Non-Universal Gaugino Masses, Dark Matter and the LHC

Brent D. Nelson

Northeastern
UNIVERSITY

with B. Altunkaynak, M. Holmes,
+ University of Michigan/University of Wisconsin

Outline

- Gaugino Sector of the MSSM (2 Slides)
- Dark Matter Hints (8 Slides)
- High-Energy Theoretical Motivation (2 Slides)
- LHC Phenomenology (4 Slides)

Quick Review

Gaugino Sector Basics

- Gauginos part of vector supermultiplets: $A_a = \{\lambda_a,\ (A_\mu)_a,\ D_a\}$, $a = 1, 2, 3$

Names	spin 1/2	spin 1	$SU(3)_C,\ SU(2)_L,\ U(1)_Y$
gluino, gluon	$\widetilde{g}$	g	$(\ \mathbf{8},\ \mathbf{1}\ ,\ 0)$
winos, W bosons	$\widetilde{W}^{\pm}\quad \widetilde{W}^0$	$W^{\pm}\quad W^0$	$(\ \mathbf{1},\ \mathbf{3}\ ,\ 0)$
bino, B boson	$\widetilde{B}^0$	B^0	$(\ \mathbf{1},\ \mathbf{1}\ ,\ 0)$

- Supersymmetry breaking independent of EWSB
  Thus in SUSY limit we have massless gauginos up to EWSB effects

- Soft SUSY-breaking gaugino masses: $\mathcal{L}_{\text{soft}} \ni -\frac{1}{2} M_a \lambda_a \lambda_a + \text{c.c.}$

- Gaugino masses run independently at one loop

$$\frac{dM_a}{dt} = \frac{1}{8\pi^2} b_a g_a^2 M_a\,, \qquad b_a = -(3C_a - \sum_i C_a^i) \ \Rightarrow\ \{b_1, b_2, b_3\} = \left\{\frac{33}{5}, 1, -3\right\}$$

- Three ratios M_a/g_a^2 therefore constant (up to two loop effects)

$$\frac{M_1}{g_1^2} \simeq \frac{M_2}{g_2^2} \simeq \frac{M_3}{g_3^2} \ \rightarrow\ M_3 : M_2 : M_1 \simeq 6 : 2 : 1 \quad \text{at EW scale}$$

