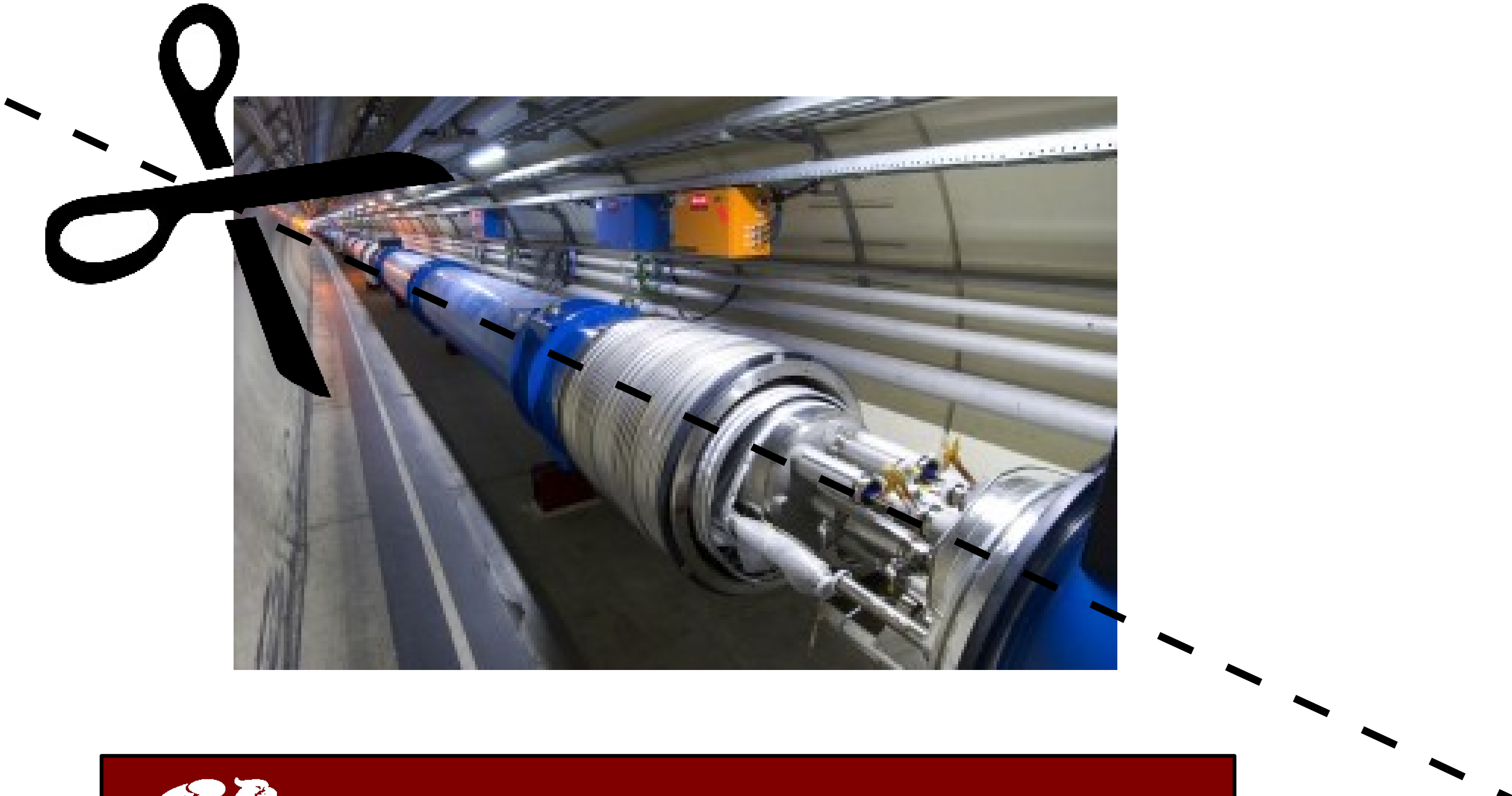
Cuts, Correlations, and Collider Searches for Non-Minimal Dark Sectors



Brooks Thomas
(Reed College)

Based on work done in collaboration with
Keith Dienes and Shufang Su [arXiv:1407.2606]

- 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 <u>minimal</u> from <u>non-minimal</u> dark sectors on the basis of that data?

- 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?

- 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 χ with mass m_χ.

