ON HEAVY SUPERSYMMETRY TIMOTHY COHEN [SLAC]

UC Davis Joint Theory Seminar November 25, 2013

ACKNOWLEDGEMENTS

Wino Dark Matter Under Siege: TC, Mariangela Lisanti, Aaron Pierce, Tracy R. Slatyer [arXiv:1307.4082]

SLAC simplified models (theory) team: TC, Kiel Howe, Jay Wacker

Snowmass backgrounds team:

Aram Avetisyan, James Dolen, James Hirschauer,

Meenakshi Narain, Sanjay Padhi, Michael Peskin, John Stupak

Snowmass simplified models (experimental) team:

Tobias Golling, Mike Hance, Anna Henrichs,

Joshua Loyal, Sanjay Padhi

Backgrounds [arXiv:1308.1636]; Simplified Models 14 TeV, 33 TeV, and 100 TeV [arXiv:soon]; Simplified Models Summary [arXiv:1310.0077]

OUTLINE

- Introduction
- Motivation
- Heavy SUSY Dark Matter
- Heavy SUSY at Colliders
- Conclusions

INTRODUCTION

TIMOTHY COHEN (SLAC)

LESSONS FROM LHC8



LESSONS FROM LHC8

ATLAS SUSY Searches* - 95% CL Lower Limits

Status: LP 2013

m_{zo} [GeV]

ATLAS Preliminary

 $\int \mathcal{L} dt = (4.4 - 22.9) \text{ fb}^{-1} \qquad \sqrt{s} = 7, 8 \text{ TeV}$

