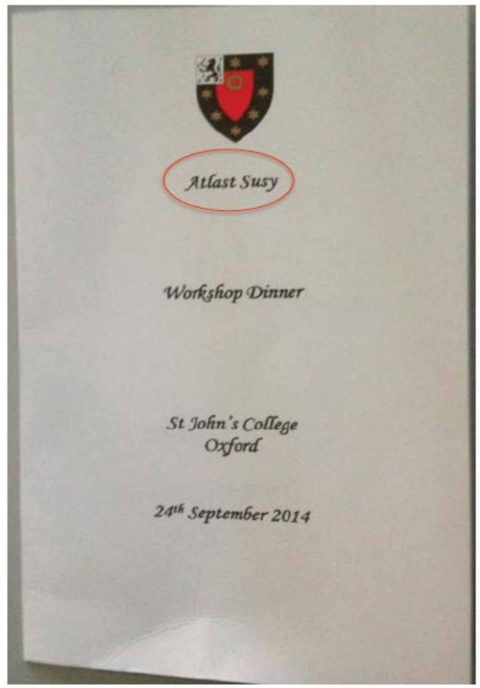
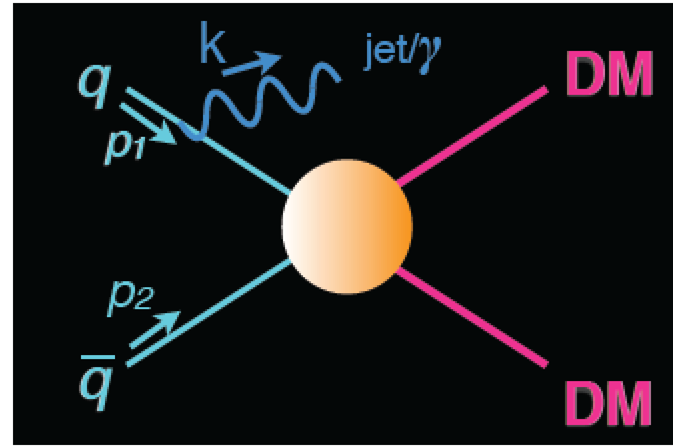
Simplified Models for LHC Dark Matter Searches





SLAC NATIONAL ACCELERATOR LABORATORY

See : 1409.2893, 1409.4075, 1410.6497 &1411.0535

T.G. Rizzo

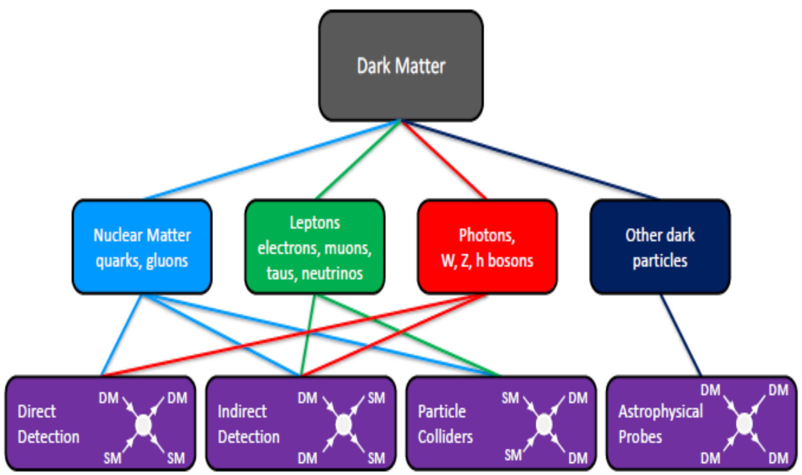
11/12/14

We know dark matter exists… but only through its gravitational interactions

Rare portrait of DM

- We know <u>for sure</u> that DM is NOT part of the SM & so it represents some kind of NP, very likely a new particle(s)

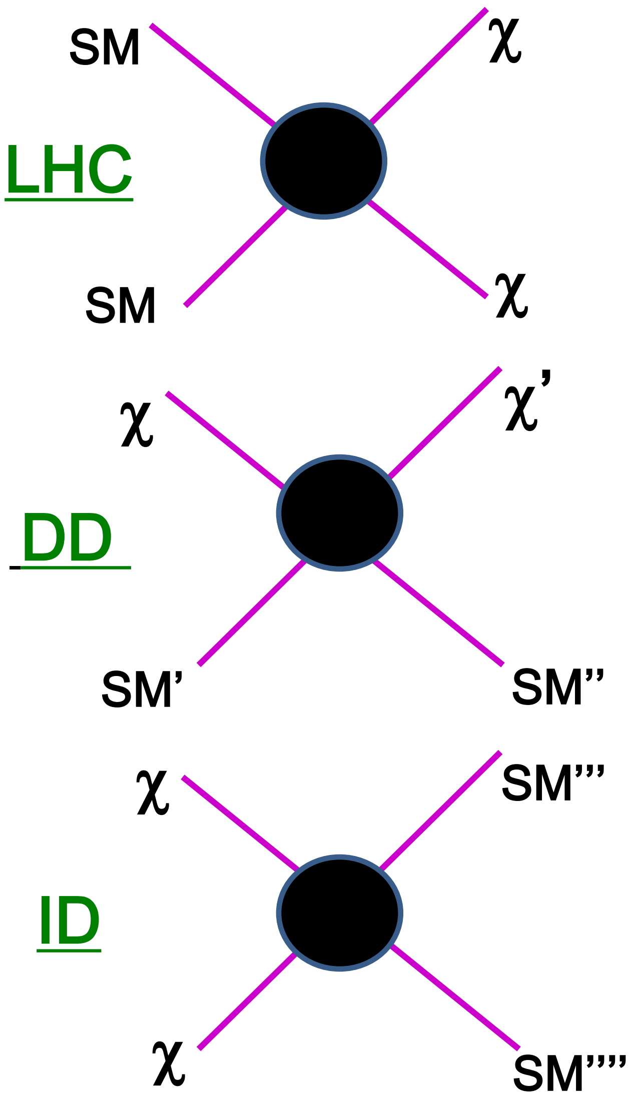
→ But we need to have some way to describe how DM can interact with the SM… *provided that it does !*



This cannot be done without introducing some biased model-dependence

The WIMP(-like) scenario is appealing not JUST because of the 'miracle' but because it offers us complementary windows into the nature of DM

WIMP-like DM : How Do We Detect It ?



This can be misleading if taken too seriously

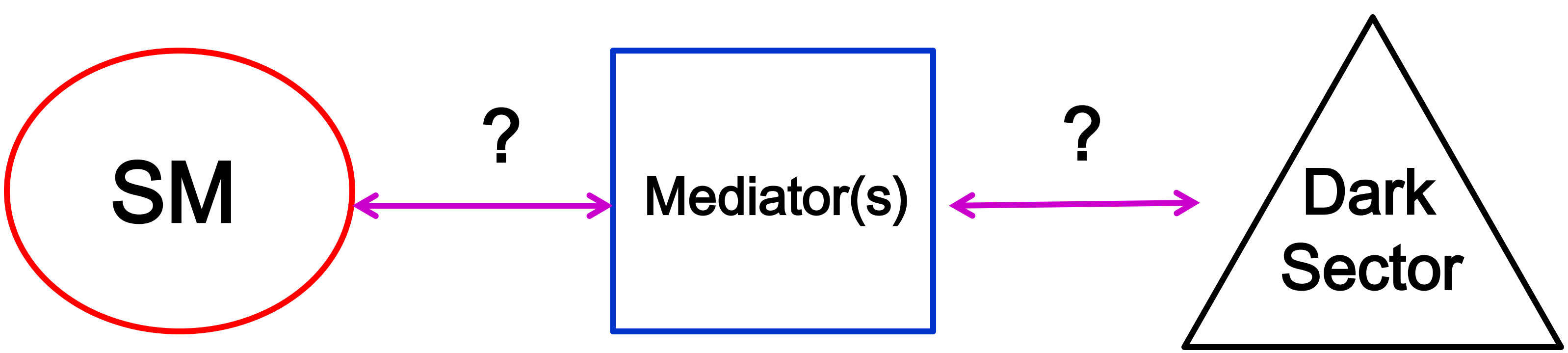
- The SM particles colliding to make DM at the LHC are not necessarily (i.e., not likely!) the same as those into which DM annihilates in ID or off of which the DM scatters in DD.

- In many cases only one (or even none) of these processes will be relevant… think of gravitinos or axions!

