Title: Scalar Simplified Models and Dark Matter at Colliders

Date: Sep 16, 2014 01:00 PM

URL: http://pirsa.org/14090080

Abstract: Dark matter is clear evidence of the existence of new physics beyond the Standard Model, and there are compelling reasons to expect that this physics can be probed at the LHC. As we prepare for Run II, we must consider a wide range of possible phenomenology, leaving no stone unturned. In this talk, I present a set of scalar and pseudoscalar models which provide a useful framework to interpret dark matter results, and can motivate new searches in novel channels at the LHC.

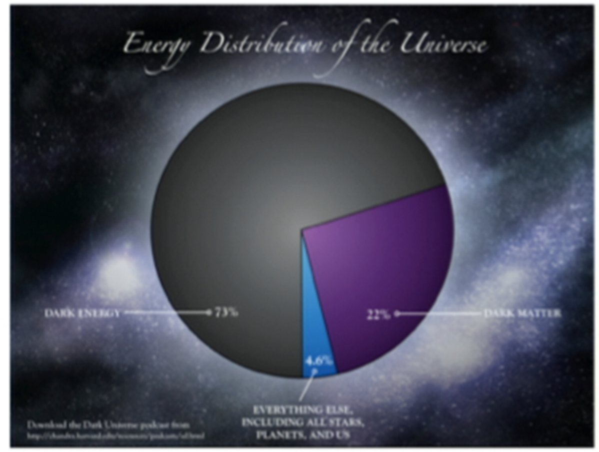
Scalar Simplified Models and Dark Matter at Colliders

Matthew R Buckley
Rutgers University

1
37

Evidence of New Physics

- Dark matter cannot be any Standard Model particle.
  - New Physics!
- What kind of new physics?
  - Neutralinos?
  - Gravitinos?
  - Axions?
  - WIMPs?
  - "Dark atoms?"
  - Something else?



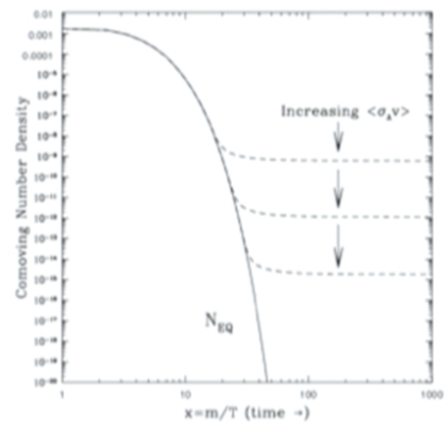
If evidence is purely gravitational, why should we expect to have signals of dark matter at colliders or direct/indirect detectors?

Why Look with Colliders?

- Familiar story: the thermal WIMP
  - Anything in thermal equilibrium in the early Universe will have a large number density, assuming $T \gg m$
  - Relic number density set by abundance at freeze-out, when

    $$H(T) \sim n(T)\langle \sigma v \rangle$$

  - True of all SM particles, as well as a dark matter candidate.
  - So a WIMP must have some annihilation cross section

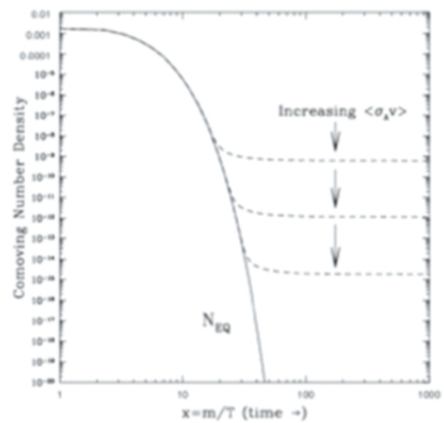


Jungman *et al* hep-ph/9506380

3
37

Why Look with Colliders?

- Is it reasonable to assume non-thermal dark matter will have non-gravitational interactions with SM?
- *Any* particle in thermal equilibrium will have thermal relic abundance.
    - If dark matter is non-thermal, the thermal component must have annihilated away.
        - (or was never in equilibrium)
        - Could annihilate into non-SM particles, but now have to explain why these are not also a thermal dark matter candidate.

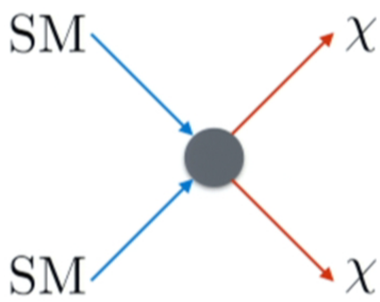


Jungman *et al* hep-ph/9506380

4
37

Why Look with Colliders?

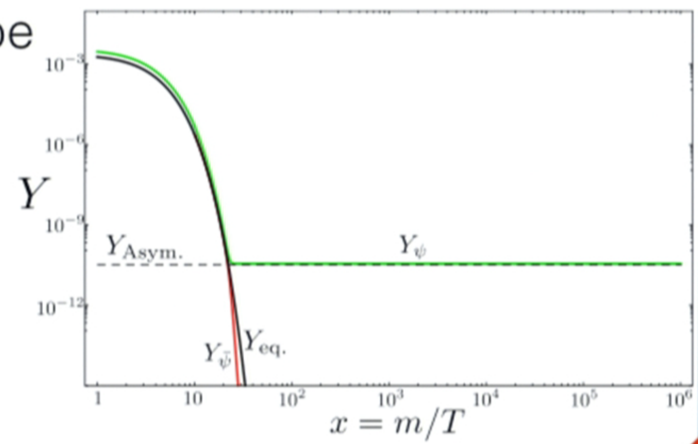
- Is it reasonable to assume non-thermal dark matter will have non-gravitational interactions with SM?
- *Any* particle in thermal equilibrium will have thermal relic abundance.
  - If dark matter is non-thermal, the thermal component must have annihilated away.
    - (or was never in equilibrium)
    - Could annihilate into non-SM particles, but now have to explain why these are not also a thermal dark matter candidate.



Asymmetric Example

- The baryons are non-thermal.
- We don't care about the $p - \bar{p}$ thermal relic for $\Omega_{\rm B}$ because it's only 1 part in 10^{10}
  - This is because the residual strong force is strong.
- Notice: $\Omega_{\rm DM} \sim 5\Omega_{\rm B}$. Maybe the other matter in the Universe is as non-thermal as we are?
  - Still need to get rid of the thermal component.

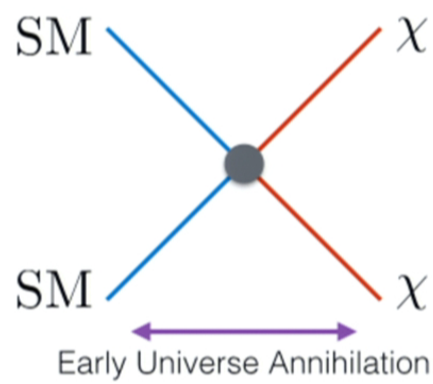
$$\langle \sigma v \rangle_{\rm ADM} \gtrsim \langle \sigma v \rangle_{\rm WIMP}$$



5
37

Multiple Directions for Dark Matter

- In general, we expect dark matter to have some interaction with SM.

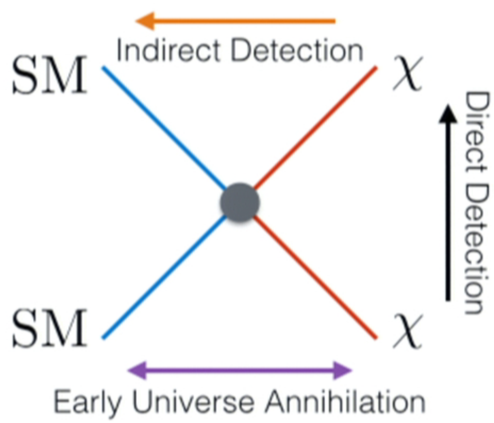


- Ways out of this are possible, and can give interesting new DM candidates (*e.g.* axions)
- However, this is a reasonable *ansatz*

6
37

Multiple Directions for Dark Matter

- In general, we expect dark matter to have some interaction with SM.

