Toward a next generation of simplified DM models

Kristian Hahn – Northwestern Univ.
(representing the work of many)

LHC DM WG Workshop
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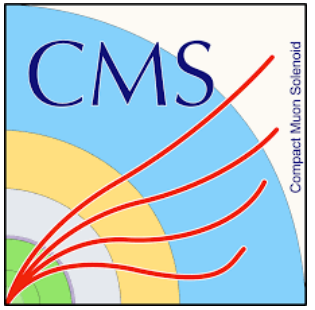
CERN



Outline

- Scalar singlet model with mixing (SMM)
- Discovery scenarios
- Other simplified models
- DM mechanisms in SUSY

Primary proposal (and focus of this presentation) is the inclusion of the SMM as recommened benchmark model

The other topics are only briefly reviewed …

- Propose to revisit these in a later meeting of the LHC DM WG

Proposals derived from discussions and studies involving several from CMS and the theory community

Towards the next generation of simplified Dark Matter models

arXiv:1607.06680

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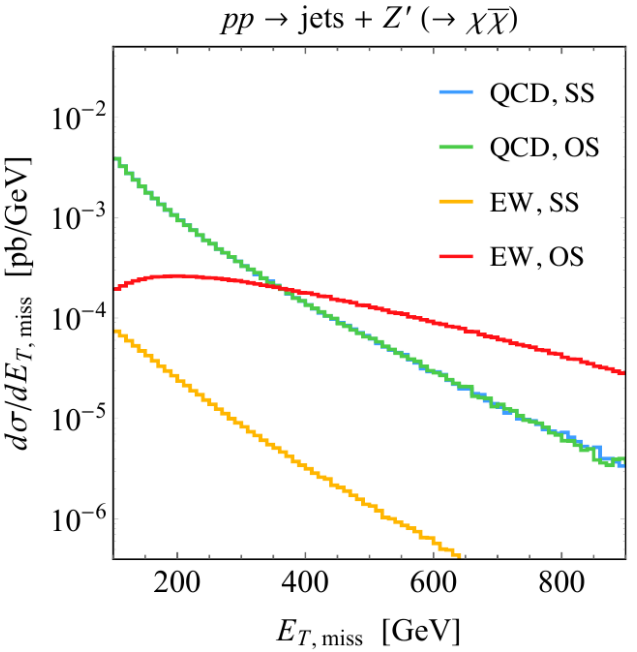
Simplified Models

Motivation

- Capture key features of DM processes @ the LHC
- Really just model "snippets", but useful :
  - Provides simple framework for probing hallmark MET signatures
  - And a basis for comparison between MET+X channels, with DD/ID, relic density
  - Avoid choosing amoung numerous UV-completions

Simplification → Caveats

- UV completion not specified
  - Possible bad high s-behaviour: breakdown of perturbative unitarity
  - Possible issues with gauge symmetry: breakdown at lower energy scales
- Can give misleading picture of sensivity of various search channels
  - Spin-1 Example : mono-W, monojet (+EW)
  - C.f. 1503.07874, 1512.00476, 1603.01267



from 1603.01267

Simplified models should not have pathologies in the channels or regions in which they are applied

- See discussions in 1510.02110, 1604.07975

With current crop of simplified models, one might:

- Restrict couplings
- Add interactions / fields
- Reduce coupling strengths

These treatements developed for mono-W in 1603.01267

For coherent comparison/combination of DM searches, must propagate to all relevant channels

Another approach: use gauge invariant & unitary models

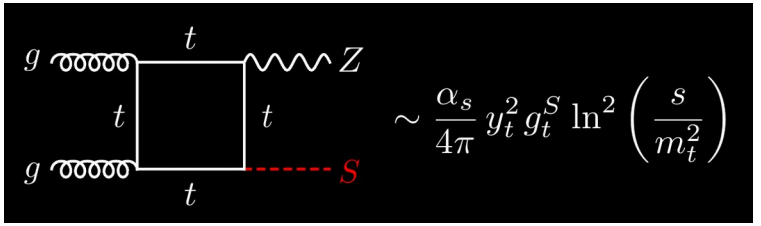
- Avoid pathologies by construction
- Ensure consistency by design

Spin-0 Simplified Models

Some “features” of the current scalar DMF models

- ttS coupling not gauge invariant
- gg → SZ divergent @ high-s
  - Although not of particular concern at the LHC …
- The ttSZ interaction also ?
  - Probably not a conern either ...
- Lack some interactions that *are* gauge invariant

$$\mathcal{L} \supset -g_t^S \frac{m_t}{v} S\bar{t}t = -g_t^S \frac{m_t}{v} S\left(\bar{t}_L t_R + \bar{t}_R t_L\right)$$



$$\sim \frac{\alpha_s}{4\pi} y_t^2 g_t^S \ln^2\left(\frac{s}{m_t^2}\right)$$

$$S|H|^2,\ S^2|H|^2,\ S^3,\ S^4$$

From U. Haisch

Scalar model with mixing (SMM)

- Example of a simple gauge invariant, unitary model
- A good basis for an apriori consistent treatment of spin-0 channels
  - VBF, W/Z associated, mono-H, mono-X … all with single model!
- Distinct phenomenology vs current scalar simplified models

The SMM

Simplest extension of the SM that includes DM

- Fermion DM
- Scalar mediatior portal

$$\mathcal{L} \supset -y_{\mathrm{DM}}\, s\, \bar{\chi}\chi - \mu\, s\, |H|^2$$

Usual mediator-DM coupling, as in DMF models

New portal interaction

Portal interaction induceds scalar/Higgs boson mixing

- Mass eignestates: h1 & h2
- Take h1 to be observed 125 GeV state

$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} h \\ s \end{pmatrix}$$

h1,h2 couplings to DM & SM fermions,W,Z through mixing

$$\mathcal{L} \supset -\, y_{\mathrm{DM}} \left(\sin\theta\; h_1 + \cos\theta\; h_2 \right) \bar{\chi}\chi$$

$$+ \left(\cos\theta\; h_1 - \sin\theta\; h_2 \right) \left(\frac{2M_W^2}{v}\, W_\mu^+ W^{-\,\mu} + \frac{M_Z^2}{v}\, Z_\mu Z^\mu - \sum_f \frac{m_f}{v}\, \bar{f} f \right)$$