	Model	e, μ, τ, γ	Jets	E_T^miss	∫£ dt[fb	¹] Mass limit		Reference
Inclusive Searches	$\begin{array}{l} \text{MSUGRA/CMSSM} \\ \text{MSUGRA/CMSSM} \\ \widetilde{q}\widetilde{q}, \widetilde{q} \rightarrow q \widetilde{\chi}_{1}^{0} \\ \widetilde{g}\widetilde{g}, \widetilde{g} \rightarrow q \widetilde{q} \widetilde{\chi}_{1}^{0} \\ \widetilde{g}\widetilde{g}, \widetilde{g} \rightarrow q q \widetilde{\chi}_{1}^{\pm} \rightarrow q q W^{\pm} \widetilde{\chi}_{1}^{0} \\ \widetilde{g}\widetilde{g} \rightarrow q q q q \ell \ell (\ell \ell) \widetilde{\chi}_{1}^{0} \widetilde{\chi}_{1}^{0} \\ \text{GMSB} (\widetilde{\ell} \text{ NLSP}) \\ \text{GMSB} (\widetilde{\ell} \text{ NLSP}) \\ \text{GGM} (bino \text{ NLSP}) \\ \text{GGM} (wino \text{ NLSP}) \\ \text{GGM} (higgsino-bino \text{ NLSP}) \\ \text{GGM} (higgsino \text{ NLSP}) \\ \text{GGM} (higgsino \text{ NLSP}) \\ \text{GGM} (higgsino \text{ NLSP}) \\ \text{Gravitino LSP} \end{array}$	$1 e, \mu \\ 0 \\ 0 \\ 1 e, \mu \\ 2 e, \mu (SS) \\ 2 e, \mu \\ 1-2 \tau \\ 2 \gamma \\ 1 e, \mu + \gamma \\ \gamma \\ 2 e, \mu (Z) \\ 0 \\ 0 \\ 1 e, \mu + \gamma \\ \gamma \\ 0 \\ 1 e, \mu + \gamma \\ \gamma \\ 0 \\ 0 \\ 1 e, \mu + \gamma \\ 0 \\ 0 \\ 1 e, \mu + \gamma \\ 0 \\ 1 e, \mu$	3-6 jets 7-10 jets 2-6 jets 2-6 jets 3-6 jets 3 jets 2-4 jets 0-2 jets 0 0 1 <i>b</i> 0-3 jets mono-jet	Yes Yes Yes Yes Yes Yes Yes Yes Yes Yes	20.3 20.3 20.3 20.3 20.7 4.7 20.7 4.8 4.8 4.8 4.8 5.8 10.5	i i <th>any m(\tilde{q}) any m(\tilde{q}) m($\tilde{\chi}_{1}^{0}$)=0 GeV m($\tilde{\chi}_{1}^{0}$)=0 GeV m($\tilde{\chi}_{1}^{0}$)=0 GeV m($\tilde{\chi}_{1}^{0}$)<200 GeV, m($\tilde{\chi}^{\pm}$)=0.5(m($\tilde{\chi}_{1}^{0}$)+m(\tilde{g})) m($\tilde{\chi}_{1}^{0}$)<650 GeV tanβ<15 tanβ<15 tanβ<18 m($\tilde{\chi}_{1}^{0}$)>50 GeV m($\tilde{\chi}_{1}^{0}$)>50 GeV m($\tilde{\chi}_{1}^{0}$)>220 GeV m($\tilde{\chi}_{1}^{0}$)>200 GeV m(\tilde{g})>10⁻⁴ eV</th> <th>ATLAS-CONF-2013-062 ATLAS-CONF-2013-054 ATLAS-CONF-2013-047 ATLAS-CONF-2013-047 ATLAS-CONF-2013-062 ATLAS-CONF-2013-062 ATLAS-CONF-2013-026 1209.0753 ATLAS-CONF-2012-144 1211.1167 ATLAS-CONF-2012-152 ATLAS-CONF-2012-152</th>	any m(\tilde{q}) any m(\tilde{q}) m($\tilde{\chi}_{1}^{0}$)=0 GeV m($\tilde{\chi}_{1}^{0}$)=0 GeV m($\tilde{\chi}_{1}^{0}$)=0 GeV m($\tilde{\chi}_{1}^{0}$)<200 GeV, m($\tilde{\chi}^{\pm}$)=0.5(m($\tilde{\chi}_{1}^{0}$)+m(\tilde{g})) m($\tilde{\chi}_{1}^{0}$)<650 GeV tan β <15 tan β <15 tan β <18 m($\tilde{\chi}_{1}^{0}$)>50 GeV m($\tilde{\chi}_{1}^{0}$)>50 GeV m($\tilde{\chi}_{1}^{0}$)>220 GeV m($\tilde{\chi}_{1}^{0}$)>200 GeV m(\tilde{g})>10 ⁻⁴ eV	ATLAS-CONF-2013-062 ATLAS-CONF-2013-054 ATLAS-CONF-2013-047 ATLAS-CONF-2013-047 ATLAS-CONF-2013-062 ATLAS-CONF-2013-062 ATLAS-CONF-2013-026 1209.0753 ATLAS-CONF-2012-144 1211.1167 ATLAS-CONF-2012-152 ATLAS-CONF-2012-152
