COLLIDER CONSTRAINTS

ON DARK MATTER

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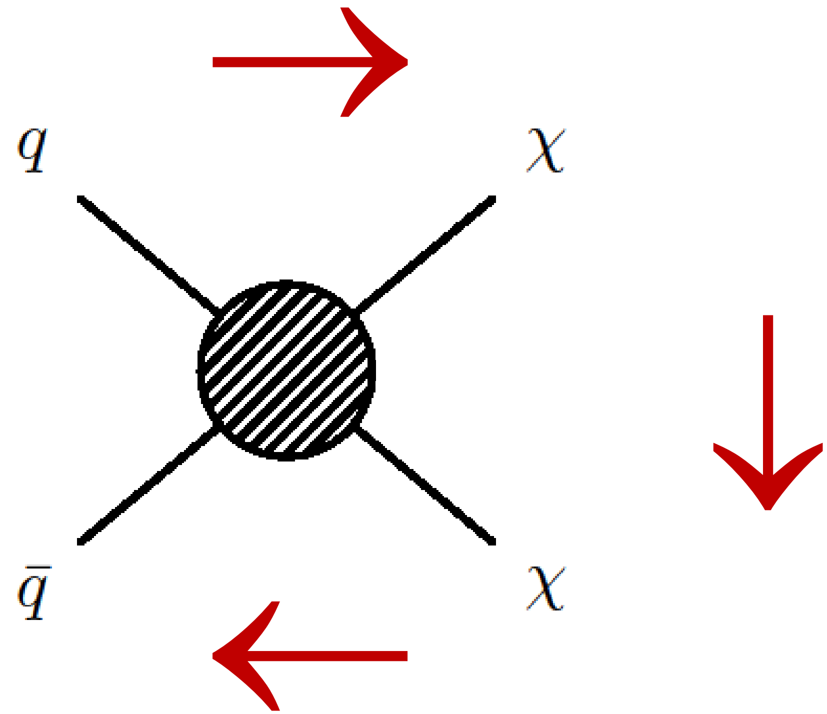
Detecting Dark Matter

production (collider searches)



scattering (direct detection)

annihilation (indirect detection)

"WIMP Miracle"

- The thermal relic picture sets the "natural scale" for the dark matter annihilation cross section:

$$\Omega_{DM} \sim 0.2 \text{ implies } \langle \sigma v \rangle \sim 2 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}$$

- Suggests electroweak-scale parameters since:

$$\langle \sigma v \rangle \sim \frac{\alpha^2}{(100 \text{ GeV})^2} \sim 10^{-26} \text{ cm}^3 \text{s}^{-1}$$

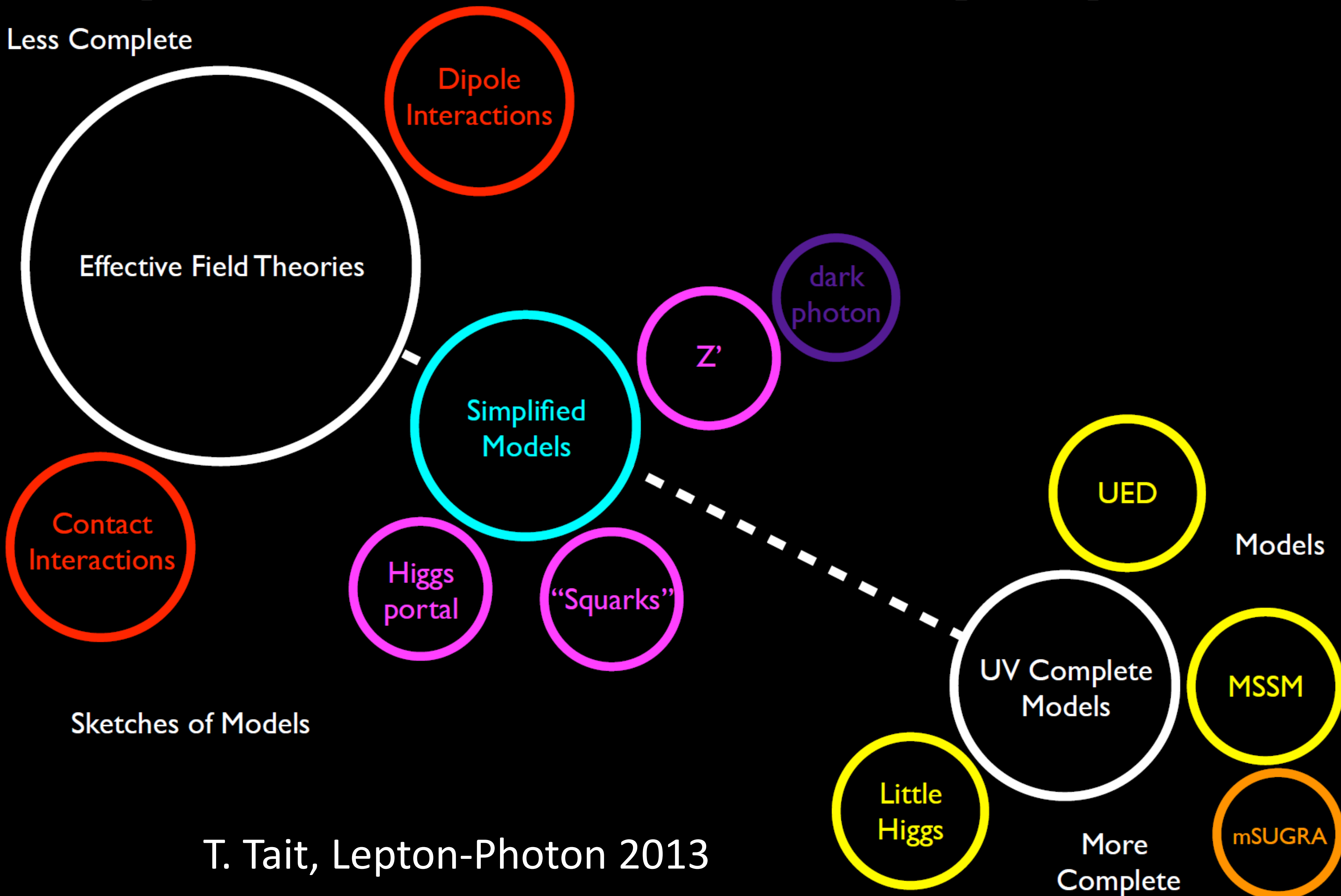
→ 1) A compelling argument, given we have other reason to expect new physics at the GeV-TeV scale.

→ 2) Realistic prospects of detection:
- annihilation signals (indirect detection)
- nuclear recoils (direct detection)
- monojets+missing ET (colliders)

Outline

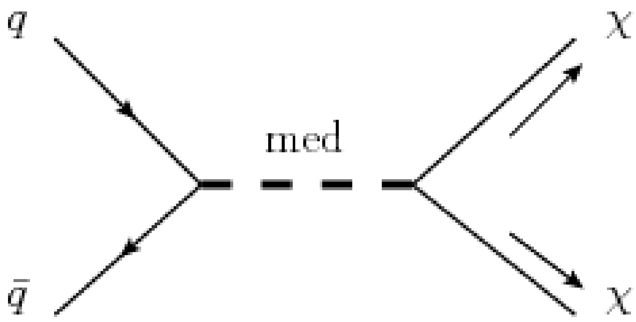
- Introduction
- Describing dark matter interactions, EFTs
- Mono-X
- Colliders vs Direct Detection
- Higgs Portal
- Beyond EFTs
- Some non-standard WIMP models

Spectrum of Theory Space

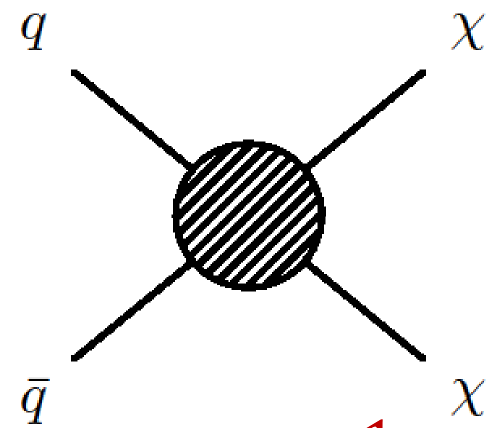


T. Tait, Lepton-Photon 2013

Effective Field Theories



$$M_{med}^2 \gg Q^2 \longrightarrow$$



$$\frac{g_\chi g_q}{Q^2 - M_{med}^2}$$

$$\frac{g_\chi g_q}{M_{med}^2} = -\frac{1}{\Lambda^2}$$

So we have a contact interaction: $\mathrm{L}_{\mathrm{EFT}} = \frac{1}{\Lambda_{\mathrm{eff}}^2}\, \bar{q} q \bar{\chi} \chi$

Advantages:

- model-independent description

Disadvantages:

- breaks down if Q^2 is large or mediators light

Effective operators for Dirac DM

Model-independent description of fermionic DM interacting with SM fermions:

$$L_{\text{eff}} = \frac{1}{\Lambda_{\text{eff}}^2} (\bar{\chi}\,\Gamma_\chi \chi)(\bar{f}\,\Gamma_f f)$$

$$\Gamma_{\chi,f} \in \{1, \gamma^5, \gamma^\mu, \gamma^\mu\gamma^5, \sigma^{\mu\nu}\}$$

