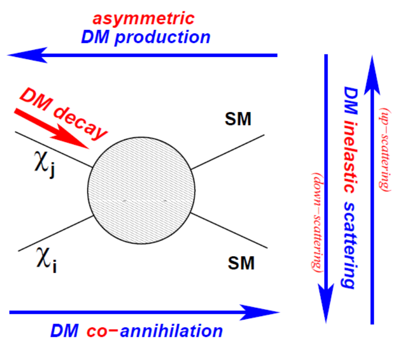
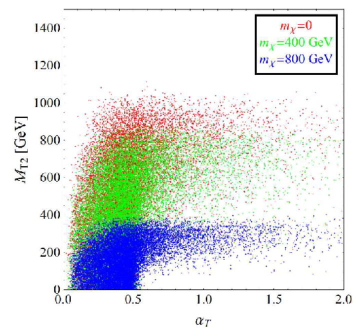
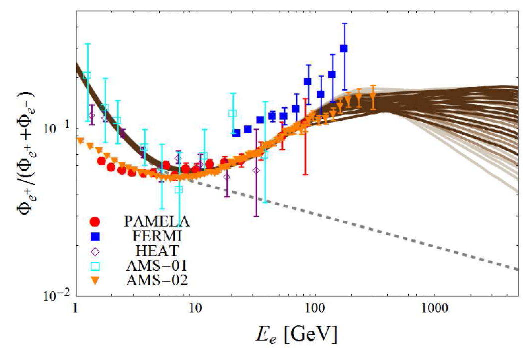
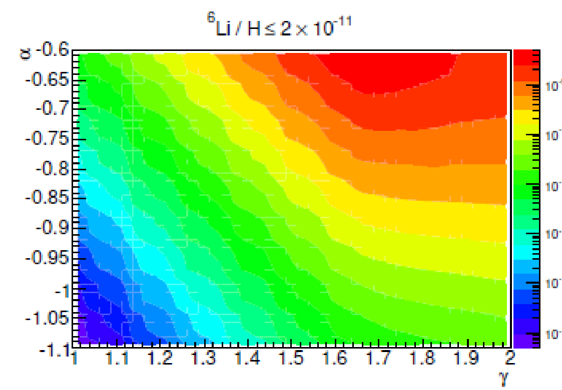
# A Non-Minimal Talk about Non-Minimal Dark Sectors




**Brooks Thomas**
**(Reed College)**

**Based on work done in collaboration with:**

- **Keith Dienes, Jason Kumar, and David Yaylali [arXiv:1406.4868]**
- **Keith Dienes and Shufang Su [arXiv:1407.2606]**

In particular, in this talk, I will be discussing the phenomenology of dark sectors which are **non-minimal** in terms of:

- The number of components (particles, degrees of freedom) which the dark sector comprises – and especially those components which contribute toward $\Omega_{CDM}$.
- The non-trivial decay widths/lifetimes of these components, subject to constraints imposed by astrophysics/cosmology.

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Likewise, because there have been a lot of recent developments on this topic, my talk itself will be non-minimal in terms of:

- The number of components (self-contained presentations) which the talk comprises.
- The non-trivial lifetimes of these components, subject to constraints imposed by the session chair.

# New Directions in Dark-Matter Complementarity

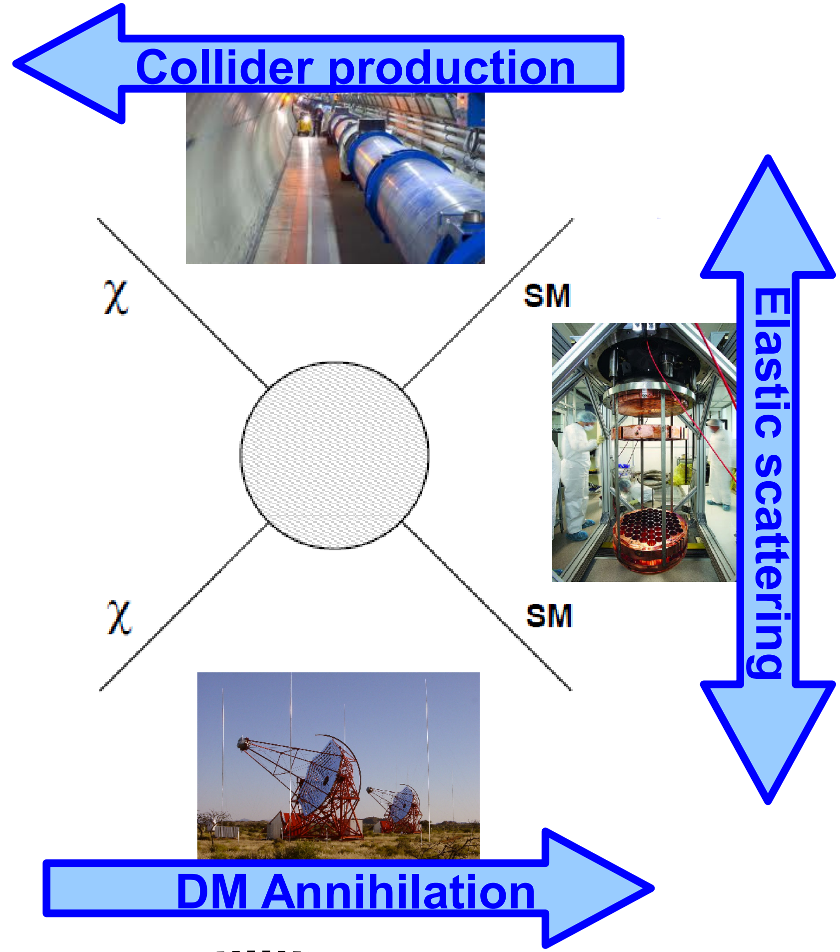
Investigating the Enriched Complementarity Relationships which Arise in Non-Minimal Dark Sectors

**Keith Dienes, Jason Kumar, B.T., David Yaylali [arXiv:1406.4868]**

# Complementarity: The Standard Picture

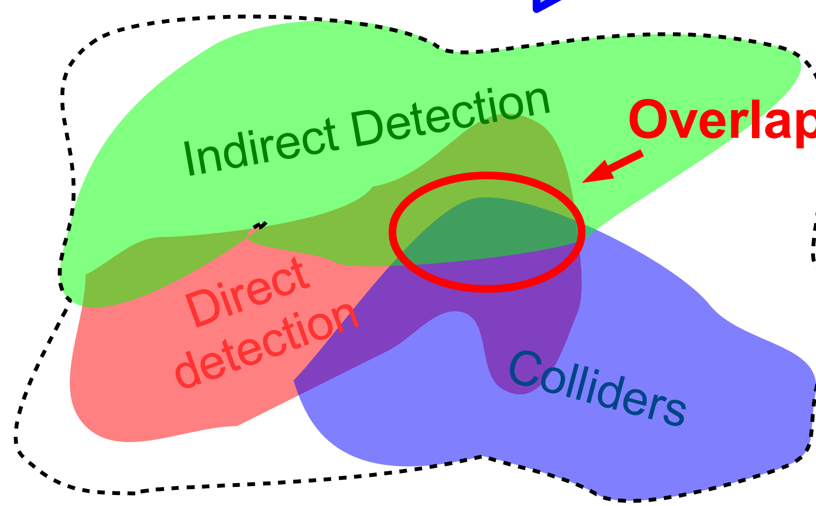
## The Underlying Principle:

A single operator which couples DM particles to SM particles generically contributes to a variety of different physical processes.