3 rd gen. ẽ med.	$\begin{array}{l} \tilde{g} \rightarrow b \bar{b} \tilde{\chi}_{1}^{0} \\ \tilde{g} \rightarrow t \bar{t} \tilde{\chi}_{1}^{0} \\ \tilde{g} \rightarrow t \bar{t} \tilde{\chi}_{1}^{0} \\ \tilde{g} \rightarrow b \bar{t} \tilde{\chi}_{1}^{+} \end{array}$	0 0 0-1 <i>e</i> ,μ 0-1 <i>e</i> ,μ	3 b 7 10 i-t-	Yes	20.1	ĝ <u>1.2</u> TeV	m($\tilde{\chi}_1^0$)<600 GeV 10 GeV 0 GeV 0 GeV	ATLAS-CONF-2013-061 ATLAS-CONF-2013-054 ATLAS-CONF-2013-061 ATLAS-CONF-2013-061
3 rd gen. squarks direct production	$ \begin{array}{l} \tilde{b}_{1}\tilde{b}_{1}, \tilde{b}_{1} \rightarrow b\tilde{\chi}_{1}^{0} \\ \tilde{b}_{1}\tilde{b}_{1}, \tilde{b}_{1} \rightarrow t\tilde{\chi}_{1}^{+} \\ \tilde{t}_{1}\tilde{\tau}_{1}(\text{light}), \tilde{t}_{1} \rightarrow b\tilde{\chi}_{1}^{+} \\ \tilde{t}_{1}\tilde{\tau}_{1}(\text{light}), \tilde{t}_{1} \rightarrow b\tilde{\chi}_{1}^{0} \\ \tilde{t}_{1}\tilde{\tau}_{1}(\text{medium}), \tilde{t}_{1} \rightarrow b\tilde{\chi}_{1}^{+} \\ \tilde{t}_{1}\tilde{\tau}_{1}(\text{medium}), \tilde{t}_{1} \rightarrow t\tilde{\chi}_{1}^{0} \\ \tilde{t}_{1}\tilde{\tau}_{1}(\text{heavy}), \tilde{t}_{1} \rightarrow t\tilde{\chi}_{1}^{0} \\ \tilde{t}_{1}\tilde{\tau}_{1}(\text{netural GMSB}) \\ \tilde{t}_{2}\tilde{t}_{2}, \tilde{t}_{2} \rightarrow \tilde{t}_{1} + Z \end{array} $	$\begin{array}{c} 0 \\ 2 \ e, \mu \ (\text{SS}) \\ 1-2 \ e, \mu \\ 2 \ e, \mu \\ 2 \ e, \mu \\ 0 \\ 1 \ e, \mu \\ 0 \\ 2 \ e, \mu \ (Z) \\ 3 \ e, \mu \ (Z) \end{array}$			0	sign of v physics	D GeV $n(\tilde{\chi}_{1}^{0})$ GeV \tilde{t}_{1})-m(W)-50 GeV, $m(\tilde{t}_{1}) << m(\tilde{\chi}_{1}^{*})$ $n(\tilde{t}_{1})$ -m $(\tilde{\chi}_{1}^{*})$ =10 GeV D GeV, $m(\tilde{\chi}_{1}^{*})$ -m $(\tilde{\chi}_{1}^{0})$ =5 GeV $n(\tilde{t}_{1})$ -m (\tilde{t}_{1}^{0}) =5 GeV $n(\tilde{t}_{1})$ +180 GeV	ATLAS-CONF-2013-053 ATLAS-CONF-2013-007 1208.4305, 1209.2102 ATLAS-CONF-2013-048 ATLAS-CONF-2013-048 ATLAS-CONF-2013-053 ATLAS-CONF-2013-027 ATLAS-CONF-2013-025 ATLAS-CONF-2013-025
EW direct	$ \begin{split} \tilde{\ell}_{L,R} \tilde{\ell}_{L,R}, \tilde{\ell} \rightarrow \ell \tilde{\chi}_1^0 \\ \tilde{\chi}_1^+ \tilde{\chi}_1^-, \tilde{\chi}_1^+ \rightarrow \ell \nu (\ell \tilde{\nu}) \\ \tilde{\chi}_1^+ \tilde{\chi}_1^-, \tilde{\chi}_1^+ \rightarrow \tilde{\nu} (\ell \tilde{\nu}) \\ \tilde{\chi}_1^+ \tilde{\chi}_2^0 \rightarrow \tilde{\ell}_L \nu \tilde{\ell}_L \ell (\tilde{\nu}\nu), \ell \tilde{\nu} \tilde{\ell}_L \ell (\tilde{\nu}\nu) \\ \tilde{\chi}_1^+ \tilde{\chi}_2^0 \rightarrow W^* \tilde{\chi}_1^0 Z^* \tilde{\chi}_1^0 \end{split} $	2 e,μ 2 e,μ 2 τ 3 e,μ 3 e,μ	0	Yes	20.7	x ¹ / ₁ , x ⁰ / ₂ 315 GeV	$ \begin{split} & \text{ieV} \\ & \text{ieV}, \ m(\tilde{\ell},\tilde{\nu}){=}0.5(m(\tilde{\chi}_1^{\pm}){+}m(\tilde{\chi}_1^0)) \\ & \text{ieV}, \ m(\tilde{\tau},\tilde{\nu}){=}0.5(m(\tilde{\chi}_1^{\pm}){+}m(\tilde{\chi}_1^0)) \\ & = 0, \ m(\tilde{\ell},\tilde{\nu}){=}0.5(m(\tilde{\chi}_1^{\pm}){+}m(\tilde{\chi}_1^0)) \\ & m(\tilde{\chi}_1^{\pm}){=}m(\tilde{\chi}_2^0), \ m(\tilde{\chi}_1^0){=}0, \ \text{sleptons decoupled} \end{split} $	ATLAS-CONF-2013-049 ATLAS-CONF-2013-049 ATLAS-CONF-2013-028 ATLAS-CONF-2013-035 ATLAS-CONF-2013-035