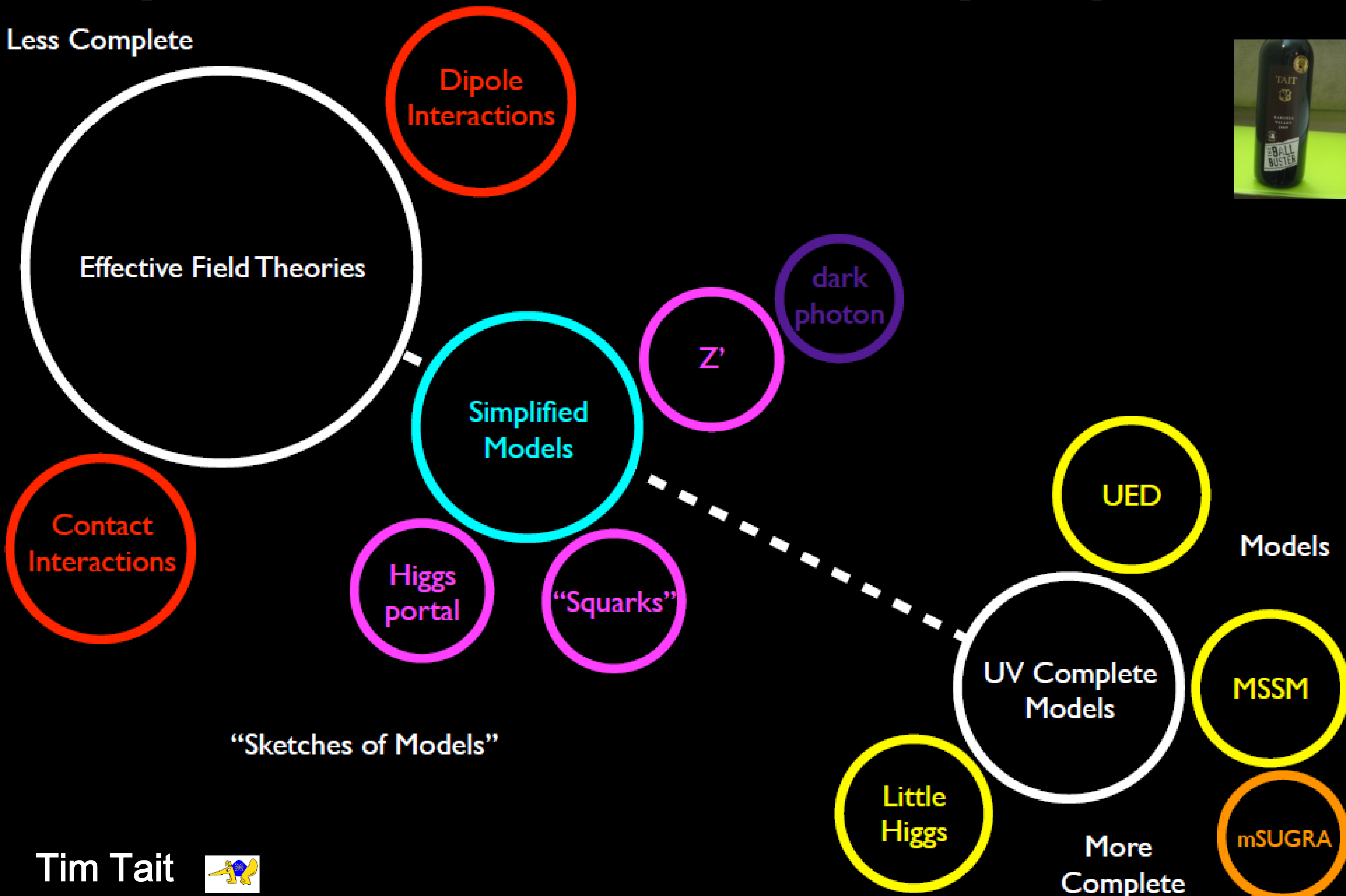
- EFT/Simplified Models generally ASSUME that the 'SM' s here are all ~same objects. Not usually so in UV-complete models

Keeping it Simple: Complementarity

- The complementarity of DM searches requires a framework through which the different processes can be related & compared. Not all will DM scenarios allow for this possibility.
- Questions: How does DM interact with the SM? How complete/general do we want the description to be? What 'price' are we willing to pay? There are pros & cons…
- The basic picture is shown below… the answers determine how much machinery we include. A vast literature exists..

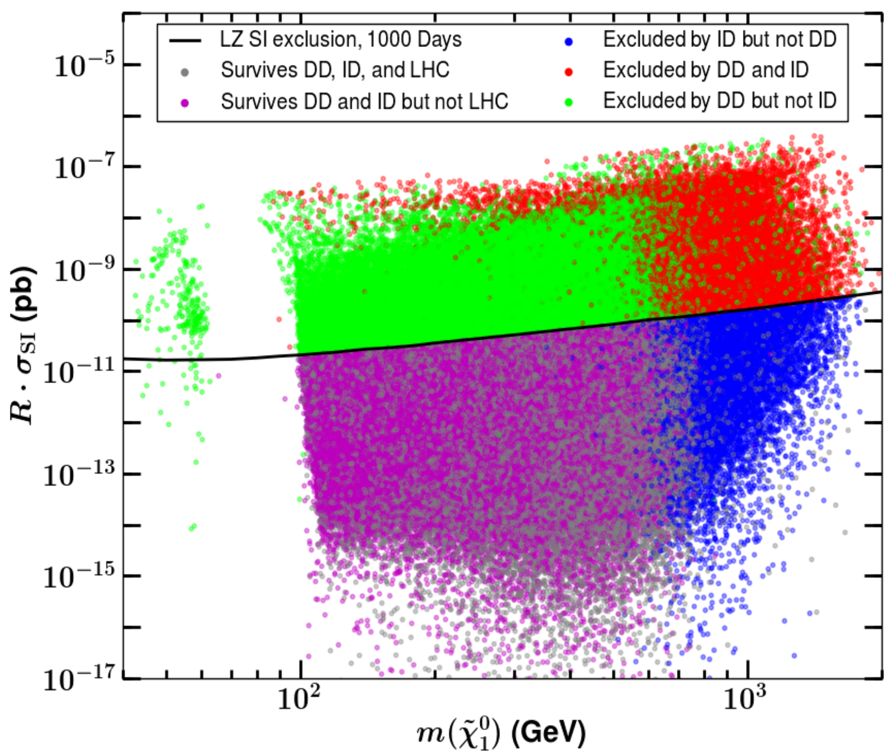


Spectrum of Theory Space



- UV- complete theories have 'no issues' & allow for detailed predictions for any set of observables & can correlate any and all experiments. BUT they generally have a lot of parameters to scan, e.g., the pMSSM & so are complex to fully analyze.

- While there are several classes of UV-complete models one can worry that studying them alone may be too restrictive & we miss many possible DM scenarios



It'd be useful to have an easier set of models to study & compare . EFT's?

So what are the options?

(Not So) Effective Field Theories

- Let the 'SM' be 'anything': leptons or quarks, gluons, W/Z or the Higgs
- Let the DM be spin-0, ½, 1,… with possibly indefinite parity
- Write down all operators of the lowest possible dimensionality, e.g., contact interactions, that connect the two sectors. These are dim-6 & -7

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	$\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi\bar{q}\sigma_{\mu\nu} q$	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	$\bar{\chi}\gamma^5\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\alpha_s/4M_*^3$
D15	$\bar{\chi}\sigma^{\mu\nu}\chi F_{\mu\nu}$	M
D16	$\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi F_{\mu\nu}$	D
M1	$\bar{\chi}\chi\bar{q}q$	$m_q/2M_*^3$
M2	$\bar{\chi}\gamma^5\chi\bar{q}q$	$im_q/2M_*^3$

Name	Operator	Coefficient
M3	$\bar{\chi}\chi\bar{q}\gamma^5 q$	$im_q/2M_*^3$
M4	$\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$	$m_q/2M_*^3$
M5	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	$1/2M_*^2$
M6	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/2M_*^2$
M7	$\bar{\chi}\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/8M_*^3$
M8	$\bar{\chi}\gamma^5\chi G_{\mu\nu}G^{\mu\nu}$	$i\alpha_s/8M_*^3$
M9	$\bar{\chi}\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/8M_*^3$
M10	$\bar{\chi}\gamma^5\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\alpha_s/8M_*^3$
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	$\chi^2 G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/8M_*^2$

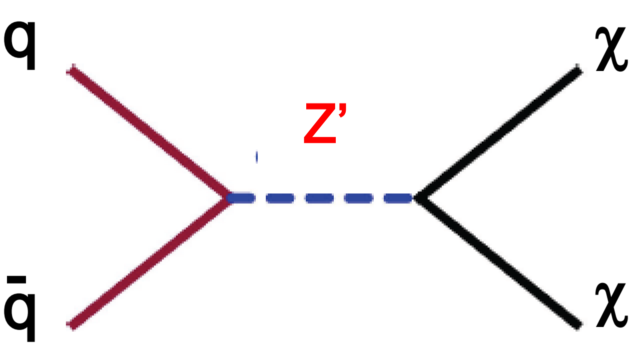
1009.0008

- The scale, Λ, & the DM mass, m, are the only free parameters…
- Do a search, express the results in terms of these 2 parameters for some choice of operators & compare with other searches. What could be easier?

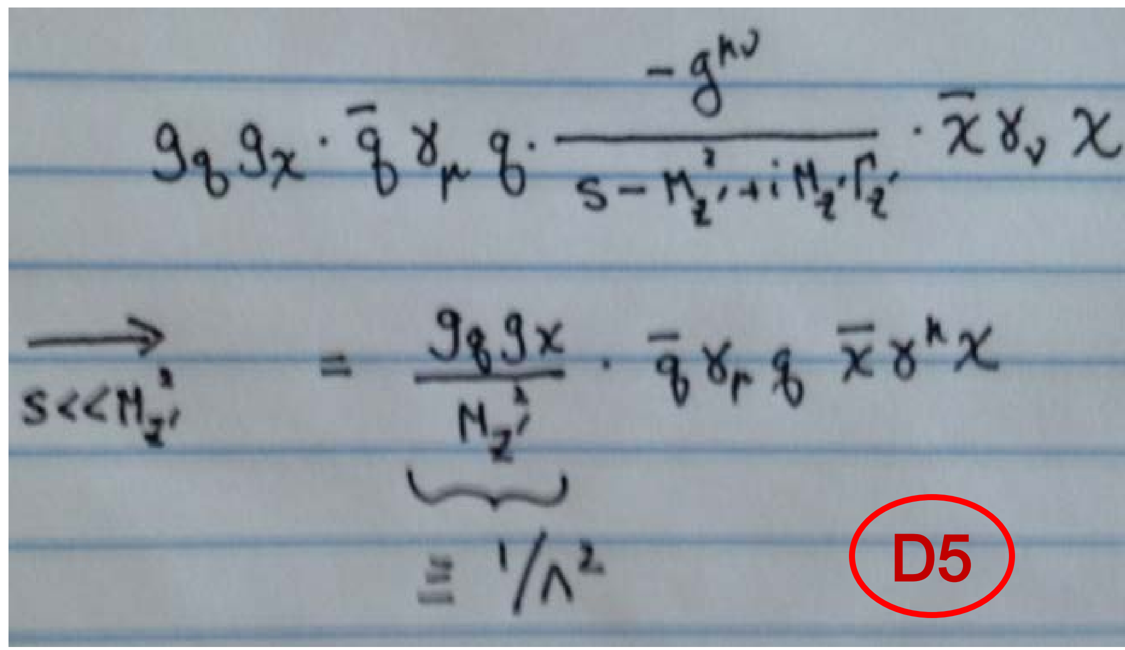
Aside: Where do these CIs come from ?

