Smoking guns of supersymmetric dark matter

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Outline

- \diamond Setting the stage: Higgs boson, dark matter and SUSY scale
- \diamond Implications of m_h~125 GeV for SUSY mass scale
- \diamond Impact of DM relic abundance and searches
- \diamond ~1 TeV higgsino DM: Smoking gun of SUSY
- Complementarity of LHC and DM searches (direct and CTA)
- \diamond Early Universe: impact of low $\rm T_R$

♦ Summary

Based on:

- K. Kowalska, L. Roszkowski, E. M. Sessolo, <u>arXiv:1302.5956</u>, JHEP 1306 (2013) 078
- L. Roszkowski, E. M. Sessolo, A. J. Williams, <u>arXiv:1405.4289</u> and <u>arXiv:1411.5214</u> (JHEP)
- K. Kowalska, L. Roszkowski, E. M. Sessolo, S. Trojanowski, <u>1402.1328</u> (JHEP)
- K. Kowalska, L. Roszkowski, E. M. Sessolo, A. J. Williams, 1503.08219
- L. Roszkowski, S. Trojanowski, K. Turzyński, <u>1406.0012</u> (JHEP) and in preparation



Where is the WIMP?

- Mass range: at least 20 orders of magnitude
- Interaction range: some32 orders of magnitude



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WIMP remains the front-runner for dark matter





Well-motivated candidates for dark matter

- vast ranges of interactions and masses
- different production mechanisms in the early Universe (thermal, non-thermal)
- need to go beyond the Standard Model
- WIMP candidates testable at present/near future

 $\log_{10}(m_{DM}/GeV)$

axino, gravitino EWIMPs/superWIMPs not directly testable, but some hints from LHC

Where is ``new physics"?



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Low energy SUSY remains the front-runner for ``new physics"



Supersymmetry



Symmetry among particles

Bosons <-> fermions



SUSY and dark matter



• stable

WIMP = LSP

(lightest supersymmetric particle)

Why SUSY

Provides sensible framework for:➤ unification (including gravity)

 Early Universe cosmology (inflation, baryo/leptogenesis, ...)
 ...



Predictions:

 \succ top quark mass m_t < 200 GeV

Expt: 173.34 +/- 0.76 GeV



Direct Detection AD 2011 - Before LHC



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Main news from the LHC so far...

L_dt = 20.3 fb¹, vs=8 TeV

Observed limit (±1 σ^{SUSY}_{theory})

Expected limit (±1 σevo

5000

0-lepton combined

Stau LSP

4000





MSUGRA/CMSSM: $tan\beta = 30, A = -2m_0, \mu > 0$

SM: $3.54 \pm 0.27 \times 10$

m_{1/2} [GeV]

Stringen

SUSY mass

on supe

Each independently implies:

800

700

600

500

300

1000

2000

3000



: vs = 8 TeV, L = 19.7 fb

Data

s = 7 TeV, L = 5.1 fb

35

...and from the media...

Is Supersymmetry Dead?

The grand scheme, a stepping-stone to string theory, is still high on physicists' wish lists. But if no solid evidence surfaces soon, it could begin to have a serious PR problem

SCIENTIFIC AMERICAN[™]

April 2012

My conjecture:

(Coined before LHC era...)

SUSY cannot be experimentally ruled out.

It can only be discovered.

Or else abandoned.



seph Lykken

L. Roszkowski, Nordita, 3 June '15

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Joseph Lykl

The 125 GeV Higgs boson and SUSY





SUSY: Constrained or Not?

SUSY is a symmetry, not a model

• <u>Constrained:</u>

Low-energy SUSY models with grand-unification relations among gauge couplings and (soft) SUSY mass parameters



Virtues:

- Well-motivated
- Predictive (few parameters)
- Realistic

Many models:

- CMSSM (Constrained MSSM): 4+1 parameters
- NUHM (Non-Universal Higgs Model): 6+1
- CNMSSM (Constrained Next-to-MSSM) 5+1
- CNMSSM-NUHM: 7+1



figure from hep-ph/9709356

Phenomenological:

Supersymmetrized SM...