Long-lived particles	Direct $\tilde{\chi}_1^+ \tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$ Stable, stopped \tilde{g} R-hadron GMSB, stable $\tilde{\tau}$ Direct $\tilde{\tau}\tilde{\tau}$ prod., stable $\tilde{\tau}$ or $\tilde{\ell}$ GMSB, $\tilde{\chi}_1^0 \rightarrow \gamma \tilde{g}$, long-lived $\tilde{\chi}_1^0$ $\tilde{\chi}_1^0 \rightarrow qq\mu$ (RPV)	0 1-2 μ 1-2 μ 2 γ 1 μ	1 jet 1-5 jets 0 0 0 0	Yes Yes - Yes Yes	4.7 22.9 15.9 15.9 4.7 4.4	$\tilde{\chi}_1^{\pm}$ 220 GeV \tilde{g} 857 GeV $\tilde{\tau}$ 385 GeV $\tilde{\tau}$ 395 GeV $\tilde{\chi}_1^0$ 230 GeV \tilde{q} 700 GeV	$\begin{array}{l} 1 < \tau(\tilde{\chi}_{1}^{\pm}) < 10 \text{ ns} \\ m(\tilde{\chi}_{1}^{0}) = 100 \text{ GeV, } 10 \ \mu \text{s} < \tau(\tilde{g}) < 1000 \text{ s} \\ 5 < \tan\beta < 50 \\ m(\tilde{\tau}) = m(\tilde{\ell}) \\ 0.4 < \tau(\tilde{\chi}_{1}^{0}) < 2 \text{ ns} \\ 1 \text{ mm} < c\tau < 1 \text{ m, } \tilde{g} \text{ decoupled} \end{array}$	1210.2852 ATLAS-CONF-2013-057 ATLAS-CONF-2013-058 ATLAS-CONF-2013-058 1304.6310 1210.7451
RPV	$ \begin{array}{l} LFV \ pp \rightarrow \tilde{v}_{\tau} + X, \tilde{v}_{\tau} \rightarrow e + \mu \\ LFV \ pp \rightarrow \tilde{v}_{\tau} + X, \tilde{v}_{\tau} \rightarrow e(\mu) + \tau \\ Bilinear \ RPV \ CMSSM \\ \tilde{\chi}_{1}^{+} \tilde{\chi}_{1}^{-}, \tilde{\chi}_{1}^{+} \rightarrow W \tilde{\chi}_{1}^{0}, \tilde{\chi}_{1}^{0} \rightarrow ee \tilde{v}_{\mu}, e\mu \tilde{v}_{\tau} \\ \tilde{\chi}_{1}^{+} \tilde{\chi}_{1}^{-}, \tilde{\chi}_{1}^{+} \rightarrow W \tilde{\chi}_{1}^{0}, \tilde{\chi}_{1}^{0} \rightarrow \tau \tau \tilde{v}_{e}, e\tau \tilde{v}_{\tau} \\ \tilde{g} \rightarrow qqq \\ \tilde{g} \rightarrow \tilde{t}_{1} t, \ \tilde{t}_{1} \rightarrow bs \end{array} $	$\begin{array}{c} 2 \ e, \mu \\ 1 \ e, \mu + \tau \\ 1 \ e, \mu \\ e \\ 3 \ e, \mu + \tau \\ 0 \\ 2 \ e, \mu (SS) \end{array}$	0 0 7 jets 0 0 6 jets 0-3 <i>b</i>	- Yes Yes Yes - Yes	4.6 4.6 4.7 20.7 20.7 4.6 20.7	$ \begin{array}{c ccccccccccccccccccccccccccccccccccc$	$\begin{split} \lambda'_{311} = & 0.10, \ \lambda_{132} = & 0.05 \\ \lambda'_{311} = & 0.10, \ \lambda_{1(2)33} = & 0.05 \\ & m(\tilde{g}) = & m(\tilde{g}), \ c\tau_{LSP} < 1 \ mm \\ & m(\tilde{\chi}^0_1) > & 300 \ GeV, \ \lambda_{121} > & 0 \\ & m(\tilde{\chi}^0_1) > & 80 \ GeV, \ \lambda_{133} > & 0 \end{split}$	1212.1272 1212.1272 ATLAS-CONF-2012-140 ATLAS-CONF-2013-036 ATLAS-CONF-2013-036 1210.4813 ATLAS-CONF-2013-007
Other	Scalar gluon WIMP interaction (D5, Dirac χ)	0 0	4 jets mono-jet	- Yes	4.6 10.5	sgluon 100-287 GeV M* scale 704 GeV	incl. limit from 1110.2693 m(χ)<80 GeV, limit of<687 GeV for D8	1210.4826 ATLAS-CONF-2012-147
	$\sqrt{s} = 7 \text{ TeV}$	√s = 8 TeV artial data	√s = full	8 TeV data		10 ⁻¹ 1	Mass scale [TeV]	

