Interpreting dark matter searches

with contact interactions and simplified models

GRAPPA
GRavitation AstroParticle Physics Amsterdam

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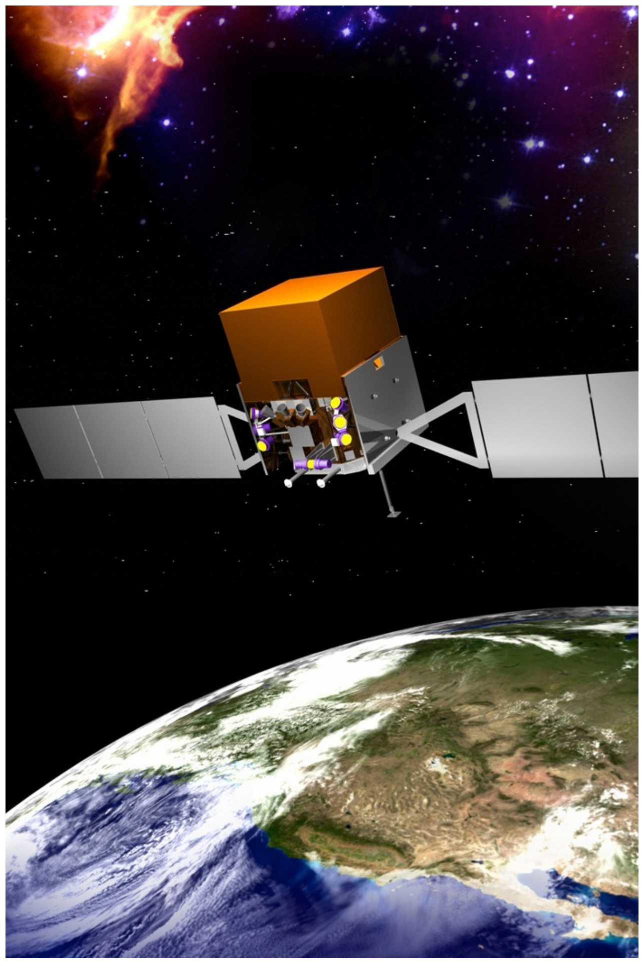
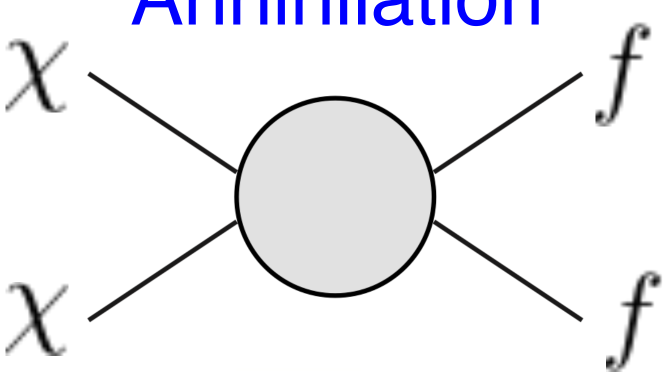
HAP Dark Matter, Karlsruhe - 22nd September 2015

Searches for dark matter

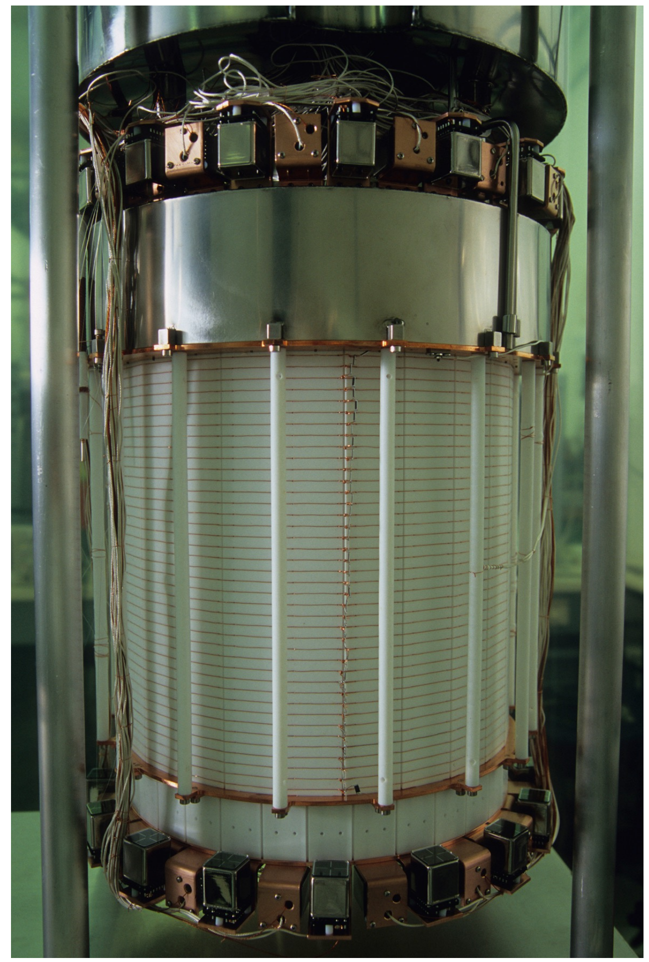
Indirect detection



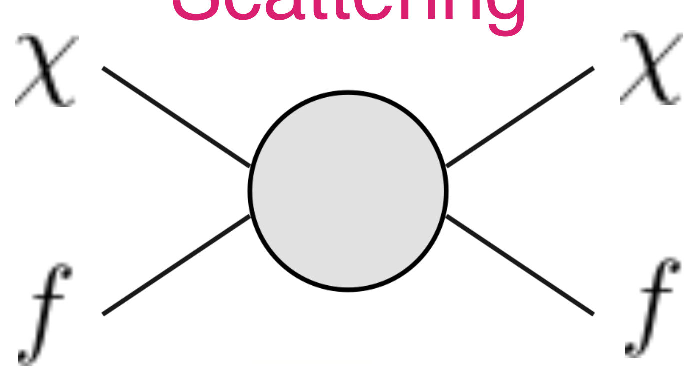
Annihilation



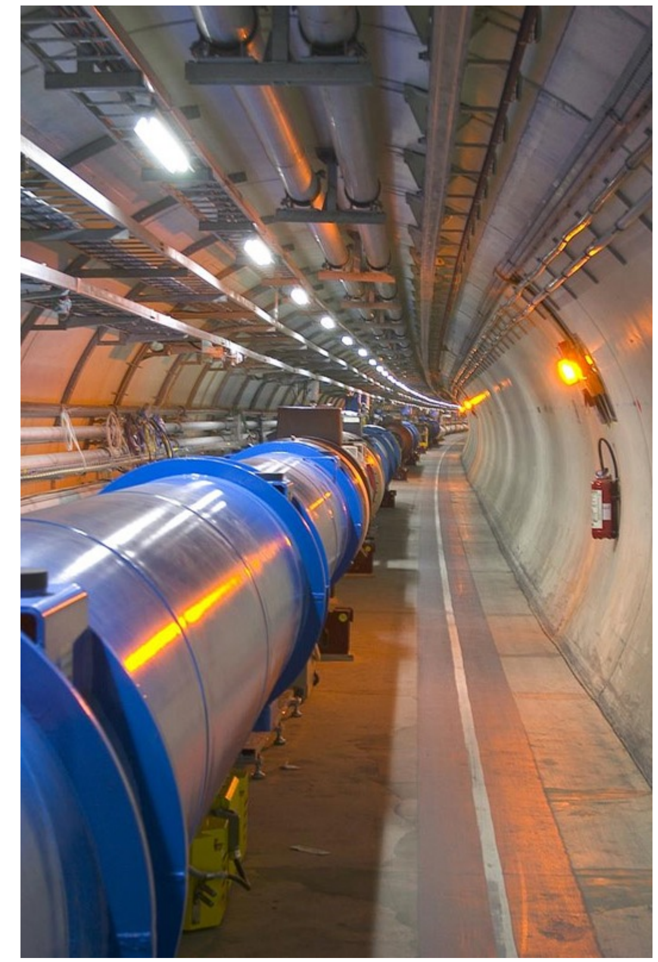
Direct detection



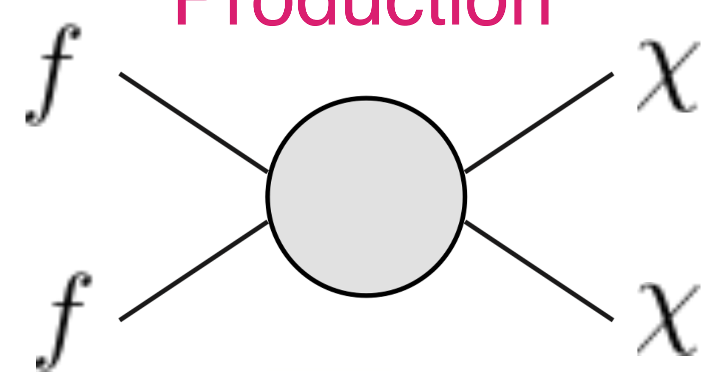
Scattering



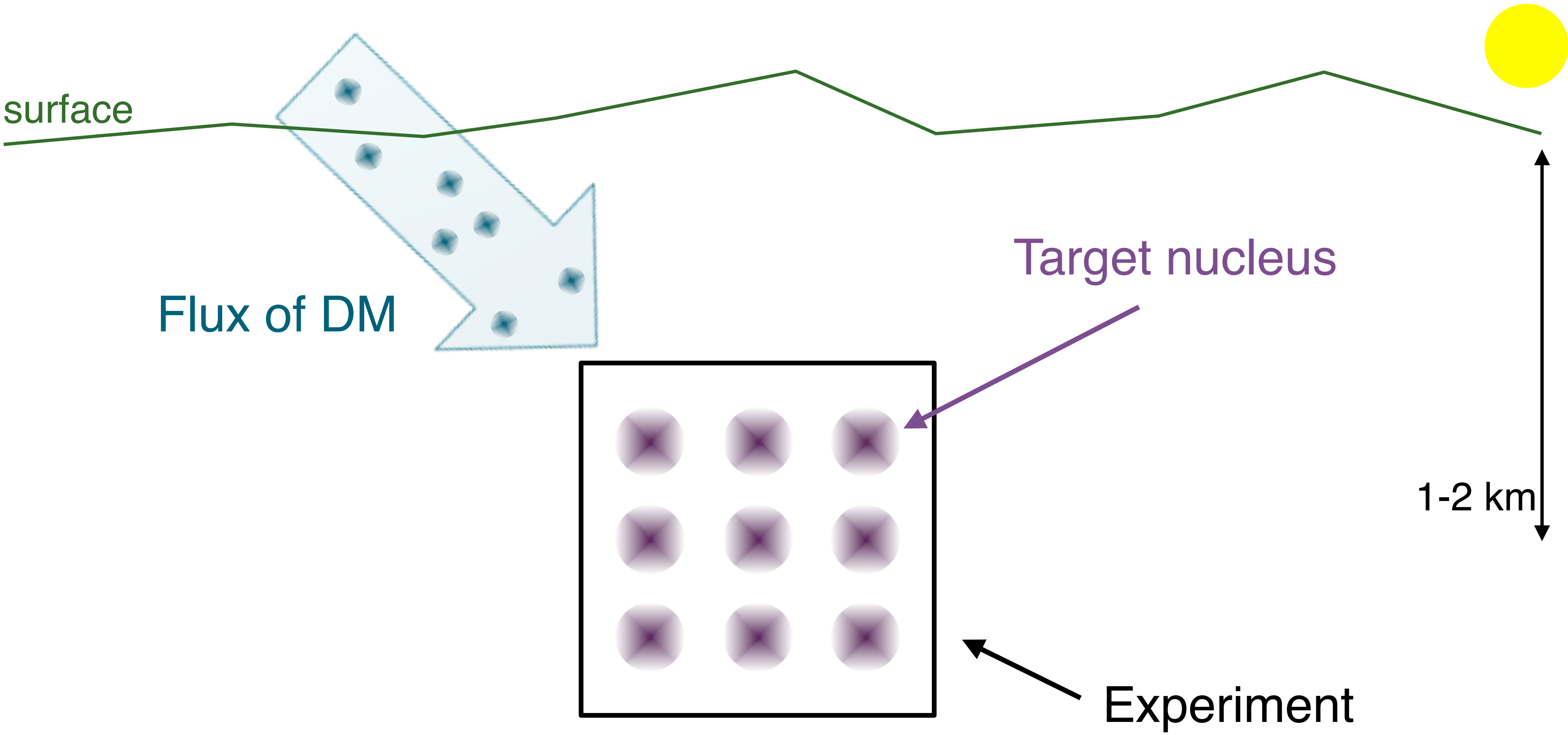
Collider



Production

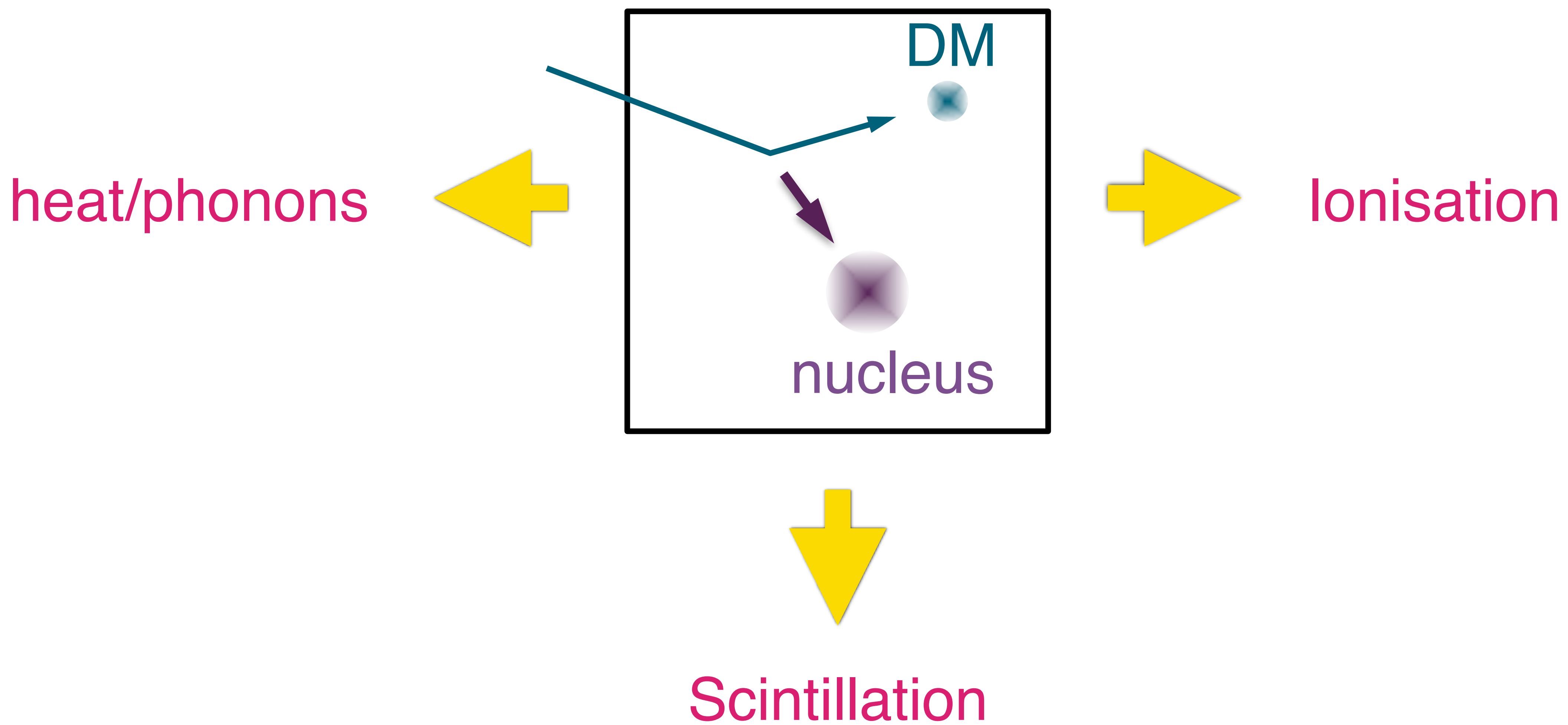


Direct detection: basics



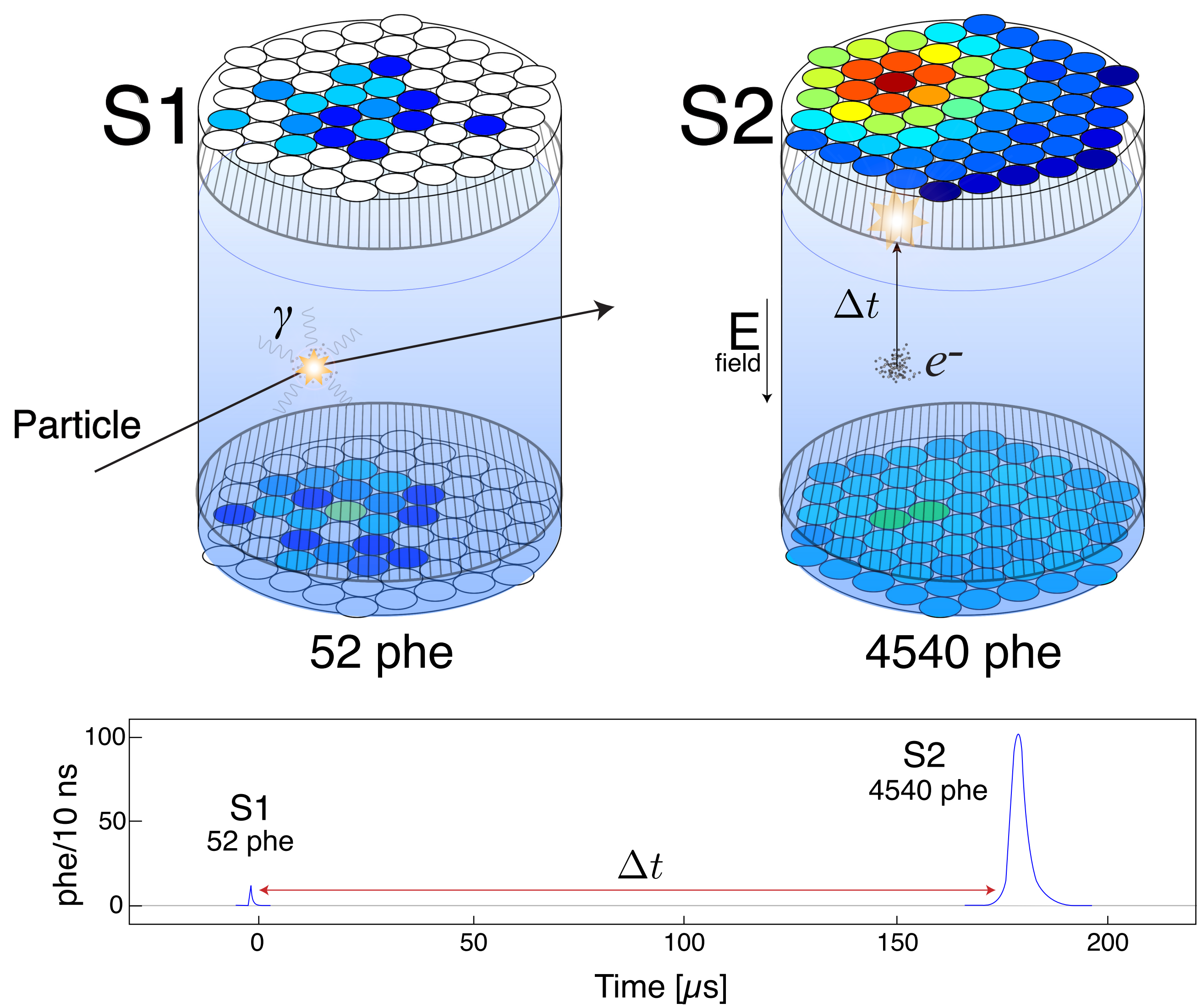
Direct detection: basics

Aim: Measure the energy deposited by the recoiling nucleus



Xenon experiments

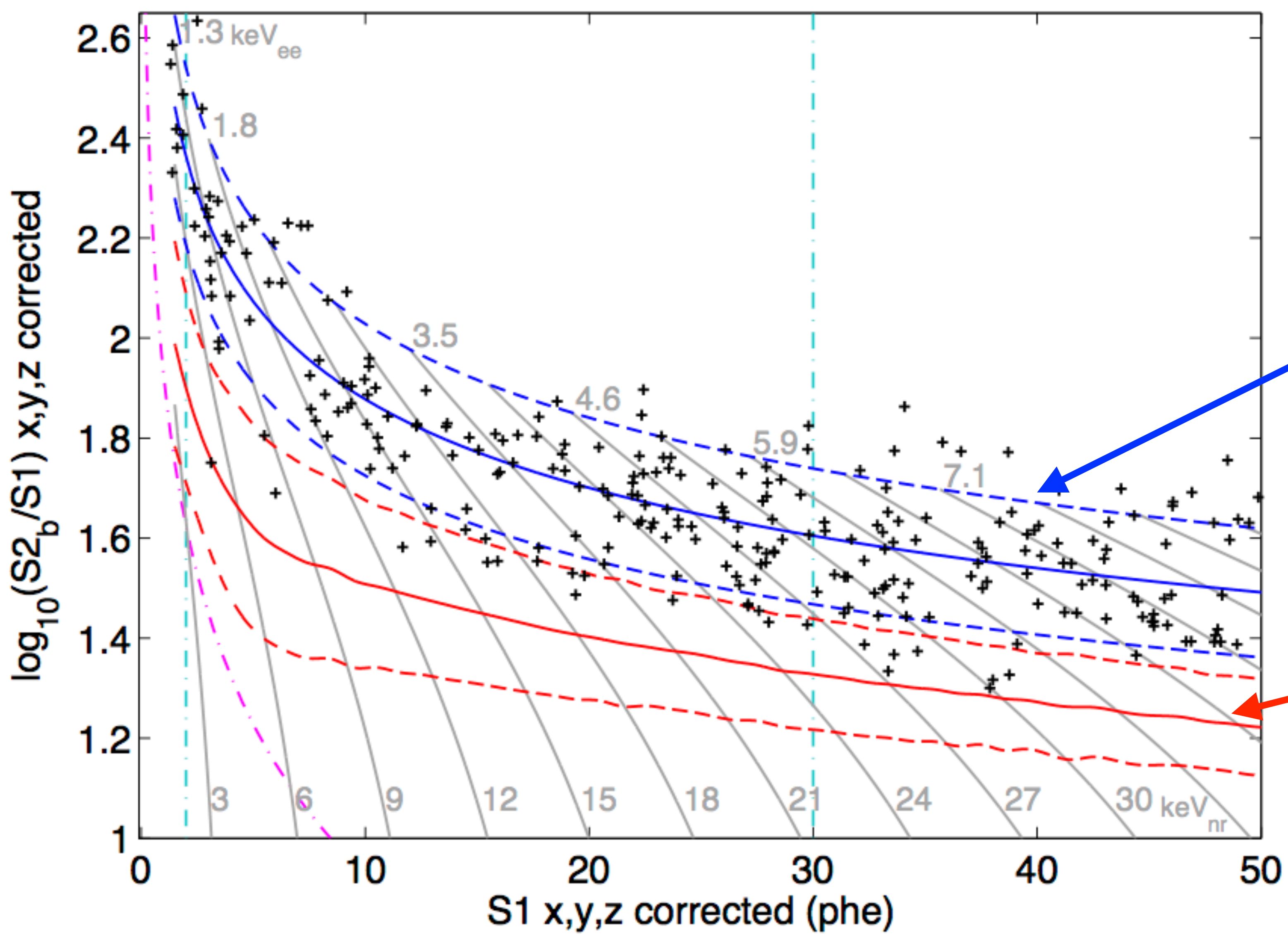
- Two-phase experiment (liquid and gas)
- Scattered particles create two pulses: S1 and S2