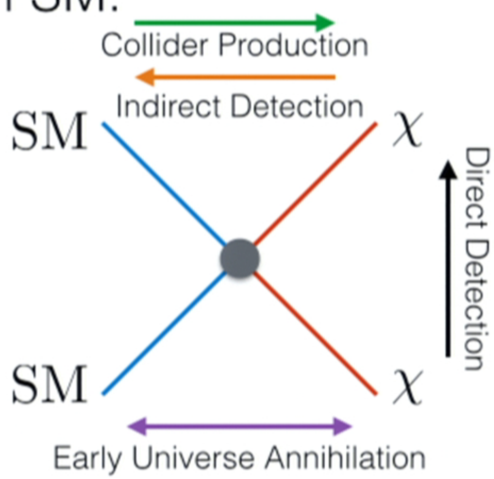


- Ways out of this are possible, and can give interesting new DM candidates (*e.g.* axions)
- However, this is a reasonable *ansatz*

6
37

Multiple Directions for Dark Matter

- In general, we expect dark matter to have some interaction with SM.



- Ways out of this are possible, and can give interesting new DM candidates (*e.g.* axions)
- However, this is a reasonable *ansatz*

6
37

Comparison Caveats

- For a given model, we can make "exact" predictions for discovery/exclusion from multiple experimental angles.
  - But must keep in mind our assumptions.
- In direct detection, for example:

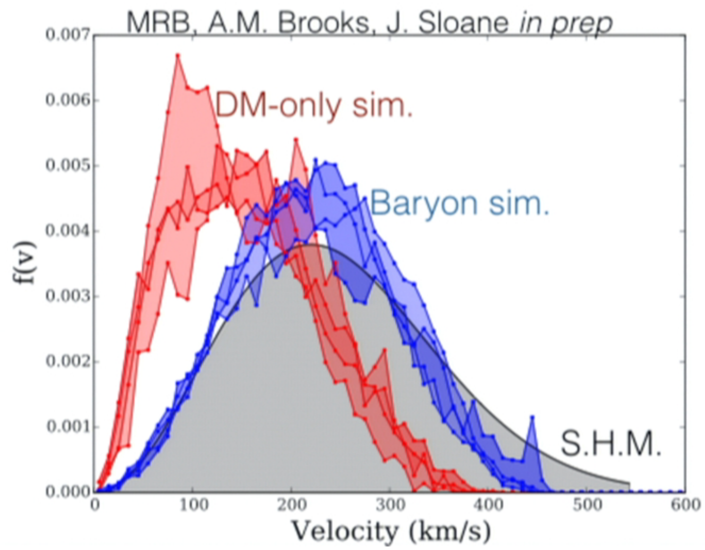
$$\frac{dR}{dE_R} = \frac{\rho_\chi}{m_\chi} \int_{v_{\min}} d^3\vec{v}\; v f(\vec{v}) \frac{d\sigma}{dE_R}$$

particle physics

astrophysics

Comparison Caveats

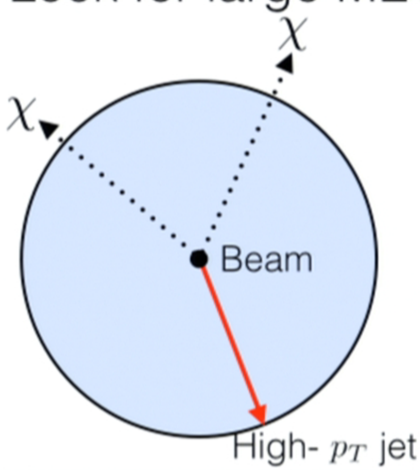
- For a given model, we can make "exact" predictions for discovery/exclusion from multiple experimental angles.
  - But must keep in mind our assumptions.
- In direct detection, for example:

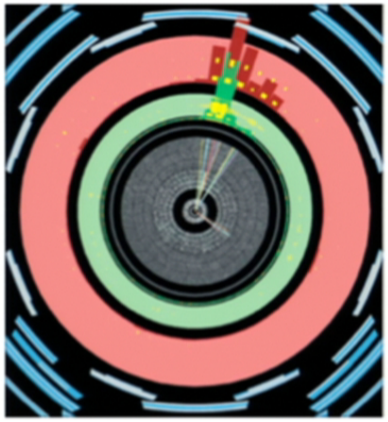


7
37

Looking with Colliders

- In a "full" theory (*e.g.* SUSY), can look for new non-DM particles, perhaps decaying down to dark matter.
- If you don't know the full theory, you look for *nothing*
- Mono-jets one of the more sensitive at LHC
  - Look for large MET and recoiling high- p_T jet

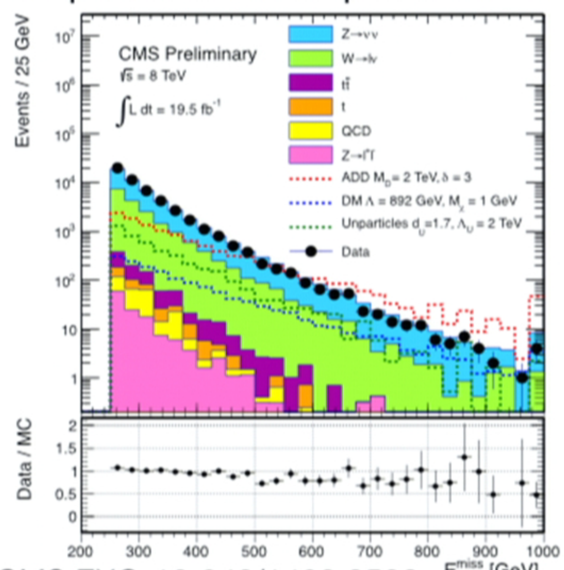




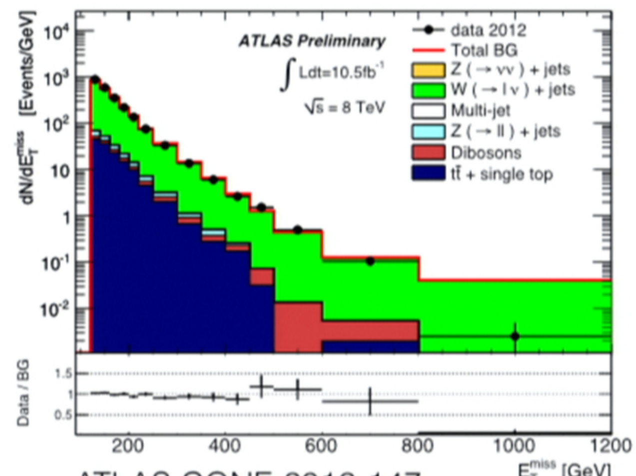
8
37

Mono-jet Searches

- Signal is buried in large background:
  - SM $(Z \to \nu\nu) + \text{jets}, W + \text{jets}$, *etc.*
  - Impressive experimental accomplishment



CMS EXO-12-048/1408.3583



ATLAS CONF-2012-147

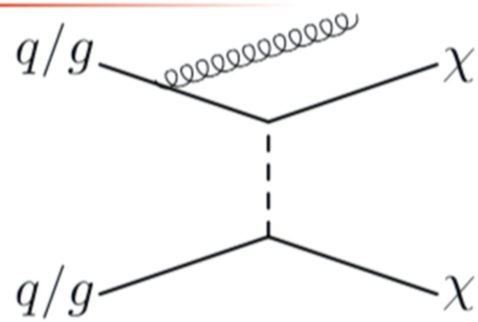
9
37

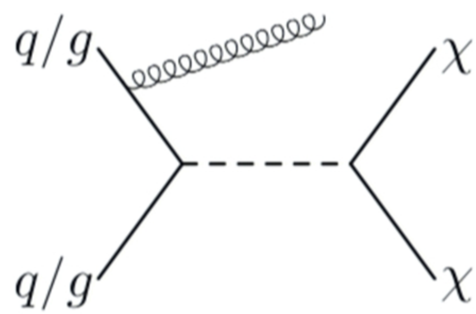
An Effective Framework

- Non-observation of high-MET excess puts limit on

$$pp \to \chi\chi + \text{jet}$$

- How to interpret this?