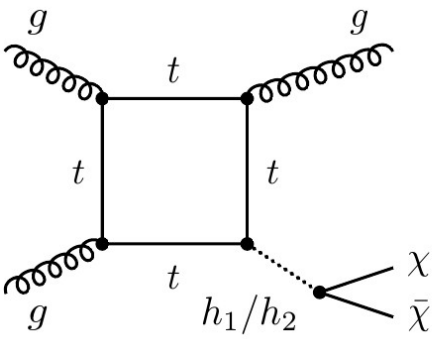
SMM *vs* DMF scalar models

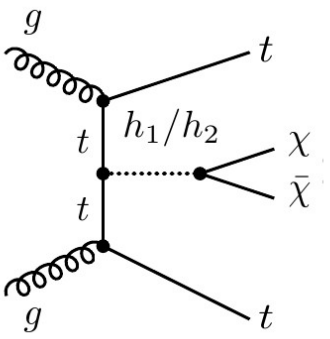
Modified coupling structure with respect to DMF

$$g_{\mathrm{DM}} \longrightarrow y_{\mathrm{DM}} \cos\theta$$

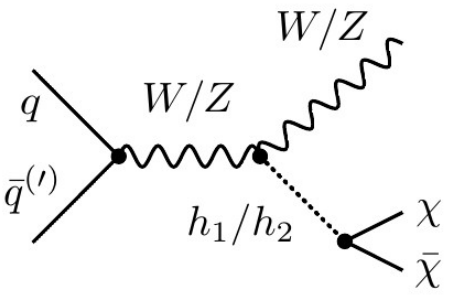
$$g_{\mathrm{SM}} \longrightarrow -\sin\theta$$

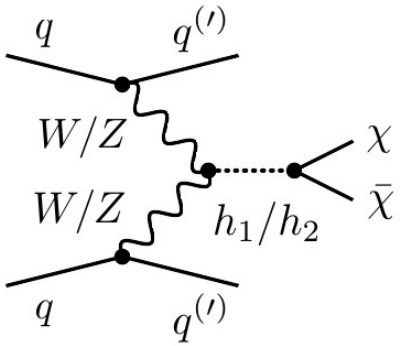
Usual monojet and HF+DM processes, as in DMF





New VBF & mono-V diagrams





Model Details

The SMM

- Starting point: singlet model from Khoze *et al.*, 1505.03019
  - ttS loop implemented as an effective operator
  - Missing h1 → h2, h2 and vice versa
  - 1505.03019 also explores more general (2HDM-inspired) mixing scenario
    - We decided to leave this for later
- Migrated to singlet SMM UFO provided by U. Haisch
  - ttS loop fully resolved
  - h1,h2 trilinear, some quartic interactions included

"DMF" models

- first pass: DMF ttDM MG model, POWHEG for monojet (as in DMF)
  - Different scale choices in POWHEG/MG → difficult to compare
- final pass: use DMSimp for both in MG

SM Higgs

- Also done with DMSimp, provides resolved ttH loop

Kinematic Scenarios

Explore SMM phenomenology in all relevant kimematic regimes, compare with DMF

- A ($m_{h_2} > 2m_\chi > m_{h_1}$) : h2 on shell → DM/h1, h1 → DM forbidden
- B ($m_{h_1} > 2m_\chi > m_{h_2}$) : h1 on shell → DM/h2, h2 → DM forbidden
- C ($m_{h_2} > m_{h_1} > 2m_\chi$) : heavy h2, light DM
- D ($m_{h_1} > m_{h_2} > 2m_\chi$) : light h2, lighter DM

Kinematics : generated pT(χχ) vs mixing angle, coupling

- monojet (1,2 jets) and tt+DM (+ 0,1jet) in SMM & DMF
- Also compare with SM h + 1,2 jet and tth + 0,1 jet

Cross section : vs mixing angle

- tt+DM (+0,1 jet) in SMM & DMF, and SM tth + 0,1 jet
- NB: Run-I Higgs global fit → sinθ < ~0.4

Scenario A : $m_{h_2} > 2m_\chi > m_{h_1}$

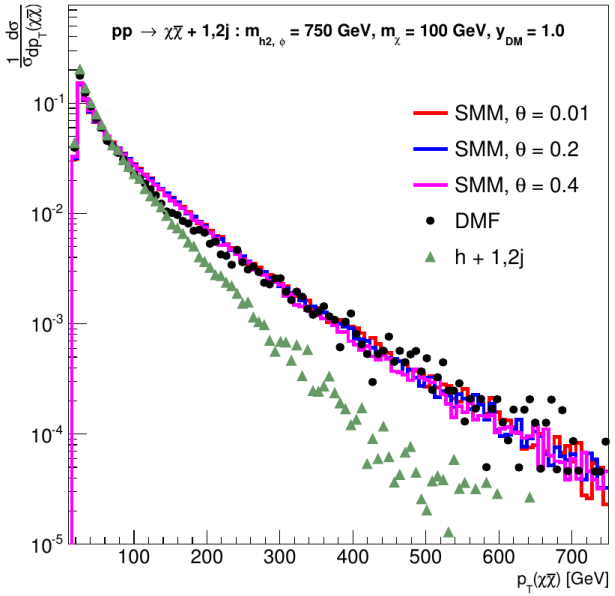
Kinematics

- New h2 scalar mediator can decay into DM
- SSM kinematics generally map to those of DMF
  - Disagreement in monojet near pT(χχ) ~ 150 GeV from new diagrams

