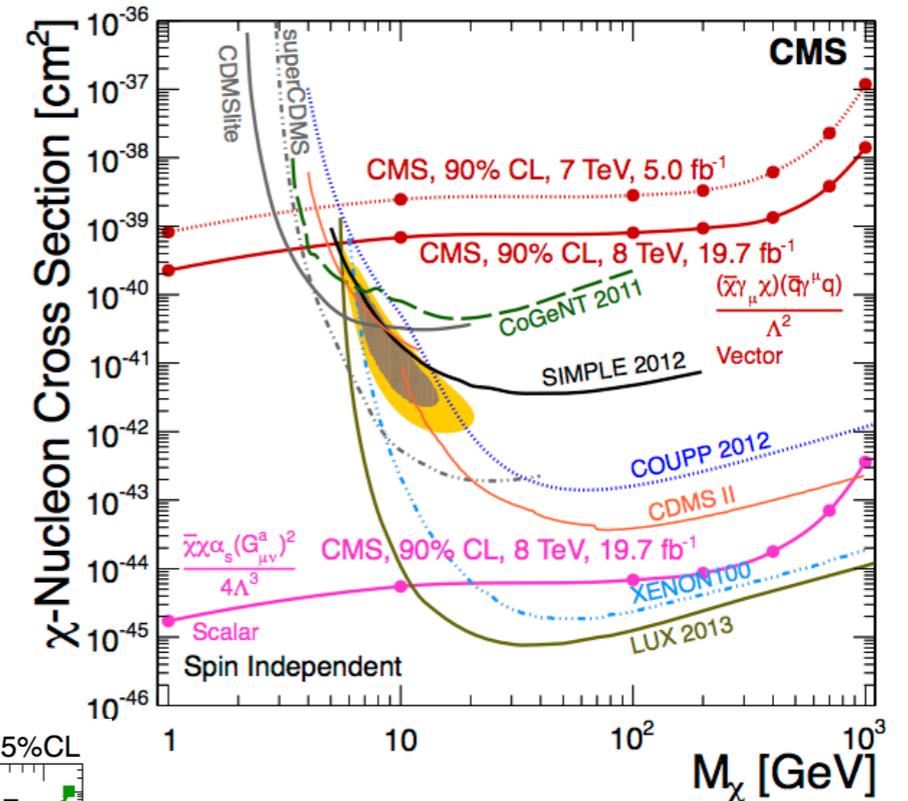
Advantage of EFT approach

- Comparison with other dark matter searches is straightforward



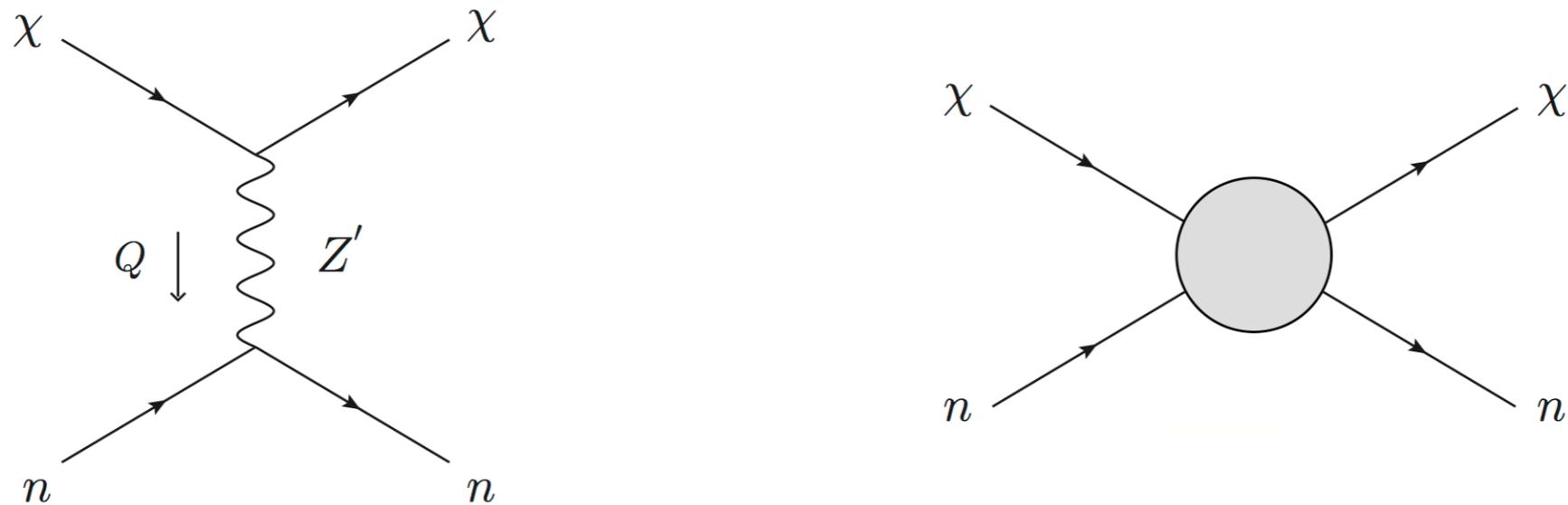
with indirect detection limits

with direct detection limits



EFT at direct detection: is it valid?

- A contact interaction at direct detection:



$$\sigma_n \sim \left(\frac{g_n g_\chi}{Q^2 - m_{Z'}^2} \right)^2 \approx \frac{g_n^2 g_\chi^2}{m_{Z'}^4} \left(1 + \frac{Q^2}{m_{Z'}^2} + \dots \right)^2$$

- Contact interaction if $m_{Z'} \gg Q = \sqrt{2m_n E_R} \approx 50 \text{ MeV}$
- Lots of theories satisfy this

A useful way to parameterise results

EFT at direct detection: is it valid?

A useful way to parameterise results... but should still be careful:

- Proposal: Explain DAMA modulation *and obtain relic density* by exchanging a pseudoscalar (Arina, Del Nobile, Panci; arXiv:1406.5542)

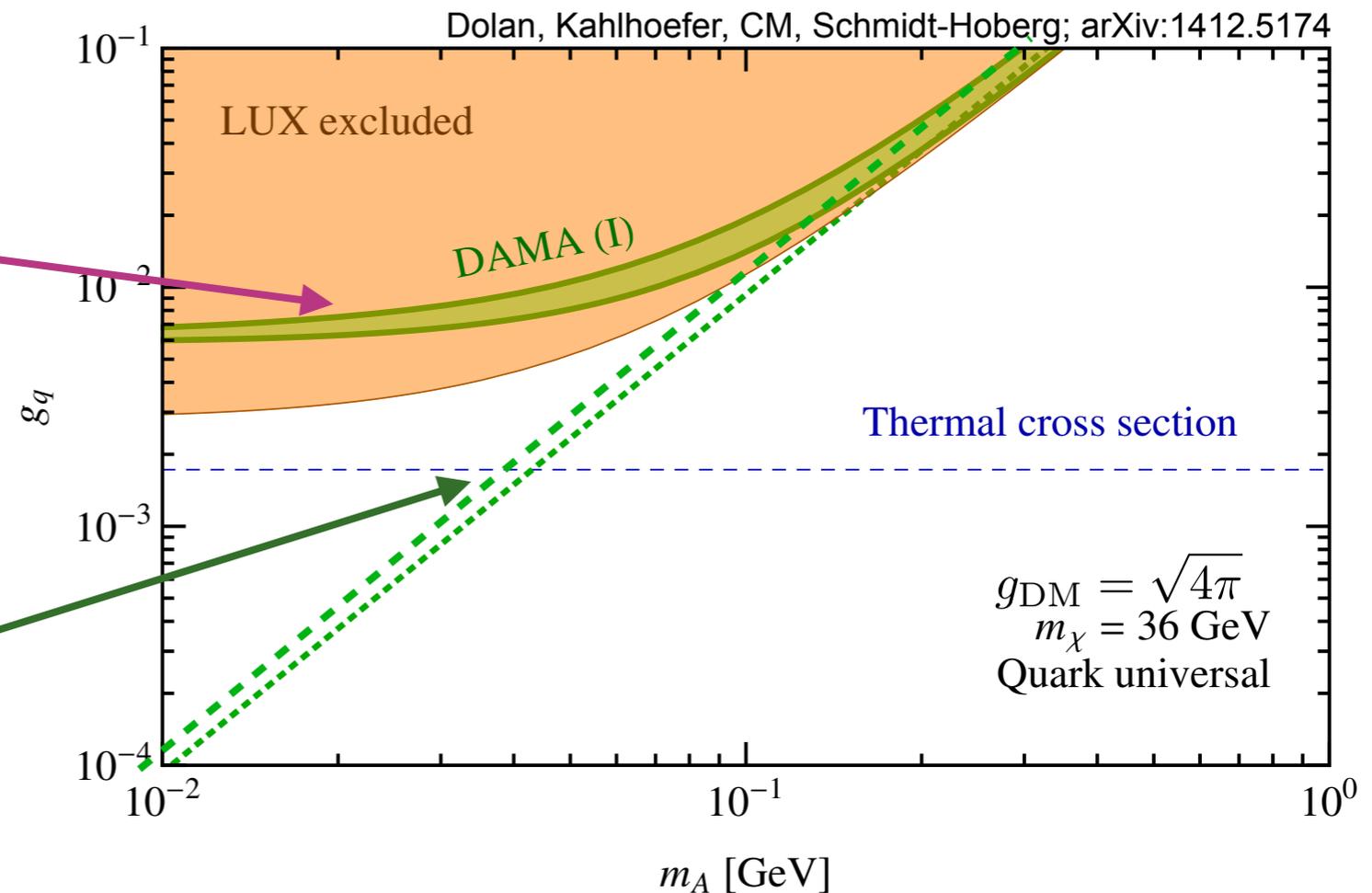
Full propagator:

$$\frac{d\sigma}{dE_R} \propto (q_{\min}^2 + m_A^2)^{-2}$$

$$q_{\min} \approx 70 - 100 \text{ MeV}$$

contact interaction:

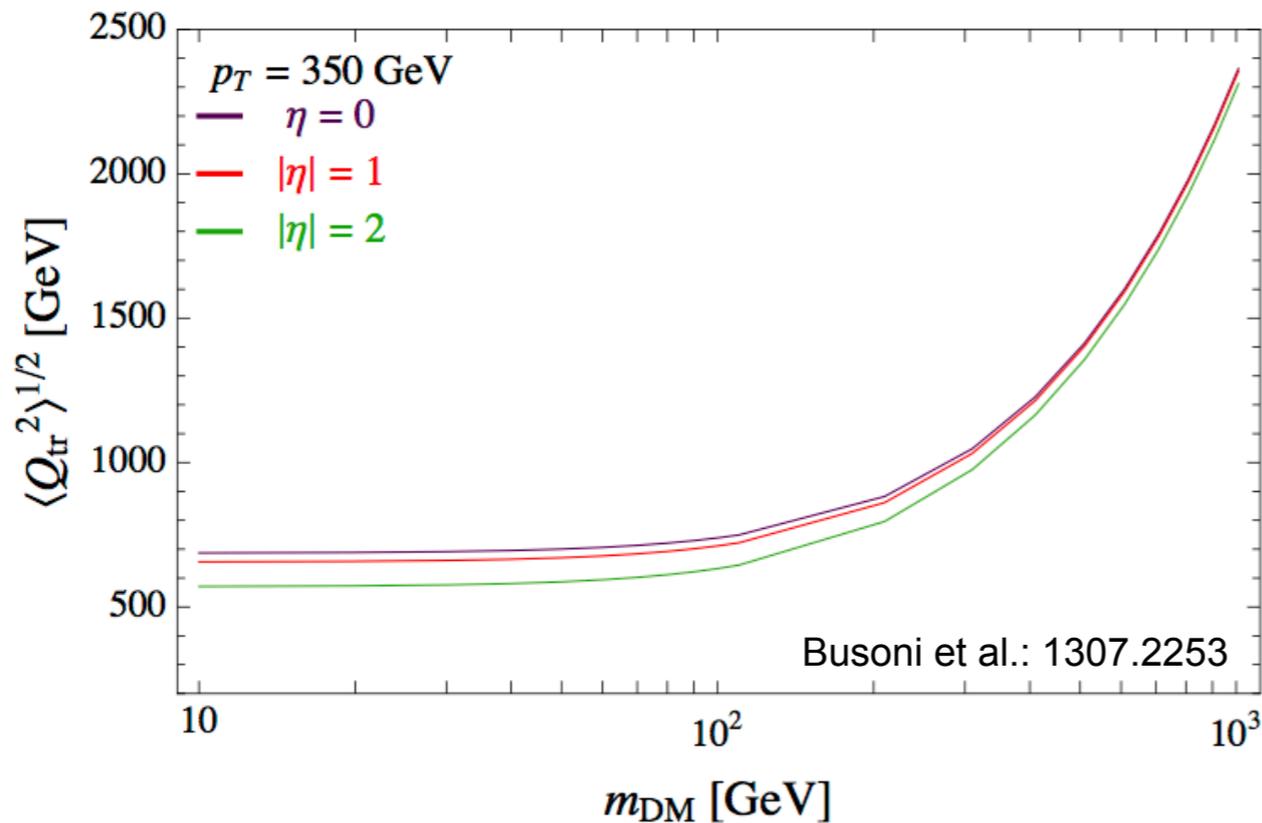
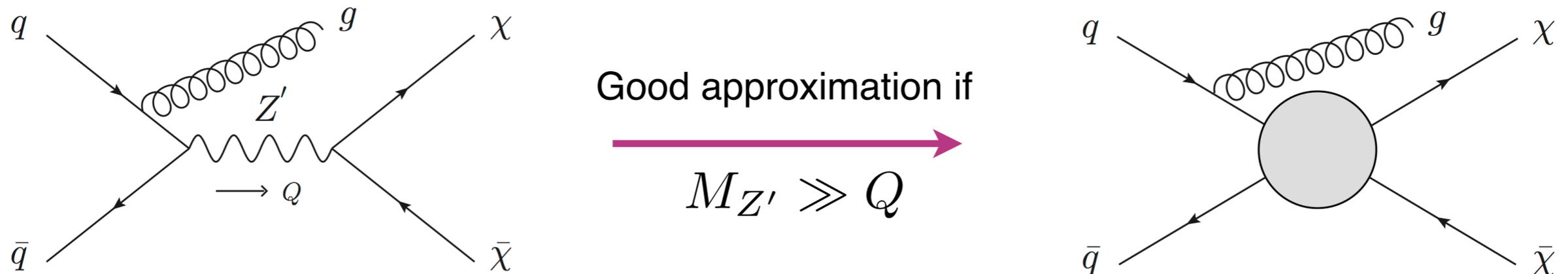
$$\frac{d\sigma}{dE_R} \propto m_A^{-4}$$



Breakdown of contact interaction completely changes conclusions

EFT in monojet: is it valid?

- A contact interaction at the LHC:

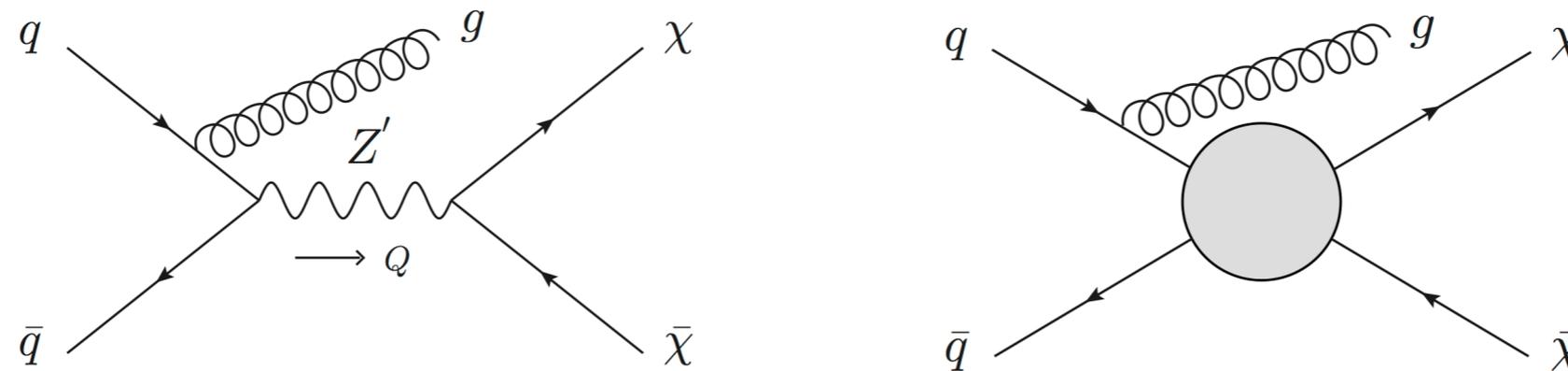


$$M_{Z'} \gtrsim \text{TeV}$$

EFT in monojet: is it valid?

Buchmueller, Dolan, CM
arXiv:1308.6799

- Better estimate: Compare a simple model with EFT result



- Assumptions:

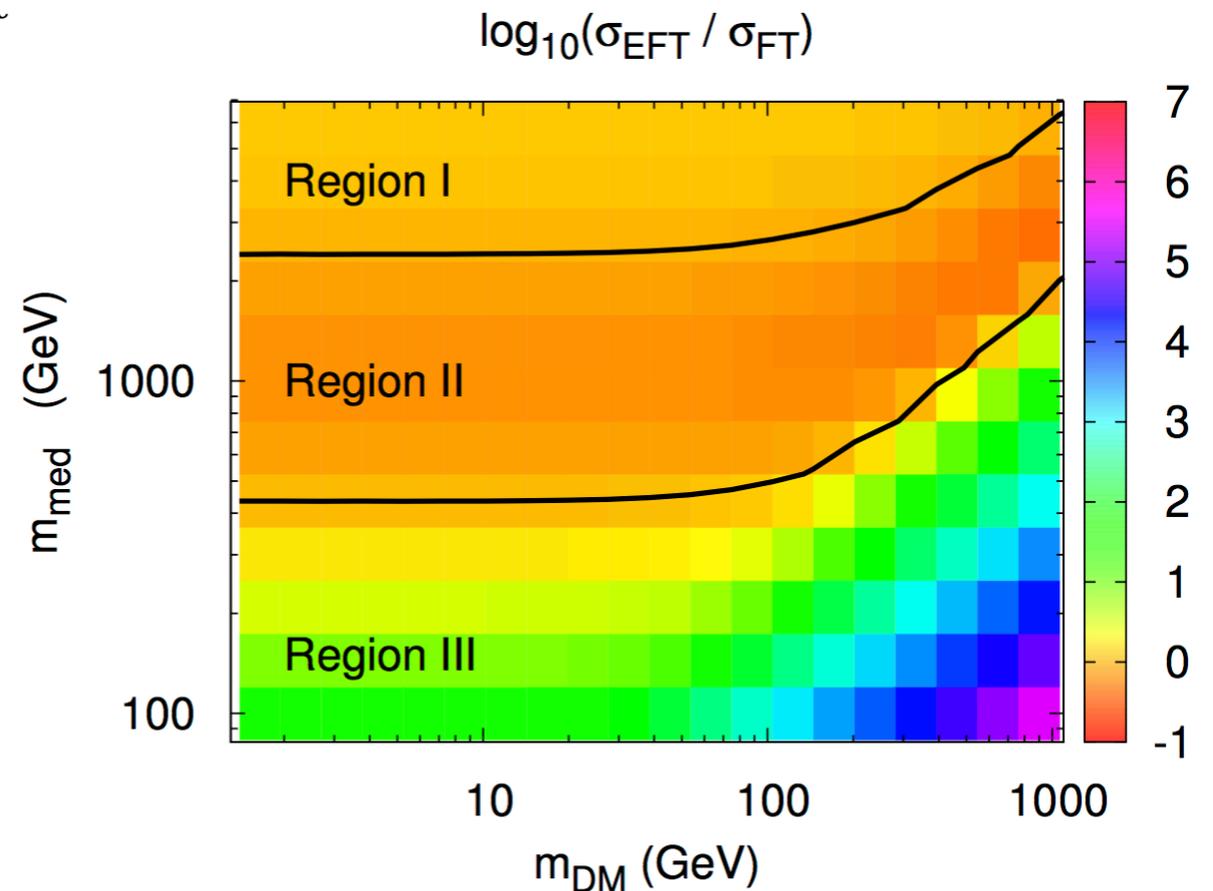
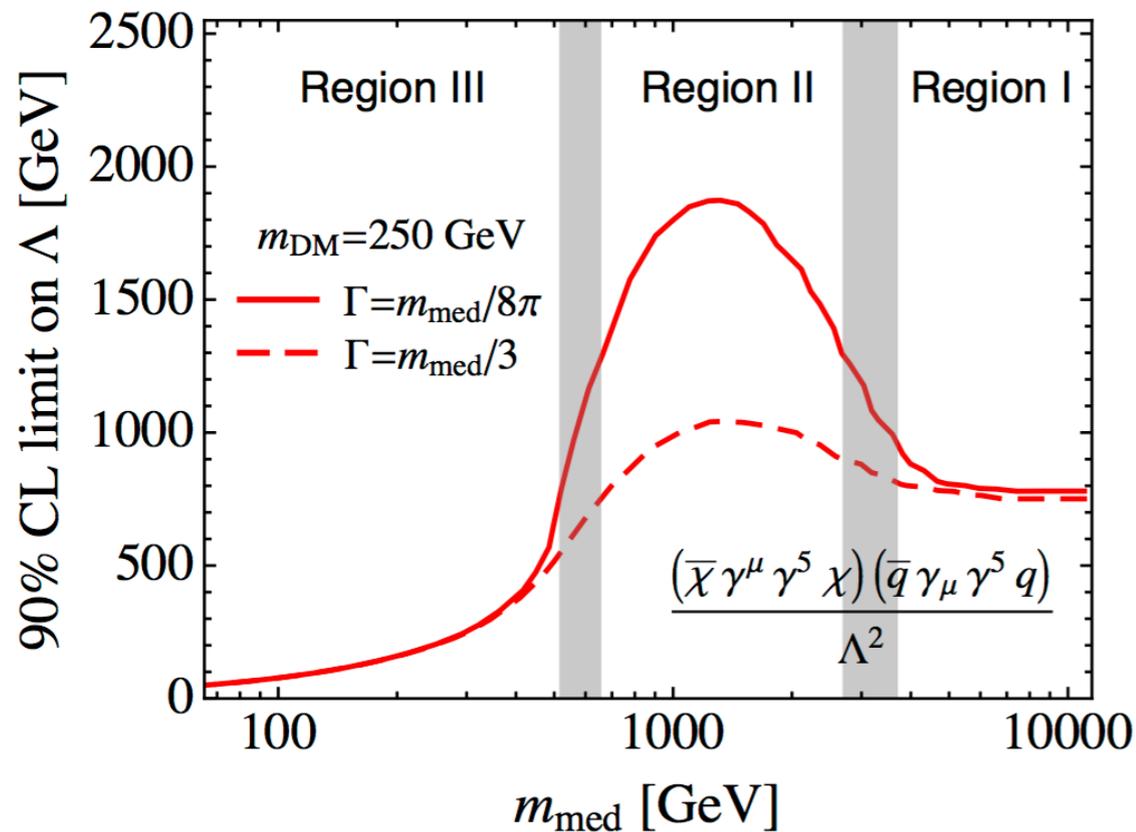
1. s-channel axial-vector mediator
2. Equal couplings to all quarks
3. No coupling to leptons or SM gauge bosons