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

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

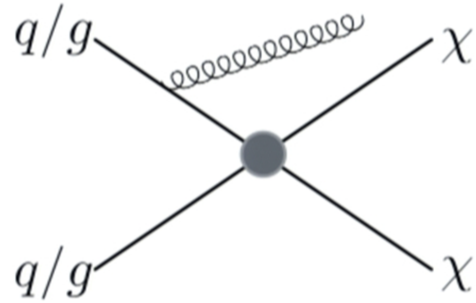
10
37

An Effective Framework

- Non-observation of high-MET excess puts limit on

$$pp \to \chi\chi + \text{jet}$$

- How to interpret this?



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

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

10
37

An Effective Framework

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

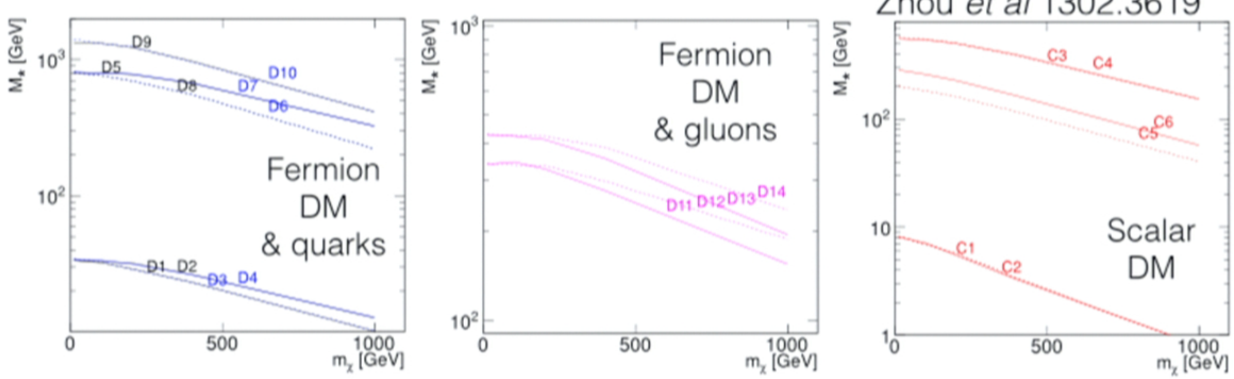
D1	$\frac{m_q}{\Lambda^3}(\bar{q}q)(\bar{\chi}\chi)$
D2	$\frac{im_q}{\Lambda^3}(\bar{q}q)(\bar{\chi}\gamma^5\chi)$
D5	$\frac{1}{\Lambda^2}(\bar{q}\gamma^\mu q)(\bar{\chi}\gamma_\mu\chi)$
D11	$\frac{\alpha_S}{4\Lambda^3}(\bar{\chi}\chi)G_{\mu\nu}G^{\mu\nu}$

C1	$\frac{m_q}{\Lambda^2}(\bar{q}q)(\chi^*\chi)$
R1	$\frac{m_q}{2\Lambda^2}(\bar{q}q)(\chi\chi)$
R3	$\frac{\alpha_S}{8\Lambda^2}(\chi\chi)G_{\mu\nu}G^{\mu\nu}$

etc.

- Allows direct comparison of experimental results

Zhou *et al* 1302.3619



An Effective Framework

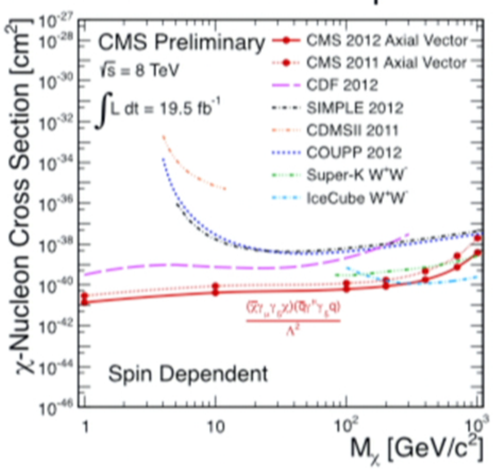
- Exhaustive list of operators in Goodman *et al.* 1008.1783

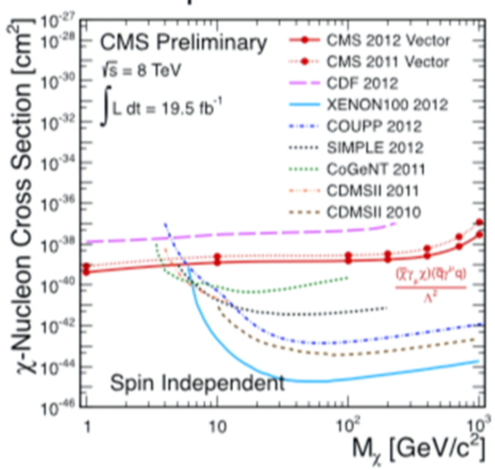
D1	$\frac{m_q}{\Lambda^3}(\bar{q}q)(\bar{\chi}\chi)$
D2	$\frac{im_q}{\Lambda^3}(\bar{q}q)(\bar{\chi}\gamma^5\chi)$
D5	$\frac{1}{\Lambda^2}(\bar{q}\gamma^\mu q)(\bar{\chi}\gamma_\mu\chi)$
D11	$\frac{\alpha_S}{4\Lambda^3}(\bar{\chi}\chi)G_{\mu\nu}G^{\mu\nu}$

C1	$\frac{m_q}{\Lambda^2}(\bar{q}q)(\chi^*\chi)$
R1	$\frac{m_q}{2\Lambda^2}(\bar{q}q)(\chi\chi)$
R3	$\frac{\alpha_S}{8\Lambda^2}(\chi\chi)G_{\mu\nu}G^{\mu\nu}$

etc.

- Allows direct comparison of experimental results





An Effective Framework

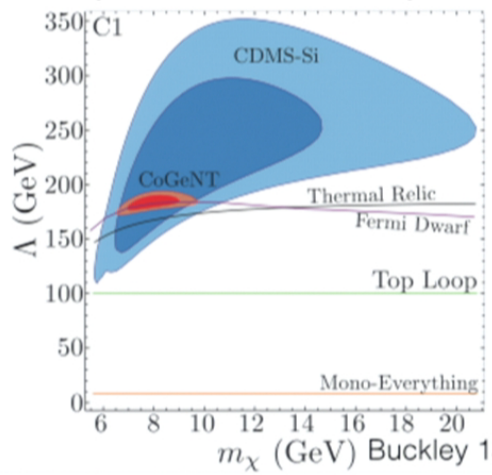
- Exhaustive list of operators in Goodman *et al.* 1008.1783

D1	$\frac{m_q}{\Lambda^3}(\bar{q}q)(\bar{\chi}\chi)$
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	$\frac{m_q}{\Lambda^2}(\bar{q}q)(\chi^*\chi)$
R1	$\frac{m_q}{2\Lambda^2}(\bar{q}q)(\chi\chi)$
R3	$\frac{\alpha_S}{8\Lambda^2}(\chi\chi)G_{\mu\nu}G^{\mu\nu}$

etc.