LUX results

- Measurement consistent with background: No dark matter here

LUX arXiv:1310.8214



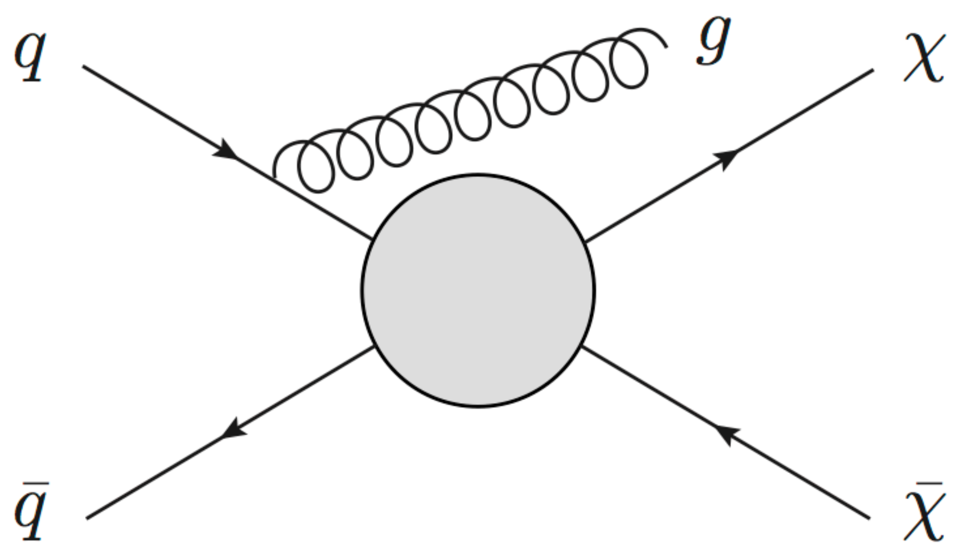
backgrounds mostly here

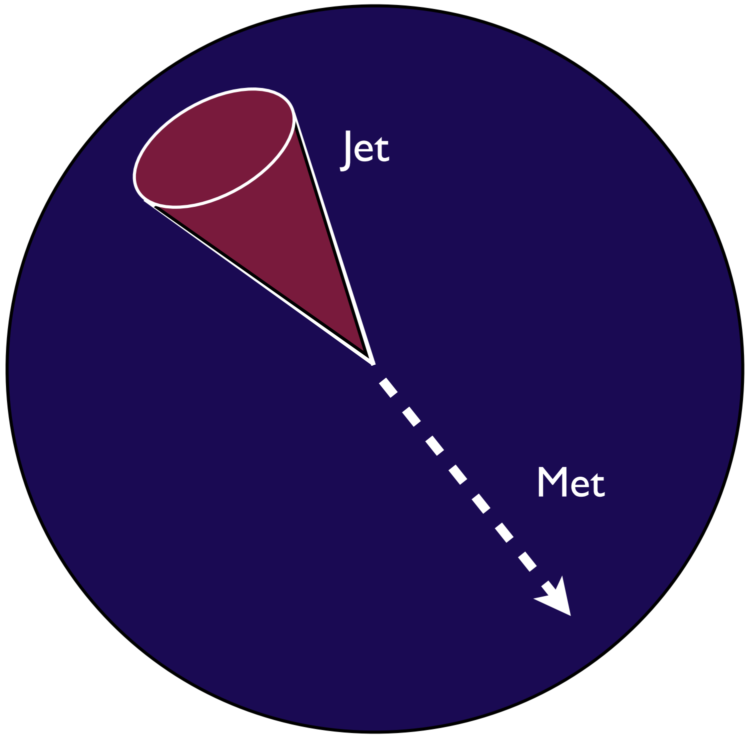
Dark matter (should be) mostly here

Monojet signature

CMS: 1408.3583
ATLAS: 1502.01518

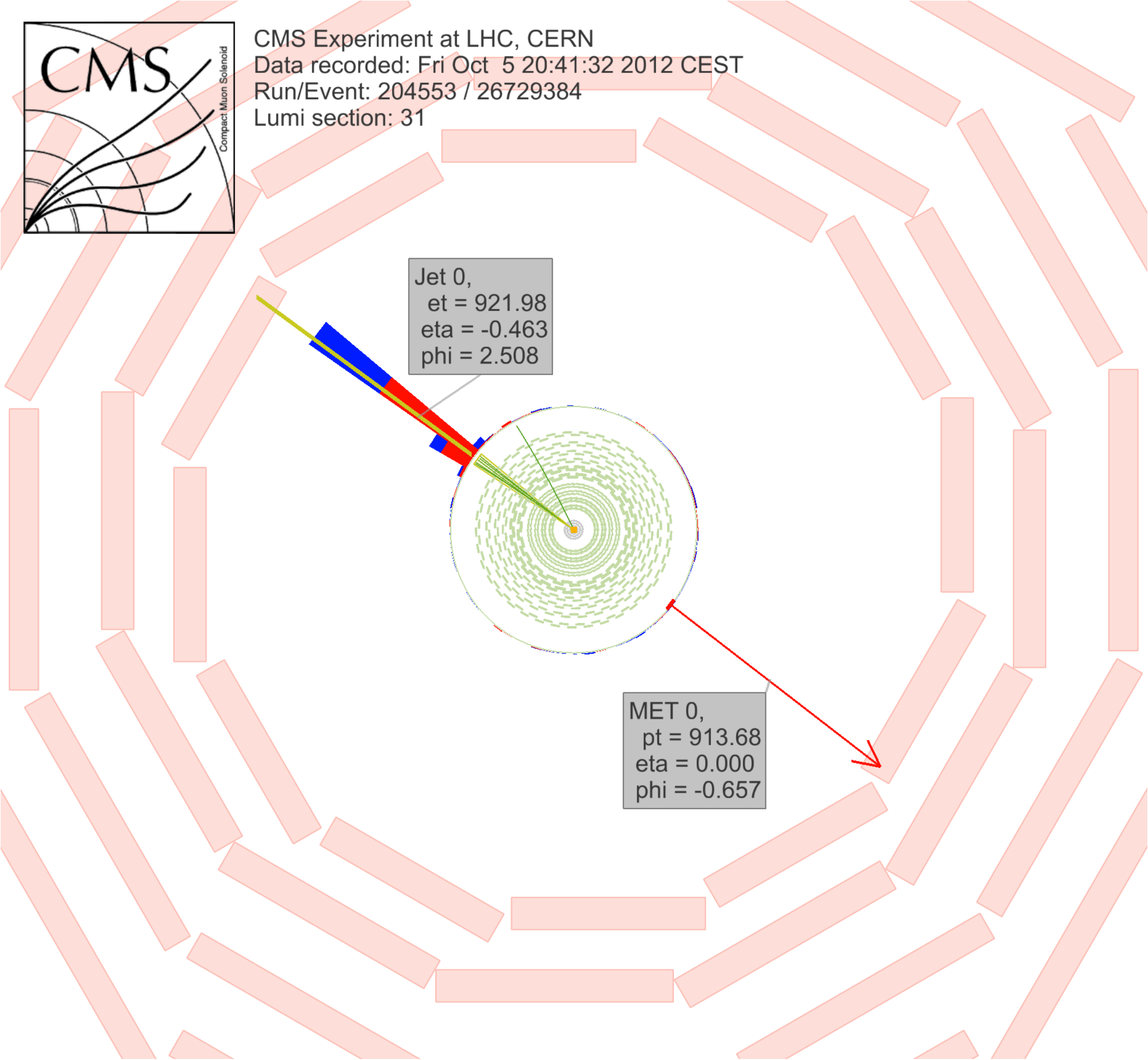
- ‘Classic’ pair production search
  - ➡ Simple and striking signature: hard jet and MET



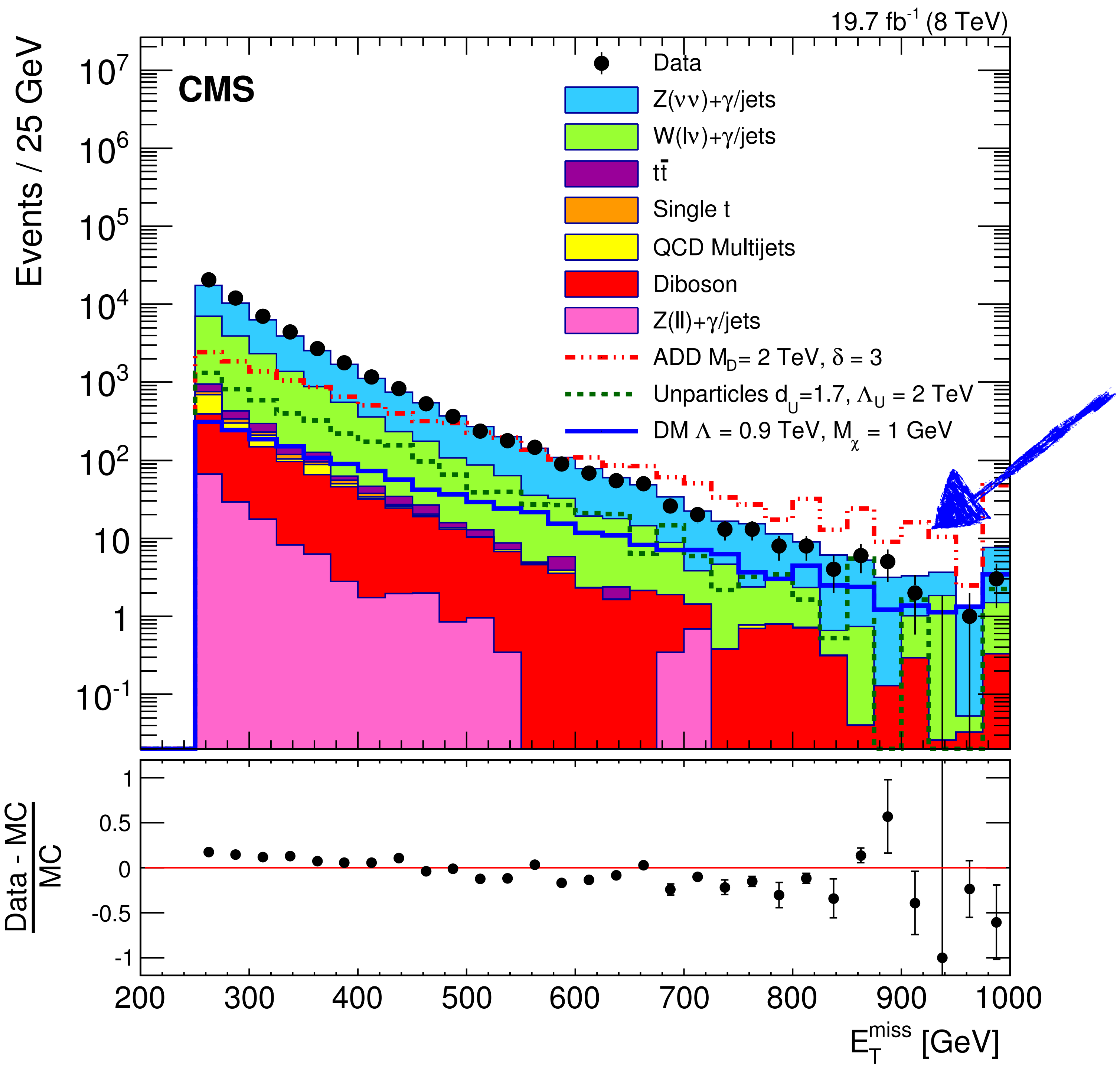


- Dark matter recoils against a QCD jet from initial state radiation (ISR)

Monojet: a real event



Monojet results

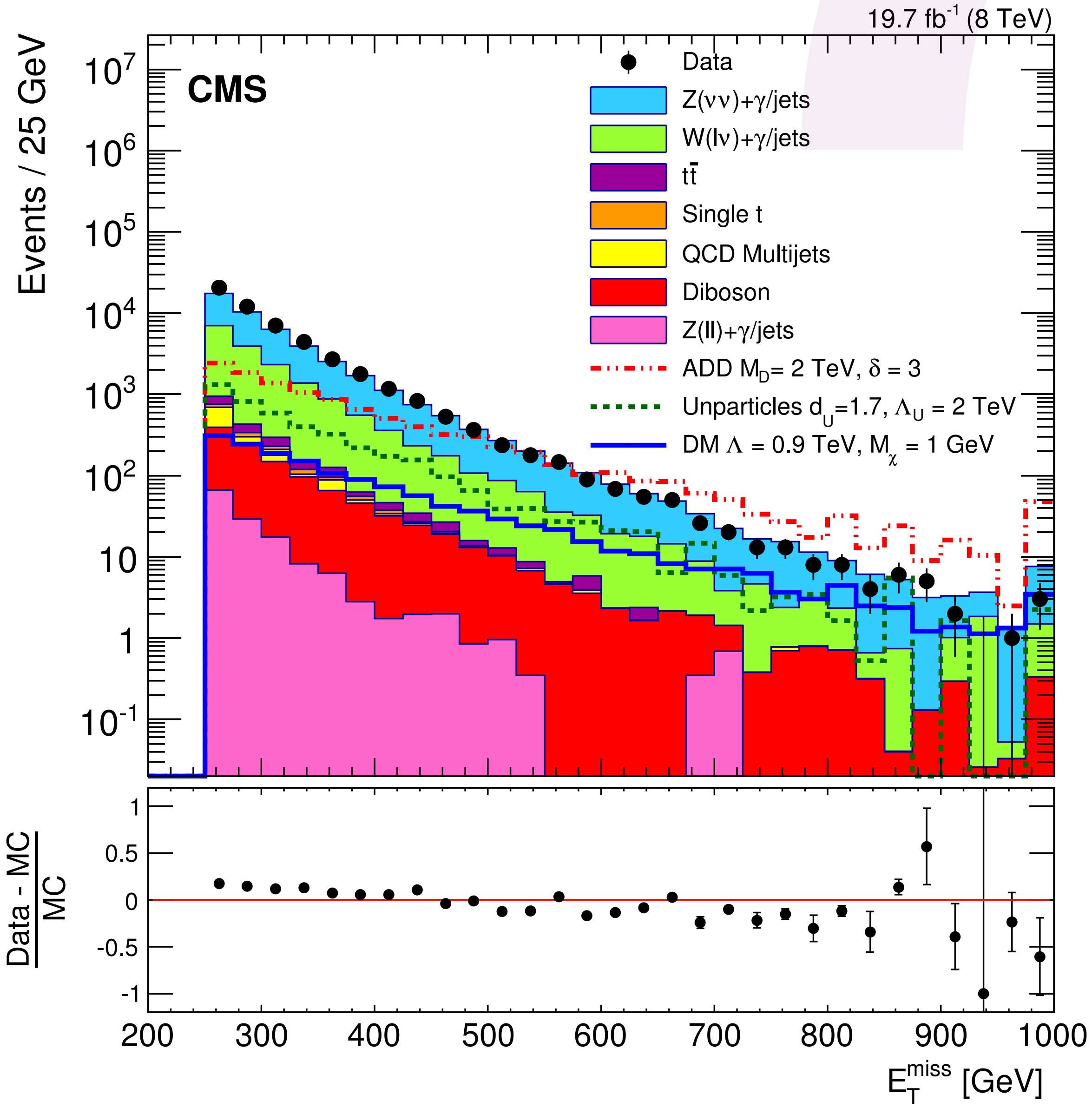


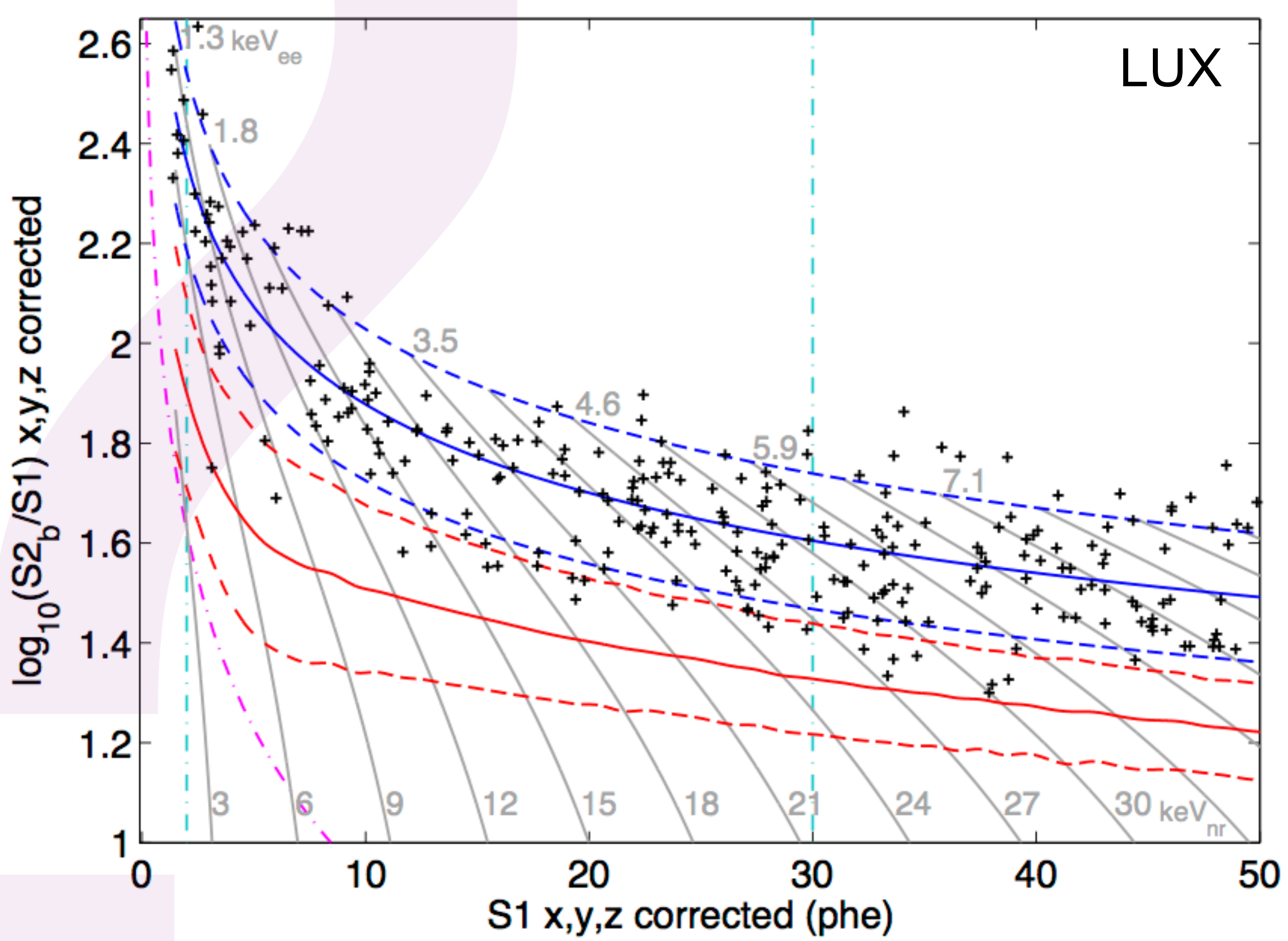
- Signal is a slight increase in the tail of the distribution
- Difficult to observe

- 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

Interpretation

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

Problem: In which framework should we interpret the search?

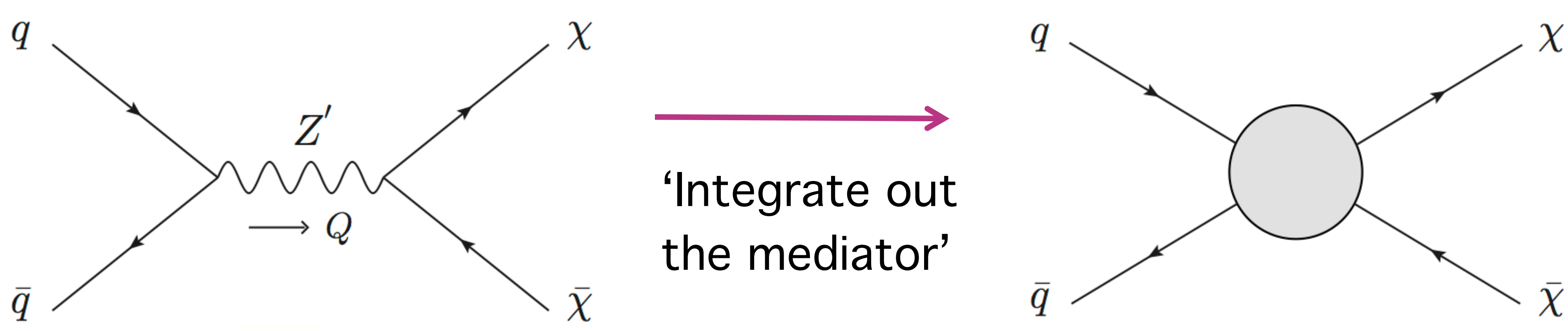
➡ There is no canonical dark matter model (outside SUSY…)

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



$$\mathcal{L} \sim g_\chi Z'_\mu \bar{\chi}\gamma^\mu \chi + g_q Z'_\mu \bar{q}\gamma^\mu q + \frac{1}{2} m_{Z'}^2 Z'_\mu Z'^\mu + \cdots$$

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

- Parameter of interest is the contact interaction scale Λ

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

This is not a new idea

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

$$\mathcal{L} = \frac{G_F}{\sqrt{2}} \left[\bar{\psi}\gamma^{\mu}(1-\gamma^5)\psi\right] \left[\bar{\psi}\gamma_{\mu}(1-\gamma^5)\psi\right] \text{ where } G_F \propto \frac{g^2_{\text{weak}}}{M^2_W}$$

- 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:

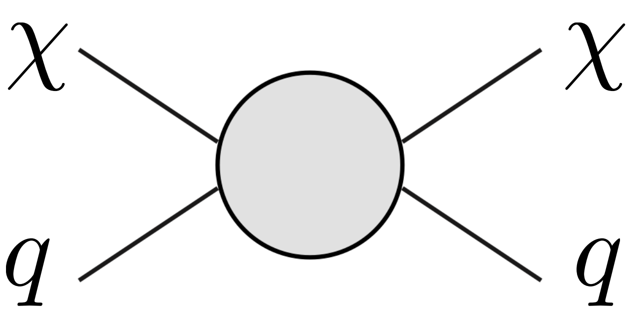
Name	Operator	Coefficient
D1	$\bar{\chi}\chi\bar{q}q$	m_q/M_*^3
D2	$\bar{\chi}\gamma^5\chi\bar{q}q$	im_q/M_*^3
D3	$\bar{\chi}\chi\bar{q}\gamma^5 q$	im_q/M_*^3
D4	$\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$	m_q/M_*^3
D5	$\bar{\chi}\gamma^{\mu}\chi\bar{q}\gamma_{\mu}q$	$1/M_*^2$
D6	$\bar{\chi}\gamma^{\mu}\gamma^5\chi\bar{q}\gamma_{\mu}q$	$1/M_*^2$
D7	$\bar{\chi}\gamma^{\mu}\chi\bar{q}\gamma_{\mu}\gamma^5 q$	$1/M_*^2$
D8	$\bar{\chi}\gamma^{\mu}\gamma^5\chi\bar{q}\gamma_{\mu}\gamma^5 q$	$1/M_*^2$
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	$\chi^{\dagger}\chi\bar{q}\gamma^5 q$	im_q/M_*^2
C3	$\chi^{\dagger}\partial_{\mu}\chi\bar{q}\gamma^{\mu}q$	$1/M_*^2$
C4	$\chi^{\dagger}\partial_{\mu}\chi\bar{q}\gamma^{\mu}\gamma^5 q$	$1/M_*^2$
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	$\chi^2\bar{q}\gamma^5 q$	$im_q/2M_*^2$
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