Name	Operator	Coefficient	DD
D1	$[\bar{\chi}\chi][\bar{f}f]$	$m_f\Lambda^{-3}$	SI
D2	$[\bar{\chi}\gamma^5\chi][\bar{f}f]$	$im_f\Lambda^{-3}$	–
D3	$[\bar{\chi}\chi][\bar{f}\gamma^5 f]$	$im_f\Lambda^{-3}$	–
D4	$[\bar{\chi}\gamma^5\chi][\bar{f}\gamma^5 f]$	$m_f\Lambda^{-3}$	–
D5	$[\bar{\chi}\gamma^\mu\chi][\bar{f}\gamma_\mu f]$	Λ^{-2}	SI
D6	$[\bar{\chi}\gamma^\mu\gamma^5\chi][\bar{f}\gamma_\mu f]$	Λ^{-2}	–
D7	$[\bar{\chi}\gamma^\mu\chi][\bar{f}\gamma_\mu\gamma^5 f]$	Λ^{-2}	–
D8	$[\bar{\chi}\gamma^\mu\gamma^5\chi][\bar{f}\gamma_\mu\gamma^5 f]$	Λ^{-2}	SD
D9	$[\bar{\chi}\sigma^{\mu\nu}\chi][\bar{f}\sigma_{\mu\nu} f]$	Λ^{-2}	SD
D10	$[\bar{\chi}\sigma^{\mu\nu}\gamma^5\chi][\bar{f}\sigma_{\mu\nu} f]$	$i\Lambda^{-2}$	–
D11	$[\bar{\chi}\chi][G_{\mu\nu}G^{\mu\nu}]$	$\alpha_S\Lambda^{-3}$	SI
D12	$[\bar{\chi}\gamma^5\chi][G_{\mu\nu}G^{\mu\nu}]$	$i\alpha_S\Lambda^{-3}$	–
D13	$[\bar{\chi}\chi][G_{\mu\nu}\tilde{G}^{\mu\nu}]$	$i\alpha_S\Lambda^{-3}$	–
D14	$[\bar{\chi}\gamma^5\chi][G_{\mu\nu}\tilde{G}^{\mu\nu}]$	$\alpha_S\Lambda^{-3}$	–

Effective operators for Scalar DM

Complex scalar DM

Real scalar DM

Name	Operator	Coefficient	DD
C1	$[\chi^*\chi][\bar{f}f]$	$m_f\Lambda^{-2}$	SI
C2	$[\chi^*\chi][\bar{f}\gamma^5 f]$	$im_f\Lambda^{-2}$	–
C3	$[\chi^*\partial_\mu\chi][\bar{f}\gamma^\mu f]$	Λ^{-2}	SI
C4	$[\chi^*\partial_\mu\chi][\bar{f}\gamma^\mu\gamma^5 f]$	Λ^{-2}	–
C5	$[\chi^*\chi][G_{\mu\nu}G^{\mu\nu}]$	$\alpha_S\Lambda^{-2}$	SI
C6	$[\chi^*\chi][G_{\mu\nu}\tilde{G}^{\mu\nu}]$	$i\alpha_S\Lambda^{-2}$	–
R1	$[\chi\chi][\bar{f}f]$	$m_f\Lambda^{-2}$	SI
R2	$[\chi\chi][\bar{f}\gamma^5 f]$	$im_f\Lambda^{-2}$	–
R3	$[\chi\chi][G_{\mu\nu}G^{\mu\nu}]$	$\alpha_S\Lambda^{-2}$	SI
R4	$[\chi\chi][G_{\mu\nu}\tilde{G}^{\mu\nu}]$	$i\alpha_S\Lambda^{-2}$	–

Can also write down EFTs describing DM interactions with SM gauge bosons or the Higgs boson.

Strong bounds on EFT operators!

Bounds on some EFT operators are becoming quite constraining!

- Direct detection, collider, and indirect detection
  → lower limits on Λ_{eff} (no signals)

- Relic density
  → upper limit on Λ_{eff} (to prevent over-closure)

For many operators, these limits are approaching!

If the EFT description is relevant for DM, we may see a signal soon!

Mono-X signal at colliders

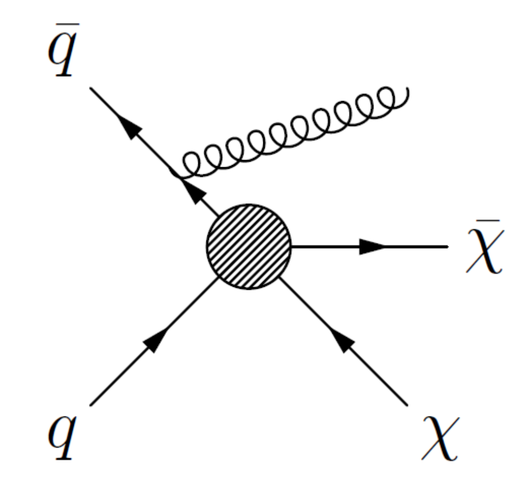
- The dominant DM production process is invisible (DM stable, weakly interacting) : $\bar{q}q \rightarrow \chi\chi$

- Need visible particles in the final state, to recoil against missing transverse energy

$$\bar{q}q \rightarrow \chi\chi + \text{ SM particle}$$

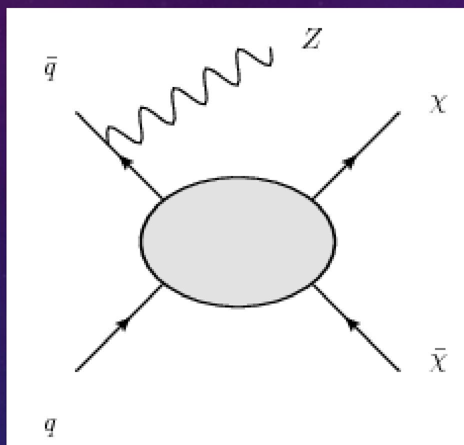
Mono-X process in which DM is visible as a high p_T state + missing E_T