- Said in Lagrangians:

$$\mathcal{L} \supset g_\chi Z'_\mu \bar{\chi} \gamma^\mu \gamma^5 \chi + g_q Z'_\mu \bar{q} \gamma^\mu \gamma^5 q \quad \text{vs} \quad \mathcal{L} \supset \frac{1}{\Lambda^2} \bar{\chi} \gamma^\mu \gamma^5 \chi \bar{q} \gamma_\mu \gamma^5 q$$

EFT in monojet: is it valid?

- Consider limit on $\Lambda = \frac{m_{\text{med}}}{\sqrt{g_q g_\chi}}$



- Region I: EFT limit is valid $m_{\text{med}} \gtrsim 3$ TeV
- Region II: EFT limit is too weak
- Region III: EFT limit is too strong $m_{\text{med}} \lesssim 500$ GeV

Region I: EFT valid

EFT limit applies to a small class of theories

- Large mediator mass:

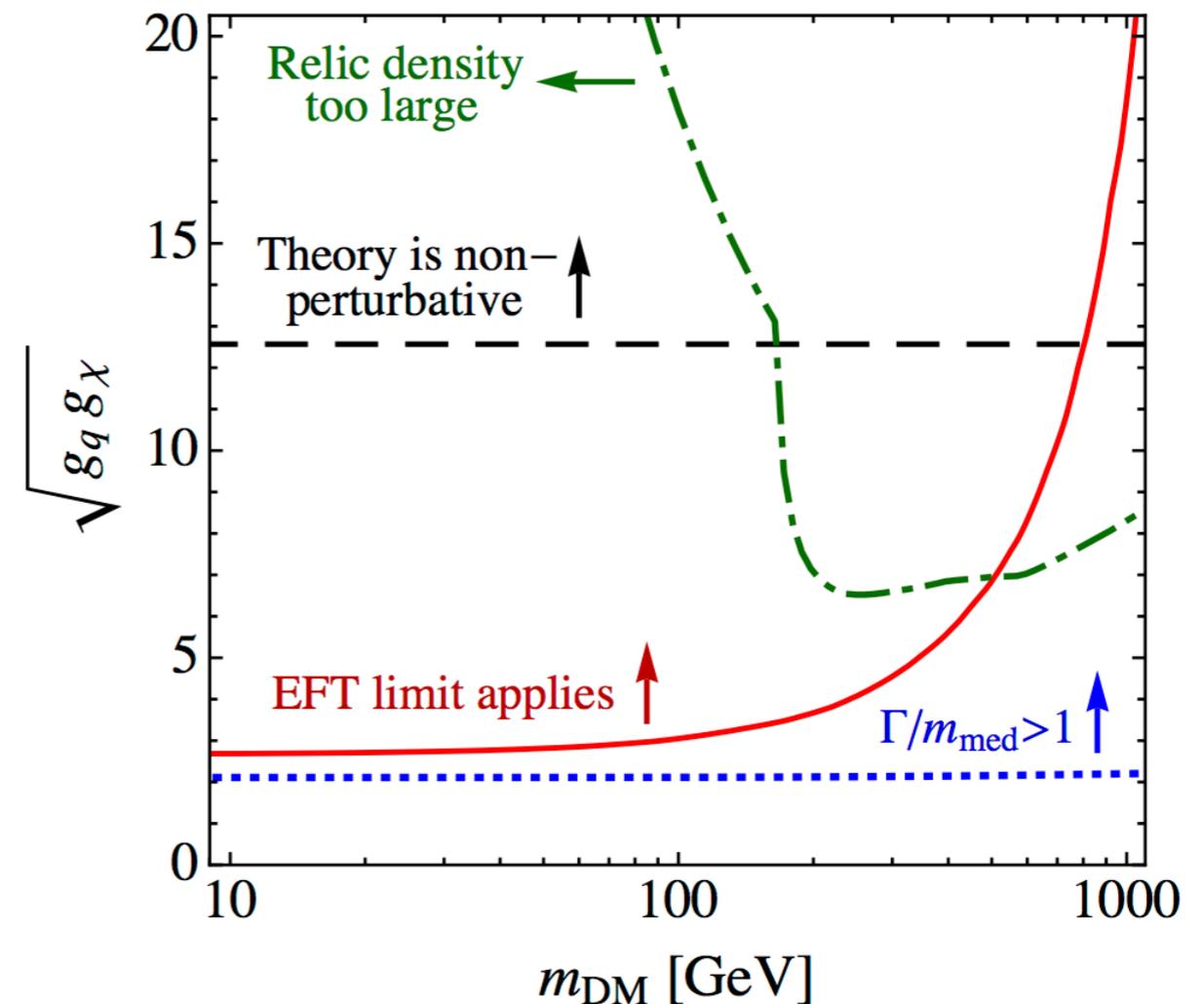
$$m_{\text{med}} \gtrsim 3 \text{ TeV}$$

- Large couplings:

$$\sqrt{g_q g_\chi} = \frac{m_{\text{med}}}{\Lambda}$$

- Large mediator width:

$$\Gamma > m_{\text{med}}$$



Region II: EFT too weak

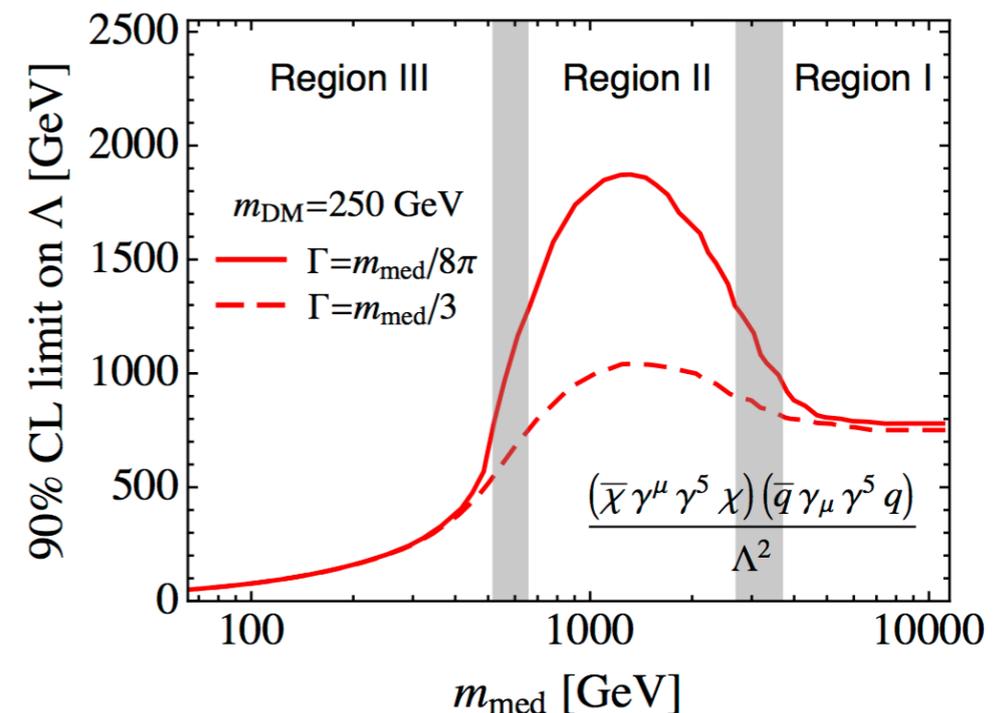
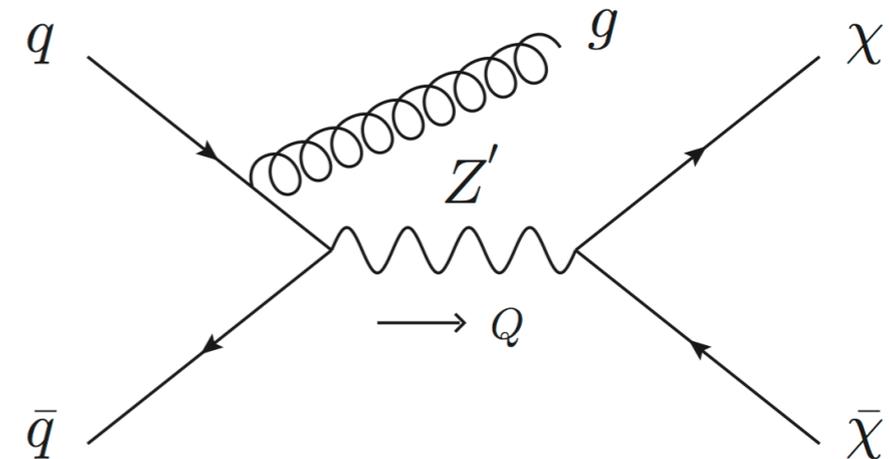
EFT does not account for s-channel resonant enhancement

- Enhanced when

$$m_{\text{med}}^2 \sim 4m_{\text{DM}}^2 + E_{\text{T}}^2$$

- The width plays a crucial role

- Peak height scales as $\Gamma^{-1/4}$



Region III: EFT too strong

EFT does not account for off-shell production

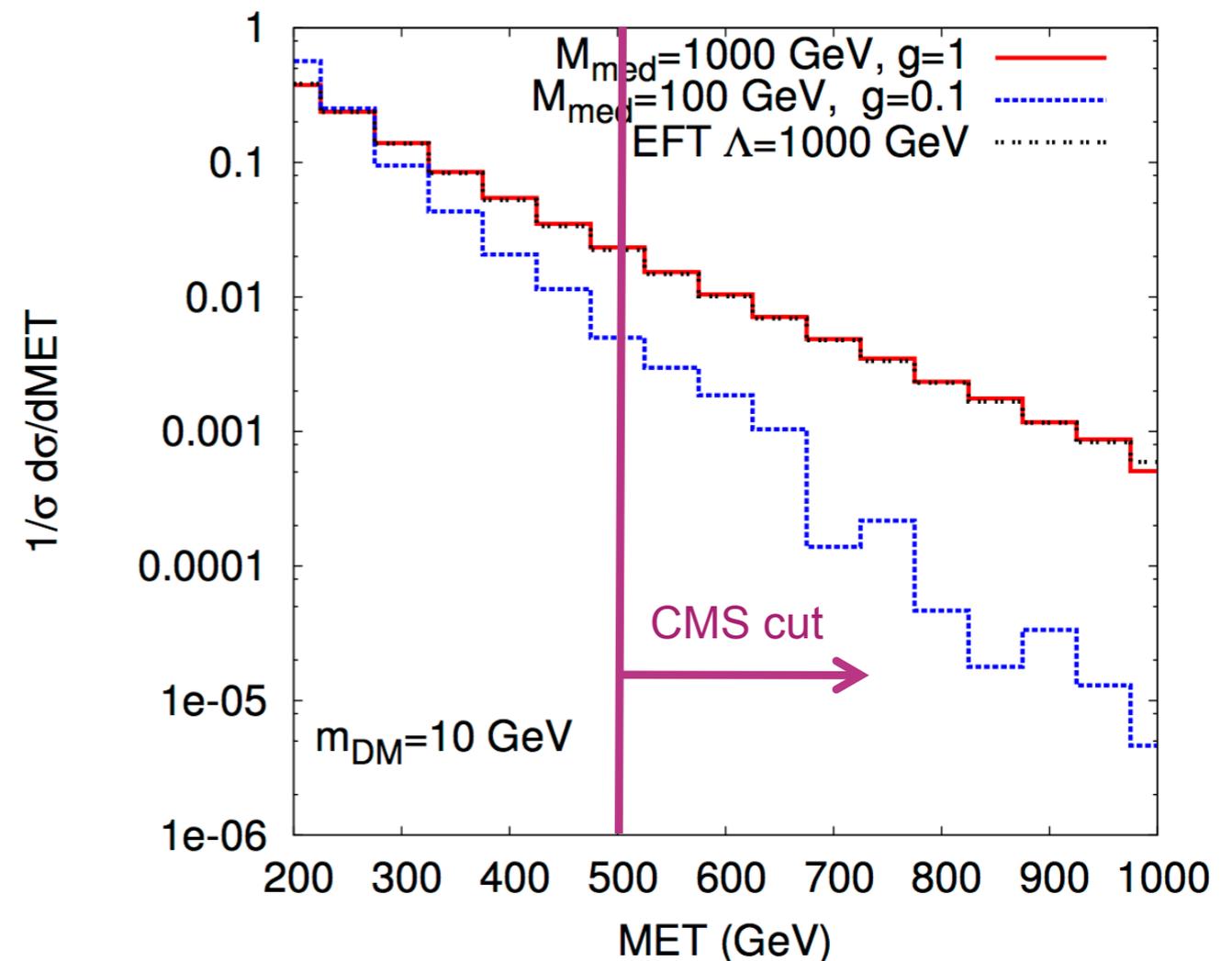
- Light mediator masses

$$m_{\text{med}} < 500 \text{ GeV}$$

- Events with a light mediator are much softer

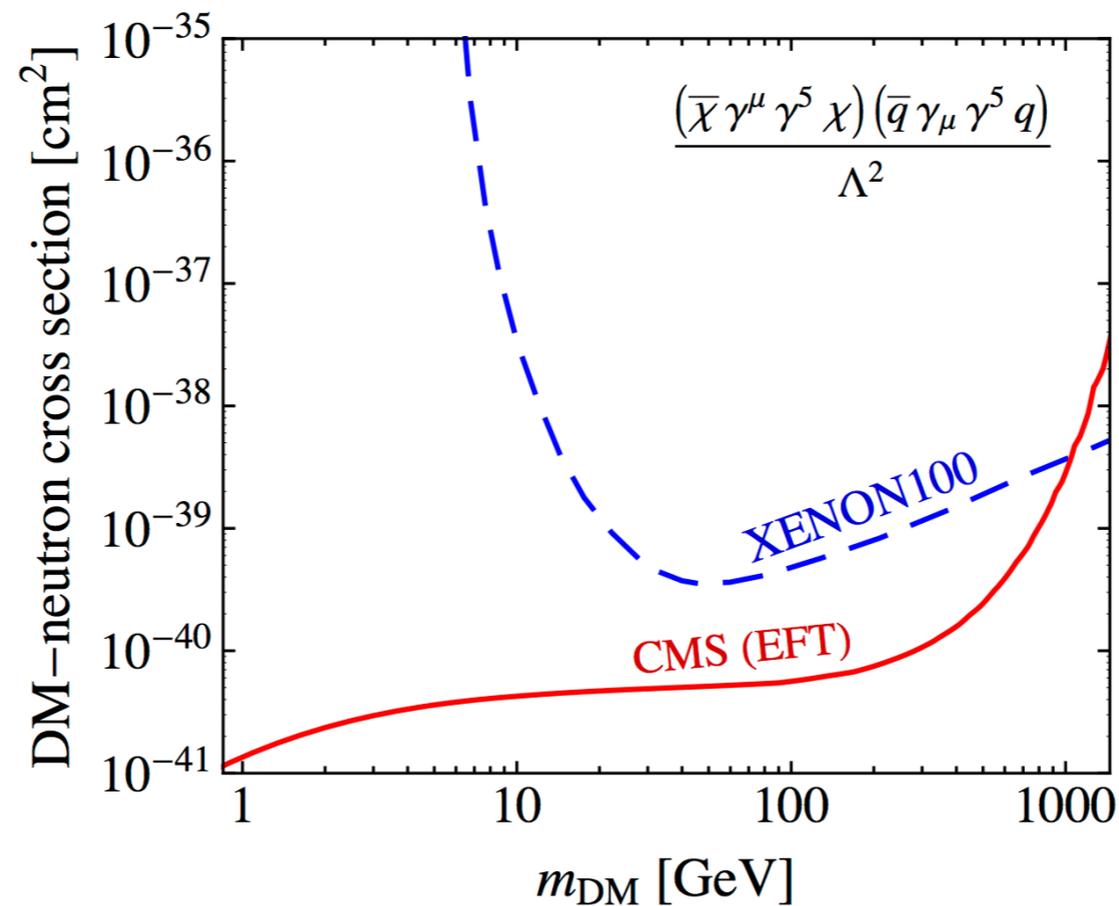
- EFT overestimates number of DM events produced