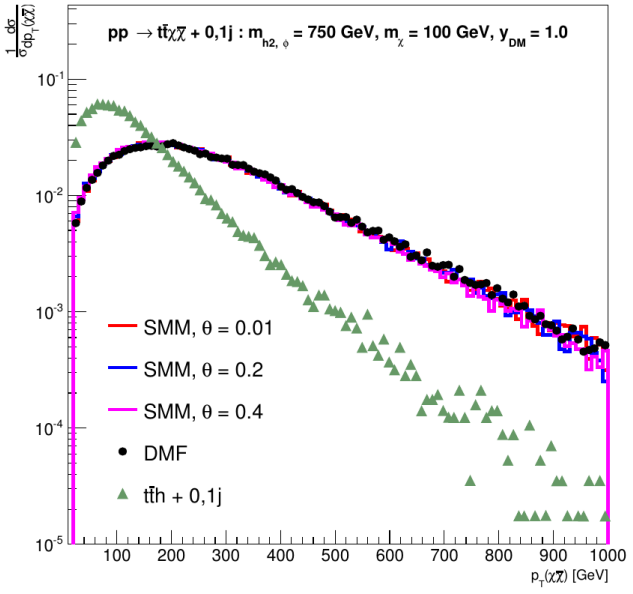
Cross section

- Suppressed relative to DMF and SM

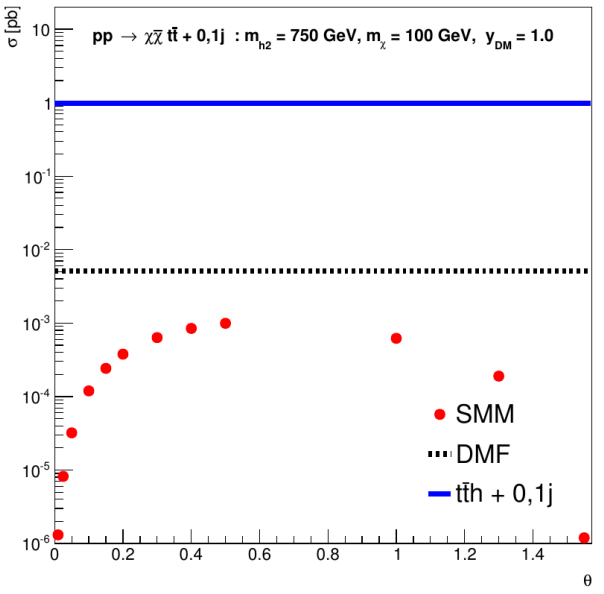
monojet



tt+DM



tt+DM



Scenario B : $m_{h_1} > 2m_\chi > m_{h_2}$

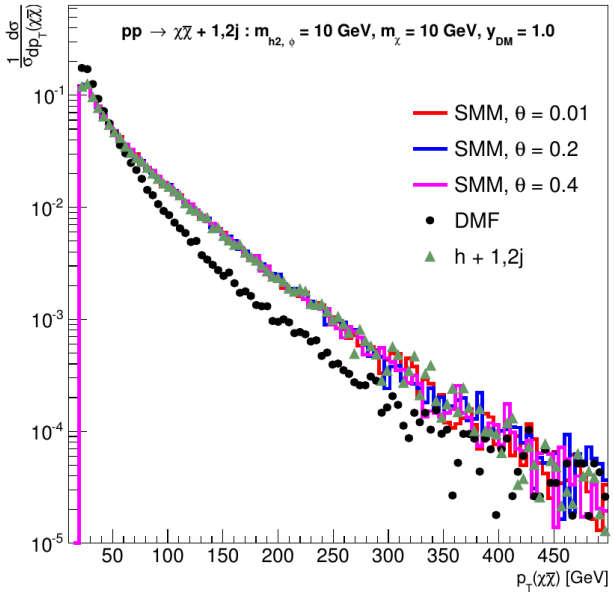
Kinematics

- h1 can decay into DM, new h2 mediator can't
- SSM kinematics map directly to those of SM Higgs

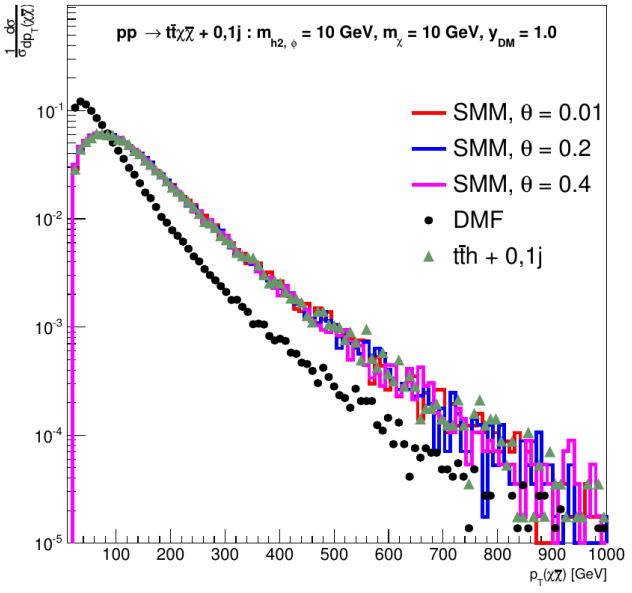
Cross section

- Approaches SM, higher than in DMF
  - Only off-shell decays in the DMF scenario ...