→ Mono-jet, mono-photon, mono-Z, mono-W, mono-Higgs

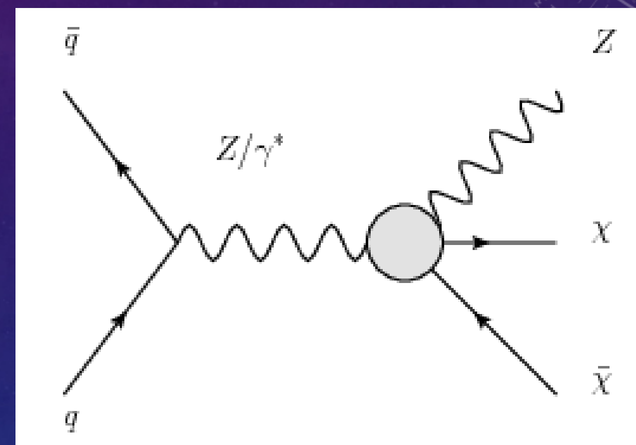


Mono-X processes

Mono-Z
initial state radiation

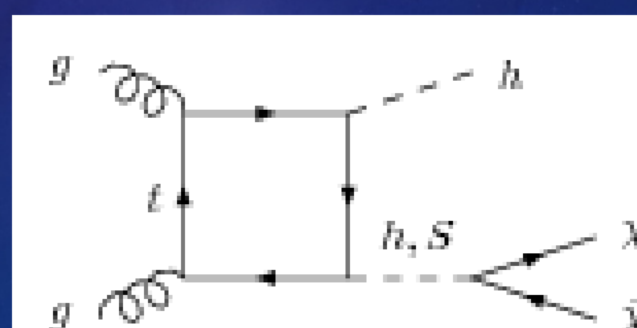


Mono-Z from DM interacting directly with Z bosons

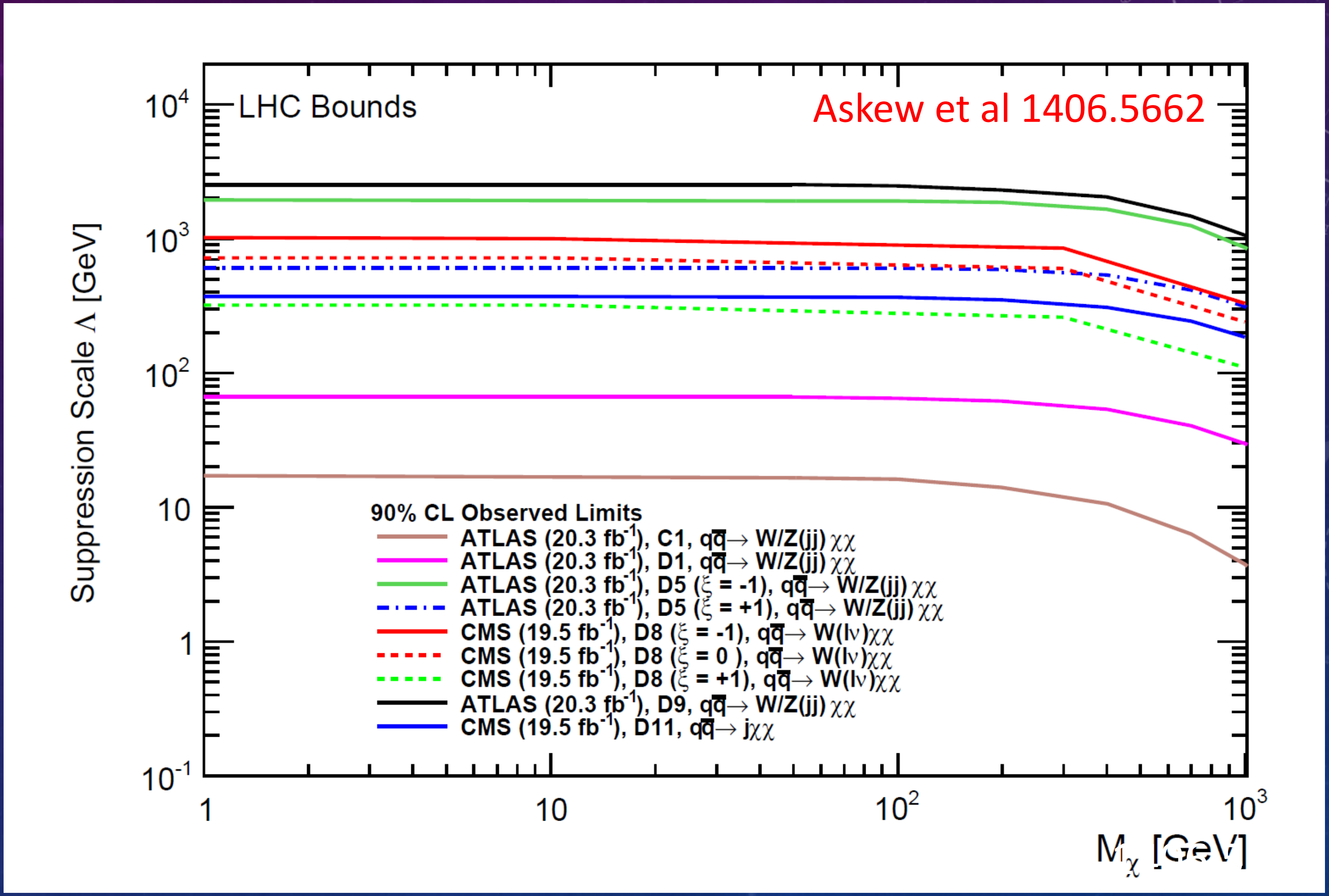


L. Carpenter et al

Mono-Higgs



LHC limits on Λ_{eff}

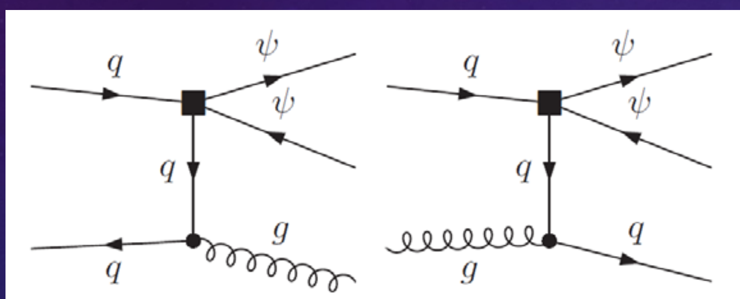


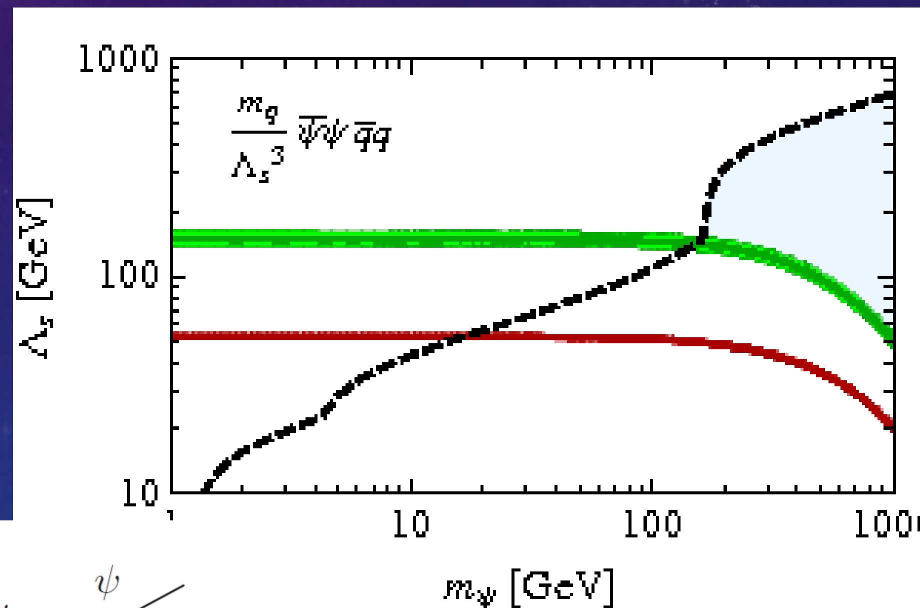
Scalar operator

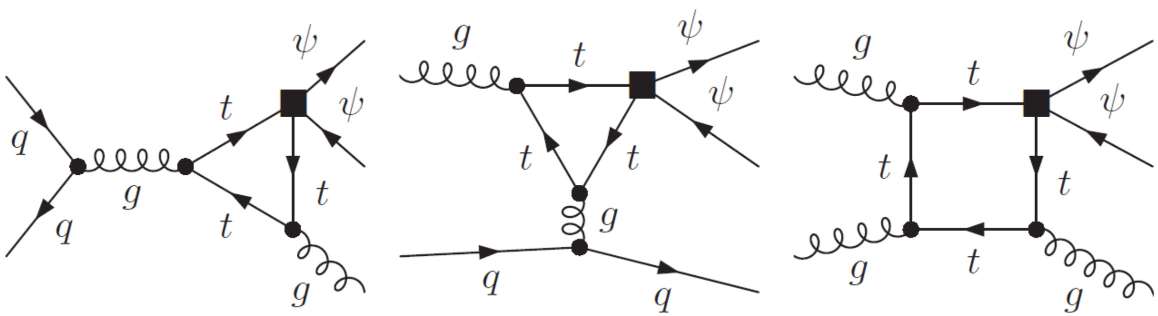
Consider a scalar operator: $\mathcal{O}_s^\psi = \frac{m_q}{\Lambda_s^3}\,\bar{q}q\,\bar{\psi}\psi$

Coupling ∝ mass motivated by minimal flavour violation

Tree-level diagrams do not give a large monojet signal, but top quark loops do.



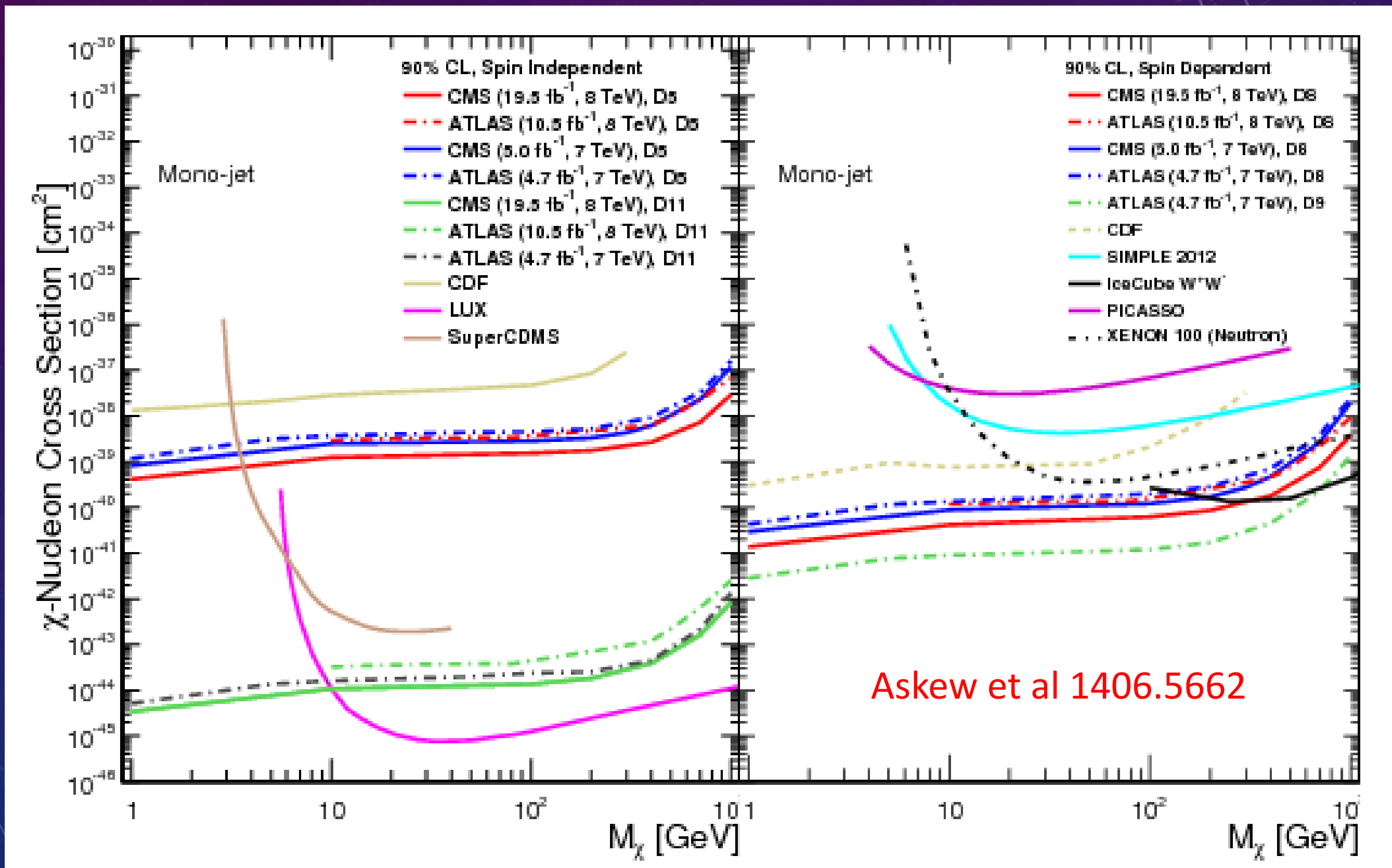




Haisch et al, arXiv:1208.4605

LHC vs direct detection

Spin-independent   Spin-dependent



Higgs Portal DM

Take the EFT approach and consider interactions of the form:

$$\frac{1}{\Lambda^n} O_{DM} O_{SM}$$

where O_{DM} = dark matter operator
O_{SM} = standard model operator

with O_{DM} & O_{SM} both singlets under the SM gauge group

The lowest dimension SM operator is the Higgs bilinear: $H^\dagger H$

→ Form "Higgs portal" operators of the form: $\frac{1}{\Lambda^n} O_{DM} (H^\dagger H)$

Types of Higgs Portals

Scalar Higgs portal: $\lambda_s S^2 (H^\dagger H)$

Vector Higgs portal: $\lambda_V V^\mu V_\mu (H^\dagger H)$

Note: these are renormalizable, with dimensionless coupling λ

Fermionic Higgs portal: $\frac{1}{\Lambda}(\bar{\chi}\chi)(H^\dagger H)$

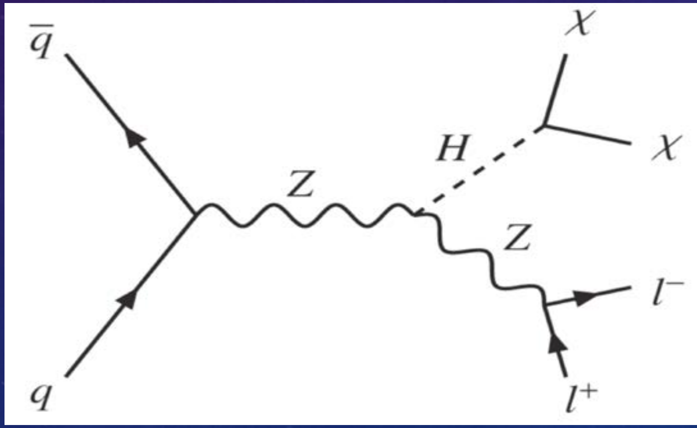
Note: Non-renormalizable (higher dimension) operator.

Higgs Portal & Higgs invisible width

If $m_{DM} < \frac{m_{\text{higgs}}}{2}$

→ Higgs width increased by decay to dark matter, $H \rightarrow \bar{\chi}\chi$

→ Constraints from LHC determinations of Higgs invisible width

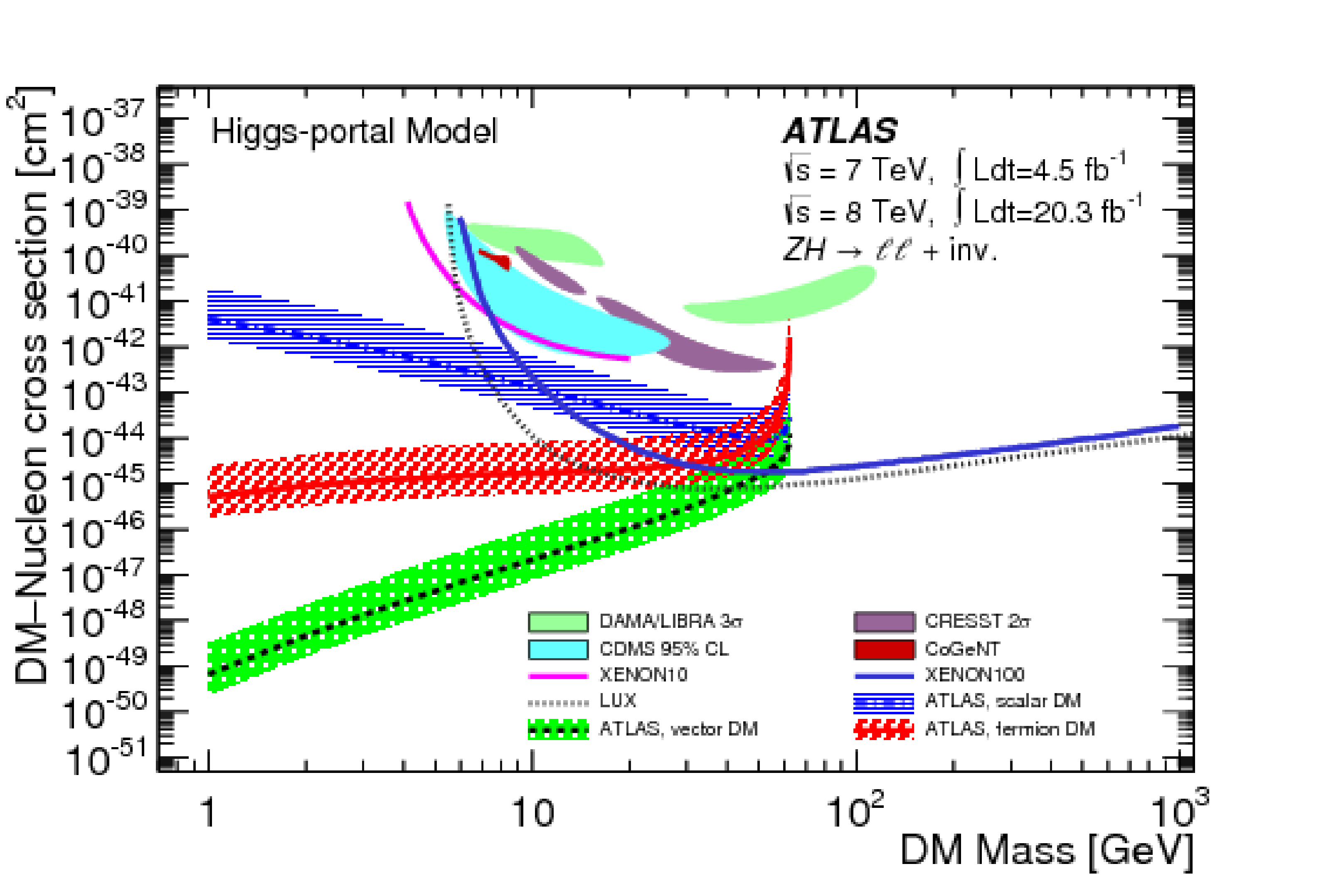


Br(inv) < 0.75

ATLAS, arXiv: 1402.3244

Note that because the SM Higgs width is so small (about 4 MeV), even modest limits on B(inv) place strong limits on Higgs portal models.

ATLAS, arXiv: 1402.3244



EFTs are useful, but have limitations

- ❑ EFT bounds can over-estimate constraints on a given model

e.g. Models with light mediators (except where $M_{mediator} > 2M_{DM}$, where an s-channel resonance is possible)

- ❑ EFT bounds can under-estimate constraints on a given model

e.g. If DM-SM interaction mediated by a new colored particle the EFT mono-jet bounds are often too conservative.

- ❑ Importantly: in many UV complete theories, there exists other dark sector particles at energy scales accessible to the LHC. Particles with SM quantum numbers, or a Z' gauge boson, … etc.