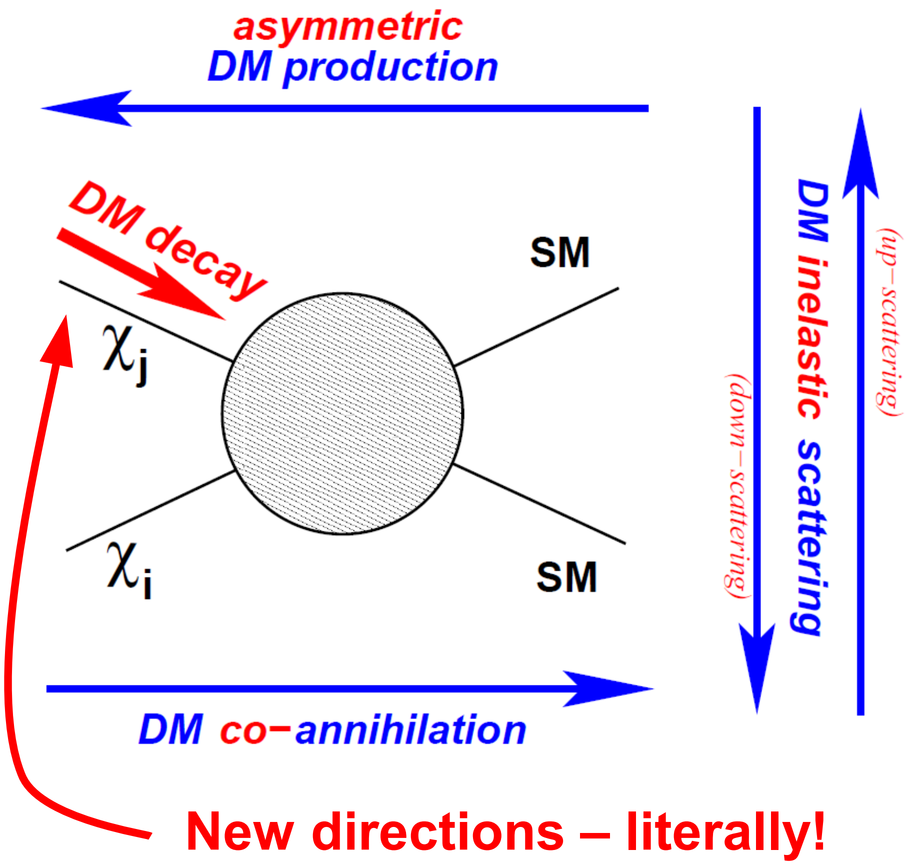

## Two facets of complementarity:

- **Coverage**: Different detection channels are sensitive in different regions of the parameter space of dark-matter models.
- **Correlations**: Observing signals in multiple channels with regions of that parameter space in which sensitivities overlap.




**DM Parameter Space**

# Complementarity: A More General Picture




In **multi-component** theories of dark matter, additional physical processes are possible. These include...

## 1 Dark-matter decay

- Heavier $\chi_i$ can decay into lighter ones even in the case in which the lightest $\chi_i$ is stable due to a symmetry.

## 2 Inelastic scattering of dark matter off with atomic nuclei

- **Upscattering** of a ligher $\chi_i$ into a heavier $\chi_j$ (prototypical inelastic DM)
  [Hall, Moroi, Murayama, '97; 'Weiner, Tucker-Smith, '01]
- **Downscattering** of a heavier, metastable $\chi_i$ into a lighter $\chi_j$ ("exothermic" DM).
  [Finkbein er, Slatyer, Weiner, Yavin, '09; Batell, Pospelov, Ritz, '09; Graham,Harnik, Rajendran, Saraswat, '11]

## 3 Asymmetric pair-production of $\chi_i$ and $\chi_j$ at colliders

## 4 Coannihilation of $\chi_i$ and $\chi_j$ (both in the early universe *and* today)

# The Fundamental Interactions

- At the energy scales $|\vec{q}| \lesssim O(100\ \mathrm{MeV})$ relevant for direct detection, interactions between the dark and visible sectors in a wide variety of theories can be modeled as **effective contact interactions**.

[See, e.g., Goodman, Ibe, Rajaraman, Shepherd, Tait, Yu '10]

- As an example, consider a dark sector comprising two Dirac fermions $\chi_1$ and $\chi_2$, with $m_2 > m_1$, whose dominant couplings to the visible sector are to SM quarks:

$$\mathcal{O}_{ij}^{(XY)} = \sum_{q=u,d,s,\ldots} \frac{c_{qij}^{(XY)}}{\Lambda^2}(\overline{\chi}_i \Gamma^X \chi_j)(\overline{q}\Gamma^Y q)$$

for $i,j = 1,2$, with $\Gamma = \{1, i\gamma^5, \gamma^\mu, \gamma^\mu\gamma^5, \sigma^{\mu\nu}\}$

Moreover, for purposes of illustration let's focus on the case in which:

- A single operator with $i \neq j$ dominates and $c_{qij}^{(XY)} \approx 0$ for all operators with $i = j$.
- The majority of the dark matter is in the metastable state $\chi_2$ – i.e, $\Omega_{CDM} \approx \Omega_2$.
- The $c_{qij}^{(XY)}$ are O(1) and flavor-universal up to an overall ratio between up- and down-type quarks.

And define:

$$\Delta m_{12} \equiv m_2 - m_1$$

$$c_{u12}^{(XY)} = \cos\theta\ , \quad c_{d12}^{(XY)} = \sin\theta$$

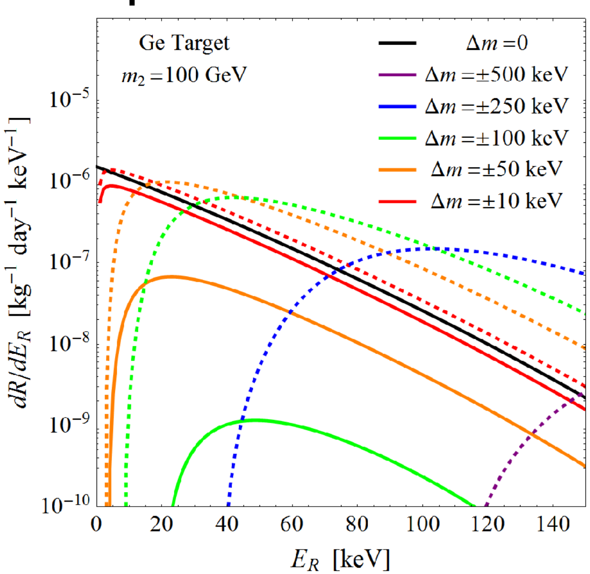
# Inelastic Scattering and Direct Detection

- In multi-component scenarios, a variety of processes can contribute to the overall scattering rate at direct-detection experiments:

- **Inelastic scattering** can have a significant impact on direct detection signals when $\Delta m_{12}$ is similar the range of recoil energies to which these experiments are sensitive:

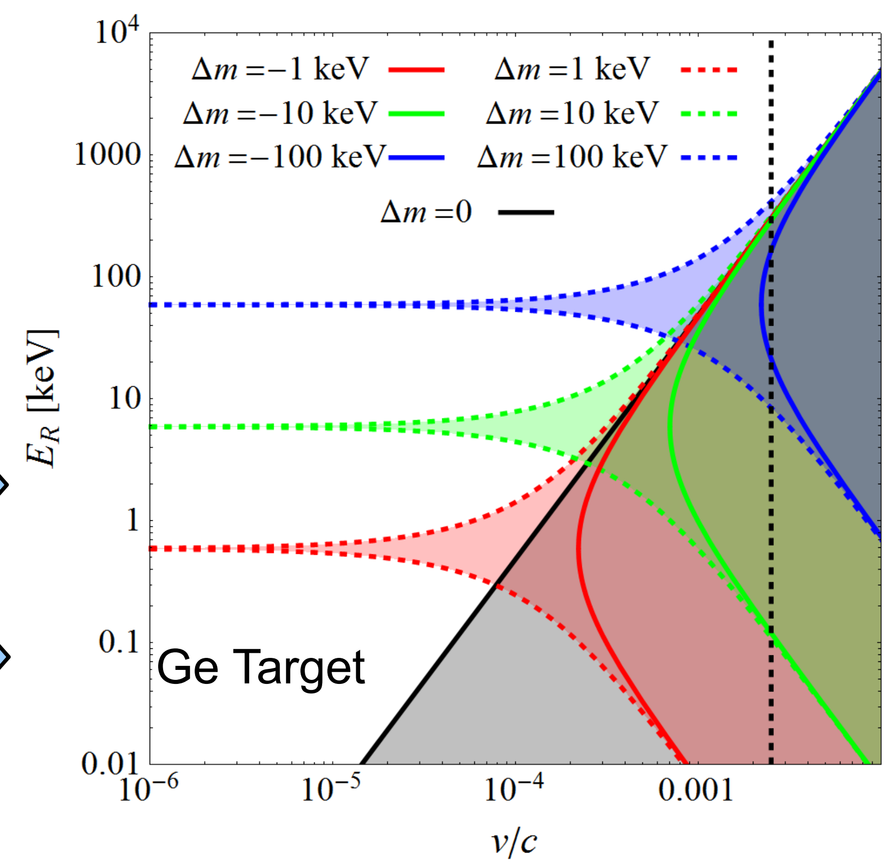
$$1\ \mathrm{keV} \lesssim E_R \lesssim 100\ \mathrm{keV}$$

Elastic scattering, upscattering, and downscattering have their own **distinctive kinematics** and contribute to the total recoil-energy spectrum in different ways.




