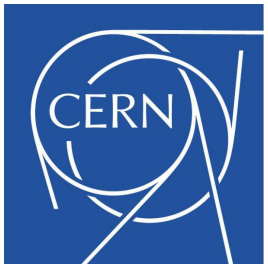
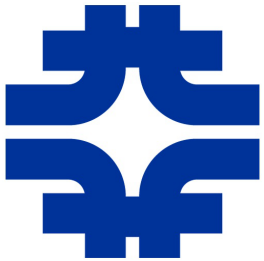
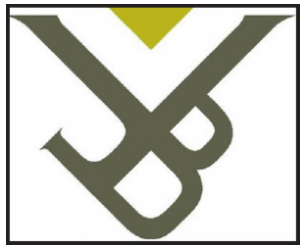


Summary of Discussion on Monojet-like Models

ATLAS/CMS DM Forum Meeting 28/01/2015

Sarah Alam Malik, CMS, Imperial College
Antonio Boveia, ATLAS, CERN
Caterina Doglioni, ATLAS, University of Geneva
Steve Mrenna, CMS, Fermilab
Steven Lowette, CMS, VUB

Mandate of ATLAS/CMS forum

FULL TEXT OF MANDATE

This talk/meeting: monojet-like and HF models

1. Agree on a list of simplified models: sufficiently complete, practical for experiments, endorsed by theory community

- minimal set of building blocks for reinterpretation

Next meetings:

1a. Reach agreement on EW models

1a. Finalize the set of grid points to be scanned

2. Harmonize technical details (generator, matching…)

- for ease of reinterpretation and comparison

3. Discuss presentation of results wrt DD experiments.

4. Role of EFT as benchmark (truncation)

5. Document the work in limited-authorship publication

Guiding principles for model list

Make practical choices for experimentalists: Tight timescale for decision on list (implementation needs discussion as well), number of points/models constrained by limited power of full simulation

Make sensible choices for theorists: List should be complete enough to assemble blocks into more complete theories

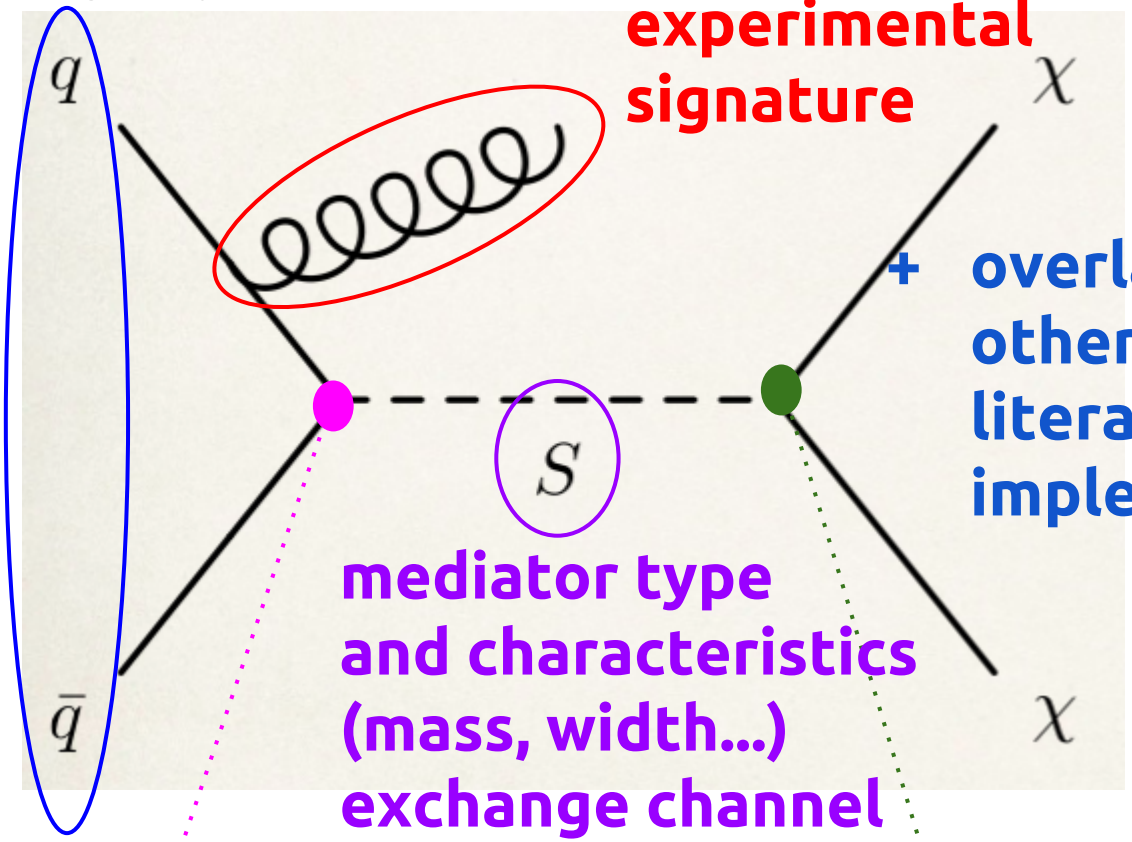
Pay attention to details: Many points to be ironed out (e.g. gluon loop production, widths, possible constraints)