→ limit on Λ is too strong



Other problems

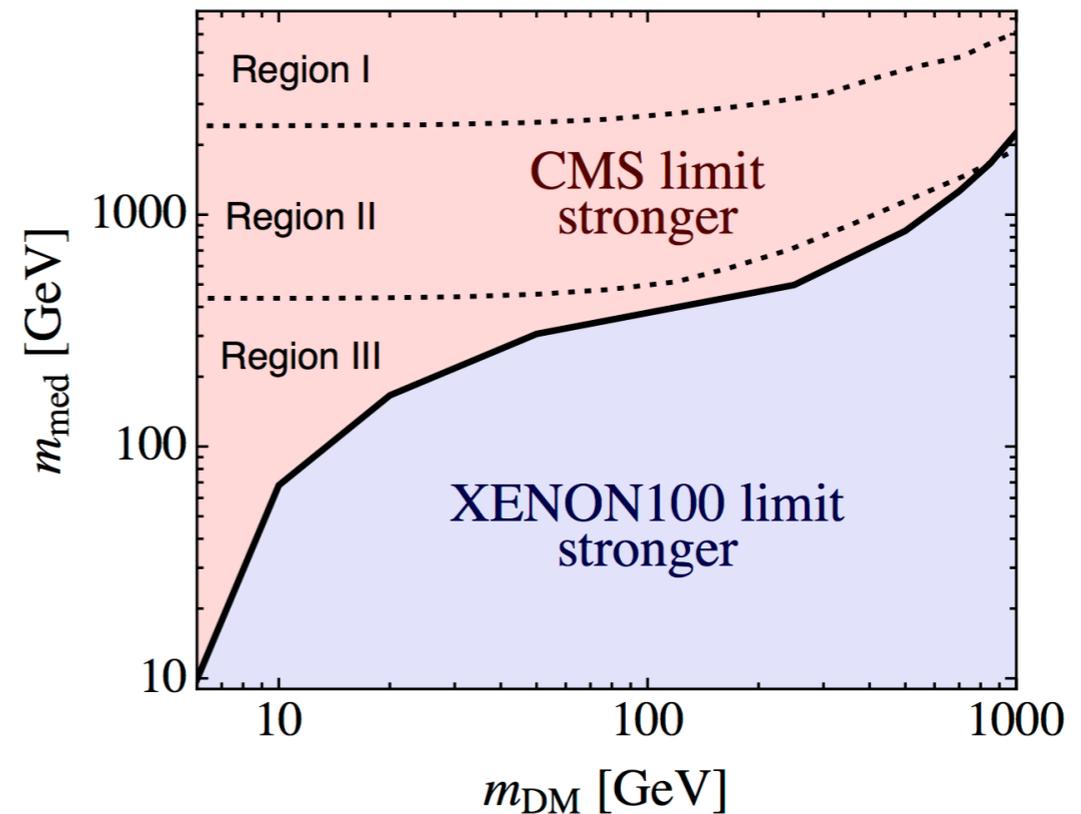
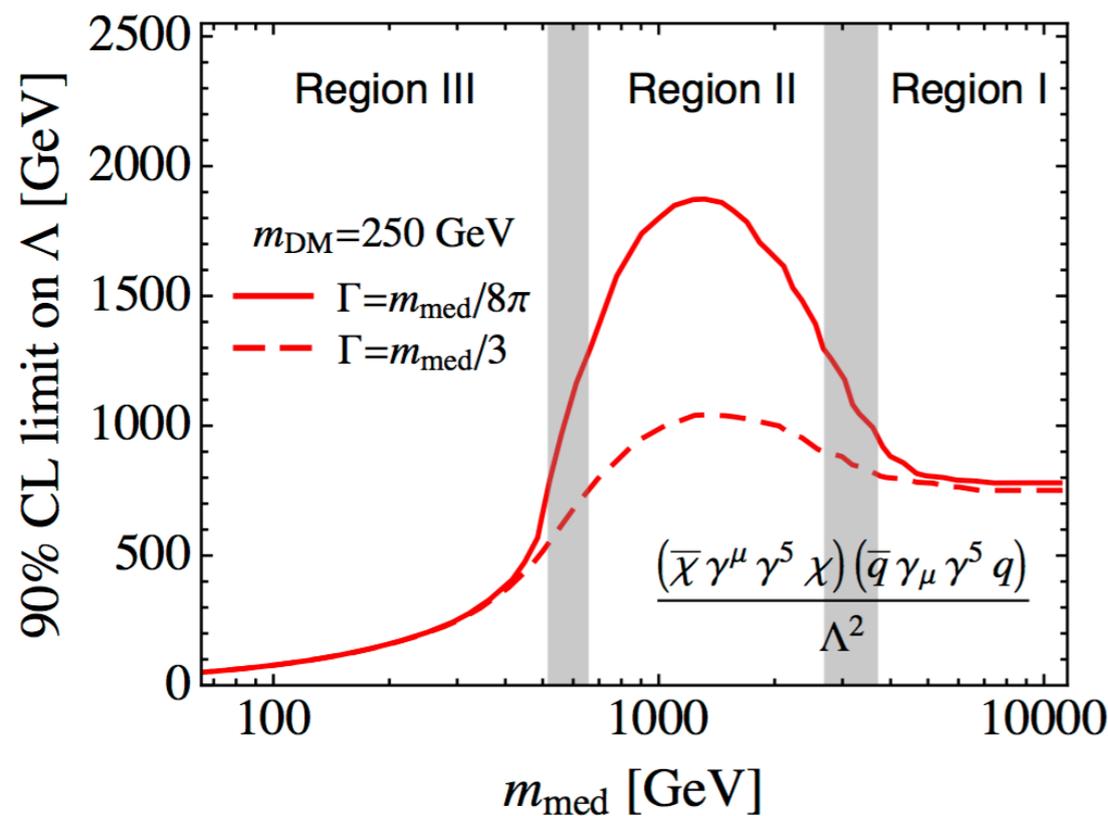
- Comparison with direct detection:



- Naive application of EFT limit gives the impression that the LHC limit is stronger for $m_{\text{DM}} \lesssim 1 \text{ TeV}$

Other problems

- Comparison with direct detection:
- Translate monojet limit to scattering cross section: $\sigma_n \propto \Lambda^{-4}$
- Remember dependence on m_{med} !



- As m_{med} decreases, direct detection limit is stronger

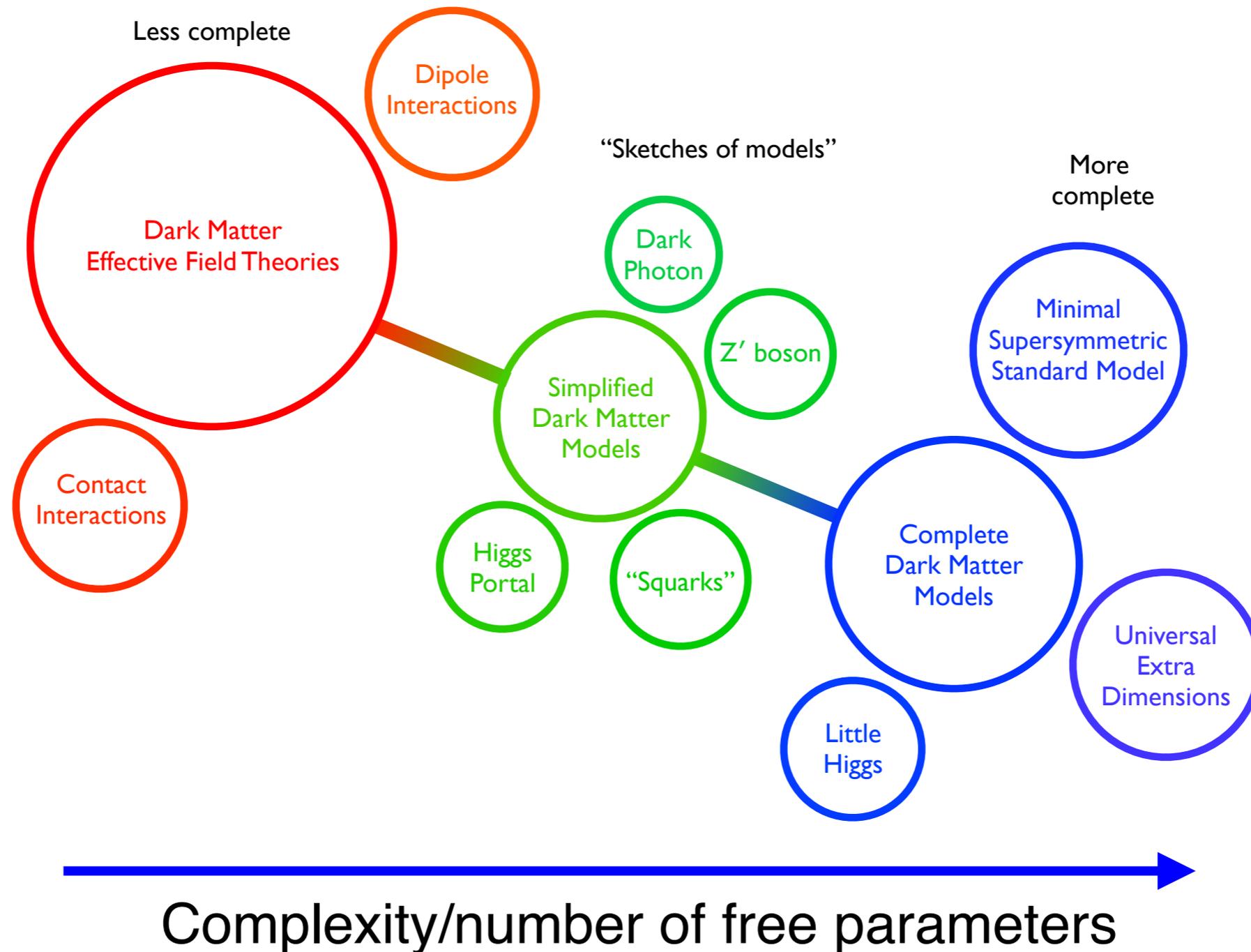
EFT interpretation: mini-summary

- EFT/contact interaction works well for direct detection
 - ➔ valid for most models (mediator > 100 MeV)
- EFT/contact interaction has problems with monojet search
 - ➔ EFT doesn't capture kinematics of monojet search
 - ➔ no resonance, no off-shell mediator production
 - ➔ Naive comparison with direct searches can be misleading

Is there a another approach for the monojet search...?

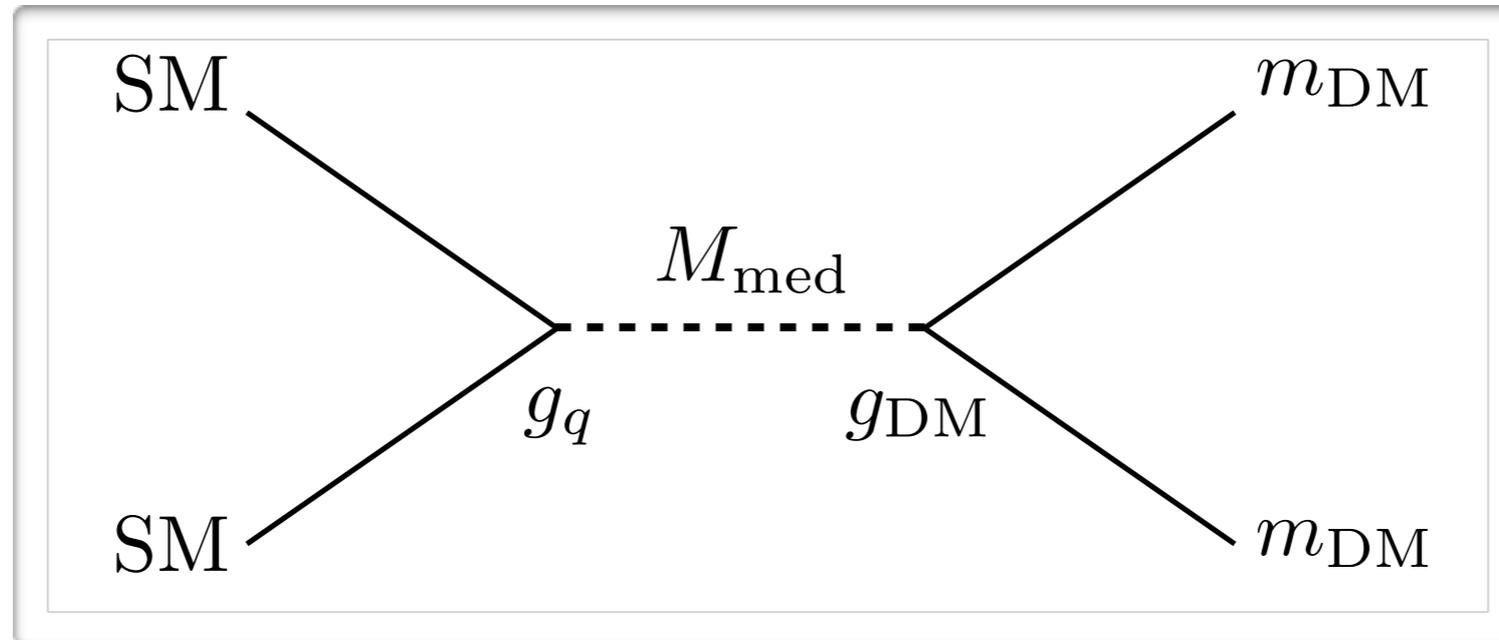
Beyond EFT...

Abdallah et al
arXiv:1506.03116



2. Simplified models

- Characterise collider dark matter production with a small number of variables



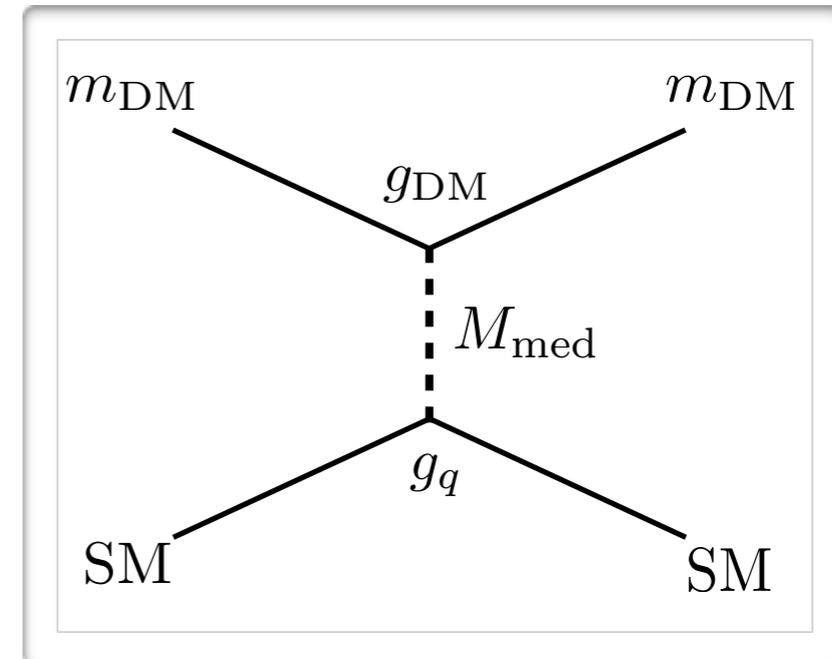
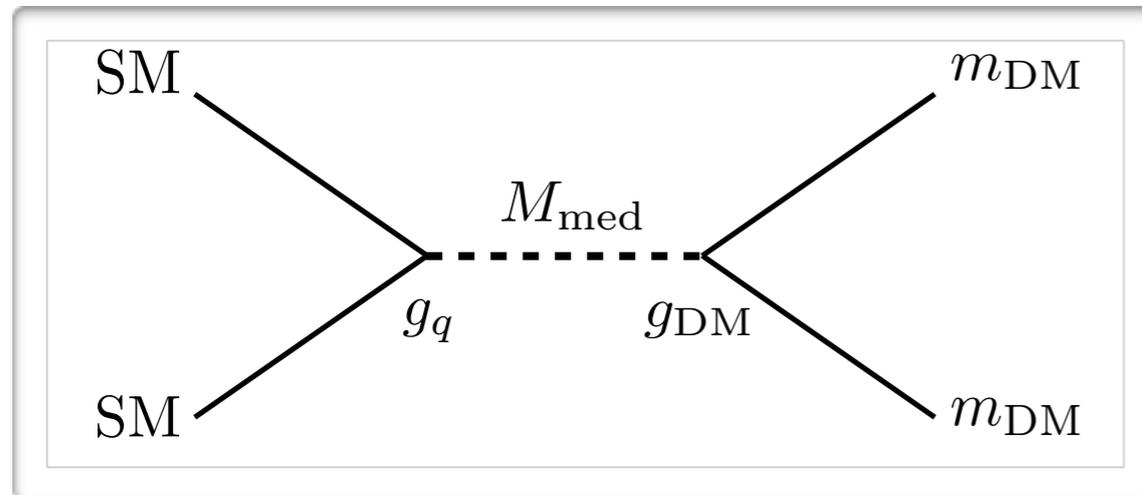
| Minimum 4 parameters | |
|----------------------|------------------|
| m_{DM} | M_{med} |
| g_q | g_χ |

| Mediators | |
|-----------|---------------|
| Vector | Axial-Vector |
| Scalar | Pseudo-scalar |

| Dark matter | |
|-------------|----------------|
| Dirac | Complex scalar |
| Majorana | Real scalar |

2. Simplified models

- Same parameters also characterise direct searches



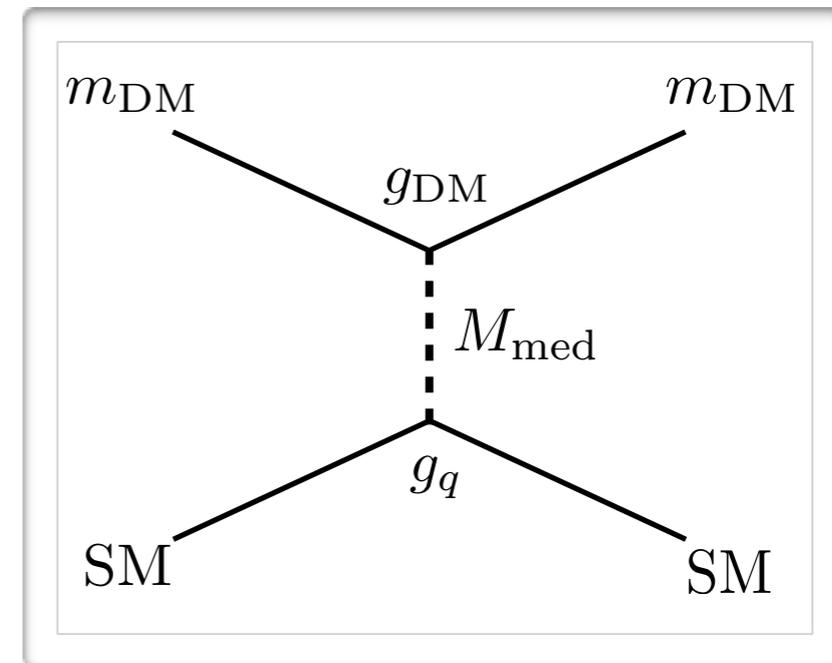
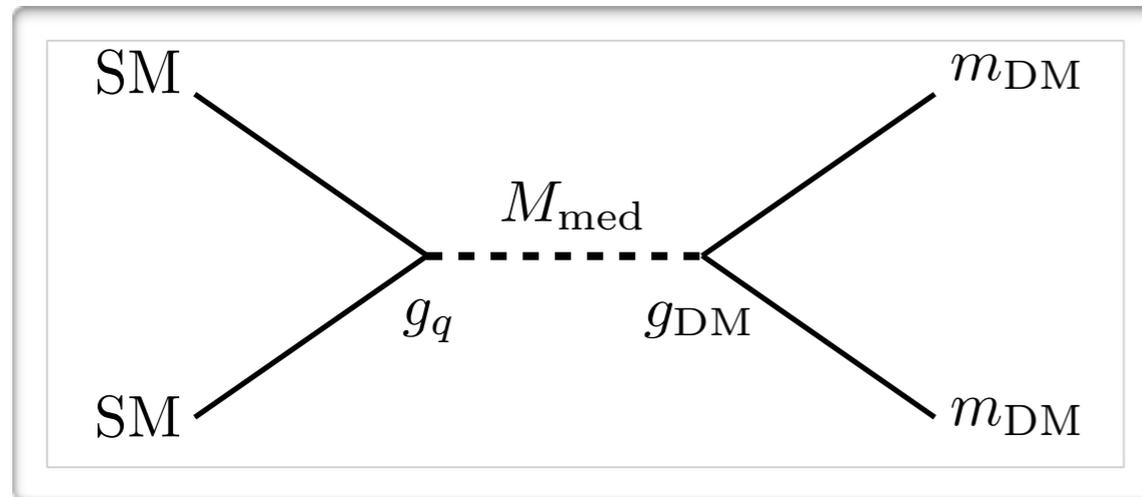
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2. Simplified models