Solid lines: upscattering

Dashed lines: downscattering



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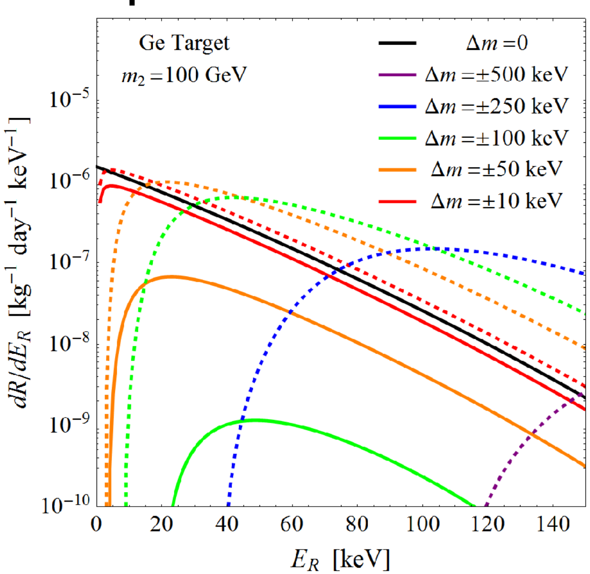


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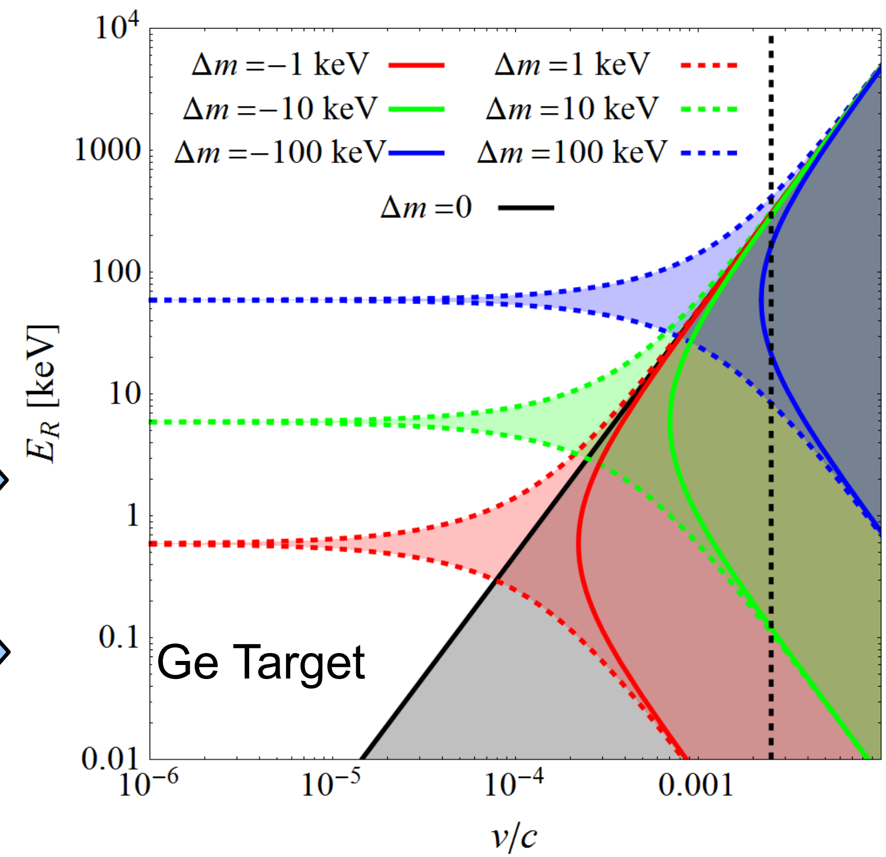
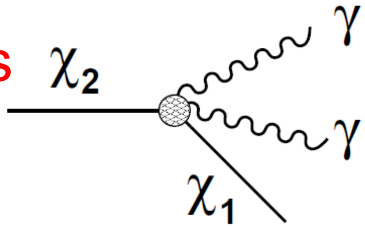


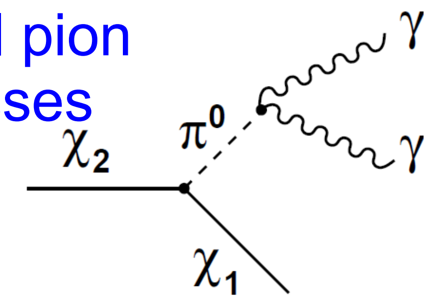
# Decays and Indirect Detection

- In the $\Delta m_{12}$ regime relevant for inelastic DM scattering off nuclei, only photons and neutrinos are accessible in $\chi_2 \rightarrow \chi_1$ + SM decays.
- Even when $\chi_1$ and $\chi_2$ couple primarily to quarks, contributions to the decay width of $\chi_2$ generically arise from diagrams involving virtual quarks/hadrons:

Contact operators




Off-shell pion processes




These contributions can be evaluated, e.g., in Chiral Perturbation theory.

- For example, for scalar (SS) and axial-vector (AA) interactions, we find:

$$\mathcal{L}^{(\mathrm{S})}_{\mathrm{int}} = \frac{B_0 \alpha_{\mathrm{EM}} \tilde{\lambda}_2 c^{(\mathrm{S})}}{4\pi \Lambda_C^2 \Lambda^2} \underline{(\overline{\chi}_2 \chi_1) F_{\mu\nu} F^{\mu\nu}} + \ldots ,$$

$$\Rightarrow \quad \Gamma^{(\mathrm{S})}_{\gamma\gamma} \approx \frac{B_0^2 \alpha_{\mathrm{EM}}^2 \tilde{\lambda}_2^2 [c^{(\mathrm{S})}]^2}{8(105\pi^5)\Lambda_C^4 \Lambda^4} (\Delta m_{12})^7$$