- Allows direct comparison of experimental results



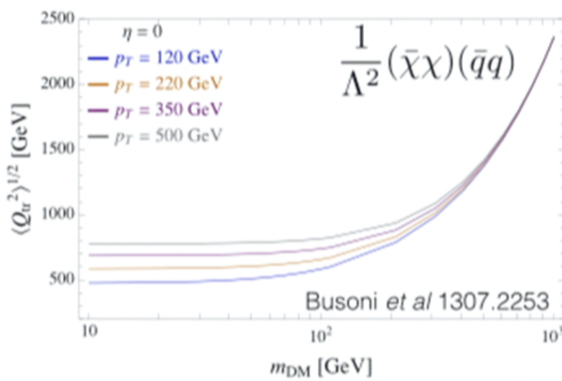
Buckley 1308.4146

11
37

Limitations of EFTs

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

- Is the physics we are probing at the LHC compatible with the EFT formalism?
  - Requiring $m_\chi < M/2$ & perturbativity gives $m_\chi \lesssim 2\pi\Lambda$
- EFT expansion requires $Q_{\rm transfer} < M = \sqrt{g_\chi g_q}\Lambda < 4\pi\Lambda$
- At LHC, expect $Q_{\rm transfer} \propto p_{T,\rm jet}$

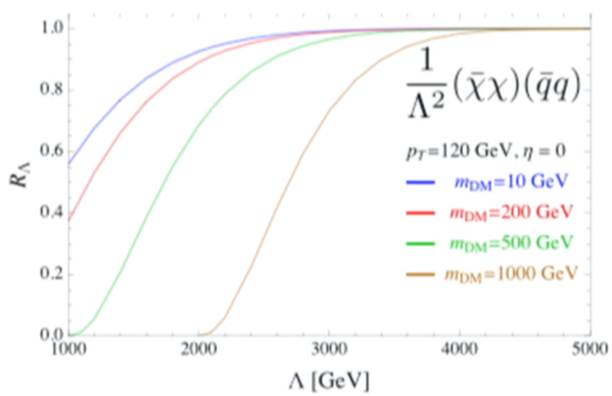


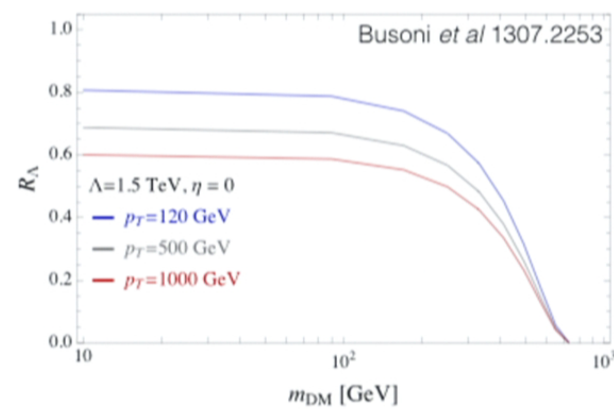
12
37

Limitations of EFTs

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

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





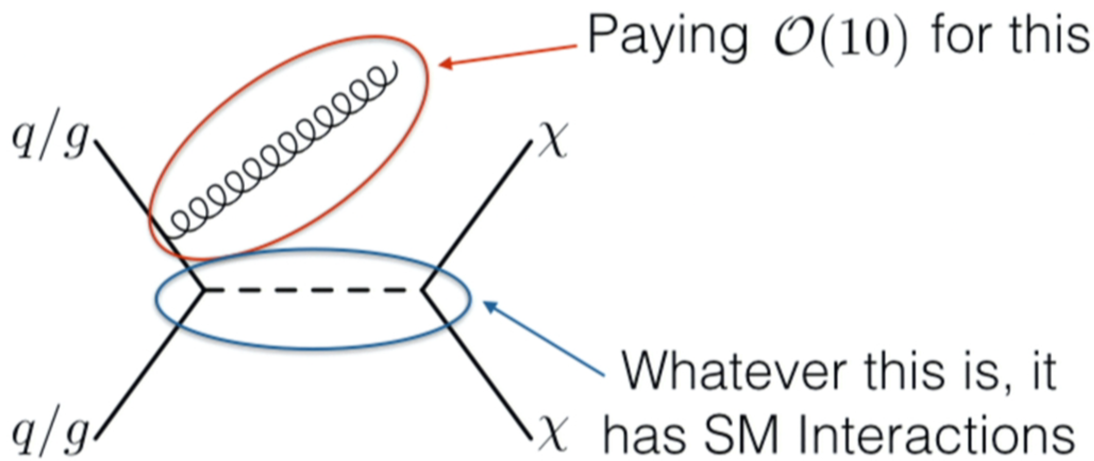
13
33

Beyond Effective Operators

- Generically, the parameter space probed by the LHC is in the region where the mediators are kinematically accessible.
  - A theory problem more than an experimental problem.
  - Monojet searches still sensitive to $\chi\chi + \mathrm{jets}$.
  - We're just interpreting the results incorrectly
  - Not looking in the "best" channels or using the maximum amount of information available.

14
33

Beyond Effective Operators

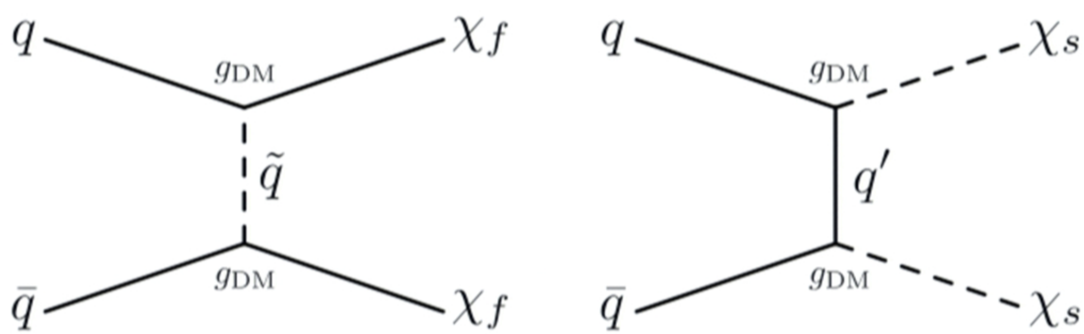


- The UV model for the unknown mediator(s) will have different mono-jet cross sections and distributions, as well as production in associated channels.
  - But we lose generality & have more parameters.

15
33

t-channel Operators

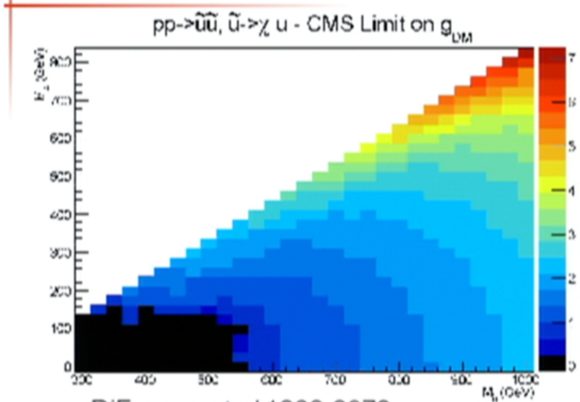
- Similar to SUSY squarks+neutralino
  - Particle content reduced to the minimal needed for DM
- 3D parameter space: $m_{\mathrm{med.}},\ m_{\chi},\ g_{\mathrm{DM}}$

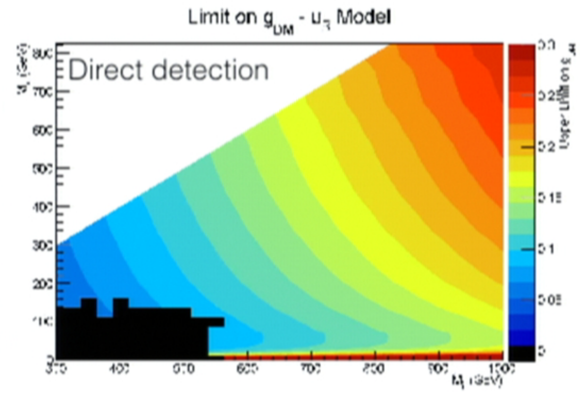


16
37

t-channel Operators

- Similar to SUSY squarks+neutralino
  - Particle content reduced to the minimal needed for DM
- 3D parameter space: $m_{\mathrm{med.}},\ m_\chi,\ g_{\mathrm{DM}}$



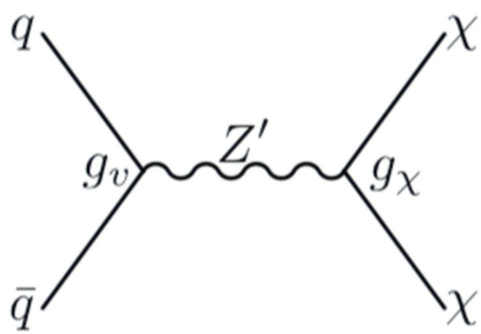


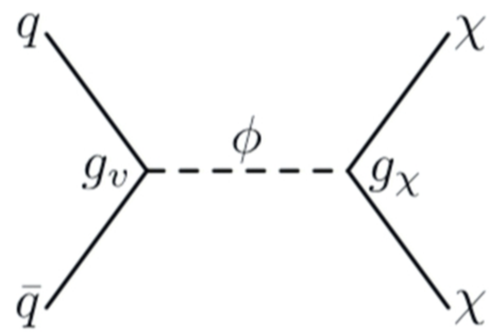
DiFranzo *et al* 1308.2679
see also Papucci *et al* 1402.285