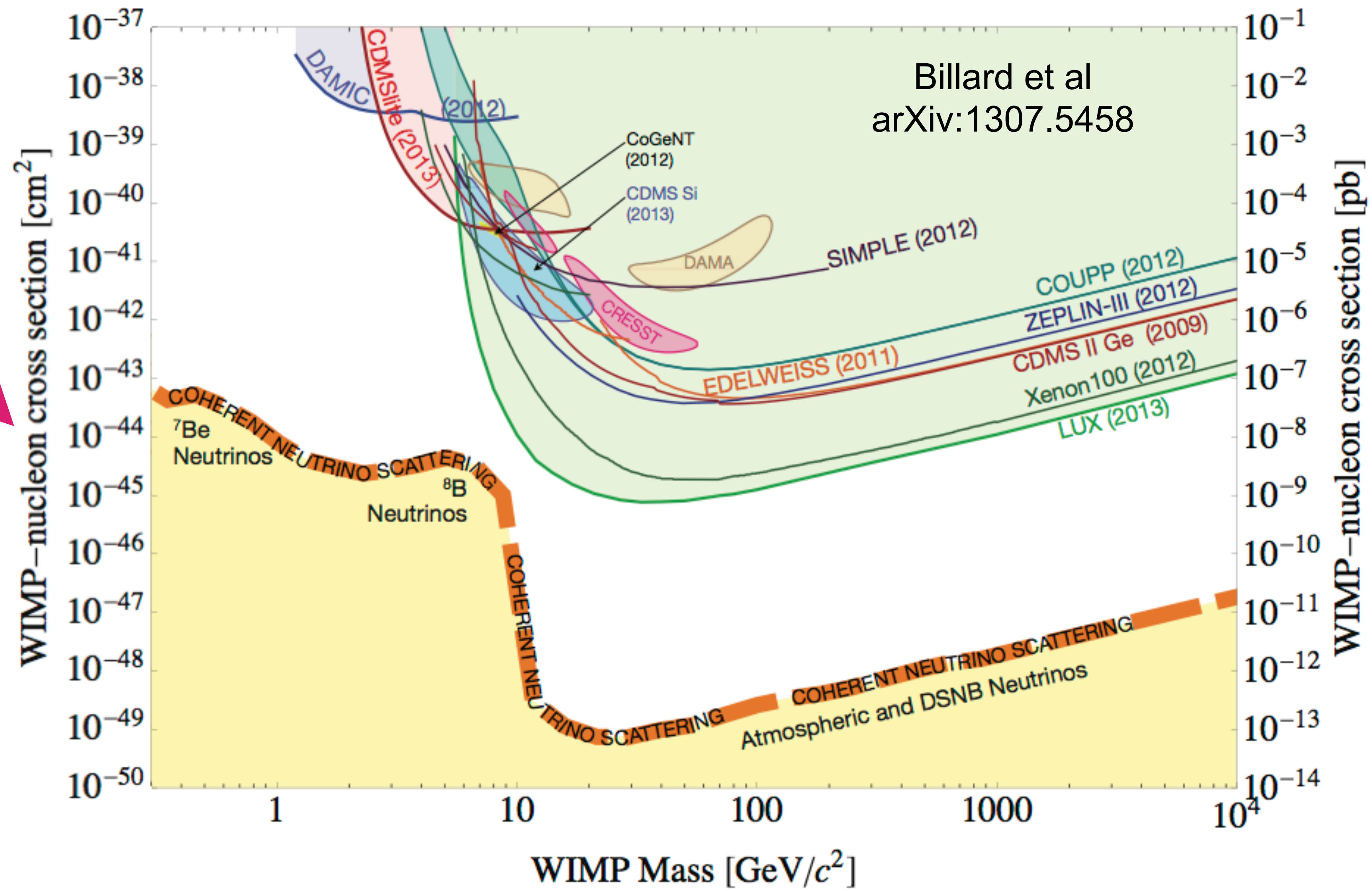
EFT in action: direct detection

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



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

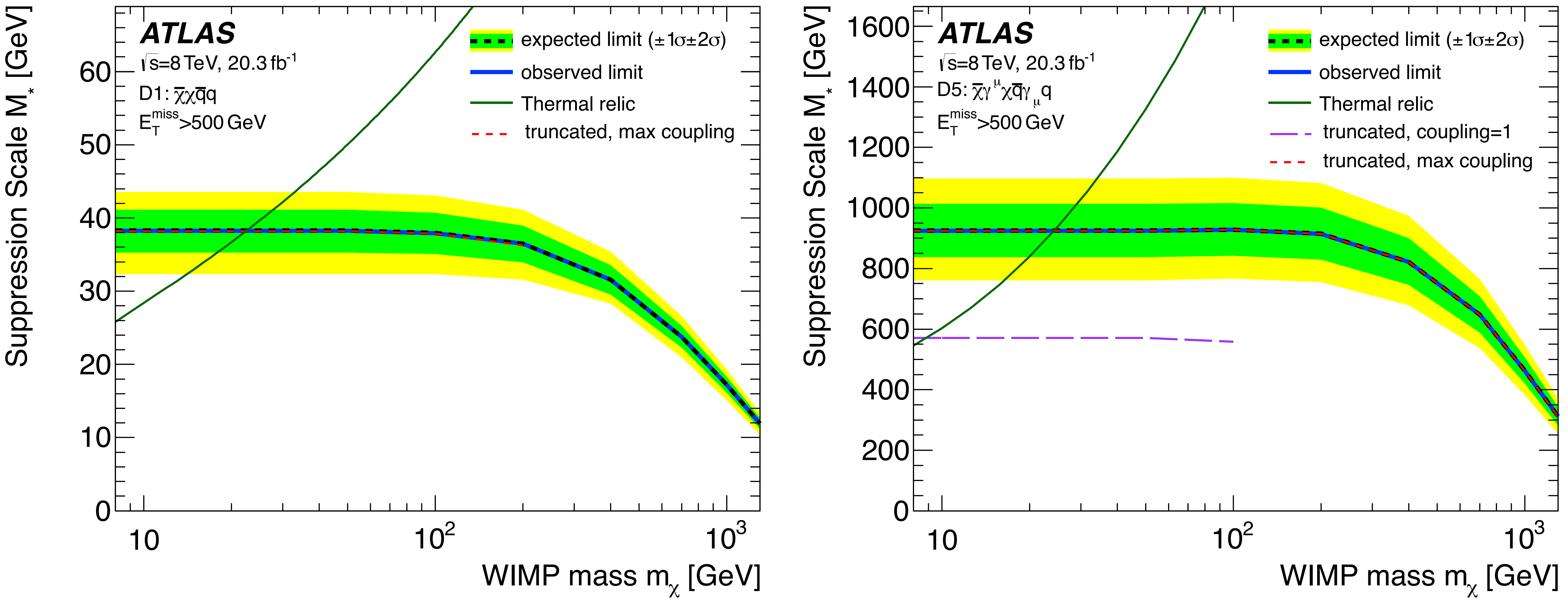
$$\mathcal{L} \sim \frac{1}{\Lambda^2}\bar{q}\gamma^\mu q\bar{\chi}\gamma_\mu\chi$$



One limit valid for multiple operators

EFT in action: monojet

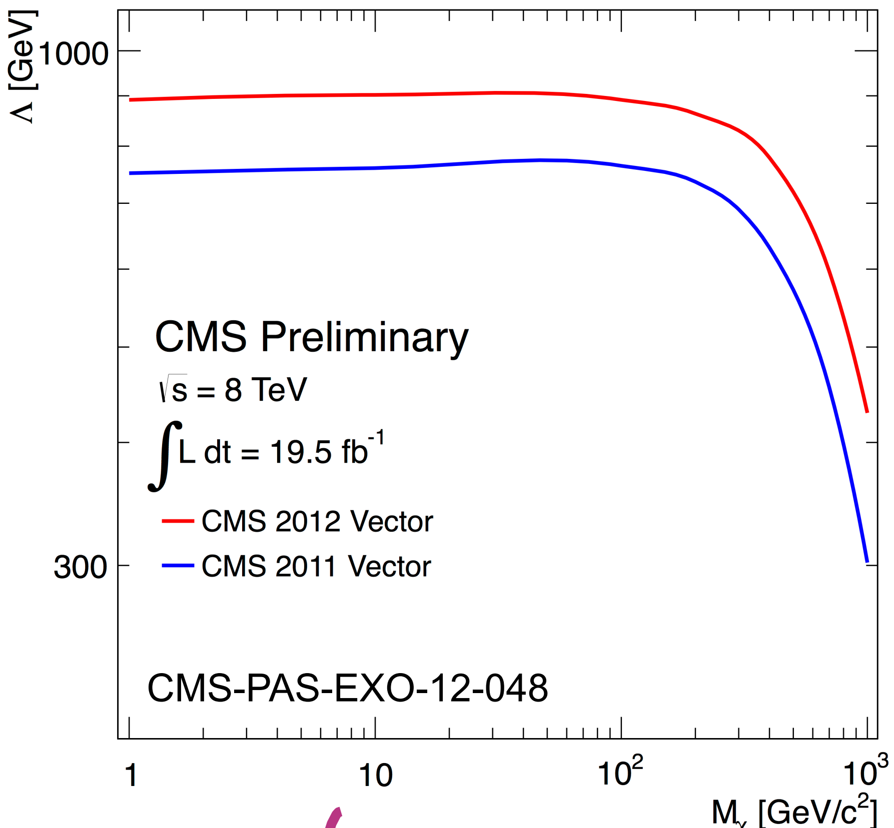
- Directly constrain Λ (or $M_\star$) for various operators



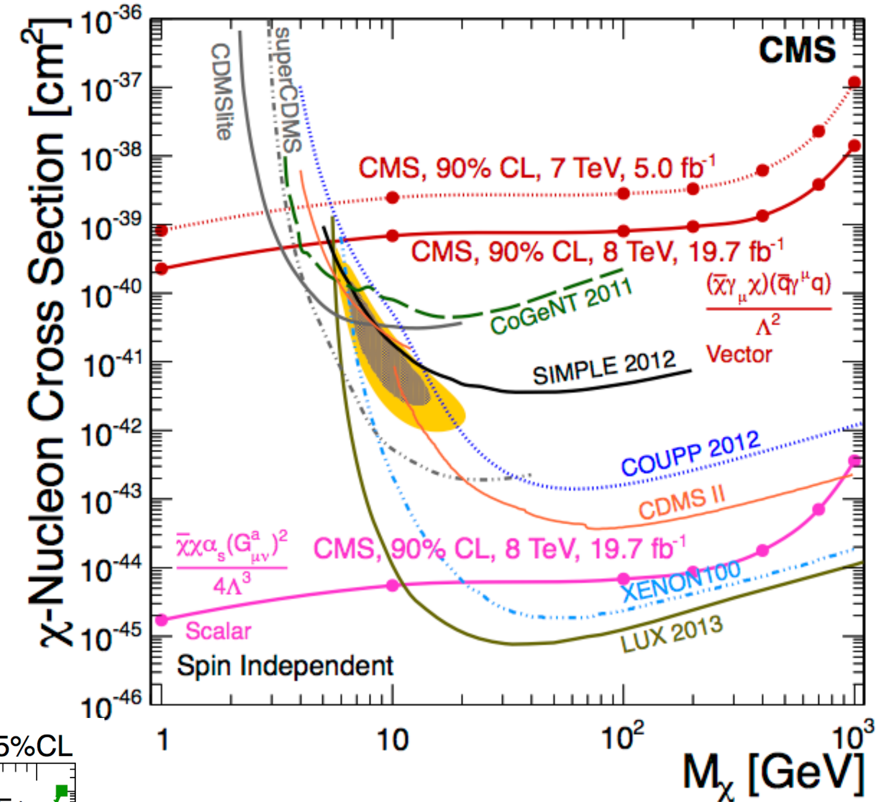
Separate limit for each operator

Advantage of EFT approach

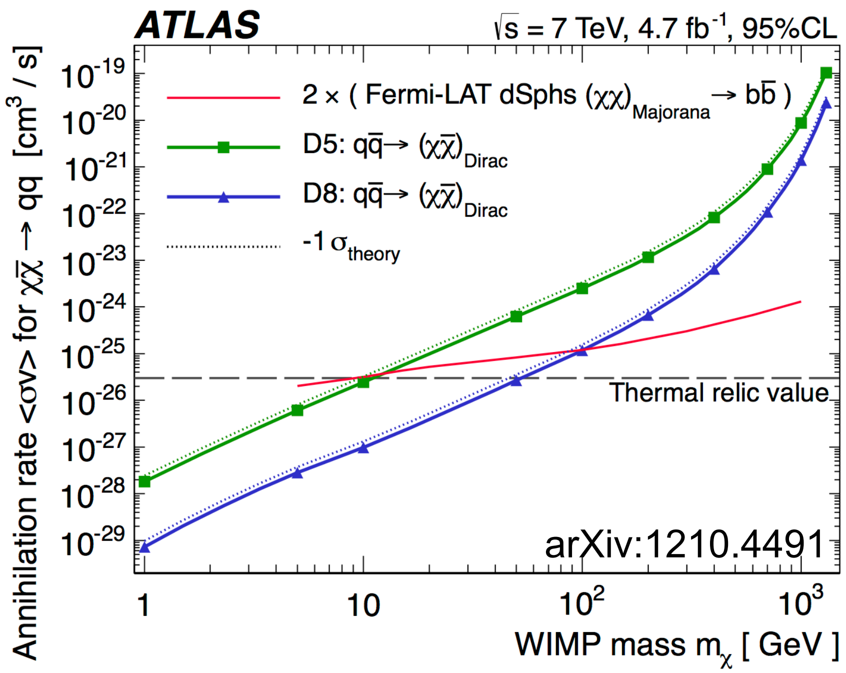
- Comparison with other dark matter searches is straightforward



with direct detection limits

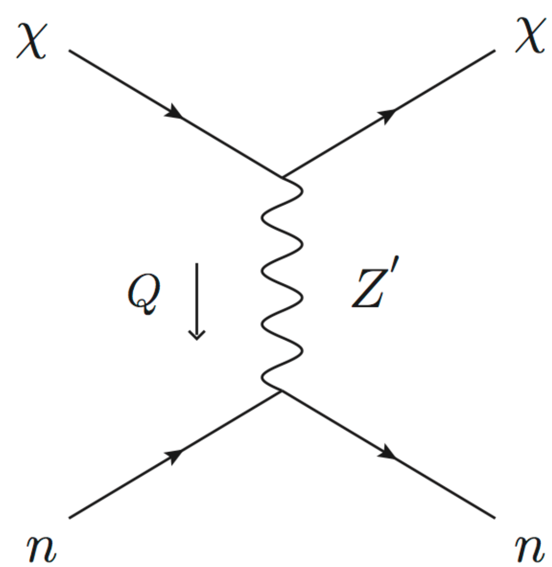


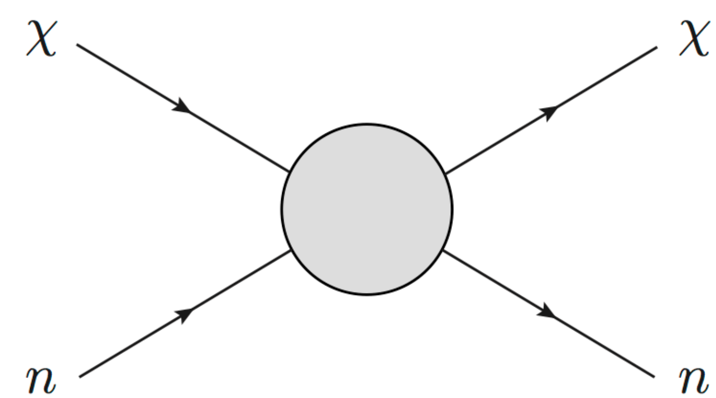
with indirect detection limits



EFT at direct detection: is it valid?

- A contact interaction at direct detection:





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

- Contact interaction if $m_{Z'} \gg Q = \sqrt{2 m_n E_{\rm R}} \approx 50 \ {\rm MeV}$
- 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)

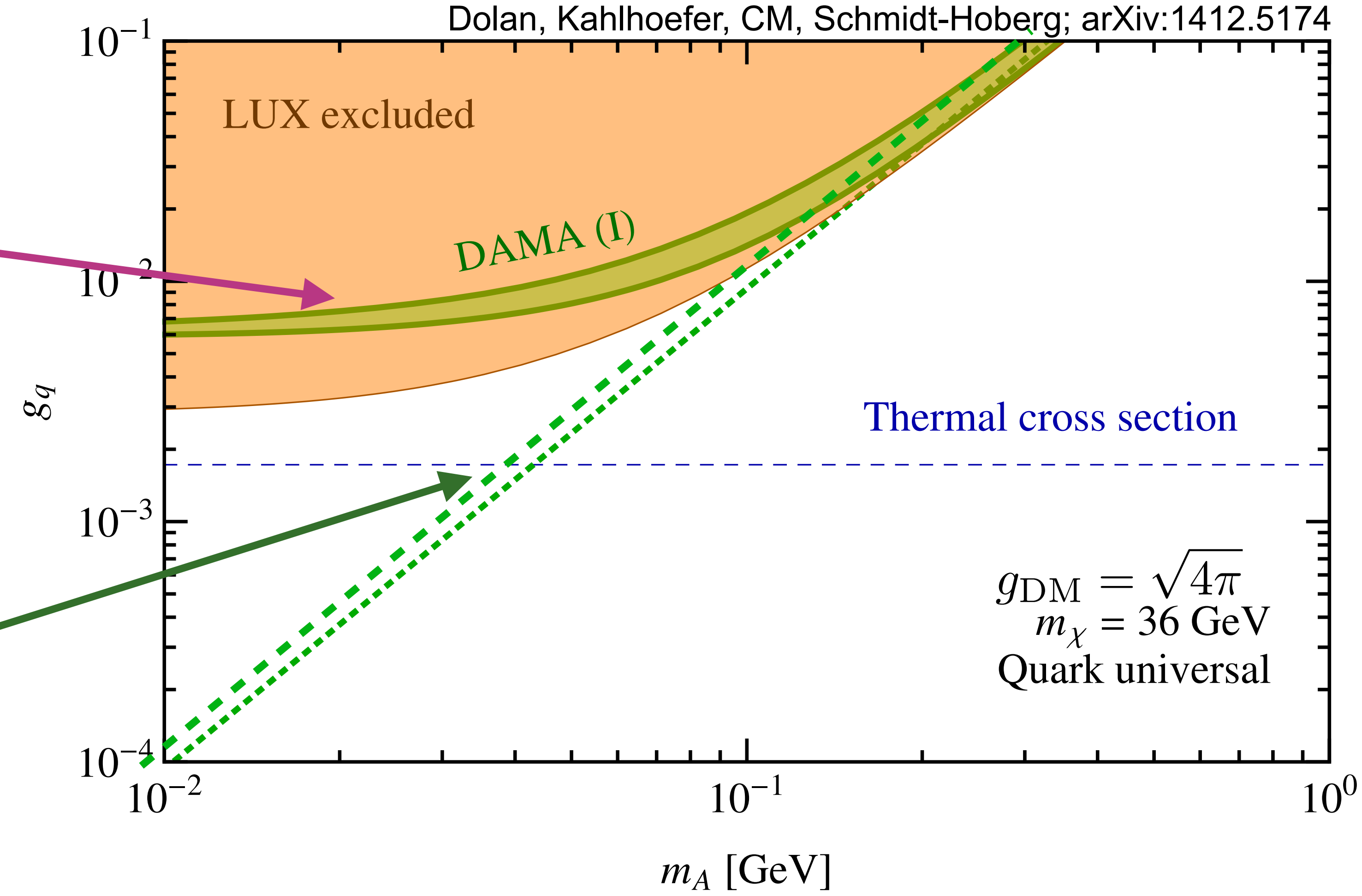
Full propagator:

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

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

contact interaction:

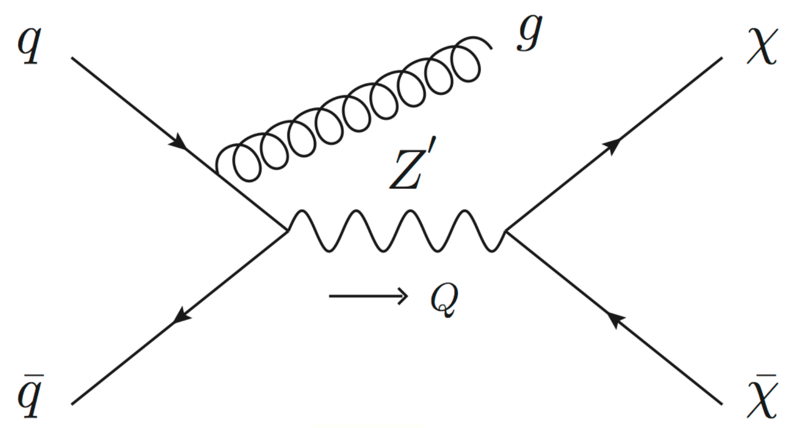
$$\frac{d\sigma}{dE_{\rm R}} \propto m_A^{-4}$$



Breakdown of contact interaction completely changes conclusions

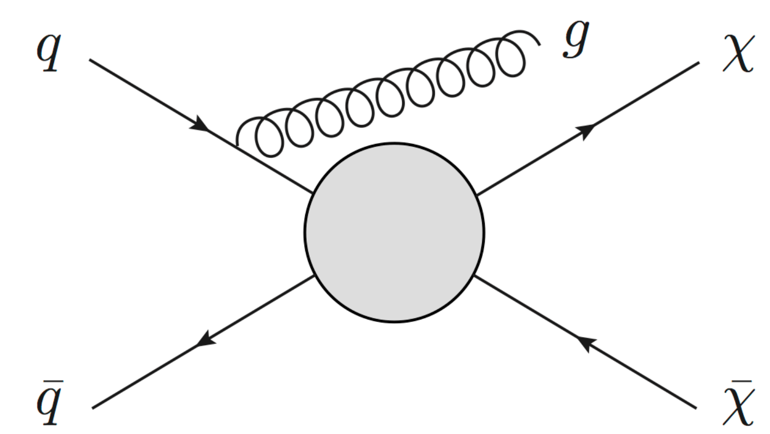
EFT in monojet: is it valid?

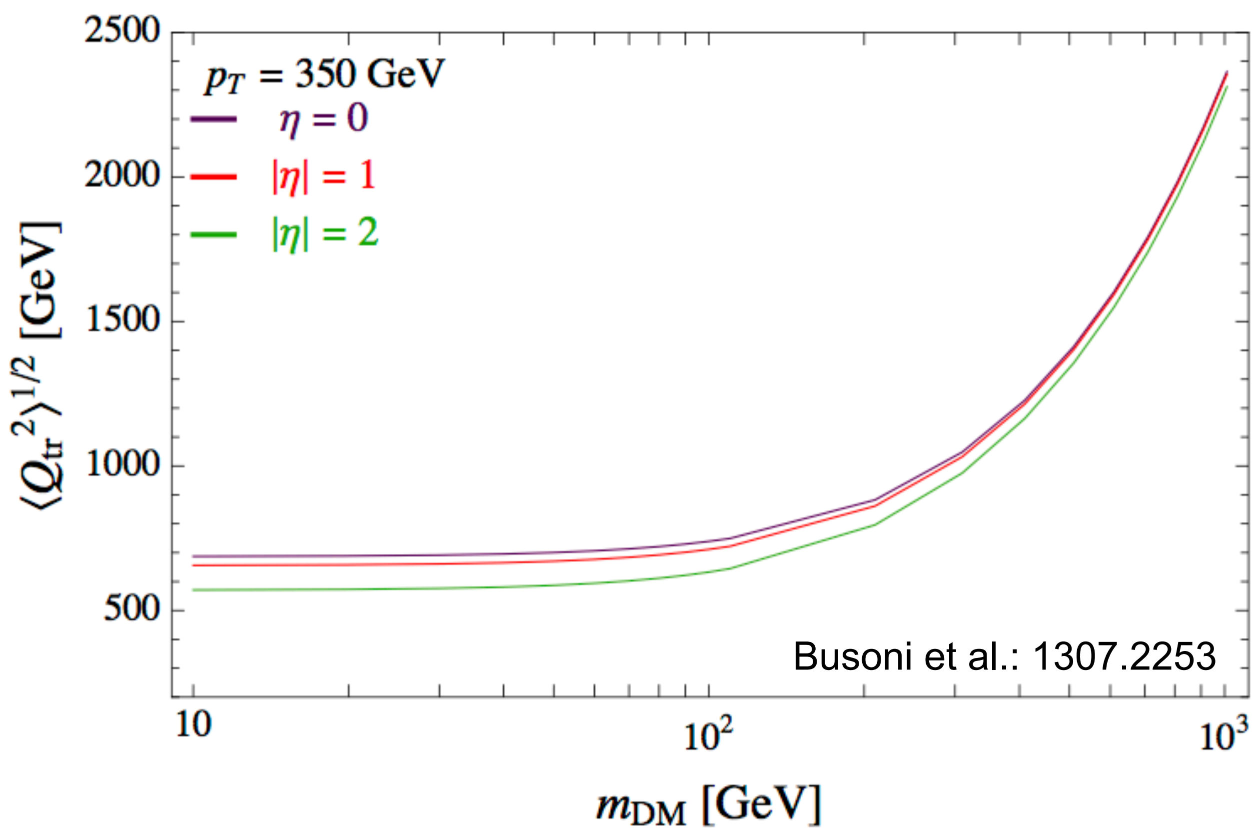
- A contact interaction at the LHC:



Good approximation if

$$M_{Z'} \gg Q$$



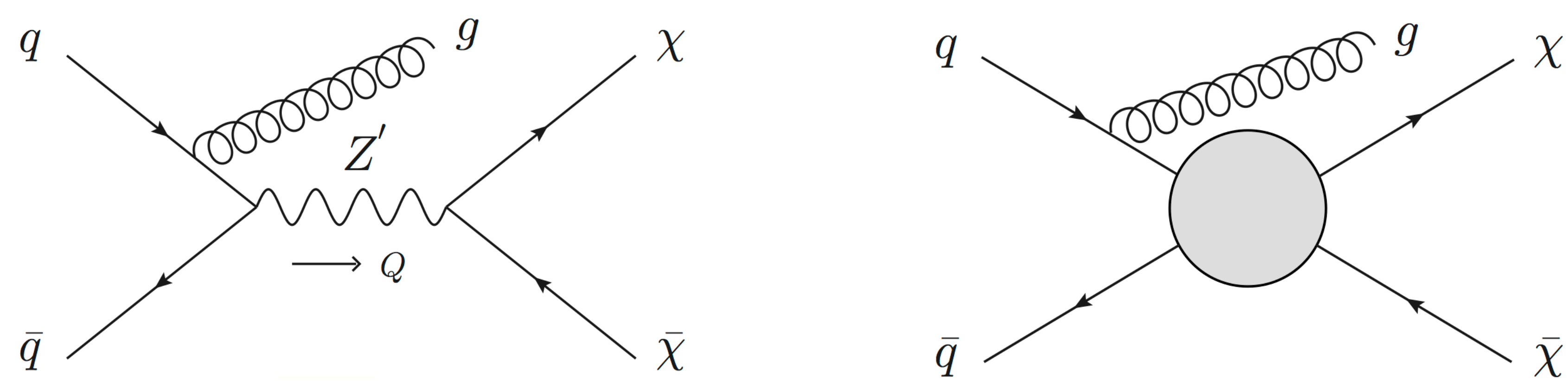


$$M_{Z'} \gtrsim \mathrm{TeV}$$

EFT in monojet: is it valid?