Prepare the ground for future work: Simplifying assumptions can be made, but we must know what we're missing / giving up (e.g. extra searchable signatures?)

Don't reinvent the wheel: Simplified models have been discussed, implemented and tested by many so far → the set of models in these slides will **start from recent discussions and literature**

How to identify a model

Diagram by Thomas Jacques



experimental signature

production mechanism

+ overlap with other searches, literature, implementation

mediator type and characteristics (mass, width...) exchange channel

coupling to SM

coupling to DM

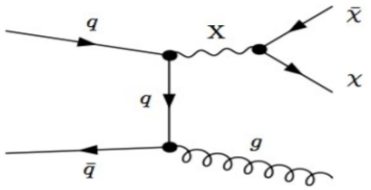
Structure of model description [twiki]

- **Dark Matter type**: type of DM particle considered
- **Mediator type(s)**: type of interaction mediated by mediator particle
- **Mediator mass(es)**: are there constraints on mediator masses / are these free parameters?
- **Channel**: exchange of the mediator: s or t channel
- **SM Couplings** : are there constraints on the couplings between mediator and SM or are these free parameters?
- **DM Couplings**: whether there are constraints on the couplings between mediator and SM / are these free parameters?
- **Includes lepton couplings**: is the model leptophobic?
- **Main signatures**: main experimental signatures produced
- **ME implementation ready**: is there a ME generator ready?
- **References**: list of model description (still incomplete!)
- **Main questions**: questions that need answered in the choices for this model

s-channel, (axial) vector model

https://indico.cern.ch/event/364603/session/1/contribution/4/material/slides/0.pdf

Vector



Vector mediator, includes models commonly used so far by ATLAS and CMS

- **Dark Matter type**: Dirac fermion
- **Mediator type**: Vector
- **Mediator masses**: **M_V**
- **Channel**: s-channel
- **SM Couplings** : **g_q**, universal coupling for quarks only (this would be the most model-independent assumption, theorists will worry about anomalies and correlations between quark and lepton couplings)
- **DM Couplings**: **g_DM**
- **Coupling possibilities:**
  - Vector coupling to DM, axial vector coupling to SM (DM@LHC v2 proceedings)
  - Vector coupling to DM, vector coupling to SM (1308.6799 and DM@LHC v2 proceedings)
  - Axial vector coupling to DM, axial vector coupling to SM (1308.6799)
  - Axial vector couplings to DM, vector couplings to DM (Haisch/Cacciapaglia's suggestion) - is it distinguishable from others?
- **Includes lepton couplings**: no
- **Width**: Calculable
- **Main signatures**: monojet, >=2jet+Met (NLO)
- **ME implementation ready**: yes, Powheg/MCFM (in progress)
- **References**: arXiv:1311.7131, DM@LHC v2 proceedings