16
37

s-channel Operators

- New resonance with couplings to dark matter and Standard Model particles.
  - See Goodman, Shepard 1111.2359, Frandsen *et al* 1204.3839, Haisch *et al* 1311.7131, Buchmueller *et al* 1407.8275, *etc.*

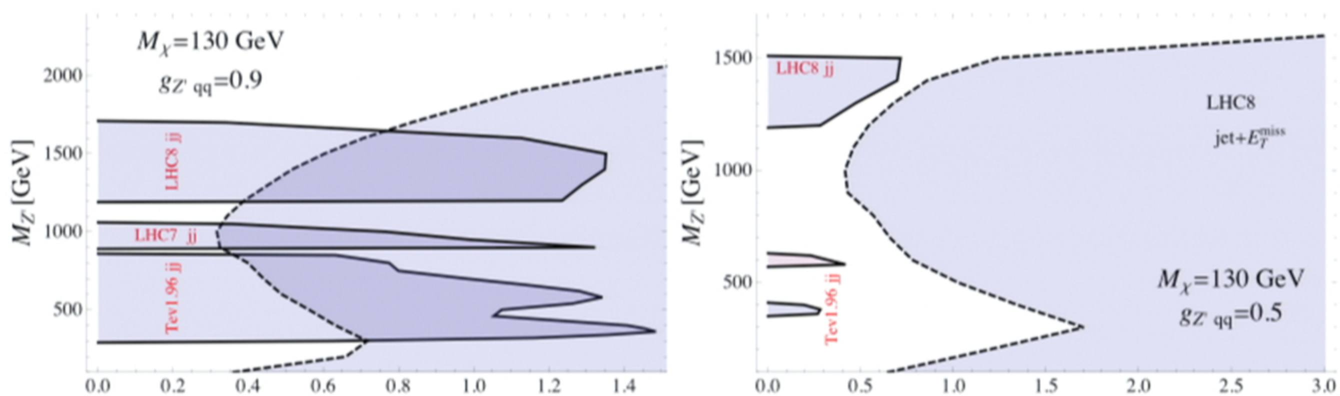




17
37

s-channel Operators

- New resonance with couplings to dark matter and Standard Model particles.
  - See Goodman, Shepard 1111.2359, Frandsen *et al* 1204.3839, Haisch *et al* 1311.7131, Buchmueller *et al* 1407.8275, *etc.*



Alves *et al* 1312.5281 g_χ g_χ

17
37

Spin-0 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
- As I'll show, constraints fairly weak at present.
  - New Physics could be lurking in LHC8 data set.

work in progress with David Feld and Dorival Gonçalves

18
37

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:

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

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

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

19
37

Spin-0 Simplified Models

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

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

- Minimal model 5-dimensional:

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

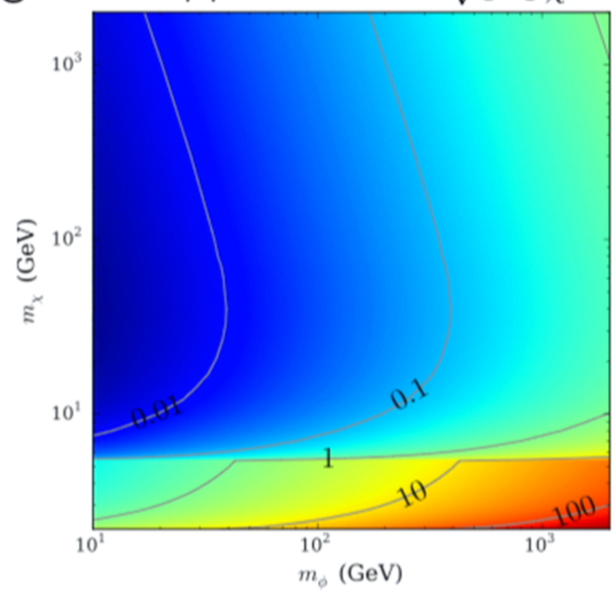
  - We keep $\Gamma_{\phi/A}$ free to leave possibilities of extra decay modes open.
  - Mediator width will affect collider bounds.

20
37

Direct Detection Bounds

- Scalar mediator benchmark will result in spin-independent direct detection signal.
  - Constraints from LUX & CDMS
  - Relatively independent of Γ_ϕ
- Keep in mind the hidden dependence on local velocity & density distributions.

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



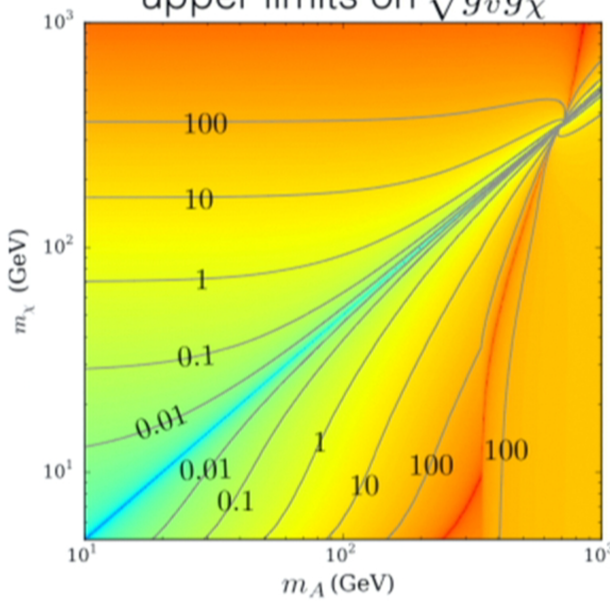
MRB, D. Feld and D. Gonçalves *in prep.*

21
37

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 $\sqrt{g_v g_\chi}$



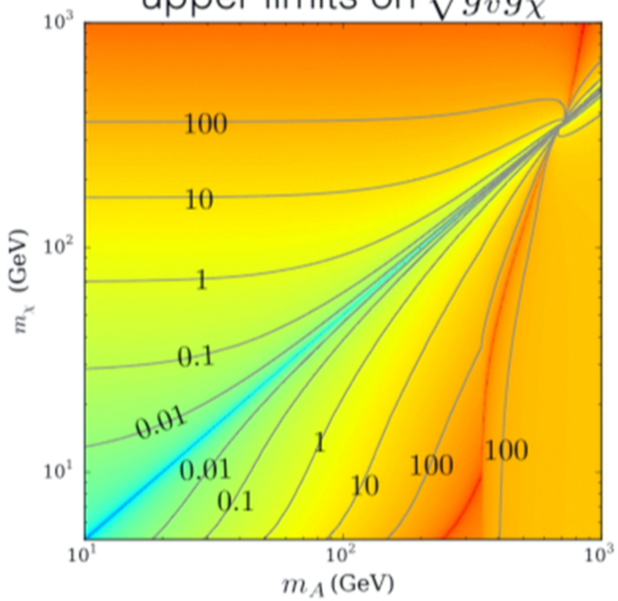
MRB, D. Feld and D. Gonçalves *in prep.*

22
37

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 $\sqrt{g_v g_\chi}$



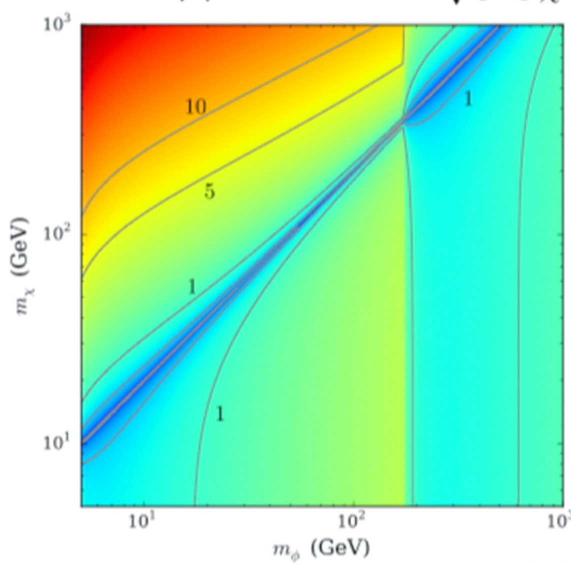
MRB, D. Feld and D. Gonçalves *in prep.*