- Same parameters also characterise direct searches



| Minimum 4 parameters | |
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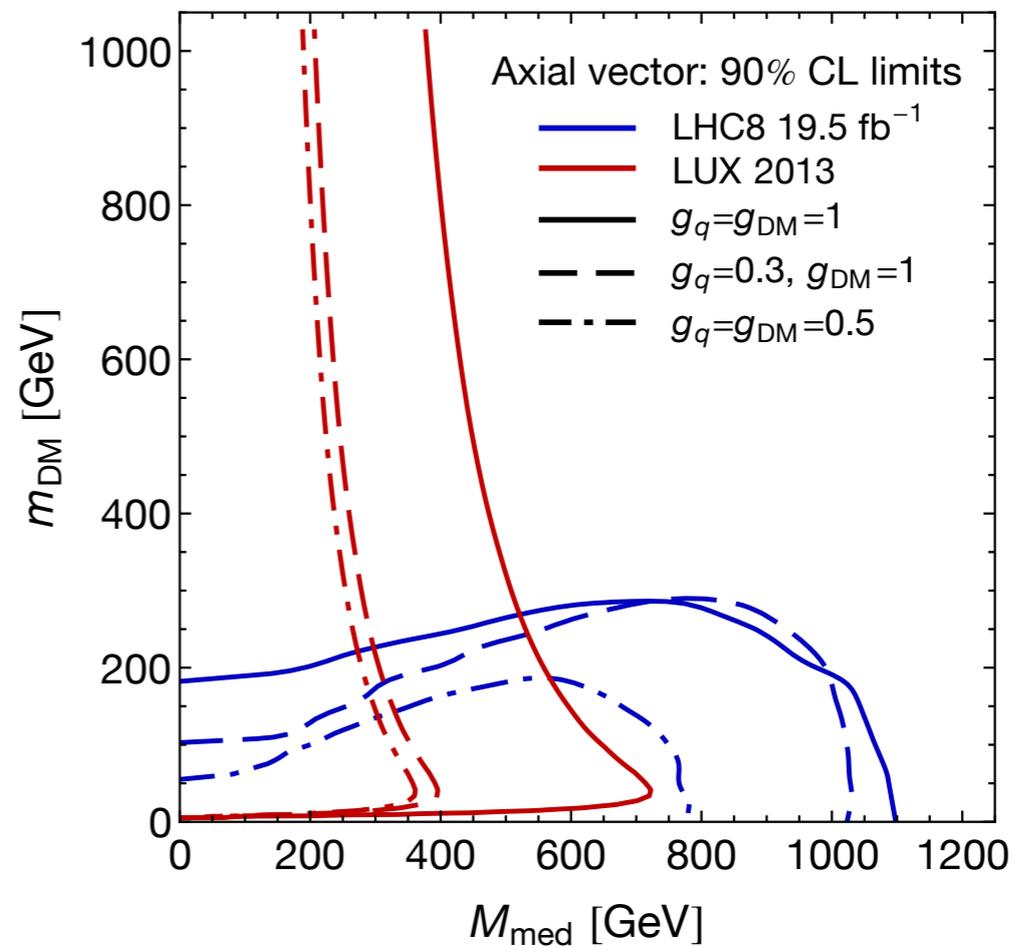
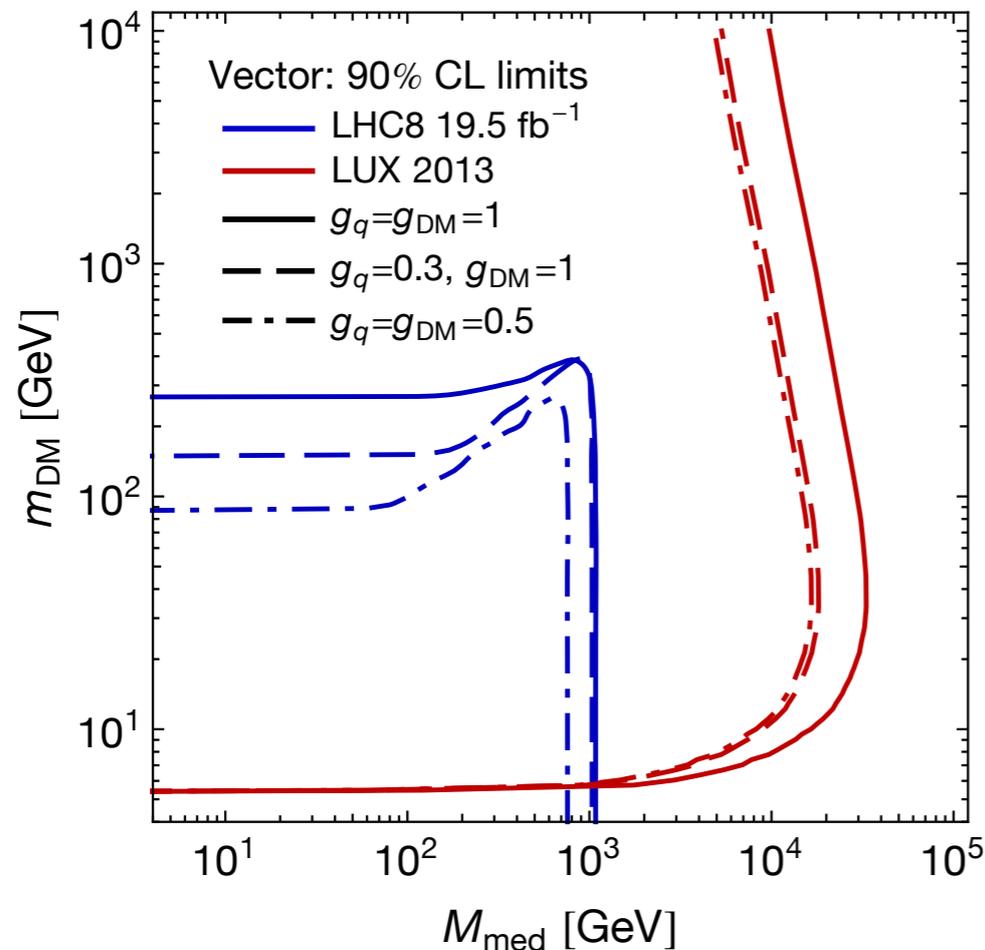
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| Dark matter | |
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Slicing through parameter space

- We need to fix two parameters to show results:

| | |
|------------------|----------|
| m_{DM} | g_χ |
| M_{med} | g_q |

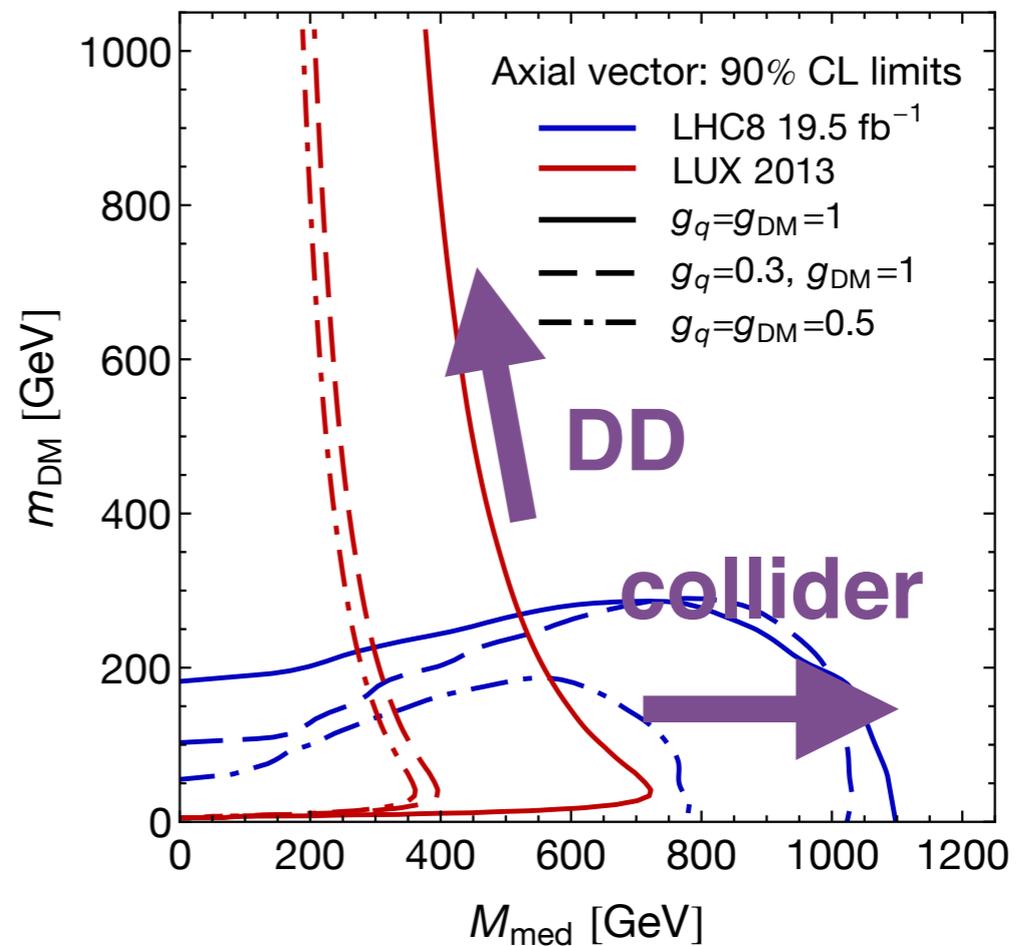
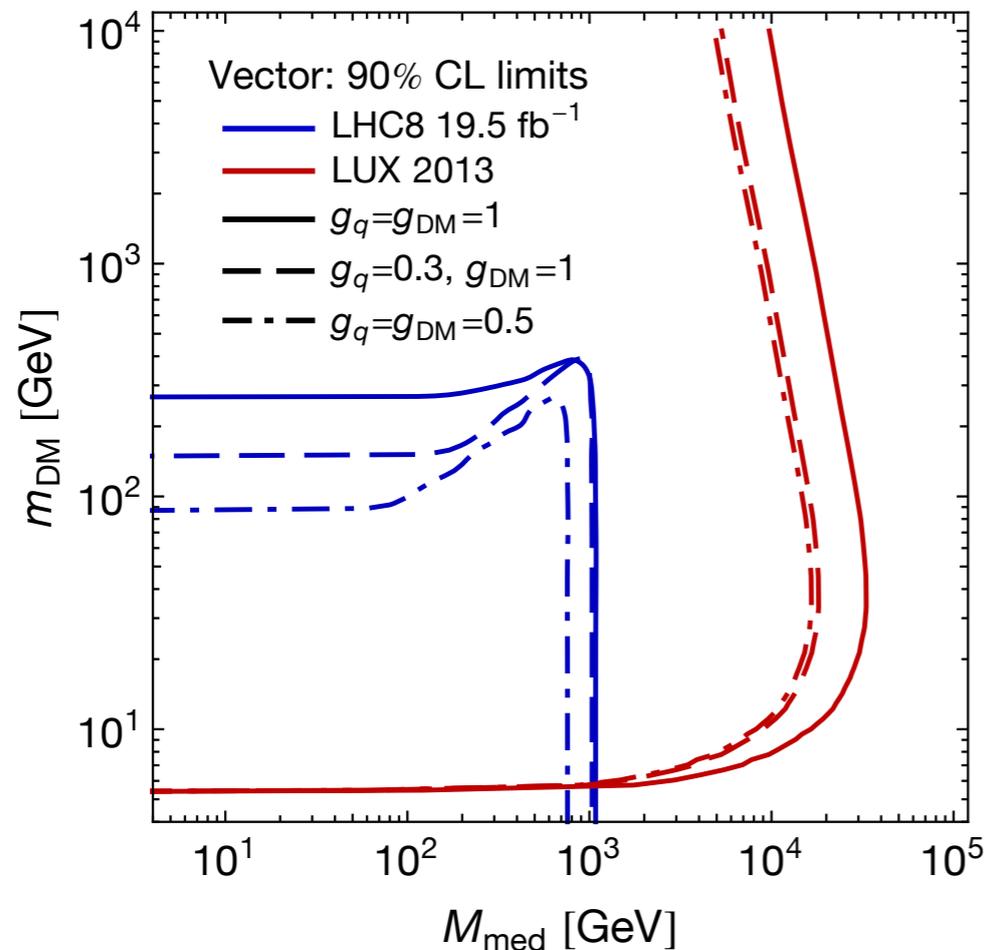


- Limits valid for all dark matter and mediator masses
- Includes resonant enhancement/off-shell suppression effects

Slicing through parameter space

- We need to fix two parameters to show results:

| | |
|------------------|----------|
| m_{DM} | g_χ |
| M_{med} | g_q |



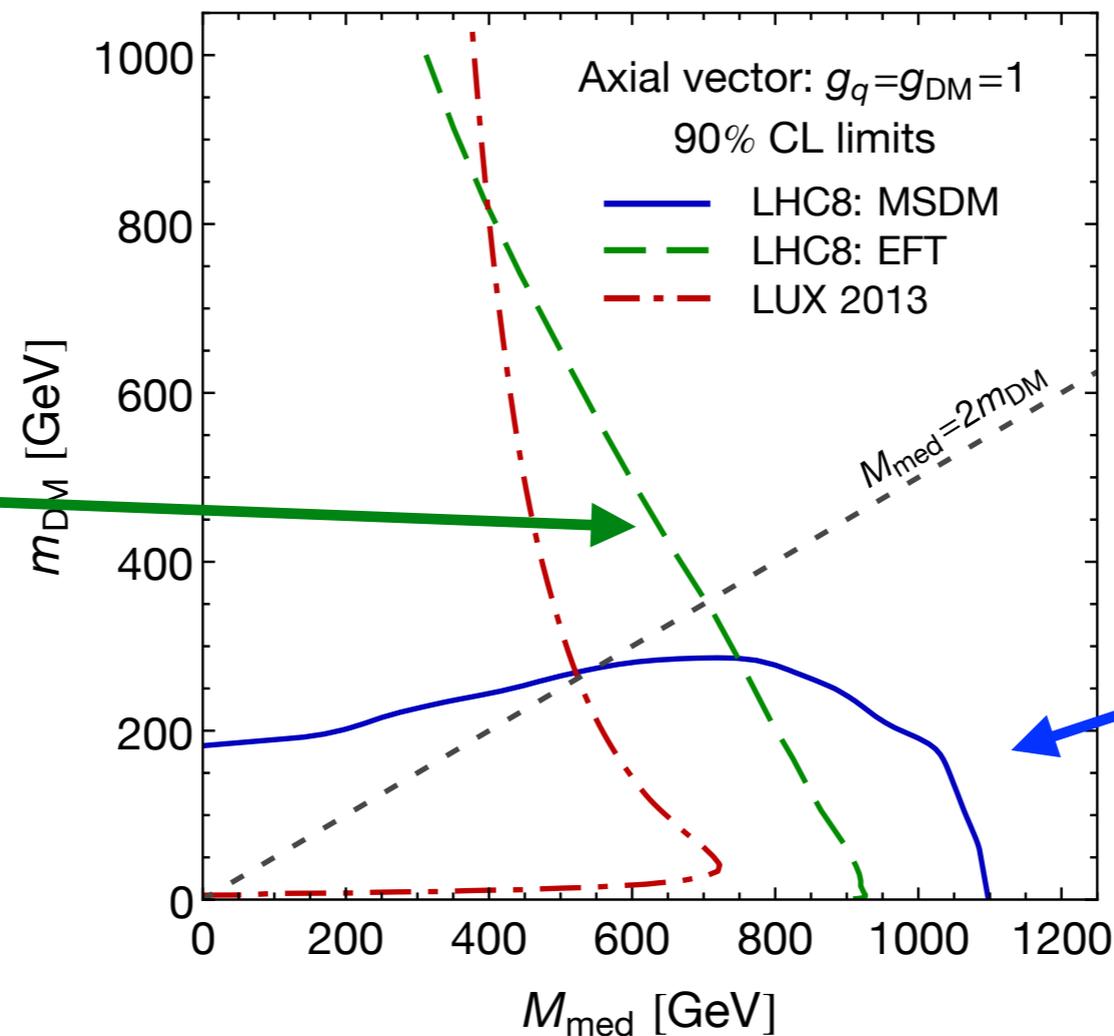
- Better elucidation of the complementarity between collider and direct searches

Slicing through parameter space

| | |
|------------------|----------|
| m_{DM} | g_χ |
| M_{med} | g_q |

- We need to fix two parameters to show results:

Exclusion limit
if you naively
used the EFT
limit



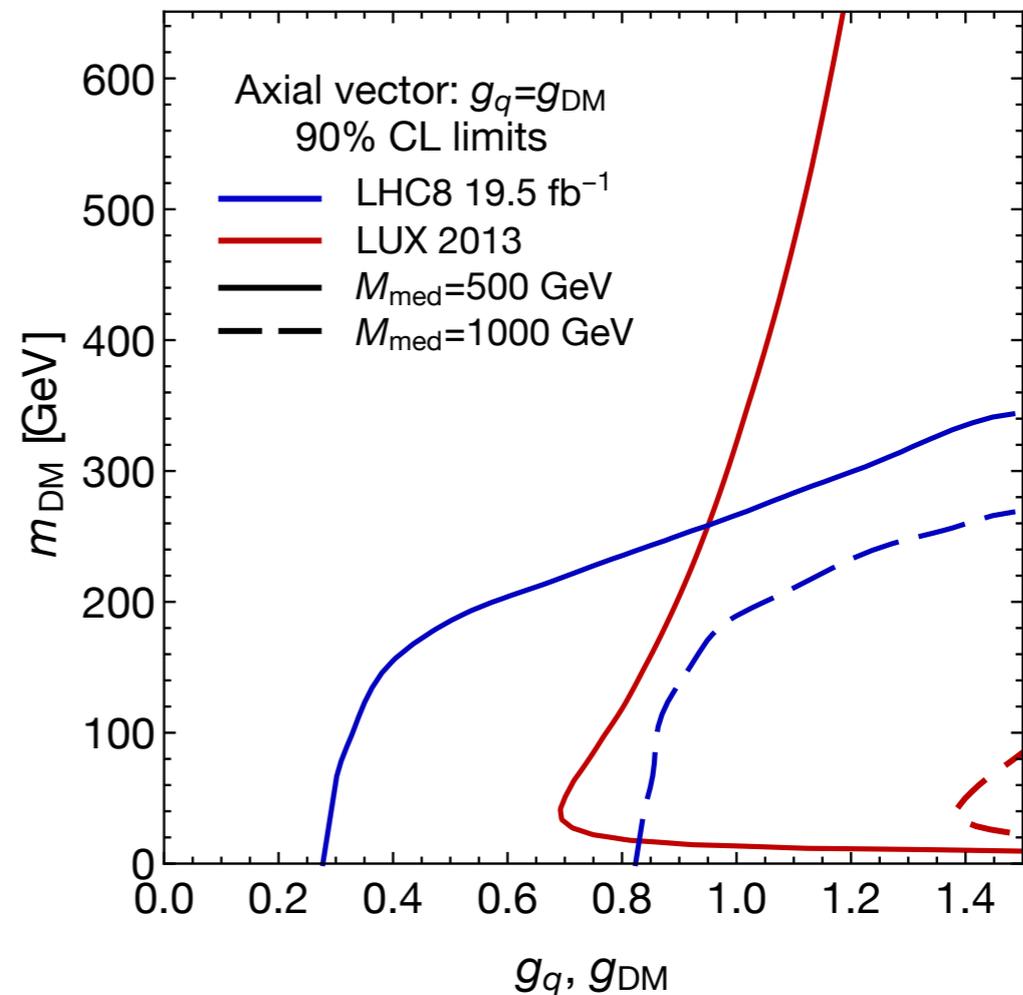
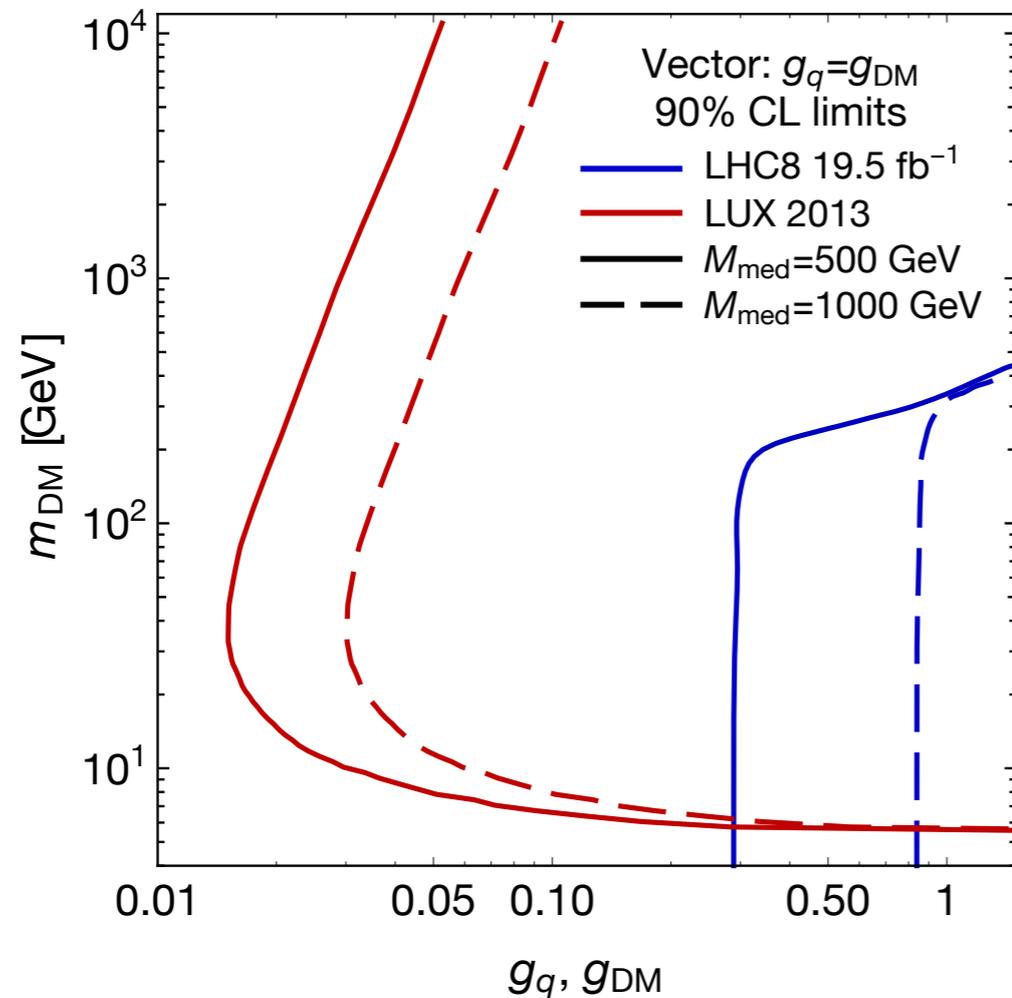
simplified model
excluded region