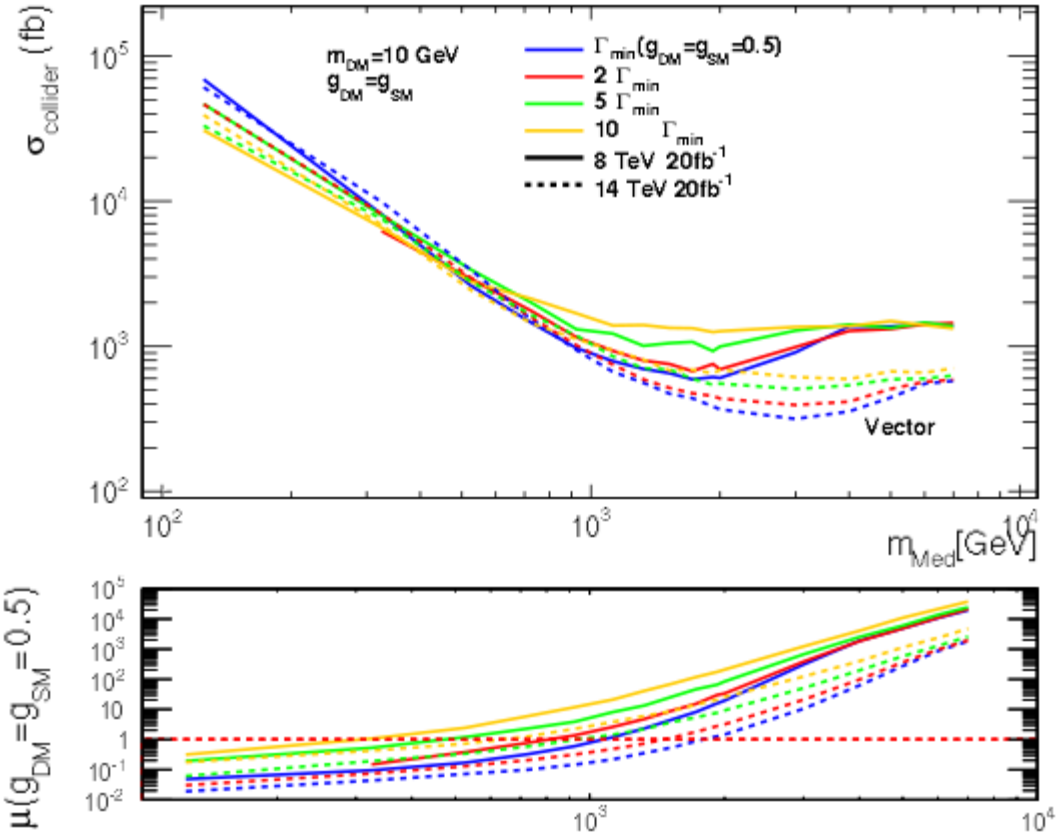
s-channel, (axial) vector model

https://indico.cern.ch/event/364603/session/1/contribution/4/material/slides/0.pdf

Main questions on width assumptions:

a. mediator decays change sensitivity of direct searches

b. width changes kinematics (http://arxiv.org/pdf/1411.0535v1.pdf)



s-channel, (axial) vector model

https://indico.cern.ch/event/364603/session/1/contribution/4/material/slides/0.pdf

Main questions on couplings:

a. which choices (axial/vector couplings to SM/DM) to make?