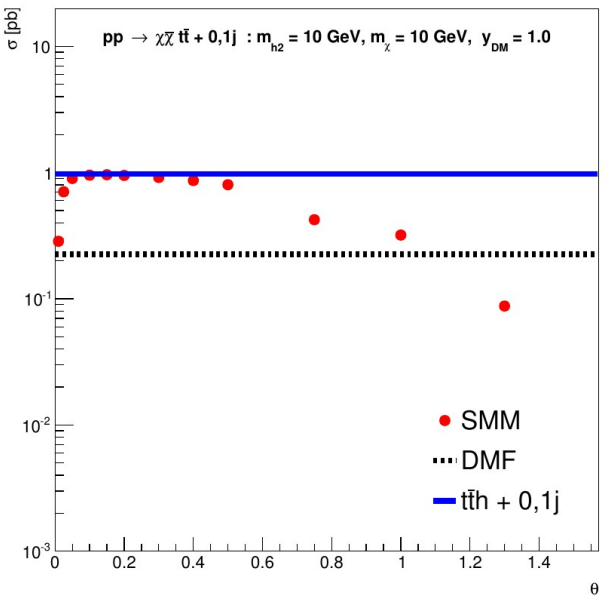
monojet



tt+DM



tt+DM

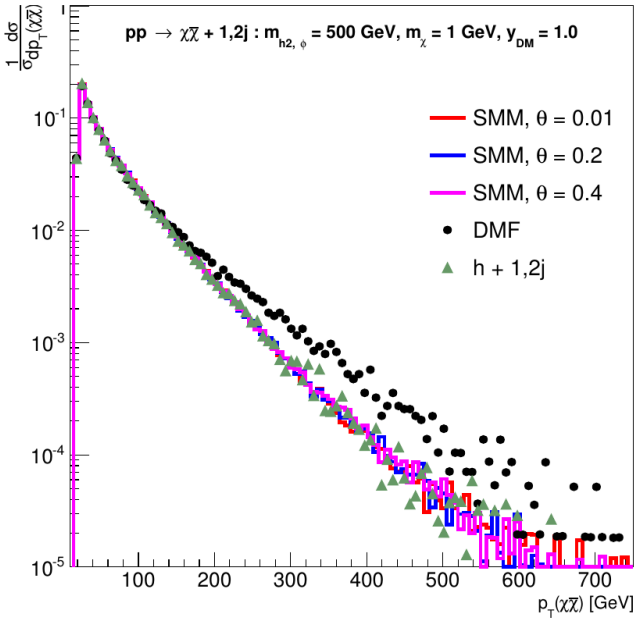


Scenario C : $m_{h_2} > m_{h_1} > 2m_\chi$

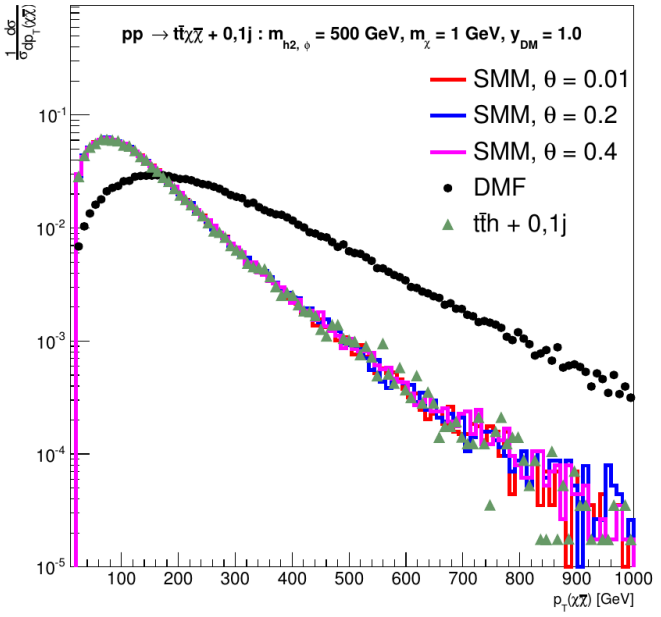
Kinematics

- h1 → DM resonantly enhanced due to small h1 width
- SSM kinematics map to those of SM Higgs

monojet



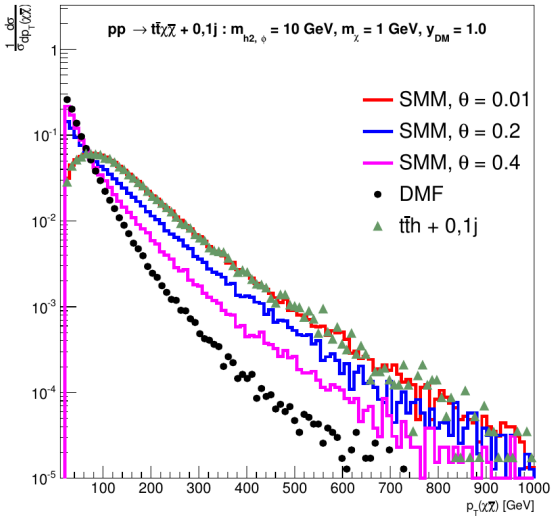
tt+DM

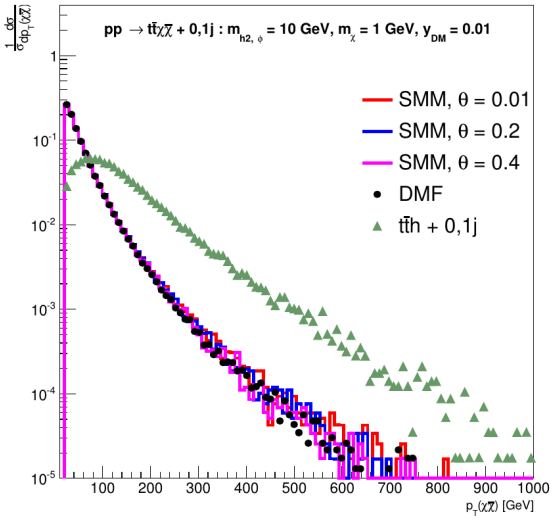


Scenario D : $m_{h_1} > m_{h_2} > 2m_\chi$

Kinematics

- Impact of mixing clear for nominal (yDM = 1.0) couplings
- Both h1 → DM and h2 → DM on-shell
- Both processes important if Γh1 and Γh2 comparable
- Kinematics evolve toward DMF as coupling is lowered