- Better elucidation of the complementarity between collider and direct searches

Slicing through parameter space

- We need to fix two parameters to show results:

| | |
|------------------|----------|
| m_{DM} | g_χ |
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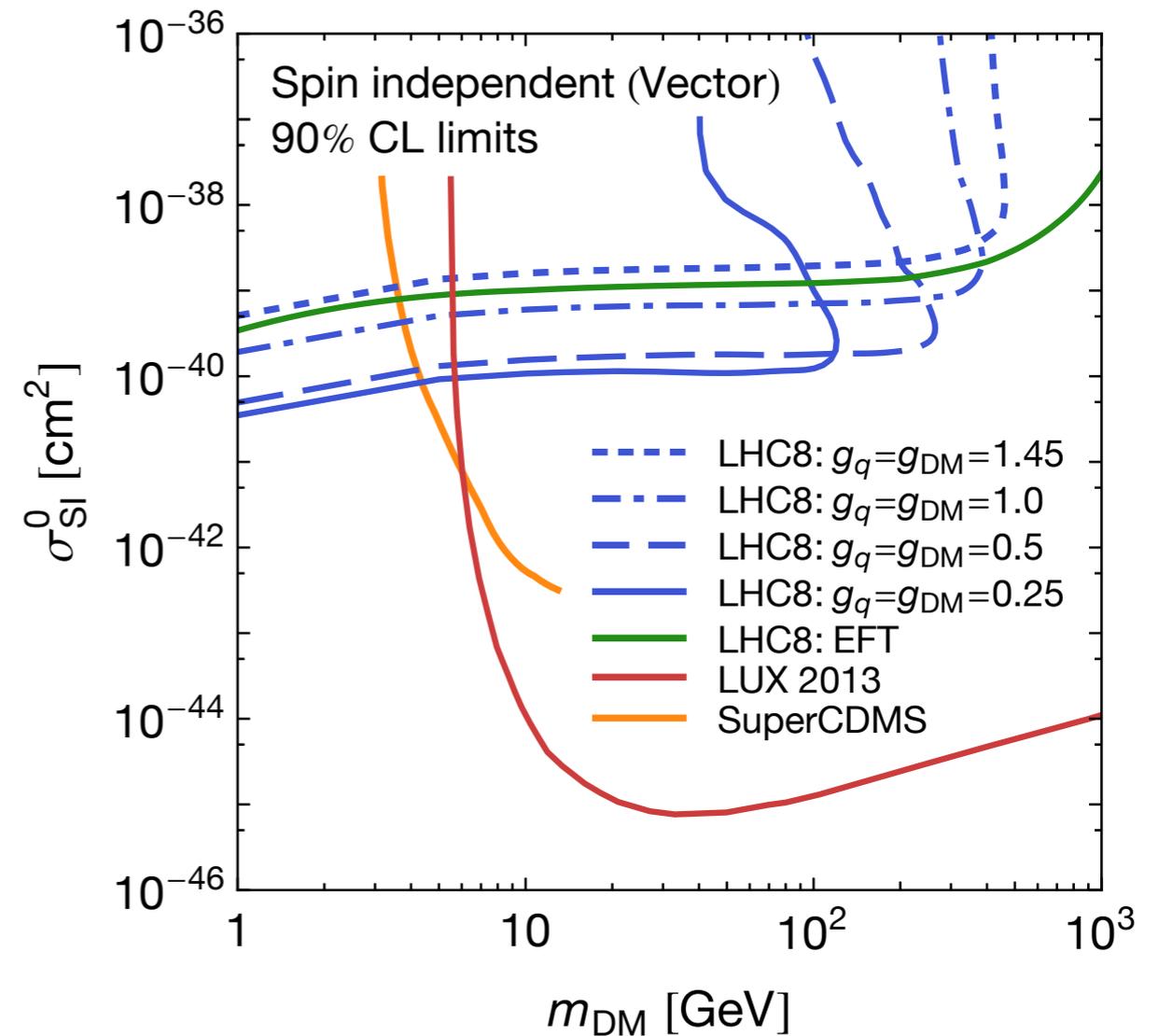
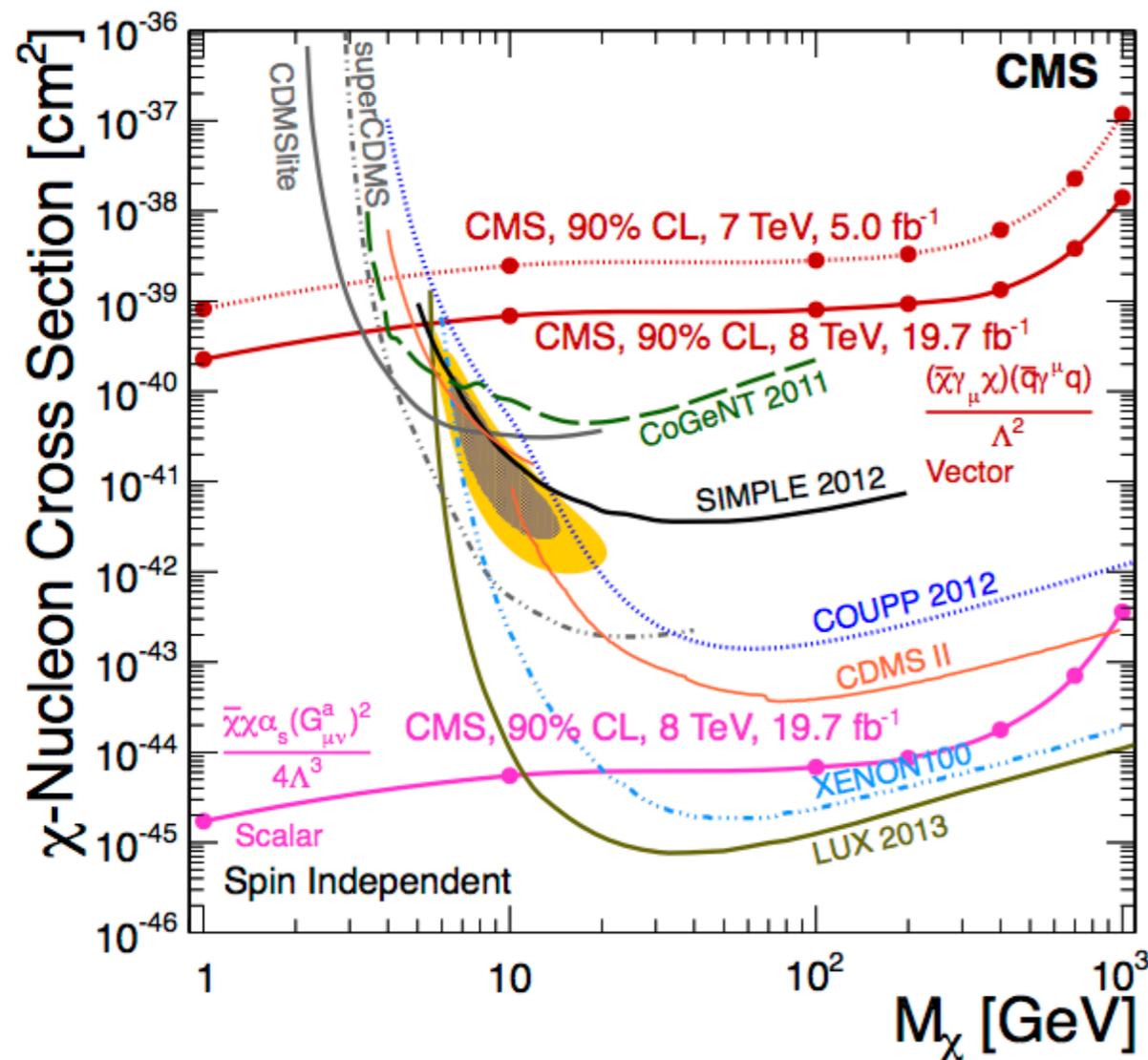


- Better elucidation of the complementarity between collider and direct searches

Comparison with direct detection

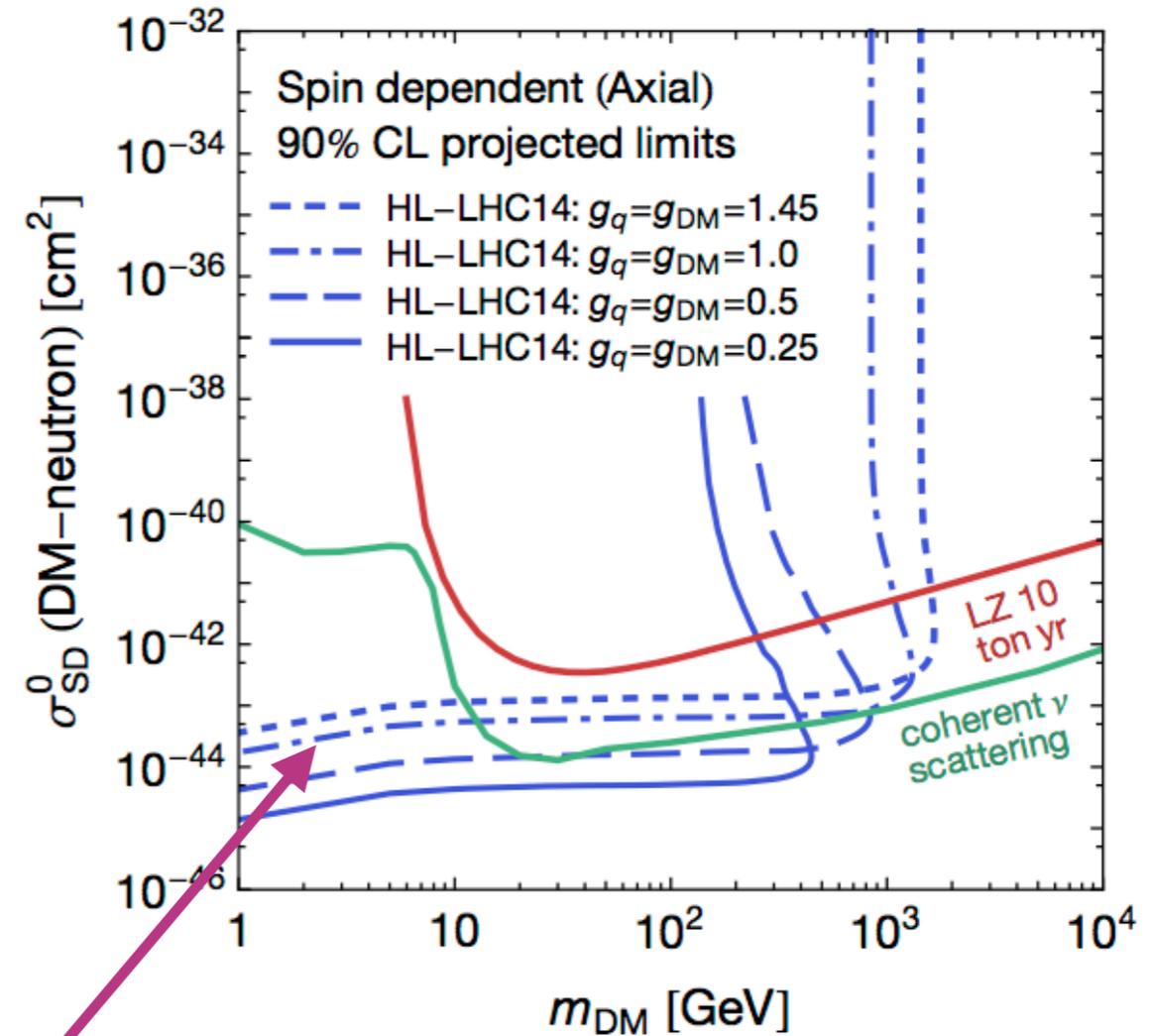
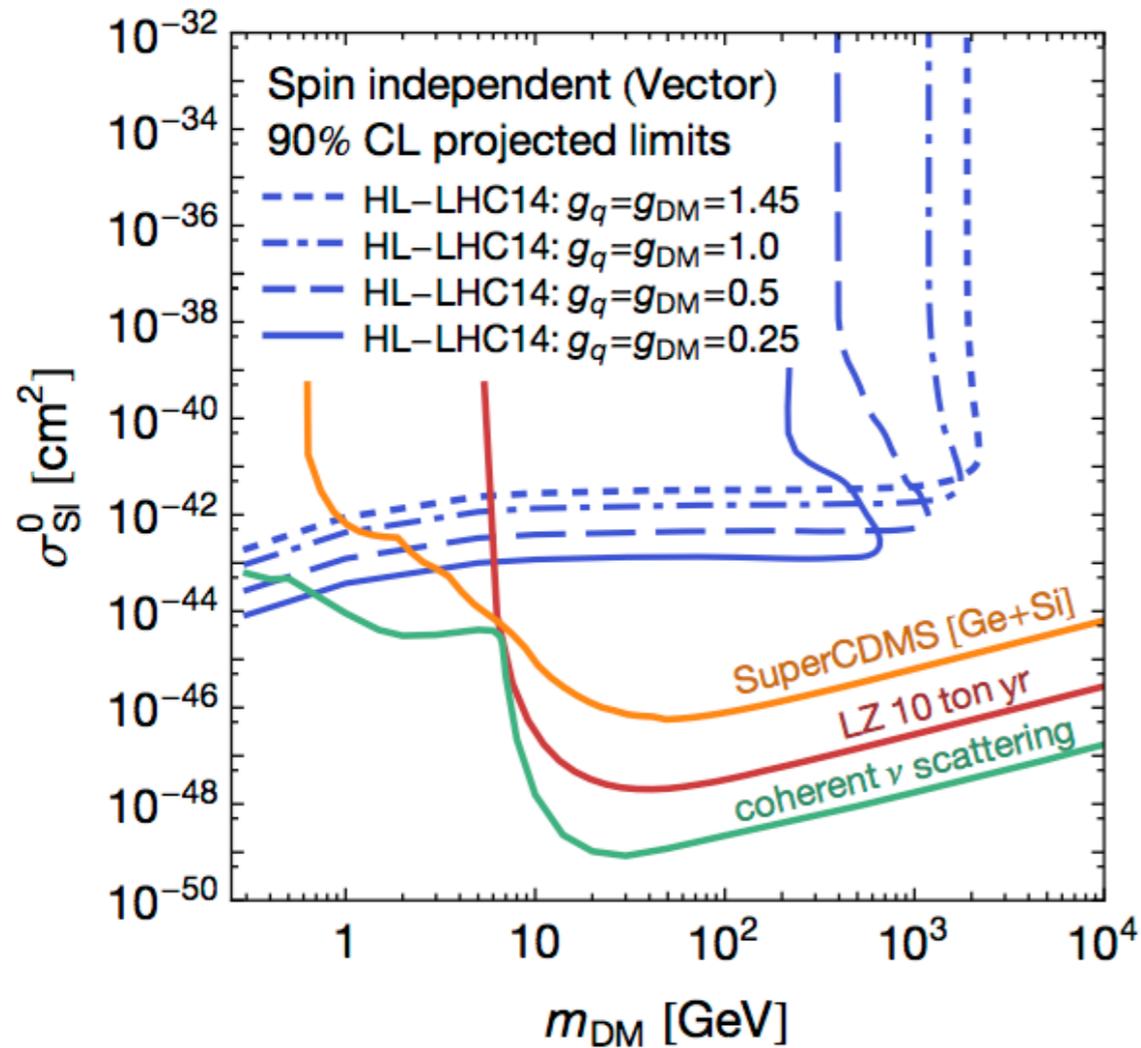
Malik, CM et al
arXiv:1409.4075

