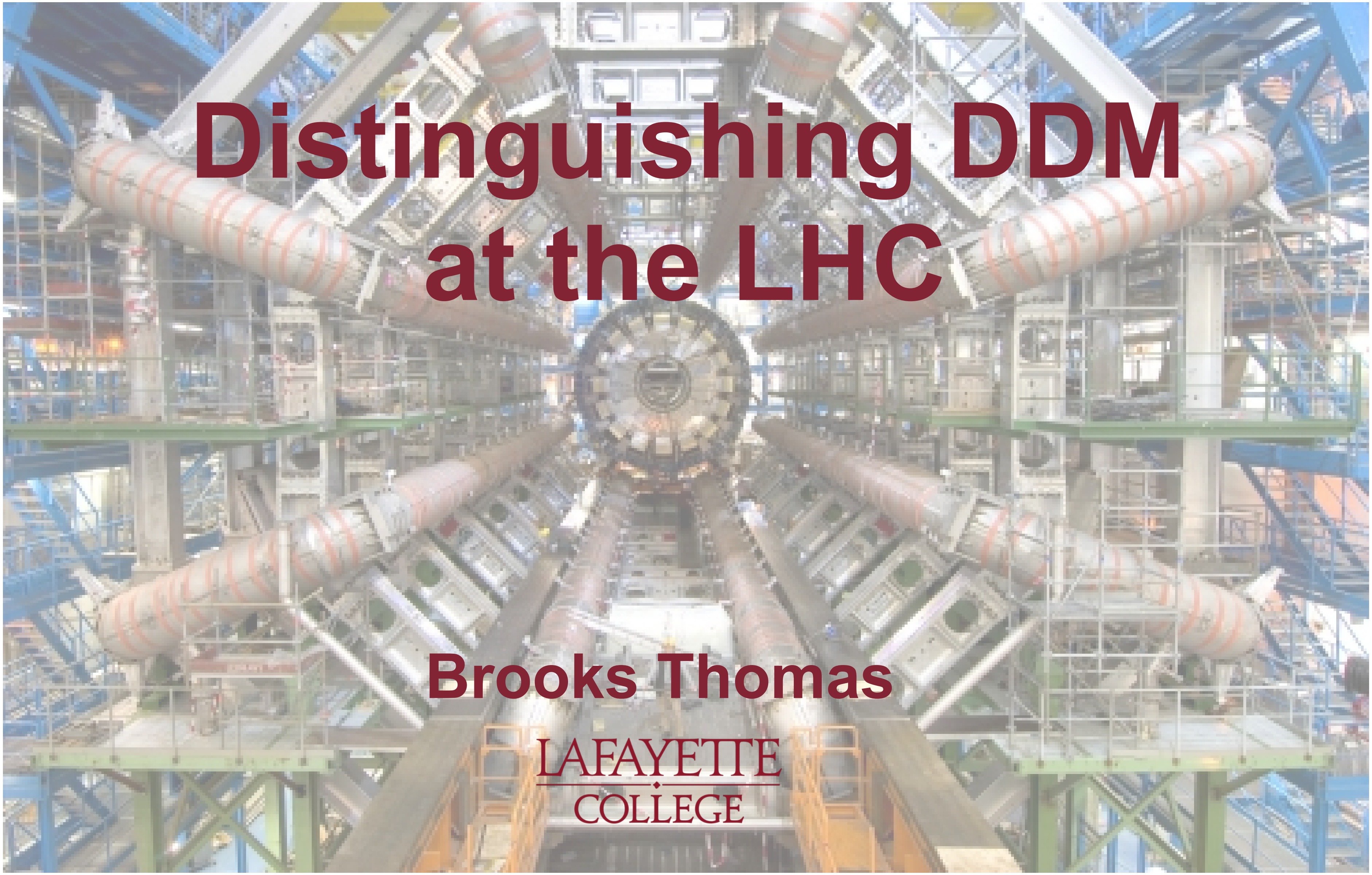


Distinguishing DDM at the LHC

Brooks Thomas

LAFAYETTE COLLEGE

- **K. Dienes, S. Su, BT [arXiv:1204.4183]**
- **K. Dienes, S. Su, BT [arXiv:1407.2606]**

Institute for Basic Science (IBS), June 12th, 2018

DDM@LHC

- The collider phenomenology of DDM ensembles – and other multi-component dark-matter sectors – involves ***two separate endeavors***:

1 ***Detecting*** the dark-sector particles

- Observing an excess some channel(s) involving substantial $\not{E}_T$.
- Basic detection strategies are the same as they are for traditional DM candidates.

2 ***Distinguishing*** DDM ensembles (and multi-component dark matter in general) from DM candidates.

- The hard – and subtle – part! Requires the development of new analyis strategies.

- Possible strategies for distinguishing DDM ensembles from traditional dark-matter candidates at the LHC might involve...

  - Correlating results in ***different channels*** arising from different parts of the DDM ensemble.
  - Correlating results observed in the main LHC detectors with results obtained in **"LHC peripherals"** (MATHUSLA, FASER, etc.).
  - Analyzing the shapes of ***kinematic distributions*** of SM particles produced alongside the dark-sector particles.

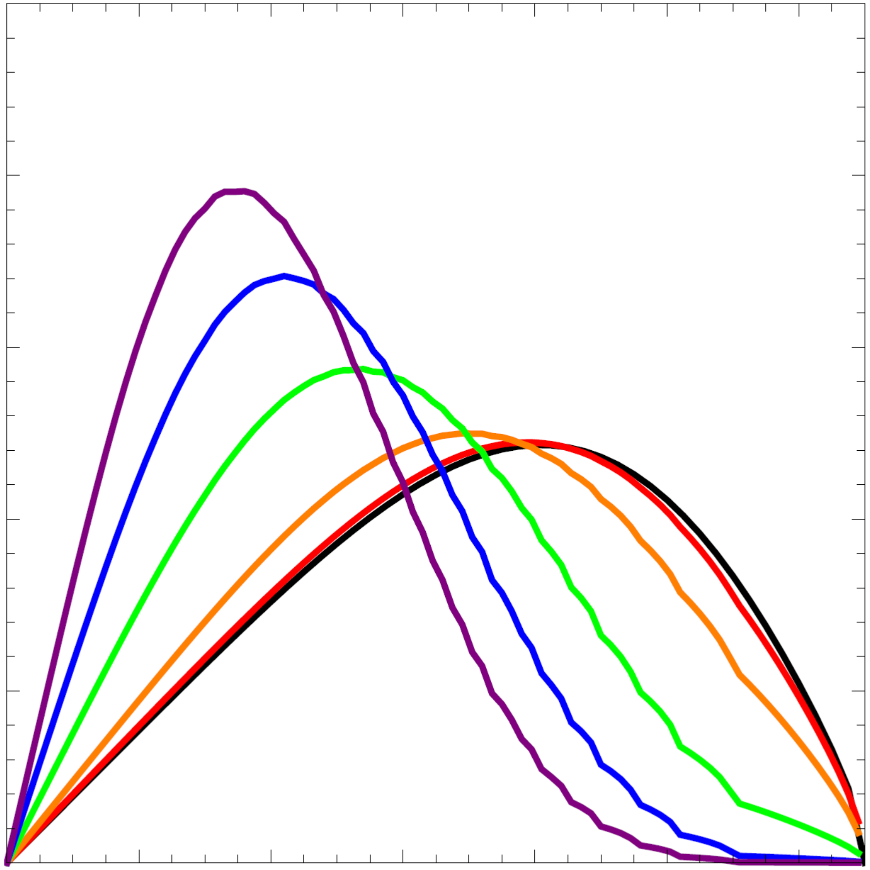
Focus of this talk.

- Over the course of this talk, I'll discuss this strategy in detail and examine the prospects for distinguishing DDM ensembles at the LHC and at future colliders.

- I'll also discuss some of the subtleties – such as those associated with correlations between kinematic variables – which make this kind of analysis more challenging that mere "bump-hunting."

Part I

Beyond the Bump Hunt

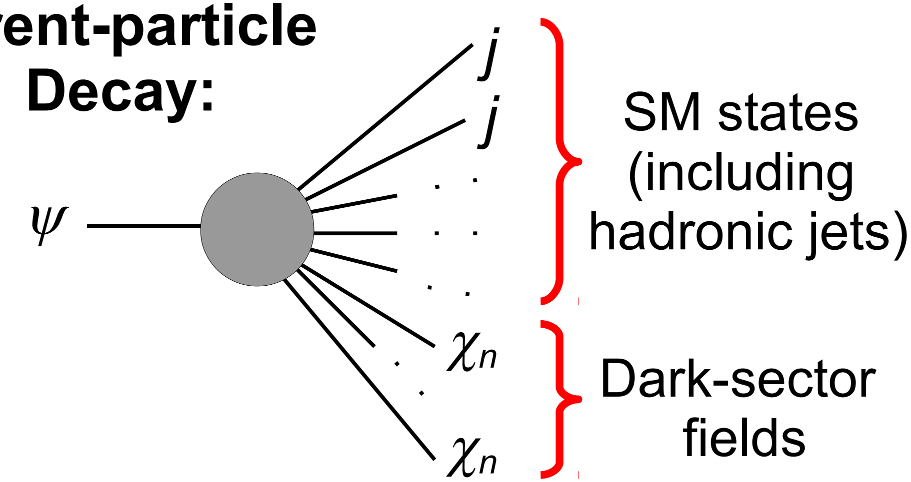


Distinguishing DDM at the LHC

- In a wide variety of DM models, dark-sector fields can be produced via the decays of some heavy **"parent particle"** ψ.
- Strongly interacting ψ can be produced copiously at the LHC. $SU(3)_c$ invariance requires that such ψ decay to final states including not only dark-sector fields, but ***SM quarks and gluons*** as well.
- In such scenarios, the initial signals of dark matter will genericall appear at the LHC in channels involving jets and $\not{E}_T$.

Further information about the dark sector particles can be gleaned from examining the **kinematic distributions** of visible particles produced alongside the DM particles.

Parent-particle Decay:

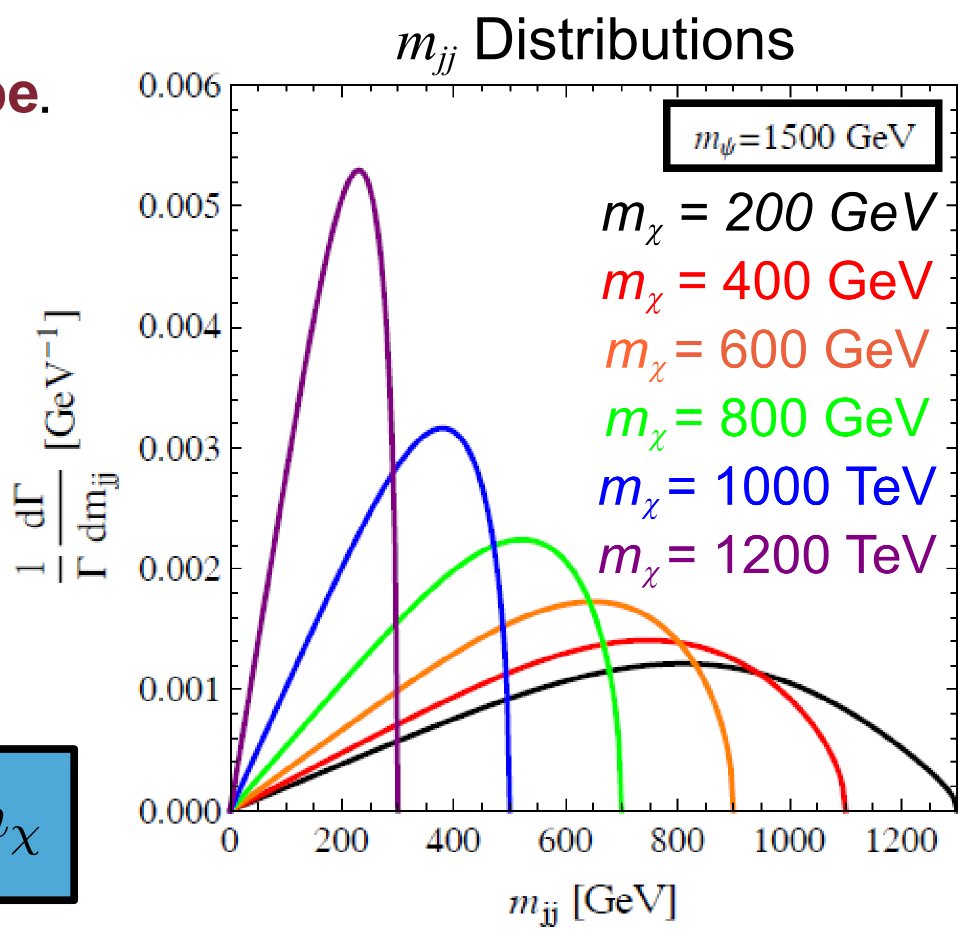


As we shall see, such information can be used to distinguish DDM ensembles from traditional DM candidates on the basis of LHC data.