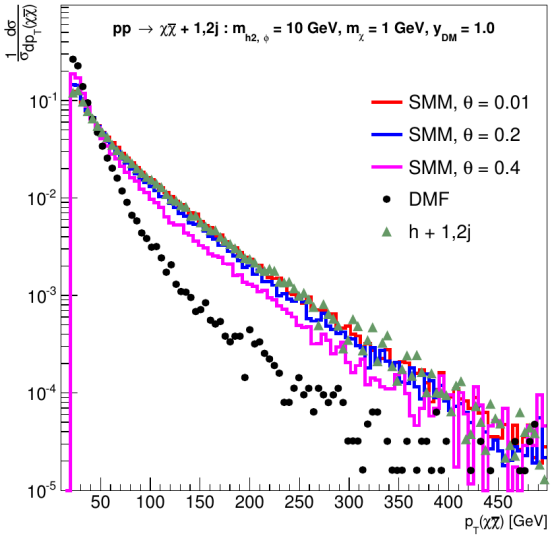


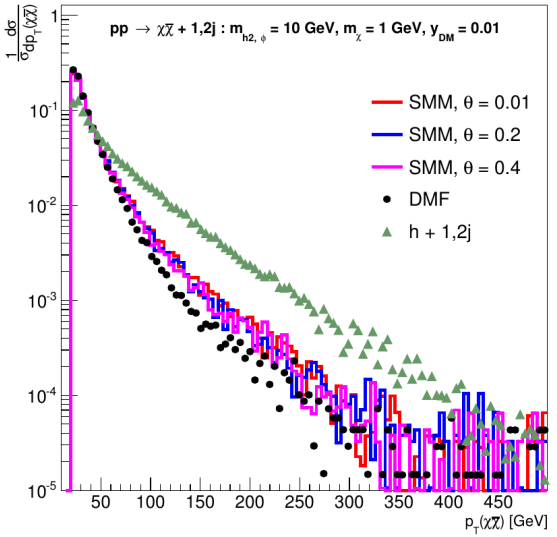


tt+DM

yDM = 1.0

yDM = 0.01



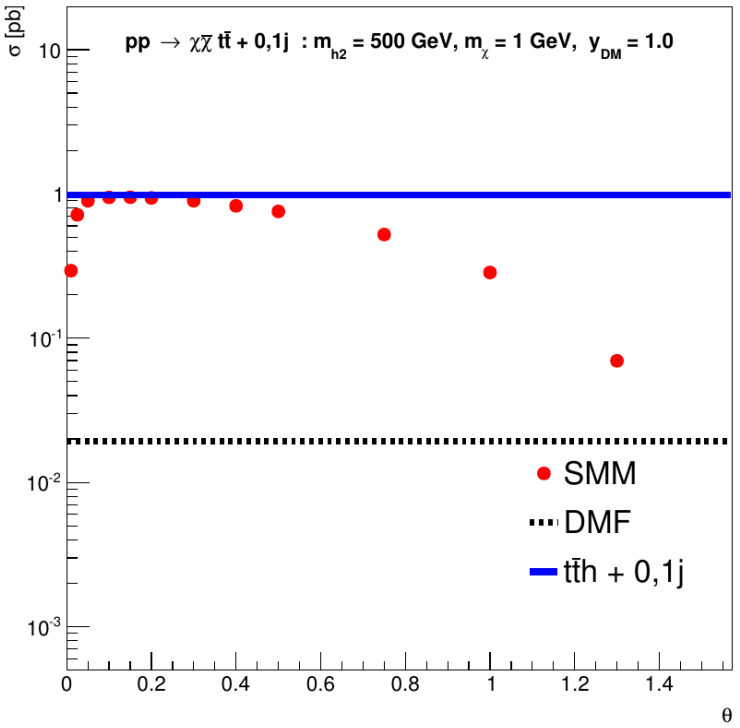


monojet

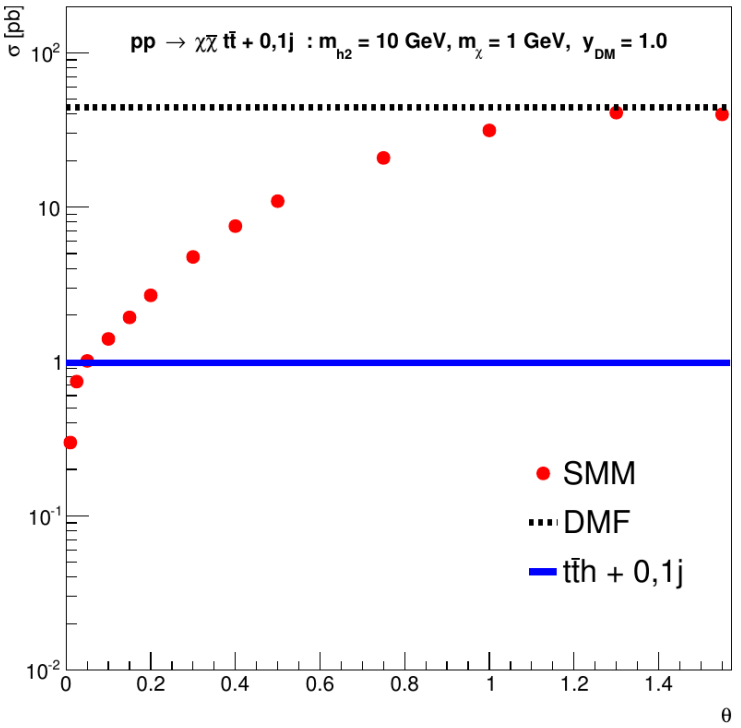
Scenario C/D Cross Sections

Approaches SM Higgs for Scenario C, > σDMF

Generally between σSM and σDMF for Scenario D



Scenario C

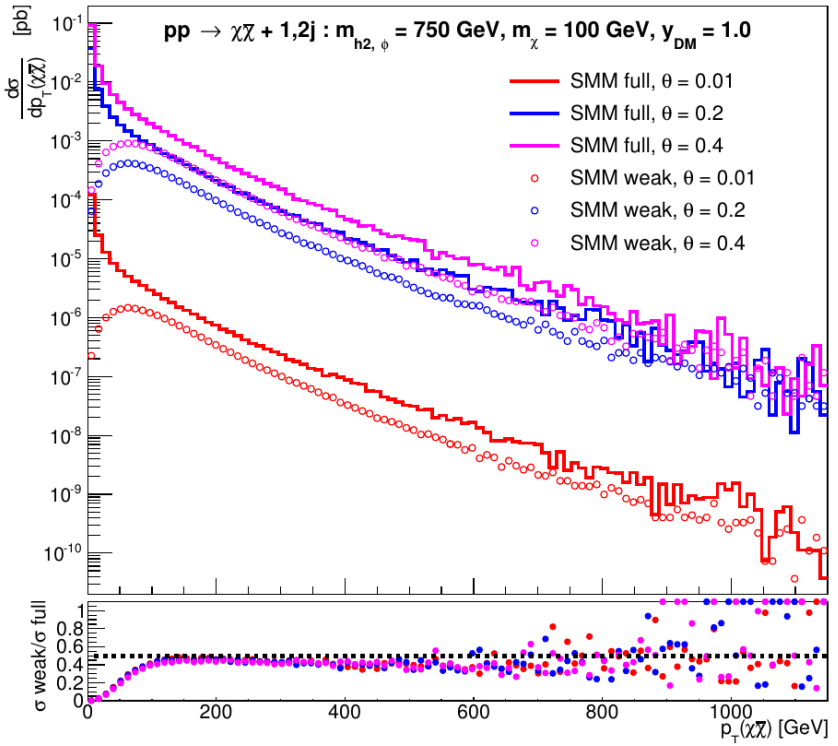


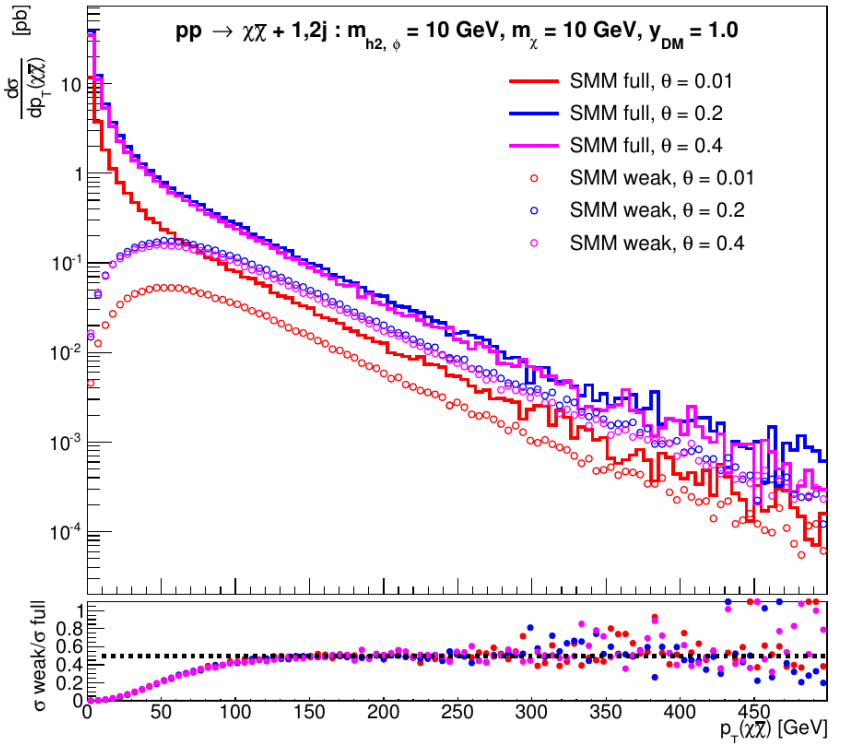
Scenario D

Scenario C/D Differential Cross Sections

Compare full pp → χχ monojet cross section *vs* that of new VB-mediated processes

- Significant contributions from new couplings at high pT(χχ)





Conclusions from SMM

- Higgs mixing is the simplest extention to the current DMF scalar models