- EFT limit overestimates at high mass/underestimates at low mass



Future projections

- Map results into cross-section plane

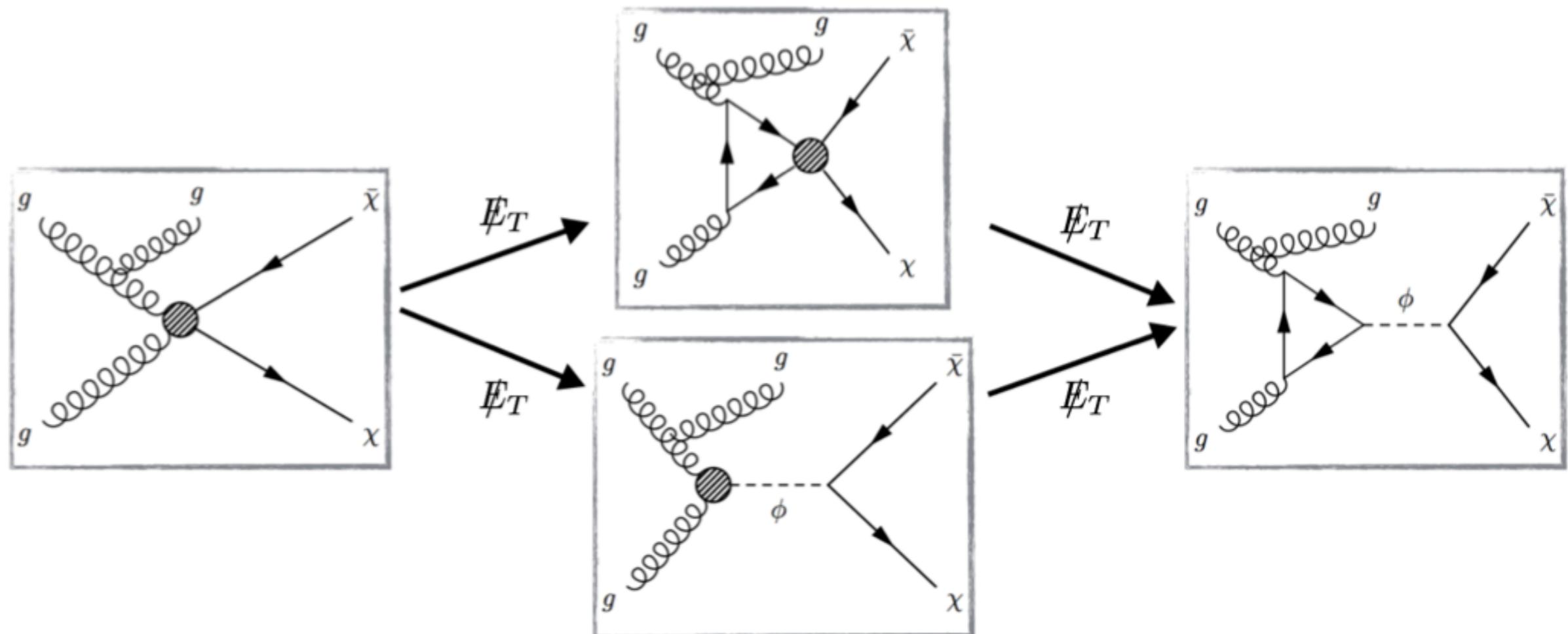


Possible to search below the neutrino floor

Scalar/Pseudoscalar

Buckley, Feld,
Goncalves
arXiv:1410.6497

- Extendable to other mediators

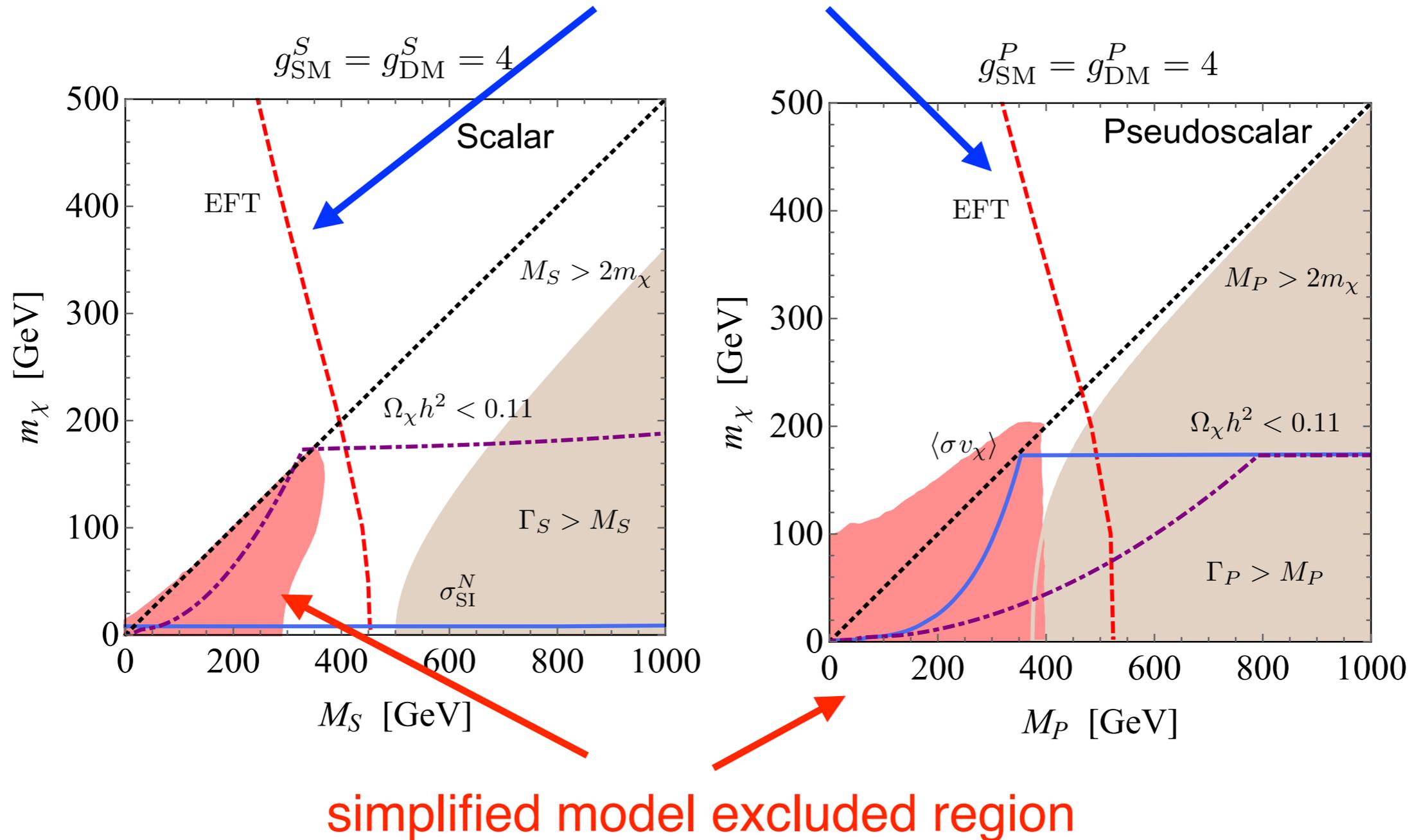


- Path from contact interaction to simplified model is more complex: resolving both the top-loop and scalar mediator

Scalar/Pseudoscalar

Haisch, Re
arXiv:1503.00691

Exclusion limit if you naively used the EFT limit

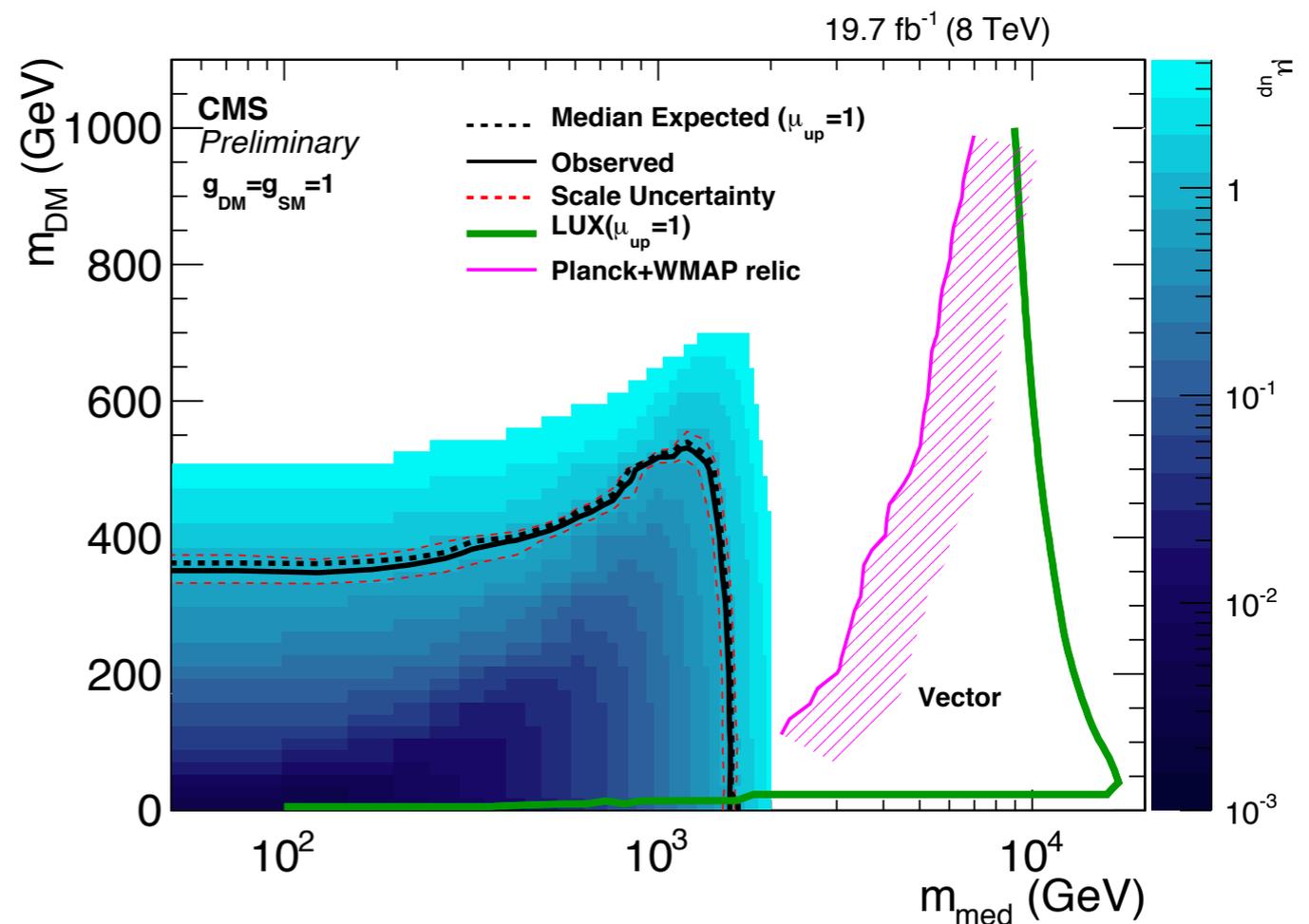


Future recommendations

- ATLAS and CMS formed a working group to reach a consensus on which approach to take going forward
[arXiv:1507.00966](https://arxiv.org/abs/1507.00966)

Use simplified models when possible - will also still see some EFT results for certain benchmark models

CMS have shown first results in the simplified model framework
CMS-EXO-12-055-PAS



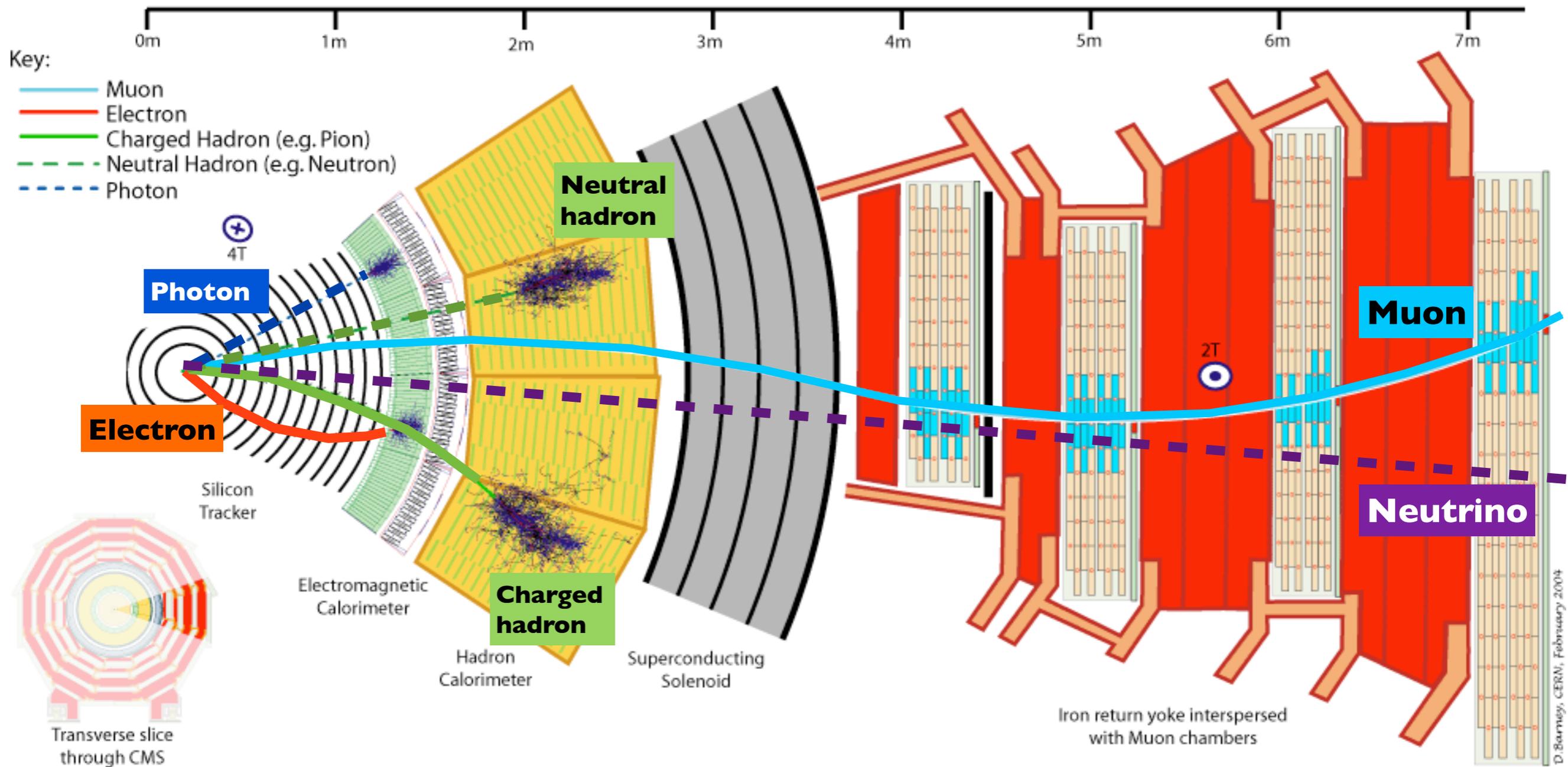
Summary

- Exciting time for dark matter searches!
 - ➔ WIMPs under assault from many experimental searches
- Crucial to interpret dark matter searches in the right framework
- Comparing LHC monojet searches with other dark matter searches is not straightforward
 - ➔ EFT approach constrains few theories and naïve comparison with direct detection can lead to incorrect conclusions
- Need to go beyond EFT
 - ➔ ‘Simplified models’ capture more physics but at the expense of extra parameters

Thank you

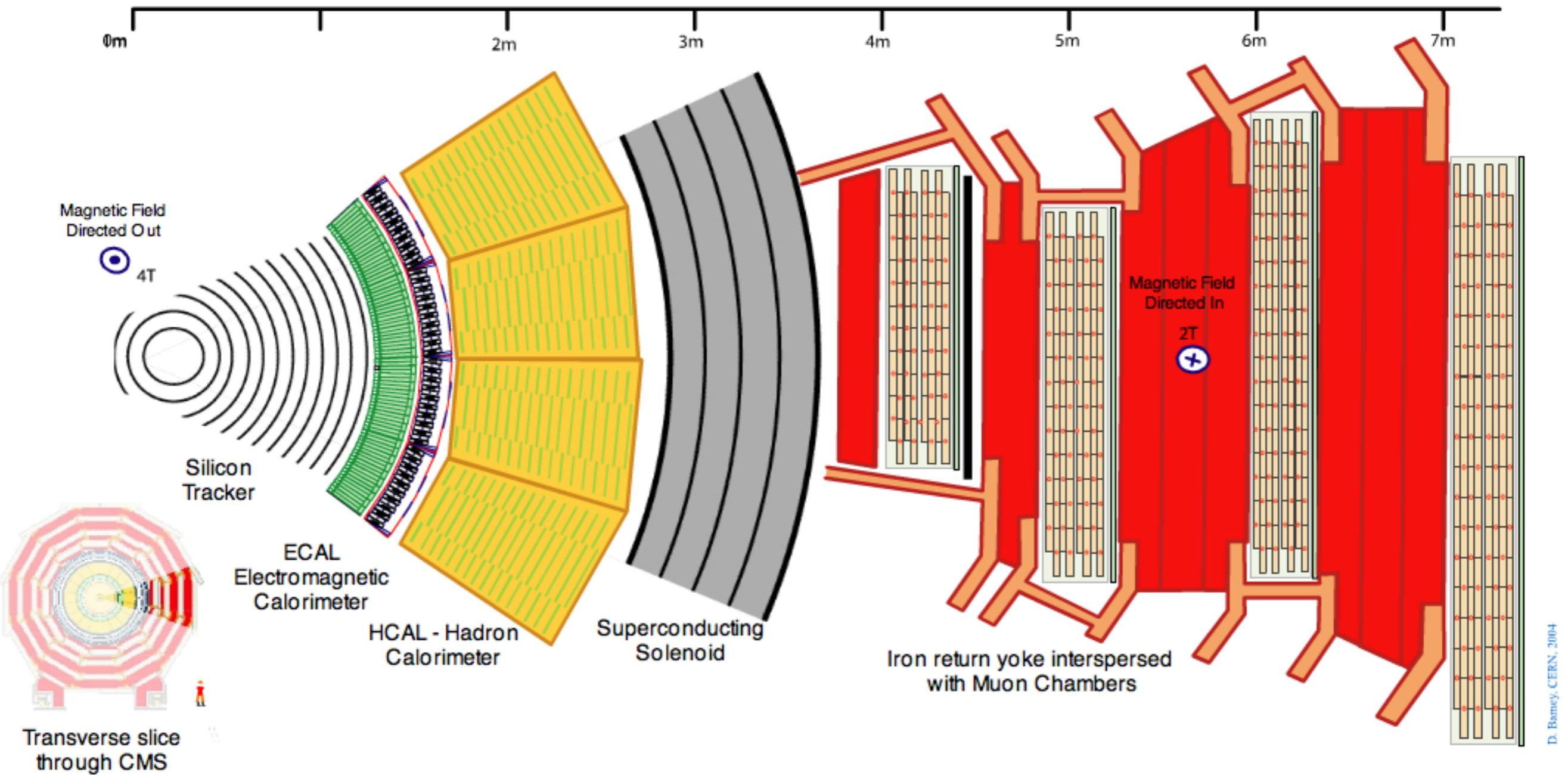
Backup

A slice through CMS



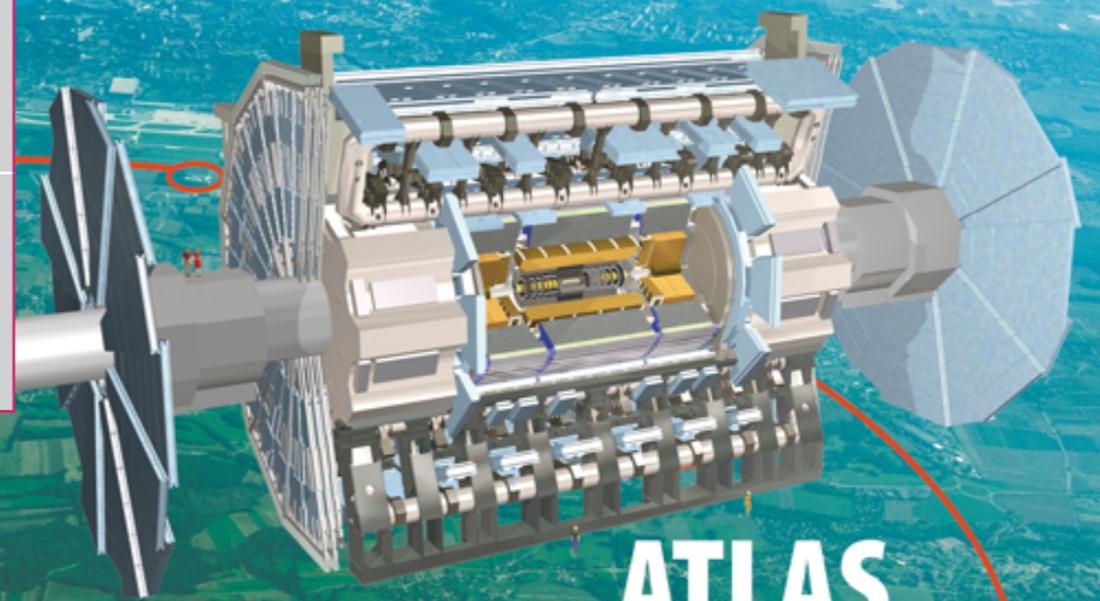
Neutrinos traverse the detector without any interaction

A dark matter event



The Large Hadron Collider

| | 2011 | 2012 | 2015-18 |
|--------------------------|--------------------|---------------------|----------------------|
| Energy (\sqrt{s}) | 7 TeV | 8 TeV | 13 TeV |
| Integrated luminosity | 5 fb ⁻¹ | 20 fb ⁻¹ | 150 fb ⁻¹ |