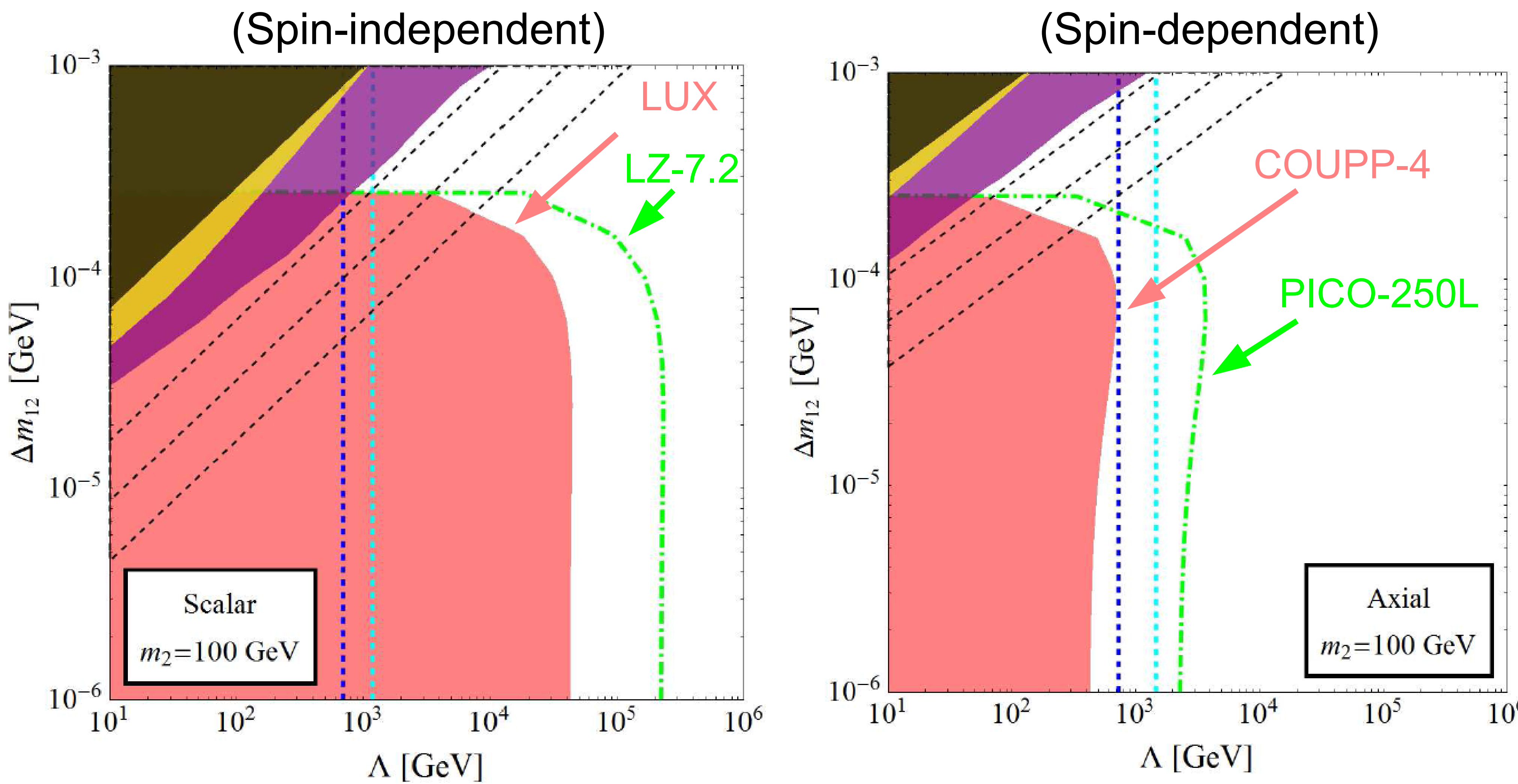
**Decay-Width Contributions**

$$\mathcal{L}^{(\mathrm{A})}_{\mathrm{eff}} = -\frac{c^{(\mathrm{A})}\Lambda_C}{\sqrt{2}\pi\Lambda^2}\left[1 + \frac{m_\pi^2}{2\Lambda_C^2}\tilde{\lambda}_3\right] \underline{(\overline{\chi}_2 \gamma^\mu \gamma^5 \chi_1)(\partial_\mu \pi^0)} + \frac{\alpha_{\mathrm{EM}} \tilde{\lambda}_4 c^{(\mathrm{A})}}{4\pi\Lambda_C^2 \Lambda^2} \underline{(\overline{\chi}_2 \gamma^\mu \gamma^5 \chi_1)\partial_\mu (F_{\nu\rho}\tilde{F}^{\nu\rho})} + \ldots$$

$$\Rightarrow \quad \Gamma^{(\mathrm{A})}_{\gamma\gamma} \approx \frac{\alpha_{\mathrm{EM}}^2 [c^{(\mathrm{A})}]^2 (\Delta m_{12})^9}{8(315\pi^5)\Lambda_C^4 \Lambda^4}\left[\tilde{\lambda}_3 + \tilde{\lambda}_4 - \frac{2\Lambda_C^2}{m_\pi^2}\right]$$

**Spectrum peaked in the X-ray for $\Delta m_{12}$ ~ O(1-100 keV). Widths constrained by diffuse X-ray data from INTEGRAL, HEAO-1, etc.**

# Interplay Between Detection Channels: Results




- Current direct-detection limits
- Diffuse XRB limit (HEAO-1)
- Diffuse XRB limit (INTEGRAL)
- Minimal stability ($\tau_2 > t_{now}$)
- Naive ATLAS/CMS monojet limit
- Naive ATLAS mono-W/Z limit
- Future direct-detection reach

# Summary

- In multi-component theories of dark matter, **new complementarity relations** exist between processes absent in single-component theories.
- In particular, a single interaction between DM and SM particles can contribute to:

  - **Inelastic scattering** at direct-detection experiments
  - **Asymmetric** dark-matter production at colliders
  - Indirect-detection signals due to **dark-matter decay**

  Absent in single-component theories!

- We have also demonstrated the power of these complementarity relations in covering the parameter space of a toy two-component dark sector.
- In the small-coupling/large-$\Lambda$ regime, there is significant overlap between the regions excluded by direct- and indirect-detection limits. Together, these complementary probes of the dark sector provide **complete coverage of the relevant parameter space** in this regime.
- By contrast, in the large-coupling/small-$\Lambda$ regime, a range of $\Delta m_{12}$ opens up for which the dark sector escapes detection. Motivates new detection strategies to "fill the gap."

# Cuts, Correlations, and Collider Searches for Non-Minimal Dark Sectors

Keith Dienes, Shufang Su, B.T. [arXiv:1406.4868]

- The first step in the study of DM at colliders is simply to observe an excess in one (or more) of the characteristic channels (with large $\not{E}_T$).
- However, once a signal of dark matter is initially identified in collider data, the questions then become:

**What information can we extract about the properties of the dark matter from collider data?**

**Can we distinguish minimal from non-minimal dark sectors on the basis of that data?**

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- A number of strategies and tools have been developed in an effort to answer these questions in particular scenarios:

- Distinguishing between different DM stabilization symmetries. — Agashe, Kim, Toharia, Walker [1003.0899]; Agashe, Kim, Walker, Zhu [1012.4460]
- $M_{T2}$ variants for determining DM-particle masses in two-component DM systems. — Barr, Gripaios, Lester [1012.4460]; Konar, Kong, Matchev, Park [0911.4126]
- Analyis of cusp and endpoint structures in kinematic distributions. — Han, Kim, Song [1206.5633,1206.5641]

...and many more!

## In this talk, I'm going to focus on another aspect of searching for non-minimality in the dark sector.

It is well known that **correlations between collider variables** can have an important impact on data-analysis strategies for any collider analysis:

- Cuts imposed on one kinematic variable (e.g., for purposes of background reduction) will affect the shape of the distribution of any other variable with which it is non-trivially correlated.
- Such cuts can potentially **wash out distinctive features** in these distributions which provide signs of dark-sector non-minimality.
- Alternatively, in certain special cases, they can actually **amplify** the distictiveness of these distributions.

Our primary goal is to investigate the impact of such correlations in developing and optimizing search strategies for non-minimal dark sectors at colliders.

# Minimal vs. Non-minimal Scenarios

**Benchmark for minimality:**

- Dark sector consists of a "traditional" dark-matter candidate – i.e., a single massive particle $\chi$ with mass $m_\chi$.

**Benchmark for non-minimality:**

## Dynamical Dark-Matter Ensembles

**K. R. Dienes, BT [1106.4546,1107.0721]**

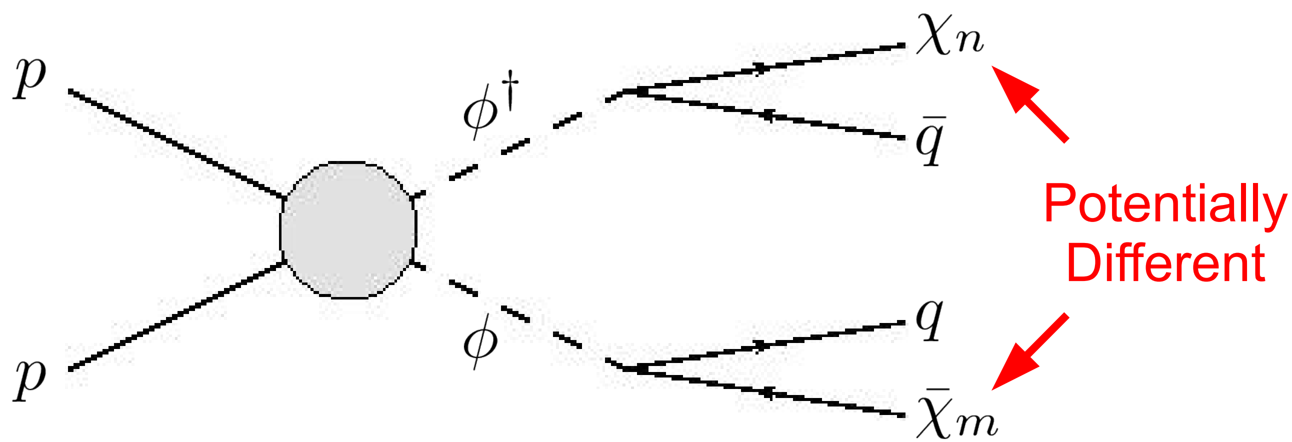
- DDM is an alternative framework for satisfying competing constraints on dark-matter lifetimes and abundances **without stability**.
- Dark-matter candidate is an **ensemble** comprising a vast number of consituent particle species $\chi_n$.
- Phenomenological constraints are satisfied by **balancing** the abundances of the individual $\chi_n$ against their decay rates.