Buchmueller, Dolan, CM
arXiv:1308.6799

- Better estimate: Compare a simple model with EFT result



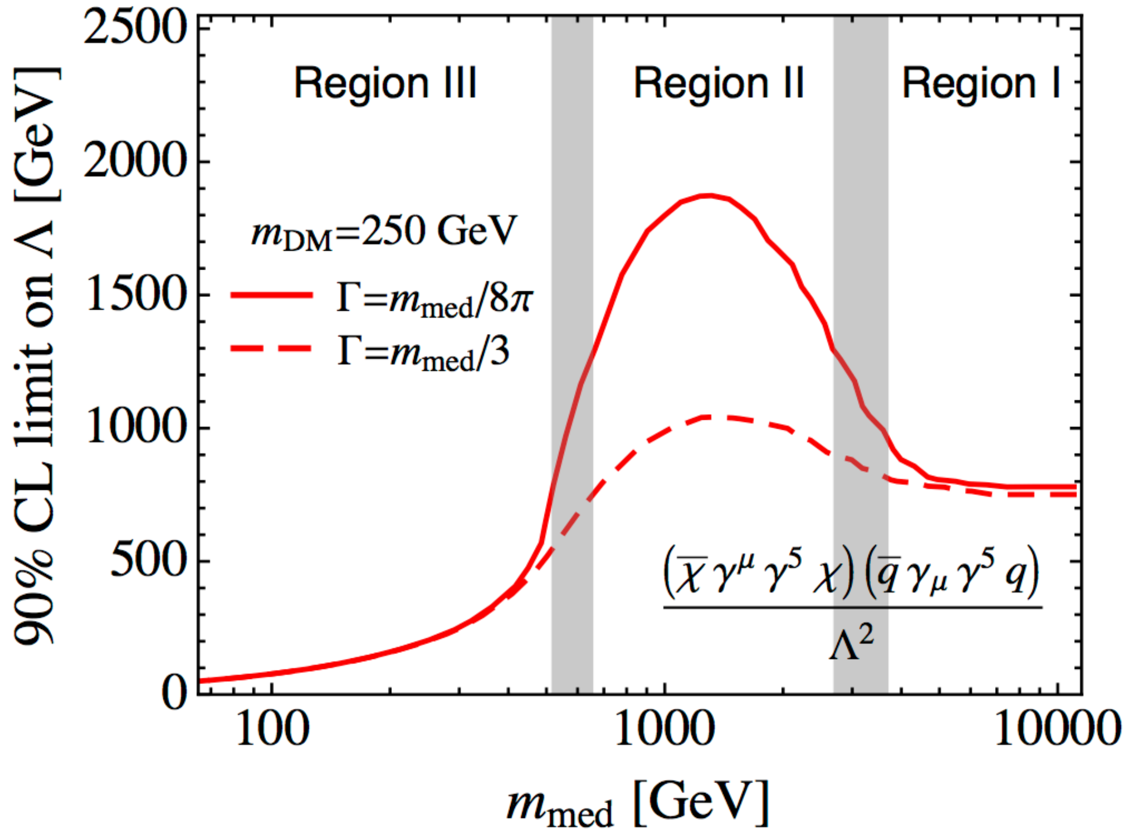
- Assumptions:
  1. s-channel axial-vector mediator
  2. Equal couplings to all quarks
  3. No coupling to leptons or SM gauge bosons

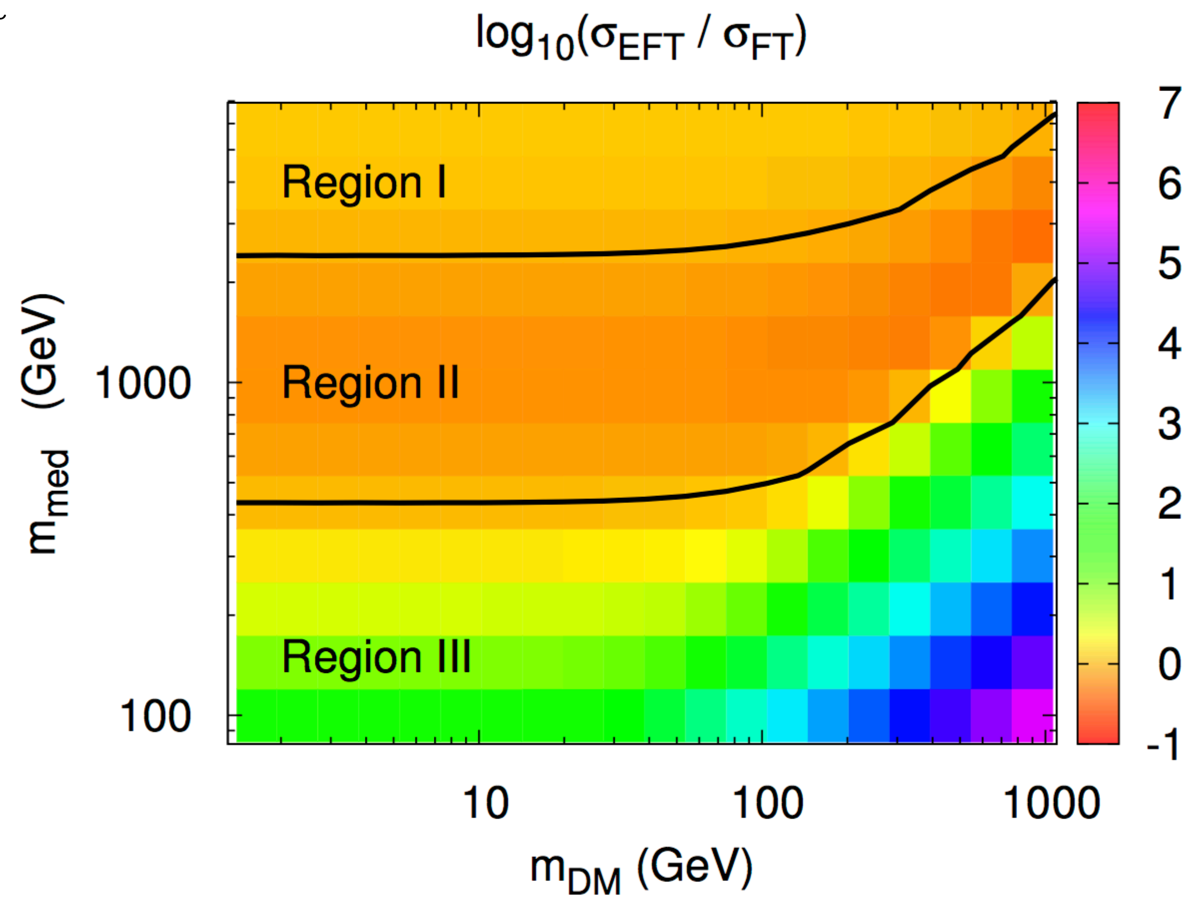
- Said in Lagrangians:

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

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

Region I: EFT valid

EFT limit applies to a small class of theories

- Large mediator mass:

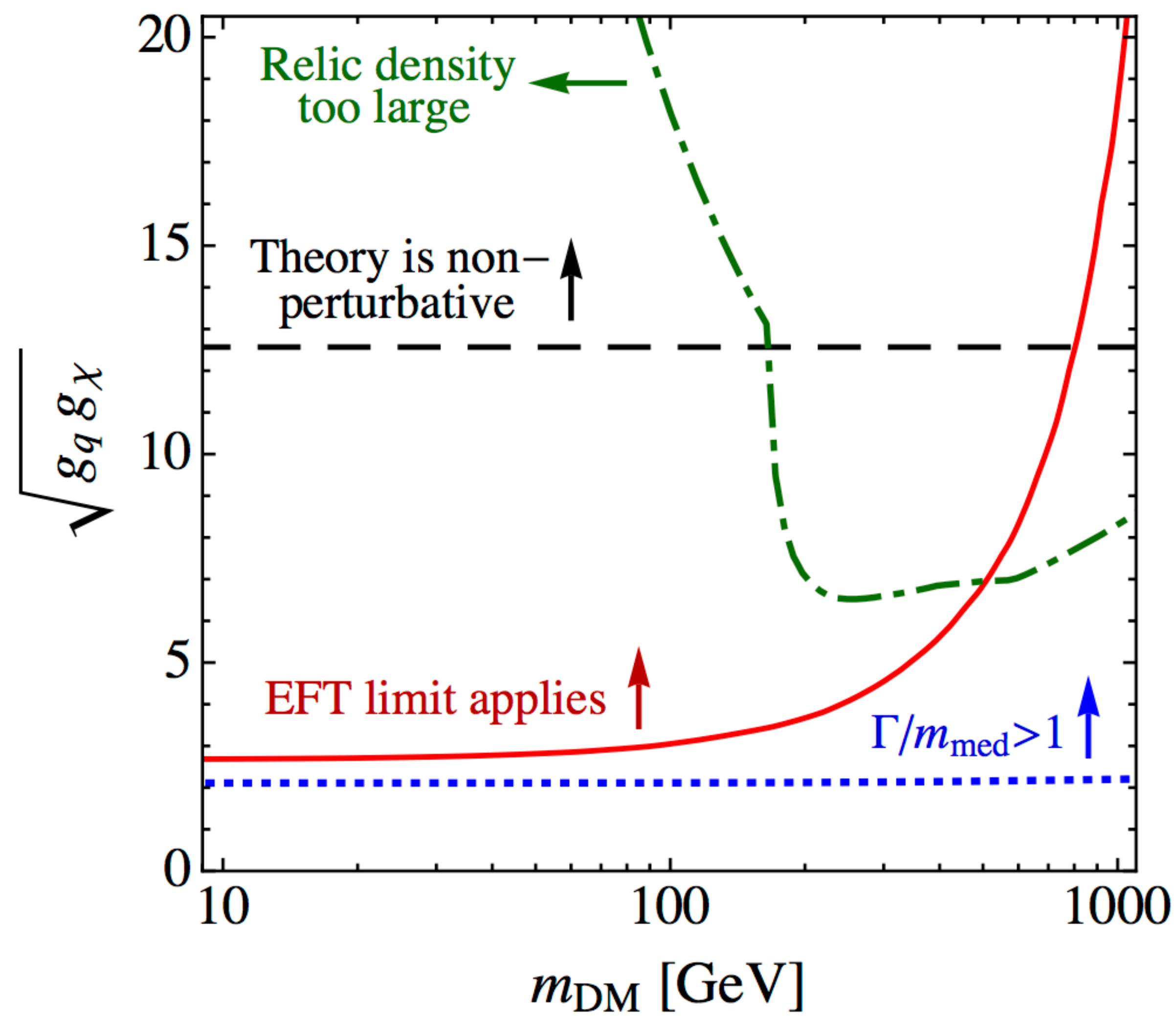
$$m_{\rm med} \gtrsim 3\ \text{TeV}$$

- Large couplings:

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

- Large mediator width:

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



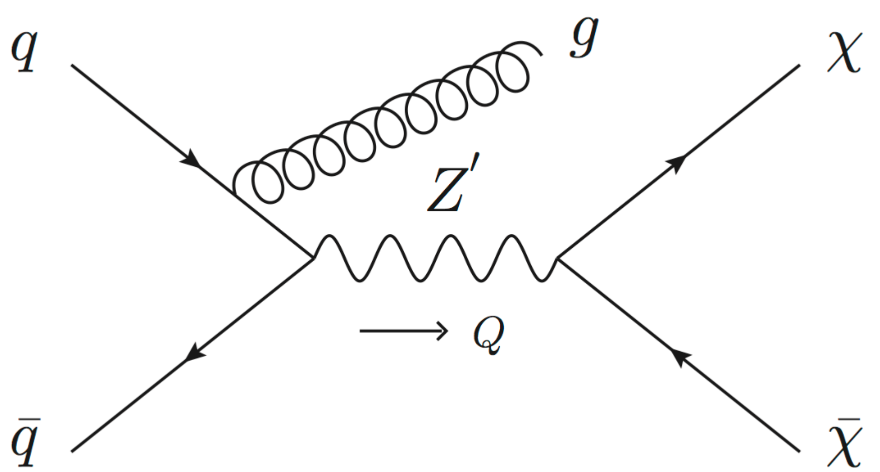
Region II: EFT too weak

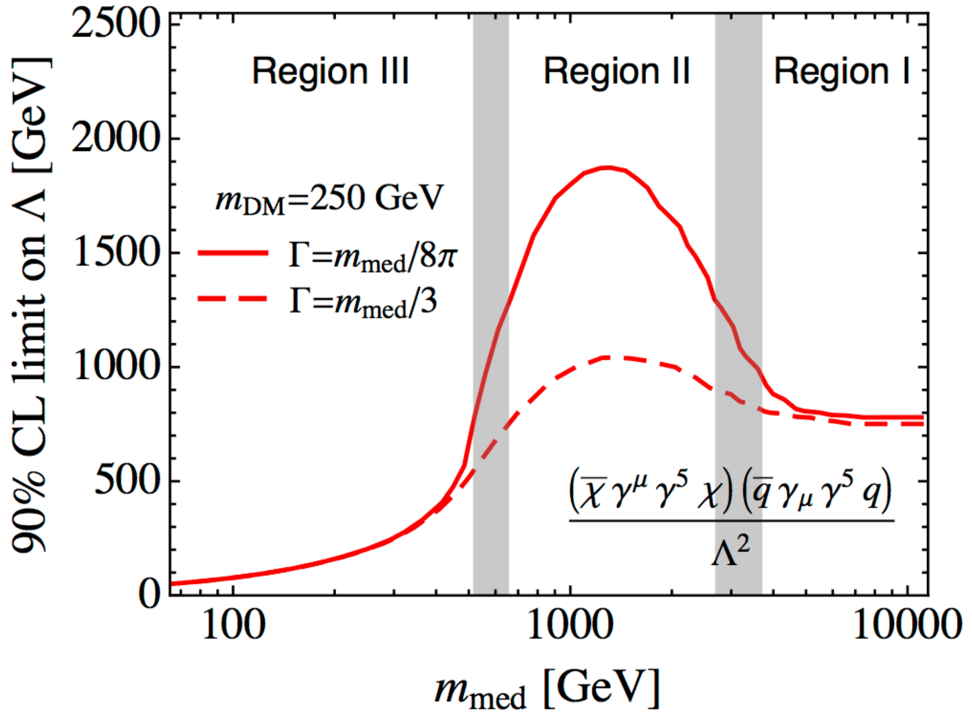
EFT does not account for s-channel resonant enhancement

- Enhanced when
  $$m_{\rm med}^2 \sim 4m_{\rm DM}^2 + \not{E}_{\rm T}^2$$

- 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

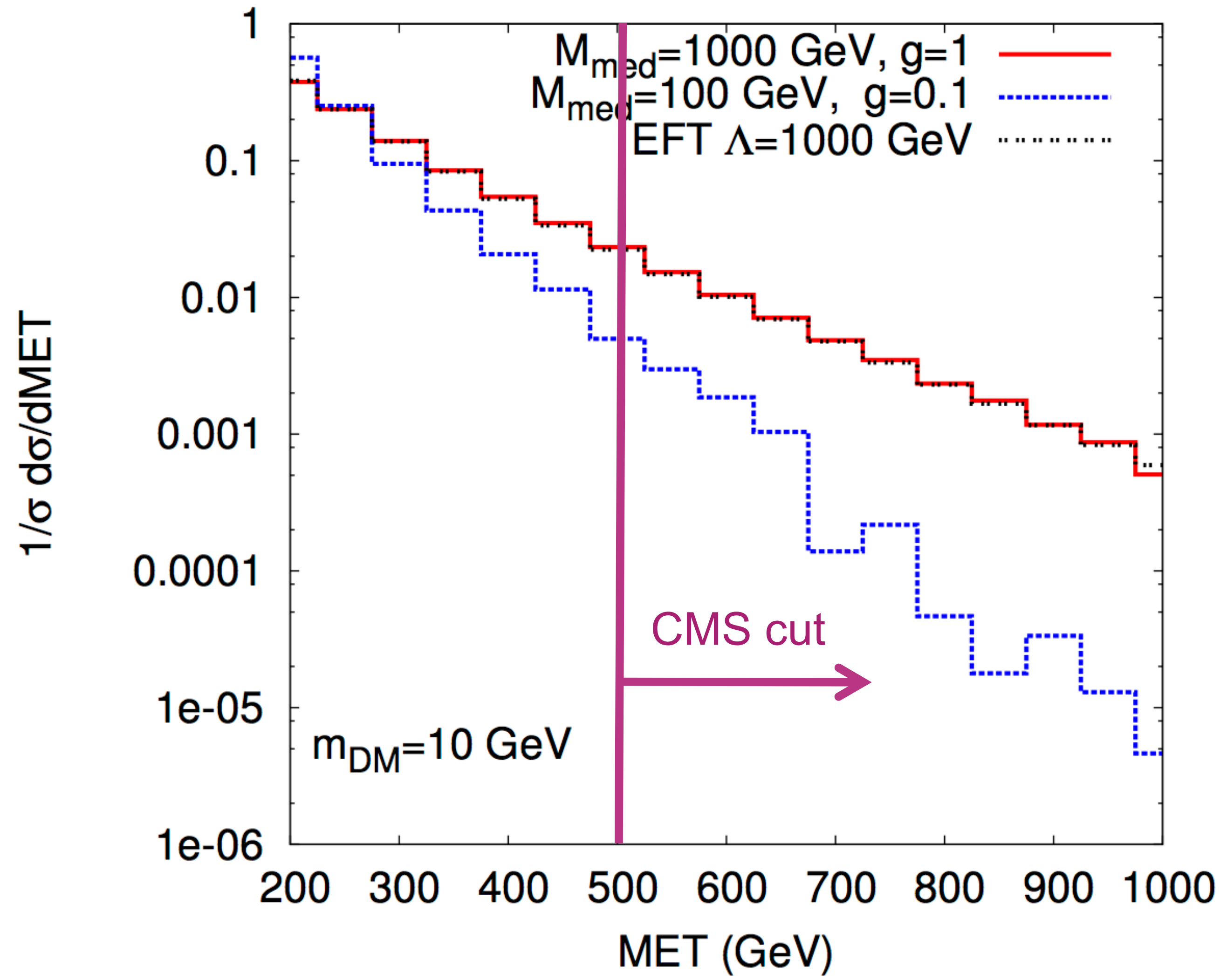
- Light mediator masses

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

- Events with a light mediator are much softer

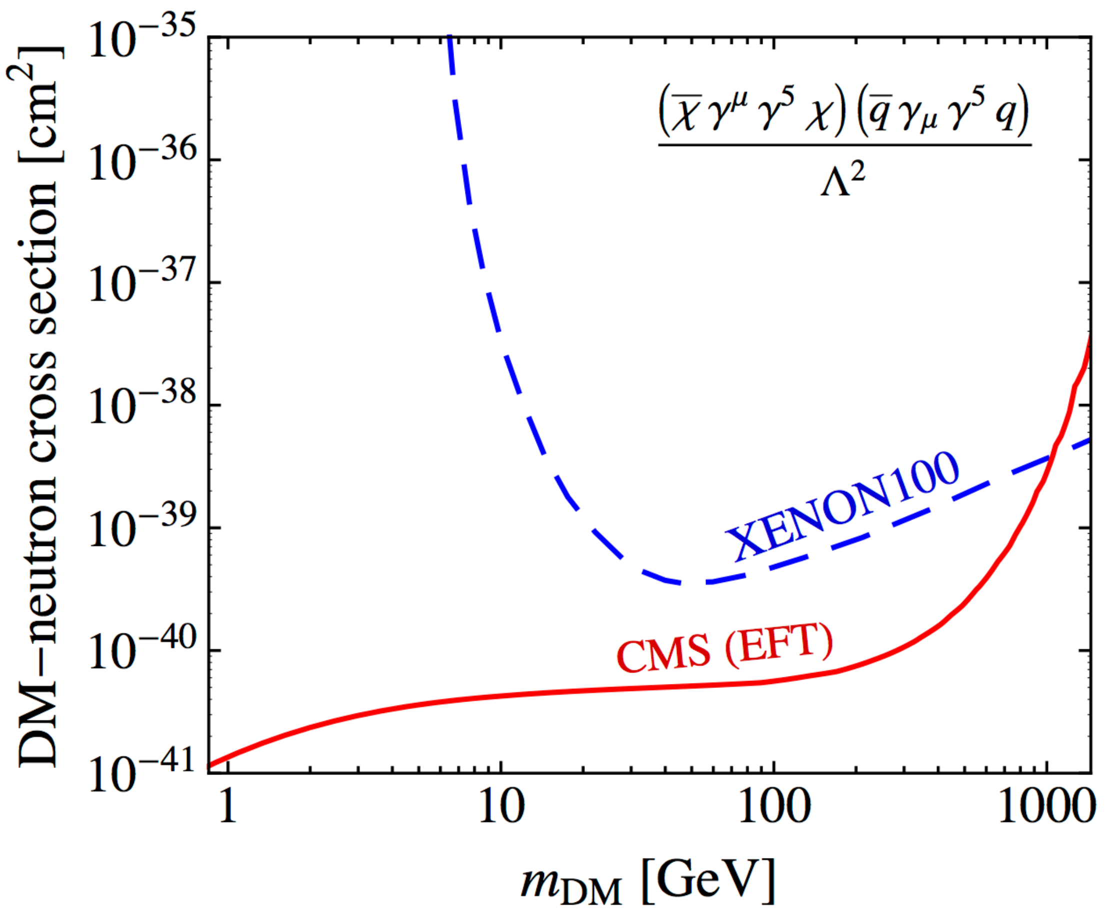
- EFT overestimates number of DM events produced

  ➡ limit on Λ is too strong



Other problems

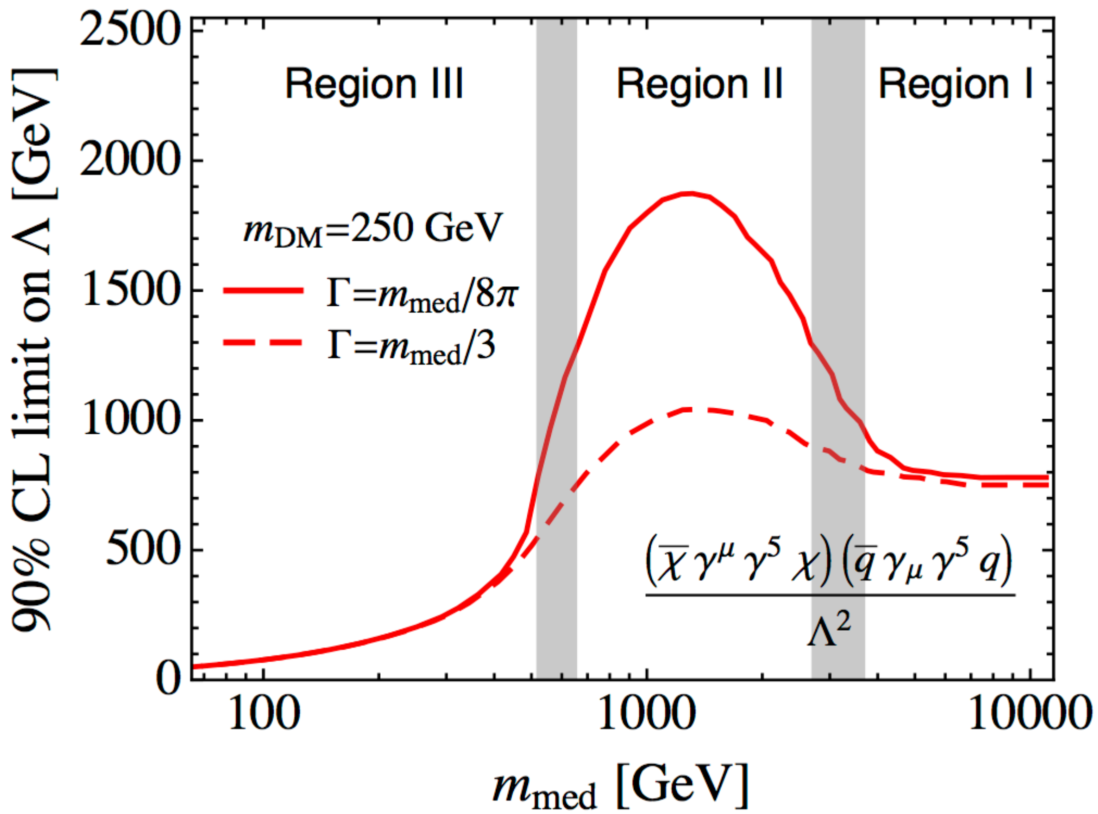
- Comparison with direct detection:

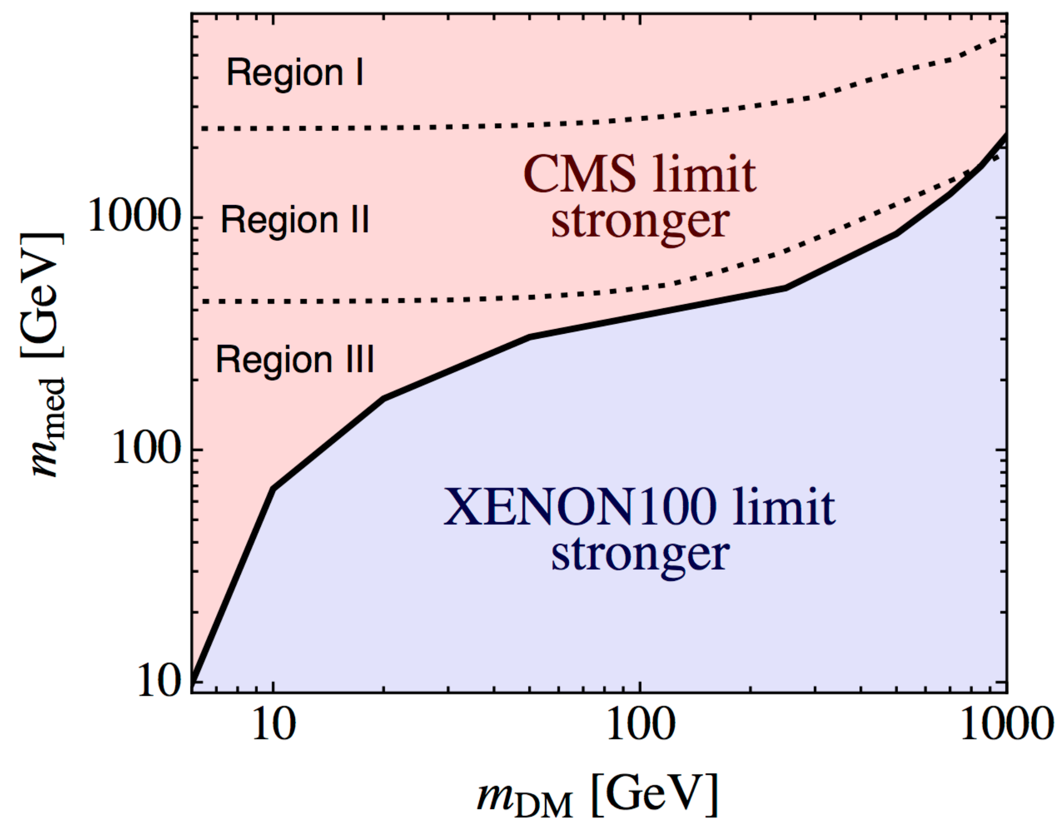


- Naive application of EFT limit gives the impression that the LHC limit is stronger for $m_{\rm DM} \lesssim 1$ TeV