Benchmark for non-minimality:

Dynamical Dark-Matter Ensembles

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

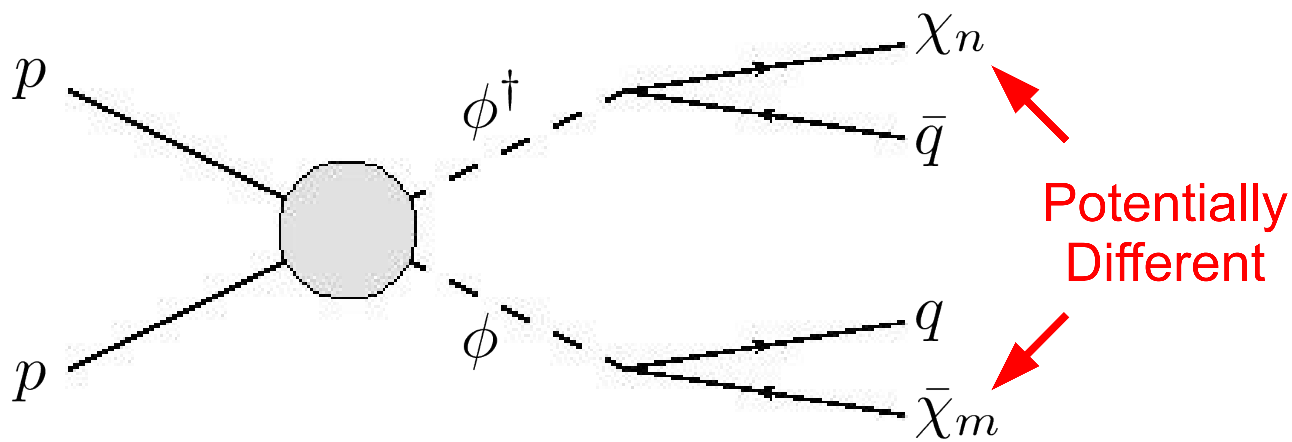
- DDM is an alternative framework for satisfying competing constraints on dark-matter lifetimes and abundances **without stability**.
- Dark-matter candidate is an **ensemble** comprising a vast number of consituent particle species χ_n.
- Phenomenological constraints are satisfied by **balancing** the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

In each case, assume some heavy, strongly-interacting "parent" particle ϕ which decays to dark-sector states χ_n via the interaction Lagrangian

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

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])

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

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

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.

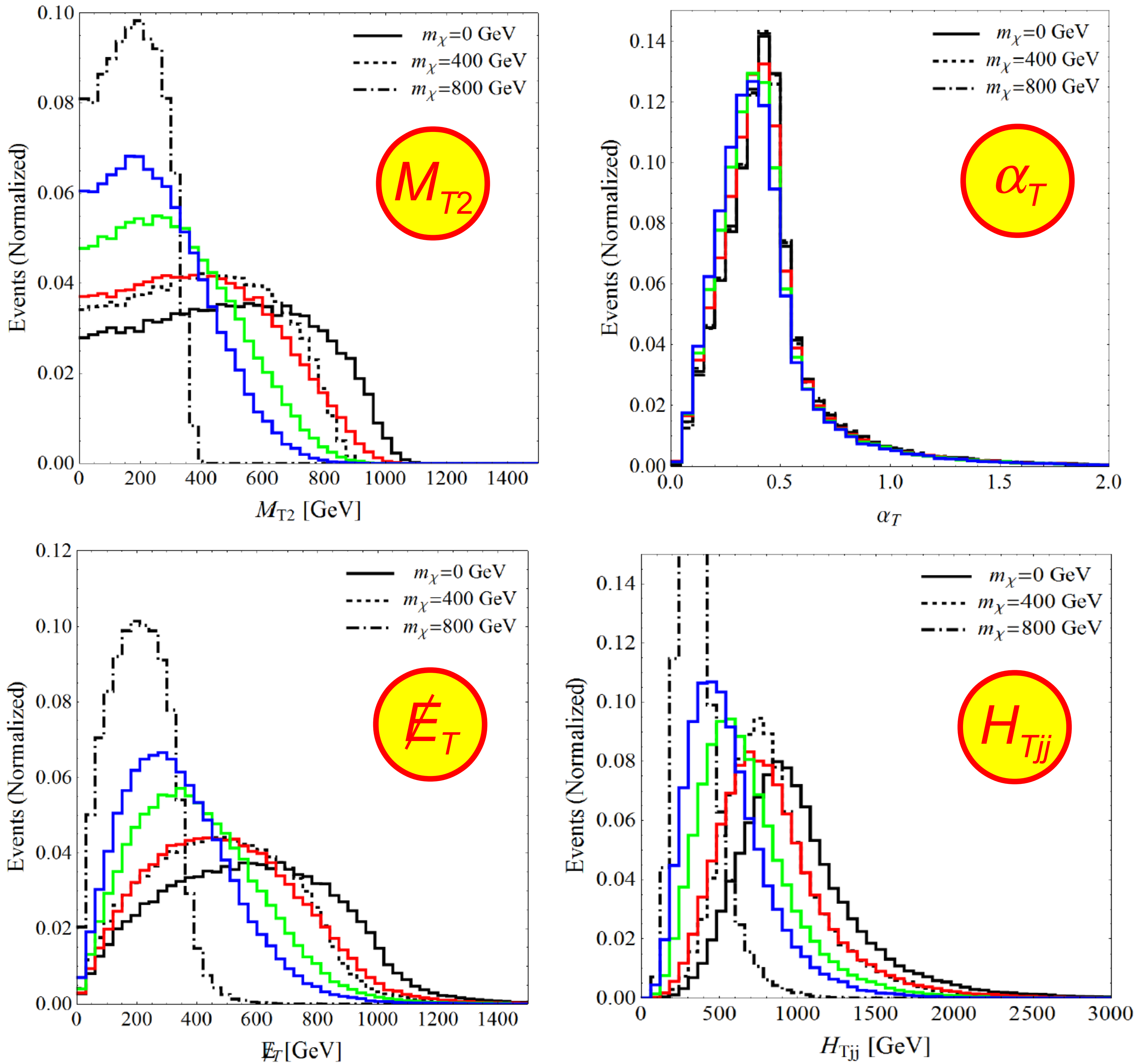
The Distributions:

Example shown here:

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

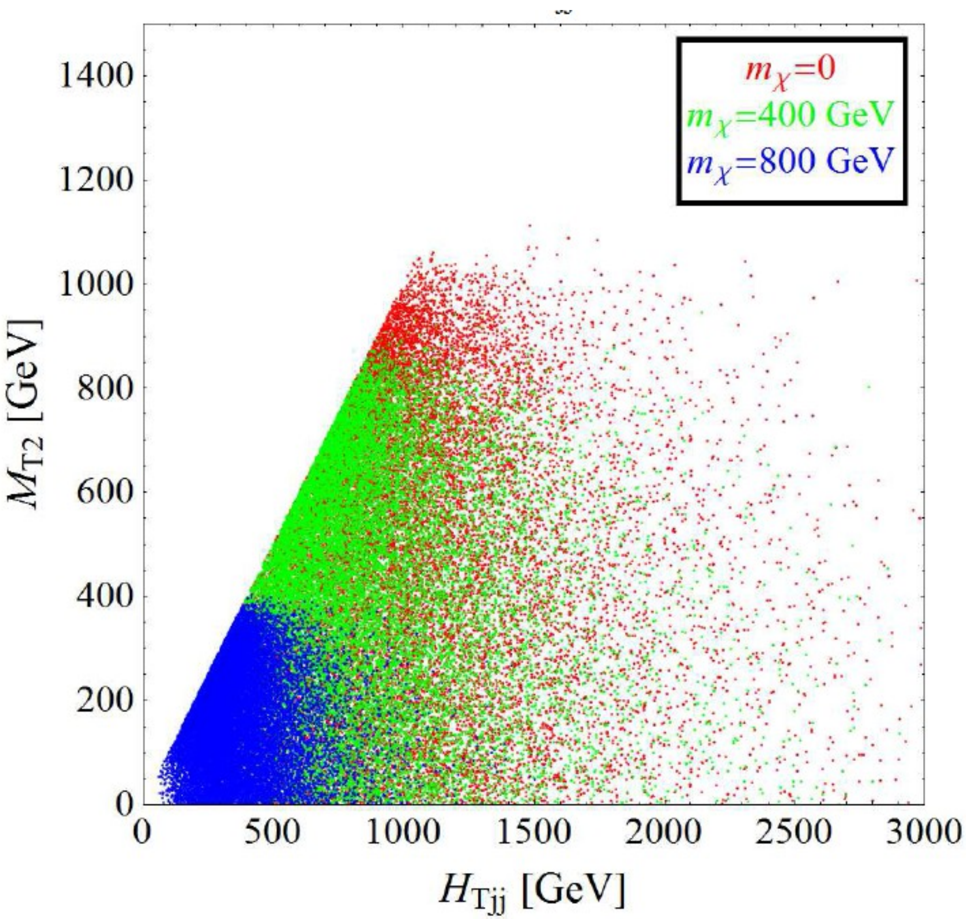
with

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



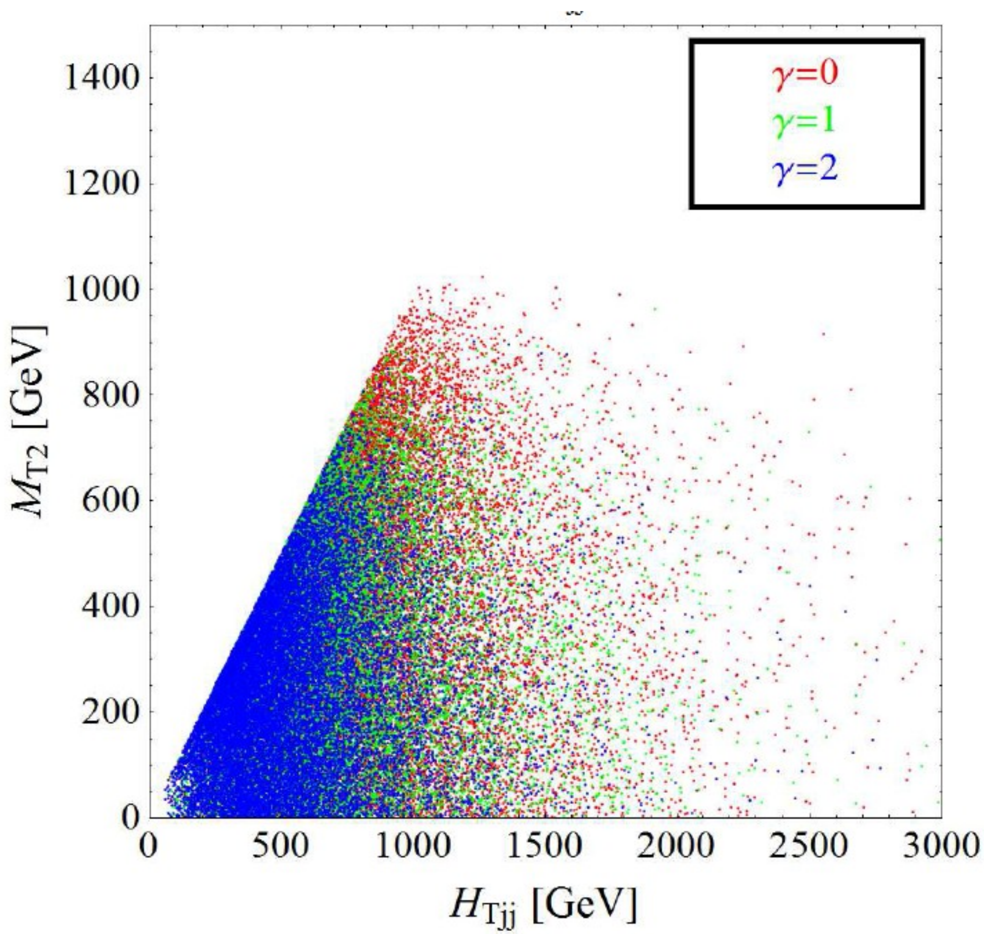
Unhelpful Correlations: $H_{T_{jj}}$ vs. M_{T2}