*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1 σ theoretical signal cross section uncertainty.

READING THE TEA LEAVES



MOTIVATION

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SUPERSYMMETRY

Data consistent with fundamental scalar Higgs.

Mass should be protected from Planck slop.

SUSY to the rescue!

WIMP dark matter. Gauge coupling unification.

Little hierarchy problem changing our view of SUSY.

SUSY MODELS

TeV scale SUSY Model building challenges 1) Flavor 2) CP Violation 3) 125 GeV Higgs boson



COMPLICATED SUSY



Required Setup



ANOTHER APPROACH

PeV scale SUSY Wells [arXiv:hep-ph/0411041] Decoupling solves 1) Flavor 2) CP Violation Consistent with 3) 125 GeV Higgs boson Also get dark matter candidate + gauge coupling unification.



Some tuning... but simple.

SUSY BREAKING

Ignore preconceptions about fine-tuning.

Wells [arXiv:hep-ph/0411041]; Arkani-Hamed and Dimopoulos [arXiv:hep-th/0405159]; Giudice and Romanino [arXiv:hep-ph/0405159]

Explore "simplest" SUSY breaking scenarios. Gravity mediation.

Assume SUSY breaking spurion is not gauge singlet. Anomaly mediation and small A-terms.

Some examples since 125 GeV Higgs: Arvanitaki, Craig, Dimopoulos [arXiv:1210.0555]; Hall, Nomura, Shirai [arXiv:1210.2395]; Kane, Kumar, Lu, Aheng [arXiv: 1112.1059]; Ibe, Yanagida [arXiv:1112.2462]; Arkani-Hamed, Gupta, Kaplan, Weiner, Zorawski [arXiv:1212.6971]

ANOMALY + GRAVITY MEDIATION

Giudice, Luty, Murayama, Rattazzi [arXiv:hep-ph/9810442]; Randall and Sundrum [arXiv:hep-th/9810155] 1) Gravity mediation for scalars:



 $m_{\widetilde{f}} \sim m_{3/2}$ 2) Anomaly mediation for gauginos: $m_{\widetilde{\lambda}} \sim \frac{\alpha_i \, b_i}{16 \, \pi^2} m_{3/2}$ $b_2 < b_1 < b_3 \longrightarrow M_2 < M_1 < M_3$ Wino or Higgsino LSP 3) Giudice-Masiero $\mu \sim m_{3/2}$ Wino LSP!

With Higgsino thresholds $\longrightarrow M_3 \simeq 6 \times M_2$

Arkani-Hamed, Gupta, Kaplan, Weiner, Zorawski [arXiv:1212.6971]

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Arkani-Hamed, Gupta, Kaplan, Weiner, Zorawski [arXiv:1212.6971]

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Altmannshofer, Harnik, Zupan [arXiv:1308.3653]

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SIMPLEST SCENARIO

Where has simplicity led us?