Other problems

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





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

EFT interpretation: mini-summary

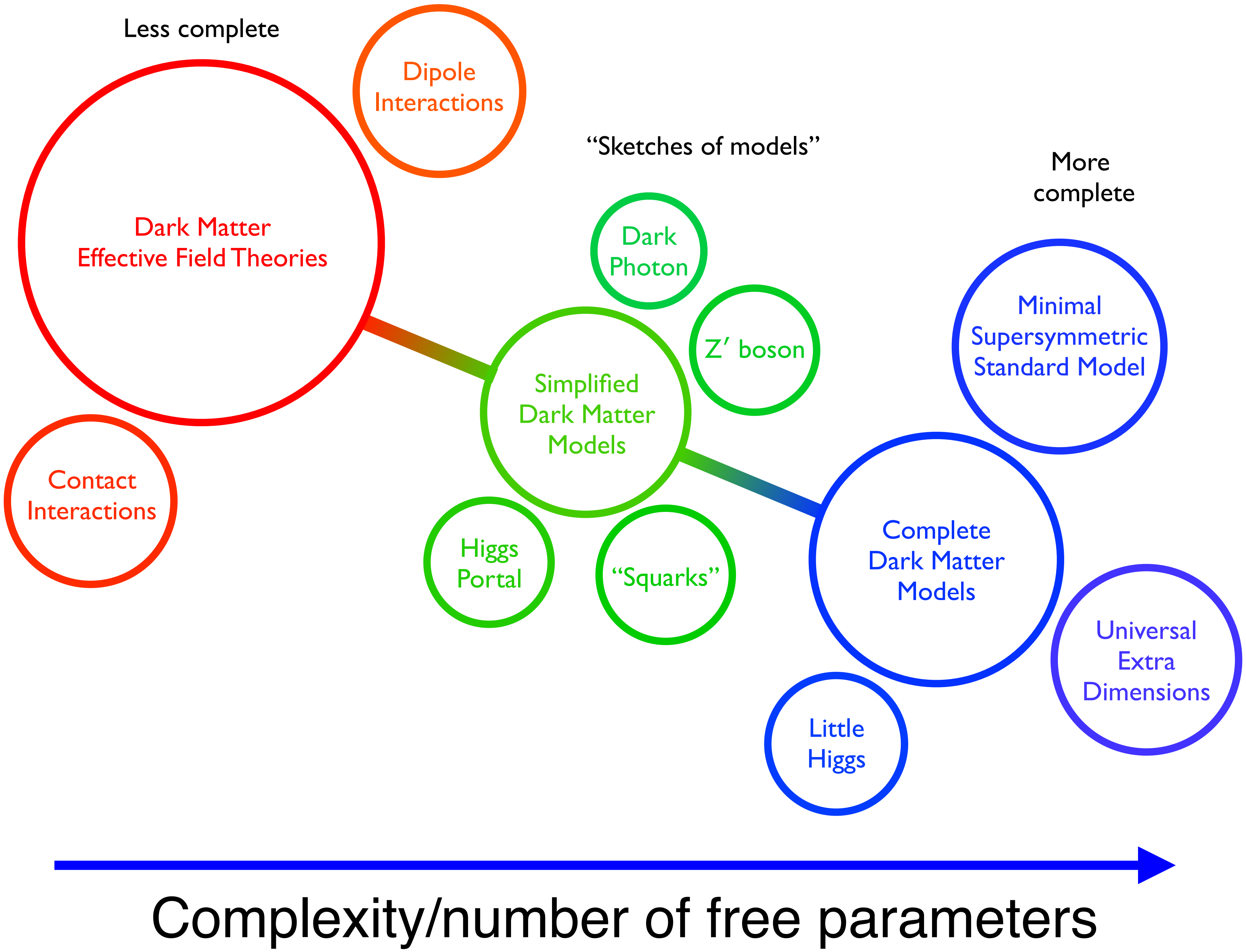
- EFT/contact interaction works well for direct detection
  - ➡ valid for most models (mediator > 100 MeV)

- 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…

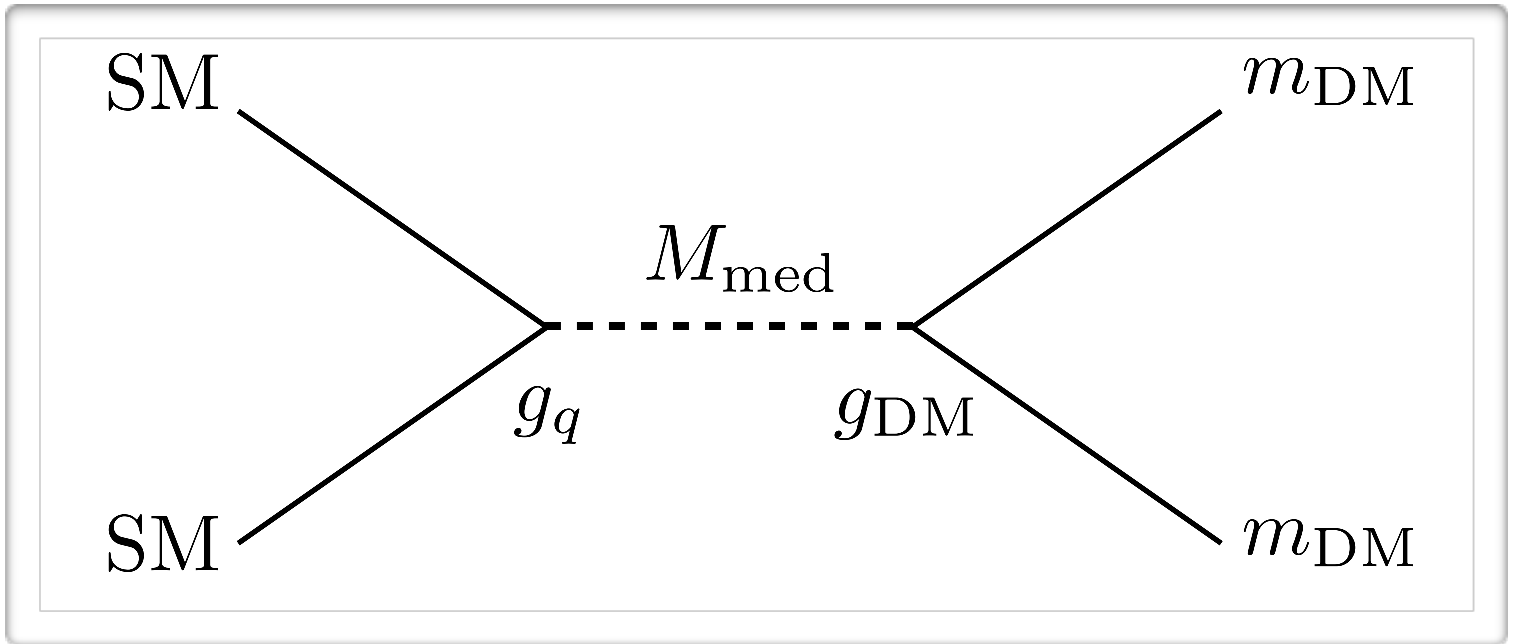
Abdallah et al
arXiv:1506.03116



2. Simplified models

Buchmueller, Dolan, Malik, CM arXiv:1407.8257

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



Minimum 4 parameters	
$m_{\rm DM}$	$M_{\rm med}$
g_q	g_χ

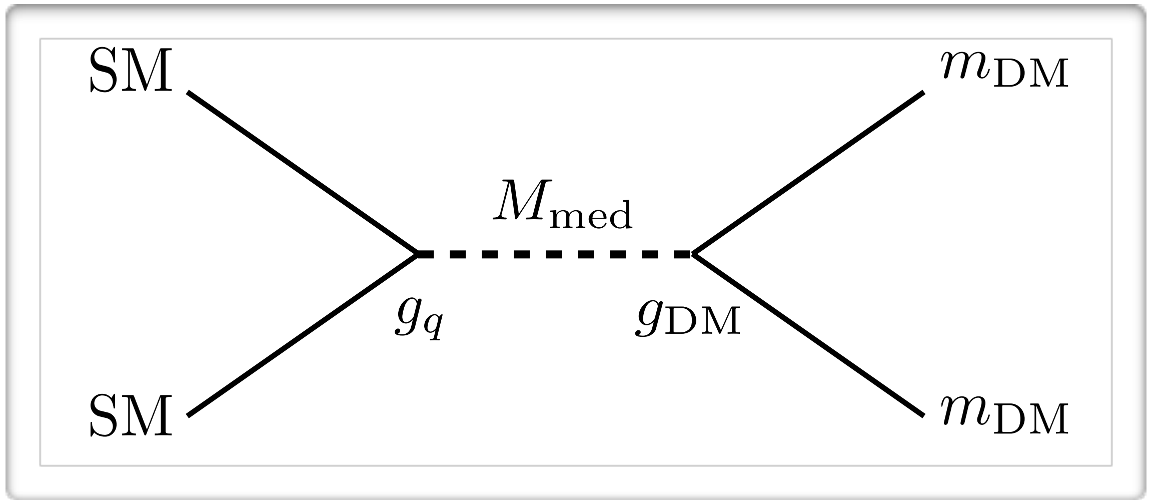
Mediators	
Vector	Axial-Vector
Scalar	Pseudo-scalar

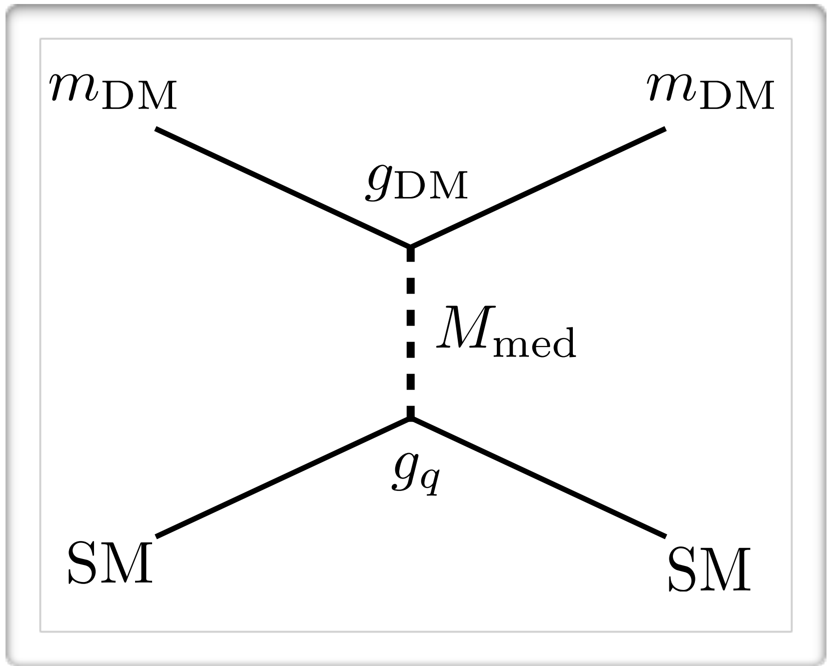
Dark matter	
Dirac	Complex scalar
Majorana	Real scalar

2. Simplified models

Buchmueller, Dolan, Malik, CM arXiv:1407.8257

- Same parameters also characterise direct searches





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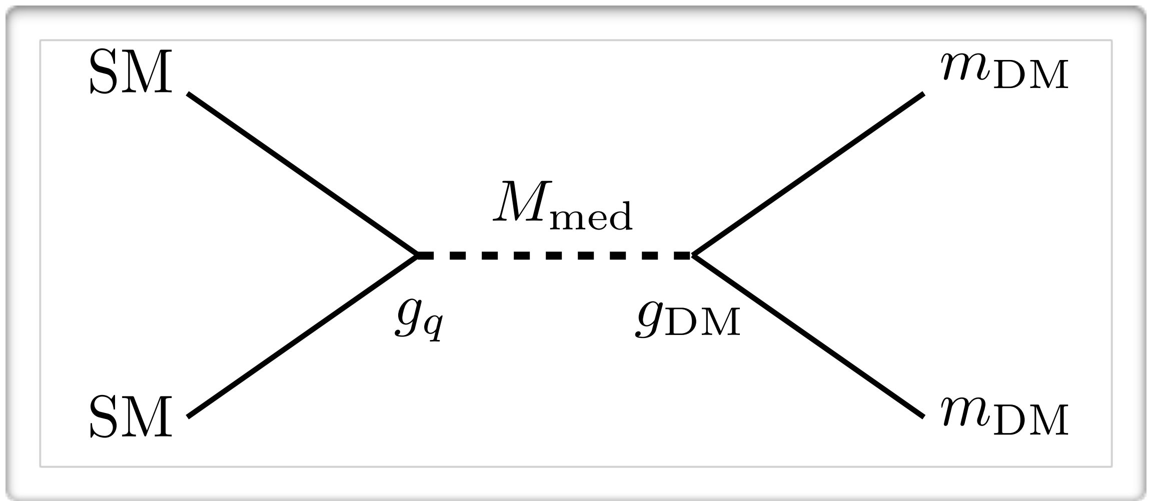

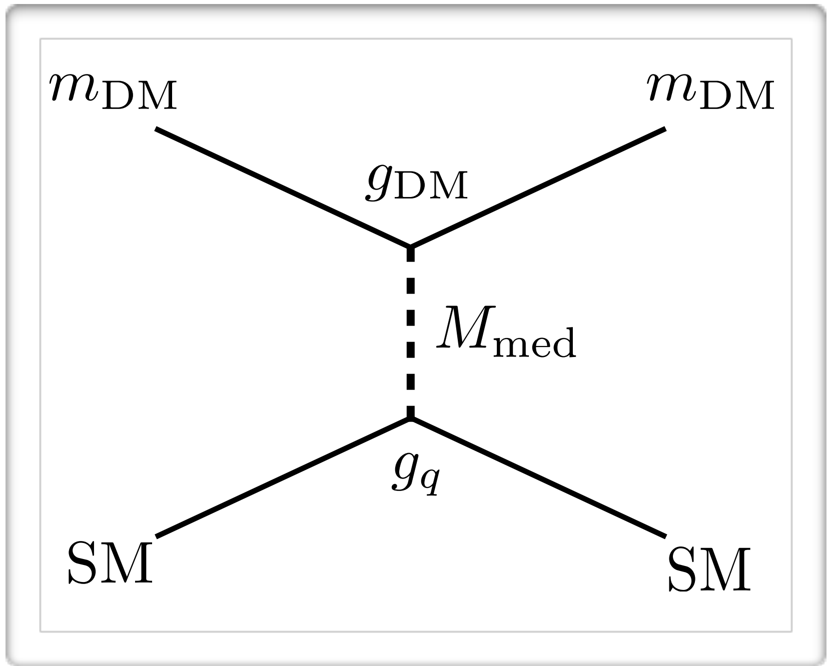

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Mediators	
Vector	Axial-Vector
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Dark matter	
Dirac	Complex scalar
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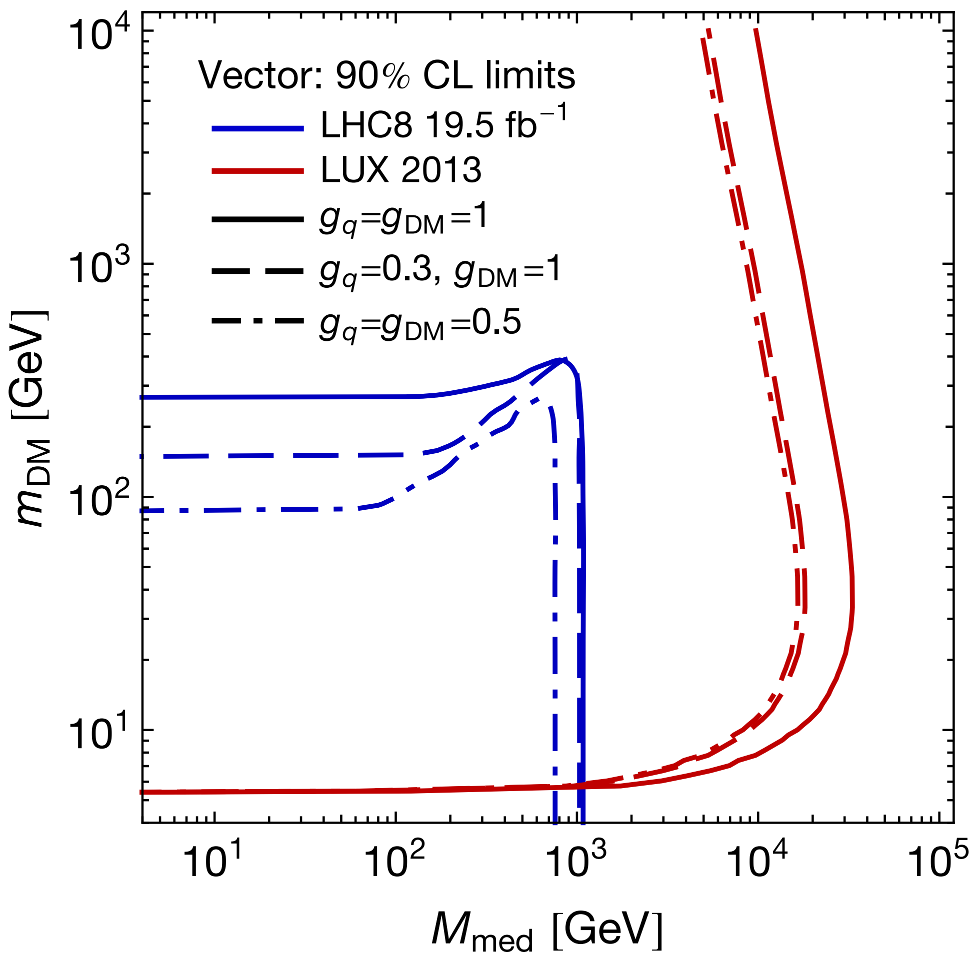
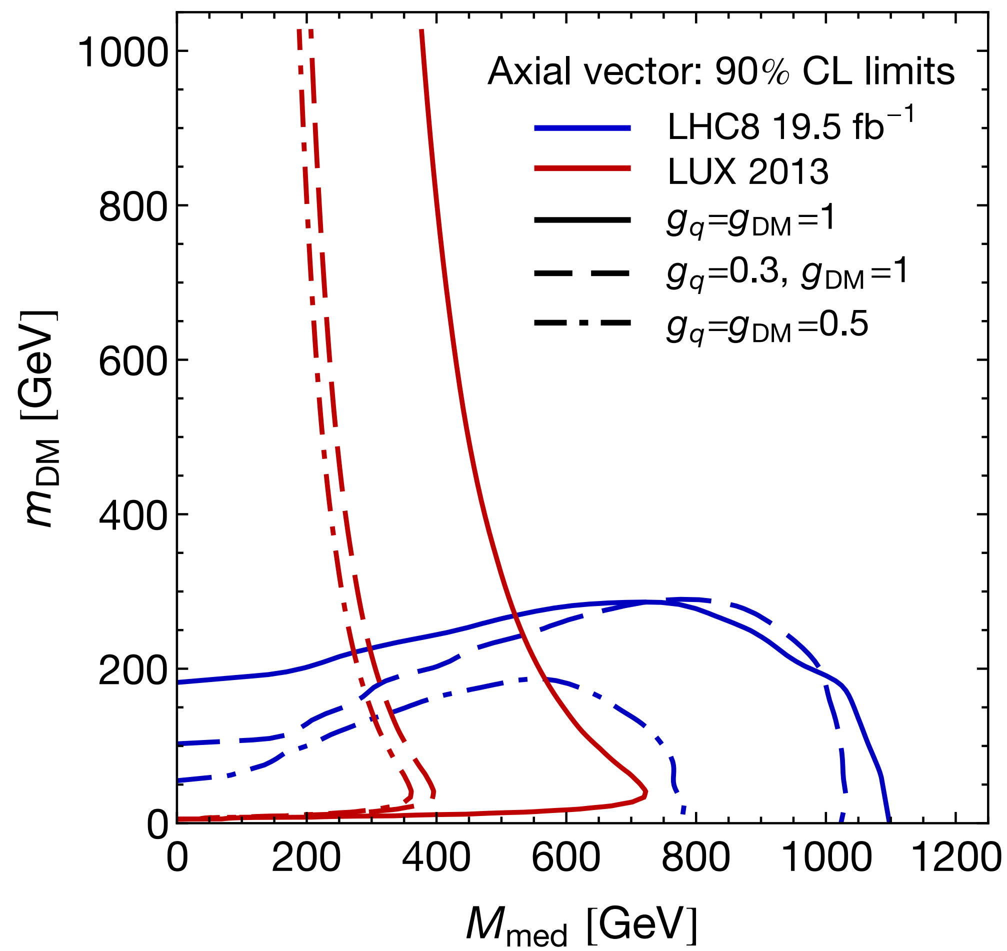
Slicing through parameter space

- We need to fix two parameters to show results:

$m_{\rm DM}$	g_χ
$M_{\rm med}$	g_q



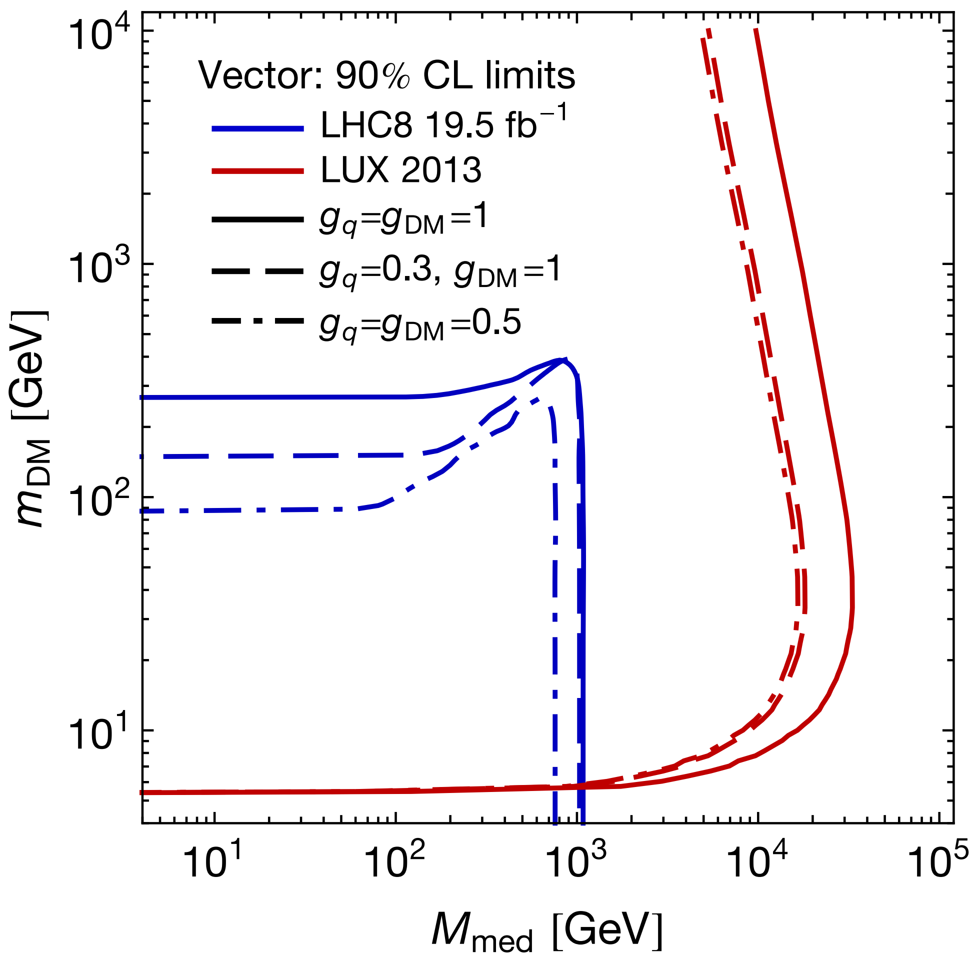


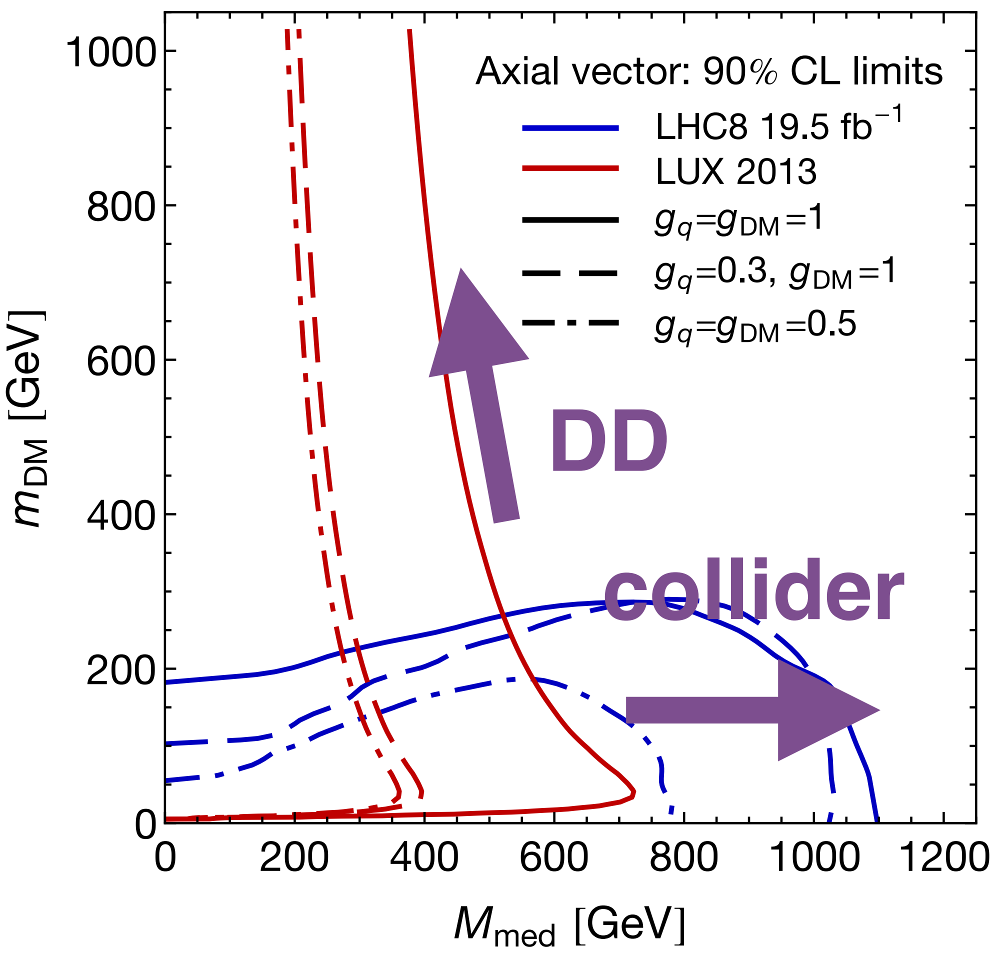
- Limits valid for all dark matter and mediator masses
- Includes resonant enhancement/off-shell suppression effects