- If a mediator between the DM & the SM is ‘heavy’ it can be ‘integrated out’ to produce a (set of) higher dimensional operator(s) linking the DM to the SM

Example:



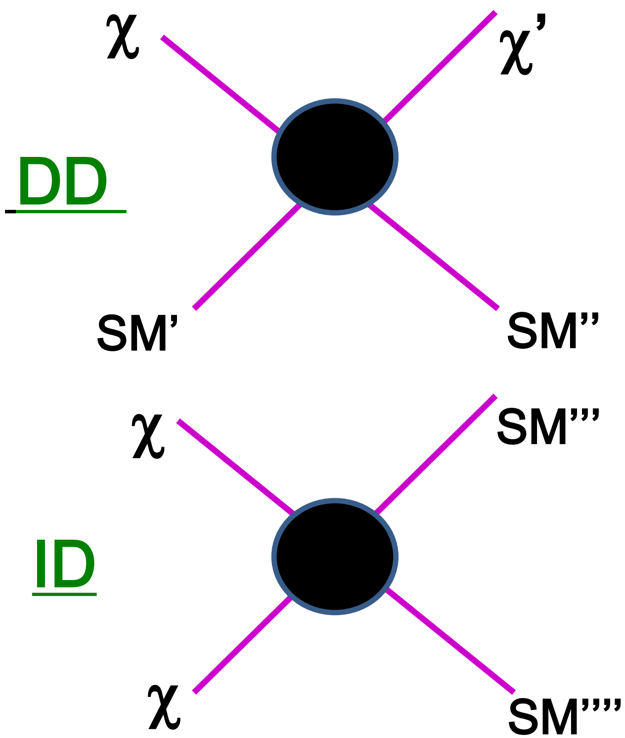
Sample s-channel mediator Simplified Model



→ Clearly fails when collision momenta approach the mass of the mediator or if the couplings (or total width) are non-perturbative

(Ab)Use of EFT’s: Life Just Ain’t That Simple

- For DD experiments the momentum flow through the blob in the diagram is always VERY small << Λ so we don’t ‘resolve’ what’s going on inside. This means the EFT limit applies here.



In the ID case the typical momentum flow through the blob is set by the DM mass, m. If m/Λ is small, then EFT is applicable here too & we can then compare DD & ID searches. This is frequently the situation.

BUT there are cases (e.g., wino DM) when this approach fails even for ID !

But things are far worse at the LHC…

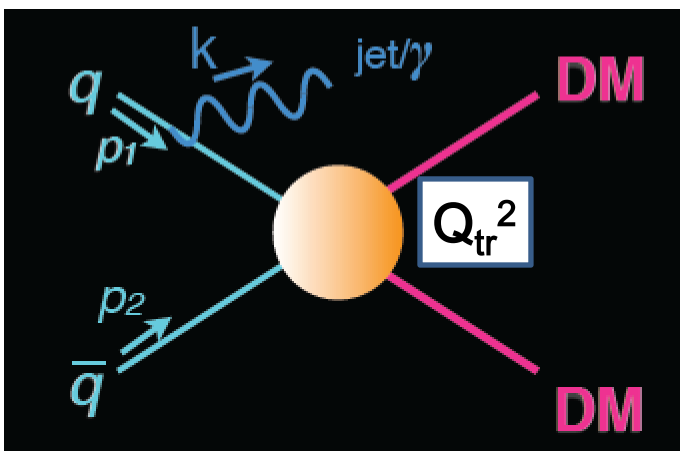
We can learn a lot about the validity of EFT by asking

(i) what fraction of the PS satisfies $Q_{tr}^2 < \Lambda^2$?

(ii) how the predictions compare with a UV-complete or S.M.

→ There are several such studies in the literature… e.g. :

- Busoni et al. (1307.2253) : directly compare monojet rates in EFT & a simplified model



eff. operator $\mathcal{O}_S = \frac{1}{\Lambda^2}(\bar{\chi}\chi)(\bar{q}q)$

$$\mathcal{L}_{\rm UV} \supset \frac{1}{2}M^2 S^2 - g_q \bar{q}qS - g_\chi \bar{\chi}\chi S$$

$$Q_{\rm tr}^2 \equiv (p_1 + p_2 - k)^2 = x_1 x_2 s - \sqrt{s}\, p_{\rm T}\left(x_1 e^{-\eta} + x_2 e^{\eta}\right)$$

> (~500 GeV)^2 @ 8 TeV

Effective Field Theories (cont.)

(i) The fraction of the PS over which the EFT is applicable:

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

fraction of eff. cross section at low momentum transfer

If ~1 the EFT is describing the process 'correctly' as momenta are small

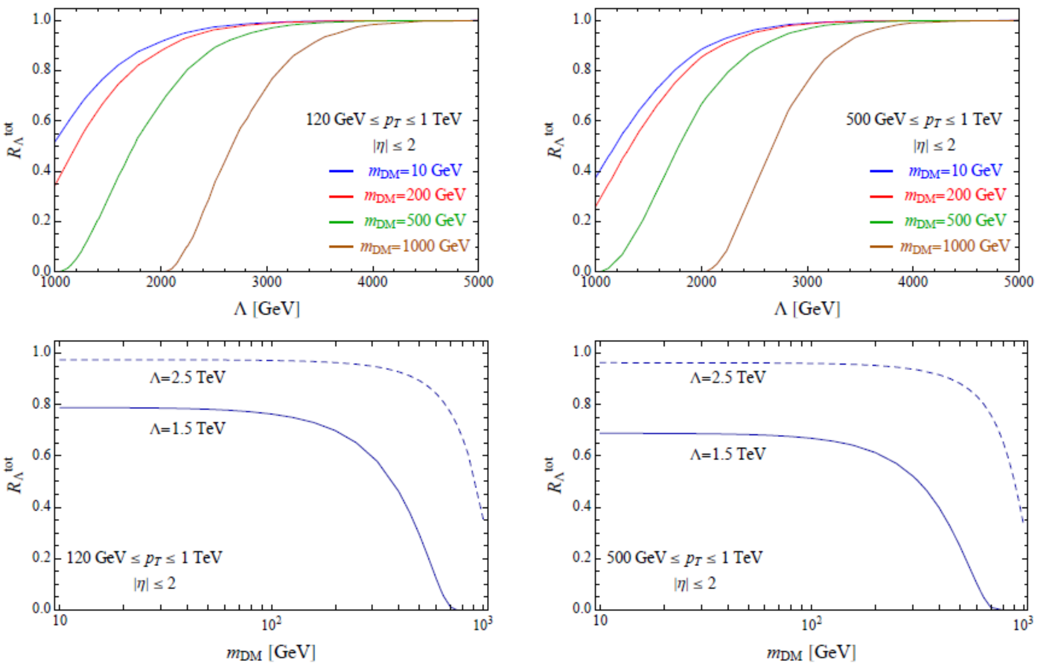


Figure 4: *The ratio $R_\Lambda^{\rm tot}$ defined in Eq. (4.6) for $\sqrt{s} = 8\,$TeV, $|\eta| \leq 2$. Top row: $R_\Lambda^{\rm tot}$ as a function of Λ, for $p_T^{\rm min} = 120\,$GeV (left panel), $p_T^{\rm min} = 500\,$GeV (right panel). Bottom row: $R_\Lambda^{\rm tot}$ as a function of $m_{\rm DM}$, for various choices of Λ, for $p_T^{\rm min} = 120\,$GeV (left panel), $p_T^{\rm min} = 500\,$GeV (right panel).*

This quantity is insensitive to the nature of the UV-completion but is to the operator choice.

Much of the time the cross section is getting support from kinematic regions where the EFT is not valid & thus is wrongly estimating the sensitivity to Λ

Worse for heavy DM!

Options?

- One suggestion is to just exclude the data from the PS regions in which the EFT model is invalid. The constraints will obviously get weaker & this possibility has been examined by both ATLAS & CMS. This procedure is strictly correct but then the resulting constraints while useful are in fact TOO weak as all the data is not being used

- It is important to use all the data to maximize the search reach & EFTs, while still useful, just don't allow for this

- We can construct a S.M. & compare it to the EFT limit

- Remember that a S.M. is just that..& not a full UV-theory but can be useful to point the way

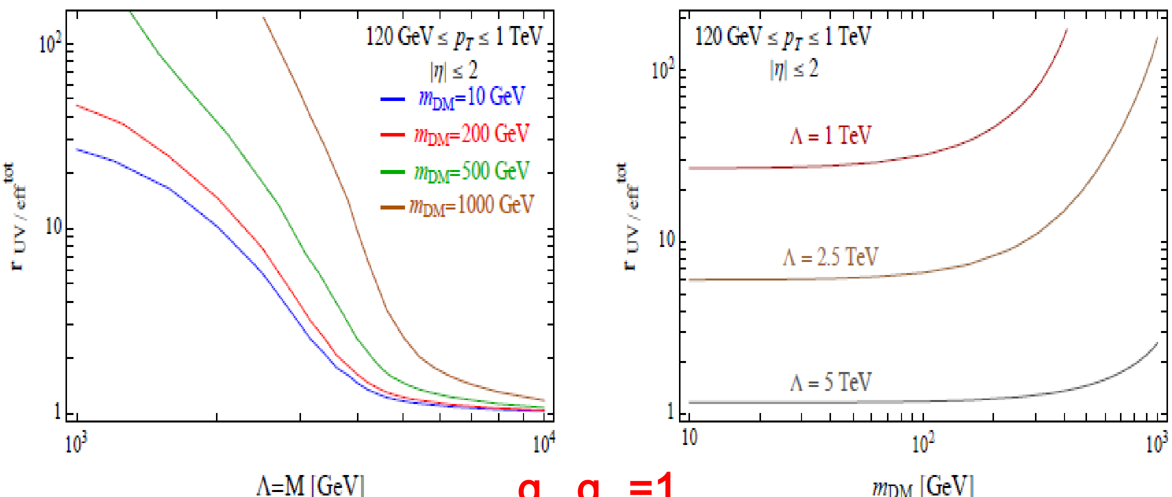
Effective Field Theories (cont.)

