The LHC and Dark Matter: Scalar Simplified Models

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A Problem of Gravity

- All evidence for dark matter is purely gravitational.
- Few positive statements we can make:
  - Exists today
  - Existed prior to CMB
  - Non-relativistic at structure formation
- Everything else is what we know dark matter *isn't*:
  - Non-EM interacting
  - Non-QCD interacting
  - Sub-*Z* interaction with nucleons
  - Doesn't interact with itself
  - Doesn't decay

  (… upper limits only)
- Why should I expect non-gravitational interactions?

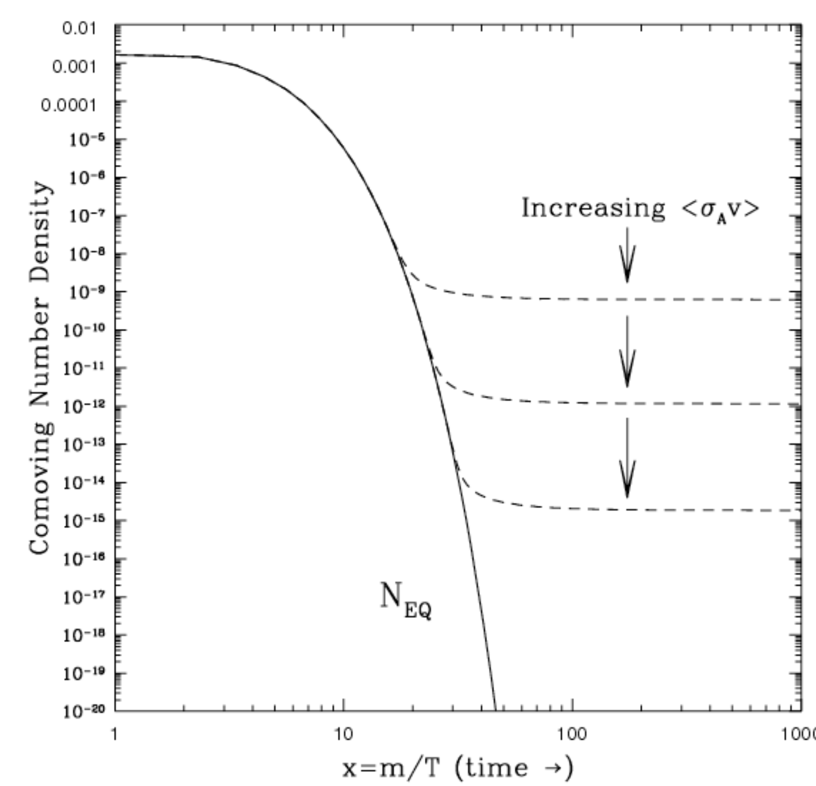
Weak-Scale Dark Matter

- Good to have motivations from elsewhere in physics.
- Observation: a stable particle interacting with the Standard Model would be present in thermal bath assuming the Universe ever had $T \gg m$.
  - Some remain as thermal relics after freeze-out.
- An electroweak-mass particle with electroweak interactions has:

$$\langle \sigma v \rangle \sim \alpha^2 / m_W^2$$

$$\Omega h^2 \sim 0.12$$

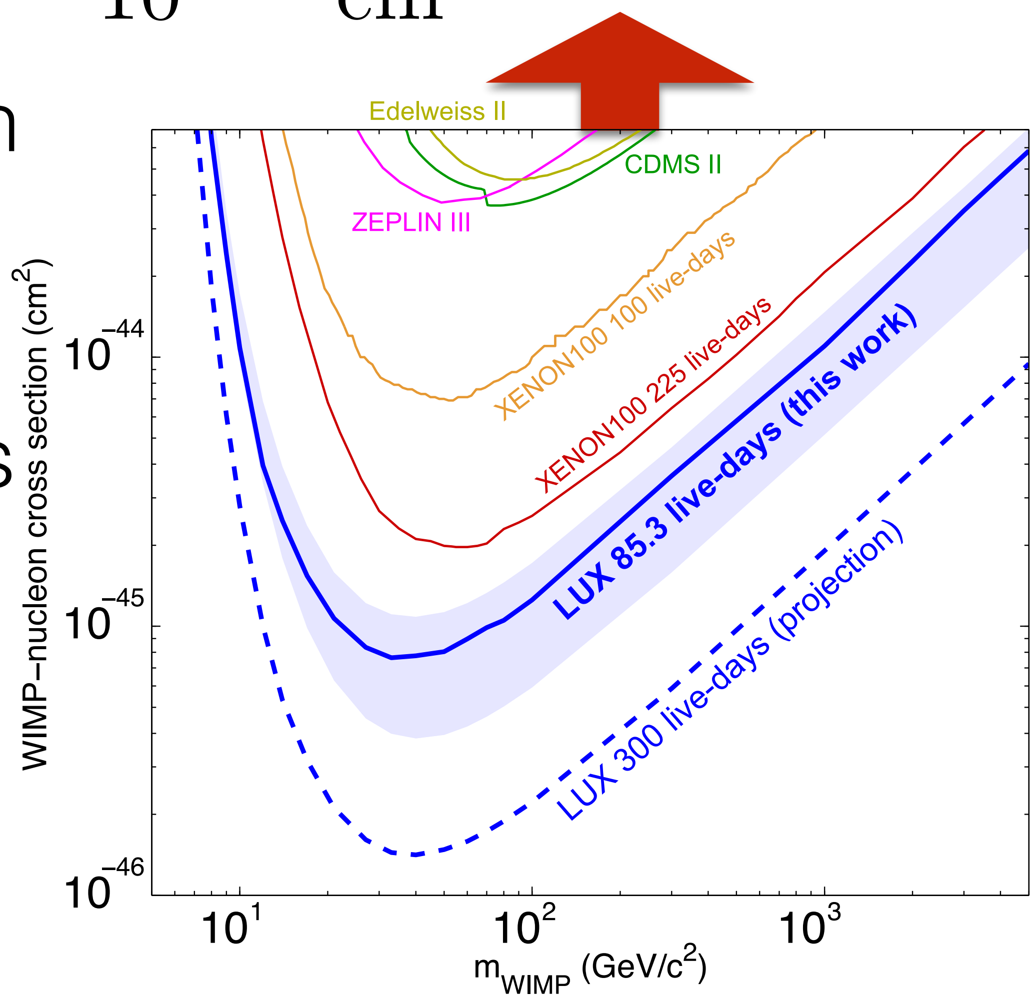
- The WIMP Miracle!
  - DM with "significant" interactions



Jungman *et al* hep-ph/9506380

A Miracle with Footnotes

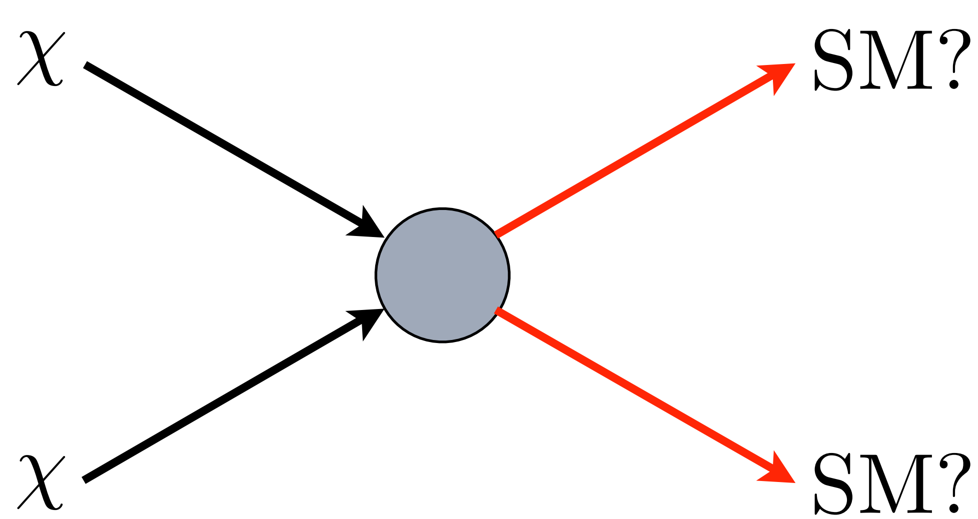
- "Pure" $SU(2)_L$ doublet fermions have extremely large direct detection rates: $\sigma \sim 10^{-35} - 10^{-36}\ \mathrm{cm}^2$
- Models with $m_\chi \sim 100\ \mathrm{GeV}$ often require particles beyond DM to annihilate with or through.
  - Pure thermal bino DM requires sfermions to annihilate away
  - Pure Wino/Higgsino DM requires $m_\chi \sim 1-2\ \mathrm{TeV}$
- Thermal relics can be obtained with new non-$SU(2)_L$ forces



LUX 1405.5906

Accessible Dark Matter

- If dark matter was in thermal equilibrium, then it needs to be able to annihilate into something. Caveats abound:
  - Dark matter might have never been in equilibrium (*e.g.* axions)
  - It might annihilate into non-Standard Model particles (have to prevent those from over-closing Universe…)
- But: *Reasonable* to consider dark matter with significant interactions with Standard Model ($\gtrsim SU(2)_L$).



Dark Matter at the LHC

- Assume dark matter is “significantly” interacting

$$\langle \sigma v \rangle \gtrsim 3 \times 10^{-26}\ \mathrm{cm}^3/\mathrm{s}$$

- Then reasonable to expect production at the LHC.
- How to motivate/parametrize/quantify search channels?

Theorist Complexity

UV Complete Theories
(supersymmetry…)

Simplified Models

Effective Operators
Contact Interaction!

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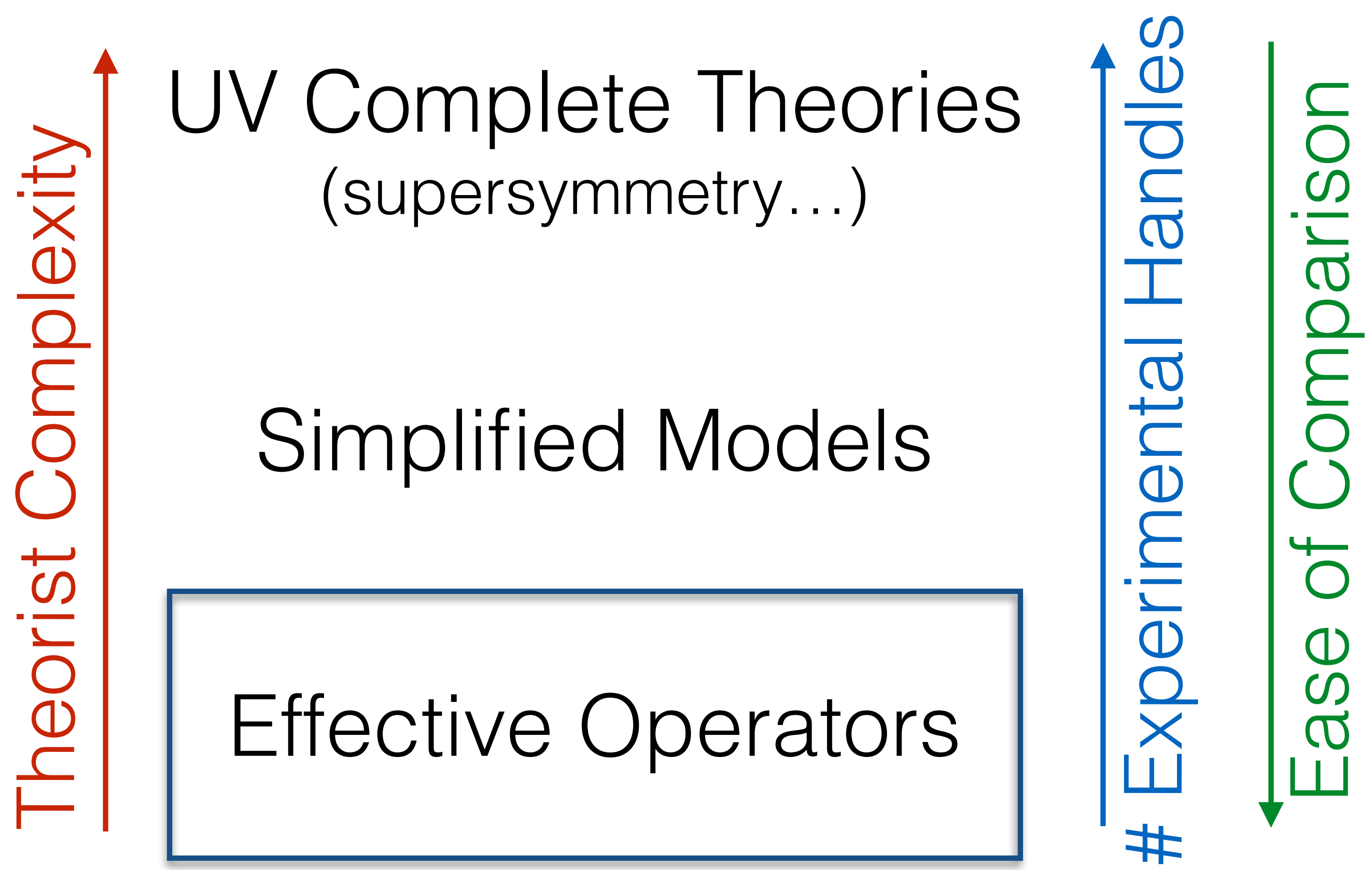
Experimental Handles