Slicing through parameter space

- We need to fix two parameters to show results:

m_{DM}	g_χ
M_{med}	g_q





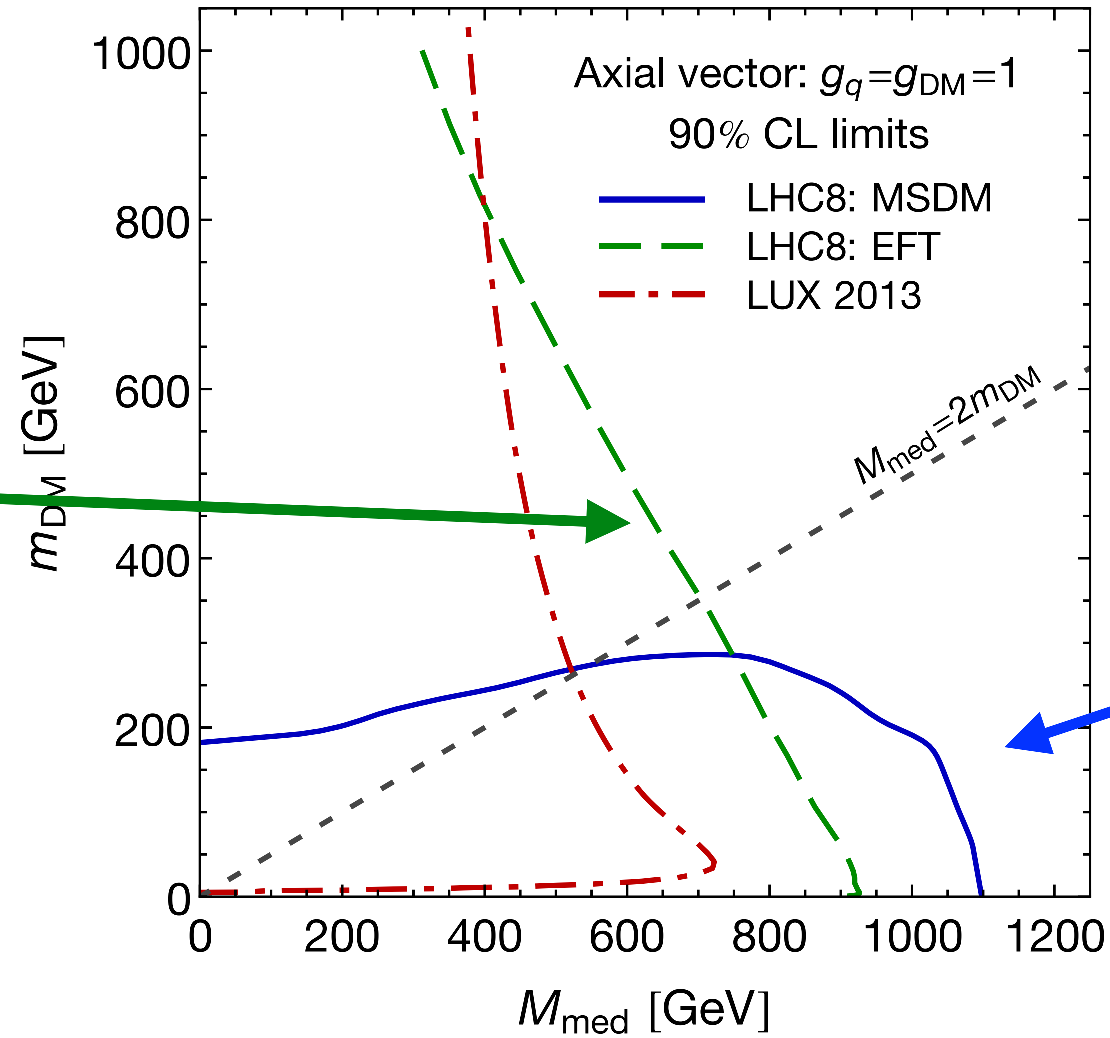
- Better elucidation of the complementarity between collider and direct searches

Slicing through parameter space

$m_{\rm DM}$	g_χ
$M_{\rm med}$	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:

$m_{\rm DM}$	g_χ
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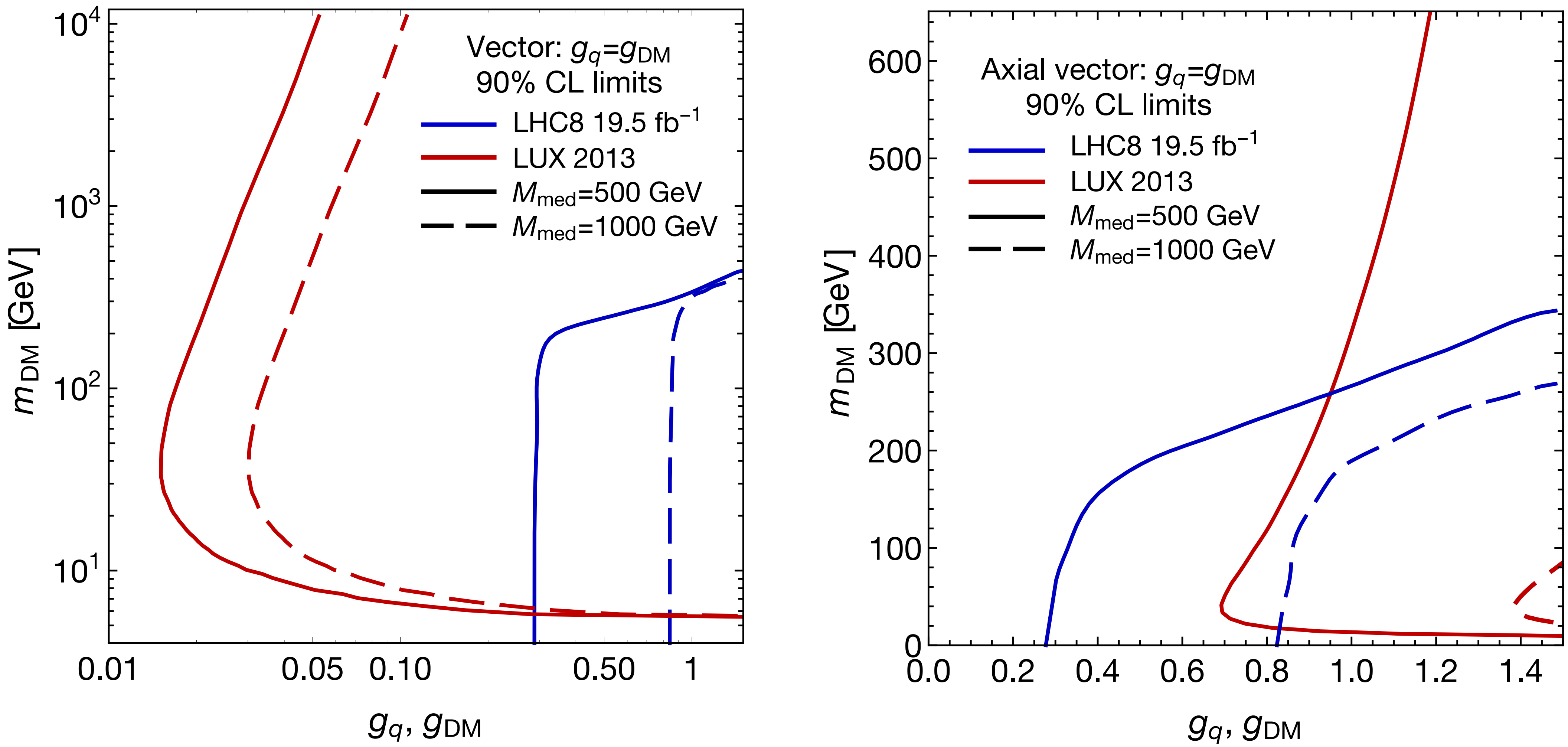
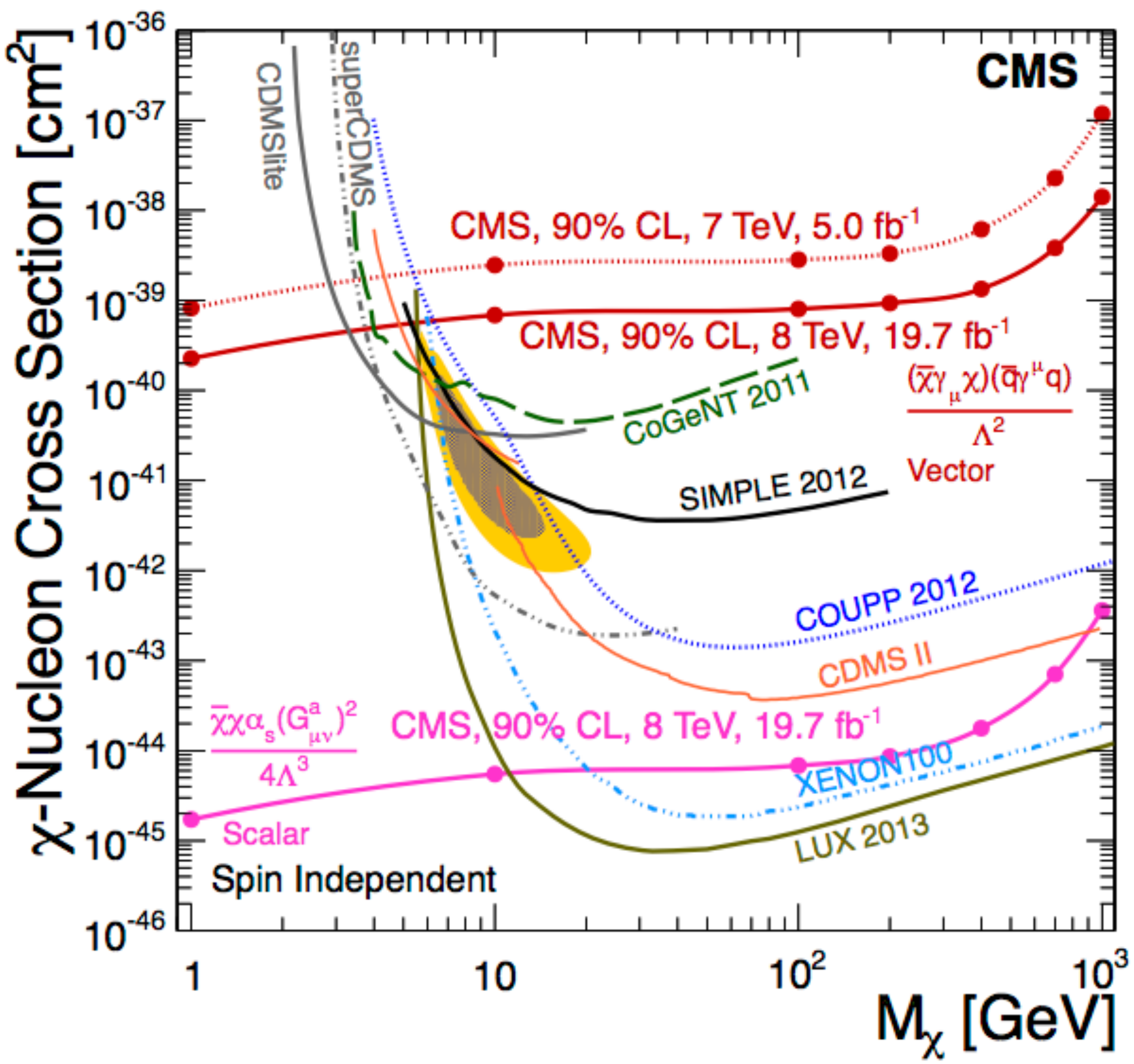


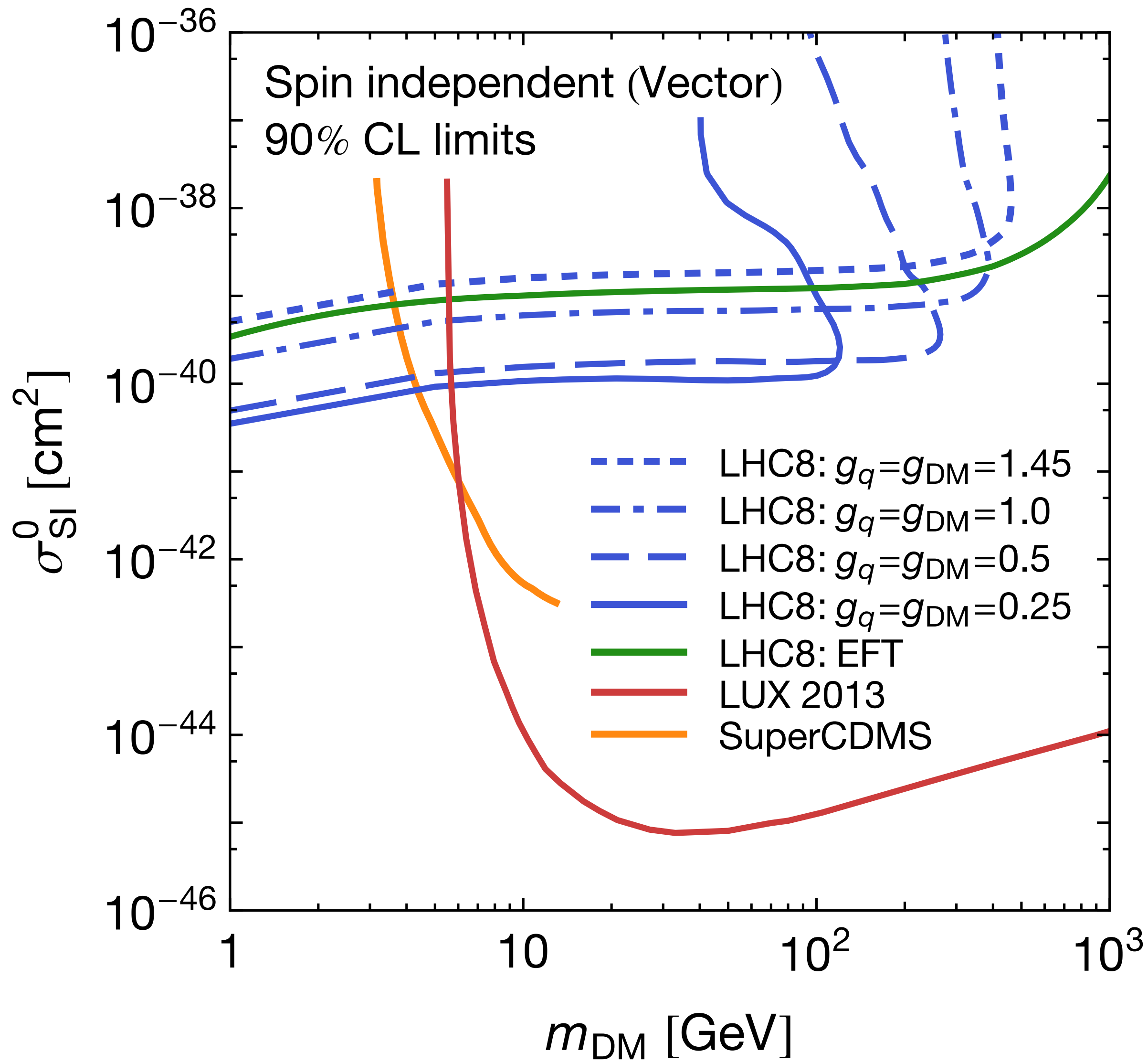
- Better elucidation of the complementarity between collider and direct searches

Comparison with direct detection

Malik, CM et al
arXiv:1409.4075

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

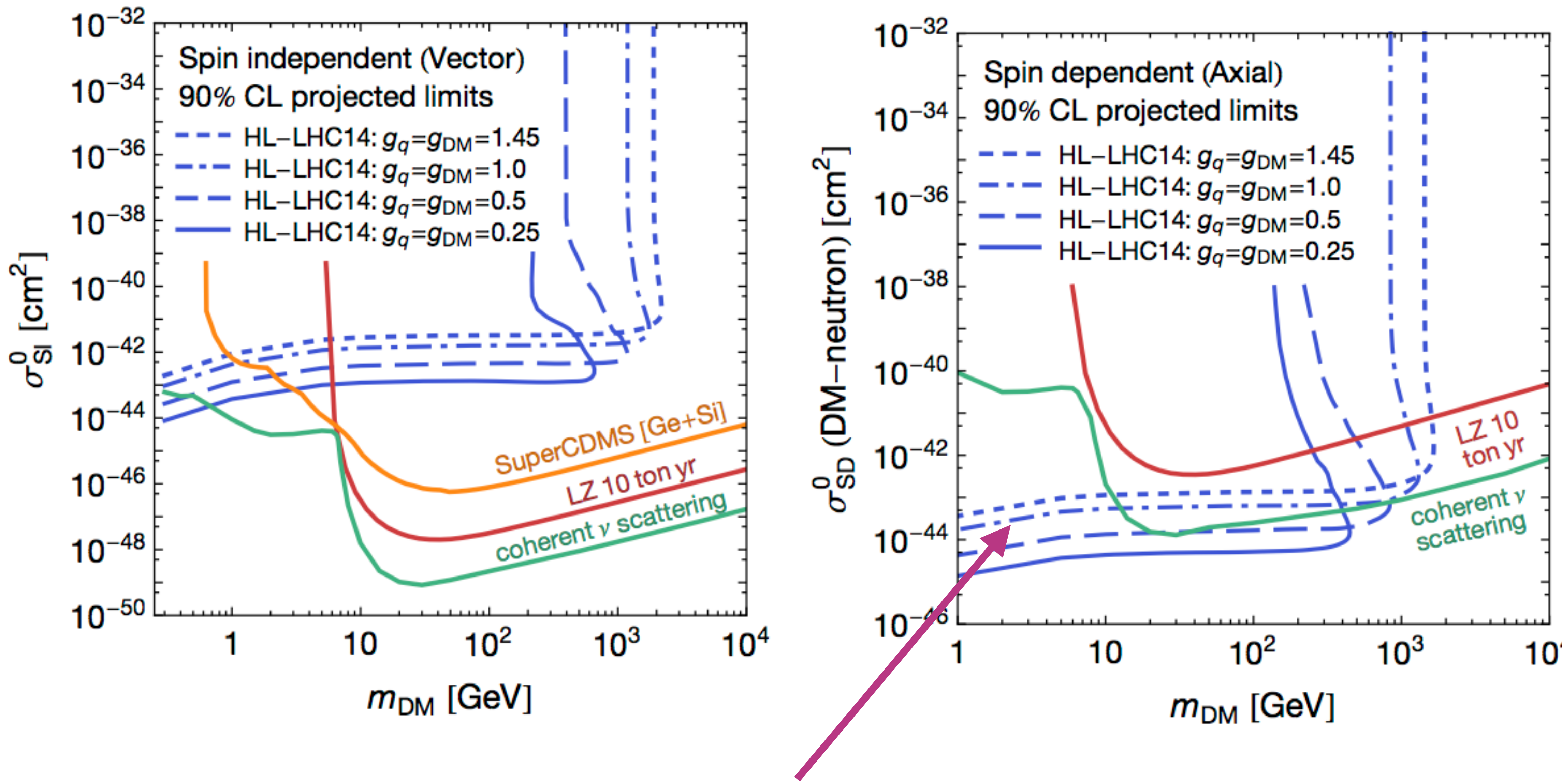




Future projections

Malik, CM et al
arXiv:1409.4075

- Map results into cross-section plane

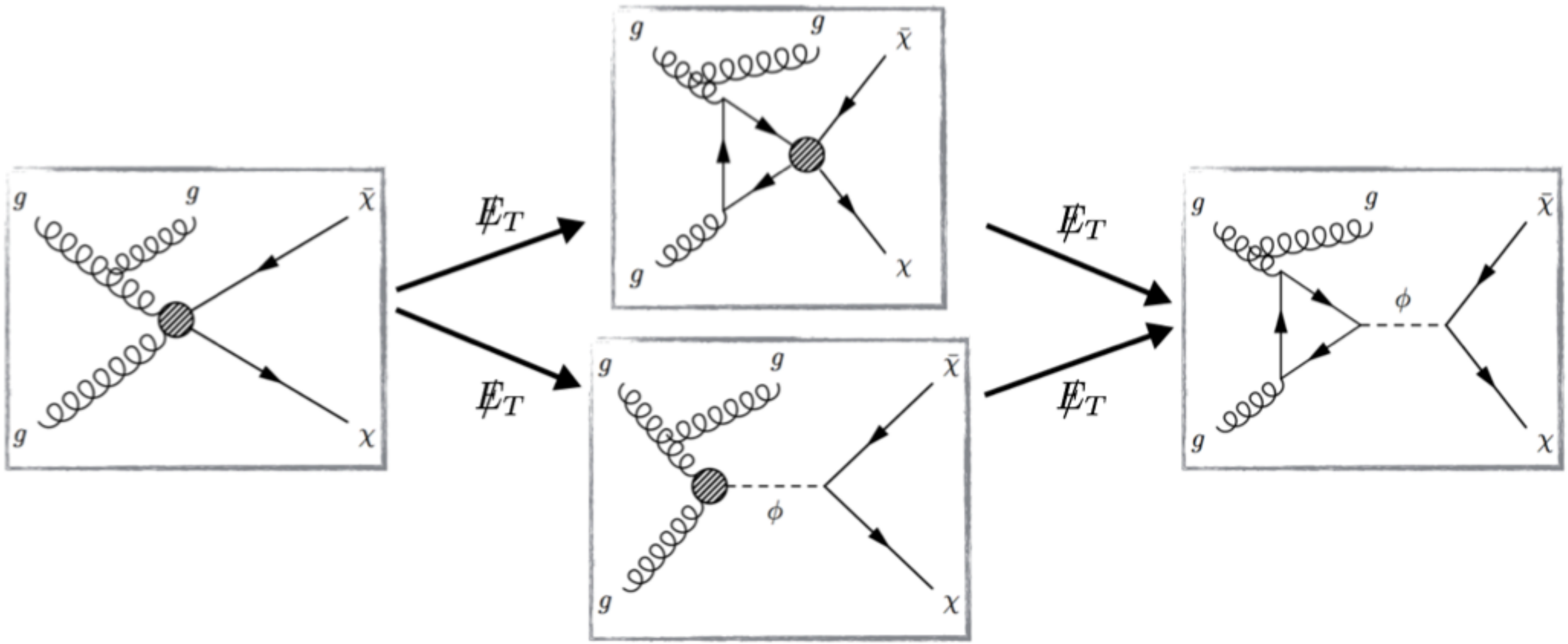


Possible to search below the neutrino floor

Scalar/Pseudoscalar

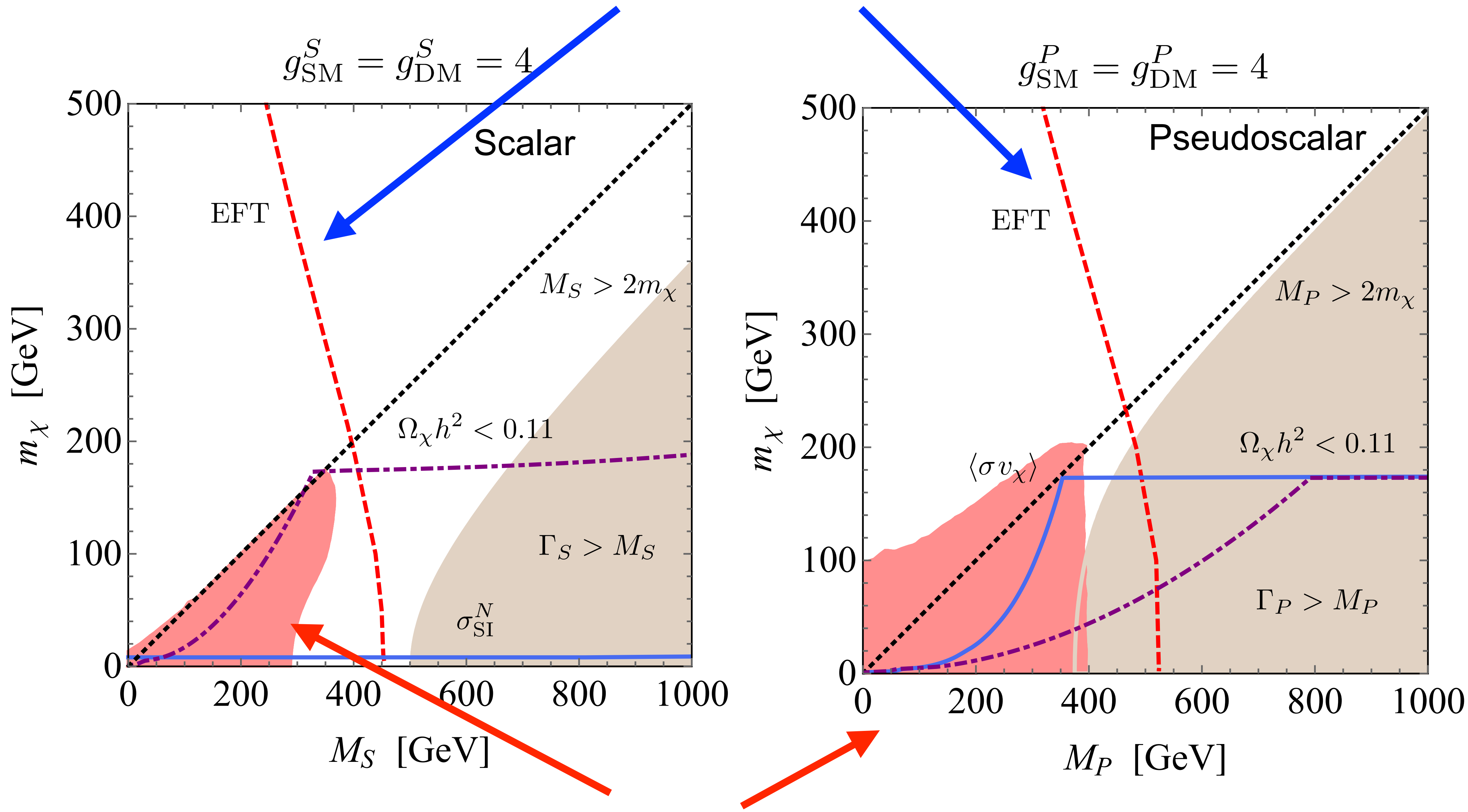
Buckley, Feld, Goncalves arXiv:1410.6497