Features:

- Many free parameters
- Broader than constrained SUSY



Many models:

- general MSSM over 120 params
- MSSM + simplifying assumptions
- pMSSM: MSSM with 19 params
- p9MSSM, p12MSSM, pnMSSM, …

• etc

~125 GeV Higgs and unified SUSY

 $m_{h_2} \simeq 125.3$ Take <u>only minimum 70125</u> GeVB and lower limits from direct SUSY searches

$$\mathcal{L} \sim e^{rac{(m_h-125.8\,{
m GeV})^2}{\sigma^2+ au^2}}$$

$$\Delta m_h^2 = \frac{3m_t^4}{4\pi^2 v^2} \left[\ln\left(\frac{M_{\rm SUSY}^2}{m_t^2}\right) + \frac{X_t^2}{M_{\rm SUSY}^2} \left(1 - \frac{X_t^2}{12M_{\rm SUSY}^2}\right) \right]$$

 $M_{\rm SUSY} \equiv \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}} \qquad \qquad X_t = A_t - \mu \cot \beta$

Add relic abundance $\Omega_{\rm DM} h^2 \simeq 0.12$ $\sigma = 0.6 \text{ GeV}, \tau = 2 \text{ GeV}$ BavesFITS (2013) BayesFITS (2013) 60 CMSSM Posterior pdf Posterior pdf Posterior pdf * Best fit 1302.5956 solid: 1σ region CM\$SM, $\mu > 0$ solid: 1σ region CMSSM, $\mu > 0$ CMSSM, $\mu \geq \hat{b}$ dashed: 2σ region dashed; 2σ region Log 50-Log Priors Log Priors $m_{h} = 125.8 \pm 0.6$ (exp) ± 3 (th) GeV $BR(B_s \rightarrow \mu^+ \mu^-) = (3.2 \pm 1.5) \times 10^{-9}$ (current) $BR(B_s \rightarrow \mu^+ \mu)$ $m_{1/2}$ (TeV) $m_{1/2}$ (TeV) 40 ~1~TeV higgsindom (``new") 20 bino DM (previously favored)¹⁰ CMS Combination 12 8 16 20 12 16 -16A curse! 8 20 -8 m_0 (TeV) m_0 (TeV) A_{i} ~125 GeV Higgs mass implies **Unified SUSY: NO other solutions** multi-TeV scale for SUSYszkowski, Nordita, 3 June '15 19

SUSY confronting data

The experimental measurements that we apply to constrain the CMSSM's parameters. Masses are in GeV.

		Constraint	Mean	Exp. Error	Th. Error
2-	\rightarrow	Higgs sector	See text.	See text.	See text.
		Direct SUSY searches	See text.	See text.	See text.
		$\sigma_p^{ m SI}$	See text.	See text.	See text.
		$\Omega_\chi h^2$	0.1199	0.0027	10%
		$\sin^2 heta_{ m eff}$	0.23155	0.00015	0.00015
	\rightarrow	$\delta \left(g-2 ight)_{\mu} imes 10^{10}$	28.7	8.0	1.0
		${ m BR}\left(\overline{B} \to X_{\rm s}\gamma\right) imes 10^4$	3.43	0.22	0.21
		$BR(B_u \to \tau \nu) \times 10^4$	0.72	0.27	0.38
		ΔM_{B_s}	17.719 ps^{-1}	0.043 ps^{-1}	2.400 ps^{-1}
		M_W	$80.385{ m GeV}$	$0.015{ m GeV}$	$0.015{ m GeV}$
		$\mathrm{BR}(\mathrm{B_s} \to \mu^+ \mu^-) \times 10^{\mathrm{\$}}$	2.9	> 0.7	10%

10 dof

most important (by far)

SM value: $\simeq 3.5 \times 10^{-9}$



We do simultaneous scan of at least 8 parameters (4 of CMSSM + 4 of SM) L. Roszkowski, Nordita, 3 June '15 20



CMSSM and direct DM searches

 $\mu > 0$



DM direct detection



~1 TeV higgsino DM: excellent prospects!

Bayesian vs chi-square analysis

(updated to include 3loop Higgs mass corrs)



Chances of direct SUSY signal at the LHC?



CMSSM: Complementarity of DD, CTA and LHC



..all parameter space covered at 2 sigma

CMSSM can be fully explored by experiment

How robust are these results?

- Particle model/assumption dependence
- Early Universe conditions
 - Standard thermal equilibrium vs low reheating T_R
 - Impact of inflaton decay?
- •

Higgs inspired ~1 TeV higgsino DM

\diamond robust, present in many SUSY models

(both GUT-based and not)

Condition: heavy enough gauginos

 $\begin{array}{l} \mbox{When} \ m_{\tilde{B}} \gtrsim 1 \ \mbox{TeV:} \\ \mbox{easiest to achieve} \ \Omega_{\chi} h^2 \simeq 0.1 \\ \mbox{when} \ m_{\tilde{H}} \simeq 1 \ \mbox{TeV} \end{array}$

implied by ~125 GeV Higgs mass
 <u>and</u> relic density

♦ most <u>natural</u> among SUSY DM

No need to employ special mechanisms (A-funnel or coannihilation) to obtain correct relic density



smoking gun of SUSY!?