(ii) The difference between EFT & SM/UV can be quantified using

$$r^{\rm tot}_{{\rm UV}/{\rm eff}} \equiv \frac{\sigma_{\rm UV}|_{Q_{\rm tr}<M}}{\sigma_{\rm eff}|_{Q_{\rm tr}<\Lambda}}$$

error of using EFT (truncated at dim-6) instead of full theory

→ This ratio clearly depends on the SM/UV completion itself



g_χ, g_q =1

For this case the ratio is very large unless the cutoff is much greater than the highest jet p_T & gets worse for heavy DM as this requires larger Q (> $2m_\chi$)

Figure 7: *The ratio* $r^{\rm tot}_{{\rm UV}/{\rm eff}}$ *defined in Eq. (4.10), as a function of* Λ (left panel) *and* $m_{\rm DM}$ (right panel). *We have set* $p_T^{\rm min} = 120\,{\rm GeV}$, $|\eta| \leq 2$, $M = \Lambda$, $g_q = g_\chi = 1$ *and* $\sqrt{s} = 8\,{\rm TeV}$.

So what do we do?

Simplified Models: Don't Kill the Messenger

- Instead of integrating out the messenger, keep it physical.

→ Price is now more parameters: the DM + mediator masses + the couplings of the DM & SM field(s) to the mediator + the total decay width of the mediator (to allow for other decays)

→ Since the messenger is physical it might be PRODUCED as well & provide additional signatures/constraints

→ The mapping of an EFT to a S.M. is not unique, e.g., the messenger can be in either the s- or t-channels. Different S.M.'s will lead to different detailed predictions. MFV ?

→ Issue: how do we find a representative set of S.M.'s to study given limited time & CPU ??

Some Specific Suggestions

Simplified Models for Dark Matter and Missing Energy Searches at the LHC

Jalal Abdallah,[1] Adi Ashkenazi,[2] Antonio Boveia,[3] Giorgio Busoni,[4] Andrea De Simone,[4] Caterina Doglioni,[5] Aielet Efrati,[6] Erez Etzion,[2] Johanna Gramling,[5] Thomas Jacques,[5] Tongyan Lin,[7] Enrico Morgante,[5] Michele Papucci,[8,9] Bjoern Penning,[3,10] Antonio Walter Riotto,[5] Thomas Rizzo,[11] David Salek,[12] Steven Schramm,[13] Oren Slone,[2] Yotam Soreq,[6] Alessandro Vichi,[8,9] Tomer Volansky,[2] Itay Yavin,[14,15] Ning Zhou,[16] and Kathryn Zurek[8,9]

1409.2893

Given these issues, two groups one ATLAS-based & the other CMS-based, independently & with different perspectives came out with some reasonable(?) suggestions

Interplay and Characterization of Dark Matter Searches at Colliders and in Direct Detection Experiments

Sarah A. Malik,[a] Christopher McCabe,[b,c] Henrique Araujo,[a] Alexander Belyaev,[d,e] Céline Bœhm,[b] Jim Brooke,[f] Oliver Buchmueller,[a] Gavin Davies,[a] Albert De Roeck,[g,h] Kees de Vries,[a] Matthew J. Dolan,[i] John Ellis,[g,j] Malcolm Fairbairn,[j] Henning Flaecher,[f] Loukas Gouskos,[k] Valentin V. Khoze,[b] Greg Landsberg,[l] Dave Newbold,[f] Michele Papucci,[m] Timothy Sumner,[a] Marc Thomas[d,e] and Steven Worm[e]

1410.4075

Simplified Models for Dark Matter Searches at the LHC: Proceedings of the DM@LHC2014 Workshop

Jalal Abdallah[1], Henrique Araujo[2], Alexandre Arbey[3,4], Adi Ashkenazi[5], Alexander Belyaev[6], Joshua Berger[7], Celine Boehm[8], Antonio Boveia[4], Amelia Brennan[9], Jim Brooke[10], Oliver Buchmueller[2], Giorgio Busoni[11], Lorenzo Calibbi[12], Sushil Chauhan[13], Nadir Daci[14], Gavin Davies[2], Isabelle De Bruyn[14], Paul De Jong[15], Albert De Roeck[4], Kees de Vries[2], Daniele Del Re[16], Andrea De Simone[11], Andrea Di Simone[17], Caterina Doglioni[18], Matthew Dolan[7], Herbi Dreiner[19], Aielet Efrati[20], John Ellis[21], Sarah Eno[22], Erez Etzion[5], Malcolm Fairbairn[21], Brian Feldstein[23], Henning Flaecher[10], Feng Eric[24], Marie-Helene Genest[25], Loukas Gouskos[26], Johanna Gramling[18], Uli Haisch[23], Anthony Hibbs[23], Siew yan Hoh[27], Walter Hopkins[28], Valerio Ippolito[29], Thomas Jacques[18], Felix Kahlhoefer[23], Valentin V. Khoze[8], Andreas Korn[30], Khristian Kotov[31], Shuichi Kunori[32], Greg Landsberg[33], Sebastian Liem[34], Tongyan Lin[35,36], Steven Lowette[14], Robyn Lucas[2,37], Luca Malgeri[4], Sarah Malik[2], Antony Martini[38], Christopher McCabe[8], Alaettin Serhan Mete[39], Enrico Morgante[18], Stephen Mrenna[40], Yu Nakahama[4,41], Dave Newbold[10], Karl Nordstrom[42], Priscilla Pani[15], Michele Papucci[43,44], Sophio Pataraia[45], Bjoern Penning[35], Deborah Pinna[46], Giacomo Polesello[47], Davide Racco[18], Emanuele Re[23], Antonio Walter Riotto[18], Thomas Rizzo[7], David Salek[15,34], Subir Sarkar[23], Steven Schramm[48], Patrick Skubic[49], Oren Slone[5], Juri Smirnov[50], Yotam Soreq[20], Timothy Sumner[2], Tim Tait[39], Marc Thomas[6,37], Ian Tomalin[37], Christopher Tunnell[15], Alessandro Vichi[44], Tomer Volansky[5], Neal Weiner[51], Stephen West[52], Monika Wielers[37], Steven Worm[37], Itay Yavin[53,54], Bryan Zaldivar[12], Ning Zhou[39], and Kathryn Zurek[43,44]

Furthermore, there has been a suggestion that ATLAS & CMS employ identical S.M.'s based on the input from a 'common' working group (a la the Higgs σ's) → →

https://twiki.cern.ch/twiki/bin/view/DMLHC/

Some Comments

- At some level the nature & number of S.M.'s to study is a question of taste also subject to the practical limitations set by the experiments (3-4-5-6 ???) …but w/o loss of coverage

- To be as broad & to allow as much variation as possible one should consider s- vs. t-channel mediators & spin-0 vs. spin-1 mediators & cases with gg vs qq-bar initial states dominating

- At LHC, VV(SS) vs. AA(PP) couplings are ~identical but are not for DD & ID (compare D5 & D8 except near kinematic limit)

- All of the proposals try to take these choices into account… however they all assume that DM is a Dirac/Majorana fermion

- Specific proposals follow…lots of overlap… for good or bad

Specific S.M. Proposals

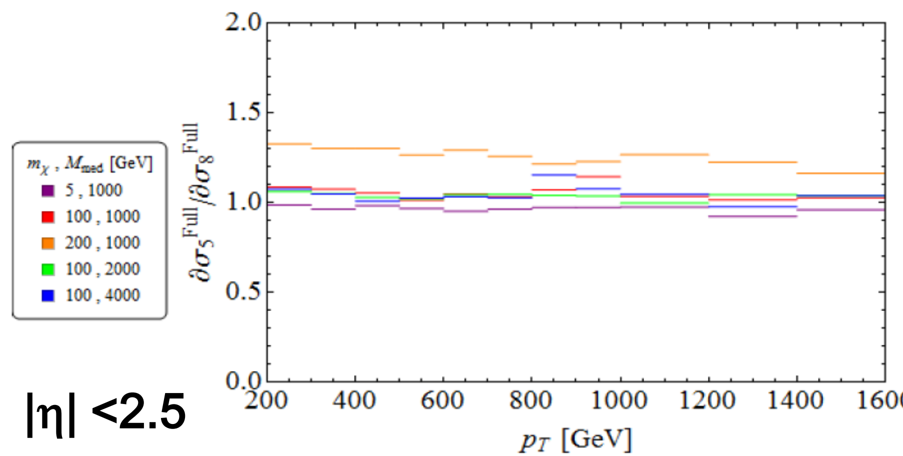
- I will concentrate on the ATLAS-oriented 1409.2893 with a few comments based on the other papers where they make specific distinct points. For all numerical details see the (>100 pages of) documents themselves.

1(a & b). s-channel mediators

g_q flavor universal
y_q " or ~ m_q (MFV)

$$\mathcal{L}_{\rm S} \supset -\frac{1}{2}M_{\rm med}^2 S^2 - y_\chi S\bar{\chi}\chi - y_q^{ij} S\bar{q}_i q_j + {\rm h.c.}\,,$$
$$\mathcal{L}_{\rm S'} \supset -\frac{1}{2}M_{\rm med}^2 S'^2 - y'_\chi S'\bar{\chi}\gamma_5\chi - y_q'^{ij} S\bar{q}_i\gamma_5 q_j + {\rm h.c.}\,,$$
$$\mathcal{L}_{\rm V} \supset \frac{1}{2}M_{\rm med}^2 V_\mu V^\mu - g_\chi V_\mu\bar{\chi}\gamma^\mu\chi - g_q^{ij} V_\mu\bar{q}_i\gamma^\mu q_j\,,$$
$$\mathcal{L}_{\rm V'} \supset \frac{1}{2}M_{\rm med}^2 V'_\mu V'^\mu - g'_\chi V'_\mu\bar{\chi}\gamma^\mu\gamma_5\chi - g_q'^{ij} V'_\mu\bar{q}_i\gamma^\mu\gamma_5 q_j\,.$$

V,A (S,P) couplings very similar @ LHC. E.g., the V/A dσ ratio for the 8 TeV monojet channel:



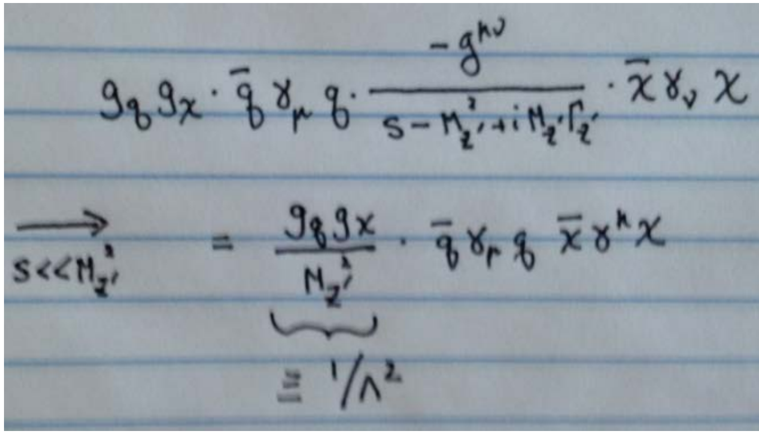
|η| <2.5

4 parameters.. Γ fixed by SM & DM mediator couplings only. Note that only the product of couplings is probed off resonance .