Traditional DM Candidates

- Let's begin by considering a dark sector which consists of a traditional dark-matter candidate χ — a **stable** particle with a mass m_χ.
- For concreteness, consider the case in which ψ decays primarily via the **three-body** process $\psi \to jj\chi$ (no on-shell intermediary).
- Invariant-mass distributions for such decays manifest a **characteristic shape**.
- Different coupling structures between ψ, χ, and the SM quark and gluon fields, different representations for ψ, *etc.* have only a small effect on the distribution.
- m_{jj} distributions characterized by the presence of a **mass "edge"** at the kinematic endpoint:

$$m_{jj} \leq m_\psi - m_\chi$$



Parent Particles and DDM Daughters

In general, the constituent particles χ_n in a DDM ensemble and other fields in the theory through some set of effective operators $\mathcal{O}_n^{(\alpha)}$:

$$\mathcal{L}_{\rm eff} = \sum_{\alpha}\sum_{n=0}^{N} \frac{c_{n\alpha}}{\Lambda^{d_\alpha - 4}}\mathcal{O}_n^{(\alpha)}$$

As an example, consider a theory in which the masses and coupling coefficients of the χ_n scale as follows:

$$c_{n\alpha} = c_{0\alpha}\left(\frac{m_n}{m_0}\right)^{\gamma_\alpha}$$

$$m_n = m_0 + n^\delta \Delta m$$

γ_α : scaling indices for couplings

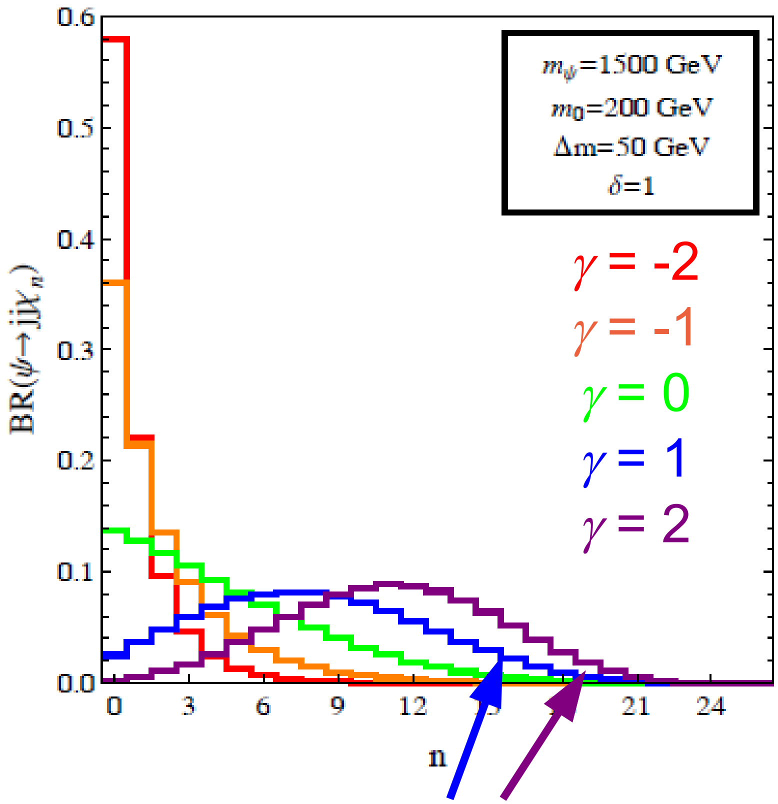
Including coupling between ψ and the dark-sector fields χ_n.

m_0 : mass of lightest constituent

δ : scaling index for the density of states

Δm : mass-splitting parameter

Parent-Particle Branching Fractions



- Once again, let's consider the simplest non-trivial case in which ψ couples to each of the χ_n via a four-body interaction, *e.g.*:

$$\mathcal{L}_{\rm eff} = \sum_n \left[\frac{c_n}{\Lambda^2}\left(\bar{q}_i t^a_{ij} \psi^a\right)\left(\bar{\chi}_n q_j\right) + \text{h.c.}\right]$$

- Assume partent's total width Γ_ψ dominated by decays of the form $\psi \to jj\chi_n$.

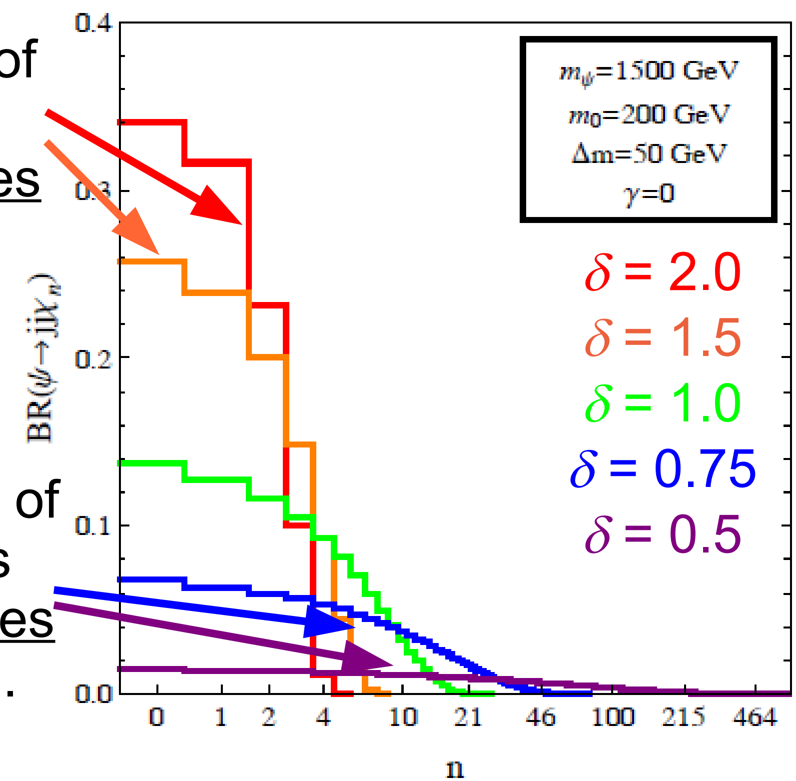
Coupling stength increases with n for γ>0...

…but phase space always decreases with n.

- **Branching fractions** of ψ to the different χ_n controlled by Δm, δ, and γ.

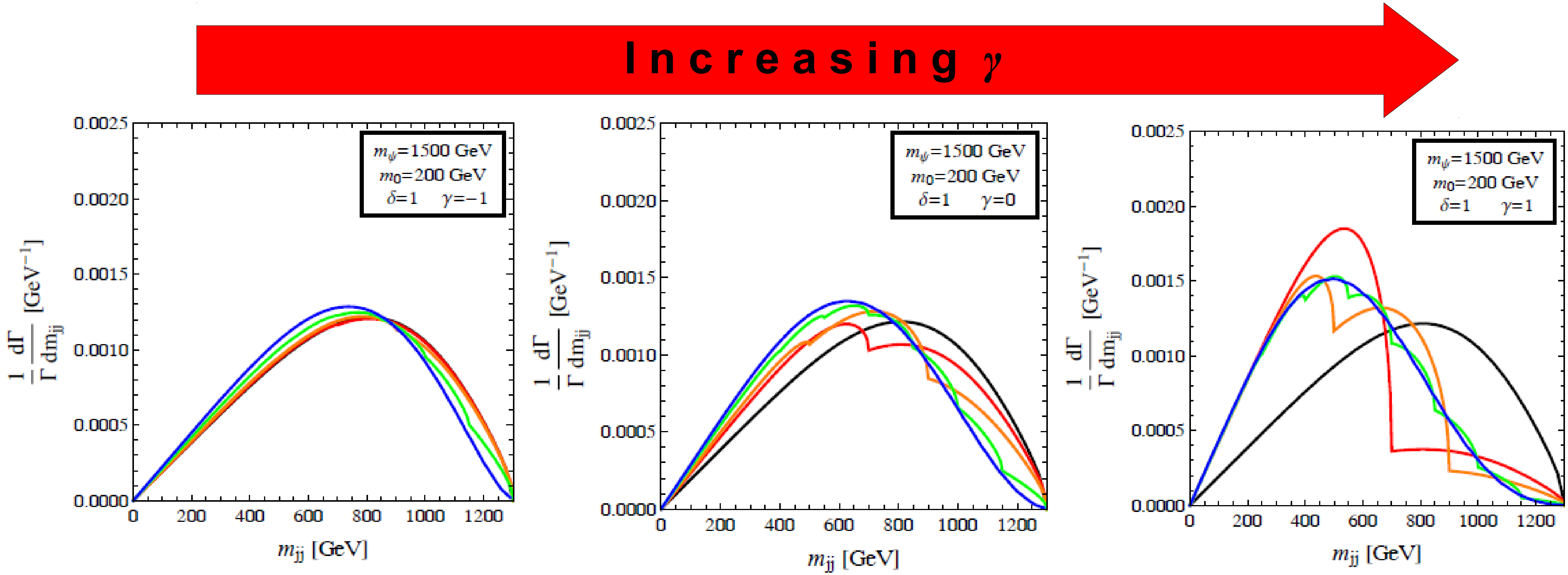
Density of states decreases with n.

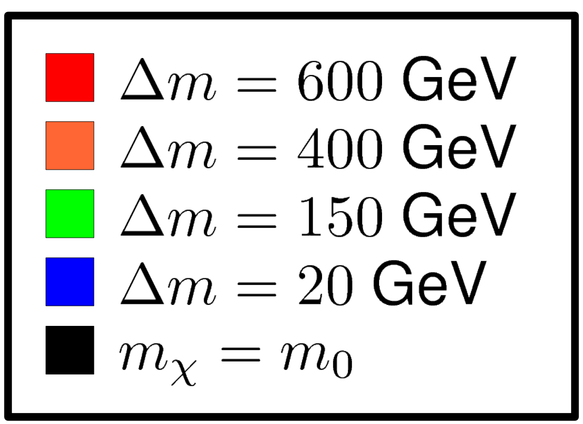
Density of states increases with n.



DDM Ensembles & Kinematic Distributions

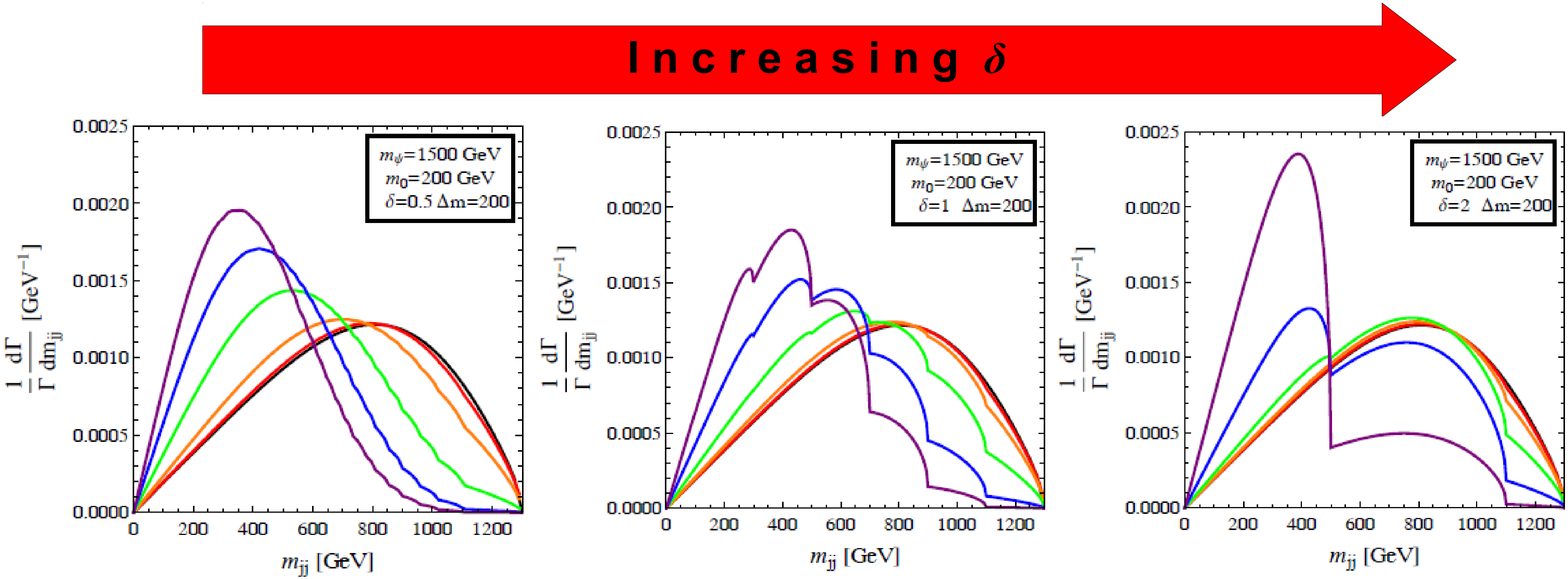
- Evidence of a DDM ensemble can be ascertained from characteristic features imprinted on the kinematic distributions of these SM particles.