Traditional Dark-Matter Candidates



$m_\phi = 1$ TeV

Dynamical Dark-Matter Models

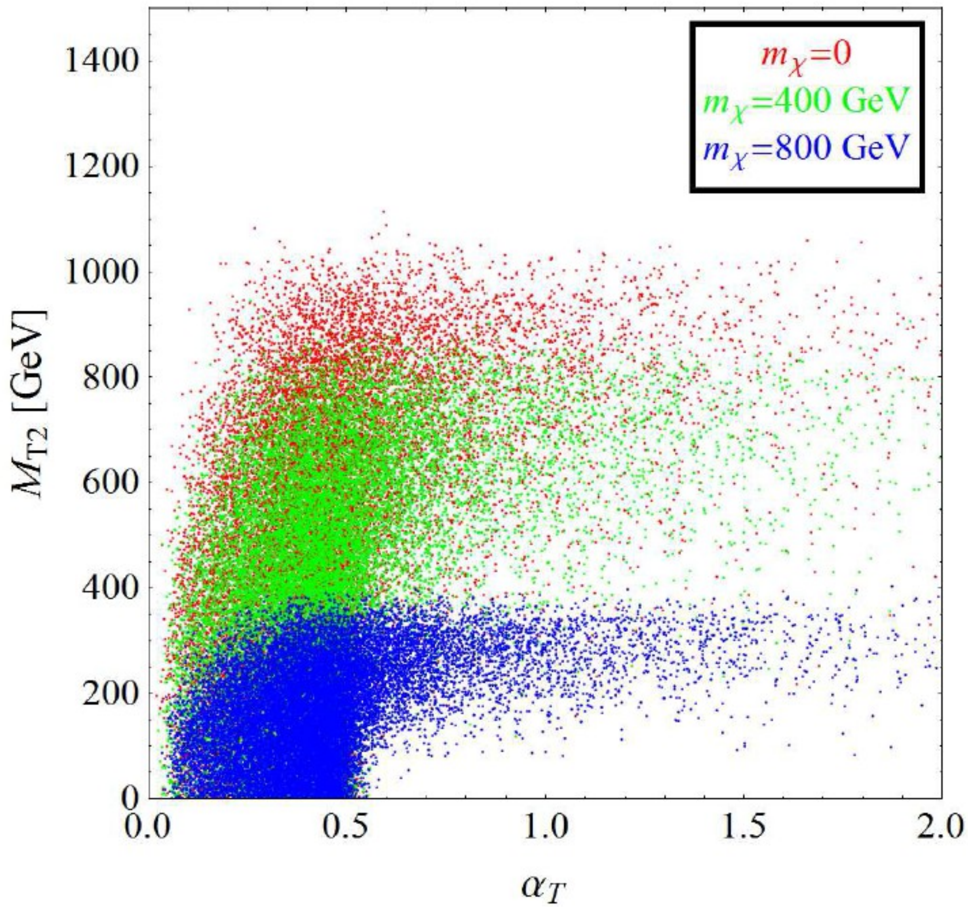


$m_0 = 100$ GeV $\quad m_\phi = 1$ TeV

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

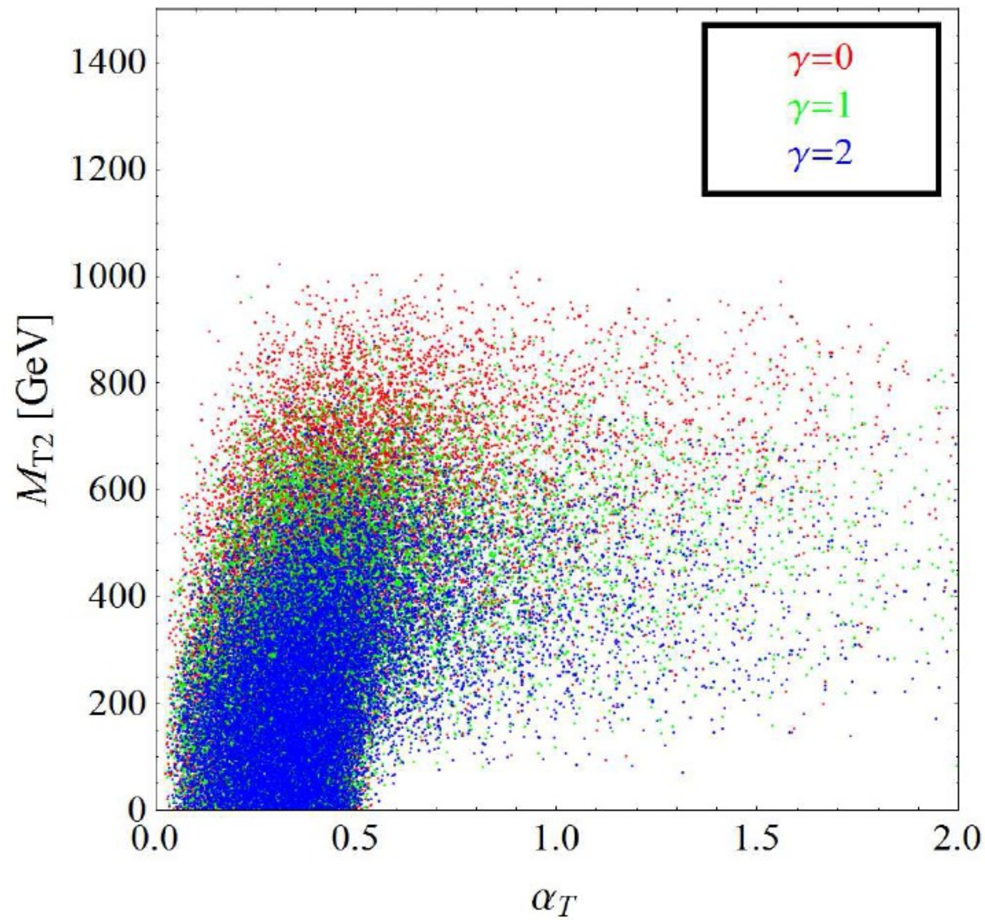