Fall and rise of higgsino DM



CTA – New guy in DM hunt race

chere







direct detection \sim





CMSSM: Complementarity of DD, CTA and LHC



..all parameter space covered at 2 sigma

CMSSM can be fully explored by experiment





Beyond CMSSM...

e.g., NUHM (Non-Universal Higgs Model)



General MSSM: only some ``islands" will be probed by direct SUSY searches (Atlas, CMS), B_s -> mu mu (CMS, LHCb), DM 1 tonne detectors and/or CTA

Direct Search for DM in general SUSY

- bino (M1) vs wino (M2) masses: free params -10Parameter Range Higgsino/Higgs mass parameter $-10 \le \mu \le 10$ (qd) $-10 < M_1 < 10$ Bino soft mass Wino soft mass $0.1 \le M_2 \le 10$ $\log_{10} \sigma_p^{\mathrm{SI}}$ $-10 \le M_3^* \le 10$ Gluino soft mass Top trilinear soft coupl. $-10 < A_t < 10$ -15 $-10 < A_h < 10$ Bottom trilinear soft coupl. τ trilinear soft coupl. $-10 < A_{\tau} < 10$ $0.1 \le m_A \le 10$ Pseudoscalar physical mass 1st/2nd gen. soft L-slepton mass $0.1 \le m_{\tilde{L}_1} \le 10$ 1st/2nd gen. soft R-slepton mass $0.1 \le m_{\tilde{e}_R} \le 10$ 3rd gen. soft L-slepton mass $0.1 \le m_{\tilde{L}_3} \le 10$ -203rd gen. soft R-slepton mass $0.1 \le m_{\tilde{\tau}_R} \le 10$ $0.75 \le m_{\tilde{O}_1} \le 10$ 1st/2nd gen. soft L-squark mass 1st/2nd gen. soft R-squark up mass $0.75 \le m_{\tilde{u}_B} \le 10$ $0.75 \le m_{\tilde{d}_R} \le 10$ 1st/2nd gen. soft R-squark down mass 3rd gen. soft L-squark mass $0.1 \le m_{\tilde{Q}_3} \le 10$ 0.01 3rd gen. soft R-squark up mass $0.1 \le m_{\tilde{t}_B} \le 10$ 3rd gen. soft R-squark down mass $0.1 \le m_{\tilde{b}_R} \le 10$ $1 < \tan \beta < 62$ ratio of Higgs doublet VEVs
- Very wide scan
- All relevant constraints
- Sommerfeld effect included

pMSSM (=p19MSSM)

General MSSM: No DM mass restrictions ... but different WIMP compositions



Are SUSY DM properties robust?

- Relic density often provides one of strongest constraints
- Re-examine assumptions about the early Universe
- Standard thermal WIMP: relic density estimates assumes high reheating temperature T_R...



Low T_R after inflation

Reheating after cosmic inflation

If assume instantaneous reheating

Turzyński, 1406.0012

$$\Gamma_{\phi} = H = \sqrt{\frac{8\pi}{3M_{Pl}^2} \rho_{\phi}}$$
 $\rho_{\phi} = \rho_{rad}(T_R) \sim T_R^4$

$$\Gamma_{\phi} = \sqrt{\frac{4\pi^3 g_*(T_R)}{45}} \frac{T_R^2}{M_{Pl}} \quad \text{ <- defines } \mathsf{T}_{\mathsf{R}}$$

If assume non-instanteneous reheating

Giudice, Kolb, Riotto, hep-ph/0005123

coupled Boltzmann equations:

$$\begin{aligned} \frac{d\rho_{\phi}}{dt} &= -3H\rho_{\phi} - \Gamma_{\phi}\rho_{\phi} \\ \frac{d\rho_{R}}{dt} &= -4H\rho_{R} + \Gamma_{\phi}\rho_{\phi} + \langle\sigma v\rangle 2\langle E_{X}\rangle \left[n_{X}^{2} - (n_{X}^{eq})^{2}\right] \\ \frac{dn_{X}}{dt} &= -3Hn_{X} - \langle\sigma v\rangle \left[n_{X}^{2} - (n_{X}^{eq})^{2}\right] \quad \left(+ \frac{b}{m_{\phi}}\Gamma_{\phi}\rho_{\phi} \right) \end{aligned}$$

Gelmini, et al., hep-ph/0602230

LR, Trojanowski,

inflaton field radiation dark matter

SUSY and reheating: high vs low T_{R}



Here neglect direct inflaton decays to DM

DM production:

- freeze-out happens at somewhat higher temperature than in the standard high T_R case
- Subsequently, until the end of reheating, DM population is quite efficiently depleted

$$egin{aligned} \Omega_\chi h^2 &(\mathrm{low} \ T_R) \sim \ &\left(rac{T_R}{T_{\mathrm{fo}}^{\mathrm{new}}}
ight)^3 \left(rac{T_{\mathrm{fo}}^{\mathrm{old}}}{T_{\mathrm{fo}}^{\mathrm{new}}}
ight) \Omega_\chi h^2 &(\mathrm{high} \ T_R) \end{aligned}$$