- **Coupling possibilities:**
  - Vector coupling to DM, axial vector coupling to SM (DM@LHC v2 proceedings)
  - Vector coupling to DM, vector coupling to SM (1308.6799 and DM@LHC v2 proceedings)
  - Axial vector coupling to DM, axial vector coupling to SM (1308.6799)
  - Axial vector couplings to DM, vector couplings to DM (Haisch/Cacciapaglia's suggestion) - is it distinguishable from others?

b. if g_DM = g_q = 1, is this model still observable at the LHC? (arXiv:1411.0535 chooses g = 0.5, these slides suggest three choices of 0.5/1/1.45)

c. should we have g_DM != g_SM choices to compare to direct mediator searches (eg dijets)? One search could be more advantageous wrt the other depending on the coupling ratio.

t-channel, colored scalar models

http://arxiv.org/pdf/1402.2285v1.pdf

http://www.int.washington.edu/talks/WorkShops/int_14_57W/People/Tait_T/Tait.pdf

t-channel (squark-exchange) model (#1, from arXiv:1402.2285)

- **Dark Matter type**: Dirac fermion
- **Mediator type(s)**: Three colored scalars (note: either all mediators or only up-type can contribute, but only x-sec will change)
- **Mediator mass(es)**: Same mass for all three mediators: **M_med** - Maximal Flavor Symmetry assumption
- **Channel**: t-channel
- **SM Couplings** : Same DM and SM coupling for all three mediators: **g**
- **DM Couplings**: Same DM and SM coupling for all three mediators: **g**
- **Includes lepton couplings**: N/A
- **Width**: Calculable, or left as free parameters
- **Main signatures**: Monojet, dijet+MET
- **ME implementation ready**: Yes, Madgraph
- **References**: arXiv:1402.2285

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

t-channel (squark-exchange) model (#2, from DM@LHCv2 proceedings)

- **Dark Matter type**: Dirac fermion
- **Mediator type(s)**: Three colored scalars
- **Mediator mass(es)**: Either degenerate masses (**M_med**) or split between first/second and third generation (**M_1,2**, **M_3**)
- **Channel**: t-channel
- **SM Couplings** : Either degenerate coupling for SM and DM (**g**) or split between first/second and third generation (**g_1,2**, **g_3**)
- **DM Couplings**: same as SM couplings
- **Includes lepton couplings**: N/A
- **Width**: Calculable, or left as free parameters
- **Main signatures**: Monojet, dijet+MET
- **ME implementation ready**: Yes, Madgraph
- **References**: DM@LHC v2 proceedings, talk "Aspects of DM searches" at U Washington by Tim Tait, 1308.2679

$$\mathcal{L} = i\bar{\chi}\partial\!\!\!/\chi - M_\chi \bar{\chi}\chi + (D_\mu \tilde{u})^* (D^\mu \tilde{u}) - M_{\tilde{u}}^2 \tilde{u}^* \tilde{u} + (g_{DM} \tilde{u}^* \bar{\chi} P_R u + h.c.)$$

t-channel, colored scalar models

http://arxiv.org/pdf/1402.2285v1.pdf
http://www.int.washington.edu/talks/WorkShops/int_14_57W/People/Tait_T/Tait.pdf

Main questions:

a. Lagrangians are similar - are there any fundamental differences between the two models?

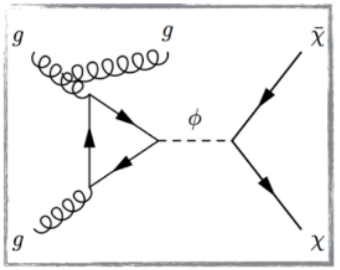
b. what SUSY models (searches) already existing constrain this model?

c. are vector t-channel models difficult to engineer? If we want to keep those for later, specific difficulties might be worth discussing in the write-up.