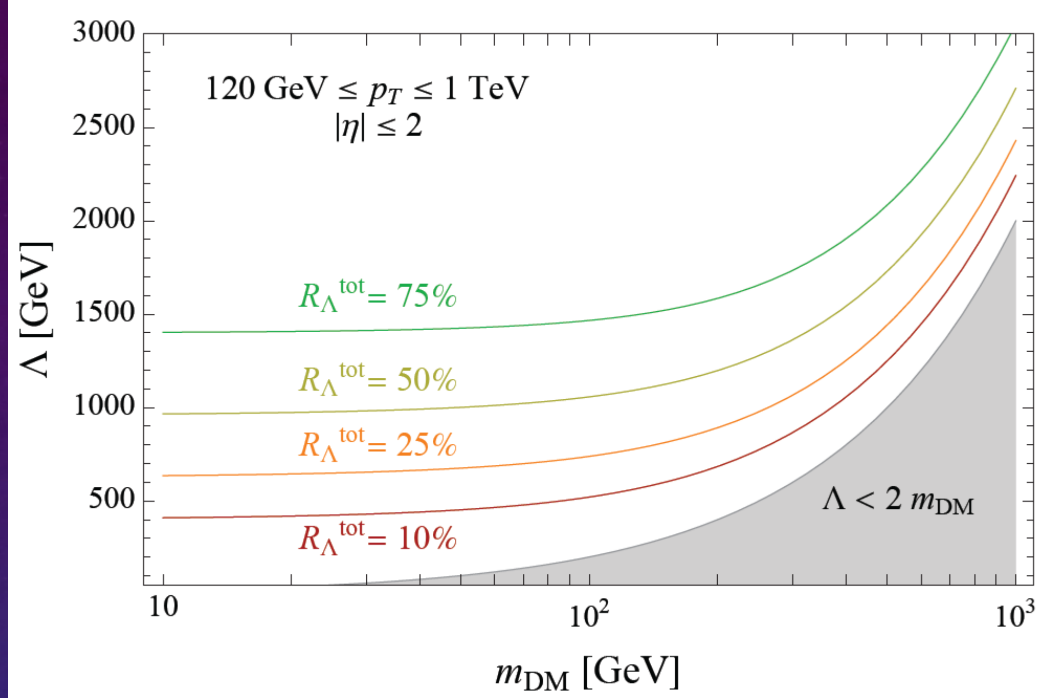
Validity of EFT description

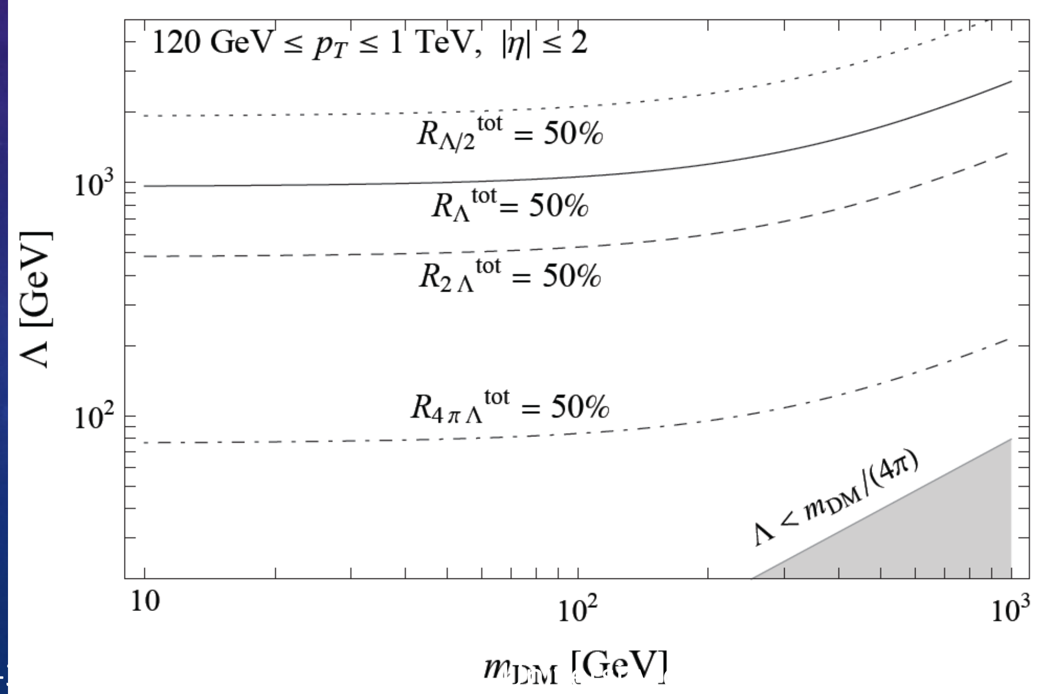
$$\Lambda = \frac{M_{med}}{\sqrt{g_q g_\chi}} > \frac{m_{dm}}{4\pi}$$

$$R_\Lambda^{\rm tot} \equiv \frac{\sigma_{\rm eff}\big|_{Q_{\rm tr}<\Lambda}}{\sigma_{\rm eff}}$$

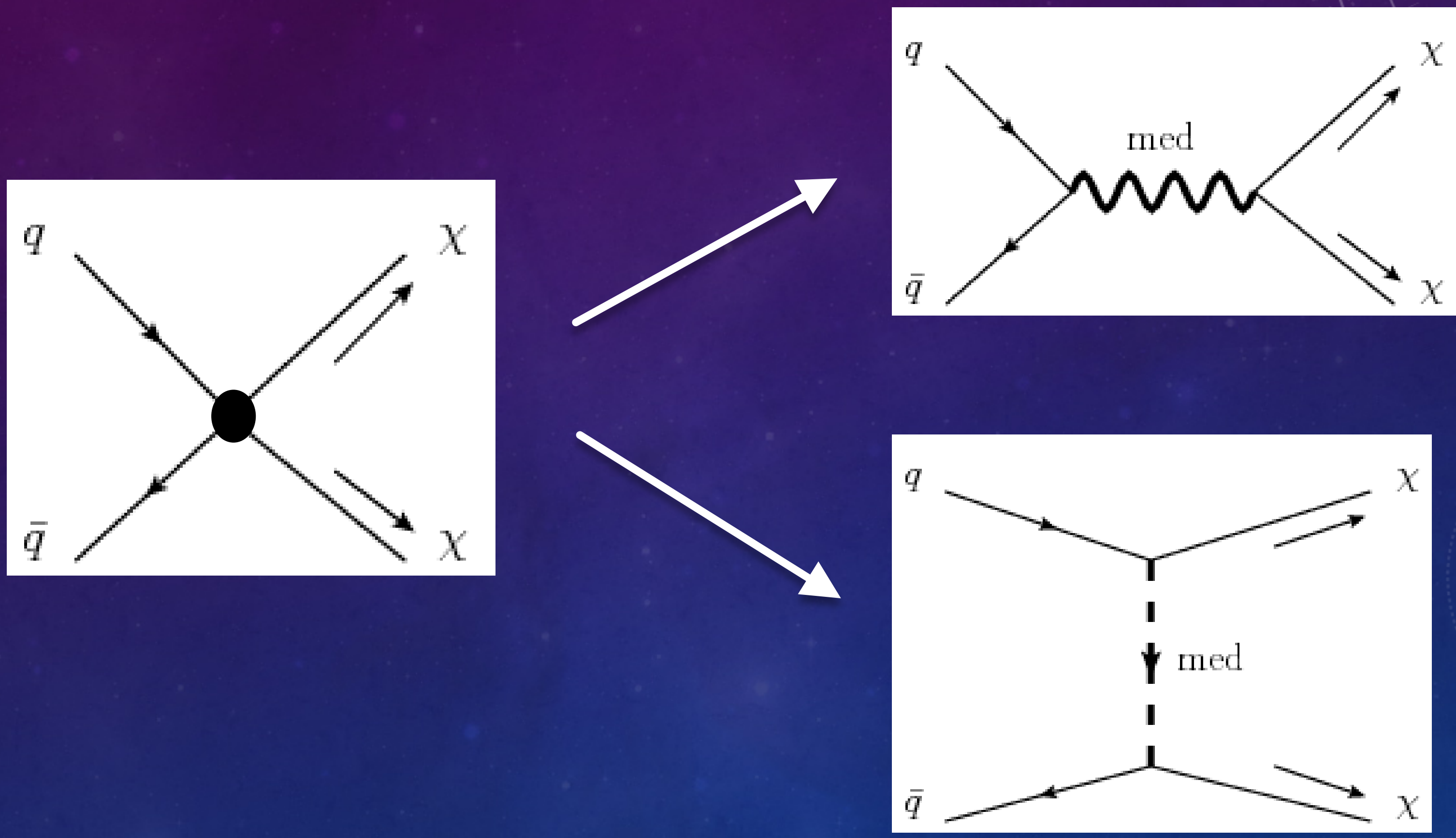
LHC searches for DM are operating in regions where the EFT description breaks down.