- In several regimes, kinematics & cross section differ significantly from those of the DMF models
- SMM displays much richer phenomenology
  - In particular, from new vector boson mediated processes
- The model is gauge invariant and unitary
  - Provides a useful basis for the comparison/combination of scalar-mediated DM searches
  - VBF, W/Z associated, mono-H, mono-X, all with single model!

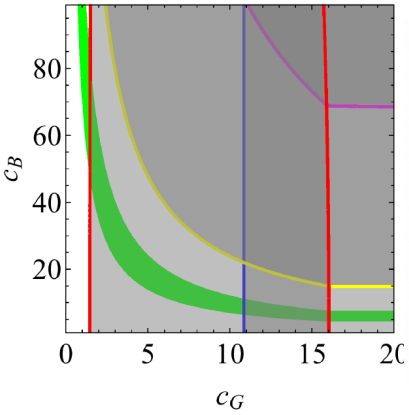
► We propose that the SMM be included in the suite of LHC DM WG recommended benchmark models

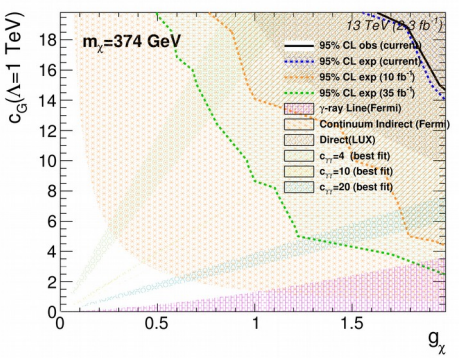
Conclusions from Other Topics

Discovery scenarios

- Use 750 GeV excess to demonstrate complementarity of visible, MET+X, DD/ID
- spin-0 models highlight this particularly

