Search for compressed SUSY in the stau-neutralino coannihilation region with a soft tau lepton and ISR jet

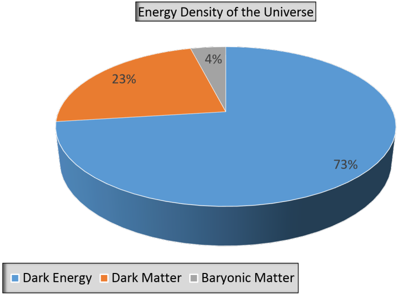
Carlos Avila[2], Luis Bravo[2], Andrés Flórez[2], Alfredo Gurrola[1], Will Johns[1], Dale Julson[1], Teruki Kamon[3], Andrew Melo[1], Klaas Padeken[1], Alejandro Segura[2], Paul Sheldon[1], **Savanna Rae Starko**[1]

06 May 2019: PHENO 2019

Vanderbilt University[1]
Universidad de Los Andes[2]
Texas A&M University[3]

Outline

The Energy Density of the Universe



- DM and dark energy account for the majority of the energy density of the universe.
- Even so, very little is known about the nature of DM. We assume a particle nature.
- Generally, we rely on the SM to describe the fundamental particles and their interactions.
- Even so, the SM is inherently *incomplete*. The SM fails to answer many broad questions:
    - matter-antimatter asymmetry in the universe, hierarchy problem, origin of neutrino masses, **particle identity of astronomical DM**
- We study particle interactions in the early universe to discern how they led to the structure of the universe that we observe today.

Early Universe Cosmology

- We make the assumption that DM was **created** and **reduced** at equal rates at the inception of the universe.
- The universe proceeded to undergo expansion.
  - Normal matter (NM) lost kinetic energy as temperatures cooled: $k_B T < m_{DM} c^2$
  - DM became more diffuse.
- Rates of DM creation and reduction, after some time, went to ~ 0. We denote this time "*freeze-out*."
- The DM density in the universe has remained approximately constant since "freeze-out." This is the *DM relic density*.

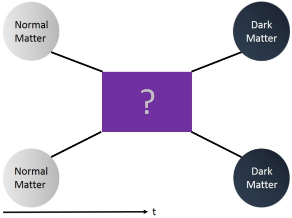


Figure 1: DM **creation** via NM annihilation

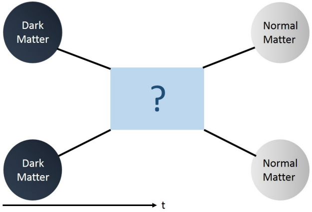
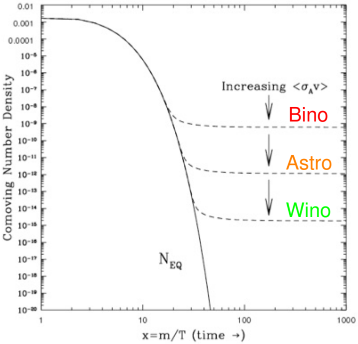


Figure 2: DM **reduction** to NM

Particle Physics, Cosmology, and Dark Matter

- We seek a DM particle with properties that lead to a consistent DM relic density with that measured by astronomers.
- For the chosen model of supersymmetry, the DM candidate is the lightest neutralino ($\tilde{\chi}_1^0$), which is mostly Bino (Z-like).
- A mostly Bino DM candidate yields an overabundance of DM in the universe compared to the amount quoted by astronomers.
- To obtain a relic DM density consistent with astronomy, stau-neutralino **coannihilation** can be introduced.
    - We allow the $\tilde{\chi}_1^0$ to coannihilate with the stau ($\tilde{\tau}$), the supersymmetric partner of the tau (τ) lepton. They coannihilate to produce normal matter.
- The DM relic density is driven down based on the dependence on the coannihilation cross-section (next slide).



Jungman *et al* hep-ph/9506380

Parameters of the DM Relic Density

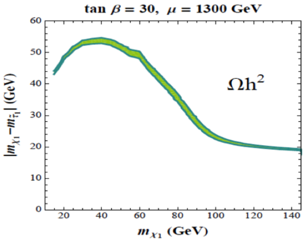


Figure 3: http://arxiv.org/pdf/1205.5842v1.pdf

- DM relic density is extremely sensitive to the mass difference between the $\tilde{\tau}$ and $\tilde{\chi}_1^0$.

- That is,

$$\Omega h^2 \propto \frac{1}{<\sigma_A> + <\sigma_{CA}>}$$
$$<\sigma_{CA}> \propto e^{-\Delta m},$$

  where Ωh^2 is the DM relic density, σ_A is the annihilation cross-section, σ_{CA} is the coannihilation cross-section, and Δm is the mass difference between the $\tilde{\tau}$ and $\tilde{\chi}_1^0$.

- Since $\sigma_{CA} \propto e^{-\Delta m}$, this motivates a search for **compressed mass spectra** ($\Delta m < 50$ GeV).

- We seek to probe compressed mass spectra at the Large Hadron Collider (LHC).
  - Two topologies characterized by small Δm:
    - Vector Boson Fusion (VBF)
    - Events with ISR
  - We focus next on the ISR topology.