G.Busoni et al, 1307.2253



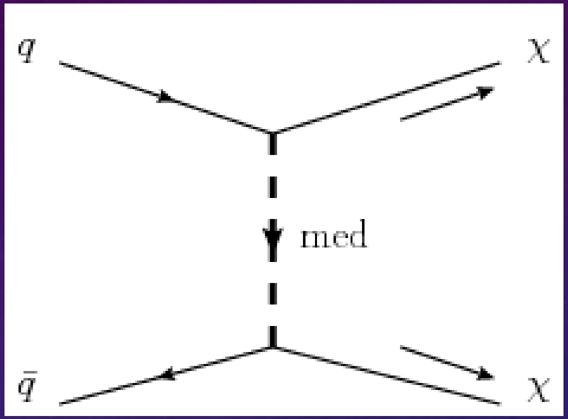


Beyond an EFT → Simplified Models



A given EFT maps to multiple simplified models

t-channel mediator

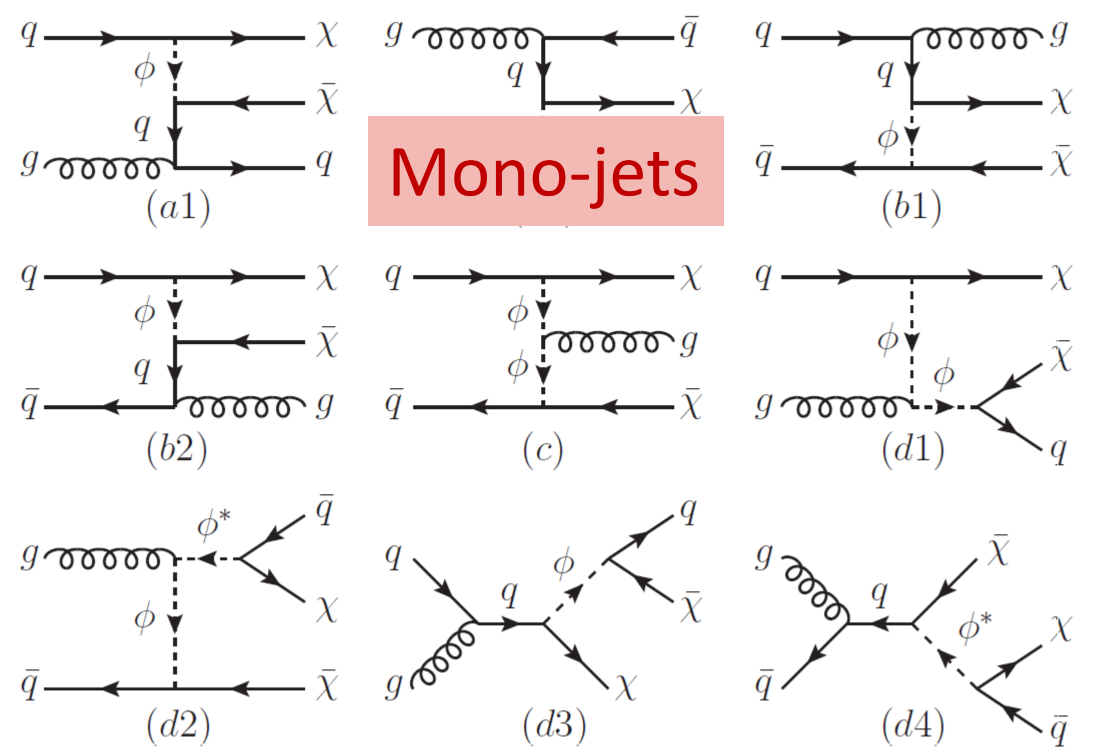


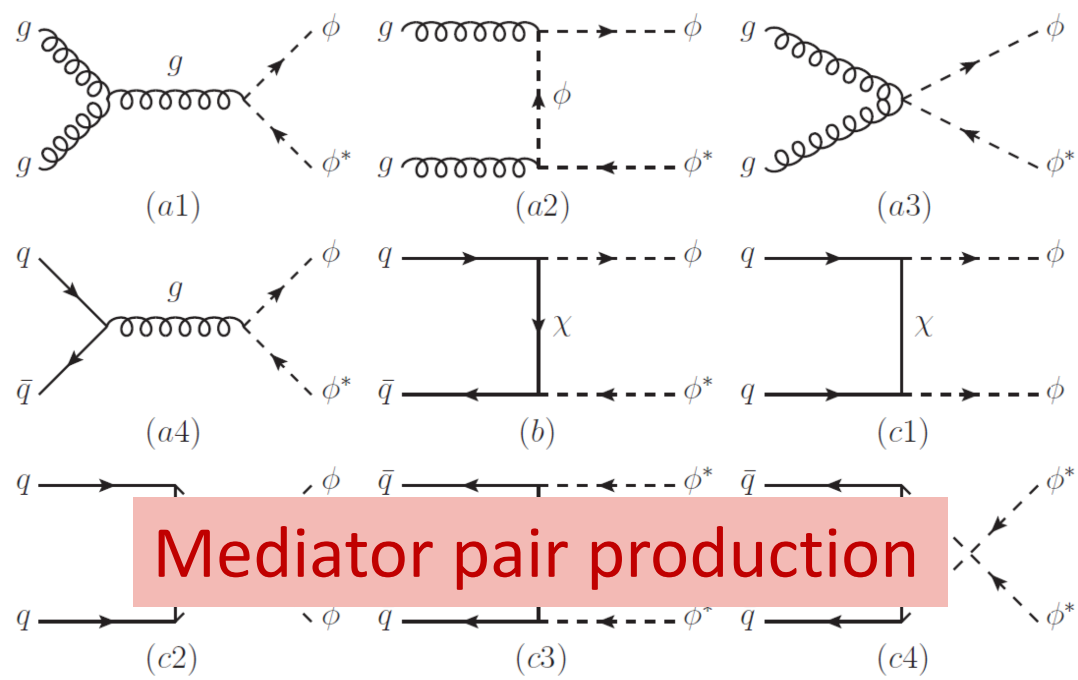
The mediator:

- If χ stabilized by a symmetry, the mediator also carries this symmetry.
- Carries SM quantum numbers
  → can be pair produced at colliders
- Is heavier than the DM
  (so the DM does not decay to the mediator)

Beyond an EFT:

t-channel scalar mediator

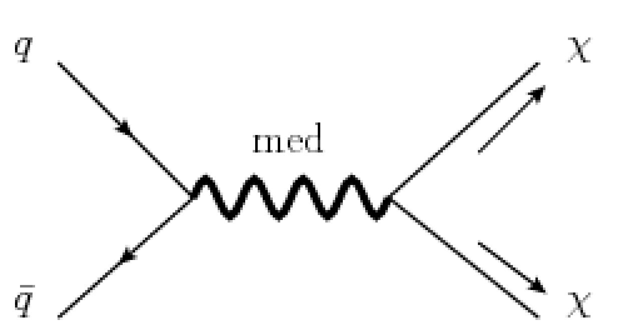


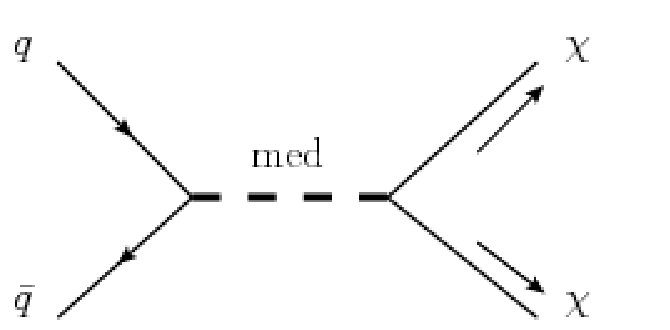


H.An et al, 1308.0592

See also:
Chang et al. , 1307.8120
Bai & Berger, 1308.0612
DiFranzo et al., 1308.2679

s-channel mediator





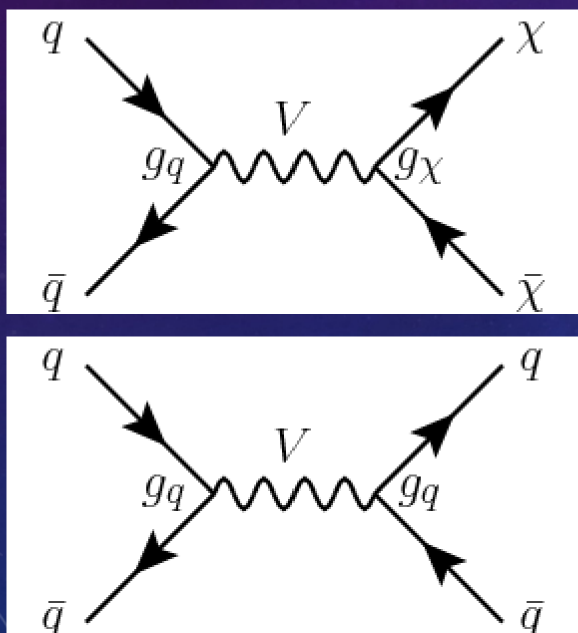
The mediator:

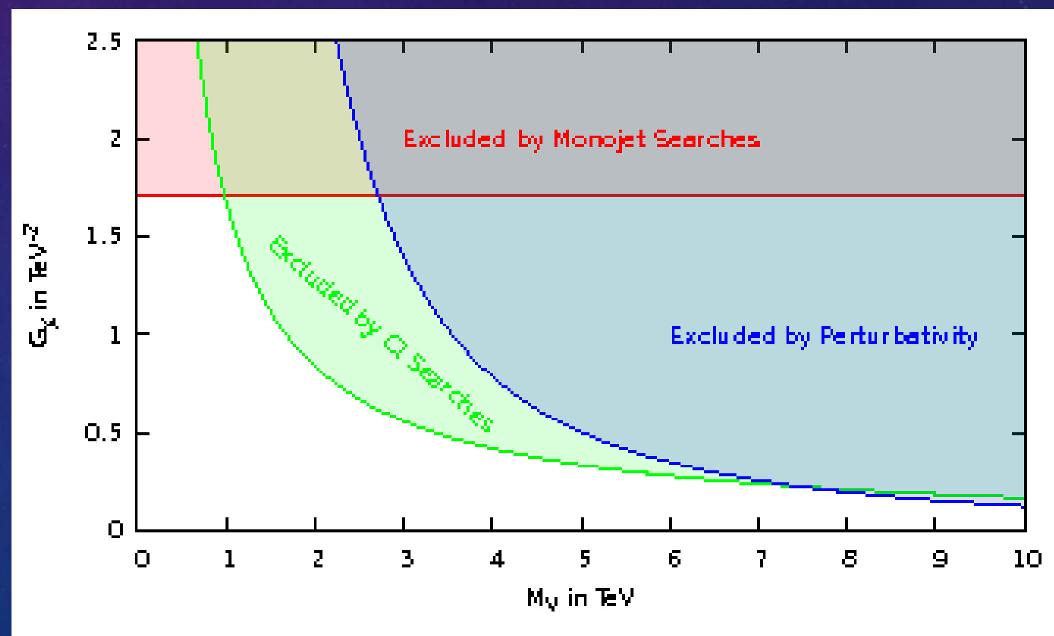
- Directly couples to the SM
  → can produce mediator at colliders
- Can be lighter or heavier than the DM
- Mass and width are important