► Should develop dicovery-oriented models that leverage multi-messenger signals

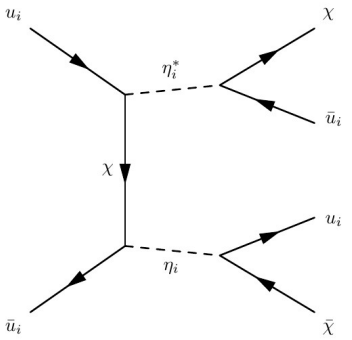




Other simplified models

- t-channel, spin-2 mediator, pseudo-dirac DM

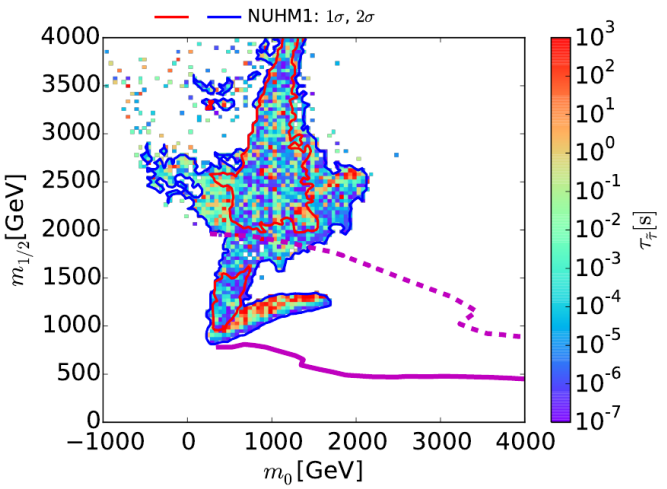
► Should be a future focus of the DM WG

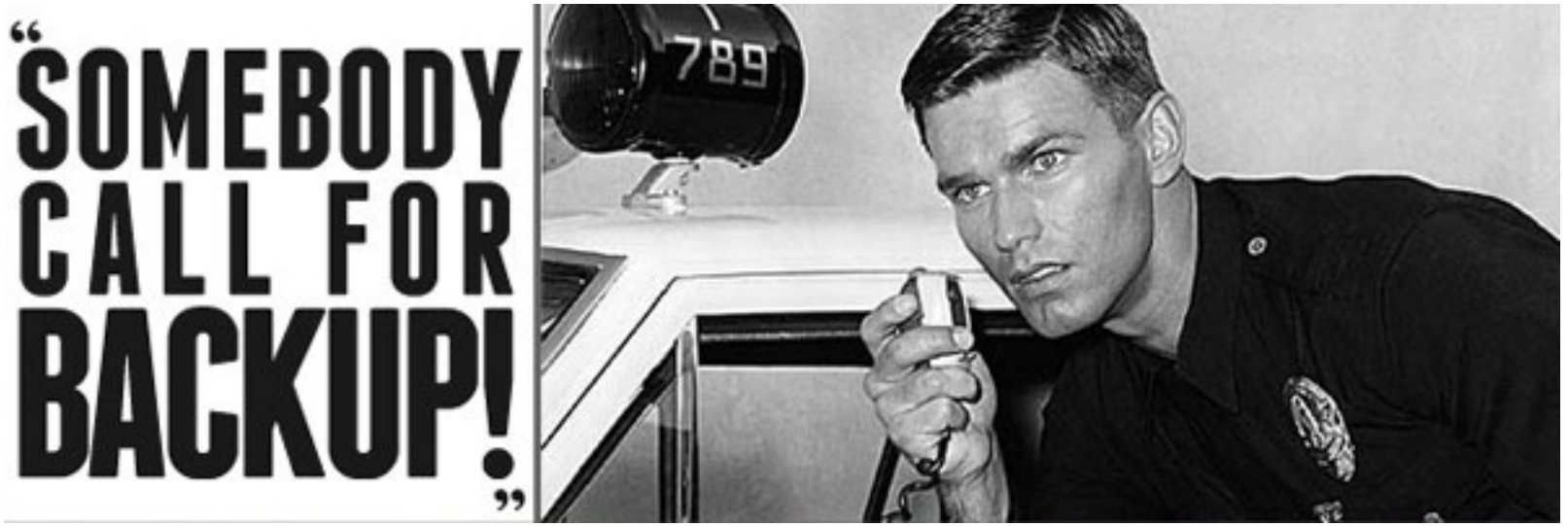


Lessons from SUSY

- cascade decays → softer MET, more complex topologies
- Displaced vertices, metastable charged particles

► SDMM extentions needed to capture properties of complete models




“SOMEBODY CALL FOR BACKUP!”
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h1/h2 Widths

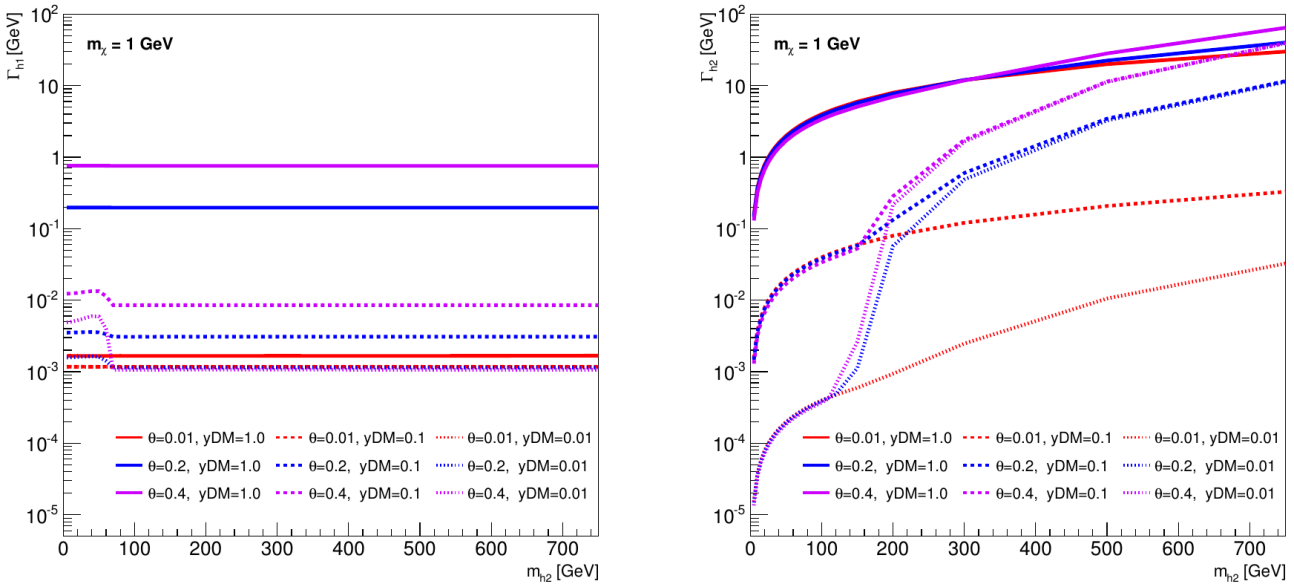


Figure 2. *The h_1 (left) and h_2 (right) total decay width in scenarios C and D for several values of $y_{\rm DM}$ and θ. In both panels the DM mass is fixed to* 1 GeV. *An increase in the total decay width of the h_1 state at low masses and low values of DM coupling $y_{\rm DM}$ is due to the contribution of the $h_1 \to h_2 h_2$ decay channel. Note that the $\theta = 0.01$ lines for $y_{\rm DM} = 0.1$ and 0.01 nearly overlap and hence are seen as a single line in the left plot.*