Probing Stau-Neutralino Coannihilation with ISR

Probing the Stau-Neutralino Coannihilation Region at the LHC with a soft tau lepton and an ISR jet

Andrés Flórez[1], Luis Bravo[1], Alfredo Gurrola[2], Carlos Ávila[1], Manuel Segura[1], Paul Sheldon[2] and Will Johns[2]
[1] Physics Department, Universidad de los Andes, Bogotá, Colombia
[2] Department of Physics and Astronomy, Vanderbilt University, Nashville, TN, 37235, USA
(Dated: December 19, 2016)

*DOI:https://doi.org/10.1103/PhysRevD.94.073007

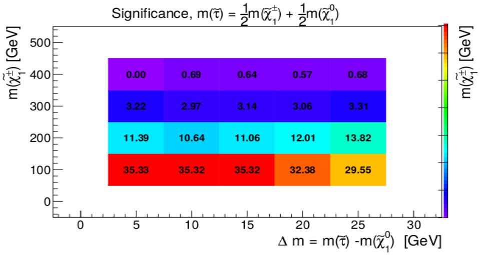
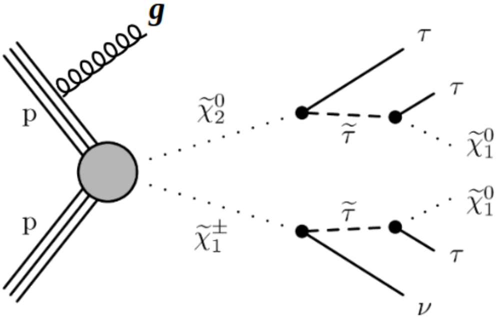


Figure 4: Significance as a function of $m(\tilde{\chi}_1^{\pm})$ and $\Delta m(\tilde{\tau}, \tilde{\chi}_1^0)$

- This search targets compressed mass spectra, where the mass difference between $\tilde{\tau}$ and $\tilde{\chi}_1^0$ is small.
- We introduce an ISR jet to boost the system, provide large missing transverse energy (E_T^{miss}), and aid in the acceptance of a "soft" τ.

$$\boxed{\tilde{\chi}_1^+\tilde{\chi}_1^- j \rightarrow \tilde{\tau}^+\tilde{\tau}^-\nu\nu j \rightarrow \tau^+\tau^-\nu\nu\tilde{\chi}_1^0\tilde{\chi}_1^0 j}$$

Motivating the Event Final State



- Event includes multiple τs.
- Since we target compressed mass spectra, mass gaps between supersymmetric particles are small$\rightarrow$We have difficulty detecting multiple τs in this event.
- An **ISR jet** provides a natural kinematic boost, allowing for easier detection of a **single hadronic tau (τ_h)**.
- Another consequence of small mass gaps between supersymmetric particles is **high $\vec{E}_T^{miss}$** from the neutrinos.

Optimization of Selection Criteria

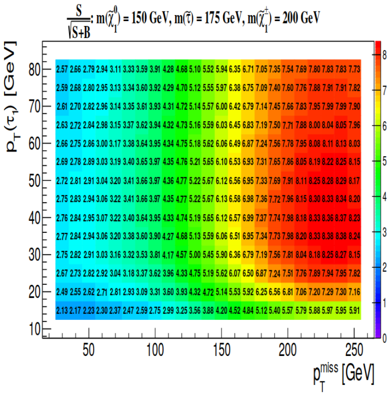


Figure 5: Significance figure of merit is $\frac{S}{\sqrt{S+B}}$, using events selected with $p_T^{lead} > 100$ GeV, $p_T(\tau_h) > 15$ GeV, and satisfying the extra lepton and b-jet vetoes. The benchmark signal point used was $m(\tilde{\chi}_1^0) = 150$ GeV, $m(\tilde{\tau}) = 175$ GeV, and $m(\tilde{\chi}_1^\pm) = 200$ GeV.

- With the target of compressed mass spectra and high significance at low $p_T(\tau_h)$, we highlight the importance of having good τ_h identification at low p_T.
- Significance is highest at high E_T^{miss}. Good modeling of the $\vec{E}_T^{miss}$ is crucial.
- Optimization of H_T (the scalar sum of the p_T of all jets with $p_T > 30$ GeV) yields no additional signal vs. background discrimination.
- A series of angular variables were also optimized but led to no further discrimination between the hypothetical signal and background distributions.