Look at these a little more closely…

$$\mathcal{L}_{\rm S} \supset -\frac{1}{2}M_{\rm med}^2 S^2 - y_\chi S\bar{\chi}\chi - y_q^{ij} S\bar{q}_i q_j + {\rm h.c.}\,,$$
$$\mathcal{L}_{\rm S'} \supset -\frac{1}{2}M_{\rm med}^2 S'^2 - y'_\chi S'\bar{\chi}\gamma_5\chi - y_q'^{ij} S\bar{q}_i\gamma_5 q_j + {\rm h.c.}\,,$$
$$\mathcal{L}_{\rm V} \supset \frac{1}{2}M_{\rm med}^2 V_\mu V^\mu - g_\chi V_\mu\bar{\chi}\gamma^\mu\chi - g_q^{ij} V_\mu\bar{q}_i\gamma^\mu q_j\,,$$
$$\mathcal{L}_{\rm V'} \supset \frac{1}{2}M_{\rm med}^2 V'_\mu V'^\mu - g'_\chi V'_\mu\bar{\chi}\gamma^\mu\gamma_5\chi - g_q'^{ij} V'_\mu\bar{q}_i\gamma^\mu\gamma_5 q_j\,.$$

It is important to note that the in all cases the mediator NOT ONLY links DM to the SM but also the SM to ITSELF (& DM to itself too!). This has important implications…



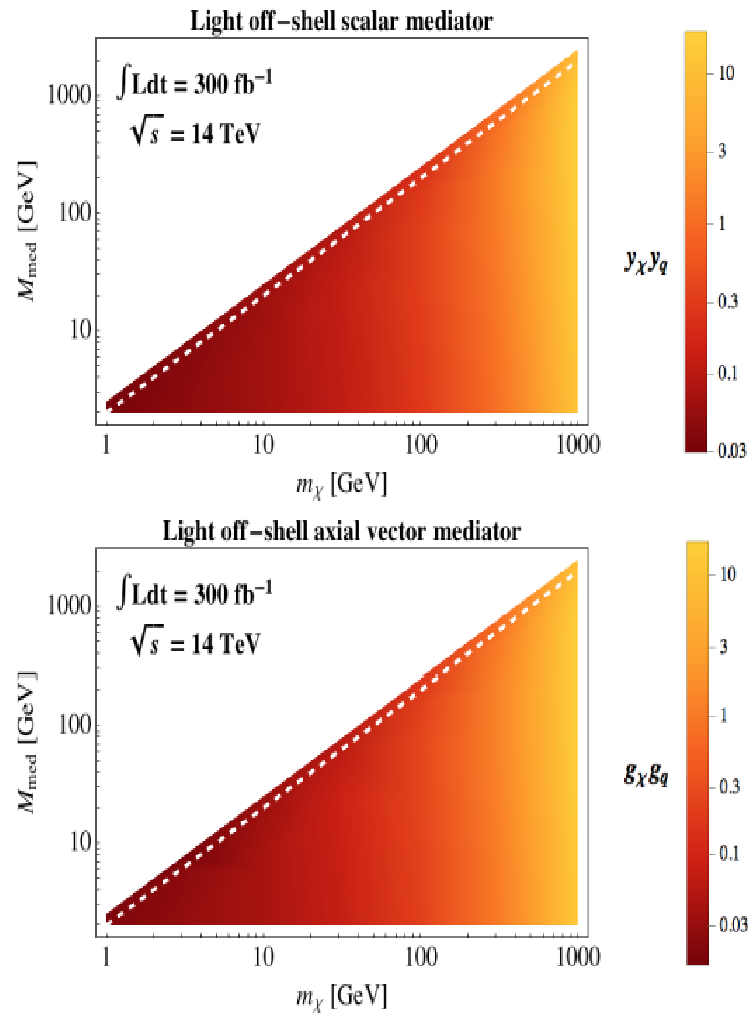
- In principle the mediator could have other exotic decays than to just the SM or DM . Often it is (strongly) suggested that the width be treated as an independent parameter

- s-channel mediators can be probed by SM CI searches and/or can lead to dijet resonances provided the are both narrow (Γ/M <0.15) and g_q is large enough
  → complementary signatures to MET

- A general comment about the monojet searches: Since 'monojet' selections allow for a 2nd hard jet & a 3rd jet veto is also employed (which can't be ignored) the correct QCD treatment is important in setting reaches

- Take care when combining searches with S.M.'s that may depend on the UV completion

Expected 14 TeV Coverage From Monojets



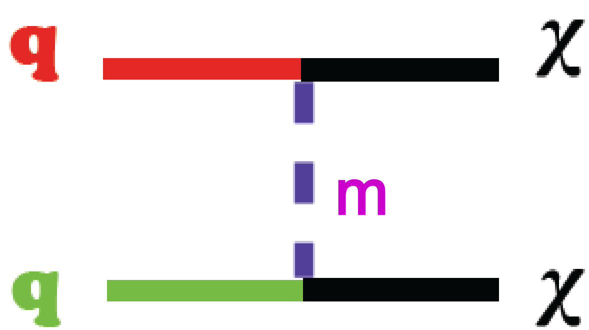
2. t-channel exchange of scalar color triplet(s). ..different production kinematics from s-channel + color radiation from mediator

$$\mathcal{L} = \mathcal{L}_{SM} + g_M \sum_{i=1,2} \left(\widetilde{Q}_L^i \bar{Q}_L^i + \tilde{u}_R^i \bar{u}_R^i + \tilde{d}_R^i \bar{d}_R^i \right) \chi + \text{mass terms} + c.c.$$

These are ‘squarks’ without SUSY coupling constraints

Usually only 3 parameters: the mediator + the (Dirac or Majorana) DM masses + the universal coupling…only d_R or a full degenerate set of Q, u & d to minimize/maximize the signal rates

Mediator pairs can be produced on-shell in gg/qq-bar fusion leading to 2 or more j’s +MET signatures often giving a better reach than monojets. Off-shell production/finite widths effects for large couplings are important



qg-fusion can yield single mediators contributing to monojets

A word of warning:

It is sometimes said that t-channel EFTs can be directly related to a sum of s-channel ones by a Fierz transformation so that there's no need to consider them.

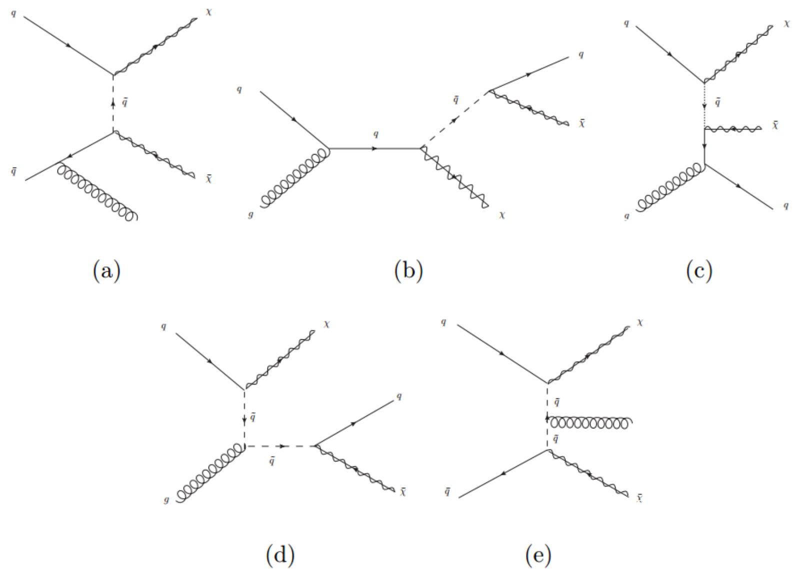
$$
\begin{aligned}
\mathcal{O} &= \frac{1}{\Lambda^2}(\bar{\chi}P_L q)\,(\bar{q}P_R\chi) \\
&= \frac{1}{8\Lambda^2}(\bar{\chi}\gamma^\mu\chi)\,(\bar{q}\gamma_\mu q) \qquad (D5) \\
&+ \frac{1}{8\Lambda^2}(\bar{\chi}\gamma^\mu\gamma_5\chi)\,(\bar{q}\gamma_\mu q) \qquad (D6) \\
&- \frac{1}{8\Lambda^2}(\bar{\chi}\gamma^\mu\chi)\,(\bar{q}\gamma_\mu\gamma_5 q) \qquad (D7) \\
&- \frac{1}{8\Lambda^2}(\bar{\chi}\gamma^\mu\gamma_5\chi)\,(\bar{q}\gamma_\mu\gamma_5 q) \qquad (D8) \\
&= \frac{1}{2\Lambda^2}(\bar{\chi}\gamma^\mu P_R\chi)\,(\bar{q}\gamma_\mu P_L q)\,.
\end{aligned}
$$

← e.g.

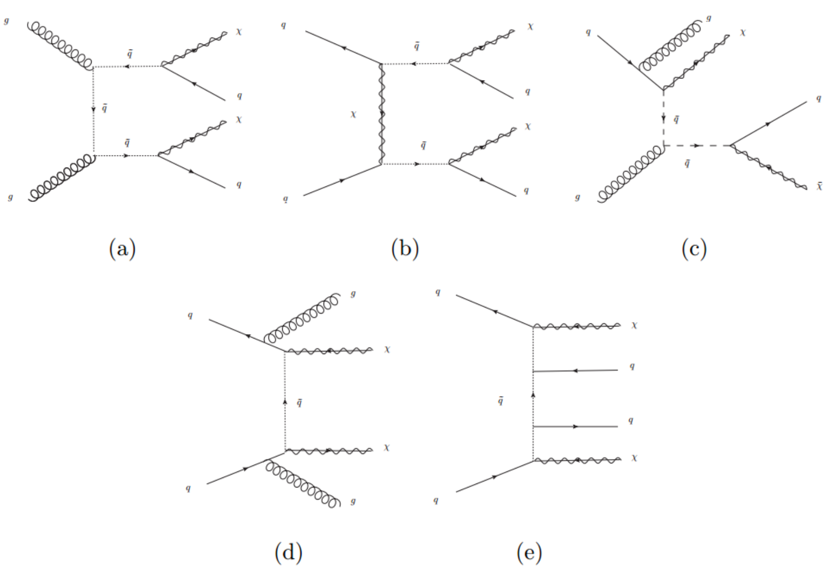
While this is true in the contact interaction limit it clearly does not hold when we go to a S.M. since the physical mediator has a fixed spin, color, etc.