22
37

Thermal Relic

- If the dark matter production 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
    $$\chi\bar{\chi} \to \phi \to f\bar{f}$$
    $$\chi\bar{\chi} \to A \to f\bar{f}$$

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



MRB, D. Feld and D. Gonçalves *in prep.*

Collider Bounds

- Expanding from dark matter EFTs to a simplified model, can relate multiple LHC collider signatures.
  - MET-related searches for $\phi \to \bar{\chi}\chi$ events
  - Standard Model resonances for $\phi \to \bar{f}f$
  - Relative size of g_v to g_χ sets dominant channels.
  - LHC will have difficulty when $g_v \ll 1$
  - Can test deviations from flavor-universal ansatz
- I will show bounds for benchmark models with $m_\chi < 2m_\phi$ in MET channels using existing CMS/ATLAS work.
  - Visible channels require construction of new searches

Collider Bounds

- I will show bounds from existing searches:
  - “mono”-jet $pp \to \not{E}_T + j(+j)$
  - tops+MET $pp \to \not{E}_T + t\bar{t}$
  - bottoms+MET (repurposed sbottom search)
  - Two benchmark mediator masses: $m_\phi = 100,\ 375\ \mathrm{GeV}$
- Additional searches possible
  - taus+MET
  - $b\bar{b}$ resonances (in association with $b, b\bar{b}, t\bar{t}\ldots$)
  - …and others

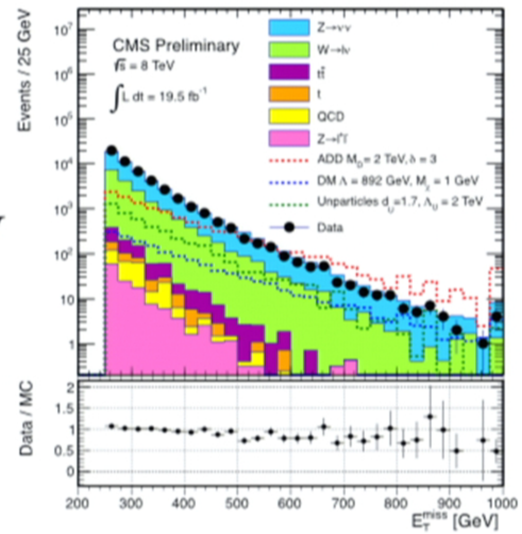
25
37

“Monojet” Searches

- Benchmark with CMS 20 fb^{-1} search (1408.3583)
- Trigger on $\not{E}_T > 120$ GeV or $p_{T,j} > 80$ GeV, $\not{E}_T > 105$ GeV and then require 1 jet with $p_{T,j} > 110$ GeV
  - 2nd jet allowed, no more than 2 with $p_{T,j} > 30$ GeV
  - 7 signal bins with

$$\not{E}_T > 250,\ 300,\ 350,\ 400,\ 450,\ 500,\ 550\ \text{GeV}$$

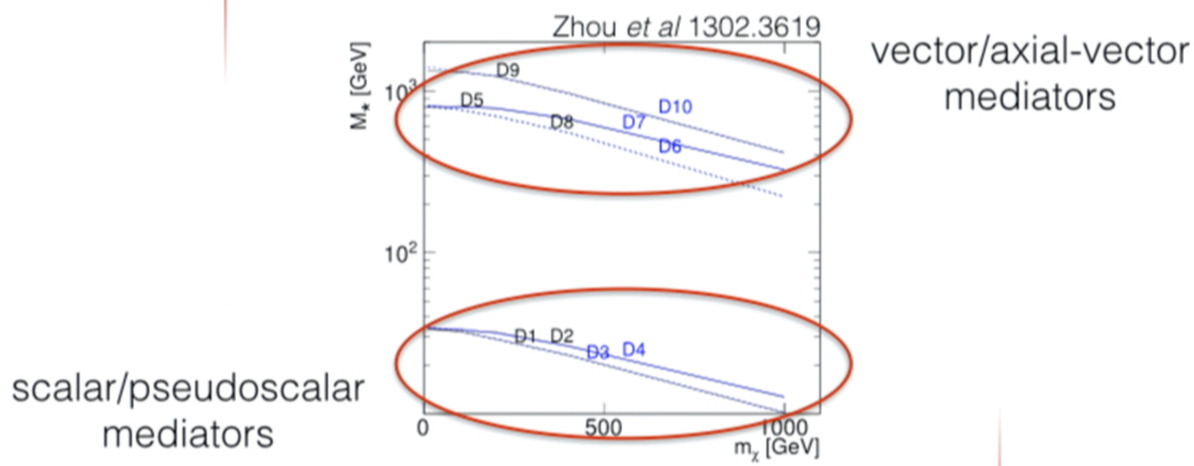
- CMS very helpfully gives enough information on backgrounds to plot 95% confidence levels for new physics models



CMS EXO-12-048/1408.3583

Production Mechanism

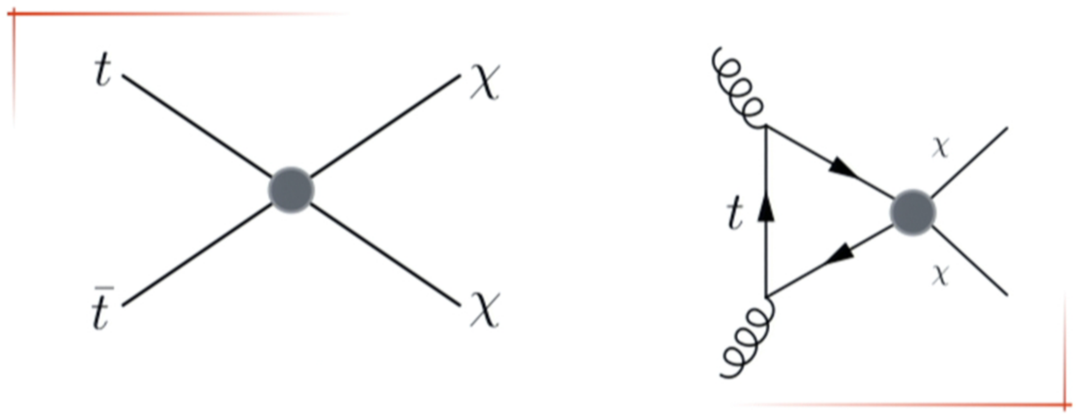
- MFV assumption means ϕ couples proportional to mass.
  - But protons don't contain many $t/\bar{t}/b/\bar{b}$
  - Seen in very weak bounds on scalar EFT operators



27
37

Production Mechanism

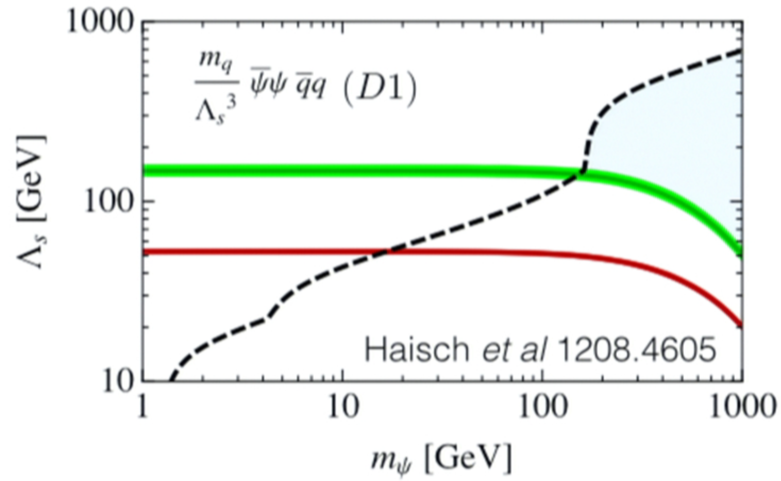
- In 1-1 analogy to Higgs production, couplings to top (and bottom) quarks lead to loop-level interaction with gluons.
  - Has been considered in EFT interactions.
  - This will be the main production mode for monojets