Gaugino Masses – EM Neutral Sector

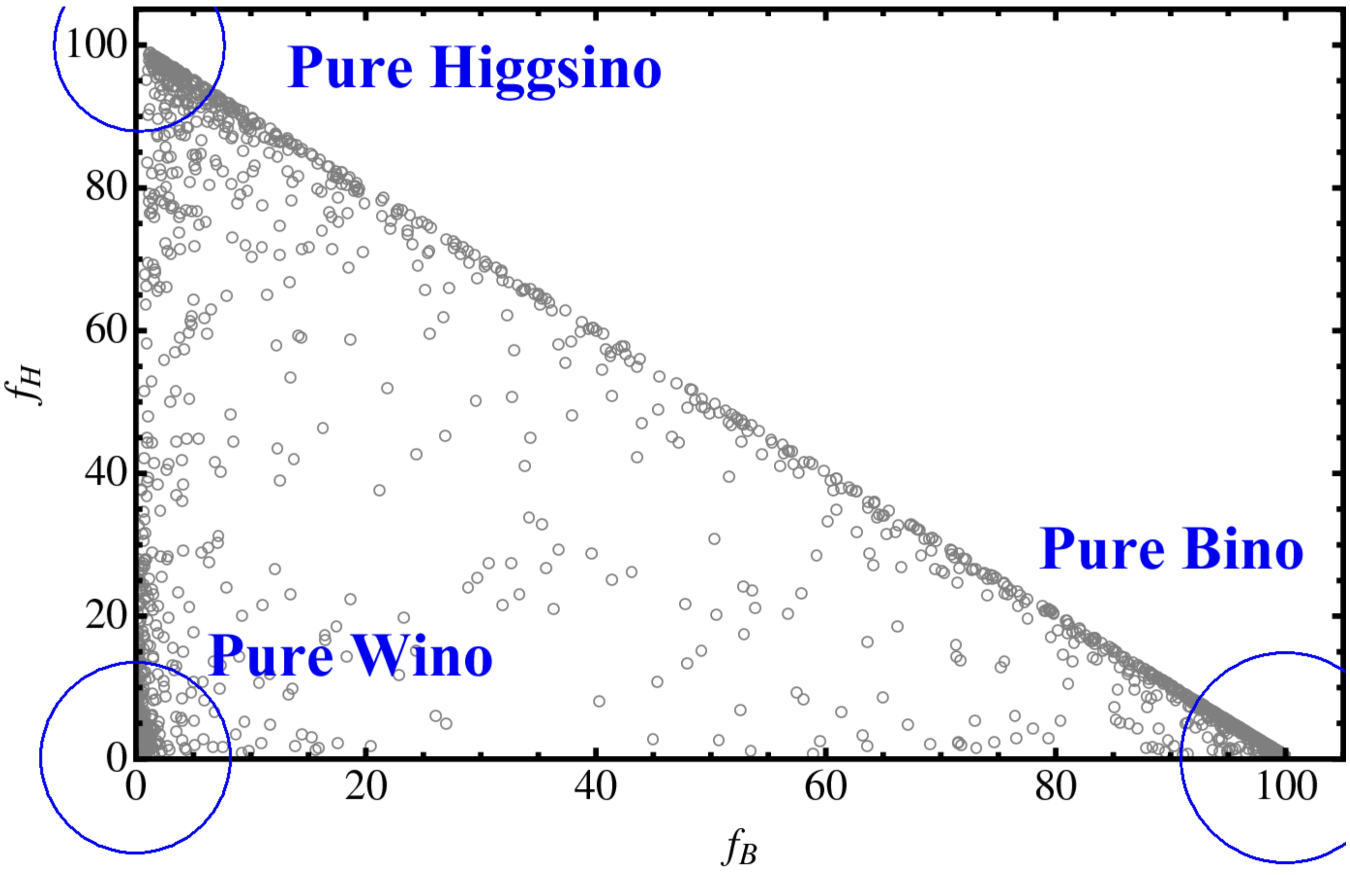
$\Rightarrow$ Can model possibilities via $M_a = m_{1/2}\,(1+\delta_a)$

Arkani-Hamed, Delgado, Giudice, NPB **741** (2006) 108

- $\delta_1 = \delta_2 = \delta_3$ produces bino-like LSP: $\widetilde{N}_1 \sim \widetilde{B}; \quad \widetilde{N}_2 \sim \widetilde{W}^0$
- $\{\delta_1 = 0,\ \delta_2 < 0\}$ produces wino-like LSP
- $\{\delta_2 > 0,\ \delta_3 < 0\}$, $|\delta_3| < |\delta_2|$ produces Higgsino-like LSP via RGEs + EWSB

$$M_Z^2 = 5.9M_3^2 - 1.8\mu^2 + 0.4m_0^2 - 0.4M_2^2 + \ldots$$

Kane, Lykken, BDN, Wang, PLB **551** (2003) 146



Dark Matter

Dark Matter Signals – the Earliest SUSY Signature

- Assumption: lightest neutralino is stable LSP ⇒ dark matter

Goldberg, PRL **50** (1983) 1419

- Prediction: annihilation into photons, positrons, anti-protons, neutrinos

Silk & Srednicki, PRL **53** (1984) 624

  - ⋆ Photons & neutrinos "point" back to source: high density areas such as galactic center or center of sun/earth
  - ⋆ Charged particles must be propagated from origin to earth numerically
  - ⋆ Both depend on the *halo profile* $\rho_\chi(r)$ assumed for the dark matter candidate, but to varying degrees

- Begin with positrons:

Cirelli et al., NPB **800** (2008) 204; **813** (2009) 1

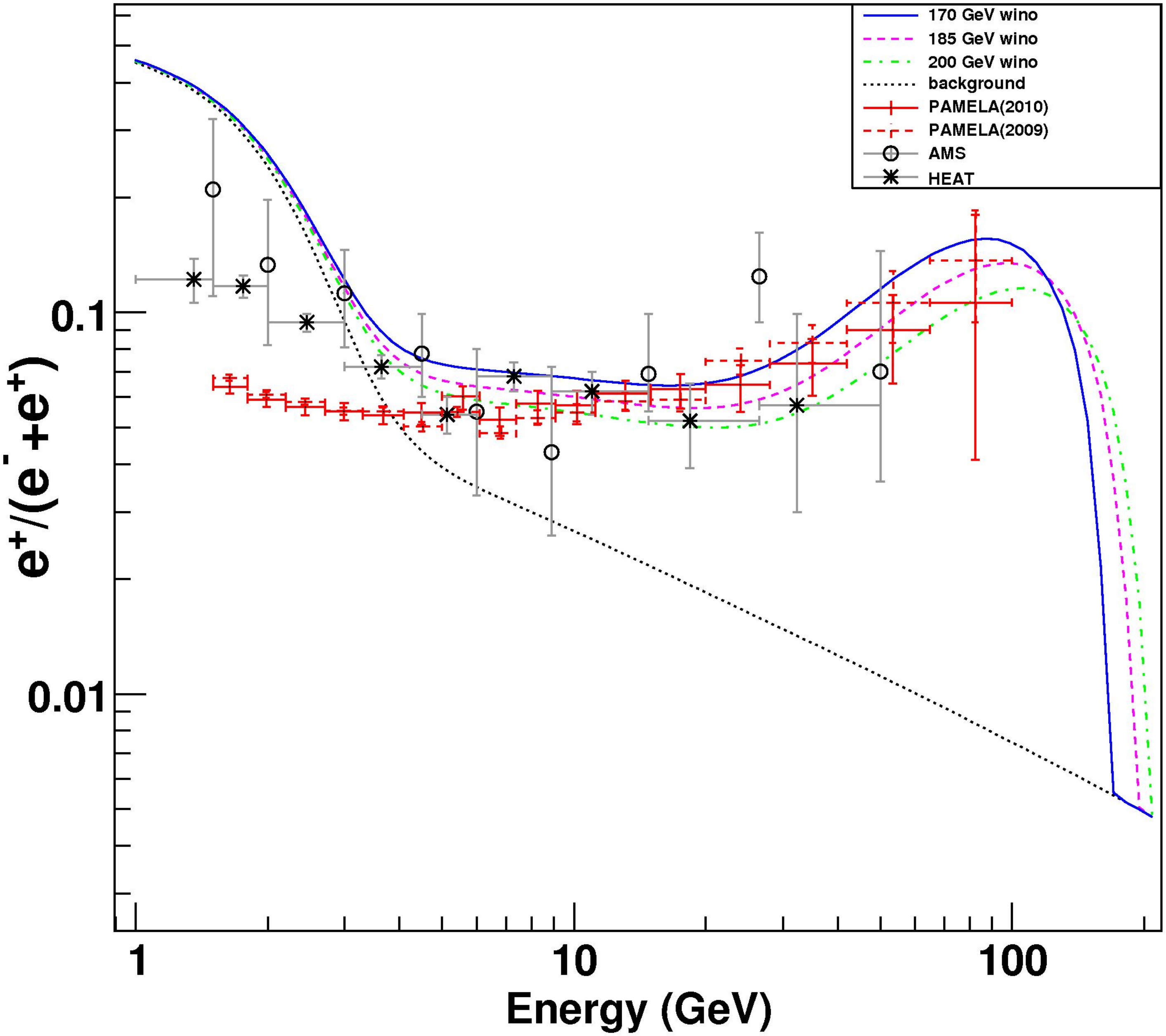
$$\Phi_{\bar{e}}(E) \simeq \frac{\tau_E B_{\bar{e}} c}{8\pi b(E)} \frac{\rho_\chi^2(r = R_0)}{m_{\widetilde{N}_1}^2} F(E)\,, \quad b(E) = 1\,\mathrm{GeV}\left(\frac{E}{1\,\mathrm{GeV}}\right)^2$$

$$F(E) = \int_E^{M_{\widetilde{N}_1}} dE' \sum_k \langle\sigma v\rangle_{\mathrm{halo}}^k \frac{dN_{\bar{e}}^k}{dE'} \cdot \mathcal{I}(E, E')$$

  - ⋆ $B_{\bar{e}}$ = boost factor, $\tau_E = \tau \times 10^{16}\,\mathrm{sec}$ is the diffusion time scale and $\mathcal{I}(E, E')$ is the halo function
  - ⋆ For SUSY models, most important final state is usually $k = W^+W^-$