s-channel, scalar/pseudoscalar model

https://indico.cern.ch/event/364603/session/1/contribution/4/material/slides/0.pdf

$$\mathcal{L}_{\text{fermion},\phi} = \mathcal{L}_{\text{SM}} + i\bar{\chi}\partial\!\!\!/\chi + m_\chi\bar{\chi}\chi + |\partial_\mu\phi|^2 + \frac{1}{2}m_\phi^2\phi^2$$
$$+g_\chi\phi\bar{\chi}\chi + \frac{\phi}{\sqrt{2}}\sum\left(g_u y_i^u \bar{u}_i u_i + g_d y_i^d \bar{d}_i d_i + g_\ell y_i^\ell \bar{\ell}_i \ell_i\right)$$
$$\mathcal{L}_{\text{fermion},a} = \mathcal{L}_{\text{SM}} + i\bar{\chi}\partial\!\!\!/\chi + m_\chi^i\bar{\chi}\chi + |\partial_\mu a|^2 + \frac{1}{2}m_a^2 a^2$$
$$+ig_\chi a\bar{\chi}\gamma^5\chi + \frac{ia}{\sqrt{2}}\sum\left(g_u y_i^u \bar{u}_i\gamma^5 u_i + g_d y_i^d \bar{d}_i\gamma^5 d_i + g_\ell y_i^\ell \gamma^5\bar{\ell}_i\ell_i\right)$$



Scalar mediator, s-channel model from M. Buckley's talk and 1410.6497

- **Dark Matter type**: Dirac fermion, scalar
- **Mediator type**: Scalar, pseudoscalar (complex case)
- **Mediator mass**: **M_phi, M_a**
- **Channel**: s-channel
- **SM Couplings** : Yukawa-like, with prefactor **g_q_i**. Simplest MFV renormalizable case: g_u = g_d = g_l = 1. Phenomenology will differ with different choices.
- **DM Couplings**: no Yukawa structure, **g_DM**, can be = g_SM
- **Includes lepton couplings**: yes
- **Width**: Minimal width calculable, other choices are model-dependent
- **Main signatures**: >=2jet+Met (also with HF)
- **ME implementation ready**: yes, for Dirac fermions (MCFM/Sherpa(soon)/Powheg(soon))
- **References**: arXiv: 1410.6497

Many questions raised for this model idea: this is the simplest, baseline option

s-channel, scalar/pseudoscalar model

https://indico.cern.ch/event/364603/session/1/contribution/4/material/slides/0.pdf

Main questions:

a. are the Yukawa pre-factors independent → can we generate different couplings independently and then combine?

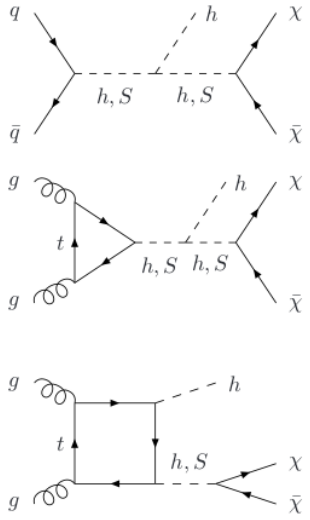
b. how does the kinematic change in case of other DM types (e.g. scalar DM)?

c. we can't neglect DM or mediator couplings to the Higgs
   i. do we treat those as baseline models or as specific cases? If treated as specific cases (seems preferred), need coherence with choices made in scalar model
   ii. do we rely on invisible Higgs searches to constrain parameter space for those specific models?

s-channel, two-scalar model w/Higgs

http://arxiv.org/pdf/1312.2592.pdf ,

This should also be discussed in the context of EW models but has implications for monojet searches: model with mixing of mediator and Higgs boson



New scalar particles may provide a portal into the dark sector [18]. The simplest possibility is to introduce a real scalar singlet, denoted S, with a Yukawa coupling to DM

$$\mathscr{L} \supset -y_\chi \bar{\chi}\chi S\,. \tag{17}$$

By virtue of gauge invariance, S may couple to the SM (at the renormalizable level) only through the Higgs field [37]. The relevant terms in the scalar potential are

$$V \supset a|H|^2 S + b|H|^2 S^2 + \lambda_h |H|^4$$
$$\longrightarrow \tfrac{1}{2}a(h+v)^2 S + \tfrac{1}{2}b(h+v)^2 S^2 + \frac{\lambda_h}{4}(h+v)^4, \tag{18}$$