28
37

Production Mechanism

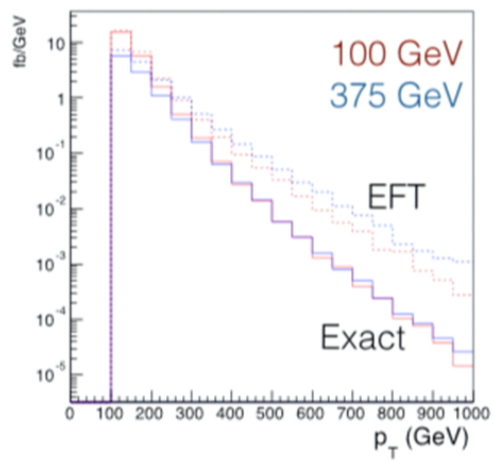
- In 1-1 analogy to Higgs production, couplings to top (and bottom) quarks lead to loop-level interaction with gluons.
  - Has been considered in EFT interactions.
  - This will be the main production mode for monojets



28
37

Tricky Tops

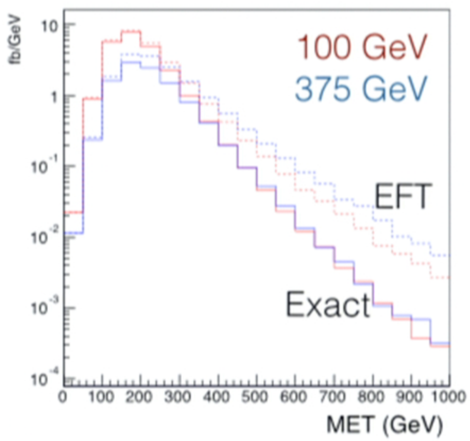
- Using a tool like MadGraph to generate ϕ through integrated-out top loop (another EFT) is problematic.
  - For monojet searches, jet p_T, and ϕ p_T (MET) are all large compared to $2m_t$. m_ϕ can be large as well.
  - Cannot treat the coupling to gluons as an EFT.
  - Not just a *K*-factor, changes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



29
37

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



29
37

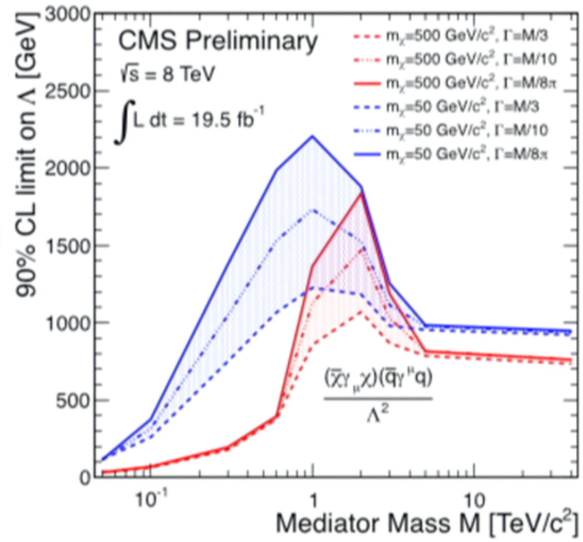
Simulation Technique

- Coupling identical to Higgs-glue-glue
  - But cannot assume that m_ϕ small compared to relevant energy scales.
  - Use MCFM modified to produce simulated events to produce $(\phi \rightarrow \chi\bar{\chi}) + j$ events with exact dependence on m_t, narrow width approximation.
    - Shower with PYTHIA8, jet-finding with FastJet
  - Compare to MadGraph5 events matched to 2 jets
    - MadGraph models built with Feynrules2.1
    - Captures finite width kinematic effects
    - Gluon coupling an EFT, but calculated at finite m_t

30
37

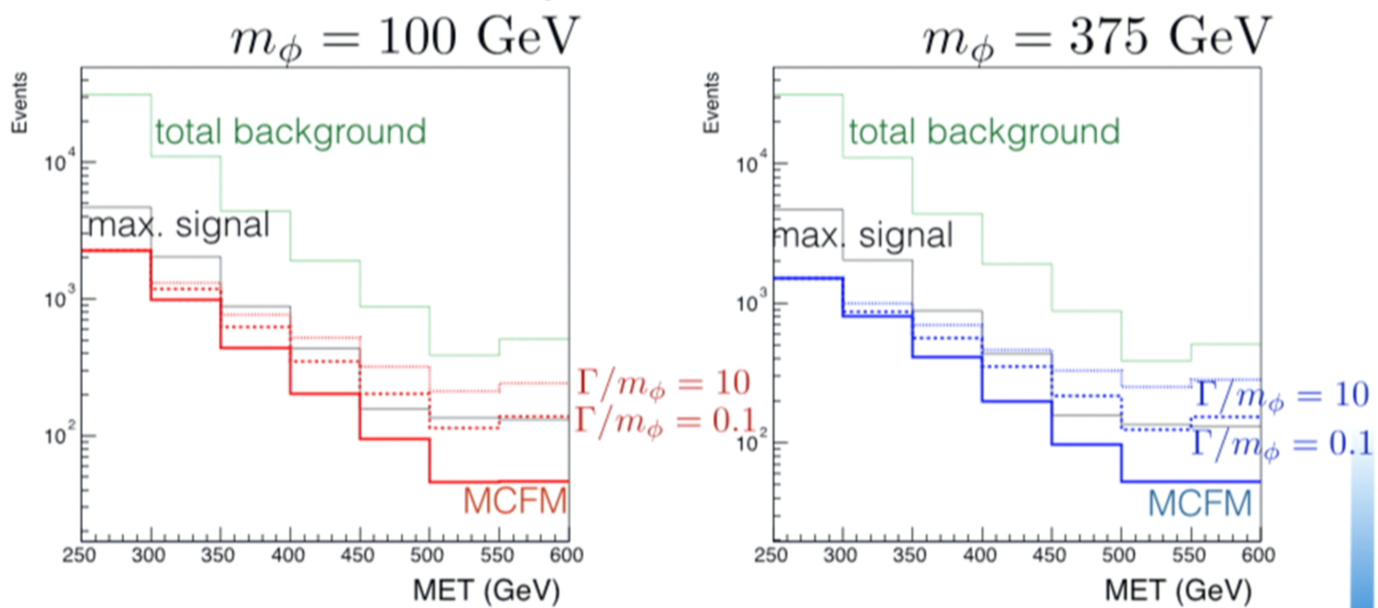
Width Effects

- 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, bounds on $(g_v g_\chi)^2 \propto \Gamma$
- 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

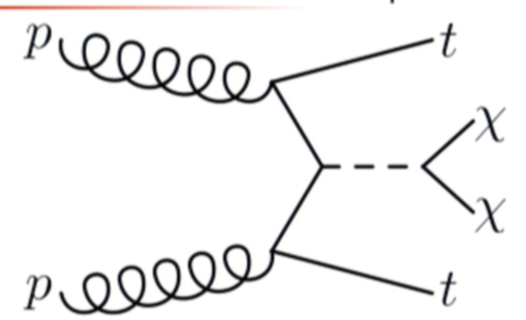
- Kinematic effect at *very* large widths.
  - Effect on CMS Monojet searches:



32
37

Tops + MET

- Here we don't need to worry (as much) about loop-induced gluon couplings.
  - Primary production from scalar emission off of real tops
  - Can use MadGraph5 models
  - Benchmark using CMS B2G-13-004, $\mathcal{L} = 19.7 \text{ fb}^{-1}$
  - Di-lepton+MET channel
  - Requires



$$\not{E}_T > 320 \text{ GeV}, \ |p_{T,j_1}| + |p_{T,j_2}| < 400 \text{ GeV}, \ |p_{T,\ell_1}| + |p_{T,\ell_2}| > 120 \text{ GeV}$$

  - Optimized for $m_\chi = 100$ GeV

33
37

Bottoms + MET

- In non-minimal models, can separate *d*-type couplings from *u*-type. (*e.g.* $\tan\beta$ in 2HDM)
  - Separate searches in distinct final states essential
- Here we adopt a sbottom search (CMS-PAS-SUS-13-018):
  - 2 jets with $p_T > 70$ GeV, at least 1 b-tagged
  - $\not{E}_T > 175\ \text{GeV}, H_T > 250\ \text{GeV}$
  - Bin events in
    $$M_T = \sqrt{[E_{T,j_2} - \not{E}_T]^2 + [\vec{p}_{T,j_2} - \vec{\not{E}}_T]^2} > 200\ \text{GeV}$$
  - Not designed to find our sort of new physics.