Helpful Correlations: α_T and M_{T2}

Traditional Dark-Matter Candidates



$m_\phi = 1$ TeV

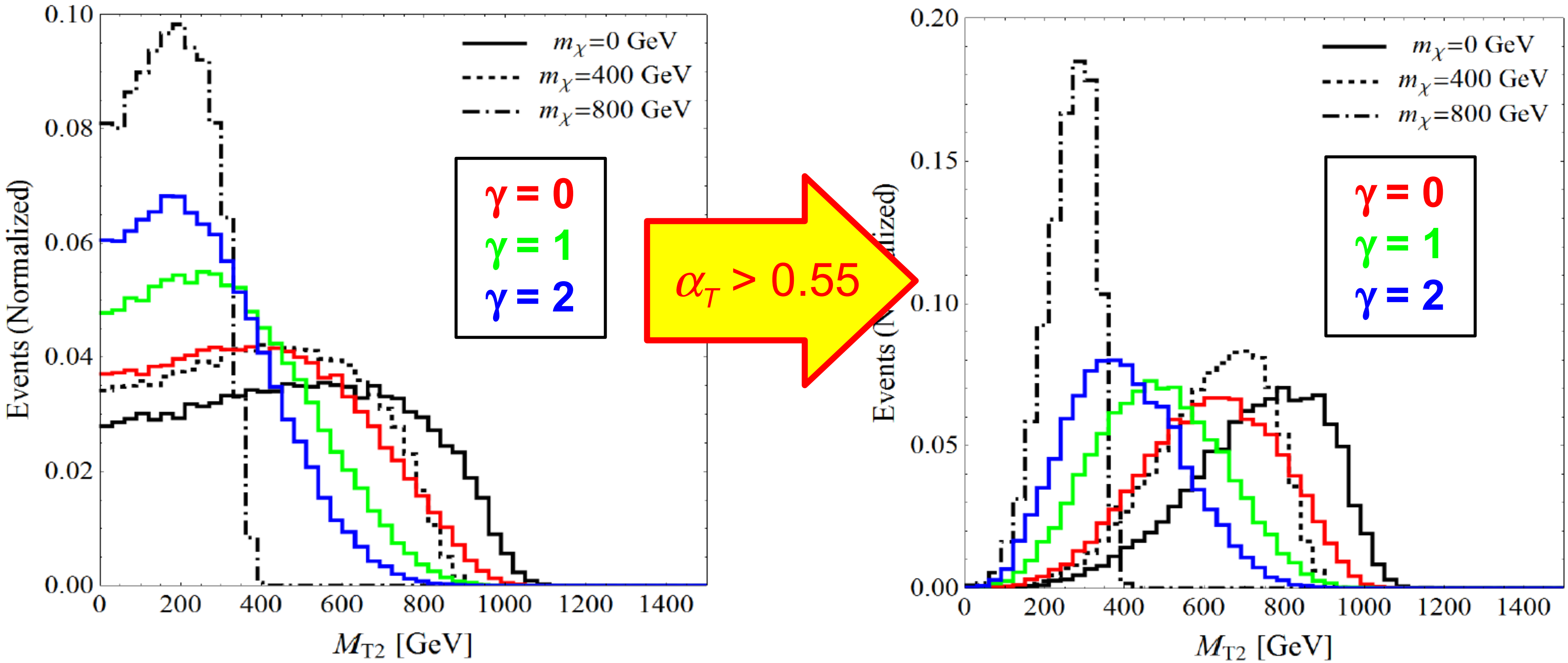
Dynamical Dark-Matter Models



$m_0 = 100$ 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 α_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_χ and coupling structures.
- Divide the distribution into appropriately-sized bins.
- For each value of m_χ 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

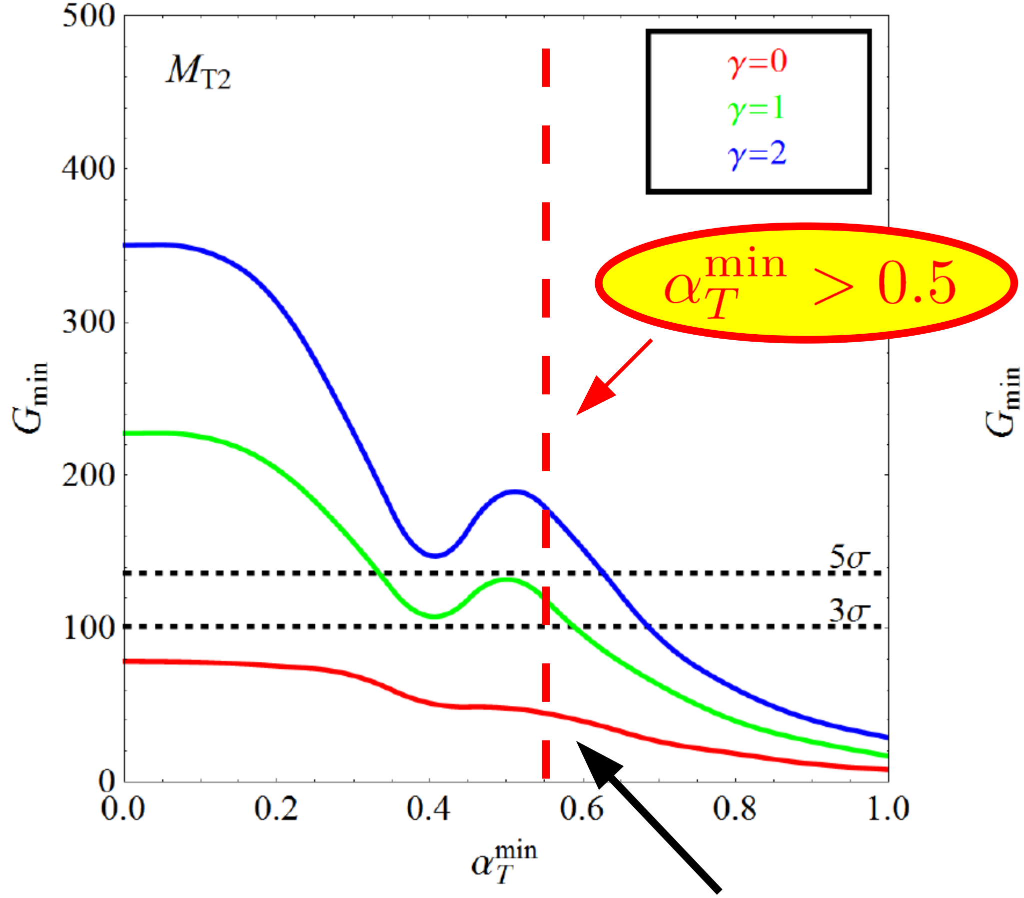
$$\boxed{G(m_\chi) \;=\; -2\ln\lambda(m_\chi)}$$