The Signal Region

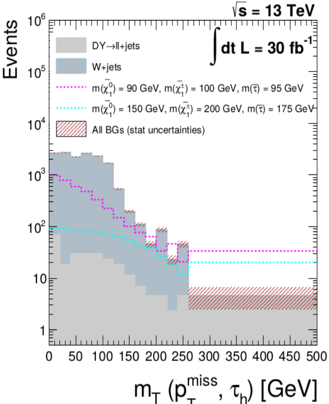


Figure 6: m_T in the SR

- Primary SR selections:
  - Exactly 1 τ_h with $20 < p_T(\tau_h) < 40$ GeV
  - ISR jet with $p_T^{ISR}(j) > 100$ GeV
  - $E_T^{miss} > 230$ GeV
- The transverse mass (m_T) between the τ_h and the $\vec{E}_T^{miss}$ is chosen as the discriminating variable for signal and background, where

$$m_T(\tau_h, \vec{E}_T^{miss}) = \sqrt{2p_T(\tau_h)E_T^{miss}(1 - \cos\Delta\phi(\tau_h, \vec{E}_T^{miss}))}.$$

- SM backgrounds (Z+Jets, W+Jets, etc.) dominate at low m_T, whereas *signal dominates at high m_T.*
- For the signals at the left, $m(\tilde{\tau})$ is conveniently chosen to be the average of $m(\tilde{\chi}_1^\pm)$ and $m(\tilde{\chi}_1^0)$.

Parameterizing the Signal Region Yield

$$\boxed{N_{SR} = \sigma \cdot L_{int} \cdot \epsilon_{\tau_h} \cdot \epsilon_{E_T^{miss}} \cdot \epsilon_{ISR}}$$

1. Understand the modeling of τ_hs ($\epsilon_{\tau_h \text{ ID}}$)
2. Understand the modeling of real $\vec{E}_T^{miss}$ ($\epsilon_{E_T^{miss}}$)
3. Understand the modeling of ISR & its correlation with the lepton and $\vec{E}_T^{miss}$ (ϵ_{ISR})
4. Understand the top quark pair ($t\bar{t}$) background contribution in the SR
5. Understand the QCD contribution in the SR stemming from fake τ_hs
6. Dominant sources of systematics: τ_h identification, E_T^{miss} trigger efficiencies, ISR modeling, pileup effects, and uncertainties on transfer factors used to make the background estimations

Results

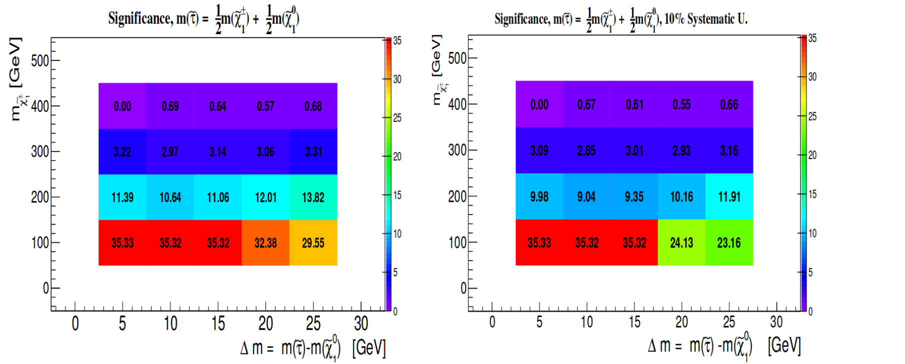


Figure 7: Significance as a function of $m(\tilde{\chi}_1^{\pm})$ and $\Delta m(\tilde{\tau}, \tilde{\chi}_1^0)$ without systematics considerations (left) and with 10% systematic effect (right)

The proposed methodology can provide $5\sigma(3\sigma)$ significance for $\tilde{\chi}_1^{\pm}$ masses up to approximately 250 GeV (300 GeV) and with $\Delta m(\tilde{\tau}, \tilde{\chi}_1^0) < 25$ GeV, allowing the ATLAS and CMS experiments to probe previously unreachable parts of the $\tilde{\tau}\tilde{\chi}_1^0$ coannihilation phase space important to the connection between particle physics and cosmology.

Summary and Conclusions

- The energy density of the universe is dominated by DM and dark energy.
- Assuming a particle nature to DM, we seek a DM particle with properties that lead to a consistent DM relic density with that measured by astronomers.
- We incorporate coannihilation in order to drive down the relic density, and this supports searches with compressed mass spectra.
- Topologies with an ISR jet provide both a large enough cross-section and sufficient discriminating power between signal and background.
- We establish a search with a soft τ_h, an ISR jet, and high E_T^{miss}.
  - This requires solid understanding of τ_h, E_T^{miss}, and ISR modeling.
- Best discovery potentials exist in regions with high m_T.
- New phase space is accessible since the proposed methodology can provide $5\sigma(3\sigma)$ significance for $\tilde{\chi}_1^{\pm}$ masses up to approximately 250 GeV (300 GeV) and with $\Delta m(\tilde{\tau}, \tilde{\chi}_1^0) < 25$ GeV.
- Current experimental analysis at CMS is in the approval stages. CADI line at CMS is SUS-19-002. Target conference is LHCP this month.

References

1. C. Ávila, A. Flórez, A. Gurrola, D. Julson and S. Starko, “Connecting Particle Physics and Cosmology: Measuring the Dark Matter Relic Density in Compressed Supersymmetry at the LHC,” arXiv:1801.03966 [hep-ph]].
2. C. Ávila, L. Bravo, A. Flórez, A. Gurrola, W. Johns, M. Segura, P. Sheldon, “Probing the stau-neutralino coannihilation region at the LHC with a soft tau lepton and a jet from initial state radiation,” Phys. Rev.D94, 073007 (2016). doi:10.1103/PhysRevD.94.073007.