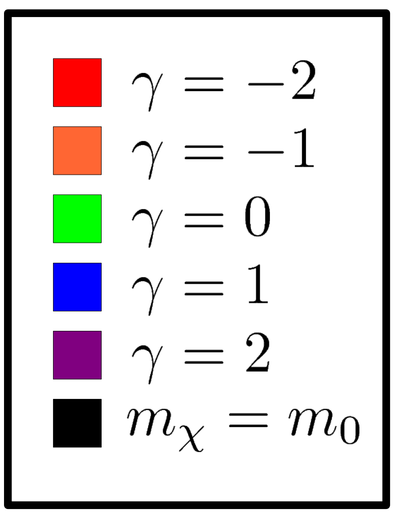




- For example, in the scenarios we're considering here, the (normalized) dijet invariant-mass distribution is given by

$$\frac{1}{\Gamma_\psi}\frac{d\Gamma_\psi}{dm_{jj}} = \sum_{n=0}^{n_{\max}} \left(\frac{1}{\Gamma_{\psi n}}\frac{d\Gamma_{\psi n}}{dm_{jj}} \times \mathrm{BR}_{\psi n} \right)$$





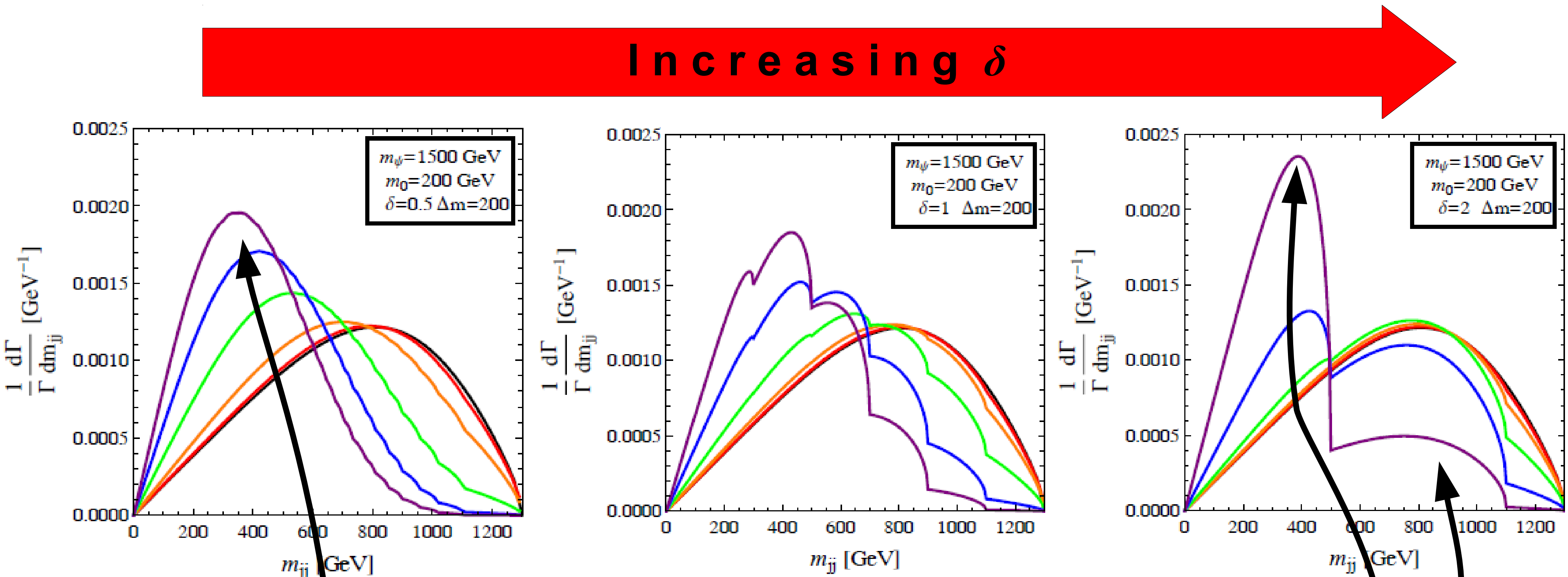
Two Characteristic Signatures:

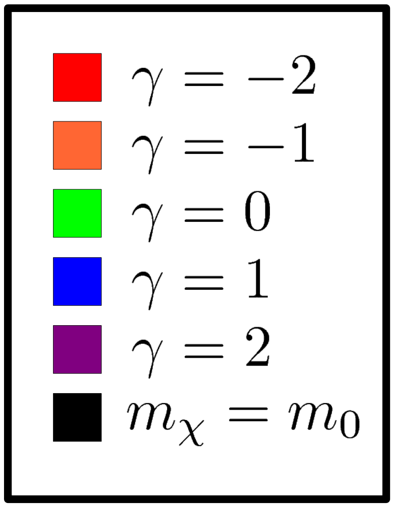
1. Multiple distinguishable peaks

Large δ, Δm: individual contributions from two or more of the χ_n can be resolved.

2. The Collective Bell

Small δ, Δm: Individual peaks cannot be distinguished, mass edge "lost," m_{jj} distribution assumes a characteristic shape.





Two Characteristic Signatures:

1. Multiple distinguishable peaks

Large δ, Δm: individual contributions from two or more of the χ_n can be resolved.

2. The Collective Bell

Small δ, Δm: Individual peaks cannot be distinguished, mass edge “lost,” m_{jj} distribution assumes a characteristic shape.

But the REAL question is...

How well can we distinguish these features in practice?

In other words: to what degree are the characteristic kinematic distributions to which DDM ensembles give rise 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 into bins with width determined by the invariant-mass resolution Δm_{jj} of the detector (dominated by jet-energy resolution ΔE_j).
- For each value of m_χ in the survey, define a χ^2 statistic $\chi^2(m_\chi)$ to quantify the degree to which the two resulting m_{jj} distributions differ.

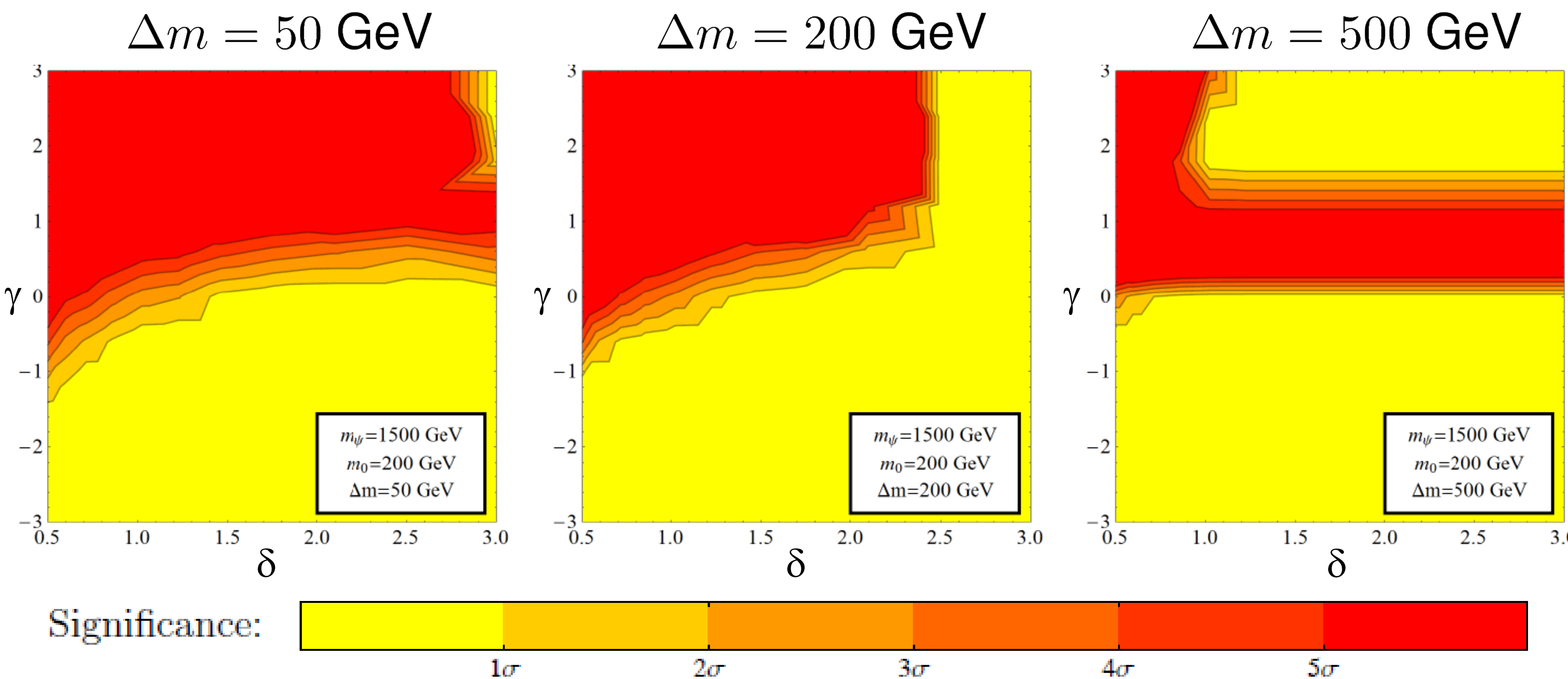
$$\chi^2(m_\chi) = \sum_k \frac{[X_k - \mathcal{E}_k(m_\chi)]^2}{\sigma_k^2}$$

$$\chi^2_{\rm min} = \min_{m_\chi} \{\chi^2(m_\chi)\}$$

- The ***minimum*** χ^2 value from among these represents the degree to which a DDM ensemble can be distinguished from ***any*** traditional DM candidate.