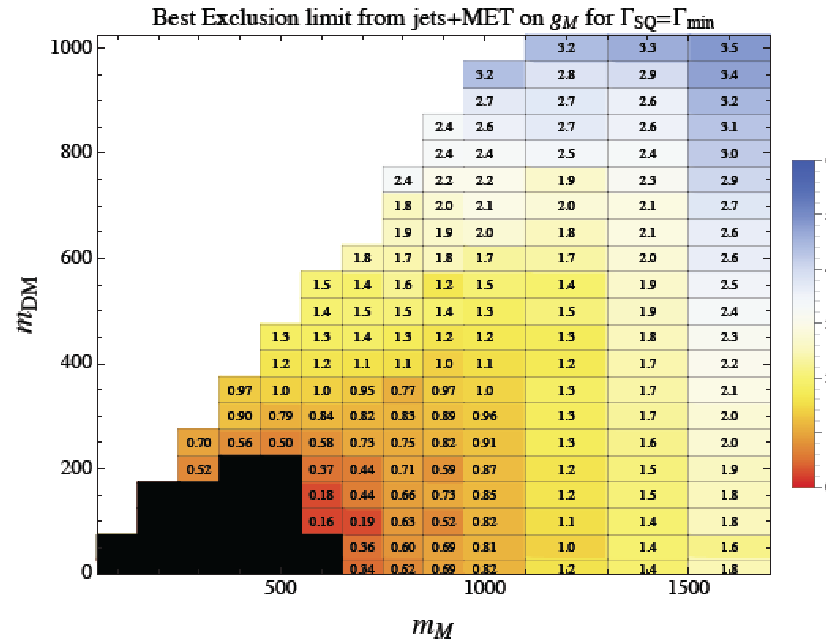
A color-triplet scalar cannot produce an s-channel exchange diagram although the first & last CI's are equivalent

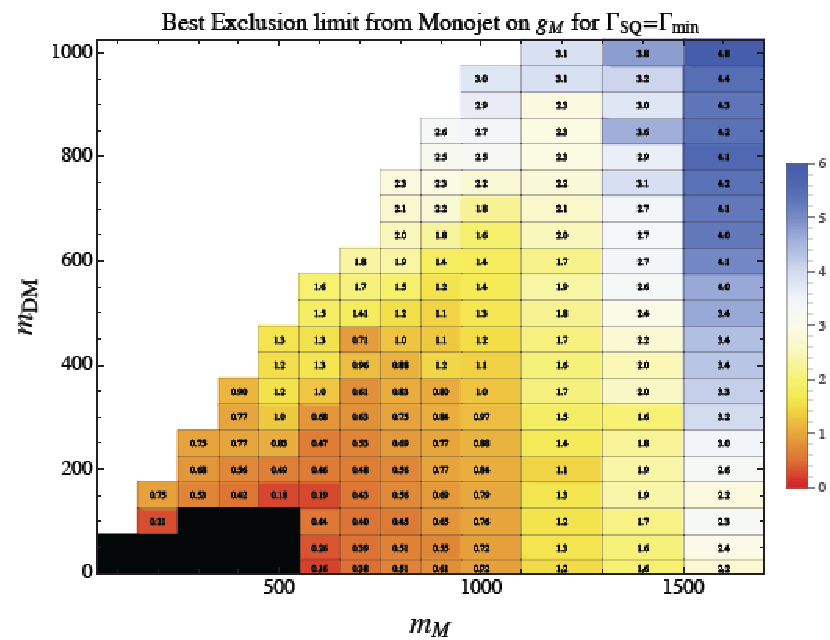
Jets+MET vs monojet searches



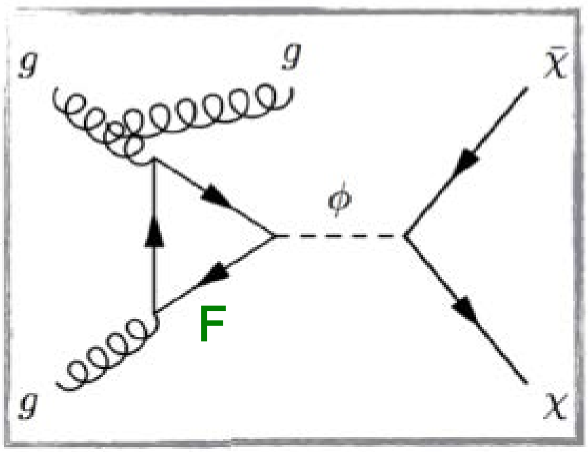
t-channel mono- & di-jet production from 1402.2285…complex compared to EFT case



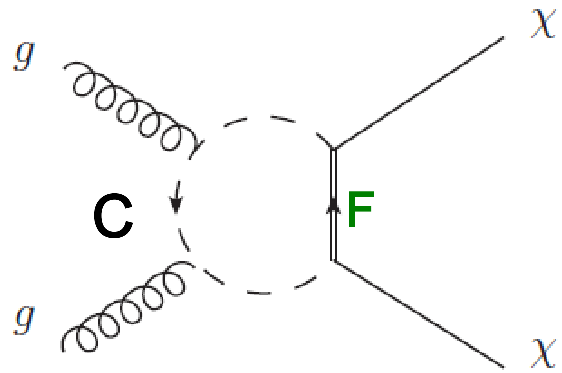




3. gg initial state DM production in s/t-channel via a loop: dim-7 EFT for Dirac or Majorana DM & more complex than above. Several 'resolutions' in 1 or 2 steps are possible & at least 2 mediators are generally required--usually a colored fermion plus some scalar, e.g. ,



The scalar CAN be the Higgs and the fermion CAN be top in which case the triangle graph must be supplemented by boxes & by radiation off tops as they are resolved for p_t's > ~$2m_t$.



More frequently F,S are new heavy states e.g., a vector-like quark whose mass is generated by a singlet Higgs vev. Then

$$1/\Lambda^3 \rightarrow \sim 1/v_s \times 1/M_s^2$$

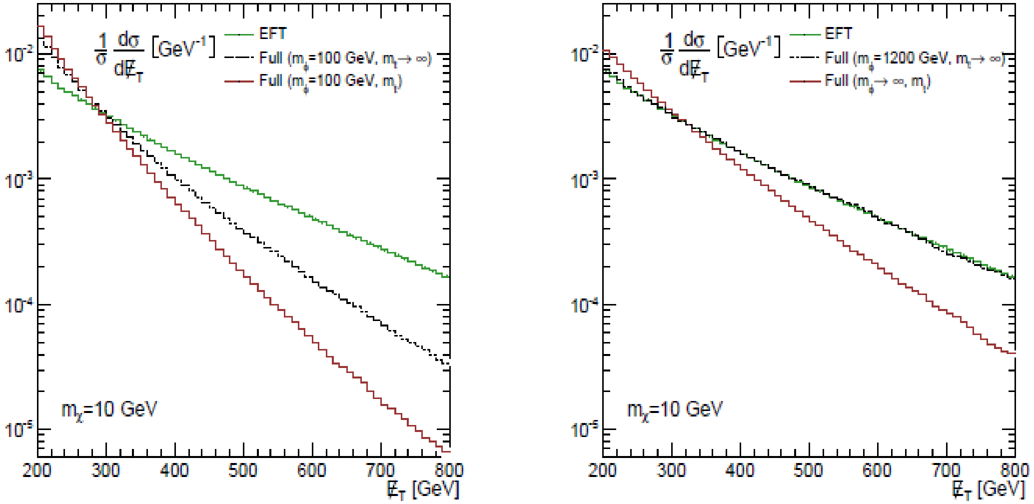


FIG. 3: Missing energy distribution for the process $pp \to \bar{\chi}\chi + j$ in the EFT $\mathcal{O}_G = \alpha_s/\Lambda^3\, \bar{\chi}\chi G_{\mu\nu}G^{\mu\nu}$ (equivalent to the left panel of Fig. 1), for a finite mediator mass with an effective coupling to gluons $m_t \to \infty$ (lower center panel of Fig. 1) and the Full Theory including the top mass effects (right panel of Fig. 1). On the left panel we display the results for a light mediator and on the right for a very heavy one (equivalent to the upper center panel of Figure 1). These distributions were generated at the parton level with MCFM and LHC at 8 TeV.

It is interesting to examine how the finite fermion (top for example) and scalar masses modify MET distributions in, e.g., monojet searches..

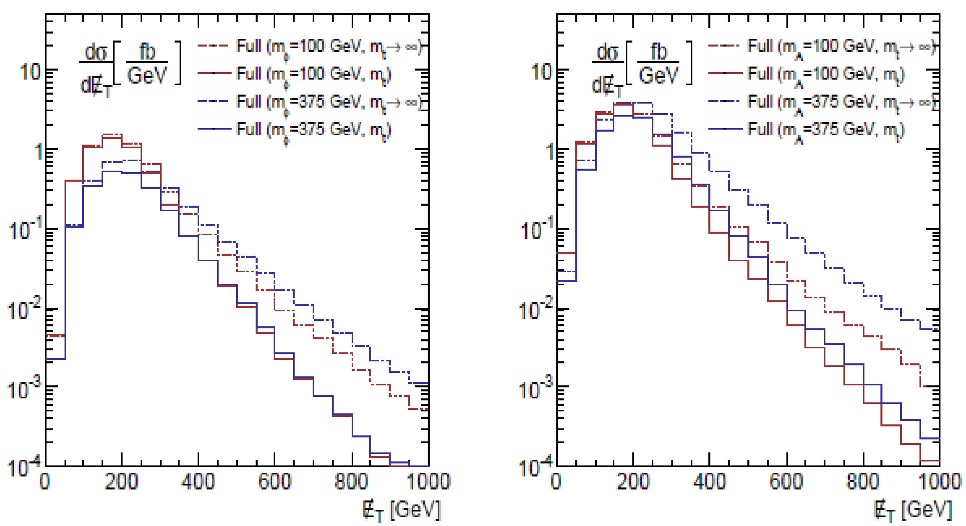


FIG. 8: Missing transverse momentum differential cross sections for the scalar (left panel) and pseudoscalar (right panel) mediators. The leading order effective gluon couplings are shown as dashed lines, and the exact loop-induced calculations are solid. We assume the LHC at 8 TeV.