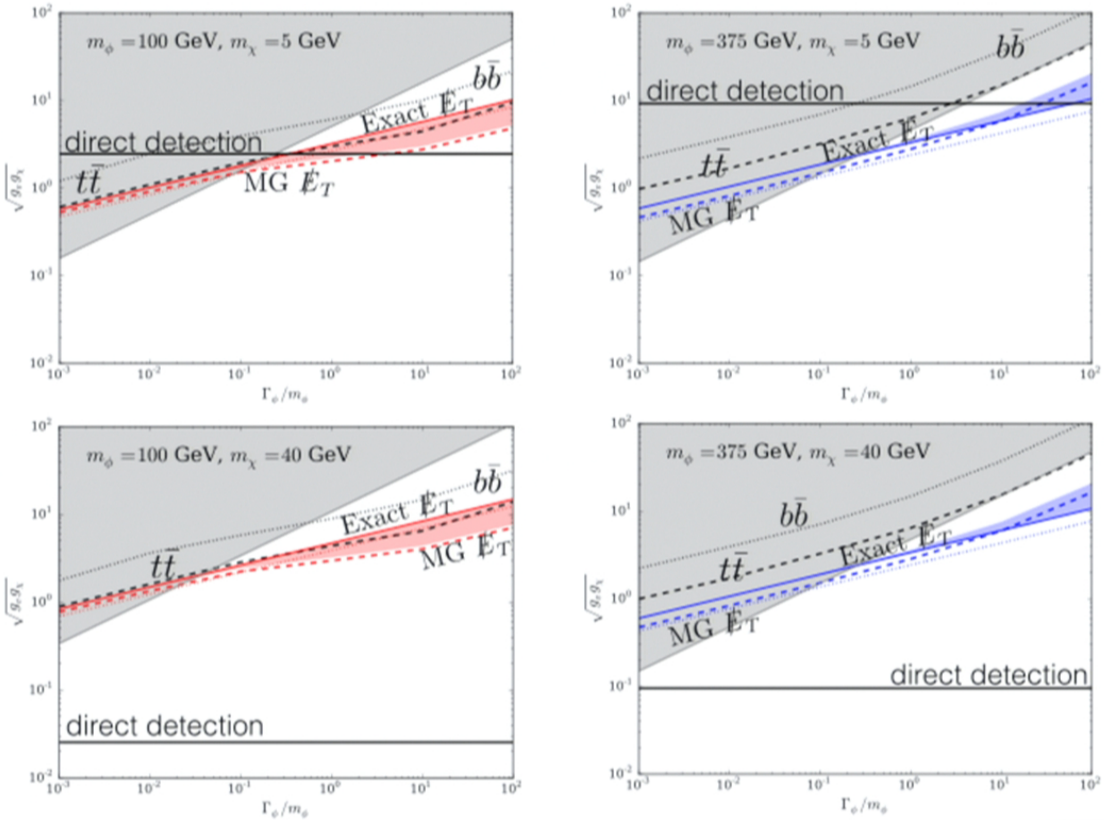
34
37

Scalar Bounds

- Today I show bounds on $\sqrt{g_v g_\chi}$ for mediators in the 100, 375 GeV benchmark models, as a function of Γ/m_ϕ
  - Bounds from monojet, top, and bottom channels

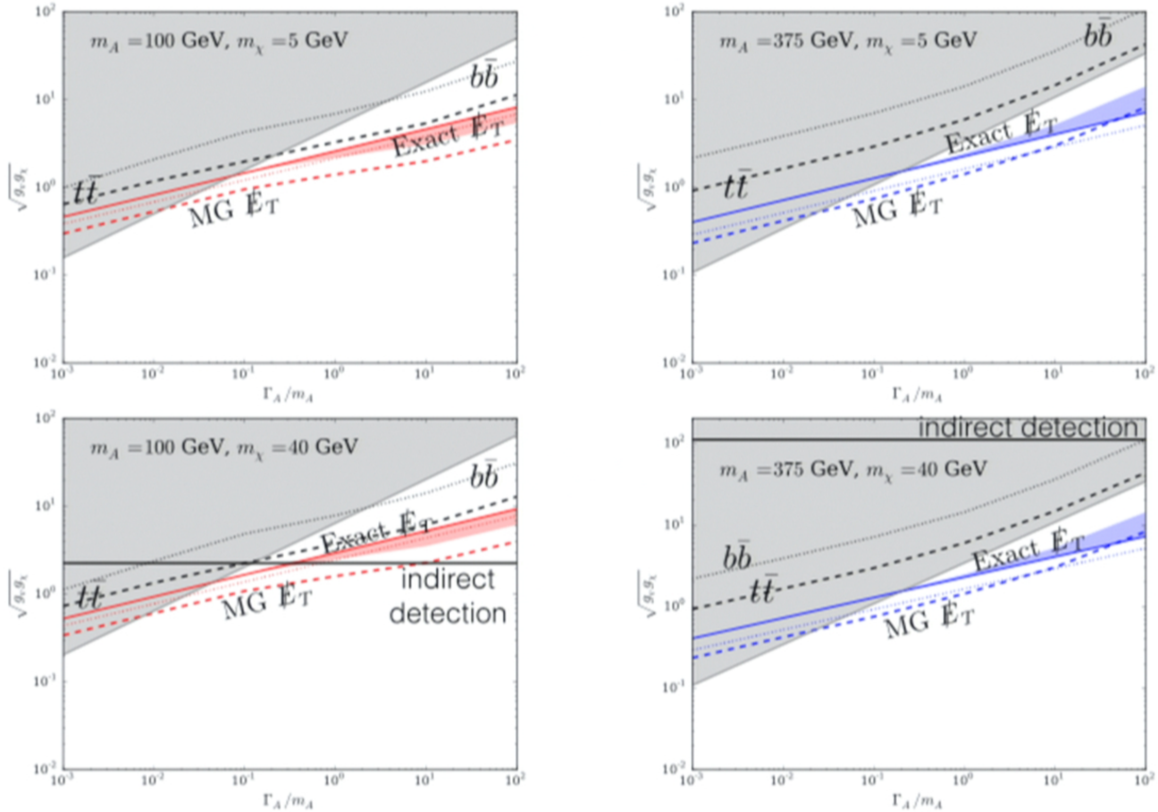
- For dark matter masses $m_\chi < m_\phi/2$, collider bounds are relatively independent of m_χ
- Scan over mediator masses in monojet channel impractical at this time.
- Bounds weak for $\Gamma/m \gg 1$, because BR into MET channels small. That is, look in some other channel!

Scalar Bounds



36
37

Pseudoscalar Bounds



37

Conclusions

- LHC Run-II is nearly upon us. Now is the time to make sure we are covering our bases for new physics searches
  - Dark matter requires new physics, and it is reasonable to expect to find it at the LHC (even if not a WIMP)
- Effective operators a useful & model independent way to parameterize our searches
  - However, EFTs largely not applicable for dark matter models which the LHC can probe
  - That is, we are leaving useful information on the table.
  - Simplified models are a way to be model independent while still accessing information in multiple channels.

38
37

Conclusions

- In my mind, scalar/pseudoscalar mediators are one of the most interesting & best motivated scenarios.
  - Loop-induced gluon-couplings, combined with large transverse momenta makes for extra work in simulation
- I've shown preliminary results, interpreted from existing LHC searches
- In LHC13, these bounds will be improved
  - However, we can consider further searches implied by these models, without MET. *i.e.* $\phi/A \to b\bar{b}, \ldots$
  - Possible links to extended Higgs sectors.
  - Lots of work to be done.

39
37