Ease of Comparison

Step 1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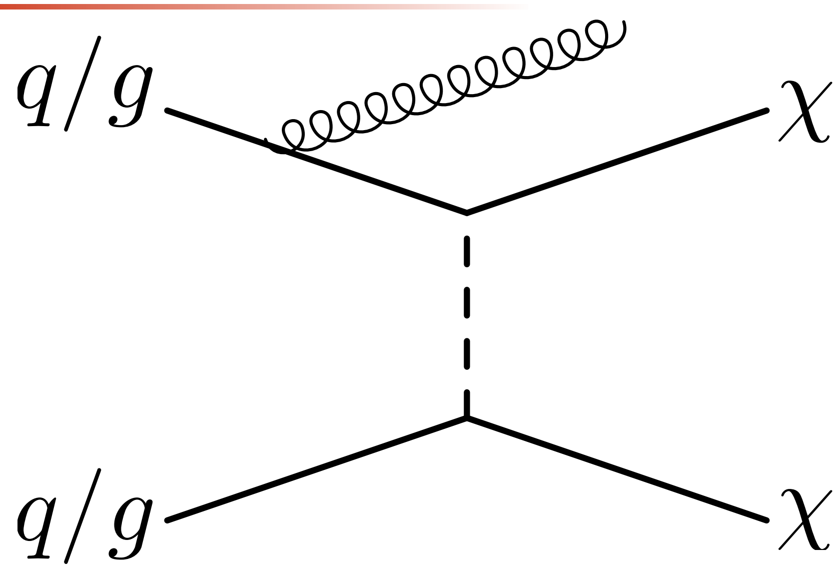
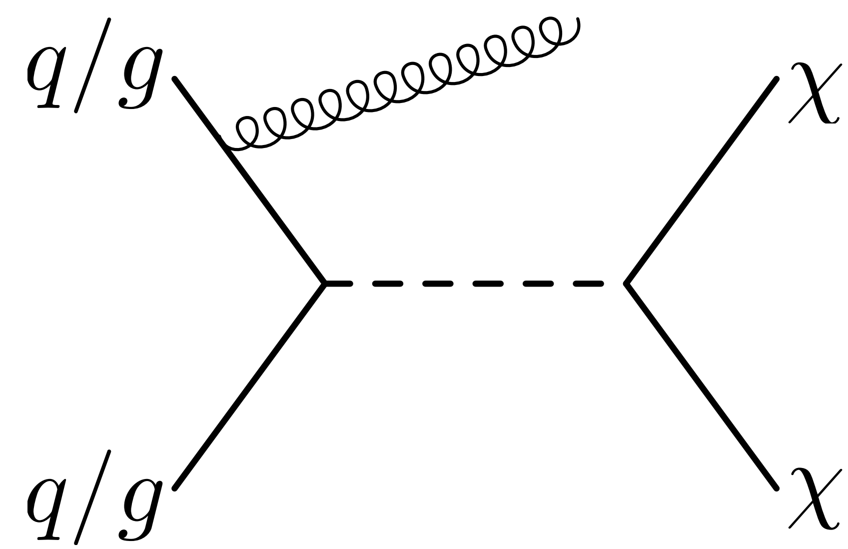
An Effective Framework

- Assume accessible new physics *just* dark matter.
- Integrate out heavy additional particles.
- LHC signature primarily $pp \to \chi\chi + \text{jet}$





$$\mathcal{L} = g_\chi \bar{q} \chi Q' + \cdots \qquad \mathcal{L} = g_q \bar{q} q \phi + g_\chi \bar{\chi} \chi \phi + \cdots$$

$$\mathcal{L}_{\text{eff.}} = \frac{1}{\Lambda^2} (\bar{q} q)(\bar{\chi}\chi) + \cdots$$

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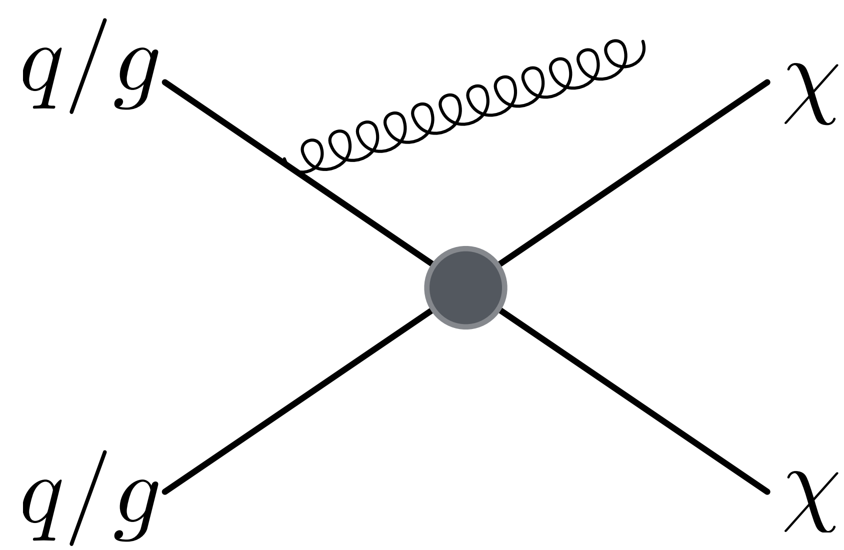

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- Exhaustive list of operators in Goodman *et al.* 1008.1783

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D2	$\frac{im_q}{\Lambda^3}(\bar{q}q)(\bar{\chi}\gamma^5\chi)$
D5	$\frac{1}{\Lambda^2}(\bar{q}\gamma^\mu q)(\bar{\chi}\gamma_\mu\chi)$
D11	$\frac{\alpha_S}{4\Lambda^3}(\bar{\chi}\chi)G_{\mu\nu}G^{\mu\nu}$

C1	$\frac{m_q}{\Lambda^2}(\bar{q}q)(\chi^*\chi)$
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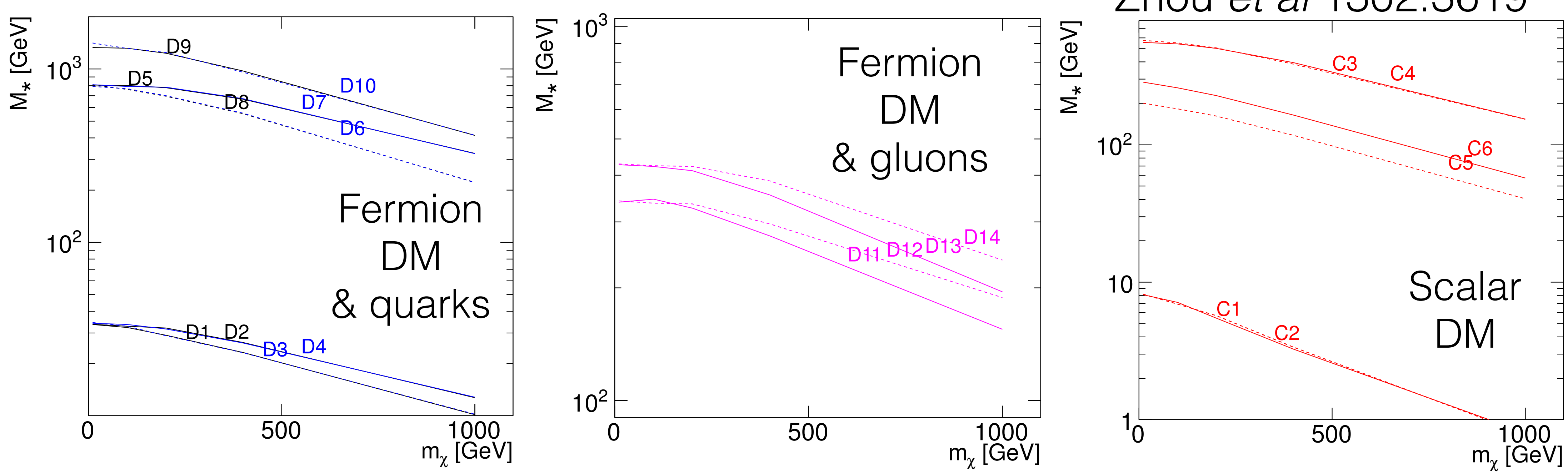
etc.

- Allows direct comparison of experimental results

Zhou *et al* 1302.3619



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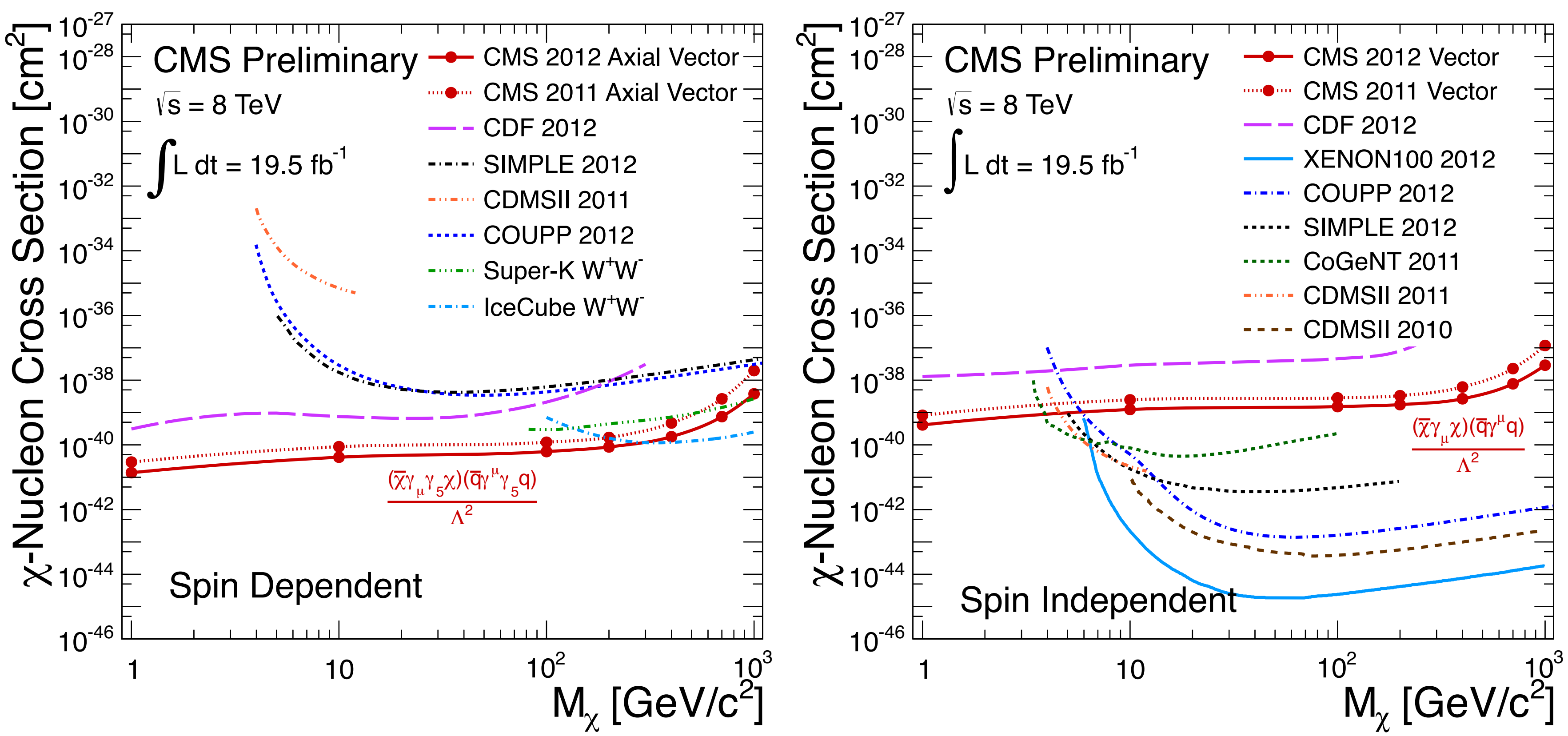

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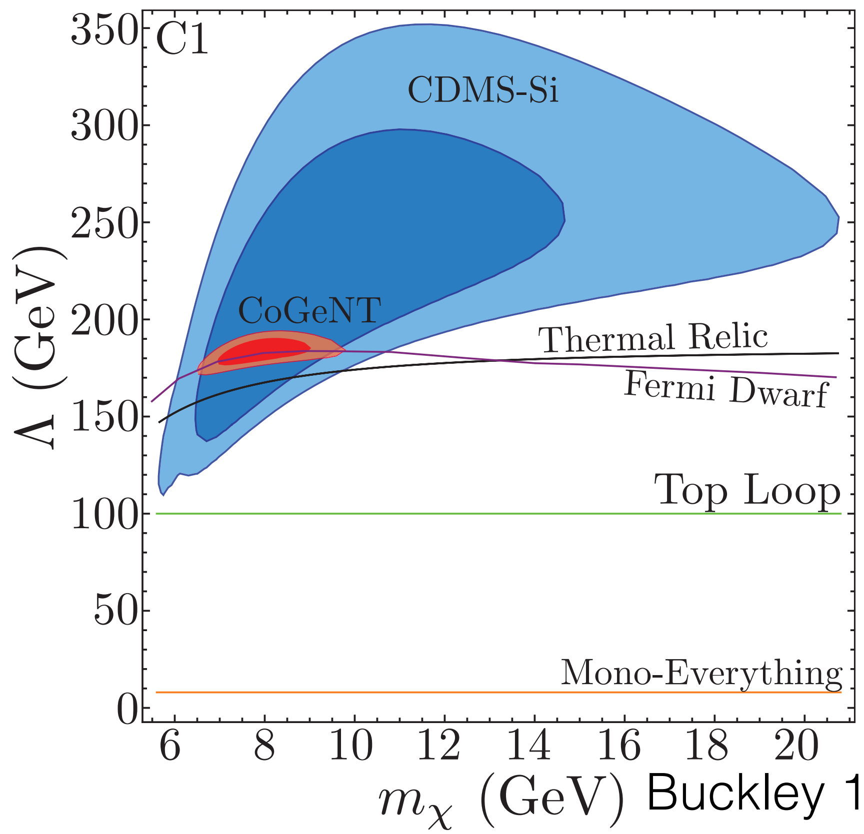

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Effective Operators

- Useful to directly compare different types of experiments.
- However, have to check that assumptions are valid. Can we really integrate out the mediators?