SUSY Fits to Positron Flux Measurements

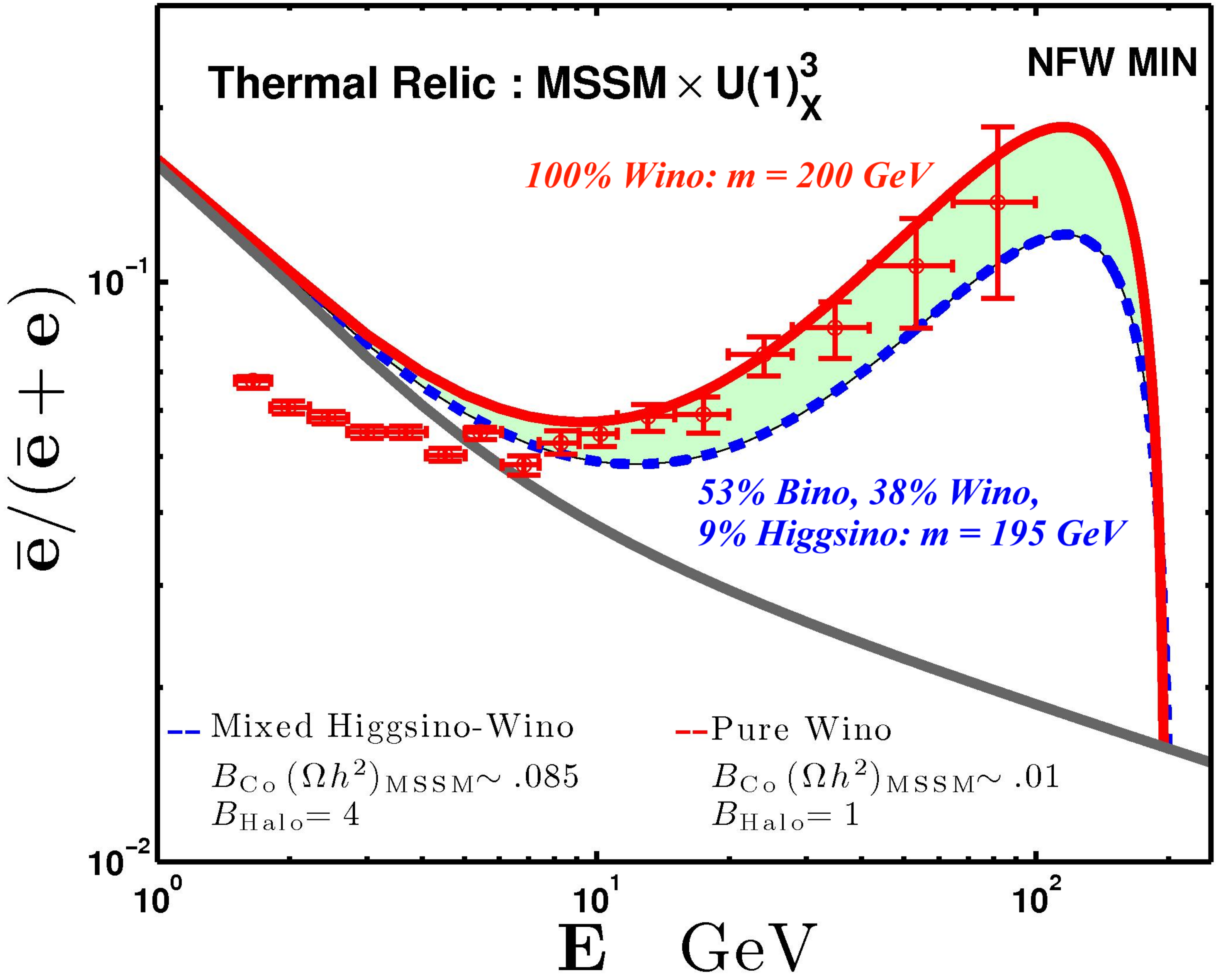
PAMELA Collaboration, arXiv:1001.3522



⇒ Best fits require $\langle \sigma v \rangle_{WW} \simeq 2 \times 10^{-24}\,\mathrm{cm}^3/\mathrm{s}$ and prefer NFW “min” profile