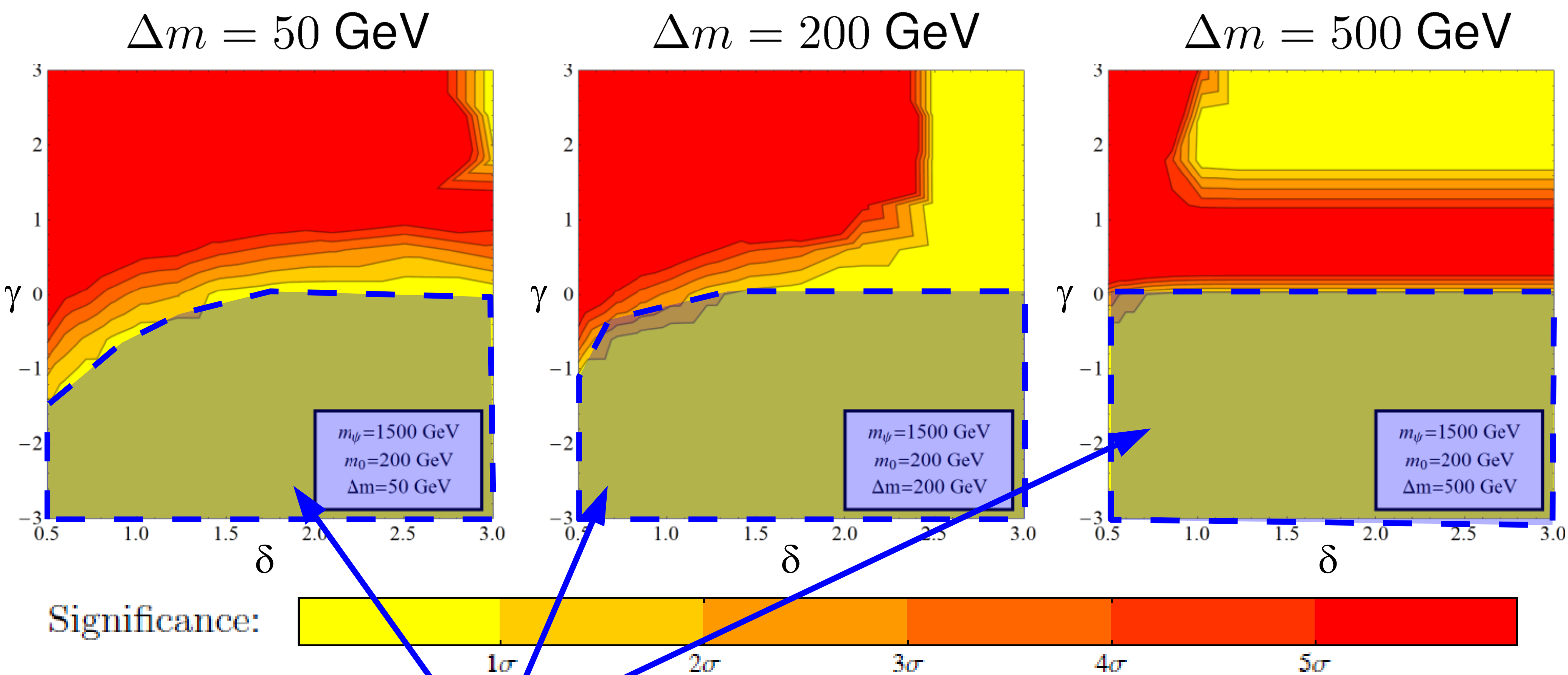
Distinguishing DDM Ensembles: Results

Results for N_e = 1000 signal events (e.g., $pp \to \psi\psi$ for TeV-scale parent, $L_{int} < 30\ fb^{-1}$)



Distinguishing DDM Ensembles: Results

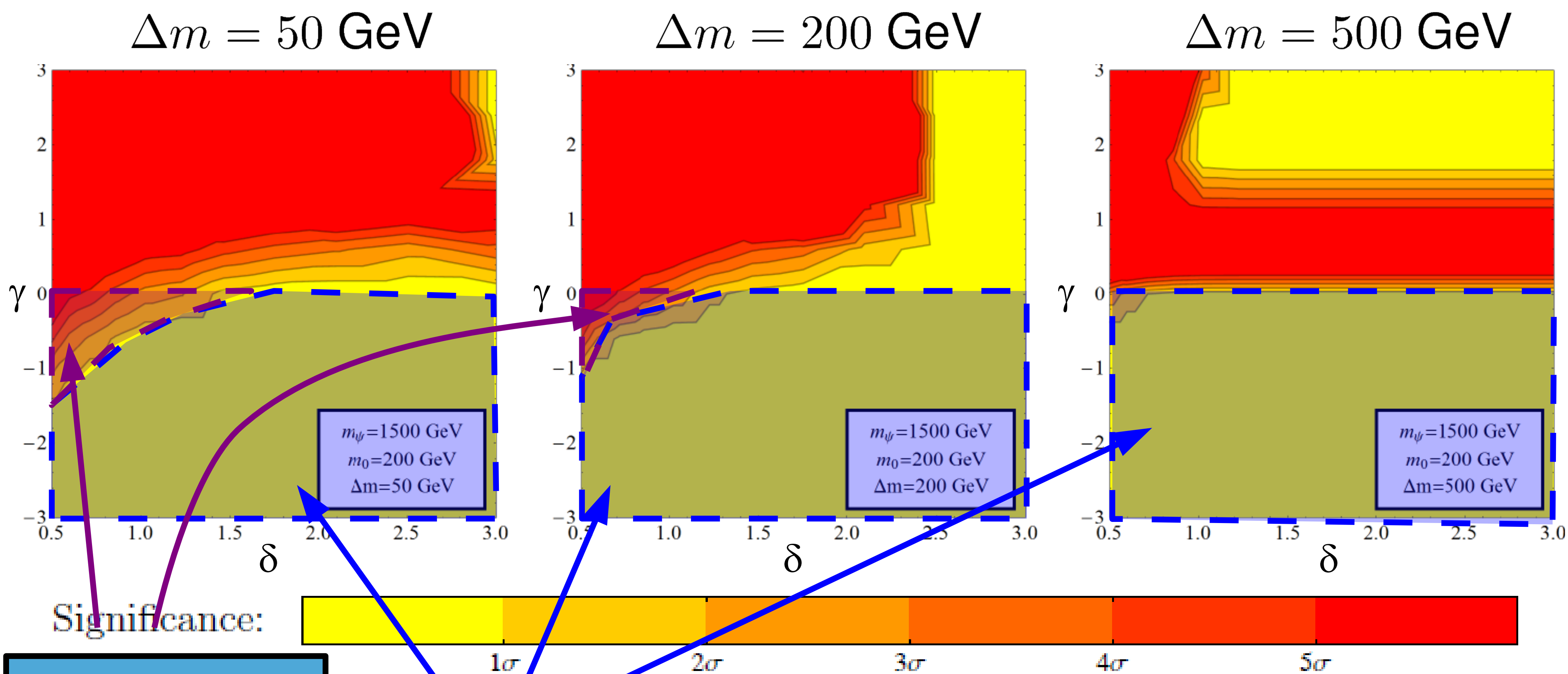
Results for N_e = 1000 signal events (e.g., $pp \to \psi\psi$ for TeV-scale parent, $L_{int} < 30\ fb^{-1}$)



BRs to all χ_n with $n > 1$ suppressed: lightest constituent dominates the width of ψ.

Distinguishing DDM Ensembles: Results

Results for N_e = 1000 signal events (e.g., $pp \rightarrow \psi\psi$ for TeV-scale parent, $L_{int} < 30\ fb^{-1}$)

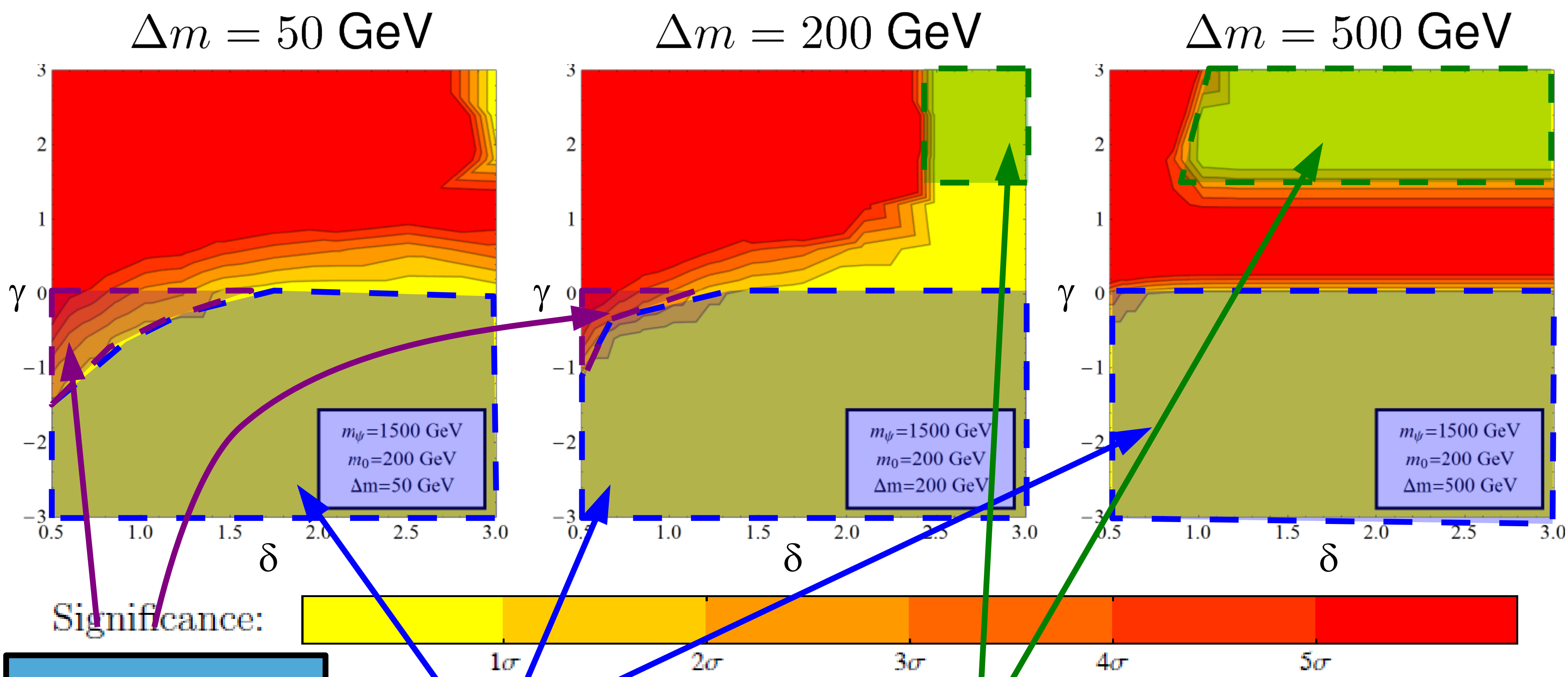


Density of states large enough to overcome γ suppression for small δ.

BRs to all χ_n with $n > 1$ suppressed: lightest constituent dominates the width of ψ.

Distinguishing DDM Ensembles: Results

Results for N_e = 1000 signal events (e.g., $pp \to \psi\psi$ for TeV-scale parent, $L_{int} < 30\ fb^{-1}$)



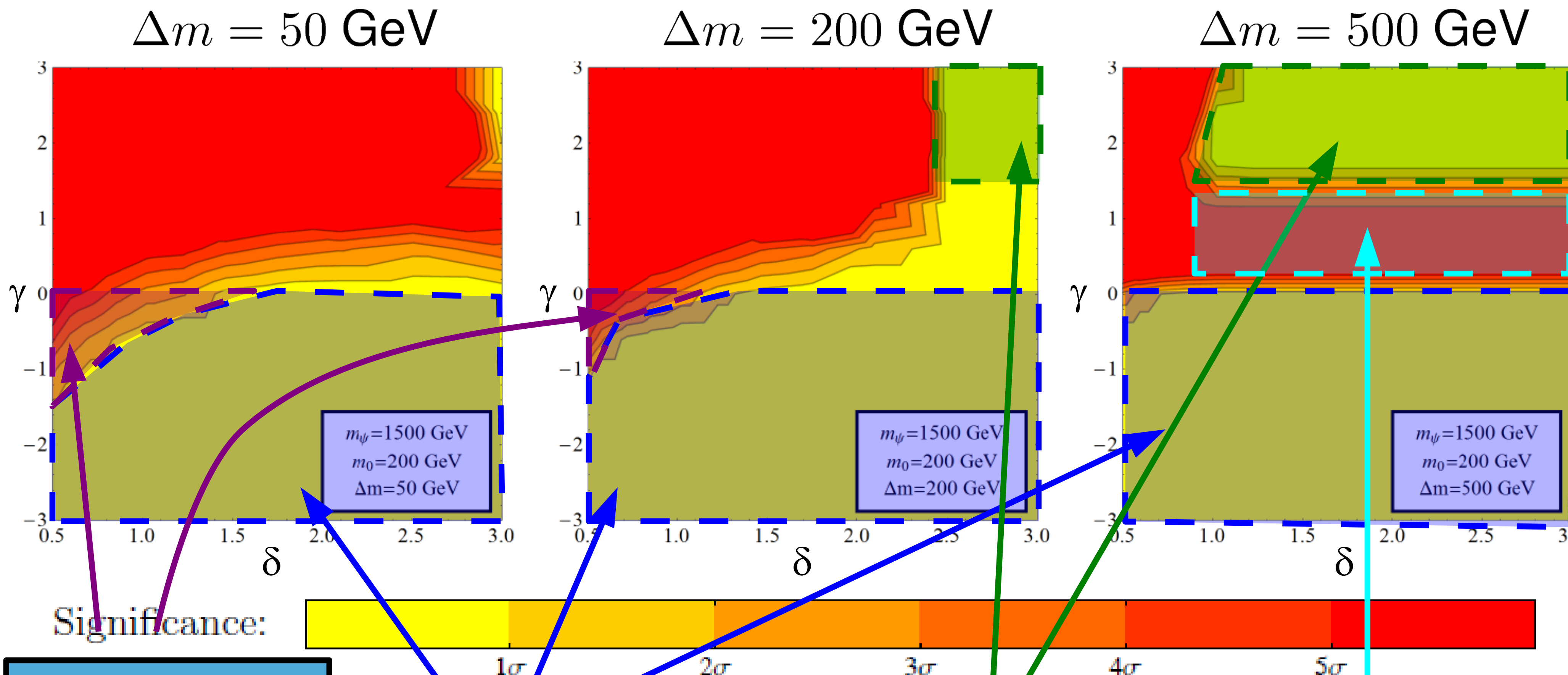
Density of states large enough to overcome γ suppression for small δ.