1) A thermal wino relic with a 3 TeV mass **or**

Allow non-thermal/subdominant winos. 2) Gluino with a ~ 16 TeV mass (likely displaced decays). 3) Scalars a loop factor heavier with O(100 TeV) masses.

No problems!

How can we test this model?!?

HEAVY SUSY DARK MATTER

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WINO DARK MATTER

Introduce an electroweak triplet fermion χ , with the Lagrangian:

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \bar{\chi} \left(i D + M_2 \right) \chi$$

In components:



MASS SPLITTING

Electroweak symmetry breaking splits chargino and neutralino.

In pure wino limit (with $M_2 = 2 \text{ TeV}$)

 $\delta = 0.1645 \pm 0.0004~{\rm GeV}$

to two-loop order.

Ibe, Matsumoto, Sato [arXiv:1212.5989]

What about tree-level mixing? $\mu \sim m_{3/2} \sim O(100 \text{ TeV})$ Leading splitting operator is dimension 7: $\mathcal{O}_{\delta} \sim \chi^a \chi^b (H^{\dagger}T^a H) (H^{\dagger}T^b H)$

Implying $\delta \simeq 0.17 \text{ GeV}$ is a robust prediction.



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Indirect Detection:

see cosmic rays

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WINOS AT COLLIDERS

Ibe, Matsumoto, Sato [arXiv:1212.5989]

LHC searches for charged stubs in the tracker



New limit using 8 TeV with 20 fb⁻¹ extends to 280 GeV

ATLAS [arXiv:1310.3675]





SOMMERFELD ENHANCEMENT

Non-perturbative effect at low velocities



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COMPUTING CROSS SECTION Boundary Conditions: $\psi_i(0) = \delta_{ij}$ and $\psi_i(\infty) = \begin{cases} \text{outgoing wave [above threshold]} \\ \text{exponentially falling [below threshold]} \end{cases}$ Sommerfeld matrix: $s_{ij} = \psi_i(\infty)$ annihilation matrix Cross section: $\sigma_i v = c_i \sum_{i \neq j} s_{ij} \Gamma_{jj'} s_{ij'}^*$ c = 2(1) for identical (distinct) particles. Index structure: 1 = neutralino + neutralino; 2 = chargino + chargino TIMOTHY COHEN [SLAC] 28 OF 54

SOMMERFELD RESONANCE

Resonant enhancement: mass splitting \simeq binding energy Position of resonance sensitive to mass splitting

Assume only EW contribution to splitting

Loop factor
times W-mass
$$\alpha_W m_W \simeq \alpha_W^2 M_2$$
 "Rydberg"
 $(M_2)_{\rm res} \simeq \frac{m_W}{\alpha_W} \simeq 2.4 \text{ TeV}$

THERMAL WINO



Planck Collaboration [arXiv:1303.5076]

Mass of "thermal wino": $(M_2)_{\text{thermal}} \simeq 3.1 \text{ TeV}$

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Hisano, Matsumoto, Nojiri [arXiv:hep-ph/0307216]

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INDIRECT DETECTION

H.E.S.S. Line Search

H.E.S.S. Collaboration [arXiv:1301.1173]

Ground based imaging atmospheric Cherenkov telescope

Search in 1 degree region at galactic center (plane excluded)

Assuming NFW profile



INDIRECT DETECTION

Fermi Stacked Dwarf Limit

Fermi Collaboration [arXiv:1108.3546]



10 Milky Way satellite galaxies 24 months of data Marginalizes over profile uncertainty Тімотну Сонем [SLAC]

CONSTRAINTS

See also Fan and Reece [arXiv:1307.4400]



CONSTRAINTS

See also Fan and Reece [arXiv:1307.4400]



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USING CTA

Bergstrom, Bertone, Conrad, Farnier, and Weniger [arXiv:1207.6773]



CAVEAT: NLO

Results use Sommerfeld enhanced tree-level hard annihilation cross section

What is the impact of including NLO corrections to hard annihilation cross section?

$$\sigma_i v = c_i \sum_{j,j'} s_{ij} \Gamma_{jj'} s_{ij'}^*$$

Subtlety in order to not double count.