- Extendable to other mediators



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

Exclusion limit if you naively used the EFT limit



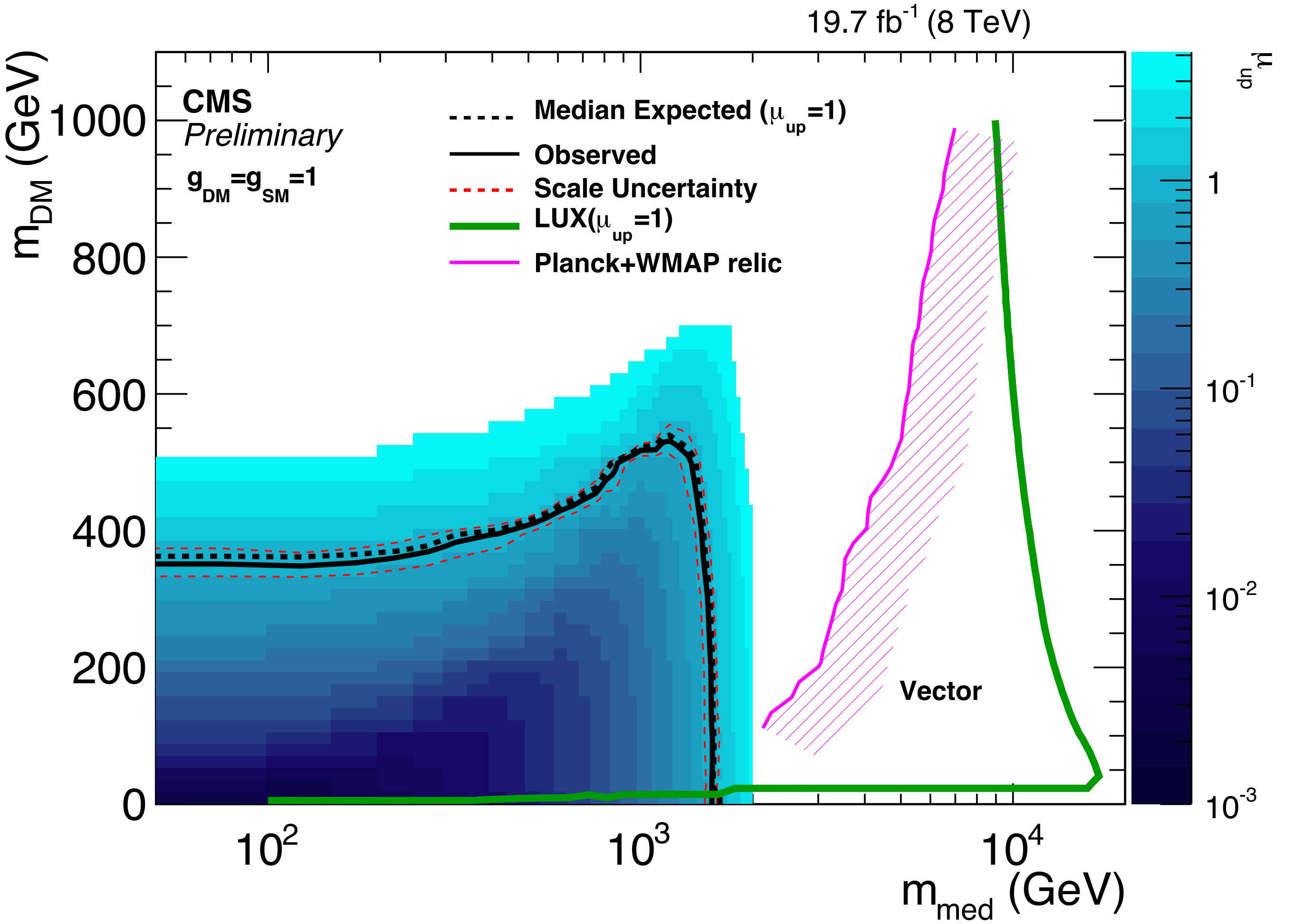
simplified model excluded region

Future recommendations

- ATLAS and CMS formed a working group to reach a consensus on which approach to take going forward
  arXiv: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



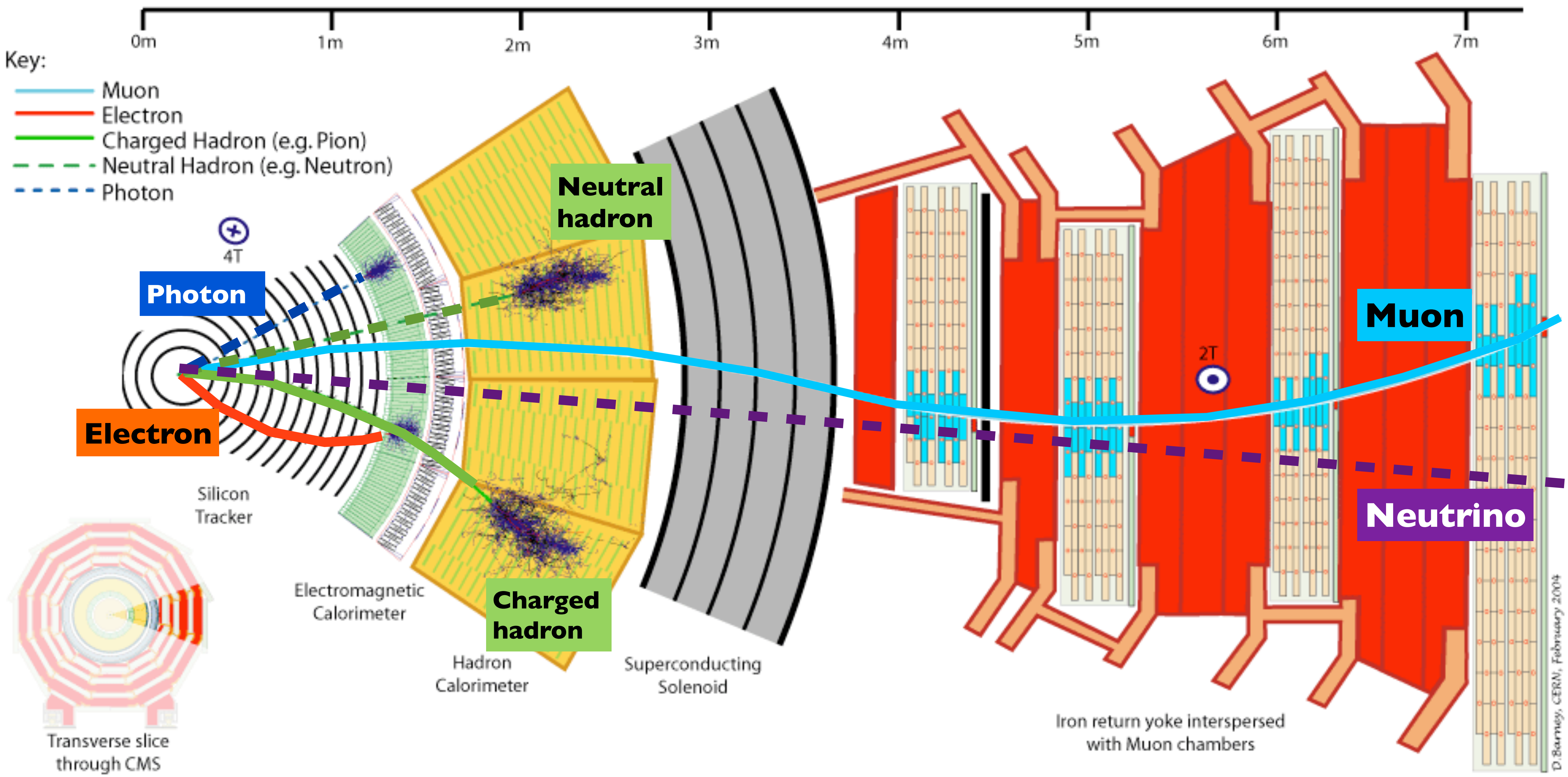
Summary

- 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

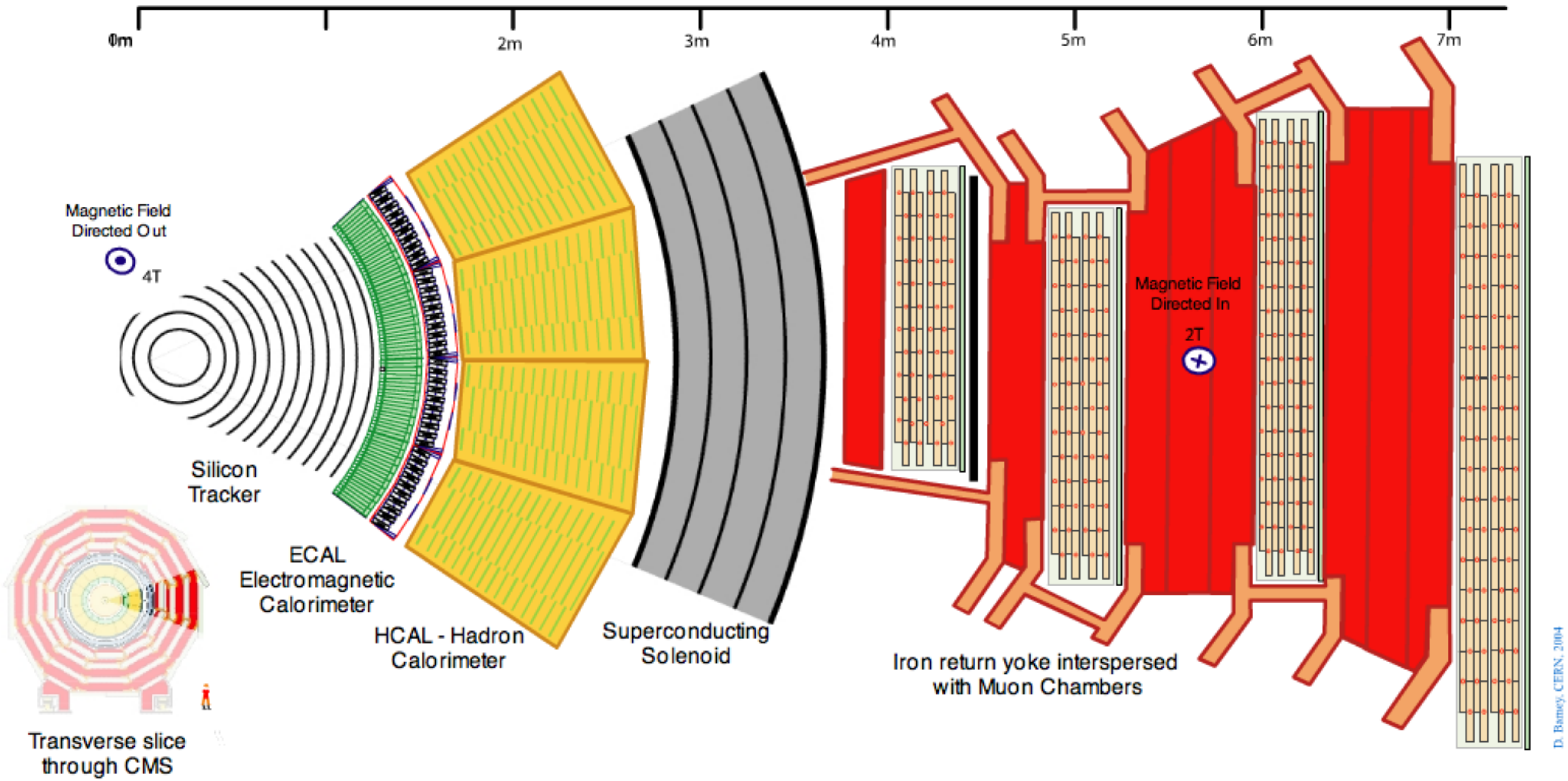
Backup

A slice through CMS



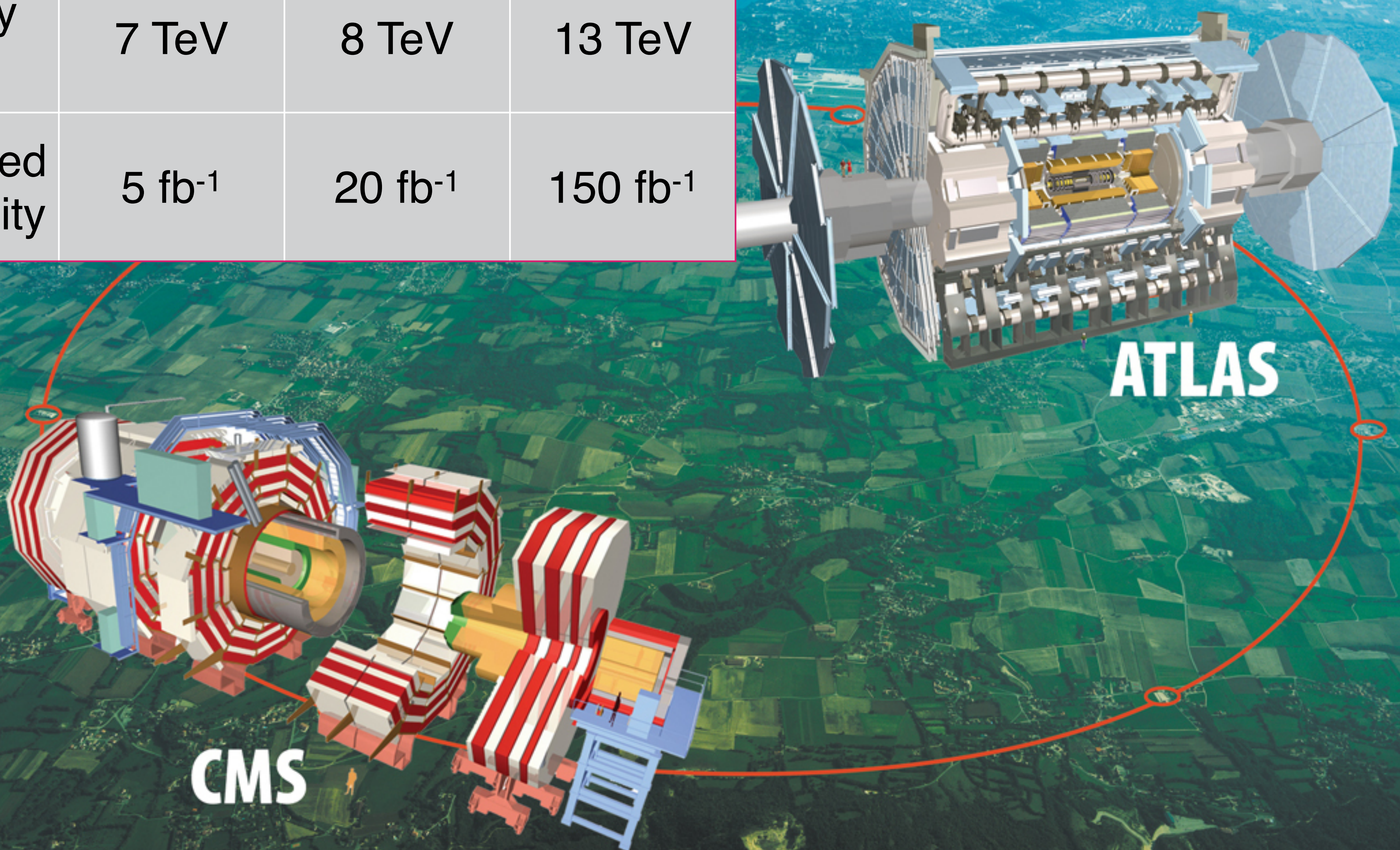
Neutrinos traverse the detector without any interaction

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}



Warning

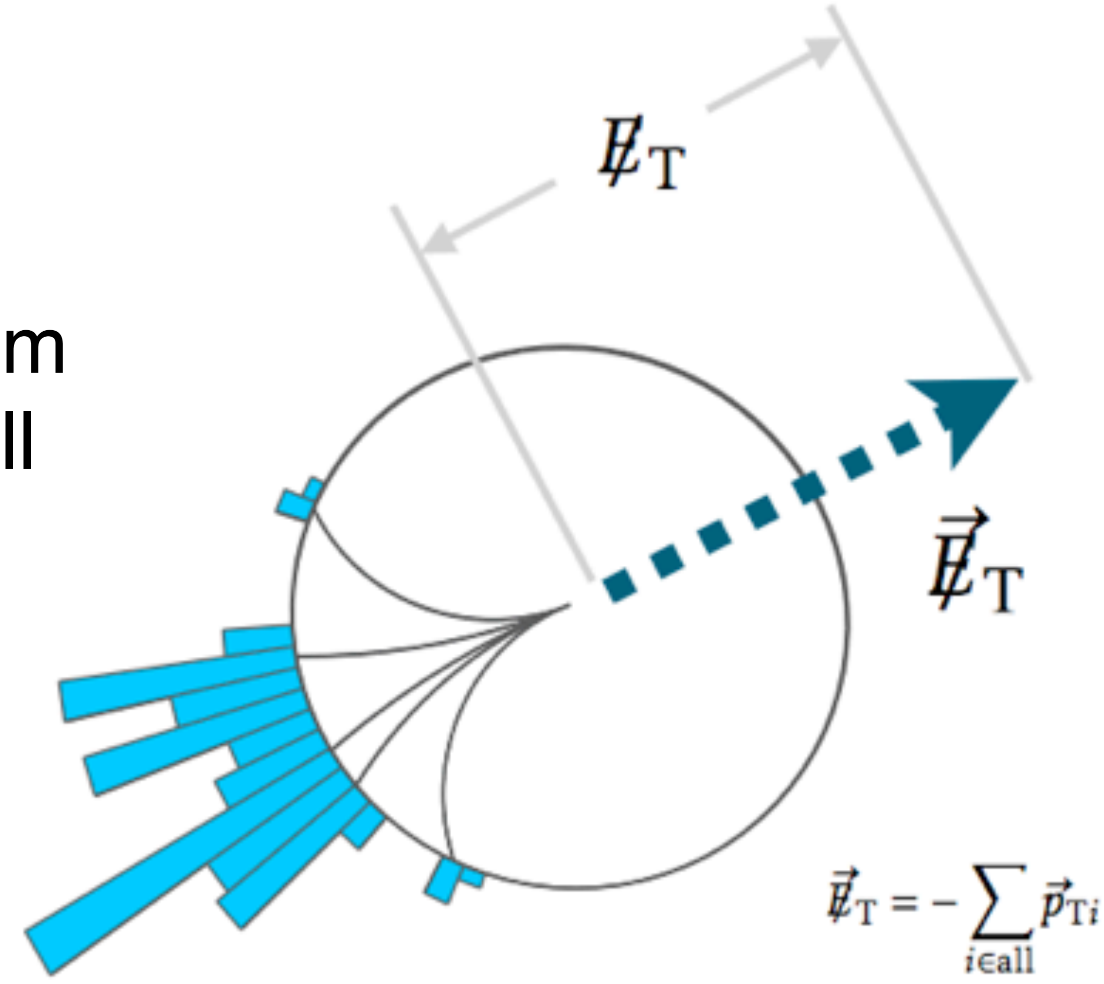
- Things to remember:
  - Colliders cannot prove stability beyond the apparatus
  - The dark matter mass reconstruction will be poor
  - Colliders cannot distinguish single and multiple invisible particles
  - May give little information on the nature of interaction, spin of the dark matter, its quantum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

Interpreting any signal will be challenging

Missing transverse energy (MET or $\not{E}_T$)

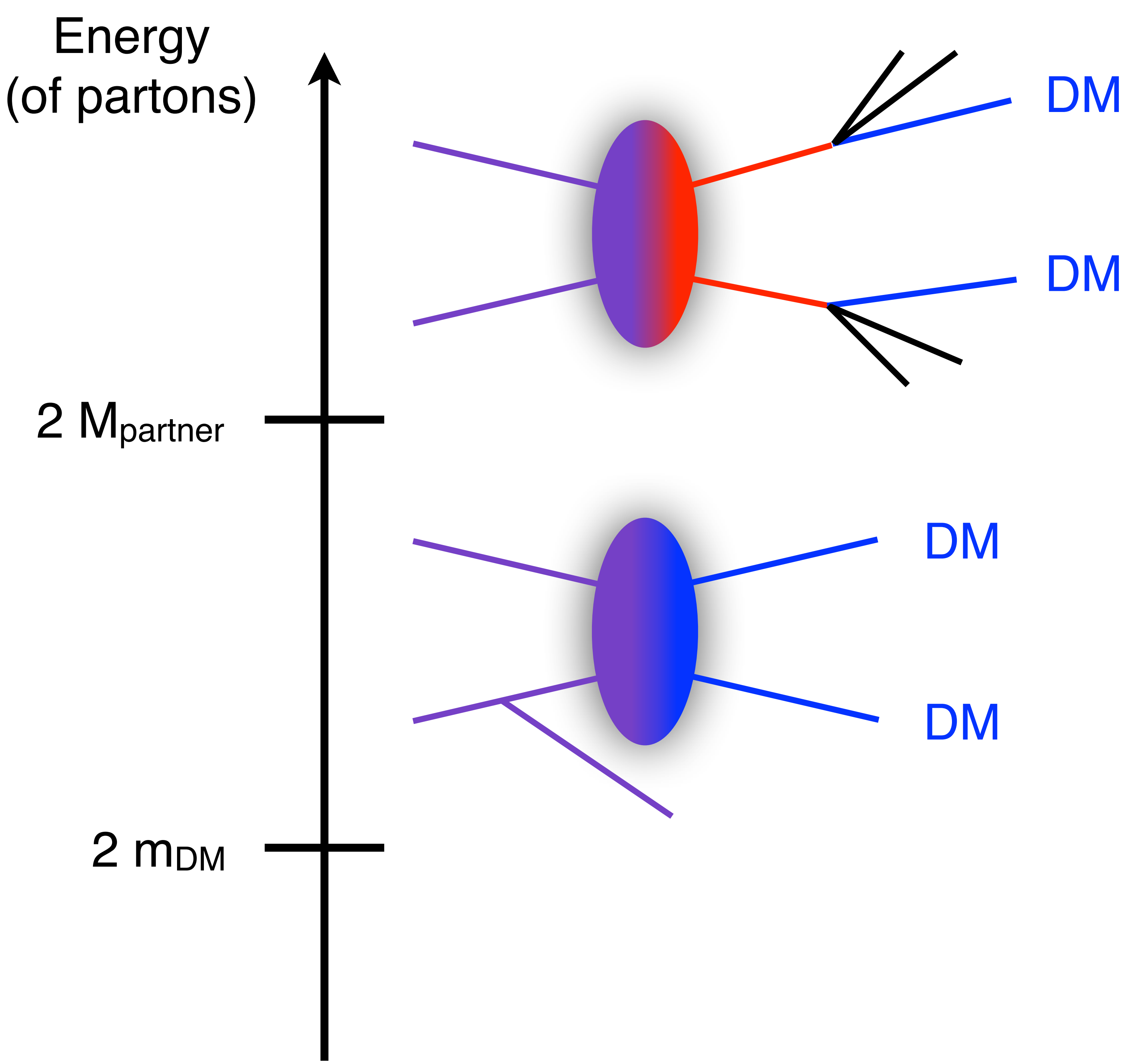
- At the heart of all collider searches for dark matter