These distributions show that the assumptions made about the nature & identity of the mediators can have a profound influence on what is seen

1410.6497

Final Comments

- Lots of details have necessarily been omitted above. The list of candidate S.M.’s here is hardly exhaustive.
- A reminder that S.M.’s are NOT full theories where, e.g., multiple mediators may be present & be relevant for different types of searches
- It is not always useful to apply other constraints before using a S.M., e.g., a line showing the ‘correct’ relic density on a plot is fine but it should not be used as input, etc.
- It is obviously more difficult to present results employing S.M.’s due to the enlargement of the parameter space… but all projections are useful & should be shown

Summary & Conclusions

- Although EFTs are valuable when used carefully, they are not very practical for LHC DM searches. UV-complete theories always work but provide only a small set of DM possibilities $\rightarrow$ Move to Simplified Models. The cost is more parameters & multiple, non-unique choices

- S.M.'s should sample spin 0 vs 1 mediators , gg vs qq-bar initial states & s- vs t-channel exchanges. (Too) many scenarios possible. Balance of effort vs completeness in coverage necessary

- It'd be GREAT if ATLAS & CMS would agree on a small set of S.M.'s to examine & compare… some effort along these lines is underway.

- Many different searches for DM are important…not just mono-X !

- Remember that S.M.'s are NOT full theories

Backups

Effective Field Theories (cont.)

- $\Lambda = M/\sqrt{g_\chi g_q} \geq M/4\pi \oplus M > (2)m_\chi$ is the usual statement
- Operators that behave almost identically at the LHC, e.g., 'VV' above vs. the analogous 'AA' coupling (or with Dirac vs. Majorana DM) will act quite differently for ID or DD as these are non-relativistic processes that can experience helicity and/or velocity-suppressed cross sections

→ The LHC is 'somewhat less' sensitive to the detailed nature of DM than is either ID or DD…which is both good & bad. E.g., the only difference in sensitivity between the 'VV' and 'AA' operators at the LHC is the PS suppression associated with DM production. But this is the point of complementarity.

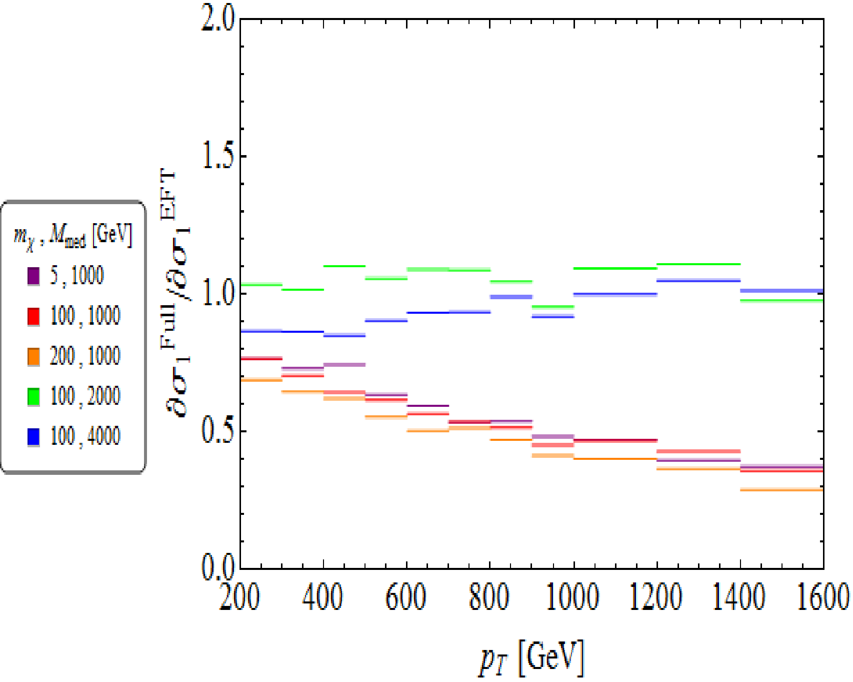
Comments

- Once the mediator is integrated out, the operators that result from s-channel & u,t-channel exchanges can be related to each other by Fierz Identities when DM is fermionic

$$\bar{\Psi}_a \Gamma_i \Psi_b \, \bar{\Psi}_c \Gamma_i \Psi_d \doteq -\sum_j F_{ij} \, \bar{\Psi}_a \Gamma_j \Psi_d \, \bar{\Psi}_c \Gamma_j \Psi_b$$

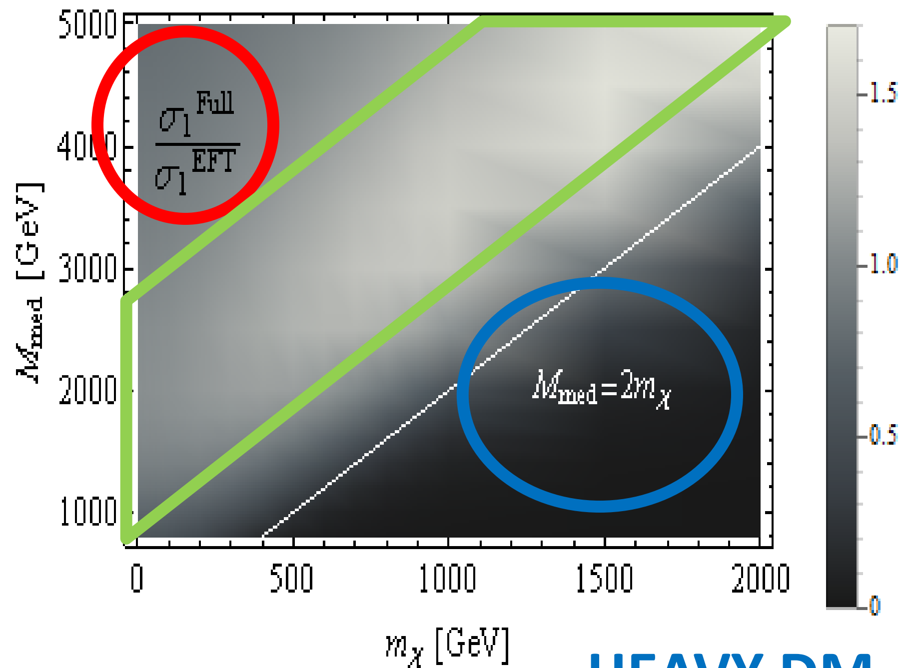
- At the LHC DM searches are always framed as 'mono-X'. DM searches should & must go beyond mono-X +MET. Other channels with MET (e.g., why not jets +MET) can also be restrictive & should be re-examined in this context especially if we go beyond EFT

Simplified Models – s channel - scalar



EFT SAFE

RESONANCE – EFT LIMITS TOO WEAK



HEAVY DM REGION – EFT LIMITS TOO STRONG

1405.3101

Effective Field Theories (cont.)

When applicable, EFT can be very powerful tools to relate different experimental probes of DM. E.g., here bounds on the DM annihilation σ from multiple experiments are compared w/ the 'thermal' relic value

$$\frac{1}{M_q^2}\,\bar{\chi}\gamma^\mu\gamma_5\chi\sum_q \bar{q}\gamma_\mu\gamma_5 q + \frac{\alpha_S}{M_g^3}\,\bar{\chi}\chi G^{a\mu\nu}G^a_{\mu\nu} + \frac{1}{M_\ell^2}\,\bar{\chi}\gamma^\mu\chi\sum_\ell \bar{\ell}\gamma_\mu\ell$$

1305.1605

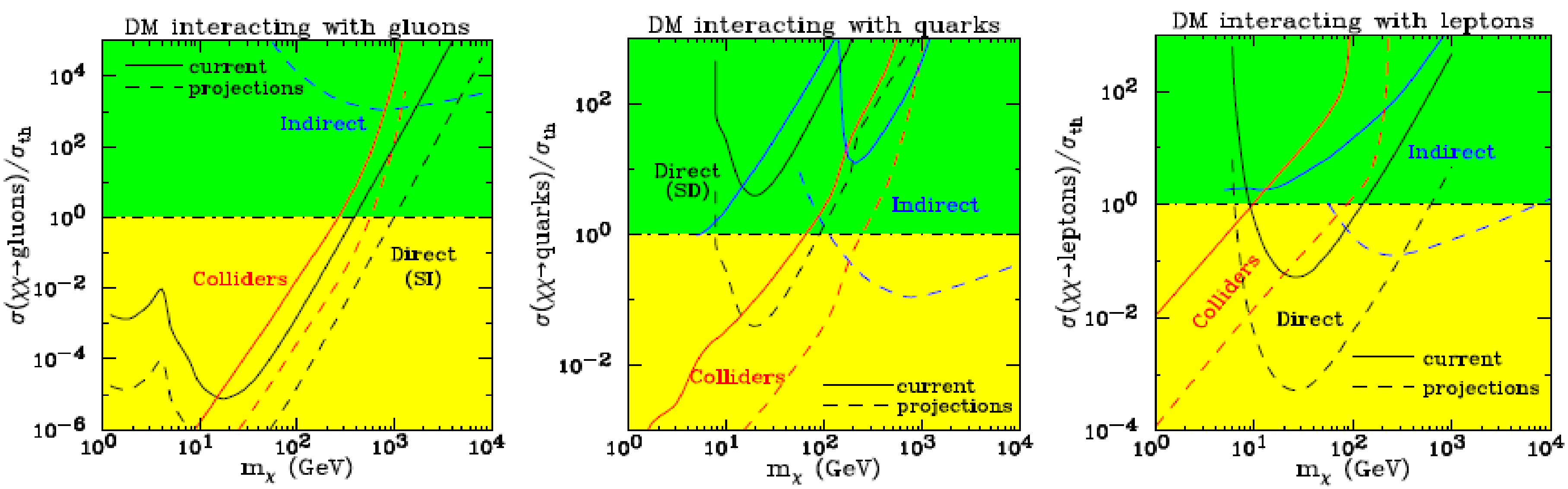


FIG. 2: Dark matter discovery prospects in the $(m_\chi, \sigma/\sigma_{\rm th})$ plane for current and future direct detection [51], indirect detection [52, 53], and particle colliders [54–56] for dark matter coupling to gluons [57], quarks [57, 58], and leptons [59, 60], as indicated.