In Summary: our simplified model is given by the Lagrangian (1.4) and involves two singlet scalar mediators, h_1 and h_2. The first scalar is the 125 GeV SM Higgs, while the second one is an additional Higgs-like scalar. In general, this simplified model is characterised by five parameters: the mass and the widths of the second scalar, m_{h_2} and Γ_{h_2}, the DM (or invisible fermion's) mass, m_χ, the mixing angle θ and the DM coupling g_χ.

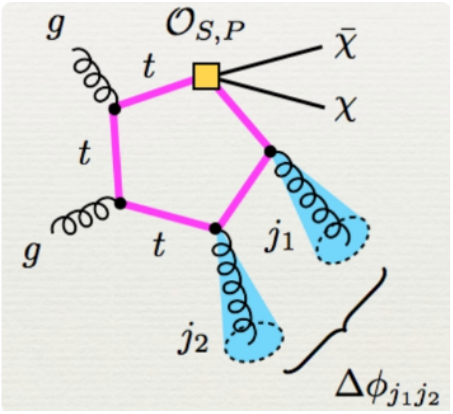
We note that these five parameters are in one-to-one correspondence with the five parameters characterising the scalar and pseudo-scalar mediated simplified models for DM searches at

s-channel, top-loop scalar model

https://indico.cern.ch/event/364603/session/1/contribution/8/material/slides/0.pdf

Scalar mediator, s-channel top loop model from U. Haisch and E. Re's talks and 1410.6497

- **Dark Matter type**: Dirac fermion, scalar
- **Mediator type**: Scalar, pseudoscalar (complex case)
- **Mediator masses**: **M_phi**, **M_a**
- **Channel**: s-channel, but also EFT
- **SM Couplings** : only coupling to top
- **DM Couplings**: no Yukawa structure, **g_DM**
- **Includes lepton couplings**: no
- **Width**: Calculable
- **Main signatures**: 2jet+Met, can exploit angular correlations
- **ME implementation ready**: in progress, Powheg
- **References**: arXiv:1311.7131
- **Main questions**:
  - validity of EFT (do we want to include it?)



General points for further discussion

General choices and considerations for all models:

- m_DM, m_Med are free parameters to scan
- Consider all 6 quarks for width calculation
- Consider loop generation of mediator as well when necessary, specialized event generators available
- All width calculations should be considered as minimal and scanned with one or two wider assumptions
- It will be difficult to do generator-level scans for experiments, full simulation is needed in many cases and desired by the collaborations. We can however provide truth-level acceptances and reconstruction correction factors so that it is the theorists doing the scan and reinterpreting the experimental results.

General questions:

- Why do we restrict ourselves to Dirac DM? What would change with scalar (real/complex) or vector, or Majorana fermion DM?
- How seriously do we consider other constraints on simplified models? E.g. arXiv: 1501.03490
- How simplified should our models be? Should we consider "less-simplified" models (eg, scalar mediator mixing with the Higgs, does not introduce too many extra parameters) within the original starting list?

How to move forward

Gather implementations of chosen models: what is the minimal information we need to simulate those models at the matrix element (Madgraph?) → organizers will collect and place it somewhere public

Check of our assumptions: scan **at truth-level** models that are not on the list (e.g. different kinds of DM), compare kinematics with models that have been chosen → need volunteers to provide models and run truth-level code

Next step: decisions on grid points

1) keep discussing on the mailing list, conclusion to be reached at the next meeting
2) systematic scan results for chosen models would be useful: how does the kinematic of search variables change?