BRs to all χ_n with $n > 1$ suppressed: lightest constituent dominates the width of ψ.

Next-to-lightest constituent χ_1 dominates the width of ψ.

Distinguishing DDM Ensembles: Results

Results for N_e = 1000 signal events (e.g., $pp \to \psi\psi$ for TeV-scale parent, $L_{int} < 30$ fb^{-1})



Density of states large enough to overcome γ suppression for small δ.

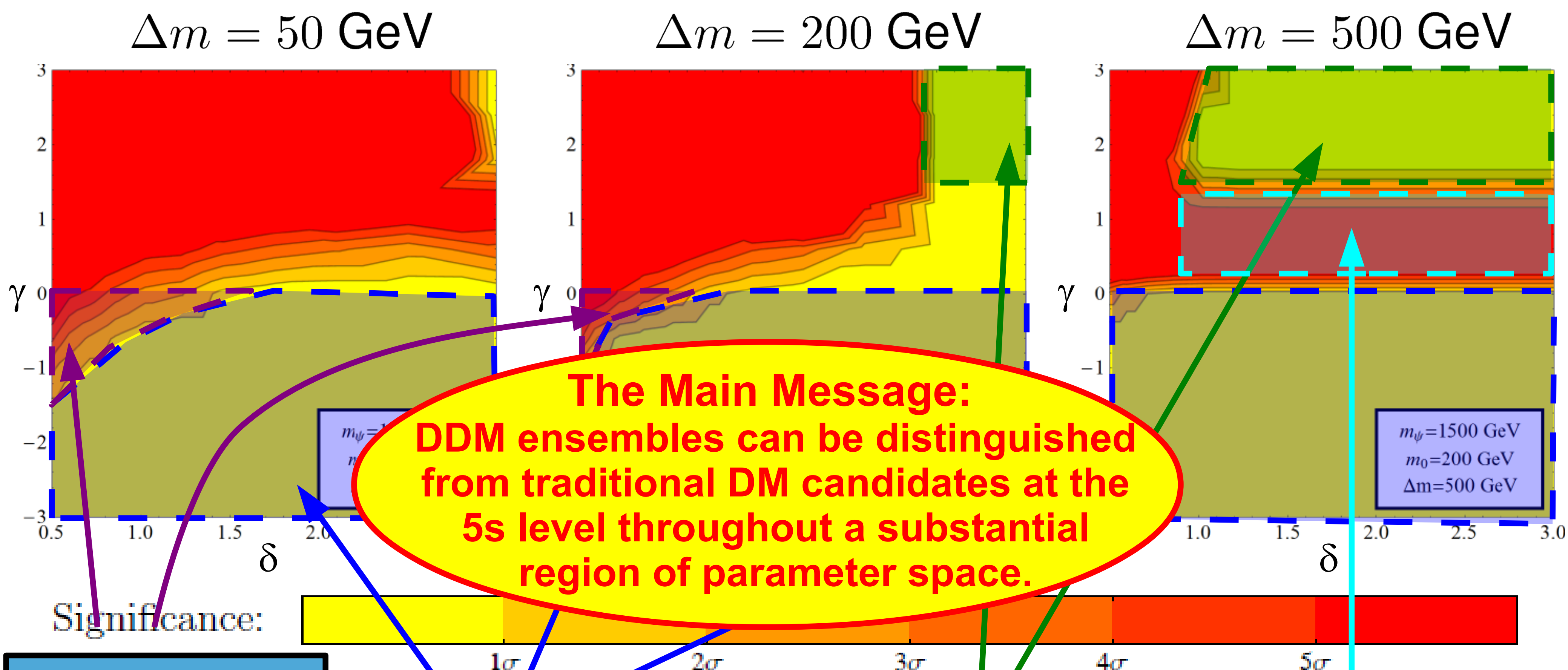
BRs to all χ_n with $n > 1$ suppressed: lightest constituent dominates the width of ψ.

Next-to-lightest constituent χ_1 dominates the width of ψ.

$\mathrm{BR}(\psi \to jj\chi_0) \approx \mathrm{BR}(\psi \to jj\chi_1)$: two distinct m_{jj} peaks.

Distinguishing DDM Ensembles: Results

Results for N_e = 1000 signal events (e.g., $pp \to \psi\psi$ for TeV-scale parent, $L_{int} < 30\ fb^{-1}$)



Density of states large enough to overcome γ suppression for small δ.

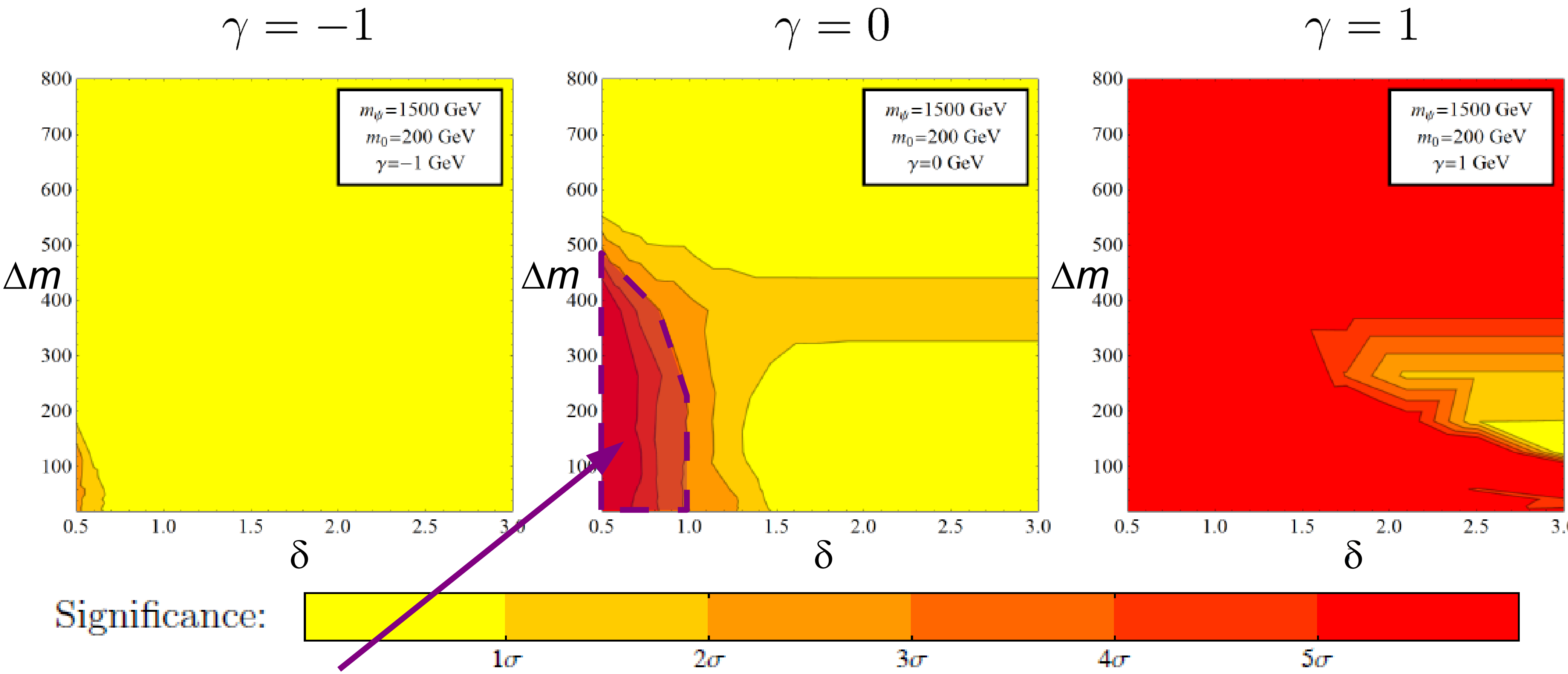
BRs to all χ_n with $n > 1$ suppressed: lightest constituent dominates the width of ψ.

Next-to-lightest constituent χ_1 dominates the width of ψ.

$BR(\psi \to jj\chi_0) \approx BR(\psi \to jj\chi_1)$: two distinct m_{jj} peaks.

Distinguishing DDM Ensembles: Results

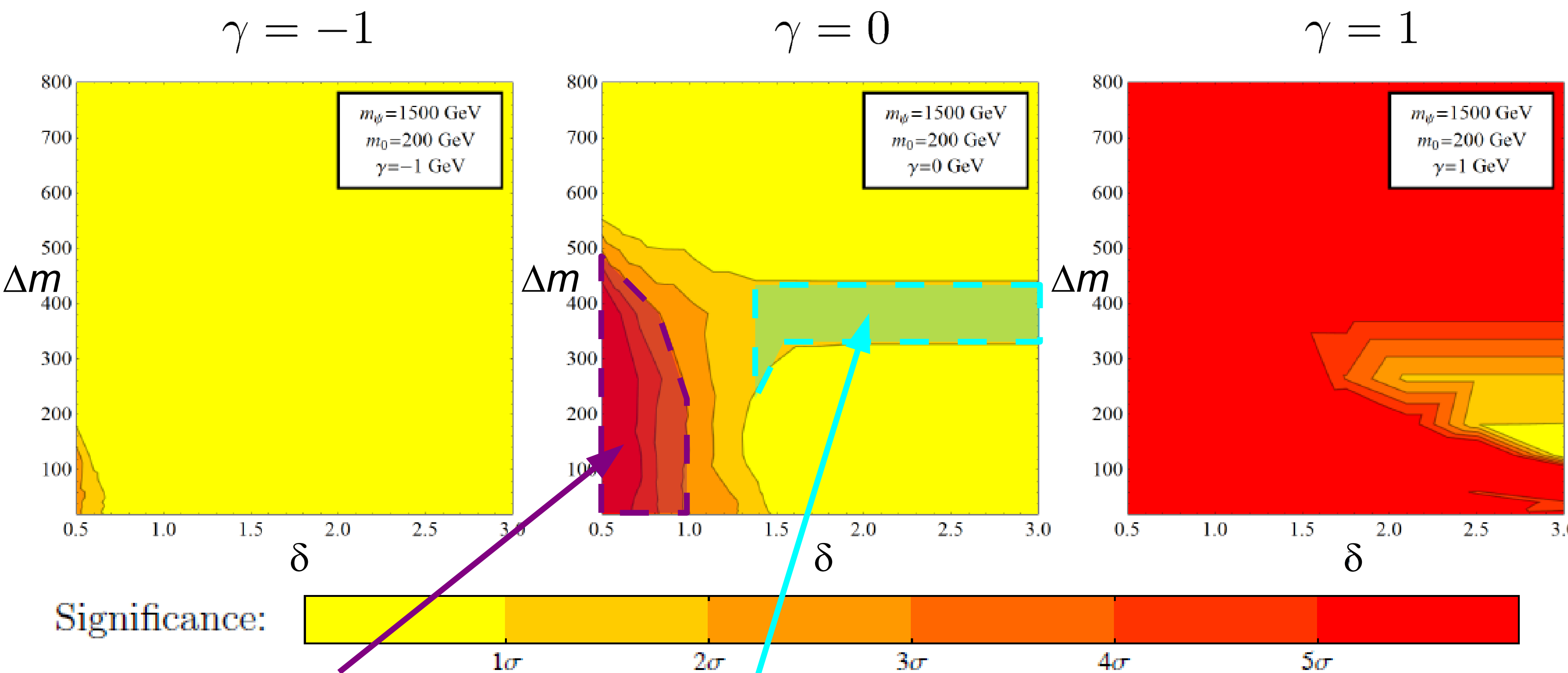
Results for N_e = 1000 signal events (e.g., $pp \rightarrow \psi\psi$ for TeV-scale parent, $L_{int} < 30\ fb^{-1}$)