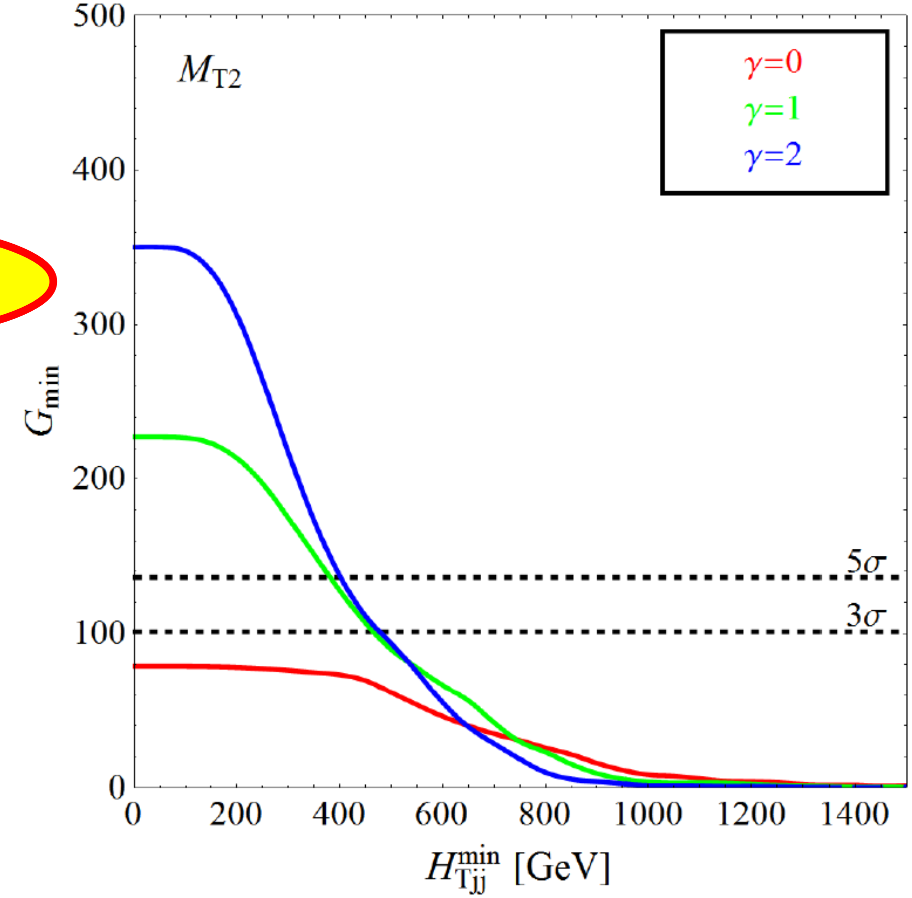
$$\boxed{G_{\min} \;=\; \min_{m_\chi}\{G(m_\chi)\}}$$

- 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)