In each case, assume some heavy, strongly-interacting "parent" particle $\phi$ which decays to dark-sector states $\chi_n$ via the interaction Lagrangian

$$\mathcal{L}_{\rm int} = \sum_{n=0}^{N} \sum_{q} \left[ c_{nq} \phi^\dagger \overline{\chi}_n q_R + \text{h.c.} \right]$$

**Search Channel:**

$$pp \to jj + \not{E}_T$$




**Parametrizing the DDM ensemble:**

Toy model with scaling behavior for masses and couplings motivated by realstic DDM models: (Dienes, BT [1107.0721,1203.1923,1506.xxxxx])

Mass spectrum: $m_n = m_0 + n^\delta \Delta m$

Coupling spectrum: $c_n = c_0 \left( \frac{m_n}{m_0} \right)^\gamma$

# Standard Collider Varibles

(for dijet events)

- Missing energy $\not{E}_T$
- $p_{T_1}$ and $p_{T_2}$ (transverse momenta of the leading two jets)
- $H_{T_{jj}} \equiv \sum_{i=1}^{2} p_{T_i}$ (scalar sum of $p_{T_1}$ and $p_{T_2}$)
- $H_T \equiv \not{E}_T + \sum_{i=1}^{N} p_{T_i}$
- $\alpha_T \equiv |p_{T_2}|/m_{jj}$ Randall, Tucker-Smith [0806.1049]
- $|\Delta\phi_{jj}|$ (difference in azimuthal angle between $\vec{p}_{T_1}$ and $\vec{p}_{T_2}$)
- Transverse mass $M_{T_1}$ (formed from $\vec{p}_{T_1}$ and $\vec{\not{p}}_T$)
- Standard $M_{T2}$ variable Lester, Summers [hep-hp/9906349]

Compare signal distibutions of these variables from different scenarios in order to identify the most auspicious strategies for distinguishing non-minimal dark sectors.

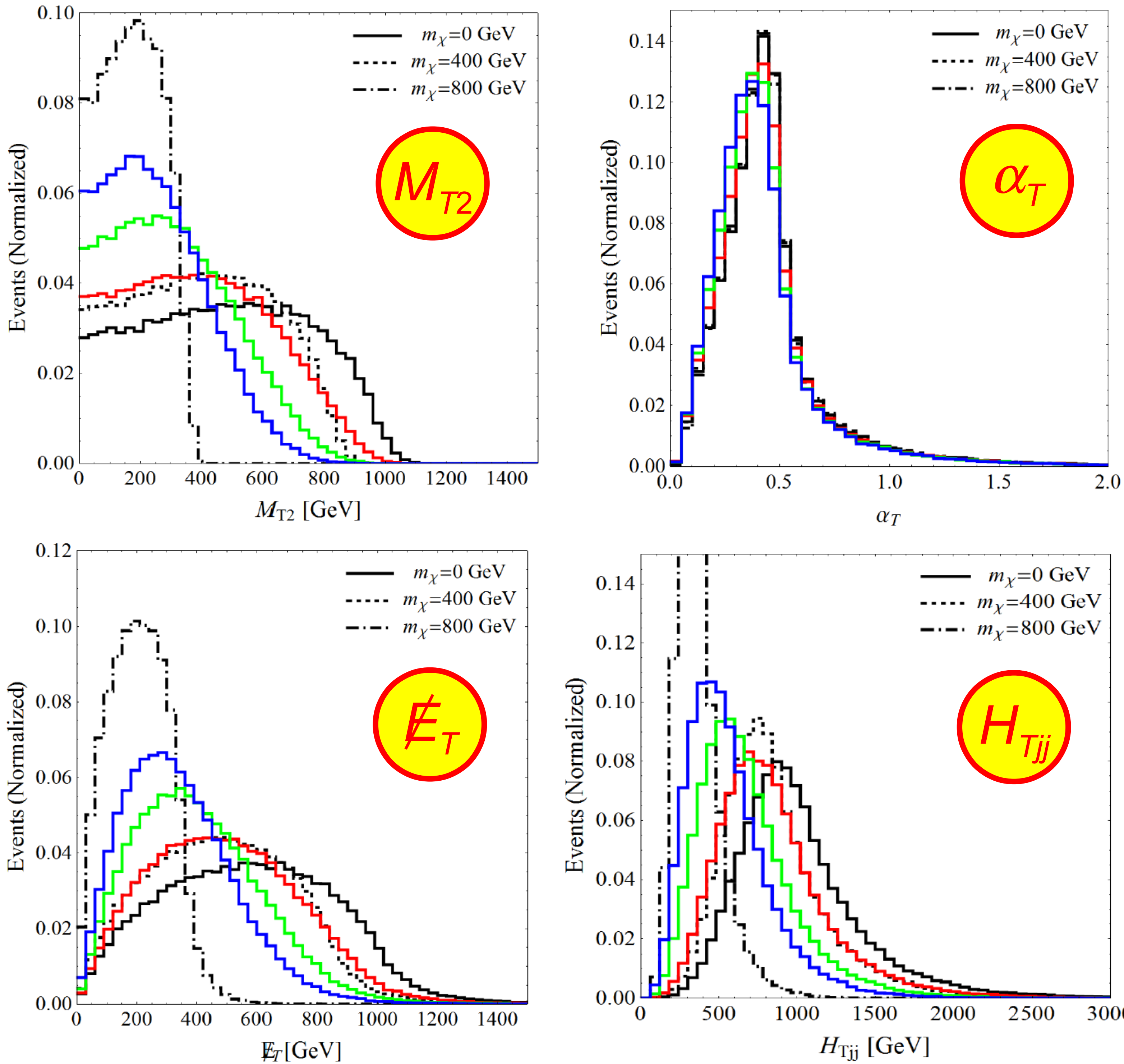
# The Distributions:

Example shown here:

$m_0 = 200$ GeV
$m_\phi = 1$ TeV
$\Delta m = 50$ GeV
$\delta = 1$

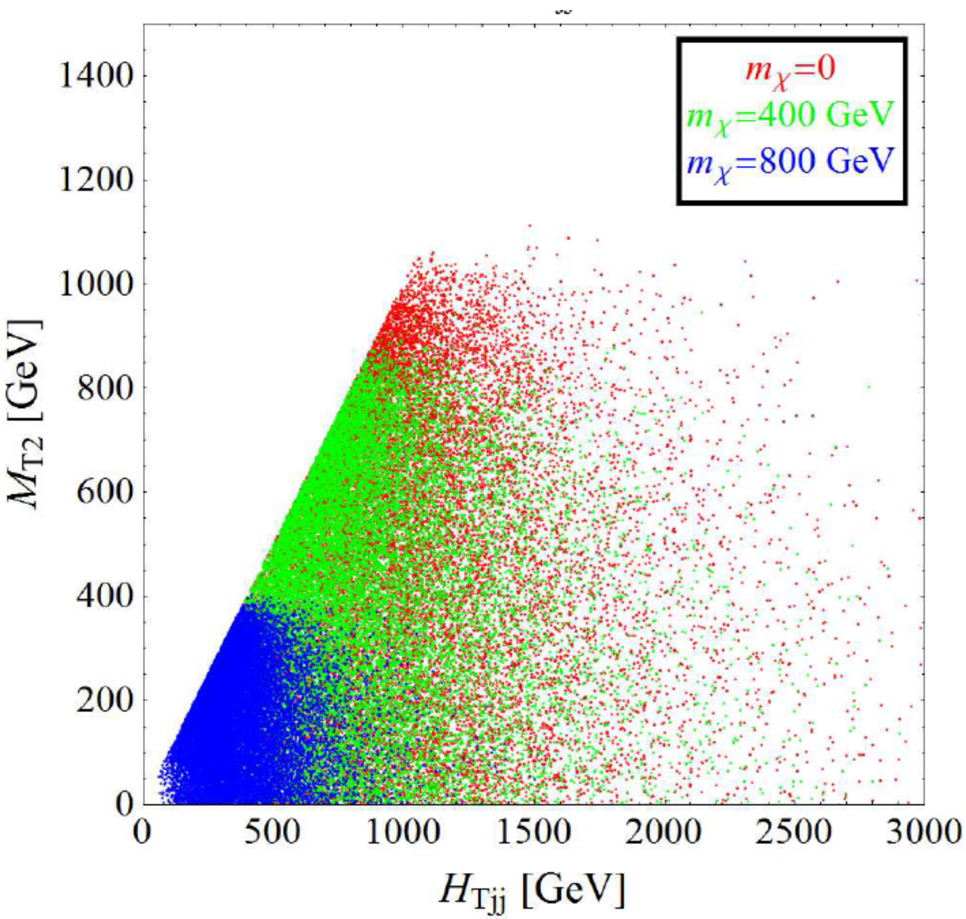
with

$\gamma = 0$
$\gamma = 1$
$\gamma = 2$



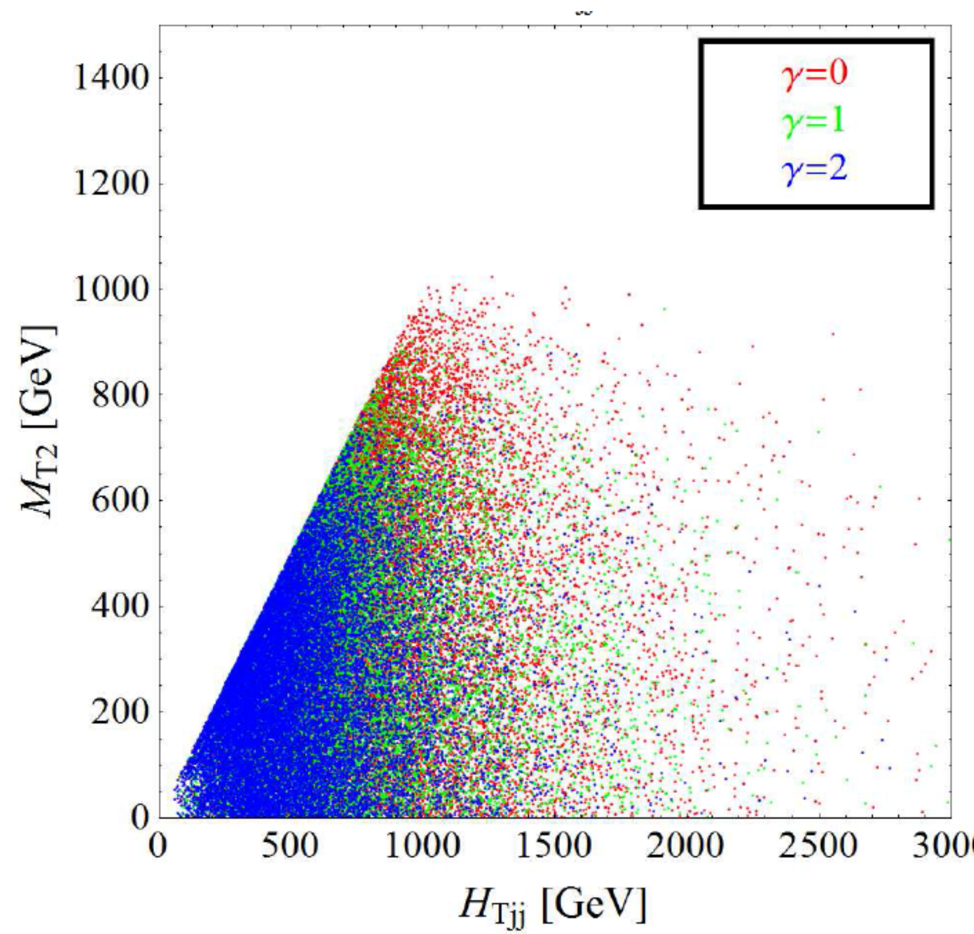
# Unhelpful Correlations: $H_{T_{jj}}$ vs. $M_{T2}$

## Traditional Dark-Matter Candidates




$m_\phi = 1$ TeV

## Dynamical Dark-Matter Models

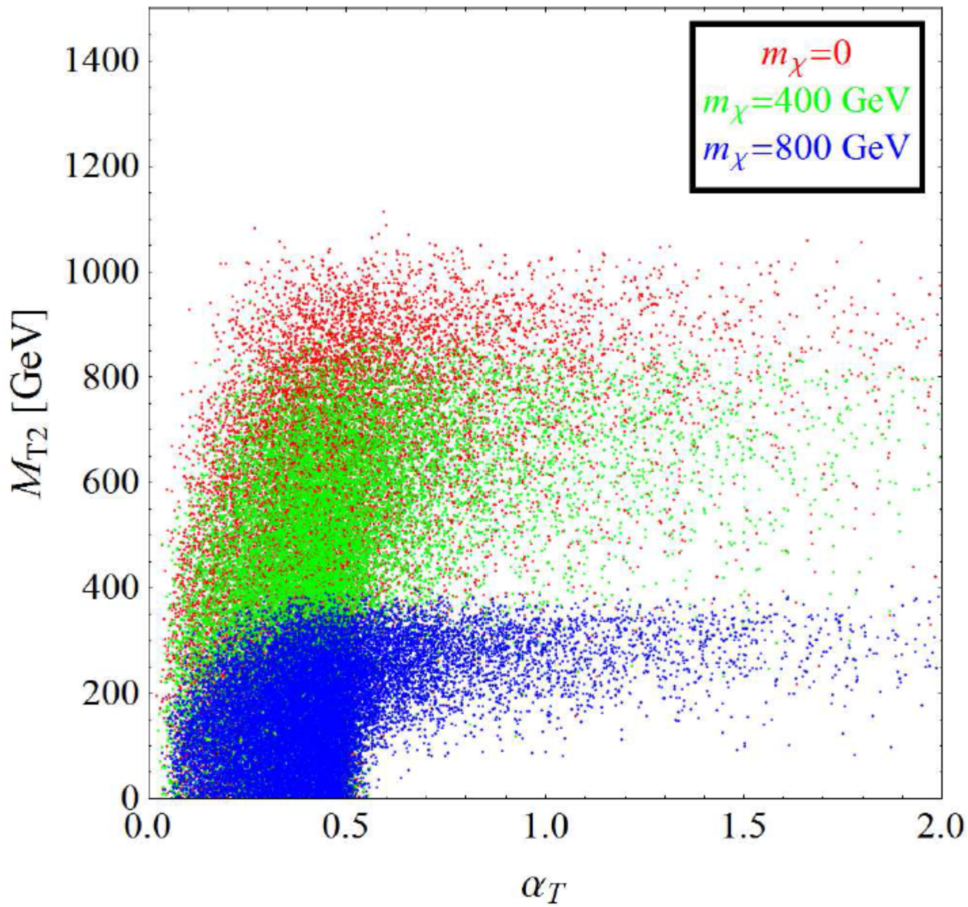



$m_0 = 100$ GeV $\quad m_\phi = 1$ TeV

$\Delta m = 50$ GeV $\quad \delta = 1$

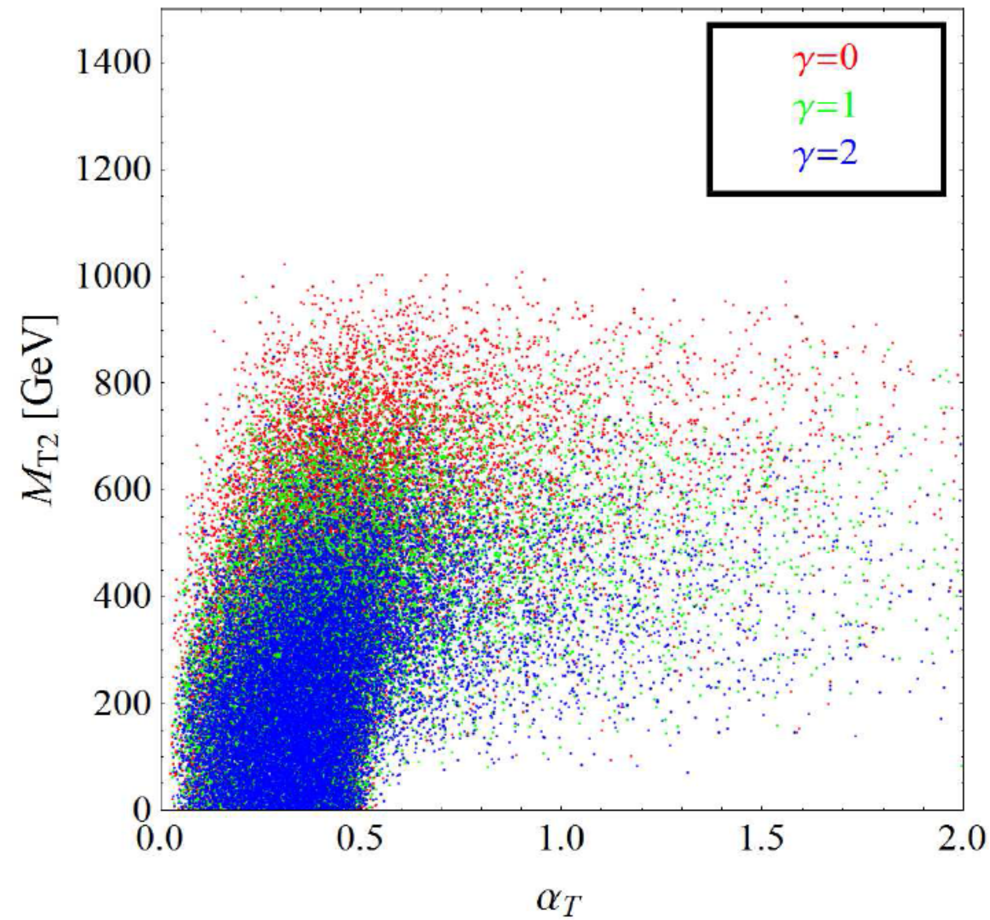
# Helpful Correlations: $\alpha_T$ and $M_{T2}$