Hryczuk & lengo [arXiv:1111.2916]

CAVEAT: NLO



Factor of ~ 4 reduction for thermal wino. Large logs: breakdown of perturbation theory?

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Hryczuk & lengo [arXiv:1111.2916]



Wino dark matter is well motivated. (Resonant) Sommerfeld enhancement is important.

Indirect detection places strong constraints.

Thermal scenario: probed above 1.6 TeV; Gluinos below ~ 10 TeV!

Non-thermal scenario: probed full mass range.

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HEAVY SUSY AT COLLIDERS

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FUTURE PROTON COLLIDERS Want to study the following collider scenarios: Know we get 14(ish) TeV LHC with 300 fb⁻¹ (50 mean pile-up) **Probably** we get 14(ish) TeV LHC with 3000 fb⁻¹ (140 mean pile-up) Will **hope** for 33 to 100 TeV proton collider with 3000 fb⁻¹ (140 mean pile-up)

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THE NEXT PROTON COLLIDER?



100 km tunnel: CERN versus China? 100 TeV needs 16 Tesla magnets (100 km ring) Current technology ~ 11 Tesla

A MONTE CARLO CHALLENGE

Generate top backgrounds: $\sigma_{\rm NLO}(p \, p \rightarrow t \, \overline{t}) = 0.8 \, {\rm nb}$ Require factor of 10 MC more than expected events $\mathcal{L} = 3 \, {\rm ab}^{-1}$ $10 \times \sigma \times \mathcal{L} = 2.4 \times 10^{10}$

Each event ~ 1 kb

24 Terabytes for tops (per pileup setting)

Need new Monte Carlo approach!

AFTER MANY MONTHS...

Avetisyan, Campbell, TC, Dhingra, et al [arXiv: 1308.1636]



SIMPLIFIED MODELS We have backgrounds

What should we do with them?

Want to assess reach of future machines

Want transparent results

Want to study all kinematic regions

Simplified Model	Decay channel		
Gluino-neutralino with light flavor decays	$\widetilde{g} ightarrow q \overline{q} \widetilde{\chi}_1^0$		
Squark-neutralino	$\widetilde{q} ightarrow q \widetilde{\chi}_1^0$		
Gluino-squark with a massless neutralino	$\widetilde{g} ightarrow \left(q \overline{q} \widetilde{\chi}_1^0 / q \widetilde{q}^* ight); \widetilde{q} ightarrow \left(q \widetilde{\chi}_1^0 / q \widetilde{g} ight)$		
Gluino-neutralino with heavy flavor decays	$\widetilde{g} ightarrow t \overline{t} \widetilde{\chi}_1^0$		

(Assuming prompt decays)

JETS + MET

Preselection

- zero selected electrons or muons
- $E_T^{\text{miss}} > 100 \text{ GeV}$
- at least 4 jets with $p_T > 60 \text{ GeV}$

Search strategy

- $E_T^{\text{miss}} / \sqrt{H_T} > 15 \text{ GeV}^{1/2}$
- The leading jet p_T must satisfy $p_T^{\text{leading}} < 0.4 H_T$
- $E_T^{\text{miss}} > (E_T^{\text{miss}})_{\text{optimal}}$
- $H_T > (H_T)_{\text{optimal}}$

JETS + MET



Dominant background:

W/Z + jets @ 14 TeV $t \overline{t}$ @ 100 TeV

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OPTIMAL CUTS



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RESULTS



RESULTS





Interested in the reach of future colliders. Simplified Models well suited to this task. Overcame Monte Carlo challenges. Among first realistic projections for 33 TeV and 100 TeV machines.

With 100 TeV, can discover 11 TeV gluinos.

Implications

Thermal winos below 1.6 TeV implies gluinos below 10 TeV Direct test of "simple" scenario!

CONCLUSIONS

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CONCLUSIONS

Models of heavy SUSY are compelling. Need concrete experimental tests. Demonstrated wino dark matter can be probed with data.

Computed mass reach for future collider experiments.

Anticipating improved limits (discovery?) for winos using CTA!

Tons of interesting new physics questions to consider for proton collisions at 100 TeV!