Beyond an EFT: s-channel vector mediator

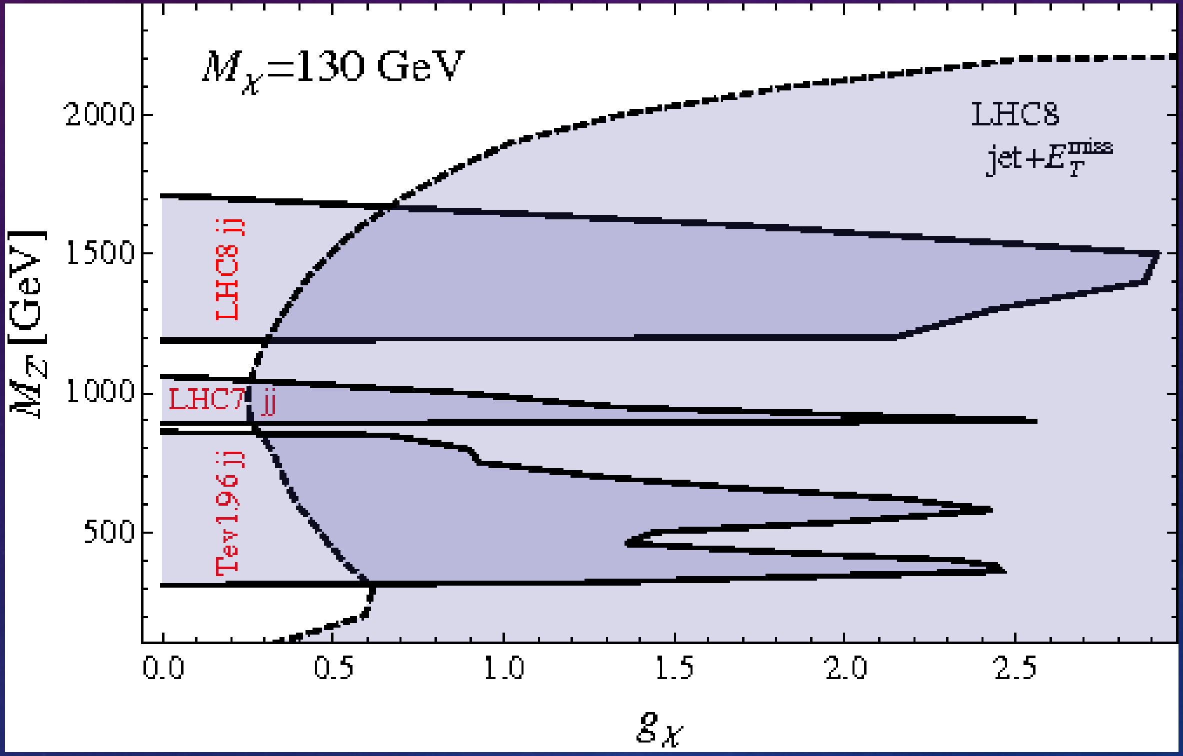
- Mono-jets + missing ET
- Dijet resonance (where mediator can be produced on shell)
- $\bar{q}q\bar{q}q$ contact interactions (at very high mediator mass)

Dreiner et al 1303.33483





Dijets vs monojets

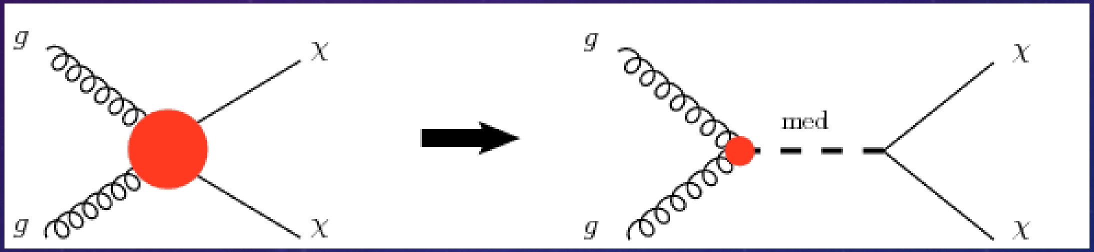


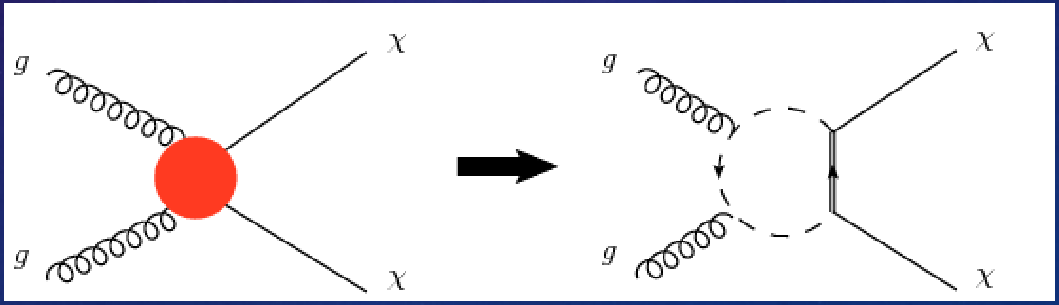
Alves et al
1312.5281

Models with gluon couplings

- Mono-jets place strong limits
- No tree-level UV completion is possible

D11	$[\bar{\chi}\chi][G_{\mu\nu}G^{\mu\nu}]$	$\alpha_S \Lambda^{-3}$	SI
D12	$[\bar{\chi}\gamma^5\chi][G_{\mu\nu}G^{\mu\nu}]$	$i\alpha_S \Lambda^{-3}$	–
D13	$[\bar{\chi}\chi][G_{\mu\nu}\tilde{G}^{\mu\nu}]$	$i\alpha_S \Lambda^{-3}$	–
D14	$[\bar{\chi}\gamma^5\chi][G_{\mu\nu}\tilde{G}^{\mu\nu}]$	$\alpha_S \Lambda^{-3}$	–



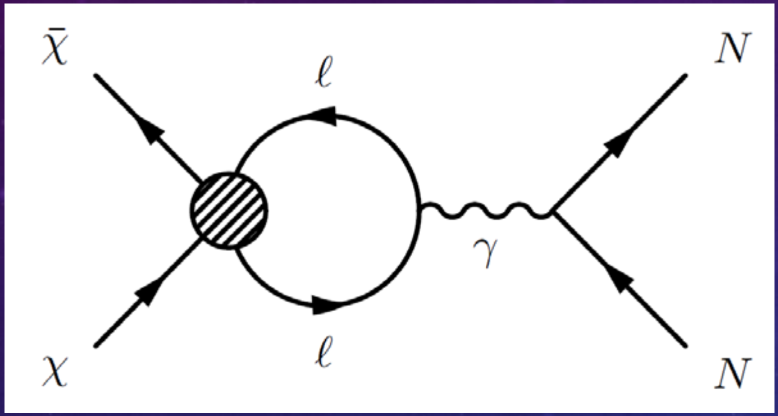


Abdallah et al 1409.2893

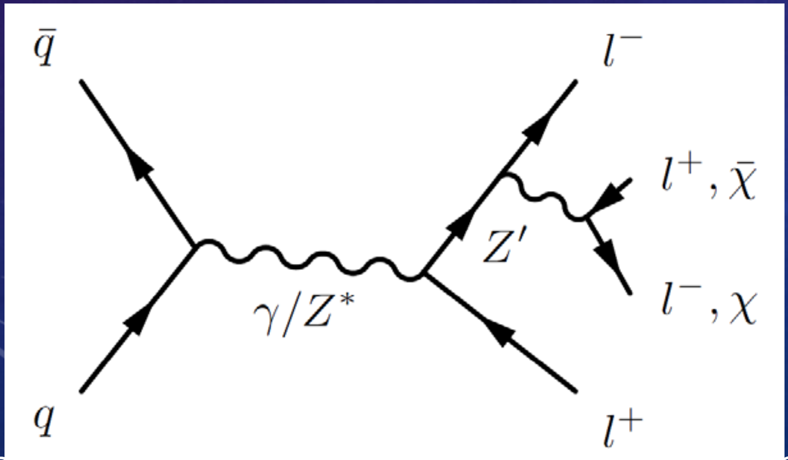
Some non-standard WIMPs

Leptophilic WIMP?