$$(g_\chi g_q) \times \frac{i}{q^2 - M^2} \to -\frac{g_\chi g_q}{M^2}\left(1 + \mathcal{O}(q^2/M^2)\cdots\right)$$

$$\Lambda^2 \equiv \frac{M^2}{g_\chi g_q}$$

- Effective theory is only valid if

$$Q_{\text{transfer}} < M = \sqrt{g_\chi g_q}\Lambda < 4\pi\Lambda$$

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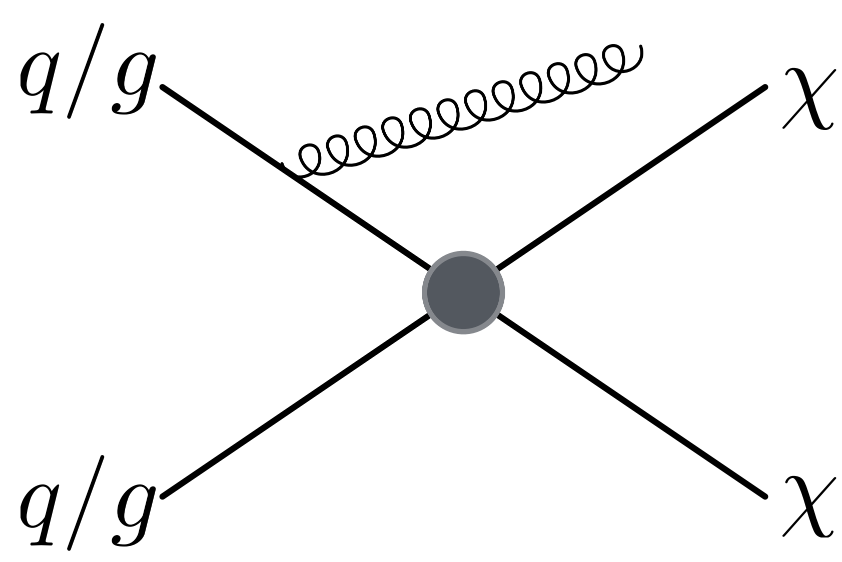

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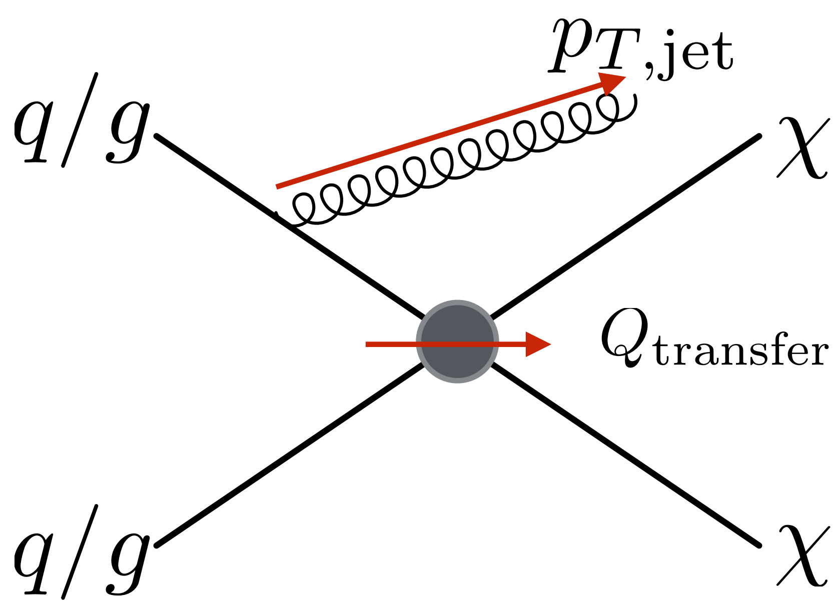

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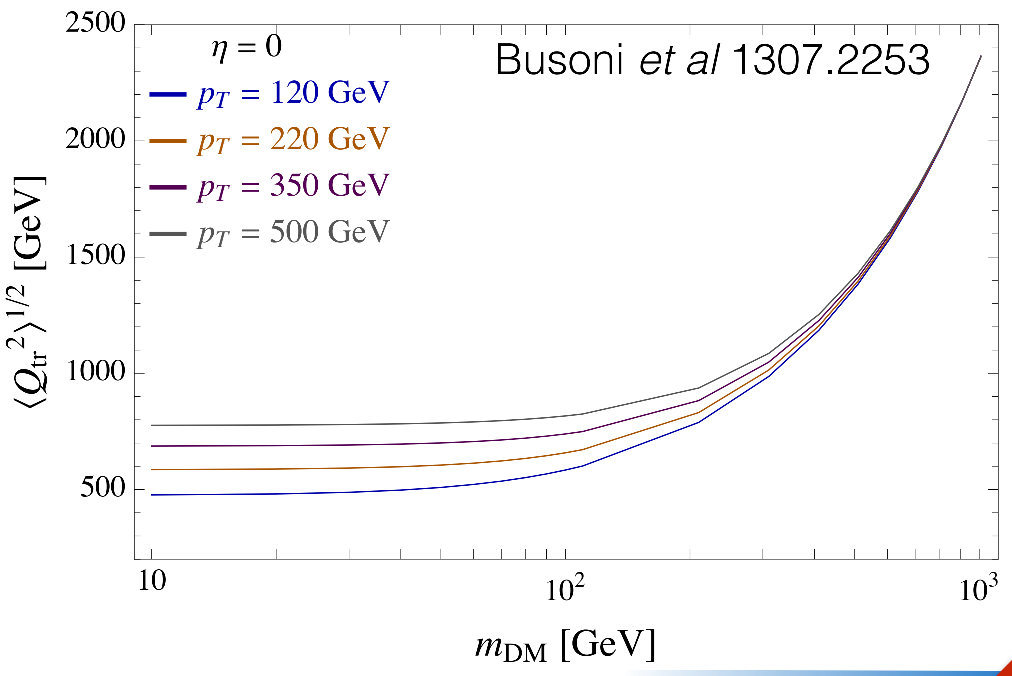

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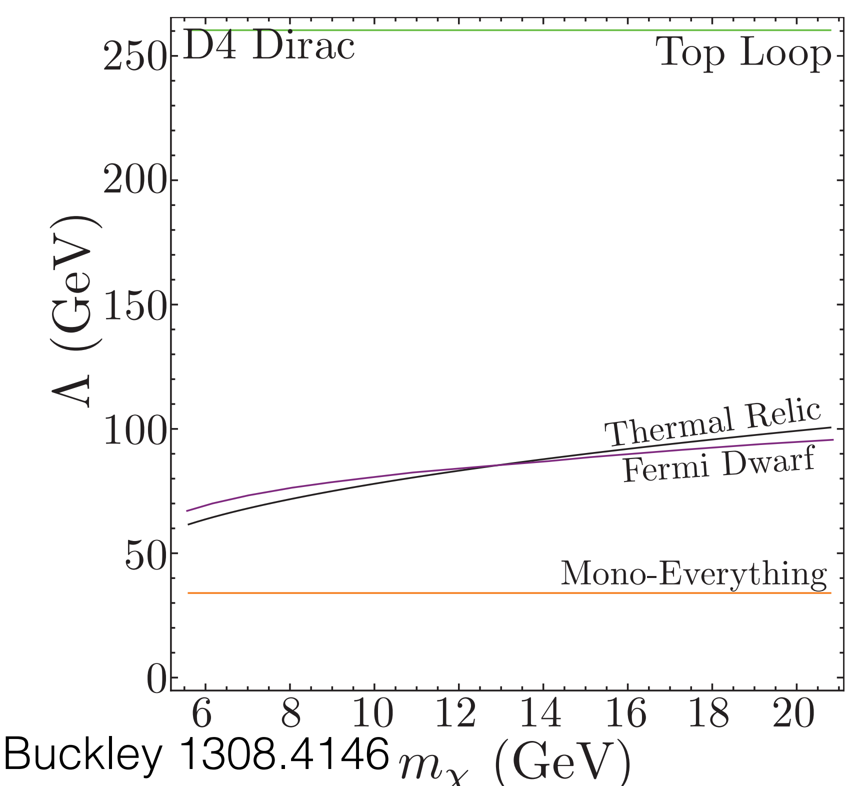

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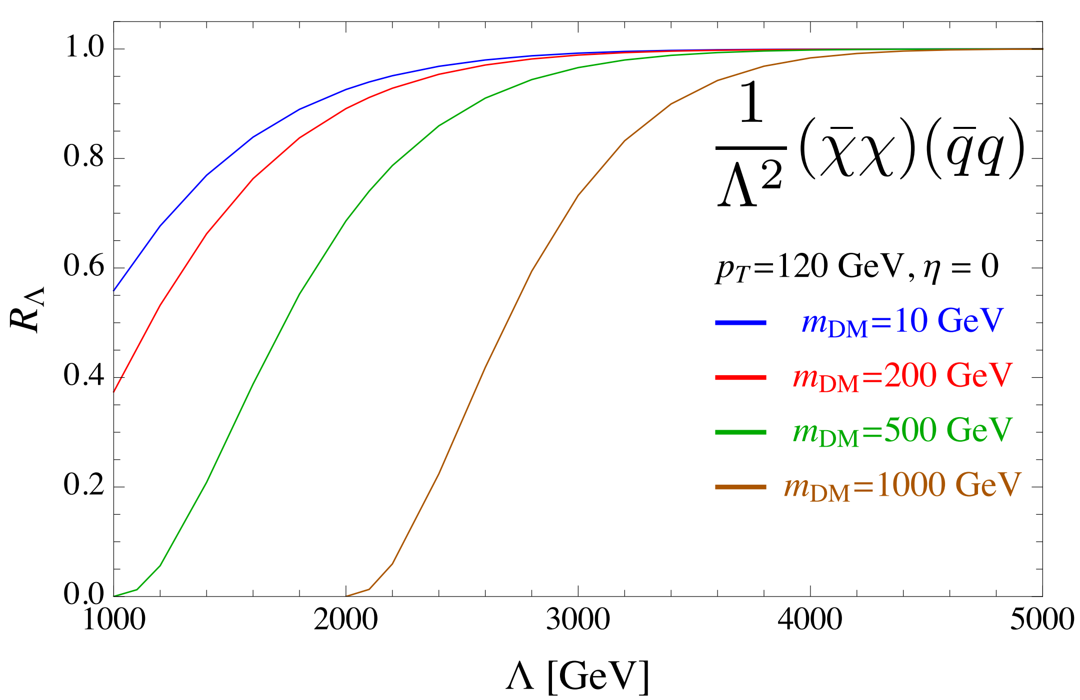
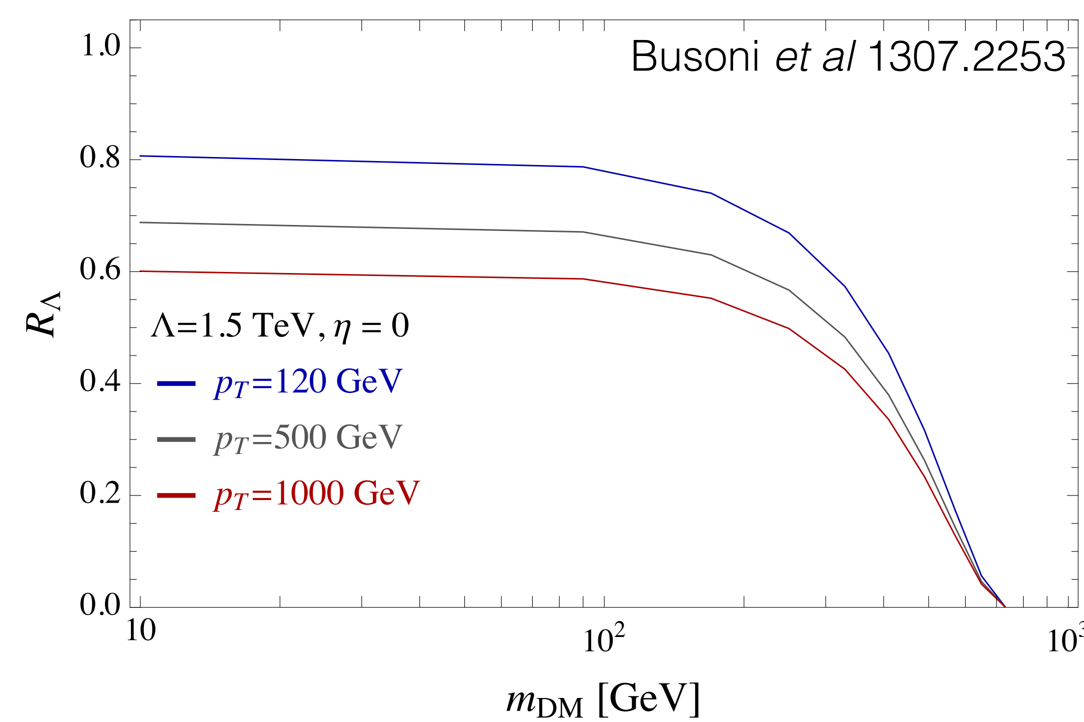
Limitations of EFTs