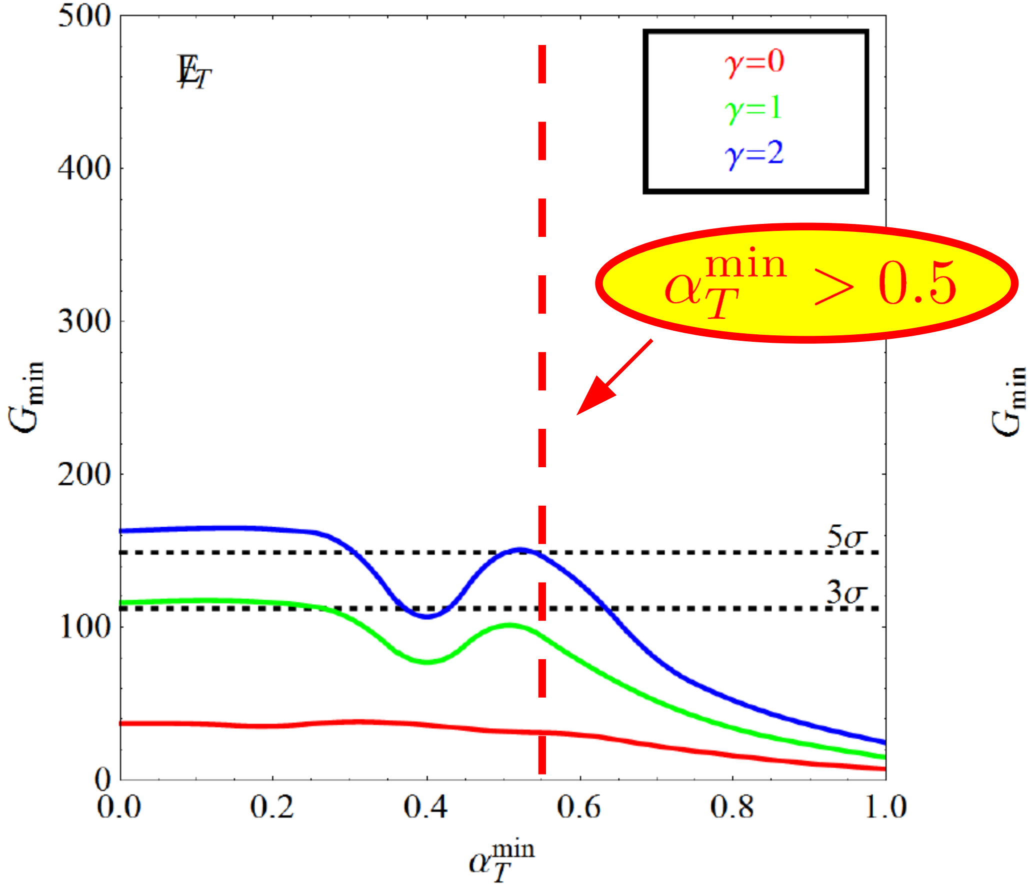


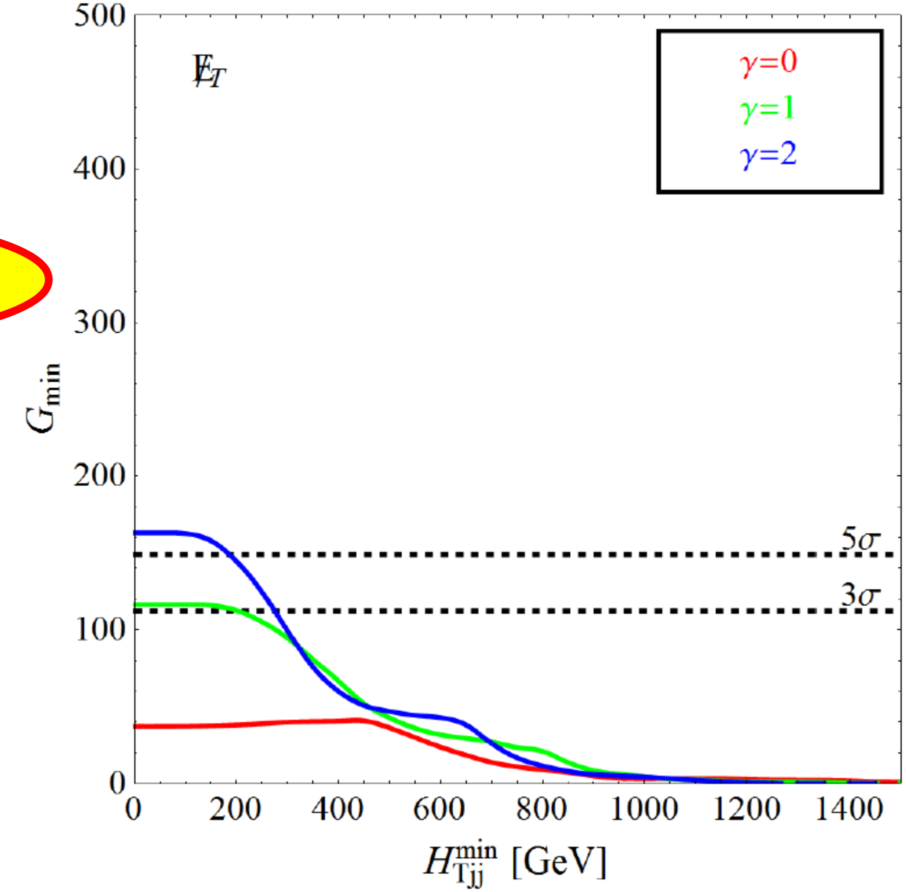
A well-chosen cut on α_T actually serves to **amplify** the distinctiveness of the singal distributions, despite the loss in statistics!

An α_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.

Conclusions

- 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 α_T can actually **enhance** the distinctiveness of these distributions.