ATLAS



CMS

Warning

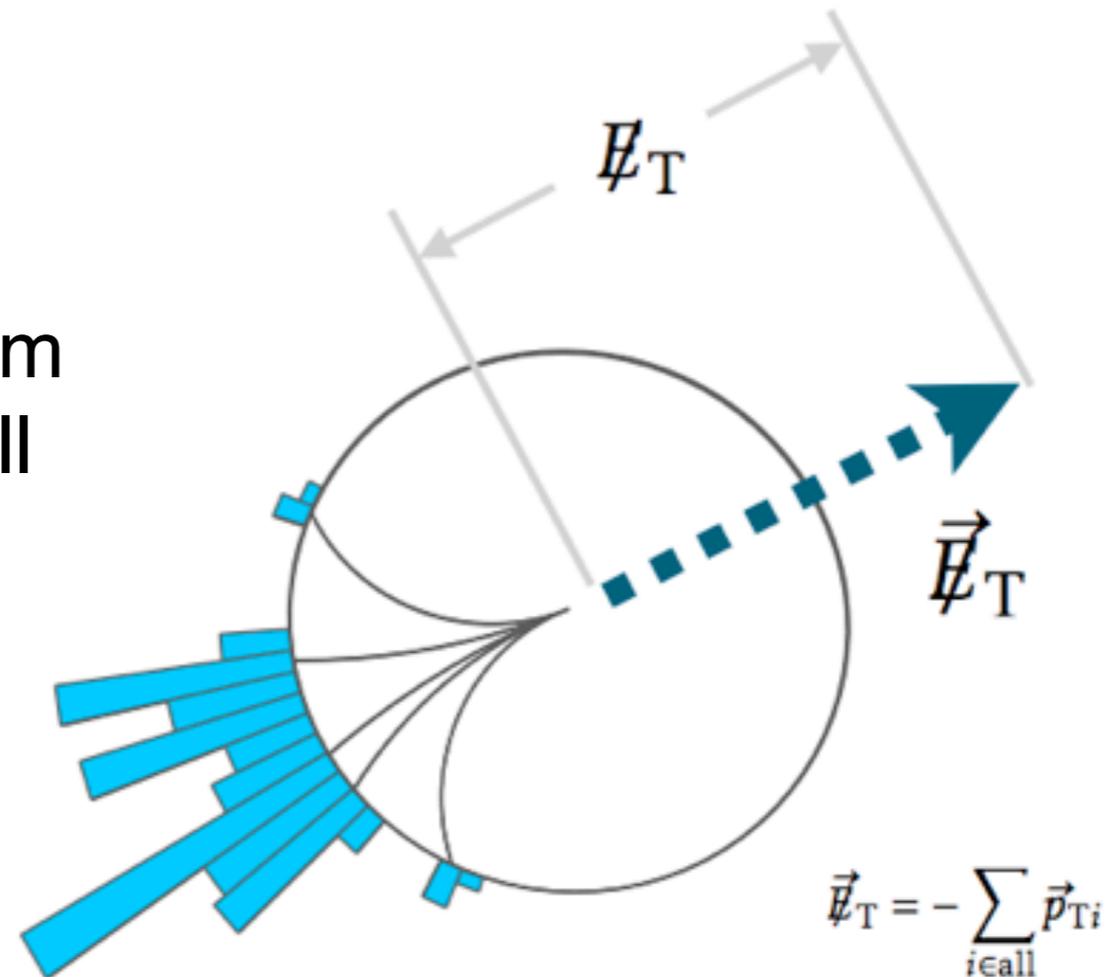
- Things to remember:
 - Colliders cannot prove stability beyond the apparatus
 - The dark matter mass reconstruction will be poor
 - Colliders cannot distinguish single and multiple invisible particles
 - May give little information on the nature of interaction, spin of the dark matter, its quantum numbers...

Interpreting any signal will be challenging

Missing transverse energy (MET or \cancel{E}_T)

- At the heart of all collider searches for dark matter

MET = negative of the vector sum of the transverse momenta of all visible particles in the event



- MET search used to discover W -boson with UA1
→ has been a major tool for hadron colliders ever since

CMS search search (ATLAS similar)

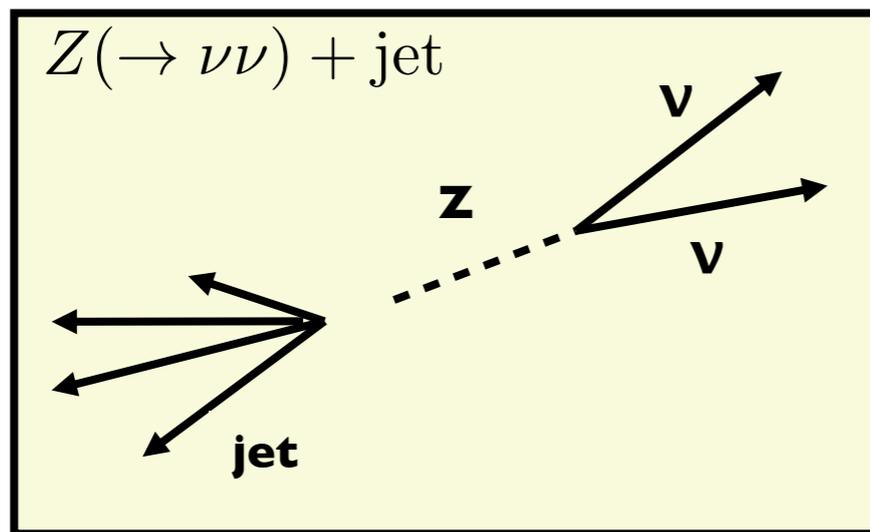
CMS: 1408.3583
ATLAS: 1502.01518

- **Event selection:**

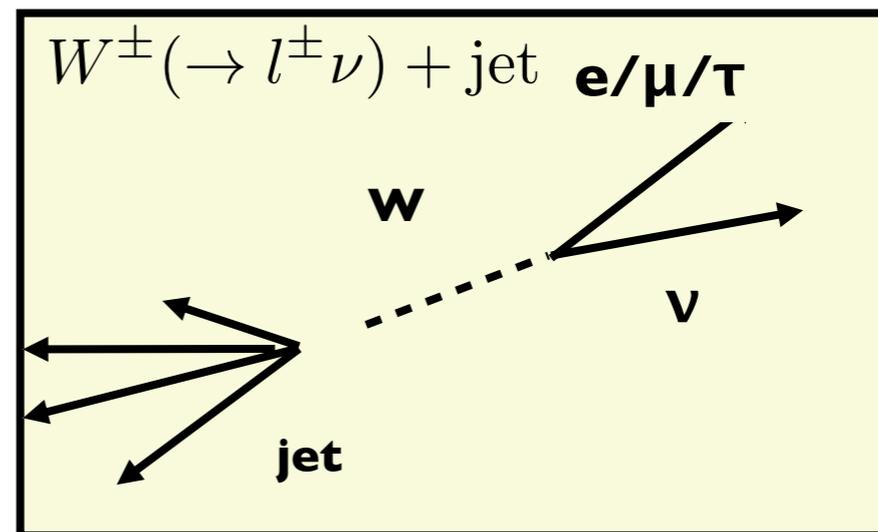
- Large missing transverse energy: $\cancel{E}_T > 500 \text{ GeV}$
- One energetic jet: $p_T > 100 \text{ GeV}$
- One additional jet if $p_T > 30 \text{ GeV}$ and $\Delta\phi(j_1, j_2) < 2.5$

- **Main backgrounds:**

Irreducible background;
looks like signal

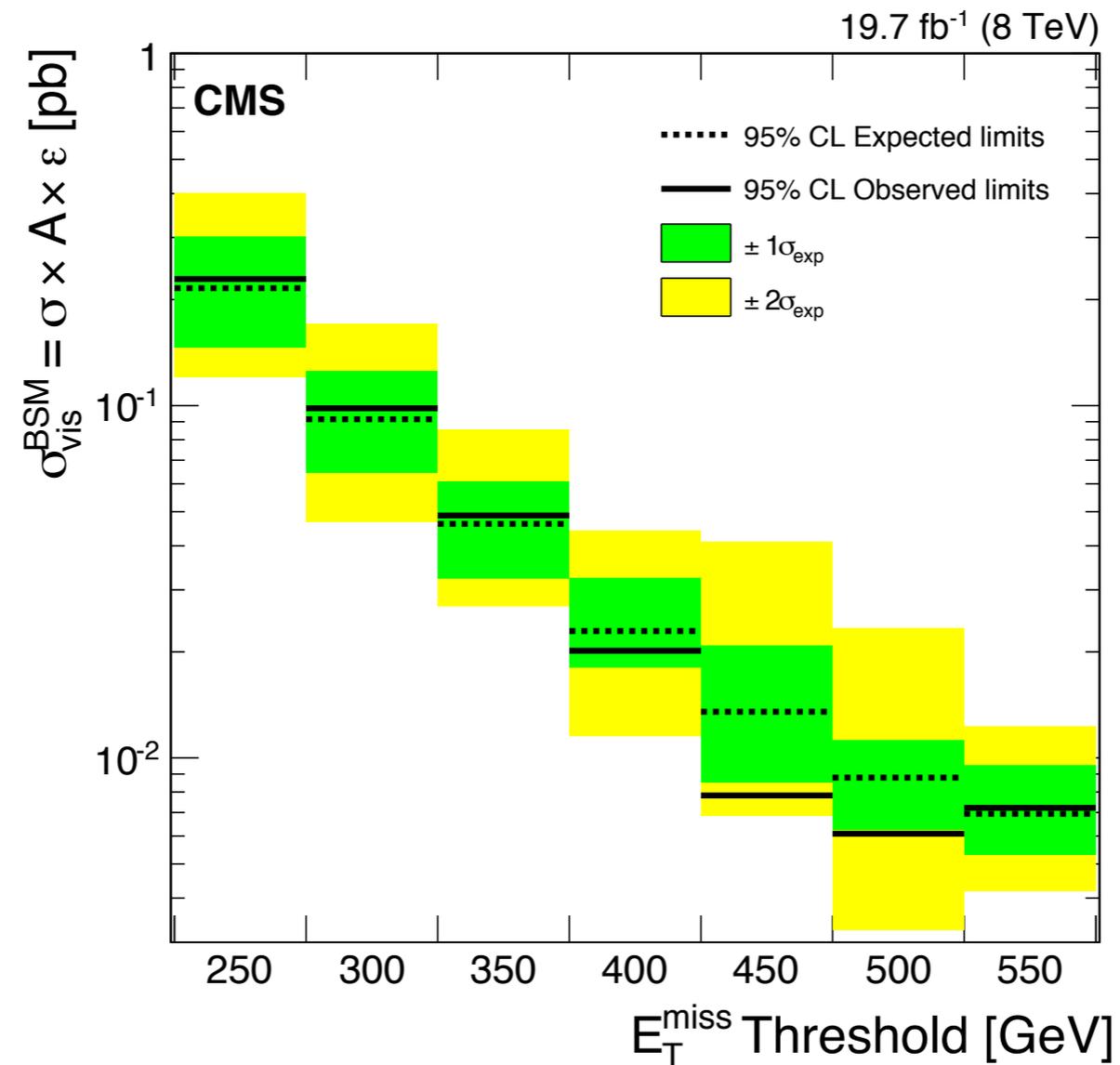


e/μ not detected
 τ decays hadronically



True model independent limit

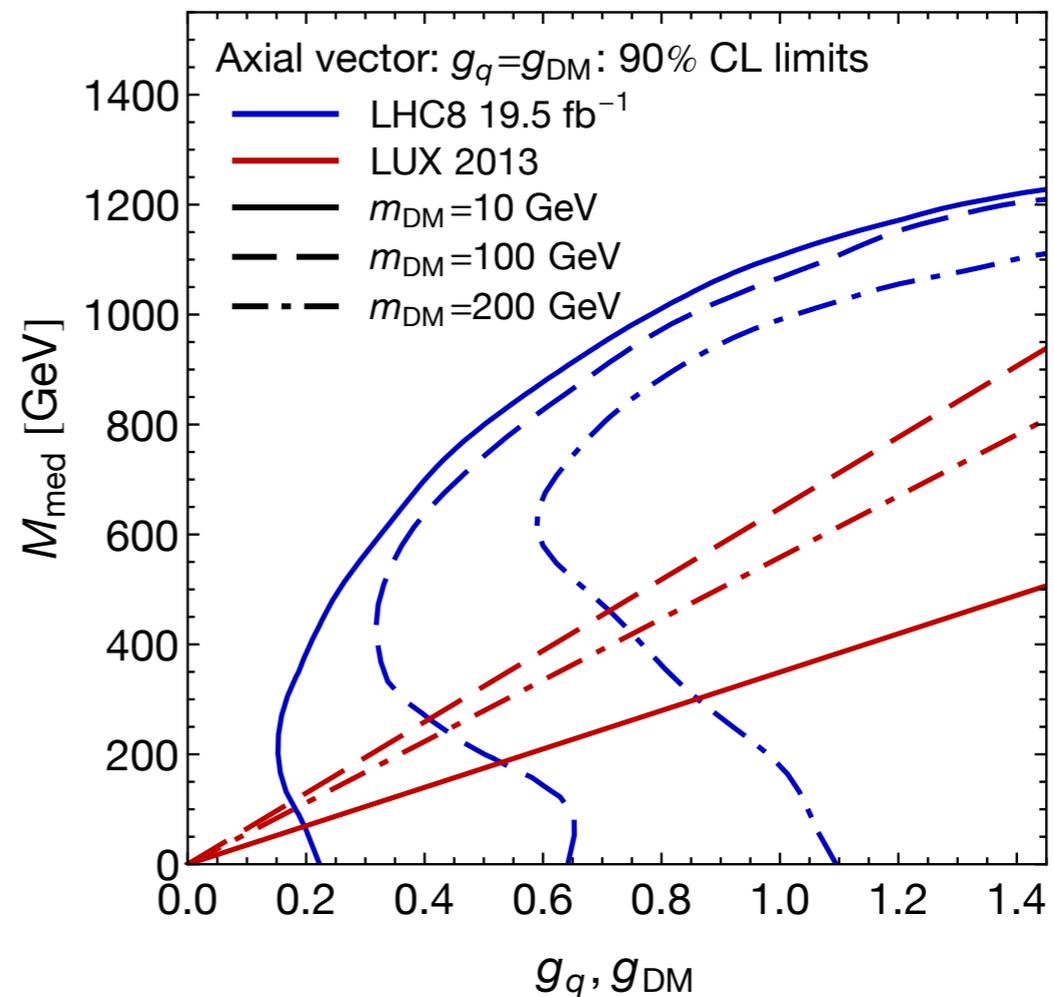
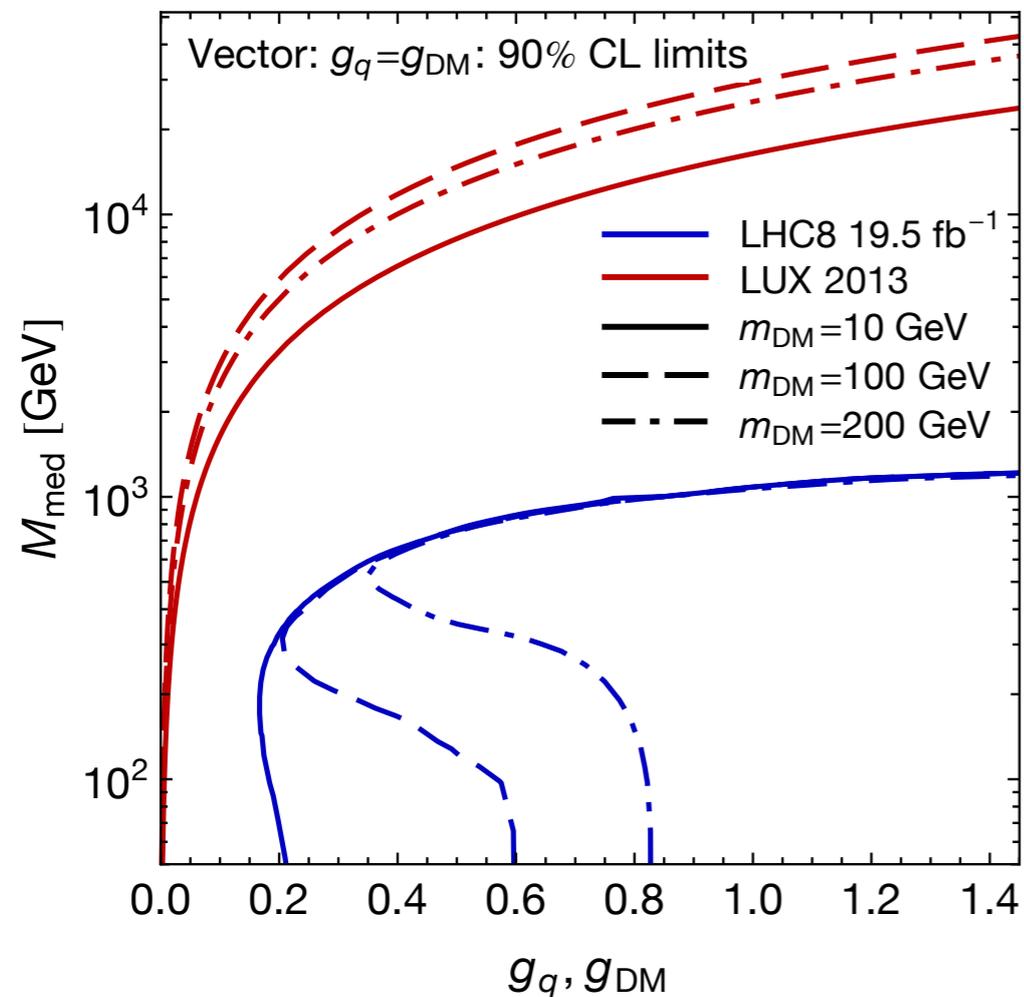
- What the experiments constrain:
cross-section x acceptance x efficiency