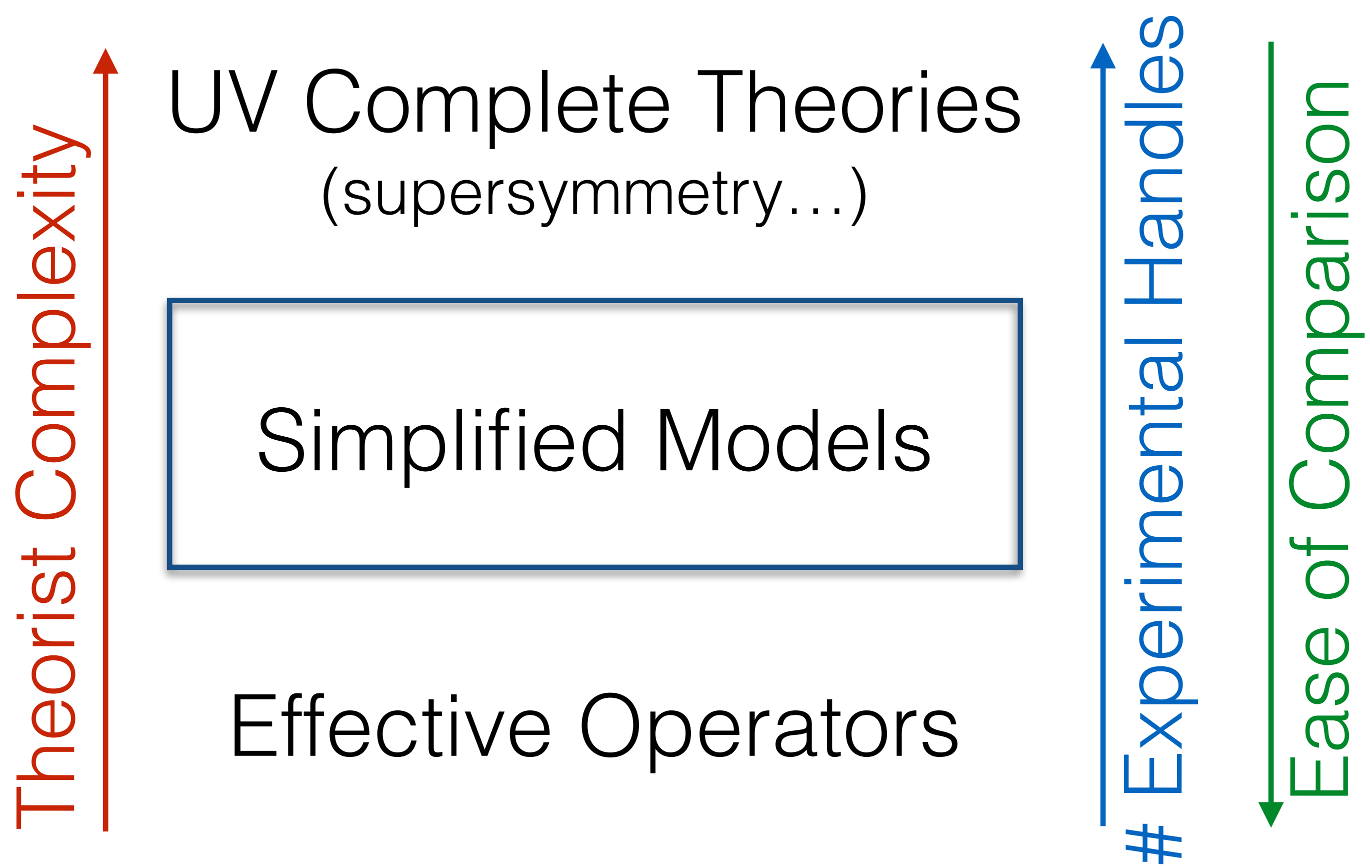
- How much of the LHC cross section comes from region where effective operator is good?

$$R_\Lambda \equiv \left(\left.\frac{d^2\sigma}{dp_T d\eta}\right|_{Q_{\rm tr}<\Lambda} \right) \Big/ \left(\frac{d^2\sigma}{dp_T d\eta} \right)$$





Step 2



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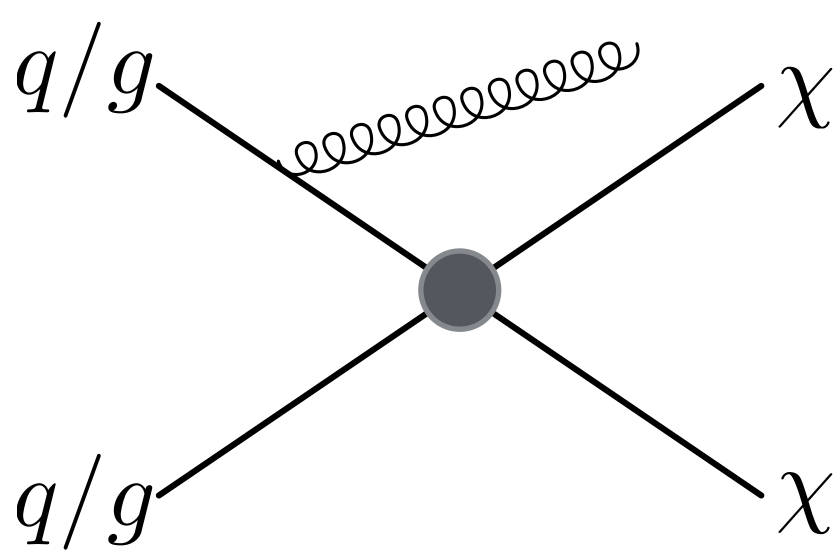
Simplified Models

- So effective operators are not generically applicable at the LHC energies.
  - Most things we can find require $M^2/g_\chi g_v$ small enough that we can produce the mediator on-shell.
- But still don't want to run all the way back to SUSY.
  - Keep it Simple:



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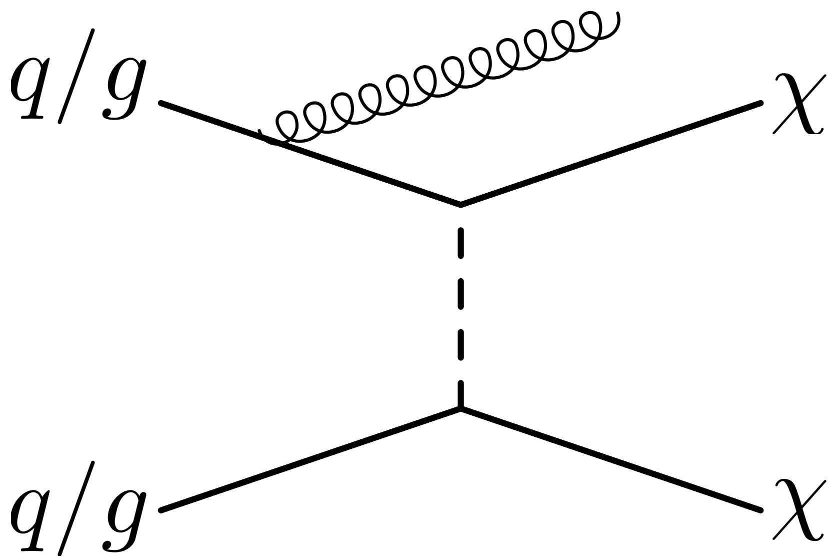
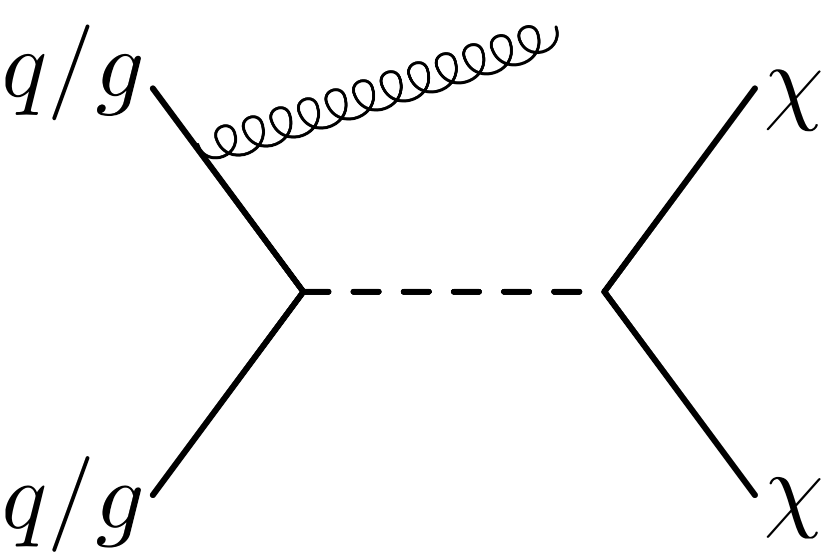
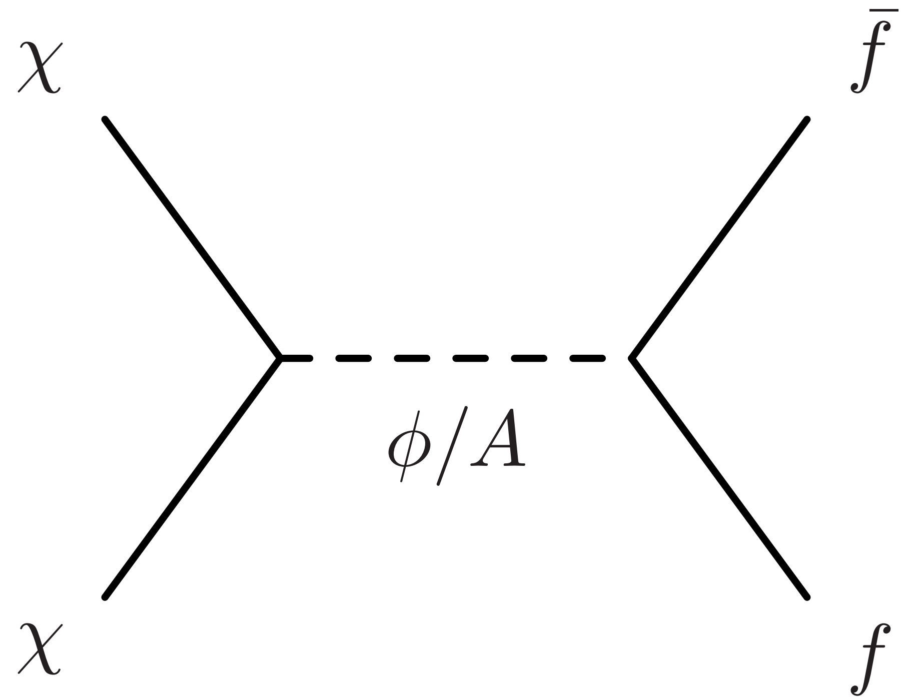




s-Channel Mediators



- Dark matter communicating to Standard Model through scalars or pseudoscalars an attractive theoretical option.
- "Easy" to accommodate in extended Higgs sectors (2HDM, NMSSM, *etc*)
- Might generically expect some mixing between new scalars and the Higgs sector
  - Can expect SM fermion couplings to be $\propto y_f$
  - MFV assumption also avoids flavor constraints

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Spin-0 Simplified Models

- Two benchmark models:
  - Scalar ϕ *or* Pseudoscalar A mediator with mass m_ϕ / m_A
  - Dirac fermionic dark matter χ with mass m_χ
  - Assuming MFV couplings to SM fermions:

$$\mathcal{L}_{\text{scalar}} \supseteq -\frac{1}{2} m_\phi^2 \phi^2 - m_\chi \bar{\chi}\chi - g_\chi \phi \bar{\chi}\chi - \frac{1}{\sqrt{2}} \sum_f g_v^f y_f \phi \bar{f} f$$

$$\mathcal{L}_{\text{pseudo}} \supseteq -\frac{1}{2} m_A^2 A^2 - m_\chi \bar{\chi}\chi - i g_\chi A \bar{\chi}\gamma^5 \chi - \frac{1}{\sqrt{2}} \sum_f i g_v^f y_f A \bar{f} \gamma^5 f$$

  - Can explore phenomenology of different g_v in up/down/lepton sectors.

Spin-0 Simplified Models

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- Minimal model 4-dimensional:

$$m_{\phi/A}, m_\chi, g_\chi, g_v$$

- Mediator width will affect collider bounds.
- Will suggest how to treat $\Gamma_{\phi/A}$ shortly.

Thermal Relic

- If the dark matter freeze-out is described by thermal freeze-out, then can require mass/coupling parameters give appropriate relic abundance.
  - If we violate the standard assumptions, allowed couplings can be larger/smaller than this prediction.
  - Here assuming only

$$\chi\bar{\chi} \to \phi \to f\bar{f}$$

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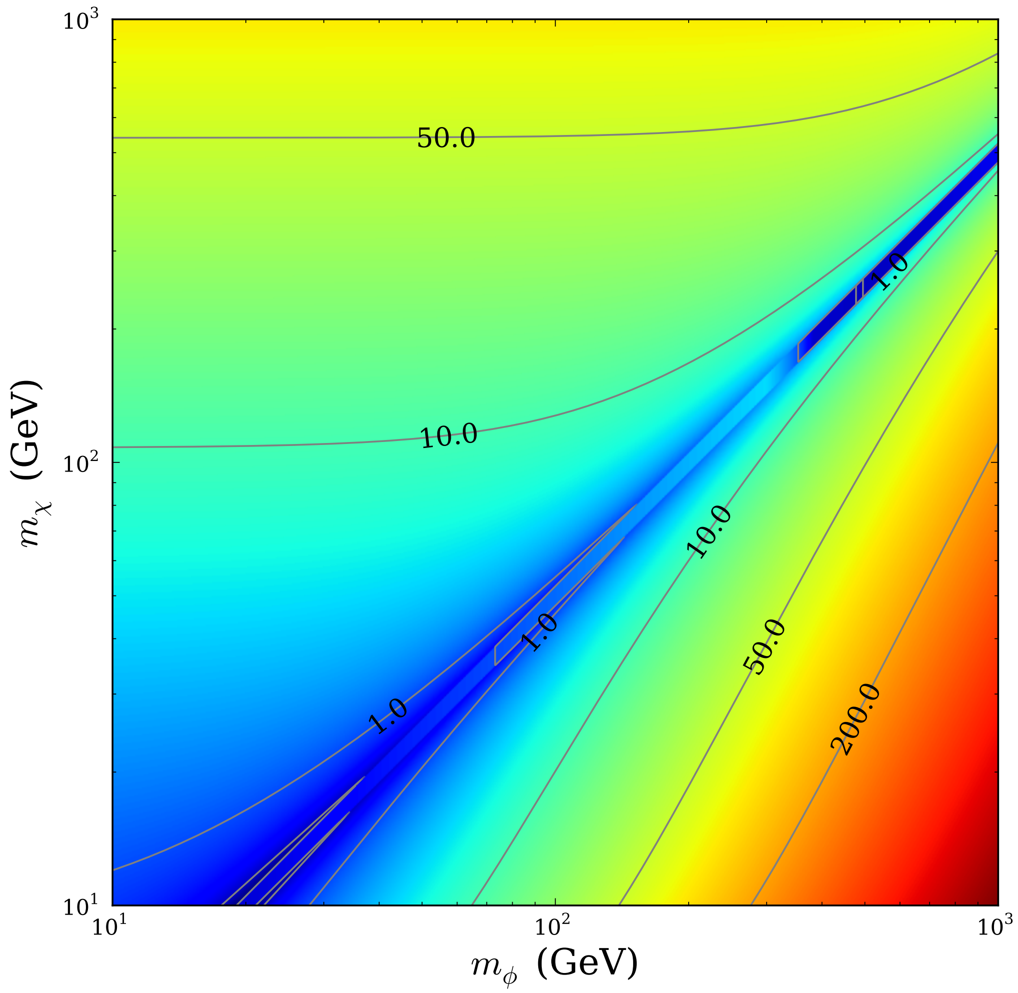
upper limits on $\sqrt{g_v g_\chi}$