## Traditional Dark-Matter Candidates




$m_\phi = 1$ TeV

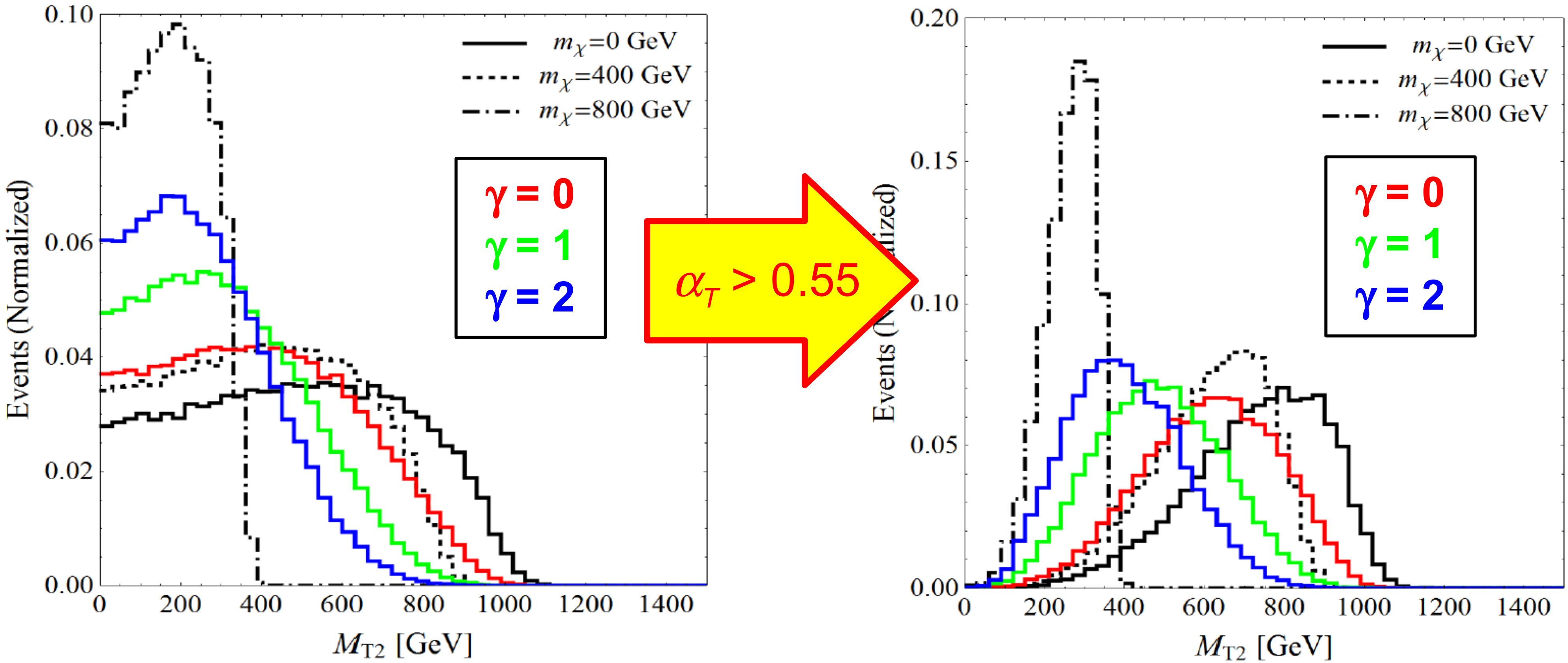
## Dynamical Dark-Matter Models




$m_0 = 100$ GeV $\quad m_\phi = 1$ TeV

$\Delta m = 50$ GeV $\quad \delta = 1$

# The Effect of the Cut




$m_0 = 200$ GeV  $m_\phi = 1$ TeV  $\Delta m = 50$ GeV  $\delta = 1$

Indeed, our $\alpha_T$ cut has a **dramatic effect** on the distinctiveness of the $M_{T2}$ distributions associated with non-minimal dark sectors!

Similar effect on other kinematic distributions.

# Quantifying distinctiveness

To what degree are the kinematic distributions associated with non-minmal dark sectors **truly** distinctive, in the sense that they cannot be reproduced by **any** traditional DM model?

## The Procedure:

- Survey over traditional DM models with different DM-candidate masses $m_\chi$ and coupling structures.
- Divide the distribution into appropriately-sized bins.
- For each value of $m_\chi$ in the survey, define the goodness-of-fit statistic $G(m_\chi)$ to quantify the degree to which the two resulting $m_{jj}$ distributions differ.

likelihood ratio

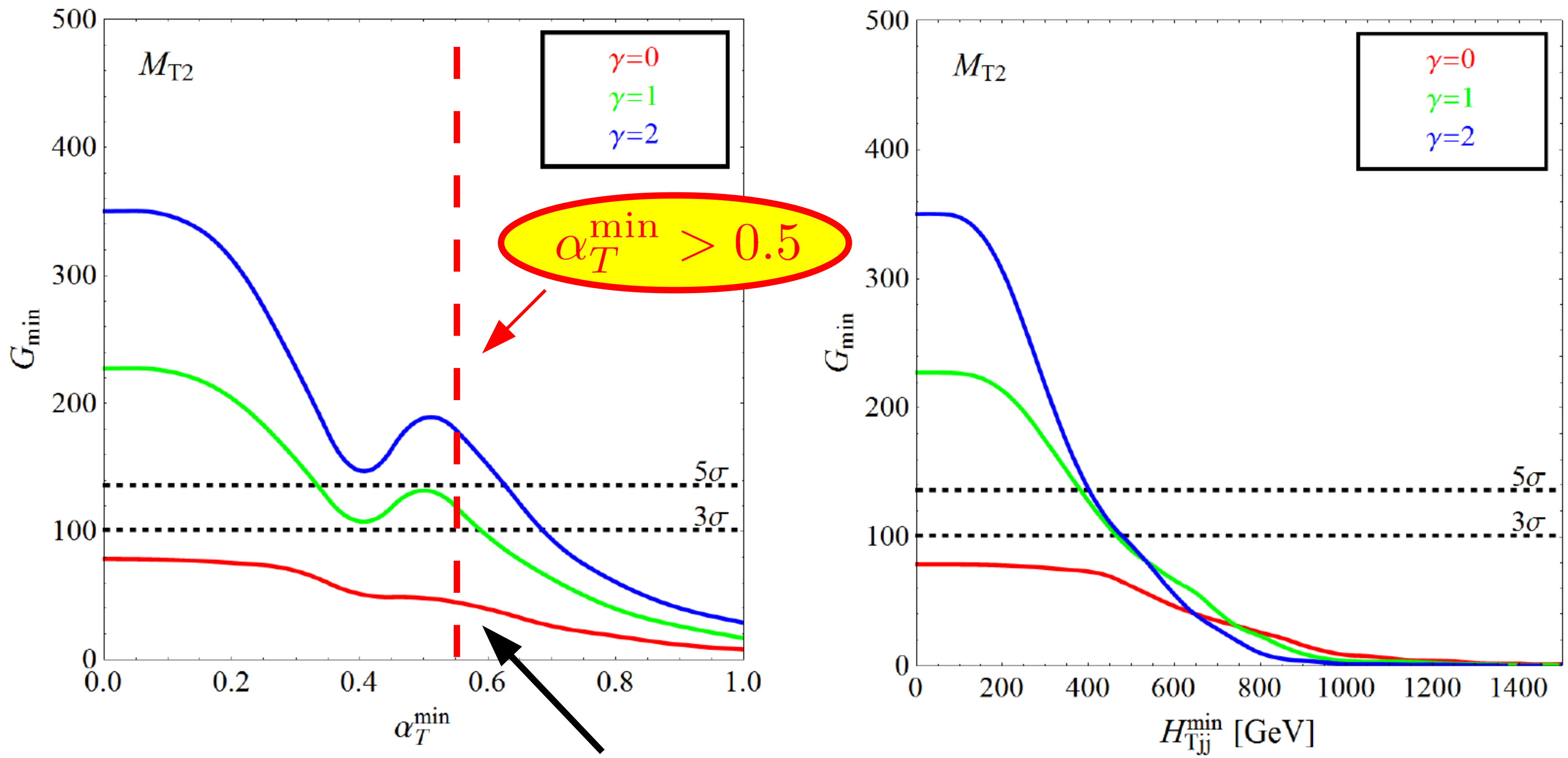
$$G(m_\chi) = -2 \ln \lambda(m_\chi)$$

$$G_{\text{min}} = \min_{m_\chi} \{G(m_\chi)\}$$

- The **minimum** $G(m_\chi)$ from among these represents the degree to which a DDM ensemble can be distinguished from **any** traditional DM candidate.

# Distinguishing Power: $M_{T2}$ Distributions

(as a function of applied cuts)

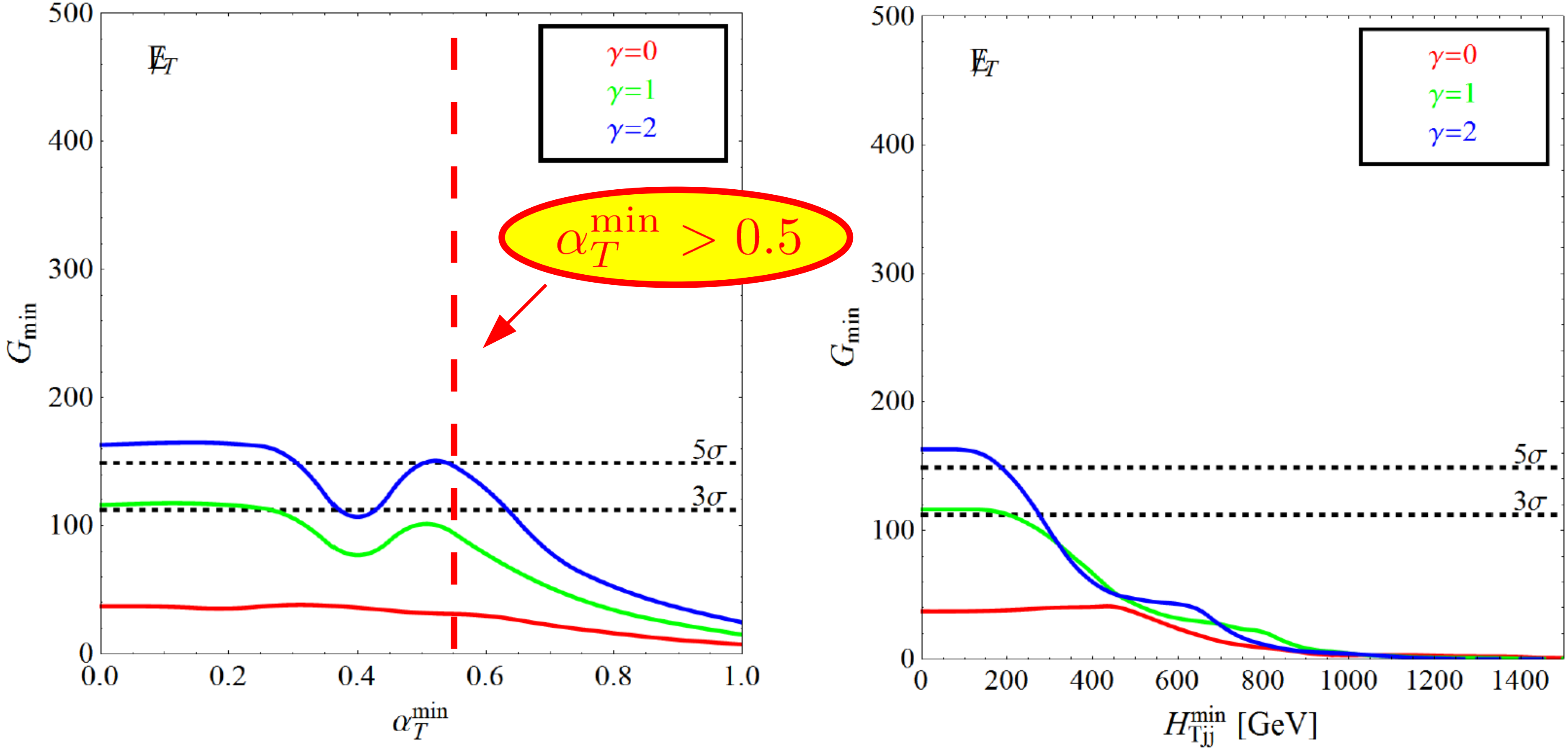



A well-chosen cut on $\alpha_T$ actually serves to **amplify** the distinctiveness of the singal distributions, despite the loss in statistics!

An $\alpha_T$ cut on this order is also helpful in reducing residual QCD backgrounds.

# Distinguishing Power: $\not{E}_T$ Distributions

(as a function of applied cuts)




Similar results to those obtained for $M_{T2}$ distributions, but with slightly less sensitivity.

# Summary

- Distinguishing between minimal and non-minimal dark sectors at colliders typically involves more that merely identifying an excess in the total number of signal events over background.
- In particular, it typically requires a detailed analysis of the **shapes** of relevant **kinematic distributions**.
- Cuts imposed on the data (for background reduction, etc.) can distort these distributions due to non-trivial **correlations** between collider variables.
- Variables such at $\not{E}_T$ and $M_{T2}$ are particularly sensitive to the stucture of the dark sector.
- Appropriately chosen cuts on particular variables such as $\alpha_T$ can actually **enhance** the distinctiveness of these distributions.

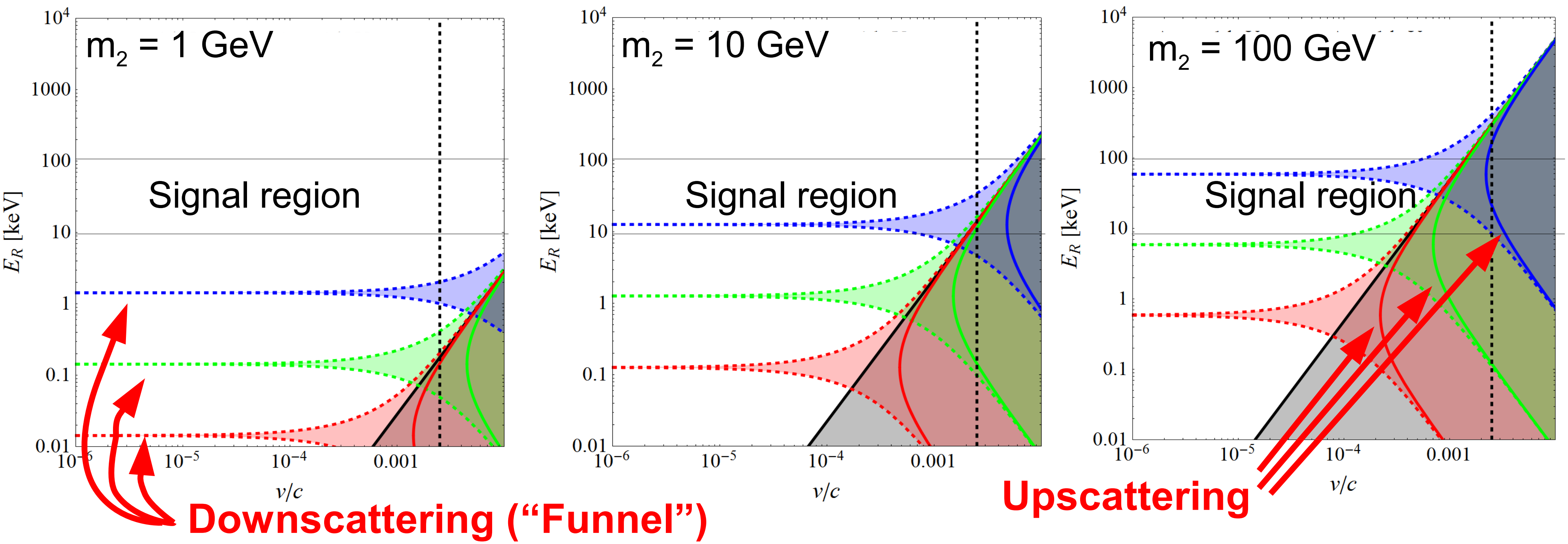
**Work in progress**: Optimizing strategies for distinguishing non-minimal dark sectors at colliders (K. R. Dienes, C. Proepper, S. Su, BT).

Stay tuned!

# Extra Slides

# Inelastic Dark Matter: Scattering Kinematics

$$E_R \approx \frac{\mu_{N2}^2 v^2}{m_N}\left[1 + \frac{\Delta m}{\mu_{N2} v^2} + \left(1 + \frac{2\Delta m}{\mu_{N2} v^2}\right)^{1/2} \cos\theta\right], \qquad \mu_{N2} \equiv \frac{m_2 m_N}{m_2 + m_N}$$




| Downscattering | Upscattering |
| --- | --- |
| $\Delta m_{12}$ = 1 keV (red dashed) | $\Delta m_{12}$ = -1 keV (red solid) |
| $\Delta m_{12}$ = 10 keV (green dashed) | $\Delta m_{12}$ = -10 keV (green solid) |
| $\Delta m_{12}$ = 100 keV (blue dashed) | $\Delta m_{12}$ = -100 keV (blue solid) |