Slicing through parameter space

- We need to fix two parameters to show results:

| | |
|------------------|----------|
| m_{DM} | g_χ |
| M_{med} | g_q |

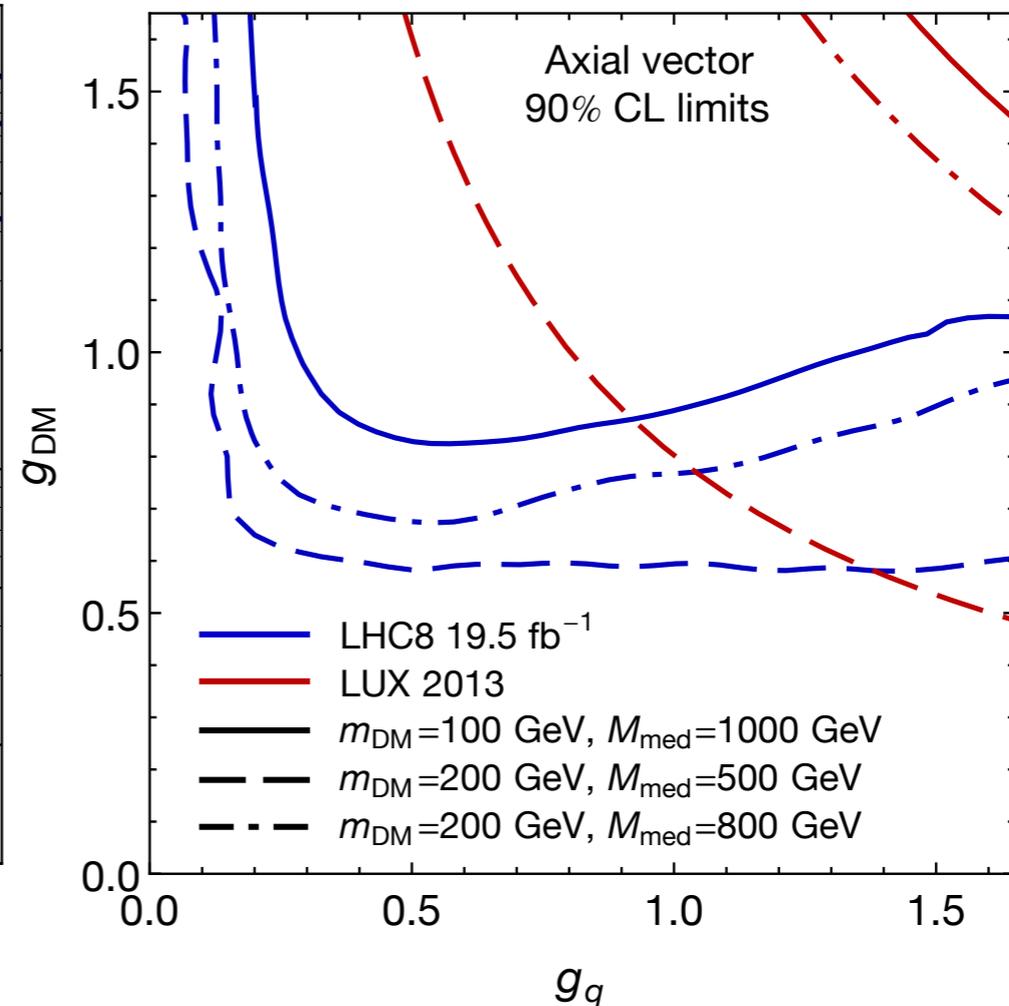
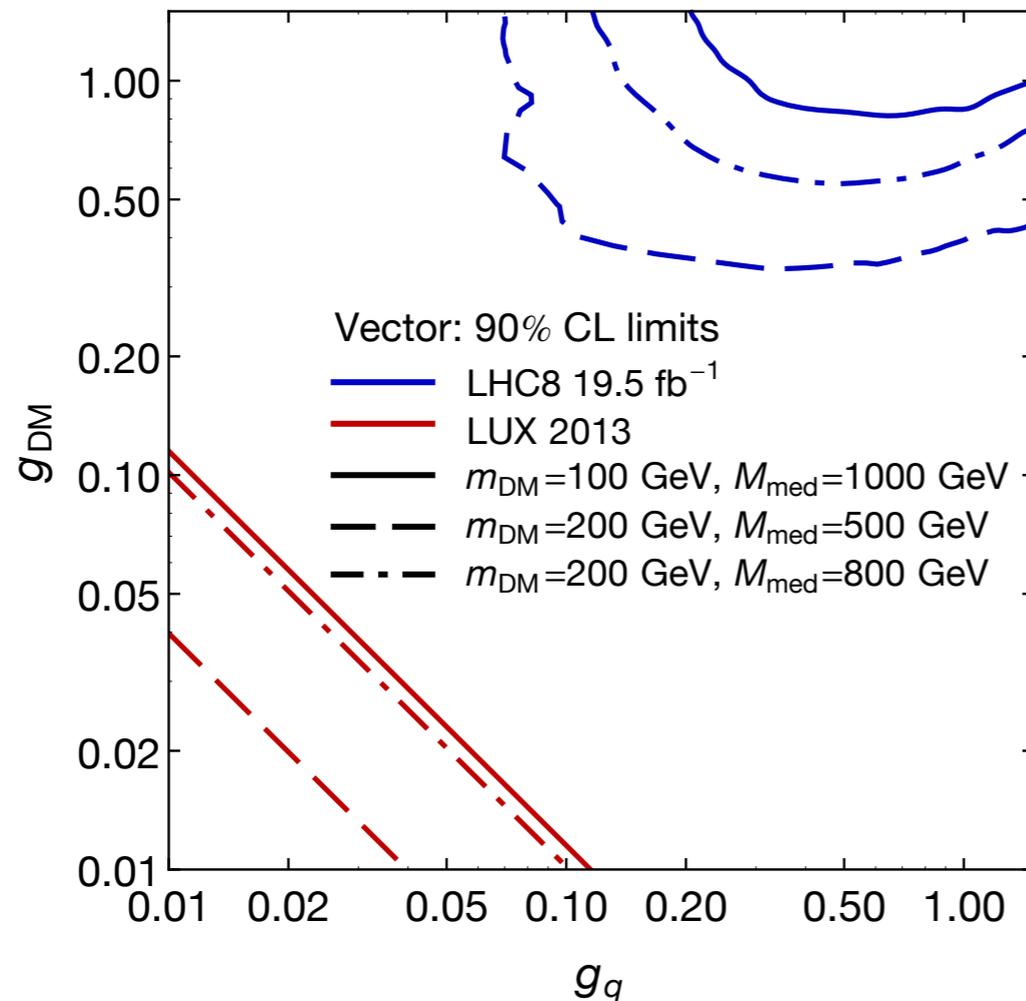


- Better elucidation of the complementarity between collider and direct searches

Slicing through parameter space

- We need to fix two parameters to show results:

| | |
|------------------|----------|
| m_{DM} | g_χ |
| M_{med} | g_q |



- Better elucidation of the complementarity between collider and direct searches

ATLAS SUSY Searches* - 95% CL Lower Limits

Status: Feb 2015

ATLAS Preliminary

$\sqrt{s} = 7, 8 \text{ TeV}$

| Model | e, μ, τ, γ | Jets | E_T^{miss} | $\int \mathcal{L} dt [\text{fb}^{-1}]$ | Mass limit | Reference | | |
|---|--|-------------------------|---------------------|--|--------------------------------|---|---|----------------------|
| Inclusive Searches | MSUGRA/CMSSM | 0 | 2-6 jets | Yes | 20.3 | \tilde{q}, \tilde{g} 1.7 TeV | $m(\tilde{q})=m(\tilde{g})$ | 1405.7875 |
| | $\tilde{q}\tilde{q}, \tilde{q} \rightarrow q\tilde{\chi}_1^0$ | 0 | 2-6 jets | Yes | 20.3 | \tilde{q} 850 GeV | $m(\tilde{\chi}_1^0)=0 \text{ GeV}, m(1^{\text{st}} \text{ gen. } \tilde{q})=m(2^{\text{nd}} \text{ gen. } \tilde{q})$ | 1405.7875 |
| | $\tilde{q}\tilde{q}\gamma, \tilde{q} \rightarrow q\tilde{\chi}_1^0$ (compressed) | 1 γ | 0-1 jet | Yes | 20.3 | \tilde{q} 250 GeV | $m(\tilde{q})-m(\tilde{\chi}_1^0) = m(c)$ | 1411.1559 |
| | $\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0$ | 0 | 2-6 jets | Yes | 20.3 | \tilde{g} 1.33 TeV | $m(\tilde{\chi}_1^0)=0 \text{ GeV}$ | 1405.7875 |
| | $\tilde{g}\tilde{g}, \tilde{g} \rightarrow qq\tilde{\chi}_1^\pm \rightarrow qqW^\pm\tilde{\chi}_1^0$ | 1 e, μ | 3-6 jets | Yes | 20 | \tilde{g} 1.2 TeV | $m(\tilde{\chi}_1^0) < 300 \text{ GeV}, m(\tilde{\chi}^\pm)=0.5(m(\tilde{\chi}_1^0)+m(\tilde{g}))$ | 1501.03555 |
| | $\tilde{g}\tilde{g}, \tilde{g} \rightarrow qq(\ell\ell/\ell\nu/\nu\nu)\tilde{\chi}_1^0$ | 2 e, μ | 0-3 jets | - | 20 | \tilde{g} 1.32 TeV | $m(\tilde{\chi}_1^0)=0 \text{ GeV}$ | 1501.03555 |
| | GMSB ($\tilde{\ell}$ NLSP) | 1-2 τ + 0-1 ℓ | 0-2 jets | Yes | 20.3 | \tilde{g} 1.6 TeV | $\tan\beta > 20$ | 1407.0603 |
| | GGM (bino NLSP) | 2 γ | - | Yes | 20.3 | \tilde{g} 1.28 TeV | $m(\tilde{\chi}_1^0) > 50 \text{ GeV}$ | ATLAS-CONF-2014-001 |
| | GGM (wino NLSP) | 1 $e, \mu + \gamma$ | - | Yes | 4.8 | \tilde{g} 619 GeV | $m(\tilde{\chi}_1^0) > 50 \text{ GeV}$ | ATLAS-CONF-2012-144 |
| | GGM (higgsino-bino NLSP) | γ | 1 b | Yes | 4.8 | \tilde{g} 900 GeV | $m(\tilde{\chi}_1^0) > 220 \text{ GeV}$ | 1211.1167 |
| GGM (higgsino NLSP) | 2 e, μ (Z) | 0-3 jets | Yes | 5.8 | \tilde{g} 690 GeV | $m(\text{NLSP}) > 200 \text{ GeV}$ | ATLAS-CONF-2012-152 | |
| Gravitino LSP | 0 | mono-jet | Yes | 20.3 | $F^{1/2}$ scale 865 GeV | $m(\tilde{G}) > 1.8 \times 10^{-4} \text{ eV}, m(\tilde{g})=m(\tilde{q})=1.5 \text{ TeV}$ | 1502.01518 | |
| 3 rd gen. \tilde{g} med. | $\tilde{g} \rightarrow b\tilde{b}\tilde{\chi}_1^0$ | 0 | 3 b | Yes | 20.1 | \tilde{g} 1.25 TeV | $m(\tilde{\chi}_1^0) < 400 \text{ GeV}$ | 1407.0600 |
| | $\tilde{g} \rightarrow t\tilde{t}\tilde{\chi}_1^0$ | 0 | 7-10 jets | Yes | 20.3 | \tilde{g} 1.1 TeV | $m(\tilde{\chi}_1^0) < 350 \text{ GeV}$ | 1308.1841 |
| | $\tilde{g} \rightarrow t\tilde{t}\tilde{\chi}_1^0$ | 0-1 e, μ | 3 b | Yes | 20.1 | \tilde{g} 1.34 TeV | $m(\tilde{\chi}_1^0) < 400 \text{ GeV}$ | 1407.0600 |
| | $\tilde{g} \rightarrow b\tilde{t}\tilde{\chi}_1^+$ | 0-1 e, μ | 3 b | Yes | 20.1 | \tilde{g} 1.3 TeV | $m(\tilde{\chi}_1^0) < 300 \text{ GeV}$ | 1407.0600 |
| 3 rd gen. squarks direct production | $\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow b\tilde{\chi}_1^0$ | 0 | 2 b | Yes | 20.1 | \tilde{b}_1 100-620 GeV | $m(\tilde{\chi}_1^0) < 90 \text{ GeV}$ | 1308.2631 |
| | $\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow t\tilde{\chi}_1^\pm$ | 2 e, μ (SS) | 0-3 b | Yes | 20.3 | \tilde{b}_1 275-440 GeV | $m(\tilde{\chi}_1^\pm) = 2m(\tilde{\chi}_1^0)$ | 1404.2500 |
| | $\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow b\tilde{\chi}_1^\pm$ | 1-2 e, μ | 1-2 b | Yes | 4.7 | \tilde{t}_1 110-167 GeV, 230-460 GeV | $m(\tilde{\chi}_1^\pm) = 2m(\tilde{\chi}_1^0), m(\tilde{\chi}_1^0)=55 \text{ GeV}$ | 1209.2102, 1407.0583 |
| | $\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow Wb\tilde{\chi}_1^0$ or $t\tilde{\chi}_1^0$ | 2 e, μ | 0-2 jets | Yes | 20.3 | \tilde{t}_1 90-191 GeV, 215-530 GeV | $m(\tilde{\chi}_1^0)=1 \text{ GeV}$ | 1403.4853, 1412.4742 |
| | $\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$ | 0-1 e, μ | 1-2 b | Yes | 20 | \tilde{t}_1 210-640 GeV | $m(\tilde{\chi}_1^0)=1 \text{ GeV}$ | 1407.0583, 1406.1122 |
| | $\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow c\tilde{\chi}_1^0$ | 0 | mono-jet/c-tag | Yes | 20.3 | \tilde{t}_1 90-240 GeV | $m(\tilde{t}_1)-m(\tilde{\chi}_1^0) < 85 \text{ GeV}$ | 1407.0608 |
| | $\tilde{t}_1\tilde{t}_1$ (natural GMSB) | 2 e, μ (Z) | 1 b | Yes | 20.3 | \tilde{t}_1 150-580 GeV | $m(\tilde{\chi}_1^0) > 150 \text{ GeV}$ | 1403.5222 |
| $\tilde{t}_2\tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + Z$ | 3 e, μ (Z) | 1 b | Yes | 20.3 | \tilde{t}_2 290-600 GeV | $m(\tilde{\chi}_1^0) < 200 \text{ GeV}$ | 1403.5222 | |
| EW direct | $\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}, \tilde{\ell} \rightarrow \ell\tilde{\chi}_1^0$ | 2 e, μ | 0 | Yes | 20.3 | $\tilde{\ell}$ 90-325 GeV | $m(\tilde{\chi}_1^0)=0 \text{ GeV}$ | 1403.5294 |
| | $\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+ \rightarrow \tilde{\ell}\nu(\tilde{\ell}\bar{\nu})$ | 2 e, μ | 0 | Yes | 20.3 | $\tilde{\chi}_1^\pm$ 140-465 GeV | $m(\tilde{\chi}_1^0)=0 \text{ GeV}, m(\tilde{\ell}, \bar{\nu})=0.5(m(\tilde{\chi}_1^\pm)+m(\tilde{\chi}_1^0))$ | 1403.5294 |
| | $\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+ \rightarrow \tilde{\tau}\nu(\tilde{\tau}\bar{\nu})$ | 2 τ | - | Yes | 20.3 | $\tilde{\chi}_1^\pm$ 100-350 GeV | $m(\tilde{\chi}_1^0)=0 \text{ GeV}, m(\tilde{\tau}, \bar{\nu})=0.5(m(\tilde{\chi}_1^\pm)+m(\tilde{\chi}_1^0))$ | 1407.0350 |
| | $\tilde{\chi}_1^+\tilde{\chi}_2^0 \rightarrow \tilde{\ell}_L\nu\tilde{\ell}_L(\bar{\nu}\nu), \tilde{\ell}\tilde{\nu}_{\tilde{\ell}_L}(\bar{\ell}\bar{\nu}\nu)$ | 3 e, μ | 0 | Yes | 20.3 | $\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$ 700 GeV | $m(\tilde{\chi}_1^\pm)=m(\tilde{\chi}_2^0), m(\tilde{\chi}_1^0)=0, m(\tilde{\ell}, \bar{\nu})=0.5(m(\tilde{\chi}_1^\pm)+m(\tilde{\chi}_1^0))$ | 1402.7029 |
| | $\tilde{\chi}_1^+\tilde{\chi}_2^0 \rightarrow W\tilde{\chi}_1^0 Z\tilde{\chi}_1^0$ | 2-3 e, μ | 0-2 jets | Yes | 20.3 | $\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$ 420 GeV | $m(\tilde{\chi}_1^\pm)=m(\tilde{\chi}_2^0), m(\tilde{\chi}_1^0)=0$, sleptons decoupled | 1403.5294, 1402.7029 |
| | $\tilde{\chi}_1^+\tilde{\chi}_2^0 \rightarrow W\tilde{\chi}_1^0 h\tilde{\chi}_1^0, h \rightarrow b\bar{b}/WW/\tau\tau/\gamma\gamma$ | e, μ, γ | 0-2 b | Yes | 20.3 | $\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$ 250 GeV | $m(\tilde{\chi}_1^\pm)=m(\tilde{\chi}_2^0), m(\tilde{\chi}_1^0)=0$, sleptons decoupled | 1501.07110 |
| $\tilde{\chi}_2^0\tilde{\chi}_3^0, \tilde{\chi}_{2,3}^0 \rightarrow \tilde{\ell}_R\ell$ | 4 e, μ | 0 | Yes | 20.3 | $\tilde{\chi}_{2,3}^0$ 620 GeV | $m(\tilde{\chi}_2^0)=m(\tilde{\chi}_3^0), m(\tilde{\chi}_1^0)=0, m(\tilde{\ell}, \bar{\nu})=0.5(m(\tilde{\chi}_2^0)+m(\tilde{\chi}_1^0))$ | 1405.5086 | |
| Long-lived particles | Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$ | Disapp. trk | 1 jet | Yes | 20.3 | $\tilde{\chi}_1^\pm$ 270 GeV | $m(\tilde{\chi}_1^\pm)-m(\tilde{\chi}_1^0)=160 \text{ MeV}, \tau(\tilde{\chi}_1^\pm)=0.2 \text{ ns}$ | 1310.3675 |
| | Stable, stopped \tilde{g} R-hadron | 0 | 1-5 jets | Yes | 27.9 | \tilde{g} 832 GeV | $m(\tilde{\chi}_1^0)=100 \text{ GeV}, 10 \mu\text{s} < \tau(\tilde{g}) < 1000 \text{ s}$ | 1310.6584 |
| | Stable \tilde{g} R-hadron | trk | - | - | 19.1 | \tilde{g} 1.27 TeV | | 1411.6795 |
| | GMSB, stable $\tilde{\tau}, \tilde{\chi}_1^0 \rightarrow \tilde{\tau}(\tilde{e}, \tilde{\mu}) + \tau(e, \mu)$ | 1-2 μ | - | - | 19.1 | $\tilde{\chi}_1^0$ 537 GeV | $10 < \tan\beta < 50$ | 1411.6795 |
| | GMSB, $\tilde{\chi}_1^0 \rightarrow \gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$ | 2 γ | - | Yes | 20.3 | $\tilde{\chi}_1^0$ 435 GeV | $2 < \tau(\tilde{\chi}_1^0) < 3 \text{ ns}$, SPS8 model | 1409.5542 |
| $\tilde{q}\tilde{q}, \tilde{\chi}_1^0 \rightarrow qq\mu$ (RPV) | 1 μ , displ. vtx | - | - | 20.3 | \tilde{q} 1.0 TeV | $1.5 < c\tau < 156 \text{ mm}, \text{BR}(\mu)=1, m(\tilde{\chi}_1^0)=108 \text{ GeV}$ | ATLAS-CONF-2013-092 | |
| RPV | LFV $pp \rightarrow \tilde{\nu}_\tau + X, \tilde{\nu}_\tau \rightarrow e + \mu$ | 2 e, μ | - | - | 4.6 | $\tilde{\nu}_\tau$ 1.61 TeV | $\lambda'_{311}=0.10, \lambda_{132}=0.05$ | 1212.1272 |
| | LFV $pp \rightarrow \tilde{\nu}_\tau + X, \tilde{\nu}_\tau \rightarrow e(\mu) + \tau$ | 1 $e, \mu + \tau$ | - | - | 4.6 | $\tilde{\nu}_\tau$ 1.1 TeV | $\lambda'_{311}=0.10, \lambda_{1(2)33}=0.05$ | 1212.1272 |
| | Bilinear RPV CMSSM | 2 e, μ (SS) | 0-3 b | Yes | 20.3 | \tilde{q}, \tilde{g} 1.35 TeV | $m(\tilde{q})=m(\tilde{g}), c\tau_{LSP} < 1 \text{ mm}$ | 1404.2500 |
| | $\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+ \rightarrow W\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow ee\tilde{\nu}_\mu, e\mu\tilde{\nu}_e$ | 4 e, μ | - | Yes | 20.3 | $\tilde{\chi}_1^\pm$ 750 GeV | $m(\tilde{\chi}_1^0) > 0.2 \times m(\tilde{\chi}_1^\pm), \lambda_{121} \neq 0$ | 1405.5086 |
| | $\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+ \rightarrow W\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow \tau\tau\tilde{\nu}_e, e\tau\tilde{\nu}_\tau$ | 3 $e, \mu + \tau$ | - | Yes | 20.3 | $\tilde{\chi}_1^\pm$ 450 GeV | $m(\tilde{\chi}_1^0) > 0.2 \times m(\tilde{\chi}_1^\pm), \lambda_{133} \neq 0$ | 1405.5086 |
| | $\tilde{g} \rightarrow qq\bar{q}$ | 0 | 6-7 jets | - | 20.3 | \tilde{g} 916 GeV | $\text{BR}(t)=\text{BR}(b)=\text{BR}(c)=0\%$ | ATLAS-CONF-2013-091 |
| $\tilde{g} \rightarrow \tilde{t}_1 t, \tilde{t}_1 \rightarrow bs$ | 2 e, μ (SS) | 0-3 b | Yes | 20.3 | \tilde{g} 850 GeV | | 1404.2500 | |
| Other | Scalar charm, $\tilde{c} \rightarrow c\tilde{\chi}_1^0$ | 0 | 2 c | Yes | 20.3 | \tilde{c} 490 GeV | $m(\tilde{\chi}_1^0) < 200 \text{ GeV}$ | 1501.01325 |

$\sqrt{s} = 7 \text{ TeV}$ full data
 $\sqrt{s} = 8 \text{ TeV}$ partial data
 $\sqrt{s} = 8 \text{ TeV}$ full data

10⁻¹ 1 Mass scale [TeV]

*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1 σ theoretical signal cross section uncertainty.