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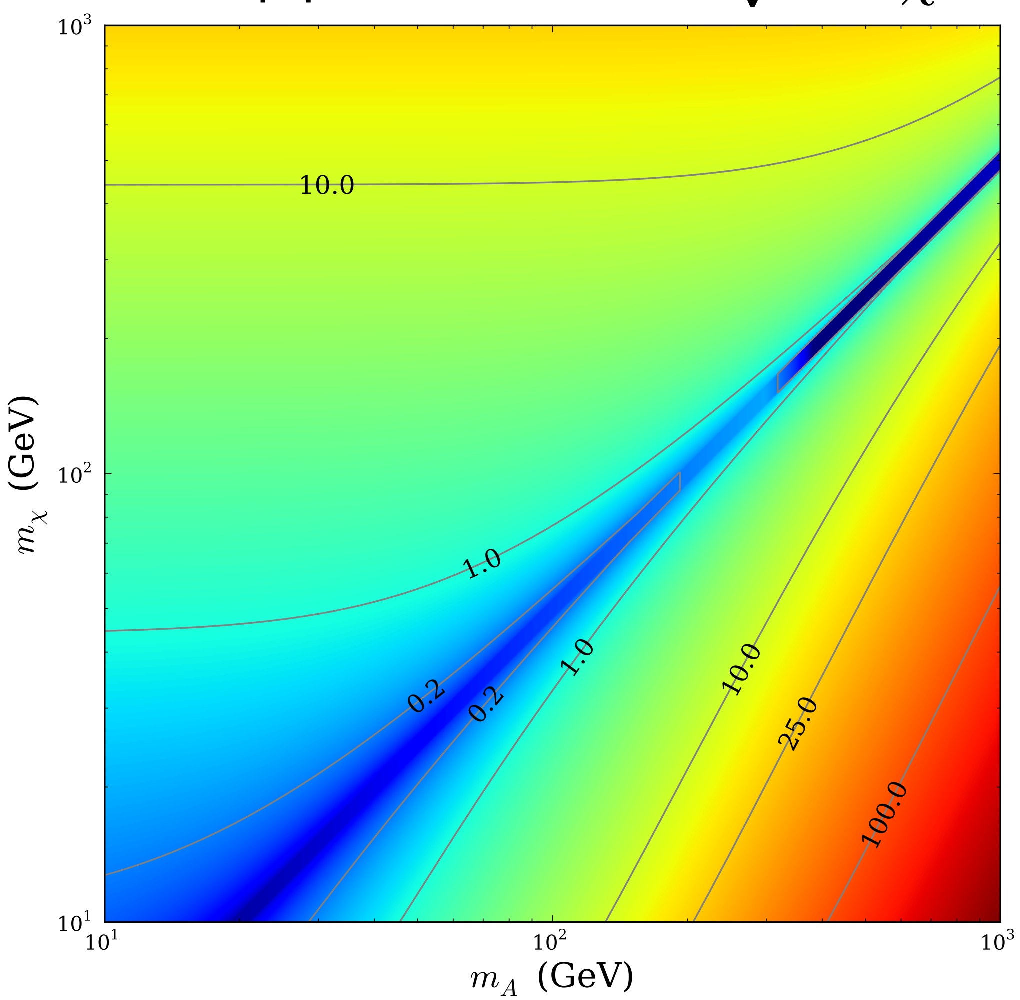

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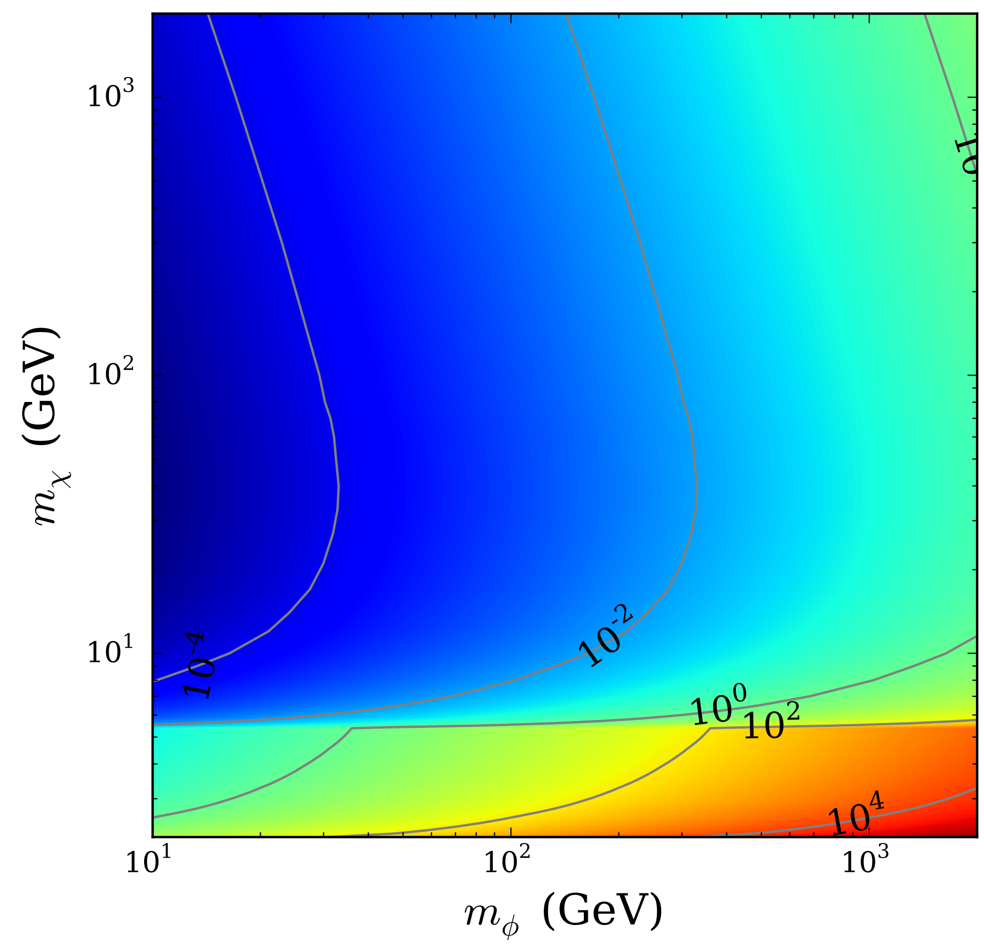
Direct Detection Bounds

- Scalar mediator benchmark will result in spin-independent direct detection signal.
  - Constraints from LUX & CDMS
  - Relatively independent of Γ_ϕ

upper limits on $\sqrt{g_v g_\chi}$



- Keep in mind the hidden dependence on local velocity & density distributions.

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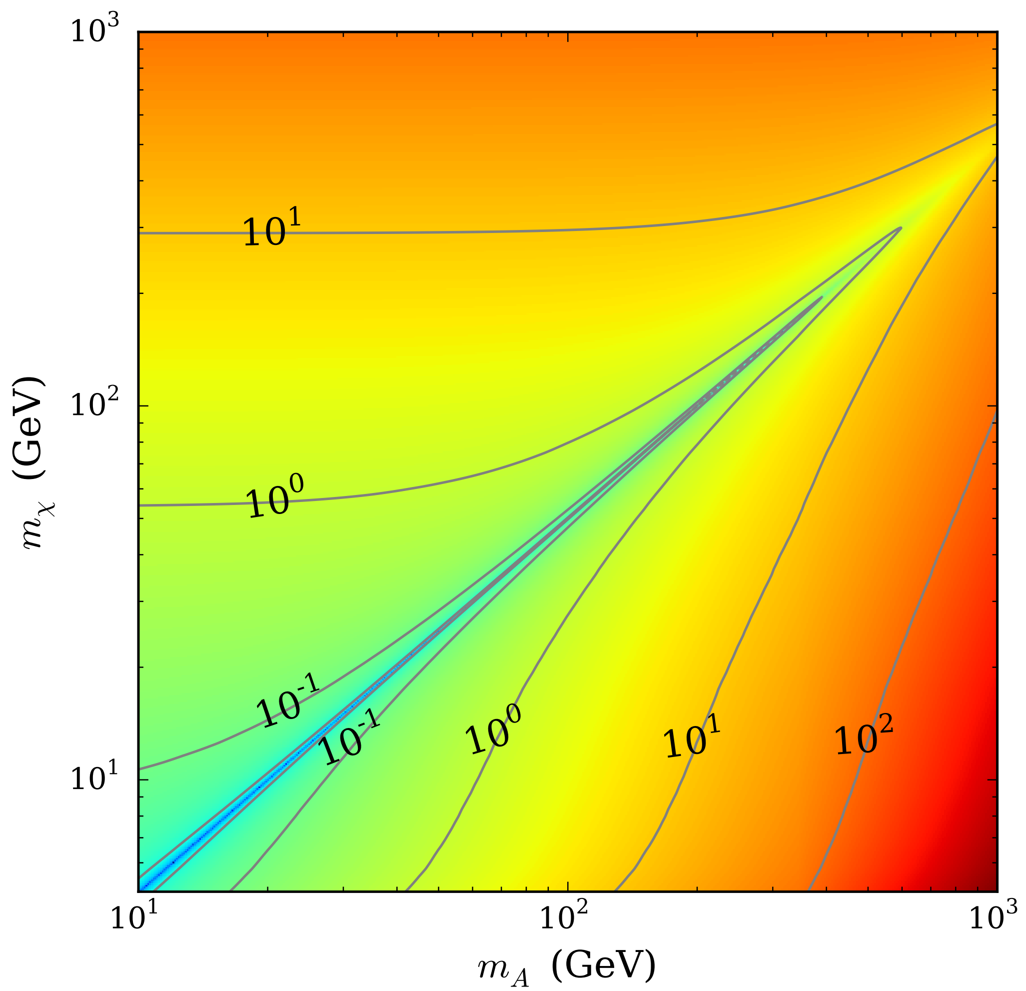
Indirect Detection Bounds

- Pseudoscalar model has thermal annihilation cross section $\propto v^0$, so bounds from present-day annihilation
- Assuming MFV, can apply dwarf galaxy constraints from annihilation into $\bar{b}b$
  - Can depend on Γ_A
  - Show here bounds assuming no additional decay channels and $g_v = g_\chi$

upper limits on $\sqrt{g_v g_\chi}$



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Collider Searches

- Looking for dark matter production.

$$pp \to \text{something} + \underset{(\chi\chi)}{\text{nothing}}$$

- Possible channels: Something = jets, tops, bottoms…
  - Minimal simplified model correlates signal rates between these channels, but must keep an open mind.
  - Example: MSSM-type 2HDM may have increased couplings to down-type quarks, boosting *b*-tagged channels.