Large number of states accessible for small Δm, δ

Distinguishing DDM Ensembles: Results

Results for N_e = 1000 signal events (e.g., $pp \to \psi\psi$ for TeV-scale parent, $L_{int} < 30\ fb^{-1}$)

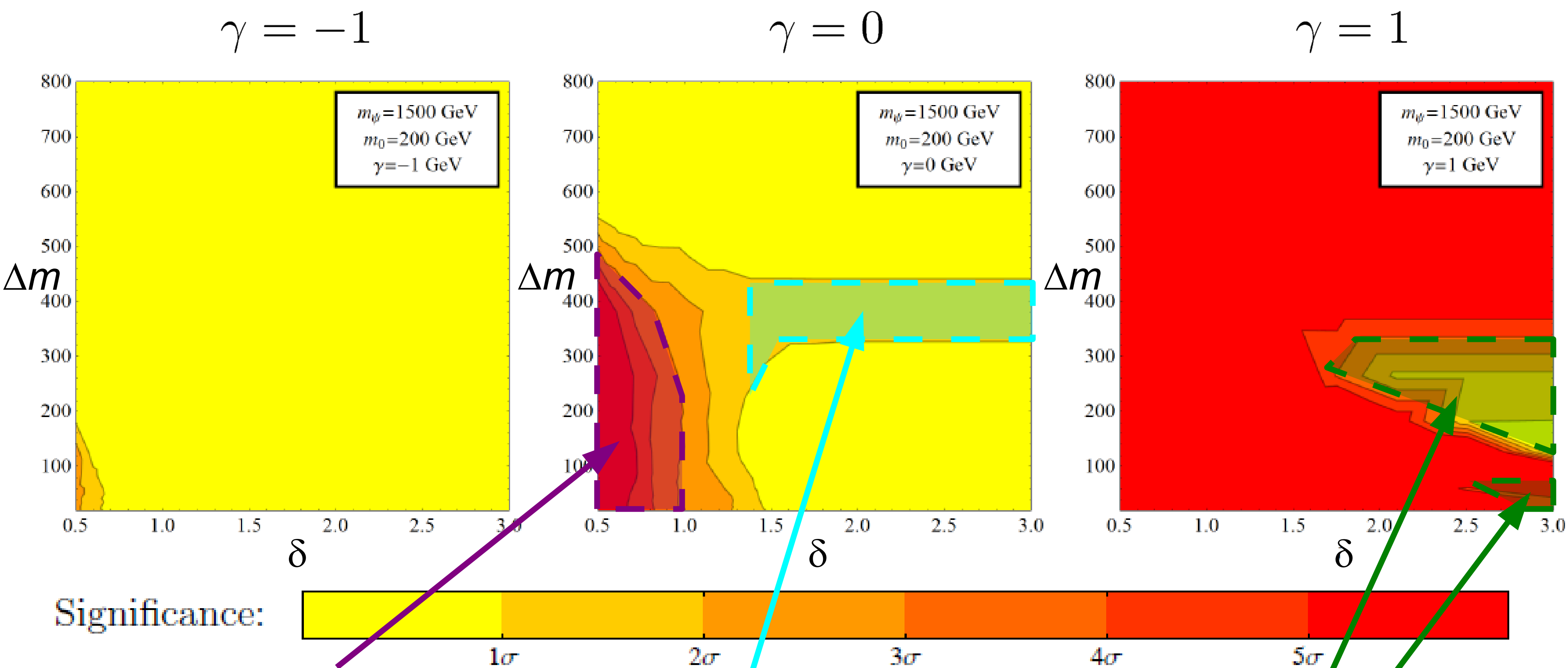


Large number of states accessible for small Δm, δ

$\mathrm{BR}(\psi \to jj\chi_0) \approx \mathrm{BR}(\psi \to jj\chi_1)$: two distinct m_{jj} peaks.

Distinguishing DDM Ensembles: Results

Results for N_e = 1000 signal events (e.g., $pp \rightarrow \psi\psi$ for TeV-scale parent, $L_{int} < 30\ \text{fb}^{-1}$)



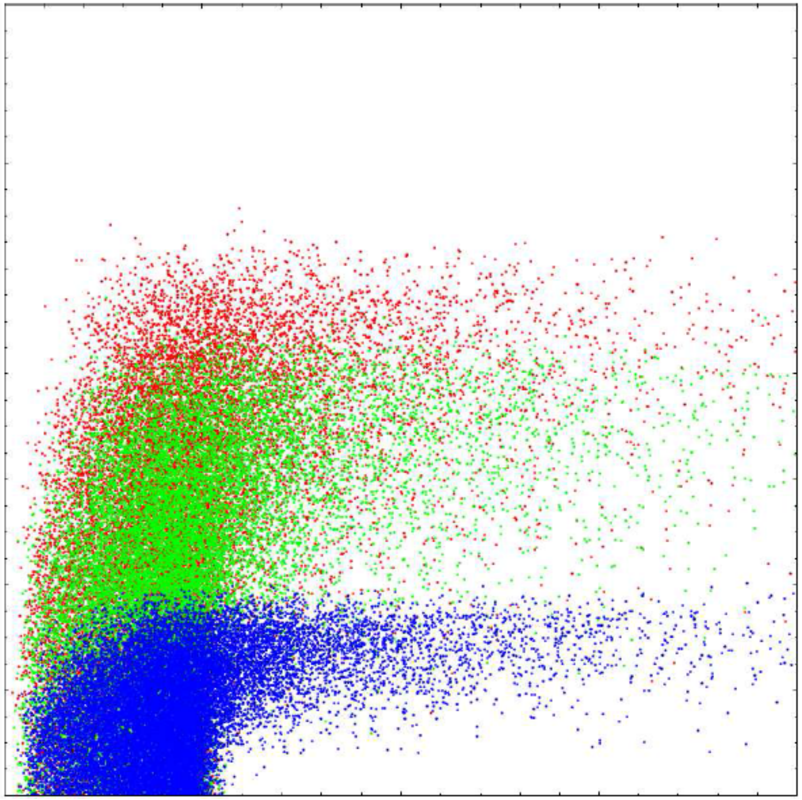
Large number of states accessible for small Δm, δ

$\text{BR}(\psi \rightarrow jj\chi_0) \approx \text{BR}(\psi \rightarrow jj\chi_1)$: two distinct m_{jj} peaks.

Only χ_0 and χ_1 kinematically accessible. One or the other dominates the width of ψ.

Part II

Cuts and Correlations



The Role of Correlations in Distribution-Based Searches

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.

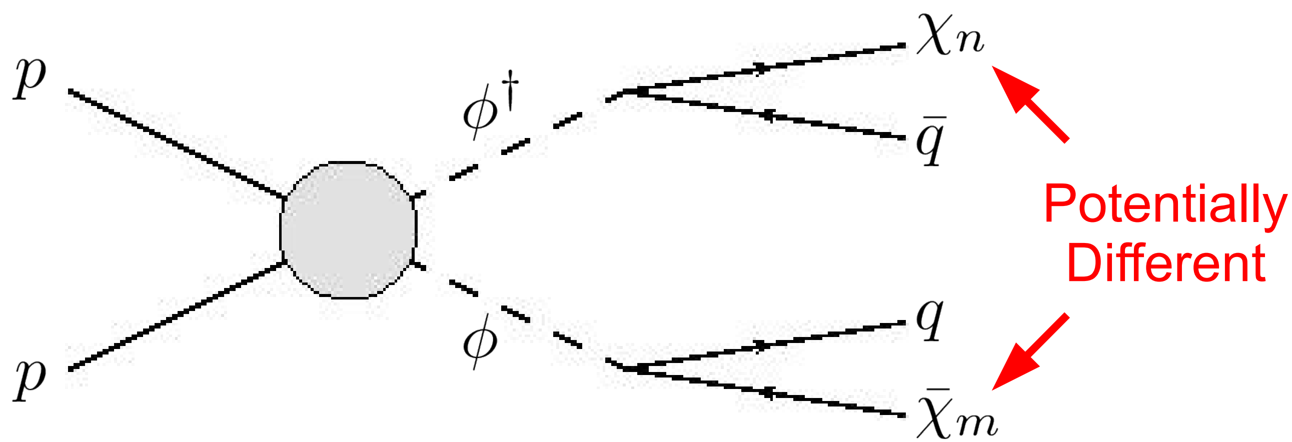
It is crucial to understand the impact of such correlations in developing and optimizing search strategies for non-minimal dark sectors at colliders.

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

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

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

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})
- $H_T \equiv \not{E}_T + \sum_{i=1}^{N} p_{T_i}$
- $\alpha_T \equiv |p_{T_2}|/m_{jj}$ CMS-PAS-SUS-08-005, 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 $\not{\vec{p}}_T$)
- 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.

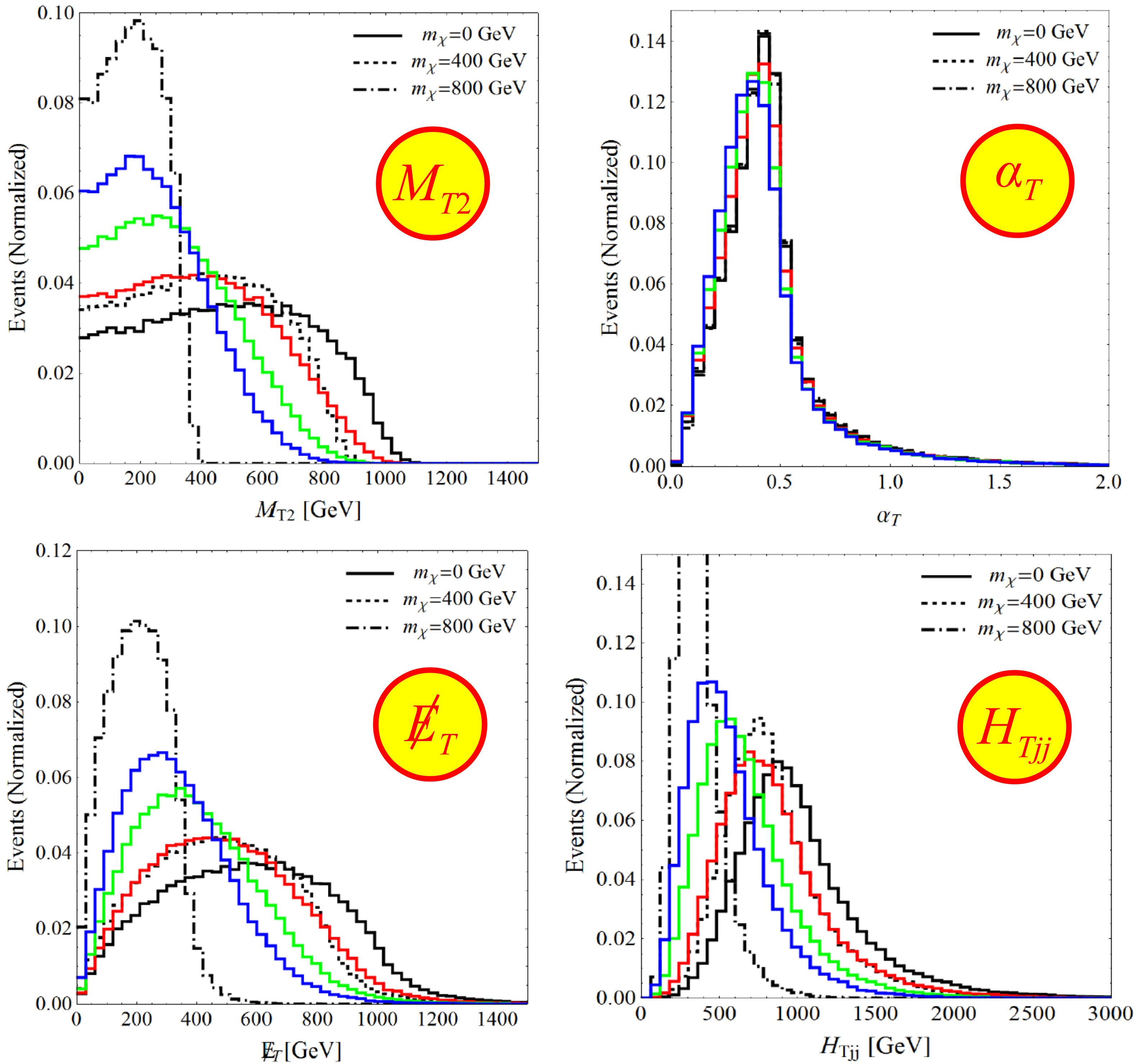
The Distributions:

Example shown here:

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

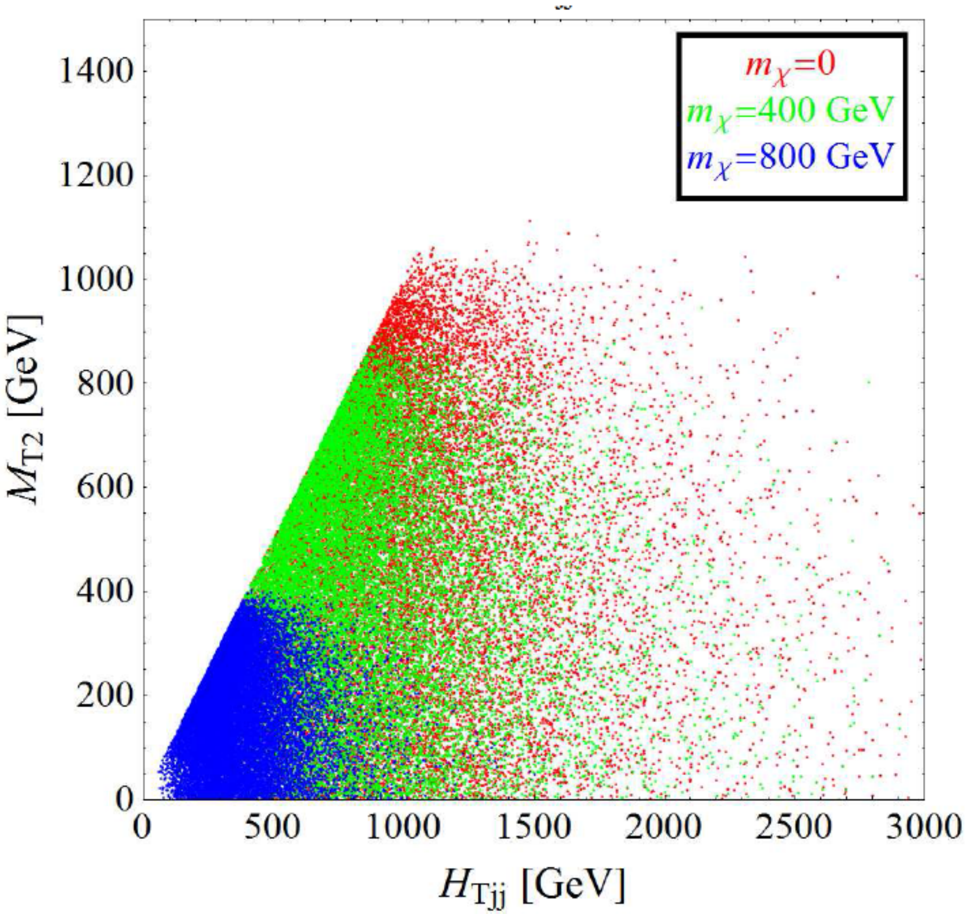
with

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



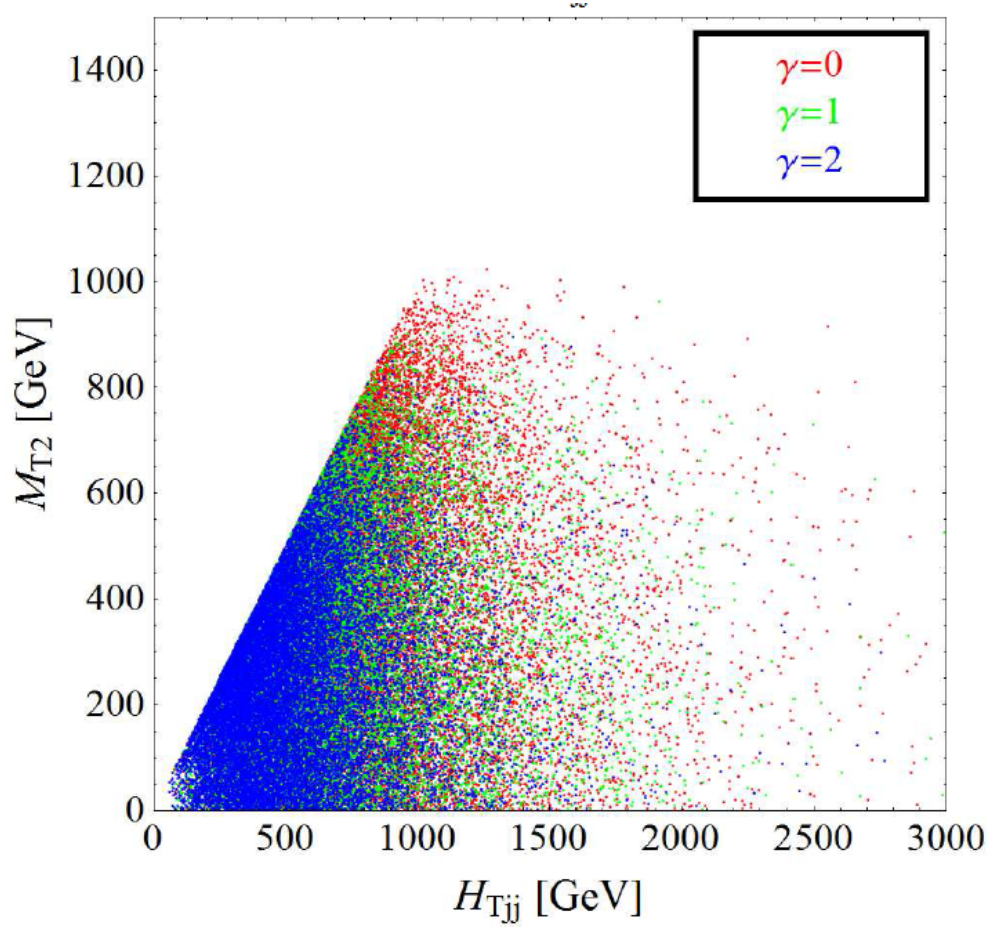
Unhelpful Correlations: $H_{T_{jj}}$ vs. M_{T2}

Traditional Dark-Matter Candidates



$$\mathrm{m}_\phi = 1 \text{ TeV}$$

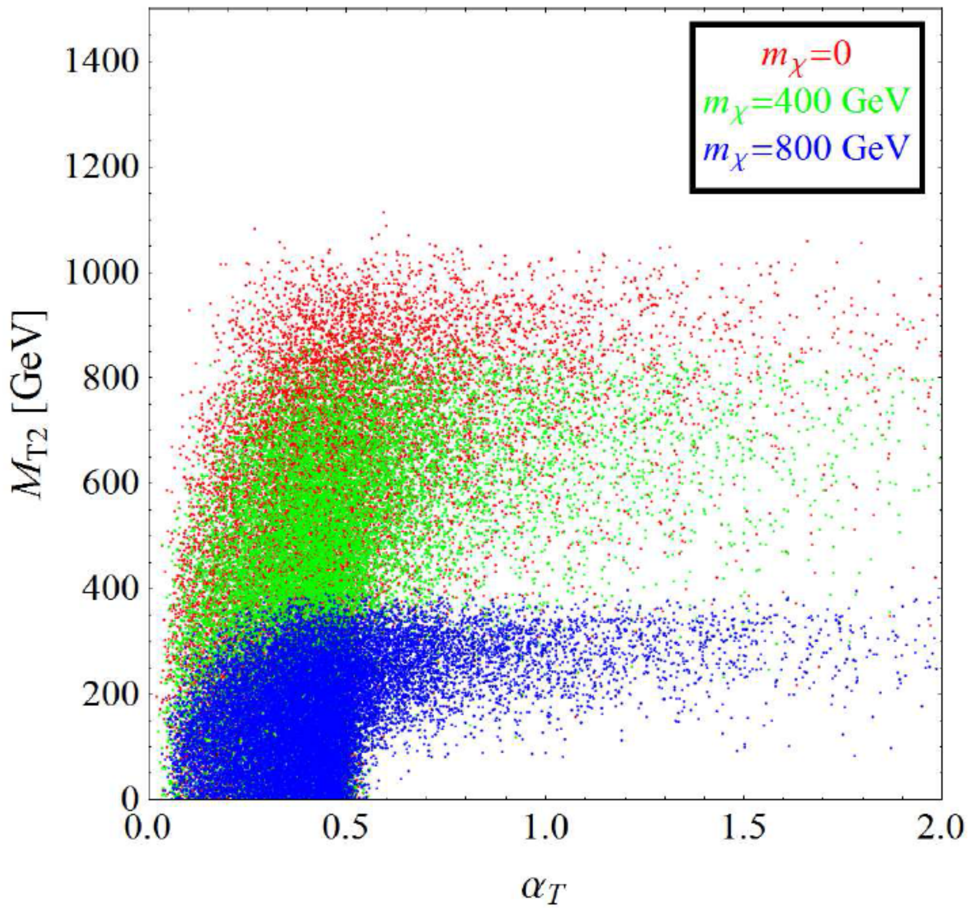
Dynamical Dark-Matter Models



$$\mathrm{m}_0 = 100 \text{ GeV} \qquad \mathrm{m}_\phi = 1 \text{ TeV}$$
$$\Delta m = 50 \text{ GeV} \qquad \delta = 1$$