2HDM

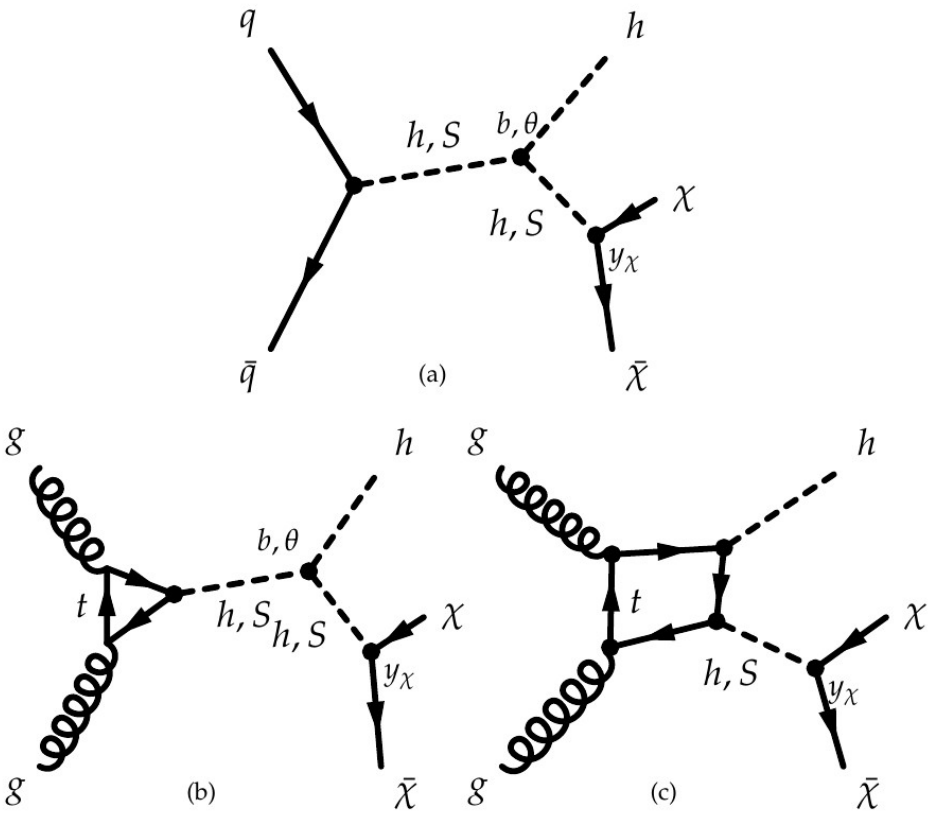
SMM perhaps simplest member of class of gauge invariant / unitary spin-0 DM models

Could also consider the wider class, incorporates 2HDMs

- 2HDM can be less restrictve vs SMM for scalar mediation
- Could naturally incorporate pseudoscalar mediator
- Stratightforward connection with SUSY
- Included in DMF recommendations for mono-Higgs

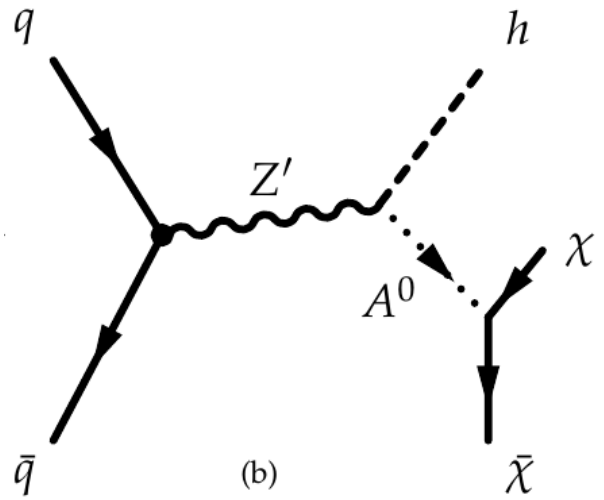
2HDM could be studied more broadly (ie: in terms of general MET+X signatures) within the LHC DM WG

- Eg: 1402.7074, 1502.06000



3.1.2 $\not{E}_T$ +Higgs from a scalar mediator

A real scalar singlet S coupling to DM can be introduced as a portal between SM and the dark sector through the Higgs field. The most general scalar potential is detailed in Ref. [ORMW07], including terms that break $\mathbb{Z}_2$. The $\mathbb{Z}_2$ symmetry, which causes the new scalar to also be a DM candidate, is not covered in this report, but follows Ref. [Car+14] introducing an additional coupling to DM that breaks $\mathbb{Z}_2$ and leads to a new invisible decay of S. For this reason, no symmetry is broken and no new interactions arise, so there is no dependence on the vacuum expectation value of S: a shift in the field leads to a redefinition of the model couplings. The new scalar S mixes with the SM Higgs boson, and couples to



3.1.3 *Higgs+$\not{E}_T$ signal from 2HDM model with a Z' and a new pseudoscalar*

In this simplified model [BLW14b], a new Z' resonance decays to a Higgs boson h plus a heavy pseudoscalar state A^0 in the 2HDM framework, which in turn decays to a DM pair. This model is represented in the diagram in Fig. 3.2 (b).

The motivation for coupling the dark matter to the pseudoscalar is that dark matter coupling to a Higgs or Z' boson is generically constrained by other signal channels and direct detection. A reason to consider this model is that it has different kinematics due to the on-shell Z' production, where for heavy Z' masses the $\not{E}_T$ and