Monojet Production

- MFV assumption means ϕ couples proportional to mass.
  - But protons don't contain many $t/\bar{t}/b/\bar{b}$
  - Seen in very weak bounds on scalar EFT operators

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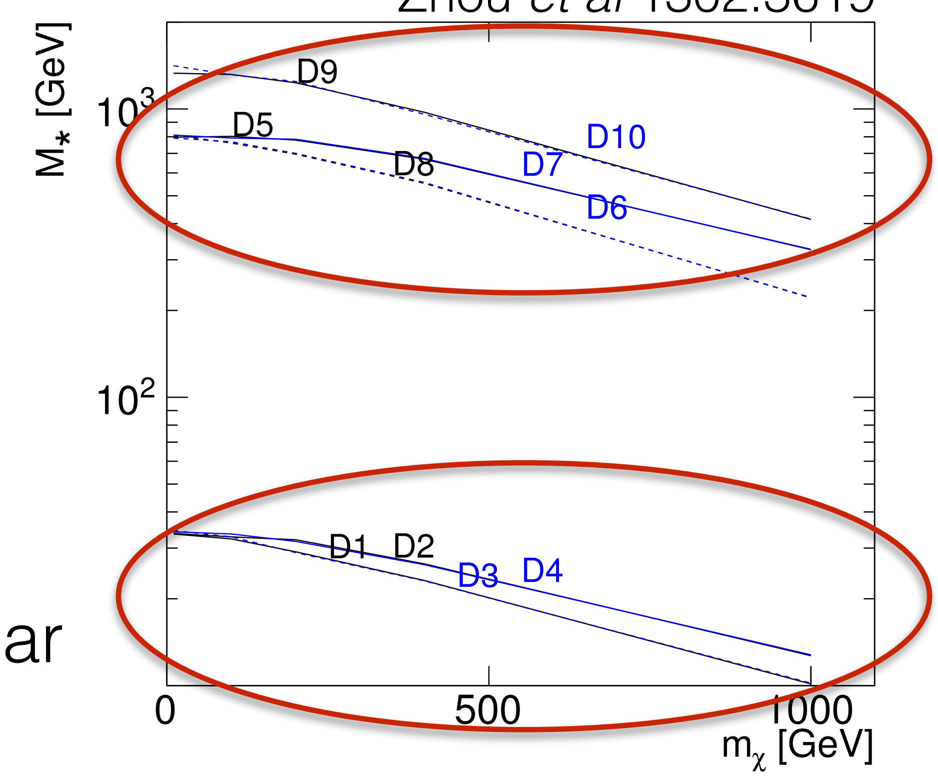
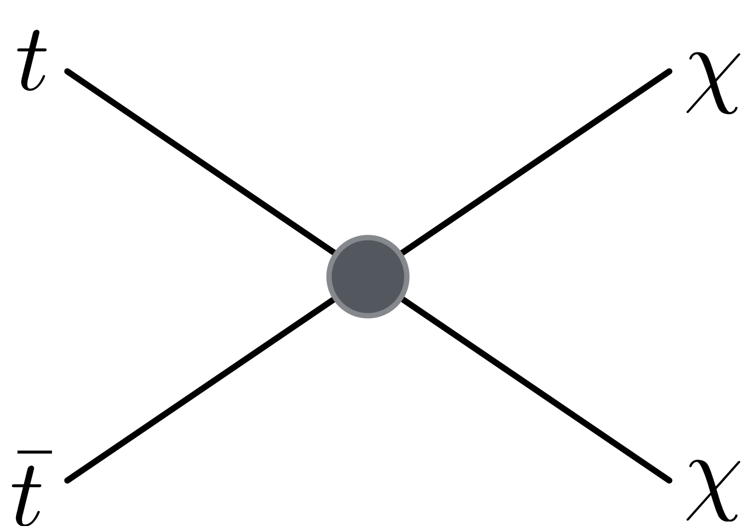


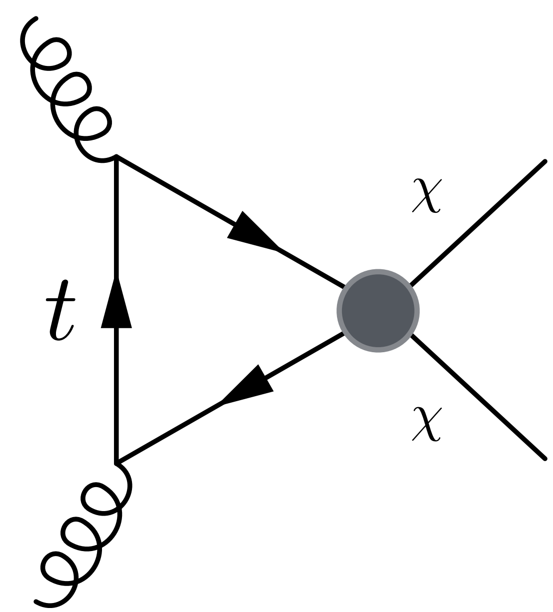
vector/axial-vector mediators

scalar/pseudoscalar mediators

Monojet Production

- In 1-1 analogy to Higgs production, couplings to top (and bottom) quarks lead to loop-level interaction with gluons.
  - Has been considered in EFT interactions.
  - This will be the main production mode for monojets





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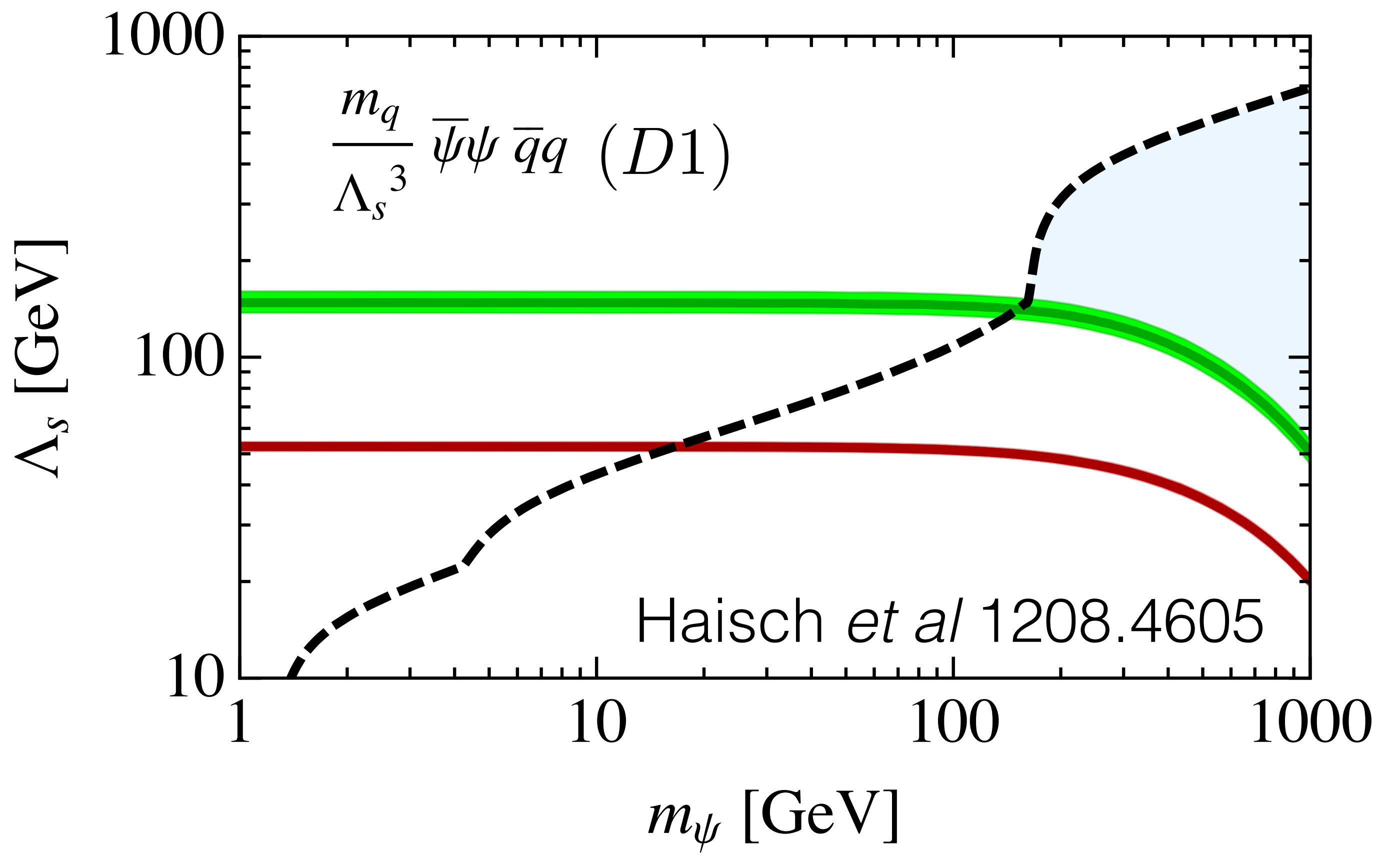
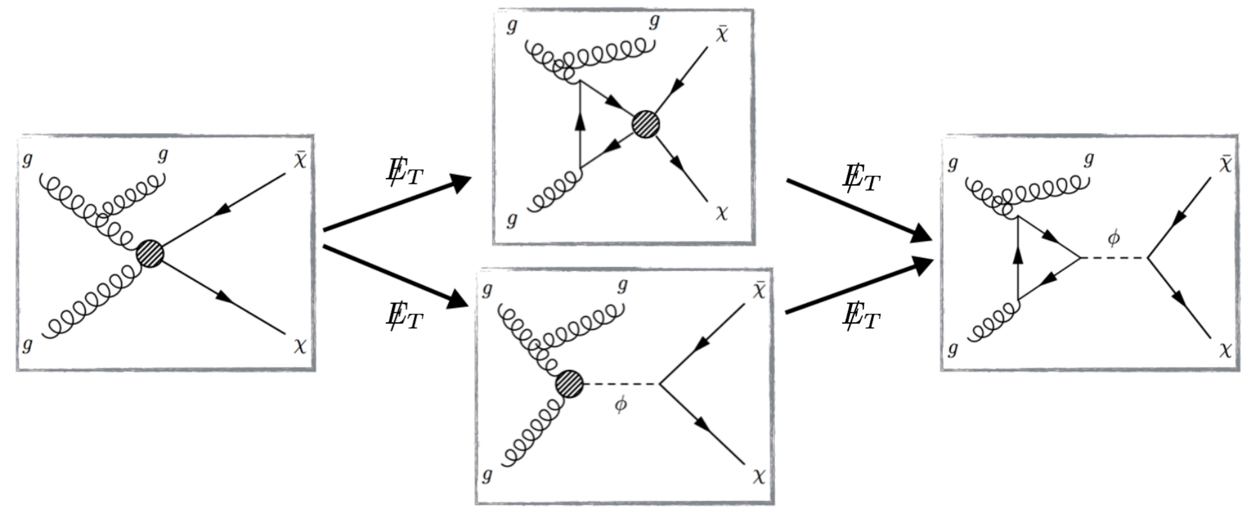
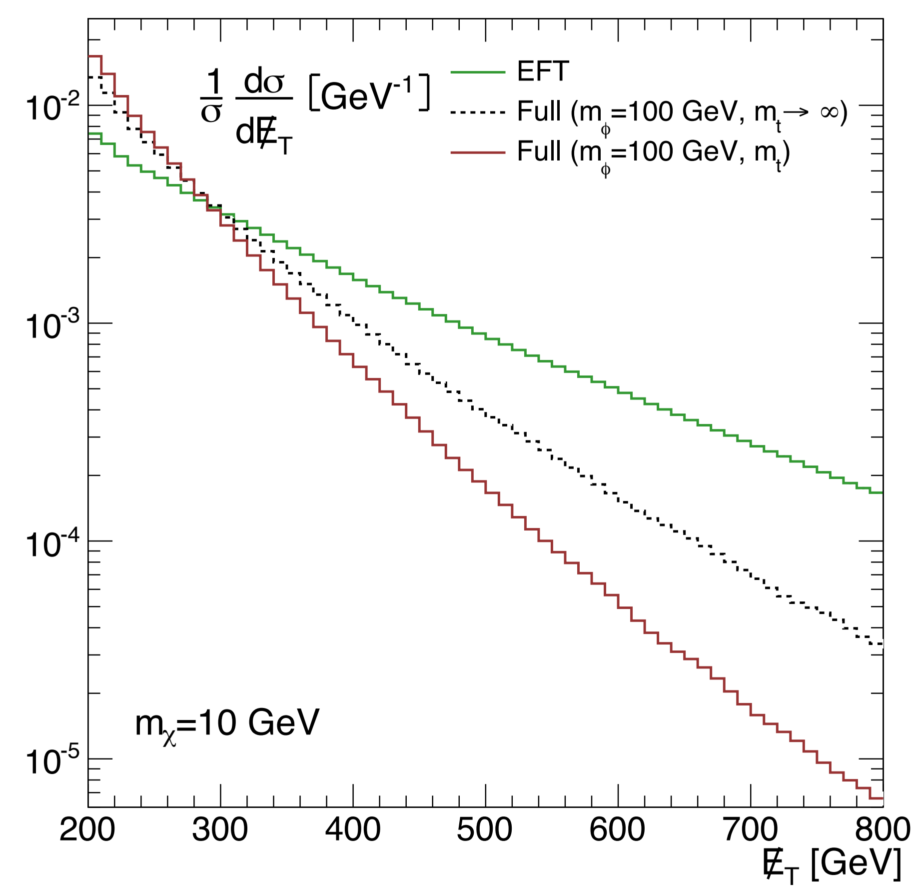


Tricky Tops

- Using a tool like MadGraph to generate ϕ through integrated-out top loop (another EFT) is problematic.
  - For monojet searches, jet p_T and ϕ p_T (MET) are all large compared to $2m_t$. m_ϕ can be large as well.
  - Cannot treat the coupling to gluons as an EFT.
  - Not just a *K*-factor, changes differential distributions
- We use MCFM to resolve loop.