- Suppose DM couples only to leptons (at tree level)
- Standard direct detection & LHC mono-X bounds don’t apply.
- Even so, this scenario is strongly constrained



Direct detection loop-suppressed, yet still yields strong limits



Collider production via Drell-Yan process

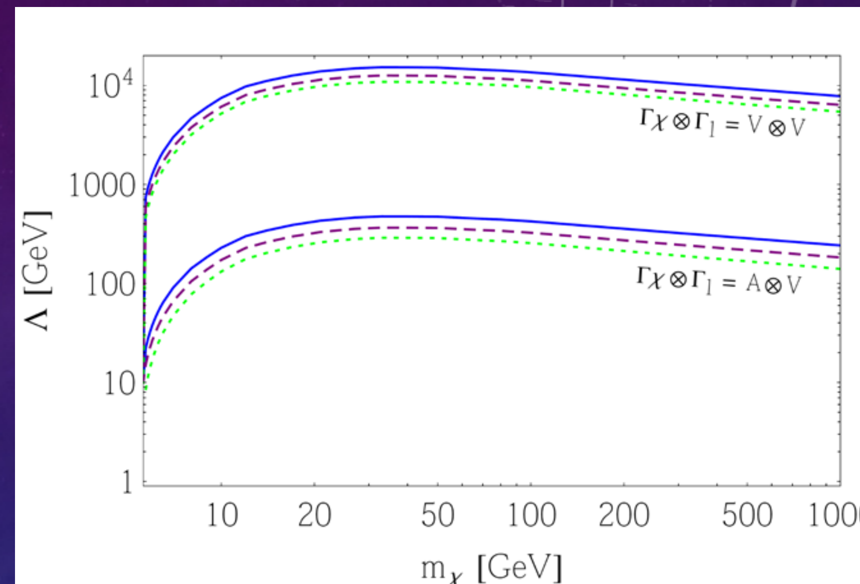
Bell et al 1407.4566. See also: Kopp 0907.3159, and Altmannshofer 1406.1269

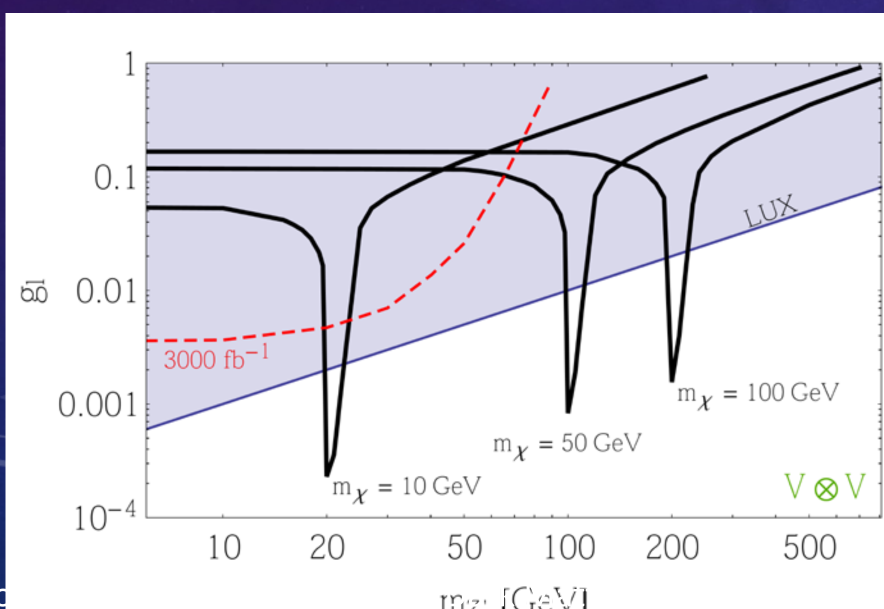
Leptophilic WIMP

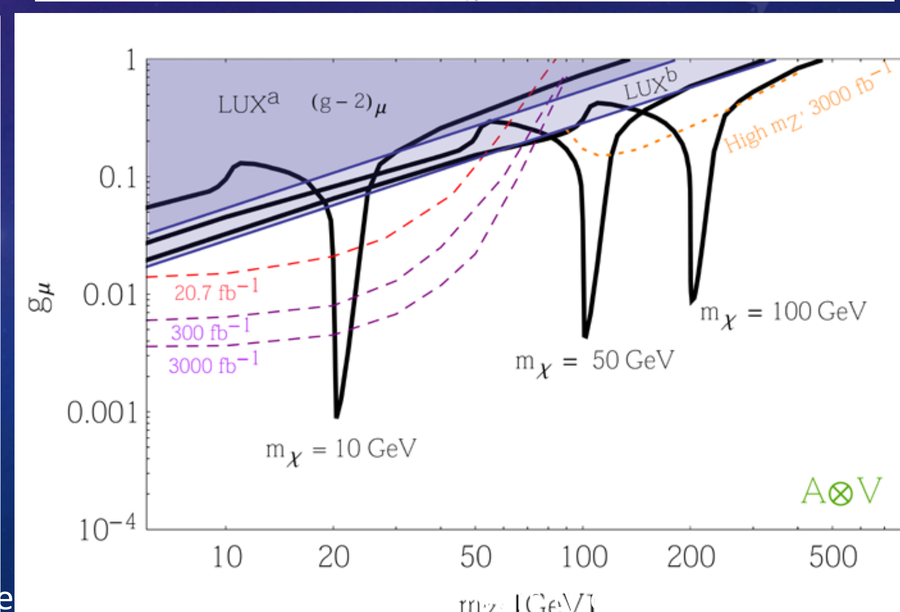
Direct detection still requires the new-physics scale to be high

→ some tension with relic density requirement

Bell et al 1407.4566.







Co-Annihilation

We often neglect all dark sector particles other than a single DM candidate. May not be valid.

Consider models in which there are 2 (or more) dark sector particles of similar mass, $\{\chi_1, \chi_2\}$, with $m_1 \approx m_2$.

- Relic density controlled by co-annihilation of χ_1 and χ_2
- χ_2 decays to χ_1 with lifetime << age of universe

Generalize the EFT description:

$$\frac{1}{\Lambda_{11}^2}(\overline{\chi_1}\Gamma_1\chi_1)(\overline{f}\Gamma_2 f)\ ,$$
$$\frac{1}{\Lambda_{12}^2}(\overline{\chi_1}\Gamma_1\chi_2)(\overline{f}\Gamma_2 f) + h.c.\ ,$$
$$\frac{1}{\Lambda_{22}^2}(\overline{\chi_2}\Gamma_1\chi_2)(\overline{f}\Gamma_2 f)\ ,$$

If $\Lambda_{11} >> \Lambda_{12}\,\Lambda_{22}$ → Self annihilation of χ_1 is suppressed

Co-annihilation

- Relic density

- Co-annihilation of χ_1 and χ_2 controls the relic density

- Indirect detection

- Suppressed (because no χ_2 in universe today)

- Direct detection

$\chi_1 + N \rightarrow \chi_2 + N$ cannot happen unless mass gap is tiny

- Colliders

New signal: $pp \rightarrow \chi_1 \chi_2 + \text{jet}$ followed by χ_2 decay

Bell, Cai & Medina, 2014

Collider signals of co-annihilation

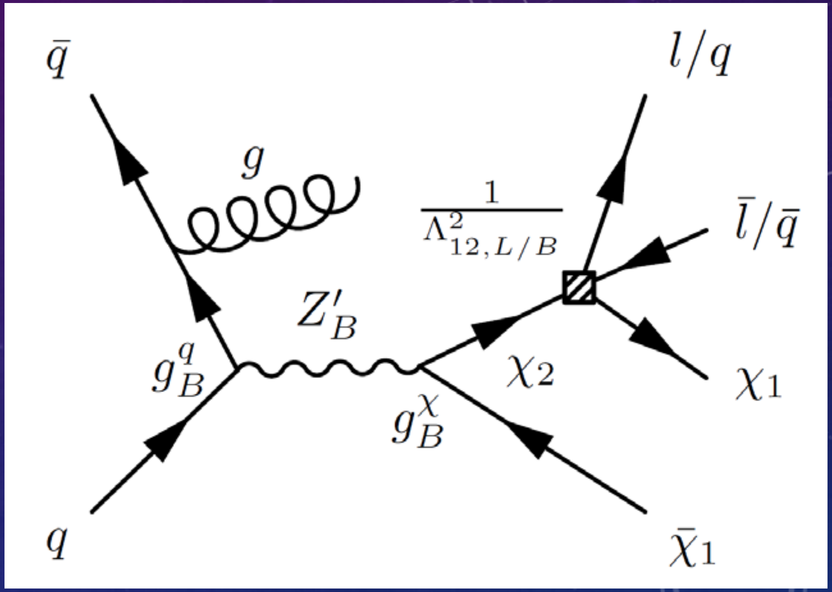
Bell, Cai & Medina, 2014

$pp \to \chi_1\chi_2 + \text{jet} \to \chi_1\chi_1 + \text{jet} + SM$

Where the χ_2 decay process is:

$\chi_2 \to \chi_1 + l^+l^-$

or $\chi_2 \to \chi_1 + \bar{q}q$



Could be observed with forthcoming LHC data!

Monojet signals also possible (from decay of χ_2 to neutrinos, or to particles too soft to be detected).

Concluding Thoughts

If we see a missing E_T signal at the LHC, that can be attributed to a new weakly interacting particle, we won't know if it's really the dark matter without other information.

- Is it stable?
  - →DM must be stable on a timescale of order 10 Gyr. Colliders will tell us about stability on only nanosecond timescales (long enough to escape the detector).
- Does it contribute all the relic density?
  - → Need to measure couplings to all SM particles.
- Consistent with direct and/or indirect detection?
  - → These techniques provide important complimentary information