Effective Field Theories (cont.)

- When are EFT applicable & when do they fail ? If the momenta that flows through the mediator approaches or surpasses the mediator mass the EFT description certainly fails. This is most likely issue at colliders (more later)

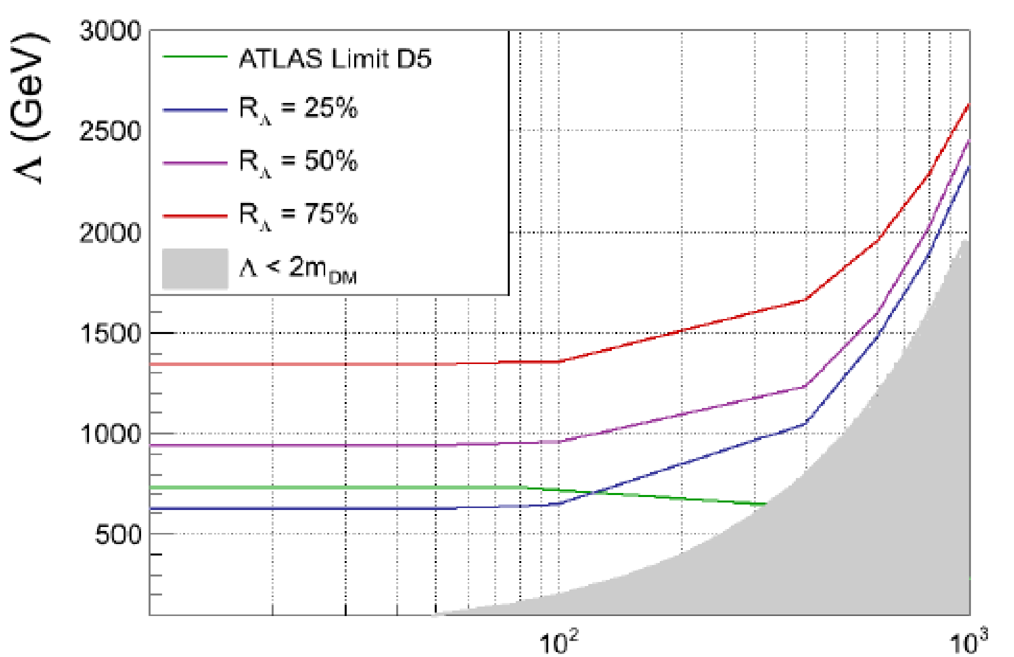
  However, clearly the EFT approach is fine for DD experiments since the Q^2 is always very small <MeV. For ID, problems with EFT only arise if the mediator mass approaches that of the DM in the t,u-channel (from above) or is twice that of DM in the s-channel where a resonance can occur

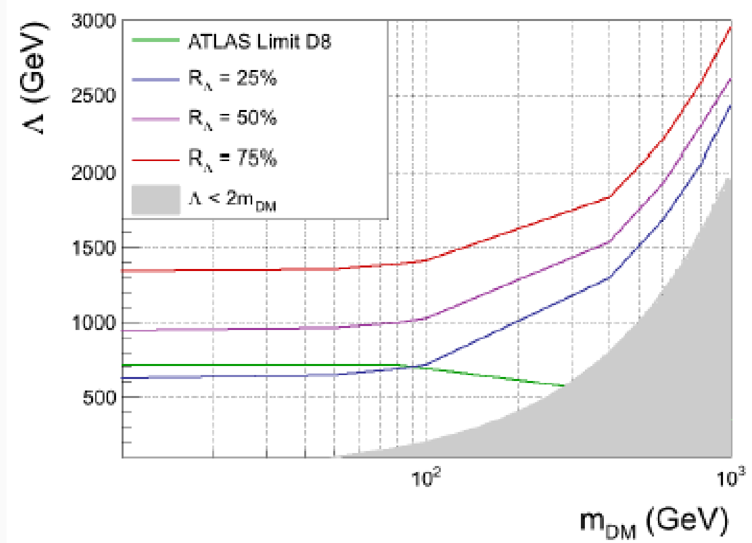
- Note that if $M_m < M_\chi$ then χ can decay (in the massless q limit) & so can't be DM

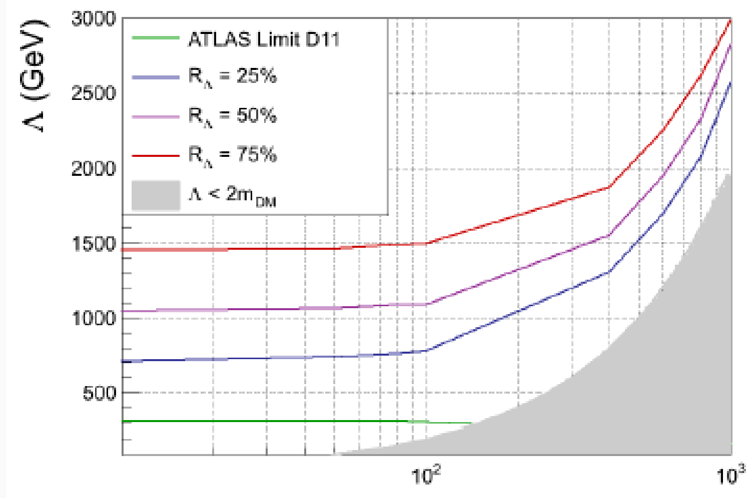
Comparison with latest ATLAS results

- Limits are in Region of R_Λ = 30% or even below!
    - Especially bad: D11 (gluon operator)
- At m_{DM} ~ 100 GeV limit goes down, whereas the R_Λ curves go up

ATLAS results from ATLAS-CONF-2012-147



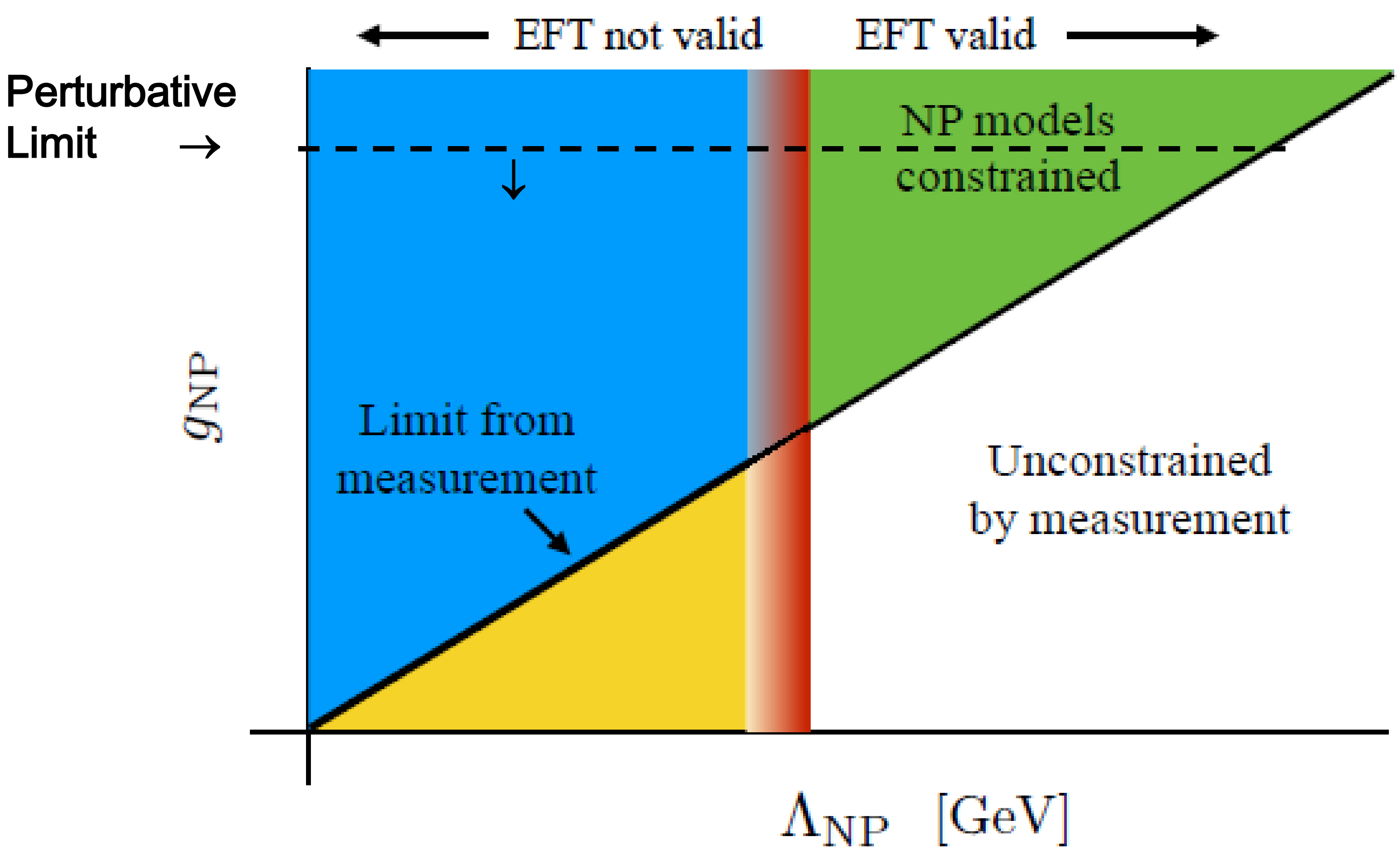




m_{DM} (GeV)

J. Gramling

This is not very encouraging…


EFT not valid
EFT valid
Perturbative Limit
NP models constrained
g_{NP}
Limit from measurement
Unconstrained by measurement
Λ_{NP} [GeV]

1408.5147