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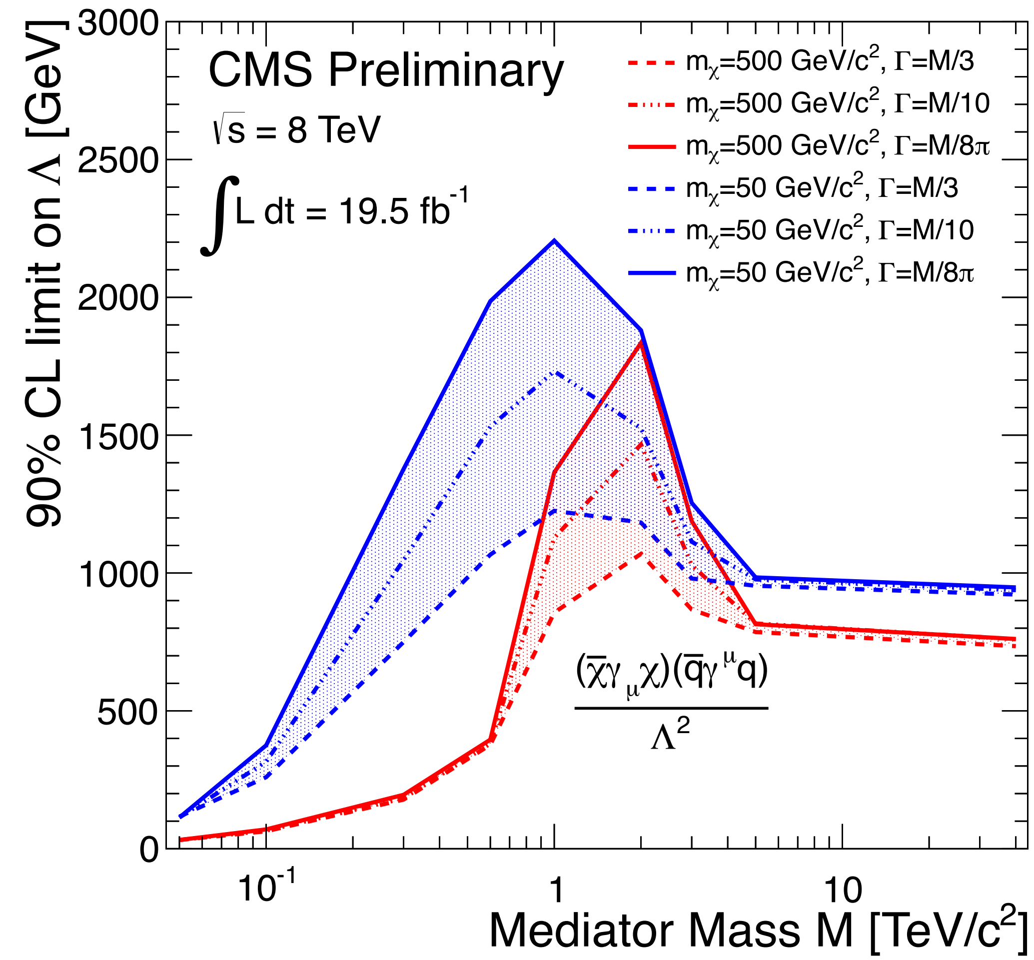
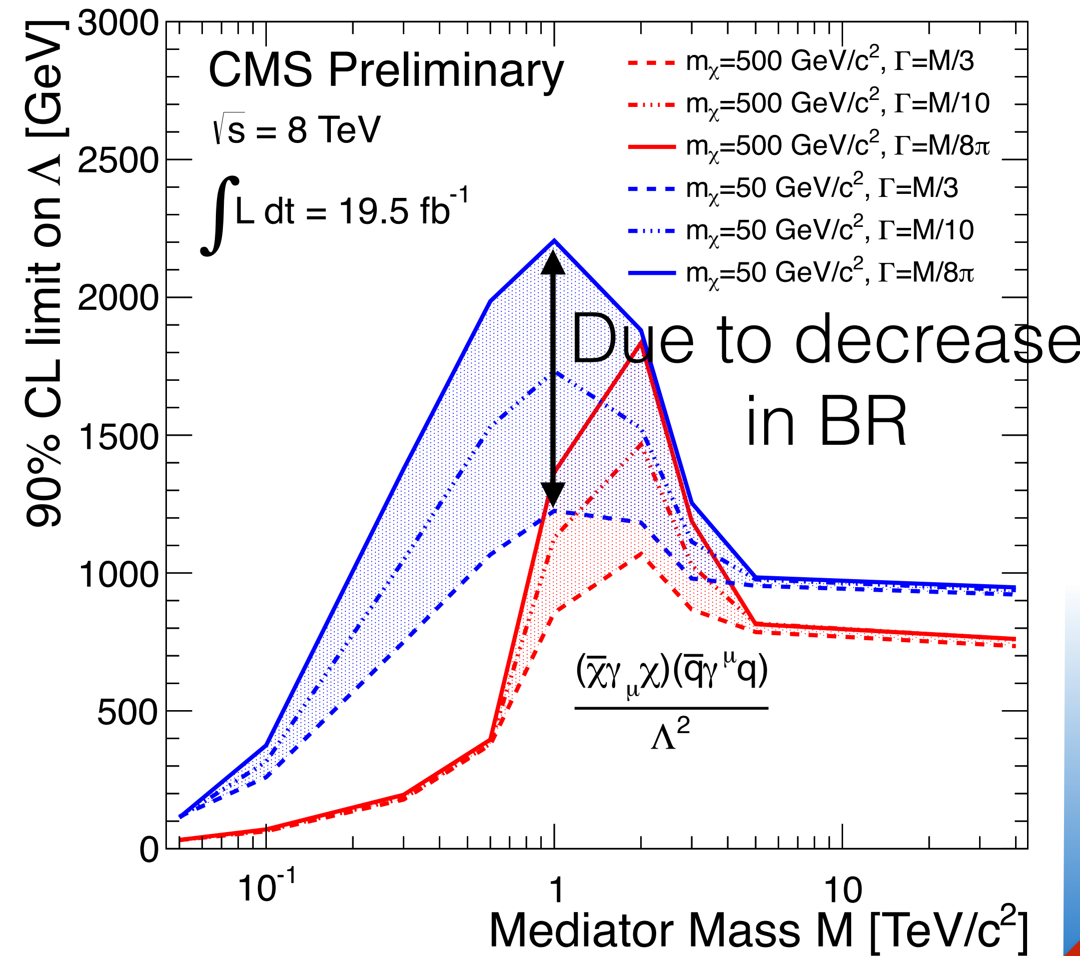
Width Effects

- We keep total width a free parameter, look to place bounds on couplings g_v, g_χ for our benchmark masses
- All else being equal, on-shell bounds $\propto g_v^2 g_\chi^2/\Gamma$
- Primary effect is decrease in signal rate $\propto \mathrm{BR}(\phi \to \chi\chi)$
- 2nd Order effect:
  - For large widths, experimental acceptance will change.
  - MCFM is narrow-width only, extrapolate using MadGraph results when $\Gamma_\phi/m_\phi \gtrsim 1$



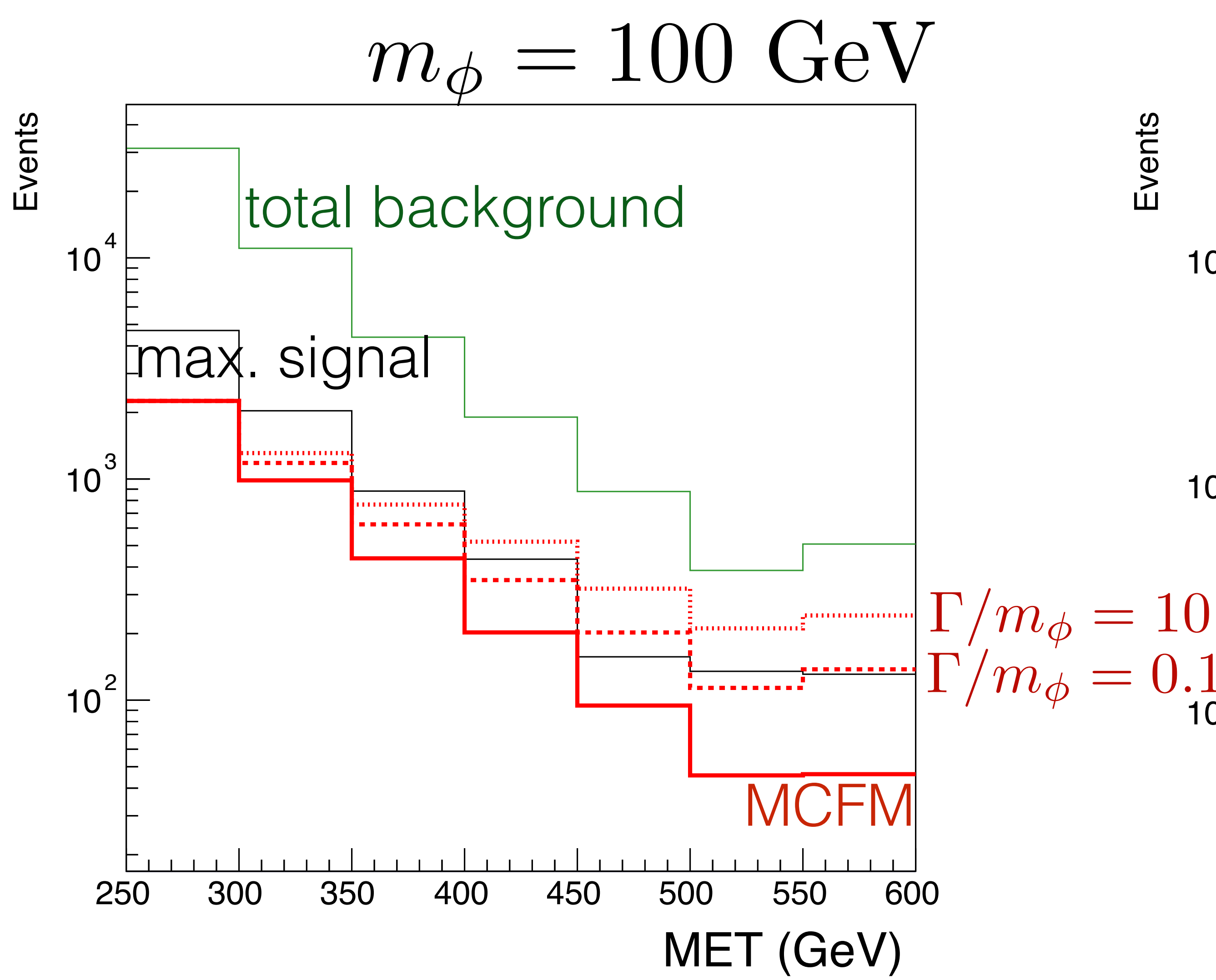
Width Effects

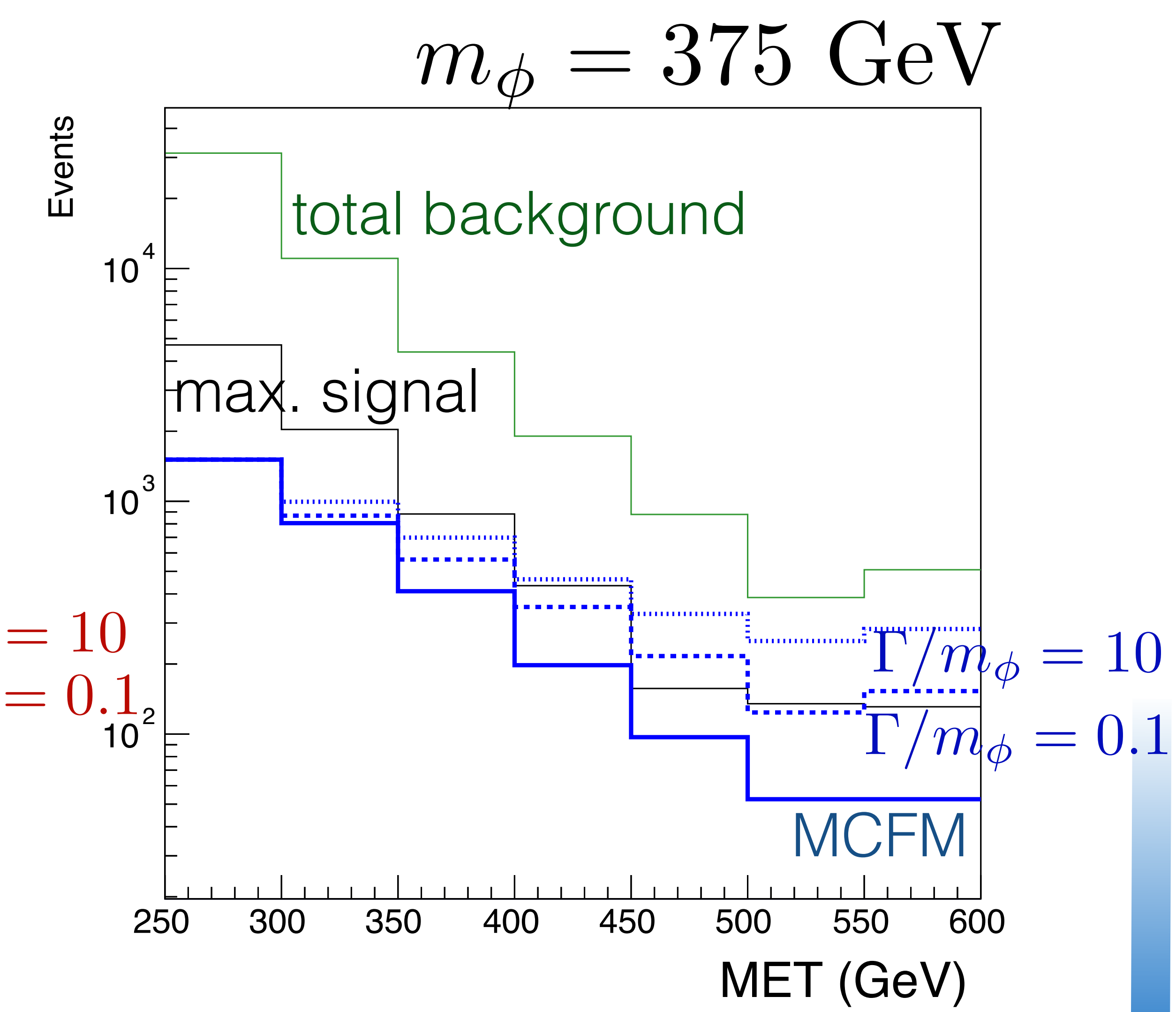
- We keep total width a free parameter, look to place bounds on couplings g_v, g_χ for our benchmark masses
- All else being equal, on-shell bounds $\propto g_v^2 g_\chi^2/\Gamma$
- Primary effect is decrease in signal rate $\propto \mathrm{BR}(\phi \to \chi\chi)$
- 2nd Order effect:
  - For large widths, experimental acceptance will change.
  - MCFM is narrow-width only, extrapolate using MadGraph results when $\Gamma_\phi/m_\phi \gtrsim 1$