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

LHC search categorisation



Dark matter produced in cascade decays from heavier new states
eg SUSY cascade searches

LHC directly produces dark matter pairs
eg Mono-X searches

LHC cannot produce dark matter

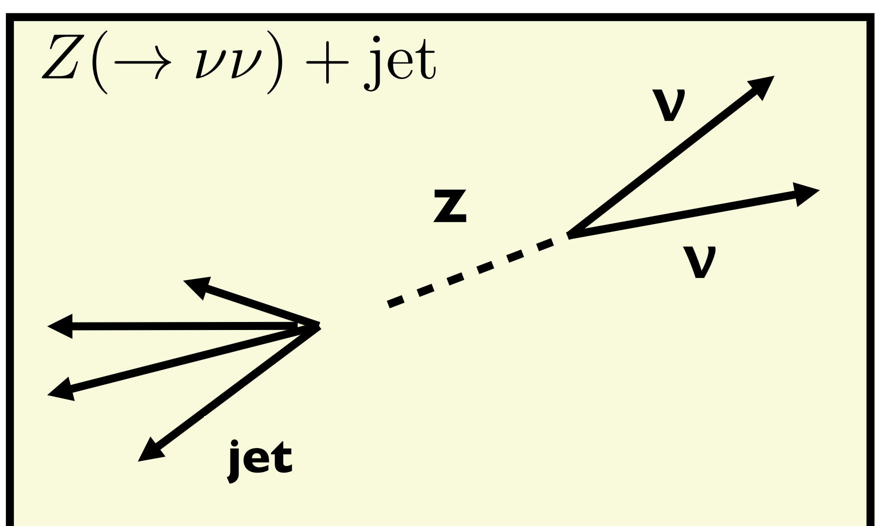
CMS search search (ATLAS similar)

CMS: 1408.3583
ATLAS: 1502.01518

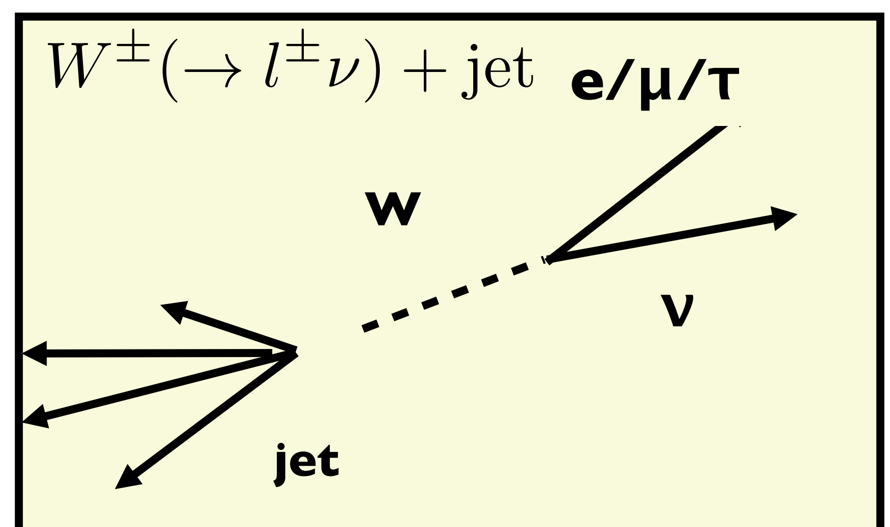
- Event selection:
  - Large missing transverse energy: $\not{E}_T > 500 \text{ GeV}$
  - One energetic jet: $p_T > 100 \text{ GeV}$
  - One additional jet if $p_T > 30 \text{ GeV}$ and $\Delta\phi(j_1, j_2) < 2.5$

- Main backgrounds:

Irreducible background;
looks like signal

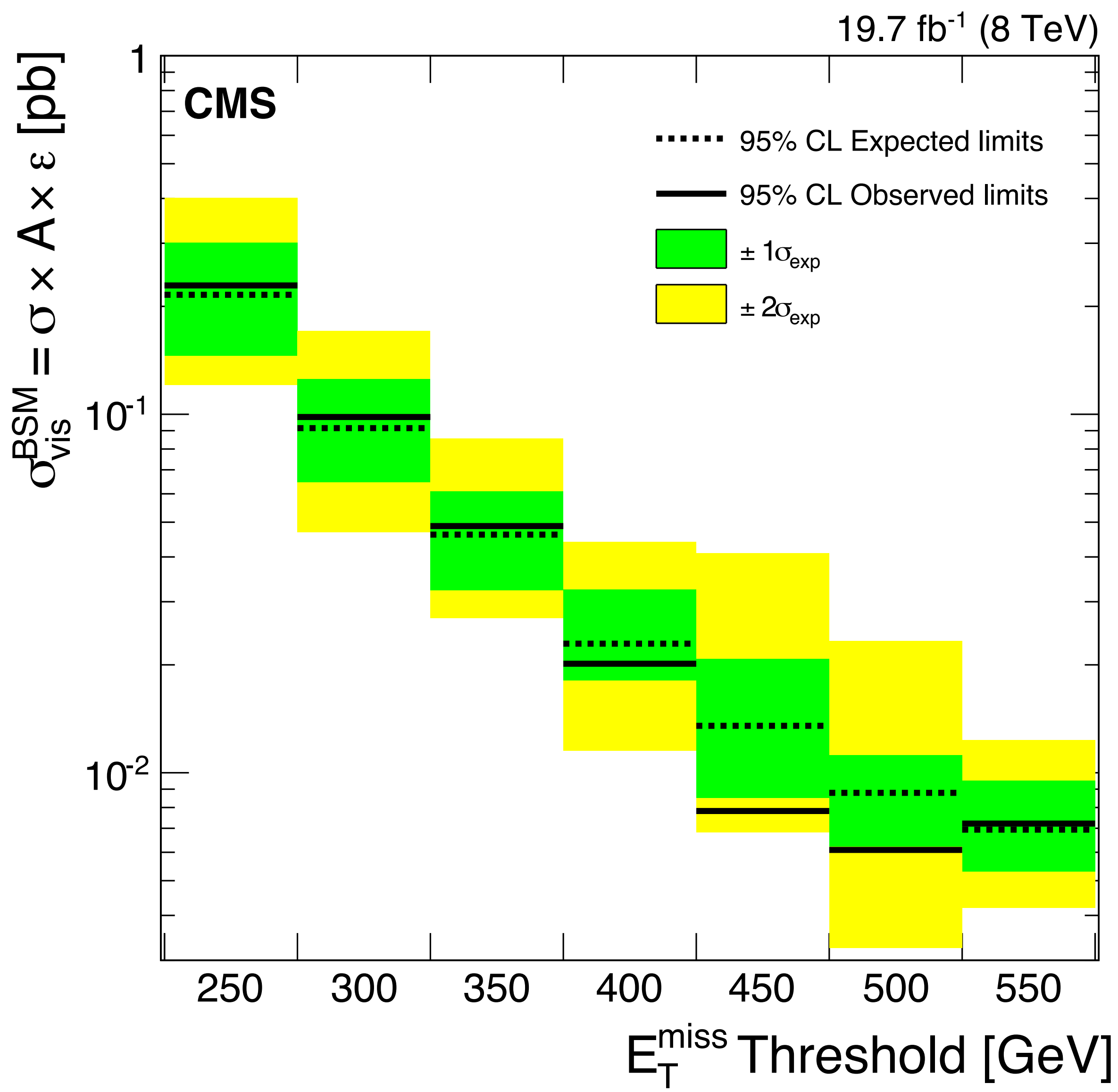


e/μ not detected
τ decays hadronically



True model independent limit

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



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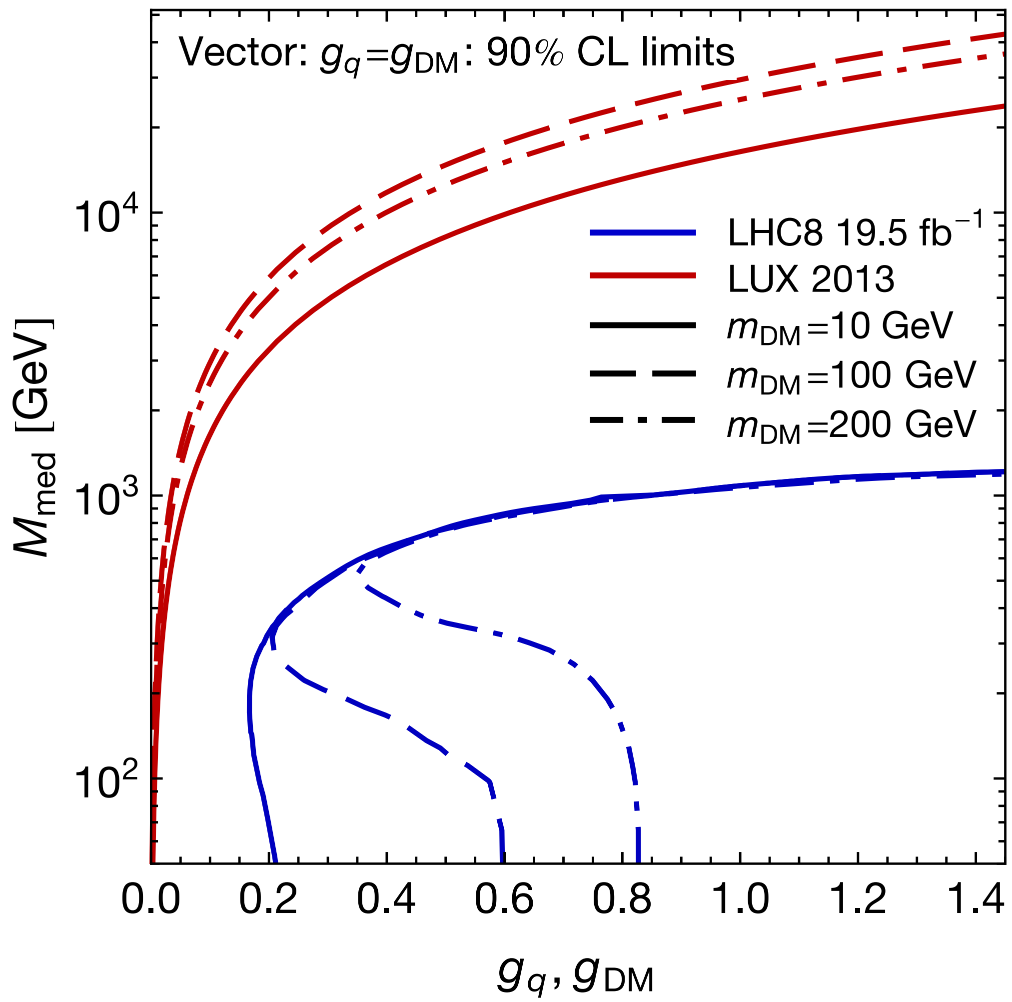

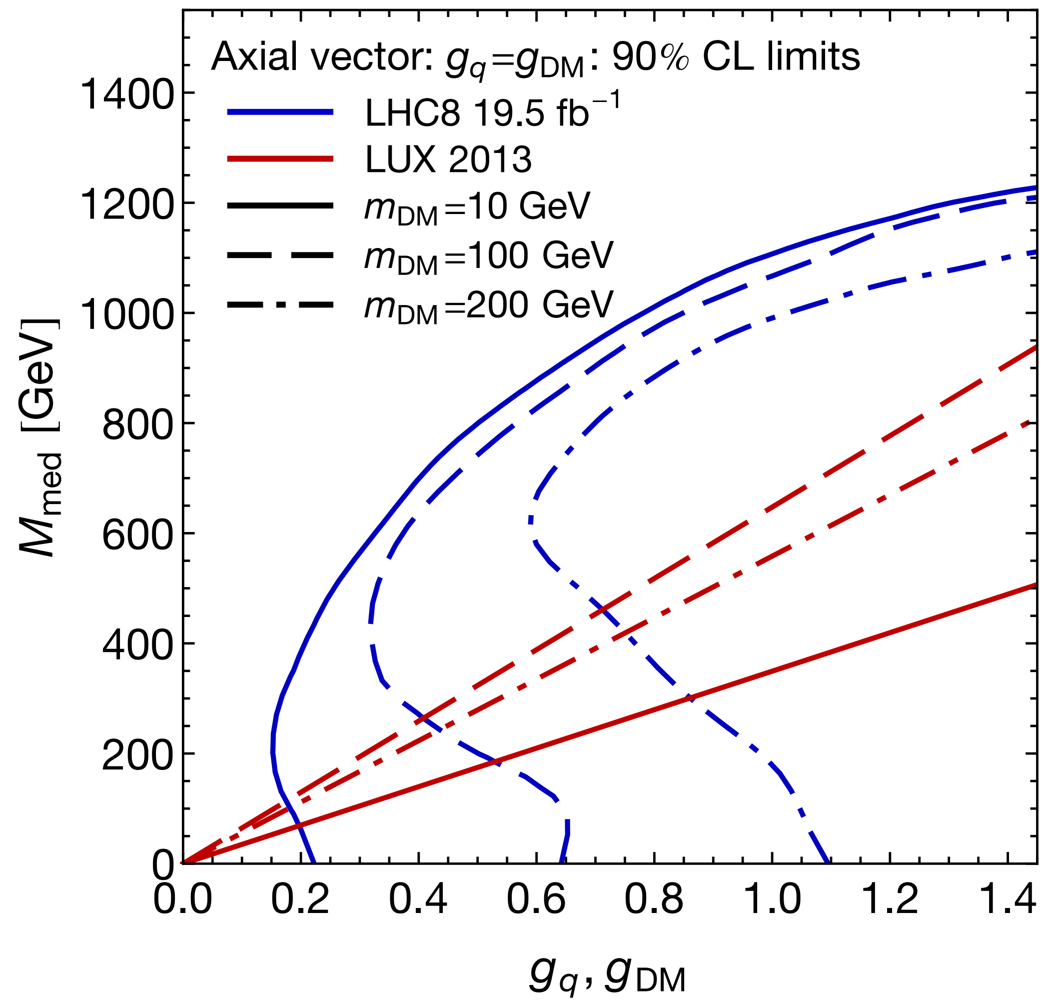

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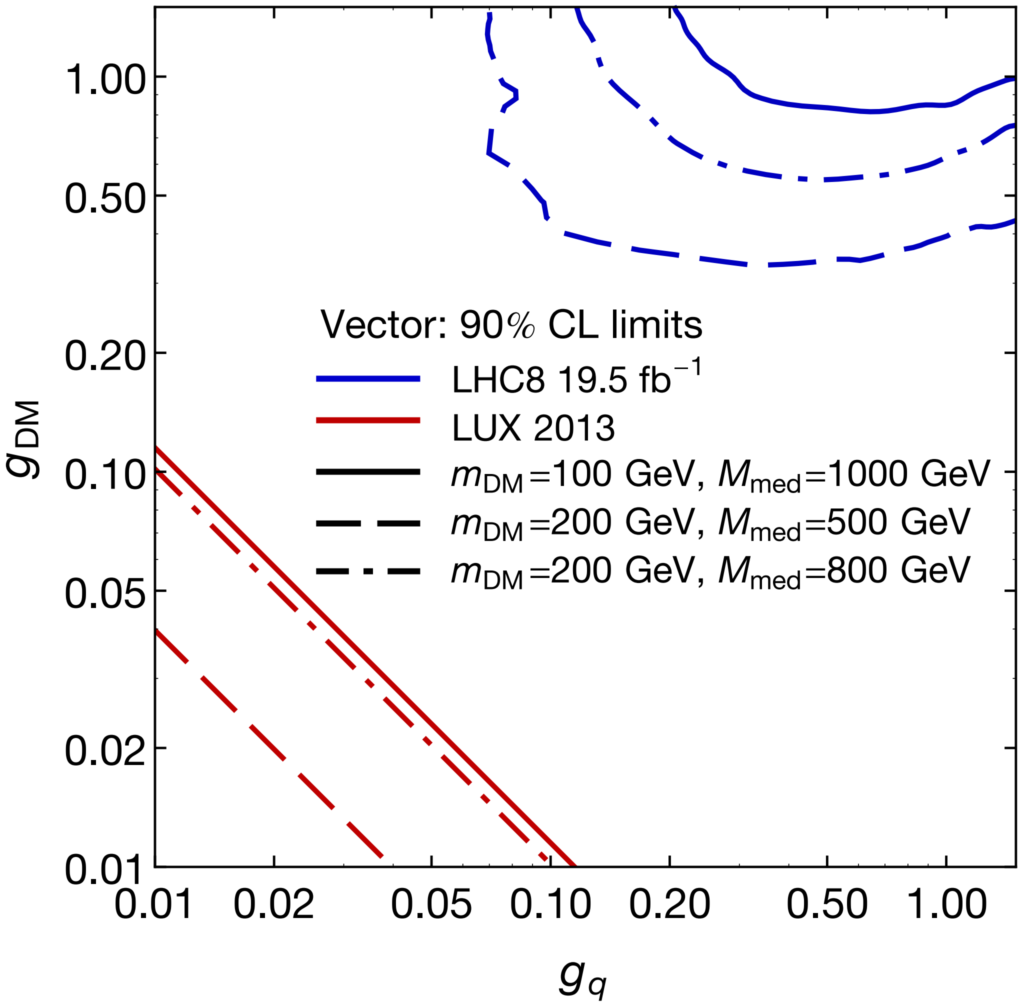
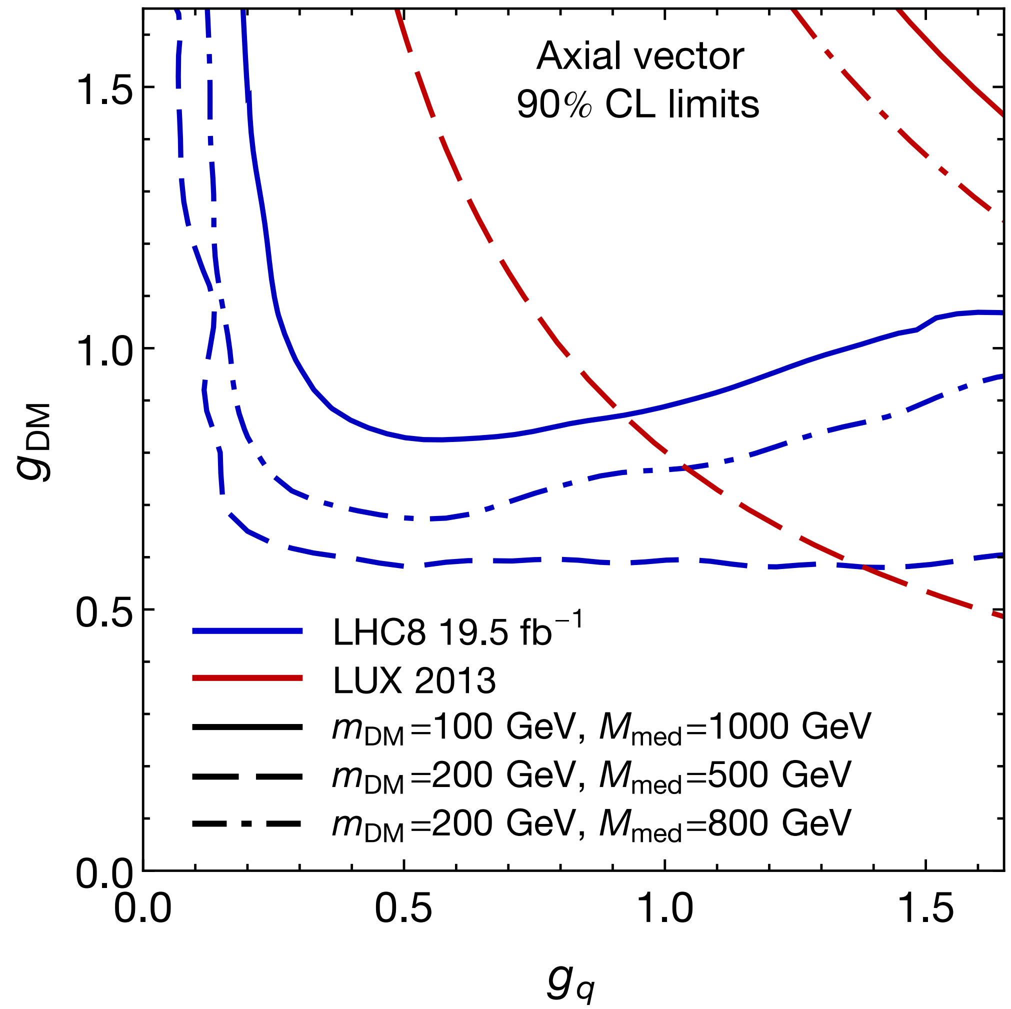
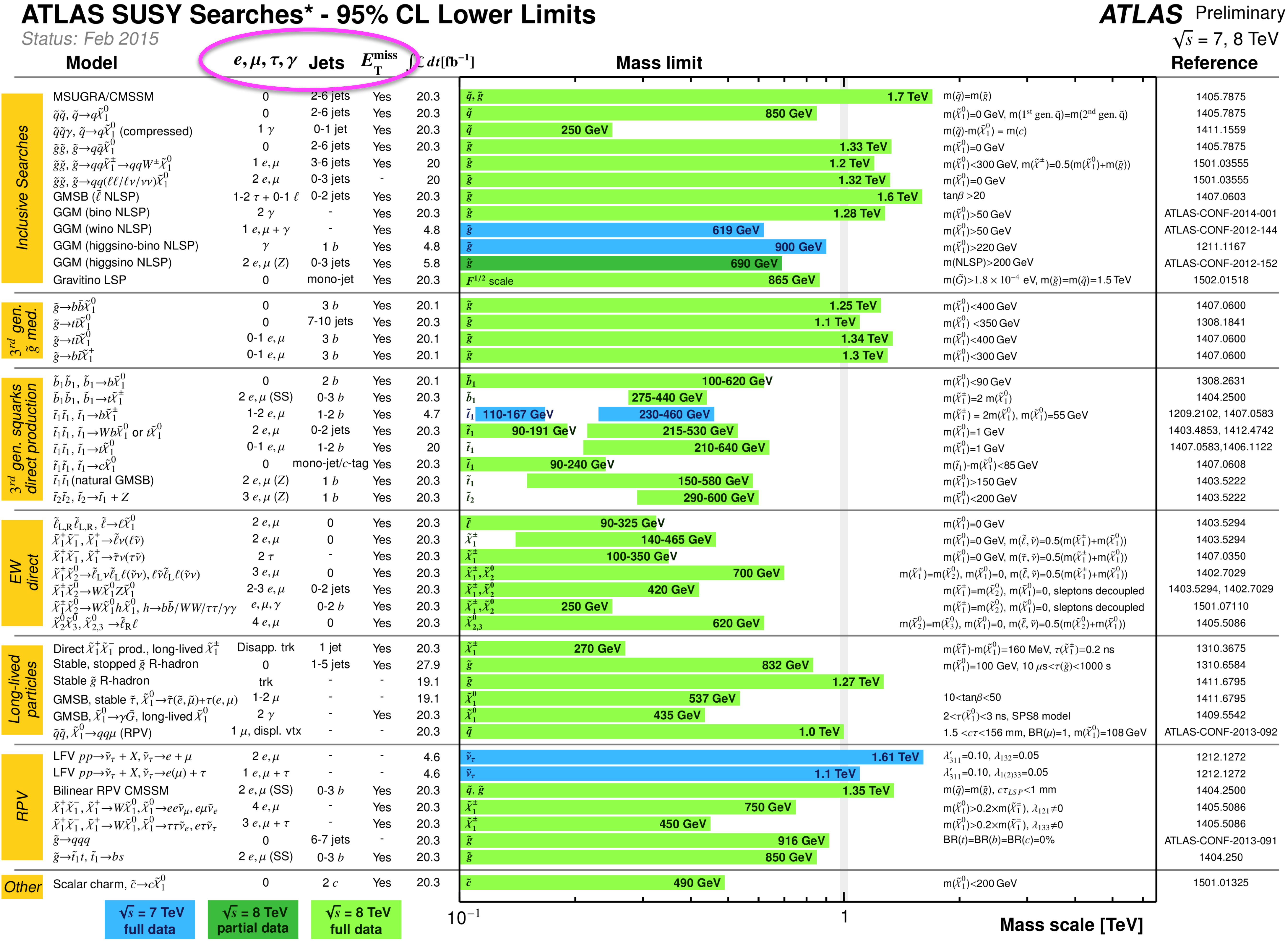




- Better elucidation of the complementarity between collider and direct searches

ATLAS SUSY Searches* - 95% CL Lower Limits

Status: Feb 2015



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