GKR, hep-ph/0005123

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$\Omega_{\chi} h^2(\text{low } T_R) < \Omega_{\chi} h^2(\text{high } T_R)$





Range

 $0.1 < M_1 < 5$

 $0.1 < M_2 < 6$ $0.7 < M_3 < 10$

 $-12 < A_t < 12$

 $-12 < A_{\tau} < 12$

 $A_{h} = -0.5$

 $0.2 < m_A < 10$

 $0.1 < \mu < 6$ $0.1 < m_{\widetilde{O}_3} < 15$

 $0.1 < m_{\widetilde{L}_3} < 15$

 $m_{\tilde{Q}_{1,2}} = M_1 + 100 \text{ GeV}$

 $m_{\widetilde{L}_{1,2}} = m_{\widetilde{Q}_3} + 1 \text{ TeV}$

 $2 < \tan \beta < 62$

Central value, error

(4.18, 0.03) [25]

(173.5, 1.0) [25]

SUSY DM and reheating: high vs low T_R

High T_R (standard case)

• Low T_{R}

LR, Trojanowski, Turzyński, <u>1406.0012</u>





SUSY DM and low T_R

LR, Trojanowski, Turzyński, <u>1406.0012</u>

We have examined also other DM relics at low T_{R:}

- bino
- wino
- gravitino
- axino



e.g., gravitino DM



- Ranges of ``usual" solutions can get significantly relaxed.
- Interesting bounds arise.



...modulo low T_R

Higgs of 125 GeV → ~1TeV (higgsino) DM – robust prediction of SUSY

Smoking gun of SUSY!?



This could be the greatest discovery of the century. Depending, of course, on how far down it goes.

To take home:

DM: jury is still out, discovery claims come and go, but...

➢ Higgs of 125 GeV → ~1TeV (higgsino) DM – robust prediction of unified (and pheno) SUSY:

Smoking gun of SUSY!?

- To be almost fully probed by 1-tonne DM detectors
- Independent probe by CTA
- Other indirect detection modes (nu, e^+, ...): no chance
- Far beyond direct LHC reach
- If higgsino mass > 1 TeV => low $T_R \sim 50 150$ GeV
- If higgsino mass < 1 TeV => more than one DM? inflaton decay?

CMSSM: Complementarity of LHC, DD and CTA

General SUSY (pMSSM):

- CTA and direct detection show good complementarity reach (far beyond direct LHC reach)
- much of higgsino region to be probed
- wino DM allowed > 3.5 TeV -> $T_R \sim 100 200 \text{ GeV}$





Warsaw 7-11 September cosmo15.ncbj.gov.pl

Welcome to Poland!

BACKUP

... a question on many people's mind...

But what about fine tuning/naturalness?!

- I prefer to follow what the data implies, rather than theoretical prejudice
- Naturalness: fundamental Higgs -> SUSY
- Fine-tuning is needed at any scale above the EW scale

```
1 TeV is not a magic number
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- mh[~]125 GeV -> M_{SUSY} ~> 1 TeV -> high FT is basically ``an experimental fact"
- If SUSY is discovered, large FT issue will have to be understood/ accepted
- If SUSY is not discovered, the issue will become irrelevant
- Naturalness" argument gone astray:

$$rac{m_t}{m_b} \sim rac{m_c}{m_s} \simeq 14 \; \Rightarrow \; m_t \simeq 60 \, {
m GeV}$$



Fine tuning issue is an expression of our ignorance about the high scale!

> **FT argument:**
$$\mu^2 = -\frac{1}{2}M_Z^2 + \frac{m_{H_d}^2(M_{\text{SUSY}}) - \tan^2\beta m_{H_u}^2(M_{\text{SUSY}})}{\tan^2\beta - 1}$$

 $m_{H_u,d}^2$: tree + 1L corrs

 $m_{H_u}^2, m_{H_u}^2$ and μ^2 need to be all fine-tuned to give M_Z^2

Since we don't know them, we expect them to be of order m_z^2

But, imagine they are derived from some fundamental theory and come out to be of order 100 TeV, but still obey EWSB

Would one still claim high FT in the theory? NO!

Low FT does not have to necessarily imply low M_{SUSY.}

FT in an effective theory may be resolved in a more complete theory E.g. GIM mechanism: divergence in 3-quark model got resolved in 4-quark model

High scale relations to reduce FT in ~1 TeV higgsino region



otherwise $\Delta_{\mu} \simeq 250$ since $\mu \simeq 1 \, {
m TeV}$

Reduce FT in ~1 TeV higgsino region



All experimental constraints satisfied

L. Roszkowski, Nordita, 3 June '15

...except (g-2)_{mu}