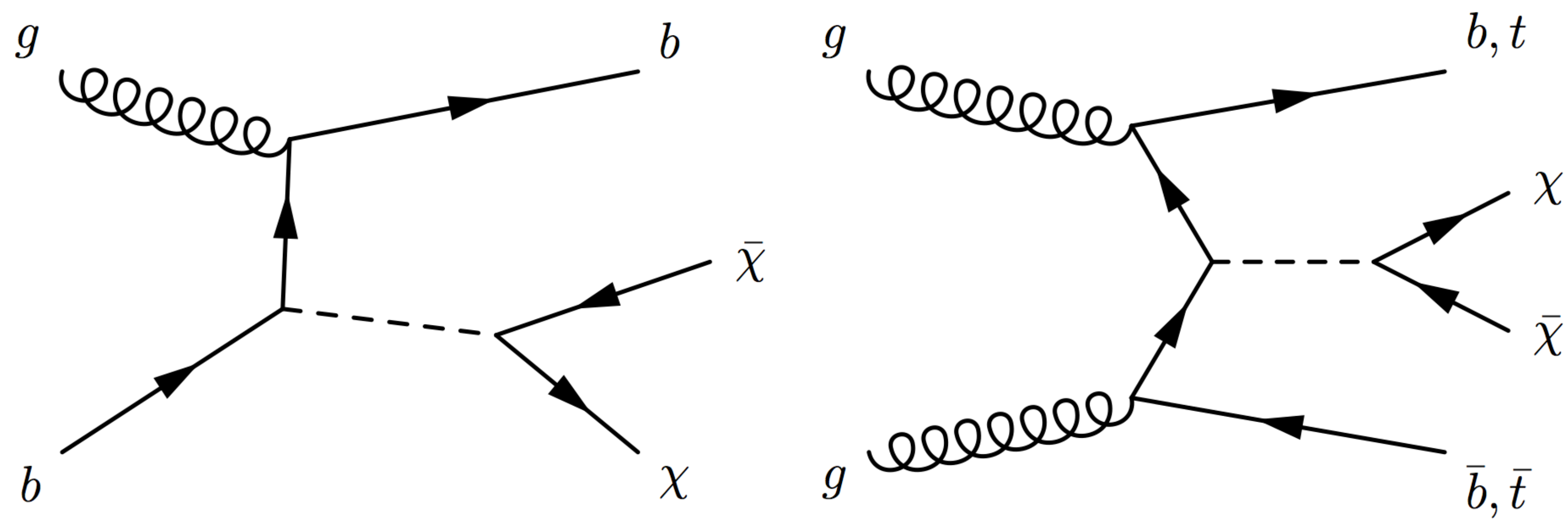
Width Effects

- Kinematic effect at *very* large widths.
  - Effect on CMS Monojet searches:



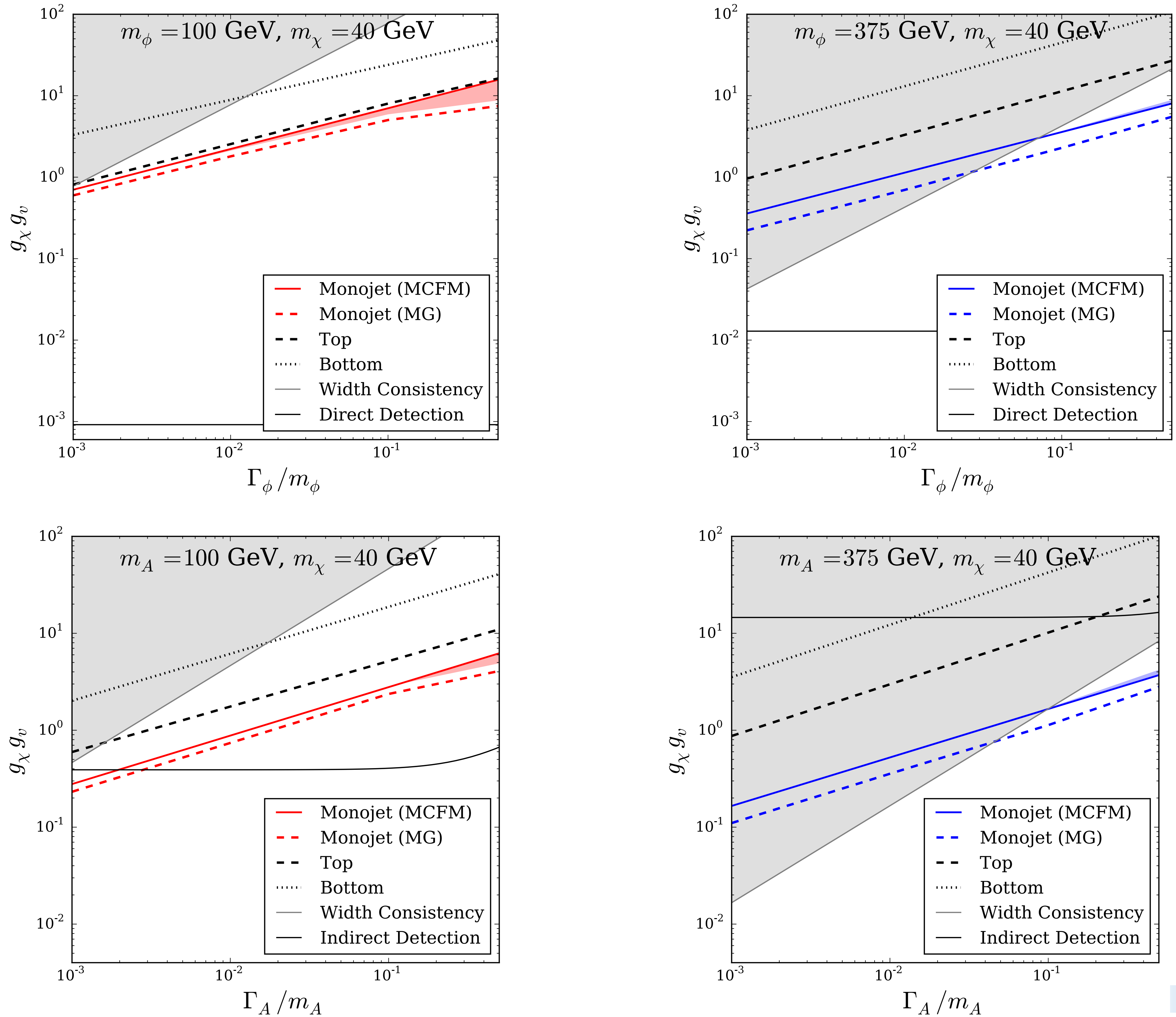


Heavy Quarks



- MadGraph-level simulation acceptable here
- CMS B2G-13-004 for in $t\bar{t}$ dilepton channel
- Use ATLAS 1410.4031 for $b/b\bar{b}$ channel
  - We assume coupling *only* to b here. Stronger bounds if coupling to both b and t

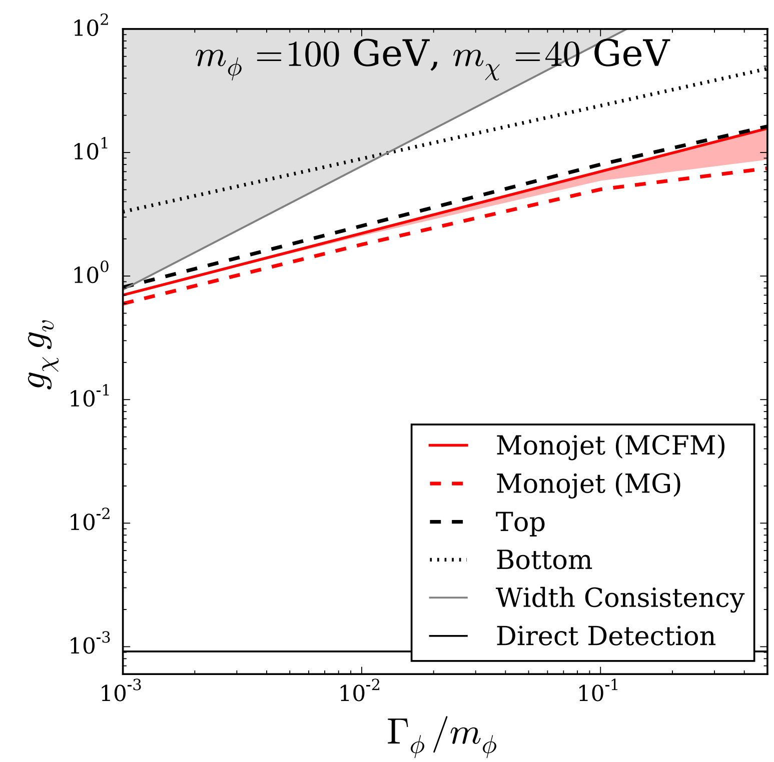
Collider Bounds



Buckley, Feld, Gonçalves 1410.6497

Discussion of Widths

- Experiments will want to scan over m_ϕ, m_χ, if nothing seen place limits on g_χ, g_v
  - To keep dimensionality down, usually assume $g_\chi = g_v$
  - But this makes particular assumption of the width, important for on-shell production.
- Our advice to experimentalists: set Γ as if $g_\chi = g_v$, and no additional decays
- CMS/Atlas including kinematic effects
- “Easy” for theorists to rescale.



Step 3

UV Complete Theories
(supersymmetry…)

Simplified Models

Effective Operators

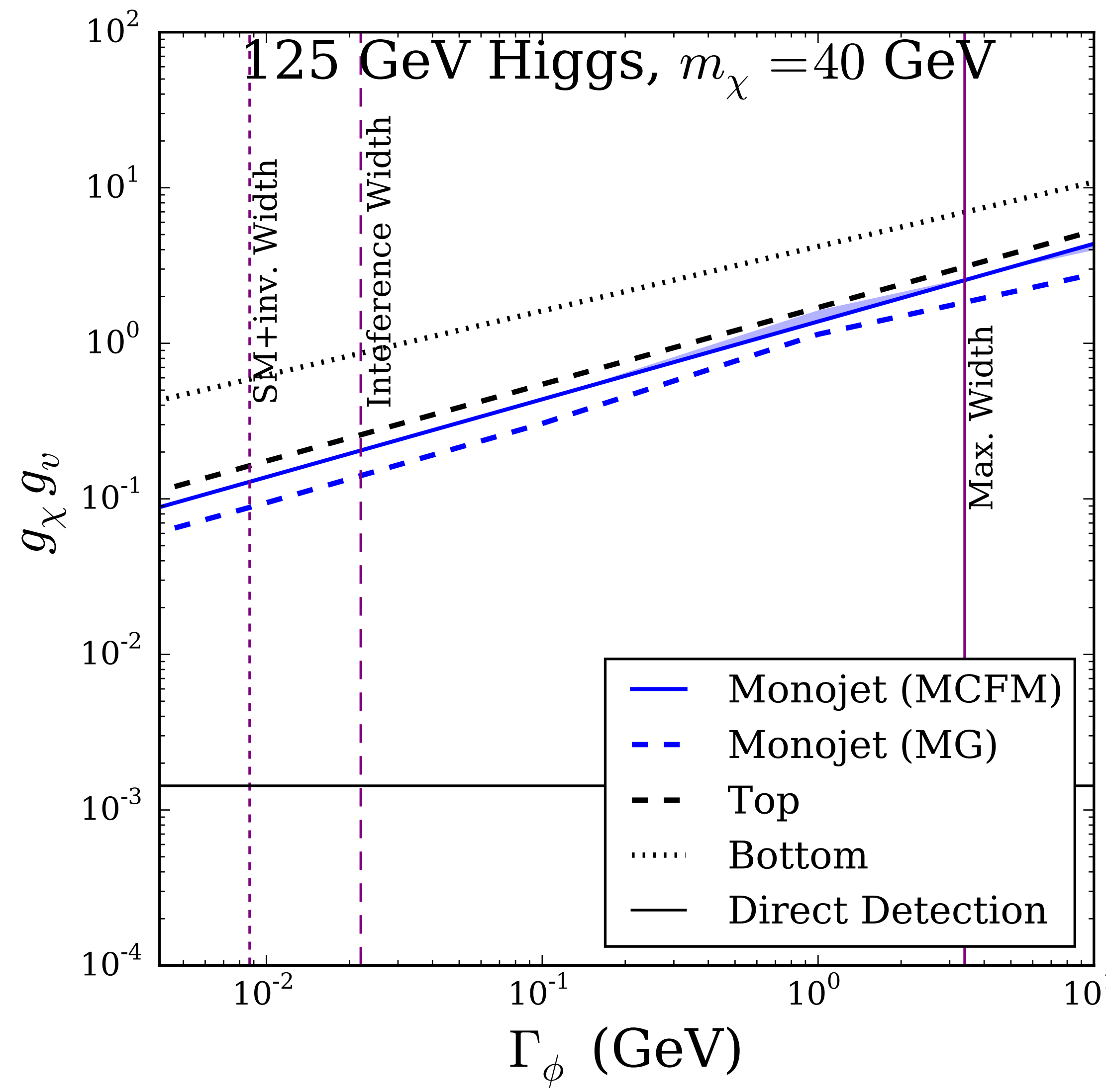
Theorist Complexity

Experimental Handles

Ease of Comparison

Higgs Portal

- Scalar mediator could be the 125 GeV Higgs
- Can search for $pp \to (h \to \chi\chi) + \text{jets}$
- If $m_\chi < m_h/2$, very powerful limits from invisible Higgs
- Direct limits from on/off-shell measurements of $h \to ZZ$
    - Some model assumptions
- Direct measurements needed
    - Note heavy-flavor channels powerful here.



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Extended Higgs Sectors

- 2HDM contain 1 extra scalar, 1 pseudoscalar.
- We know that SM Higgs lives in the alignment limit.
  - Associated CP-even Higgses may have suppressed production via W/Z
  - Production then through fermion couplings *a la* simplified models.
- Dark Matter is a problem that needs a solution, so reasonable to look for $H/A \to \chi\chi$
  - Often significantly lower background.
  - We still know very little about Higgs sector.

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Conclusions

- Effective operators have limited applicability at colliders.
  - *Fantastic News:* If we are producing dark matter we are producing the mediators
- Simplified Models a good intermediate step to avoid overcommitment to a particular UV theory.
- Searches in monojets, heavy flavor
- CMS/ATLAS/theory working groups converging on common language
- Correct simulation of monojets still a difficulty: May have missed the window for Monte Carlo generation.