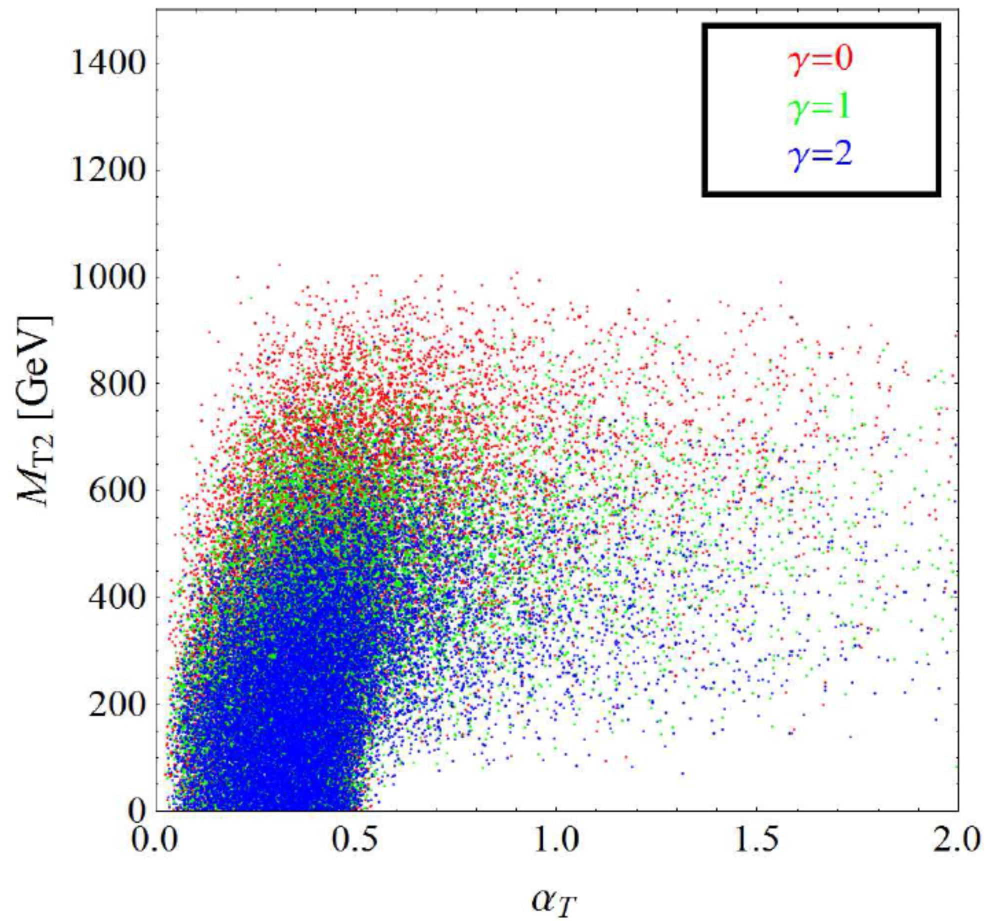
Helpful Correlations: α_T and M_{T2}

Traditional Dark-Matter Candidates



$m_\phi = 1$ TeV

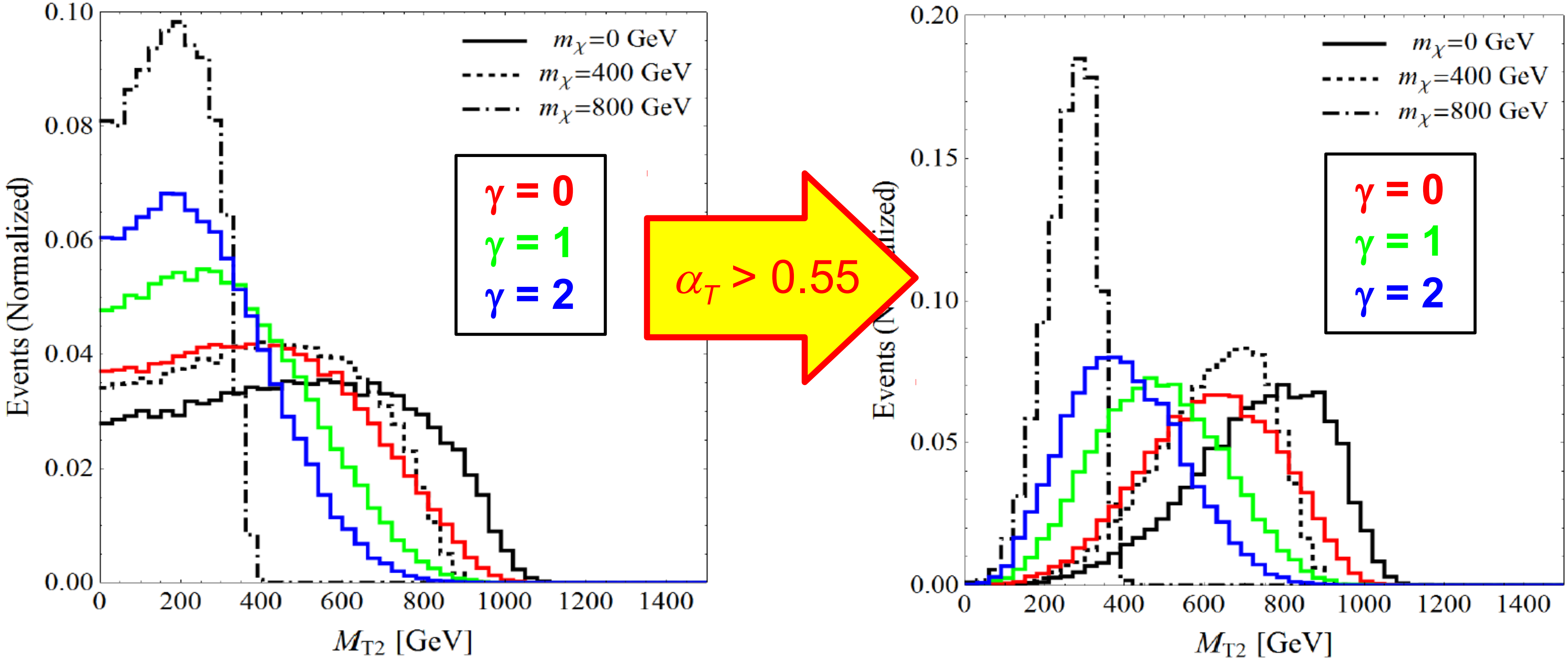
Dynamical Dark-Matter Models



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

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

The Effect of the Cut



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

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

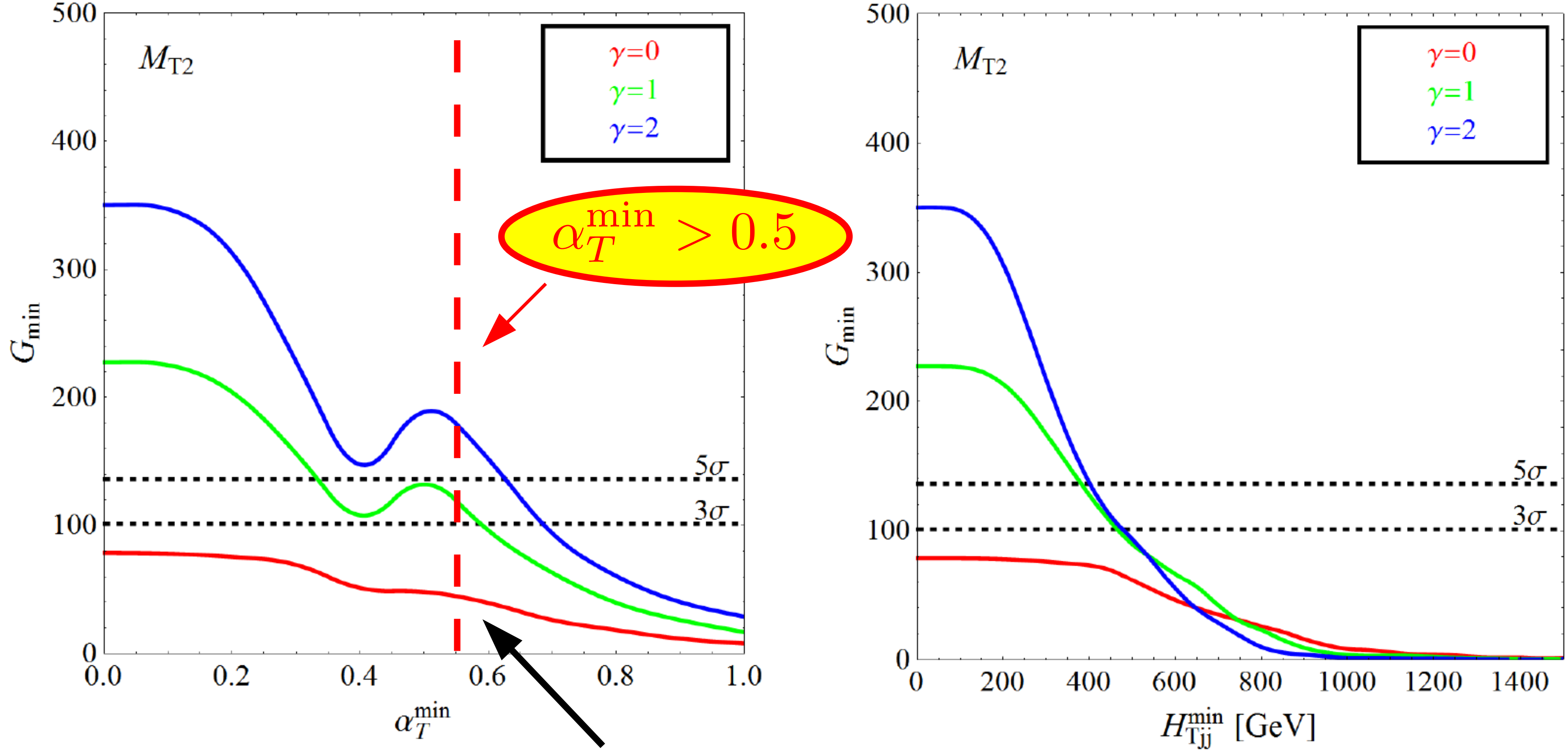
$$G(m_\chi) \;=\; -2\ln\lambda(m_\chi)$$

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

- 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} Distibutions

(as a function of applied cuts)

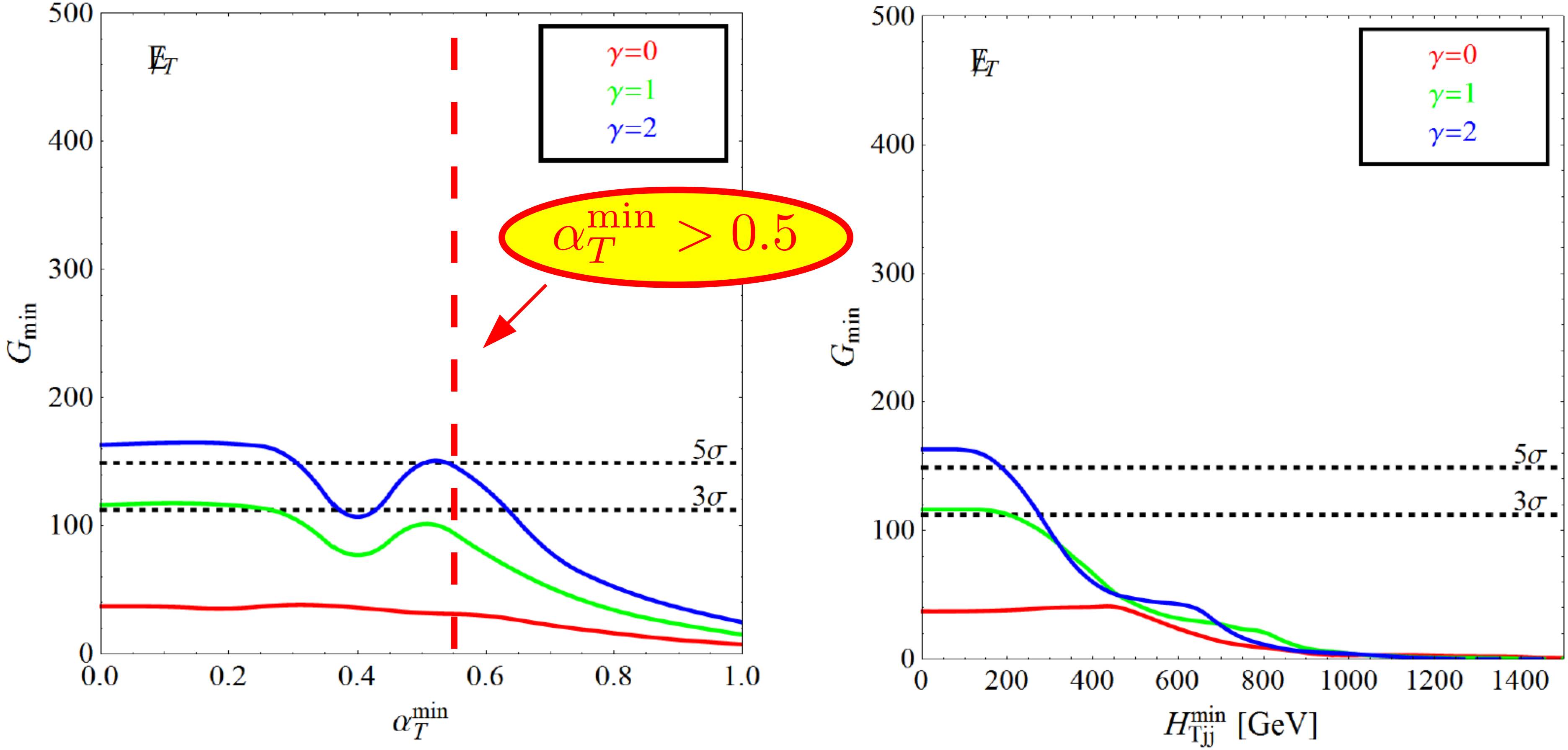


A well-chosen cut on α_T actually serves to **amplify** the distinctiveness of the signal distributions, despite the loss in statistics!

An α_T cut on this order is also helpful in reducing residual QCD backgrounds.

Distinguishing Power: $\not{E}_T$ Distibutions

(as a function of applied cuts)



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

Summary

- DDM scenarios give rise to a variety of ***distinctive signatures*** at colliders – signatureswhich can be used to differentiate DDM ensembles from traditional DM candidates.
- For example, ensembles can give rise to distinctive features in the ***kinematic distributions*** of SM fields produced in conjunction with the χ_n via the decays of other heavy particles.
- Within a broad range of scenarios, a DDM ensemble can potentially be distinguished from any traditional dark-matter candidate ***at the 5σ level*** at the LHC or at future colliders.
- ***Correlations between kinematic variables*** play an important in distribution-based searches. Event-selection criteria must be chosen carefully in order not to obscure signals of dark-sector non-minimality.