Feldman, Kane, Lu, BDN, arXiv:1002.2430

SUSY Fits to Positron Flux Measurements

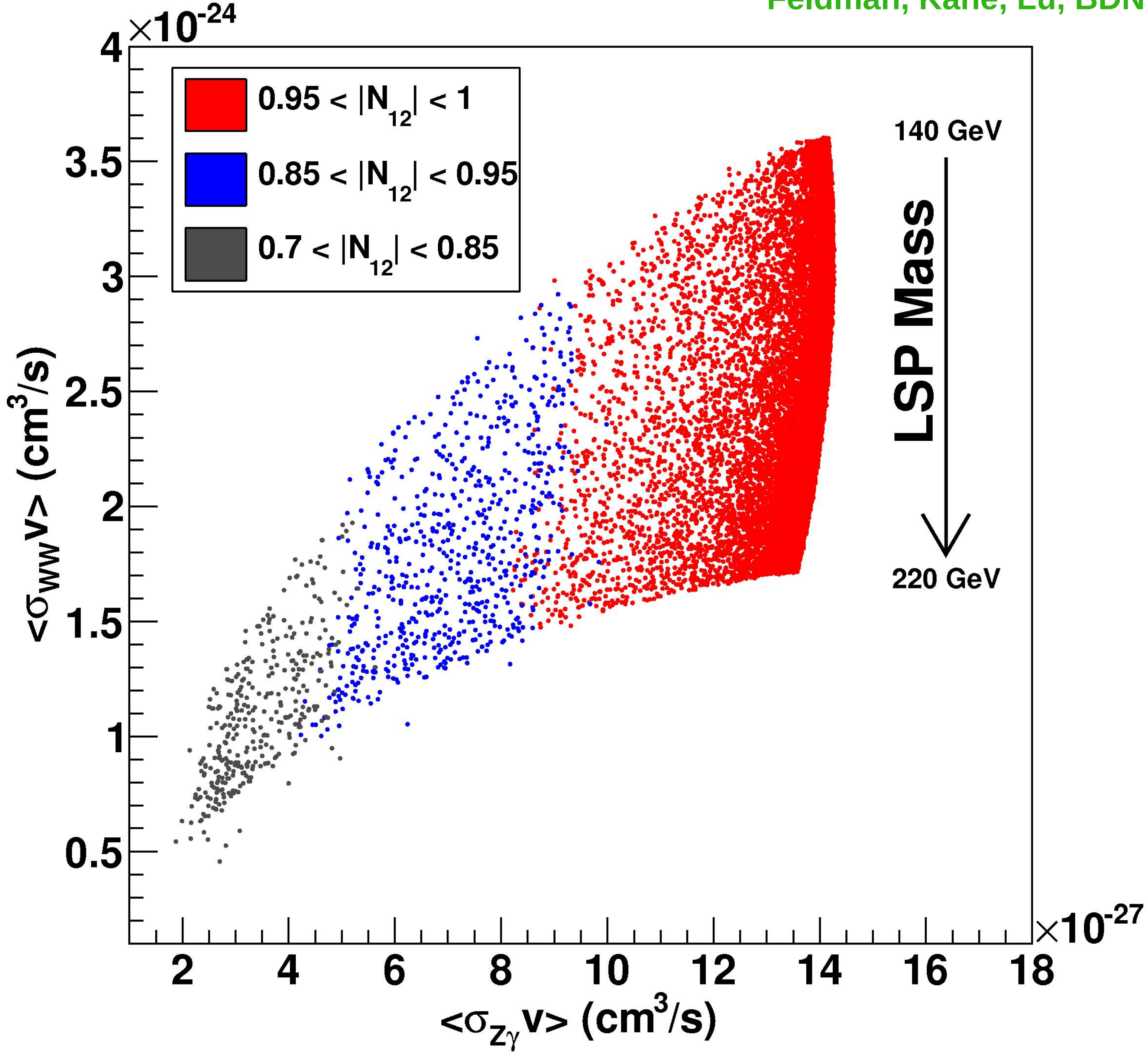


⇒ Pure wino not necessary – but must compensate with $B_{\bar{e}}$ (here B_{HALO})

Feldman, Liu, Nath, BDN, arXiv:0907.5392

Photons versus Positrons

Feldman, Kane, Lu, BDN, arXiv:1002.2430



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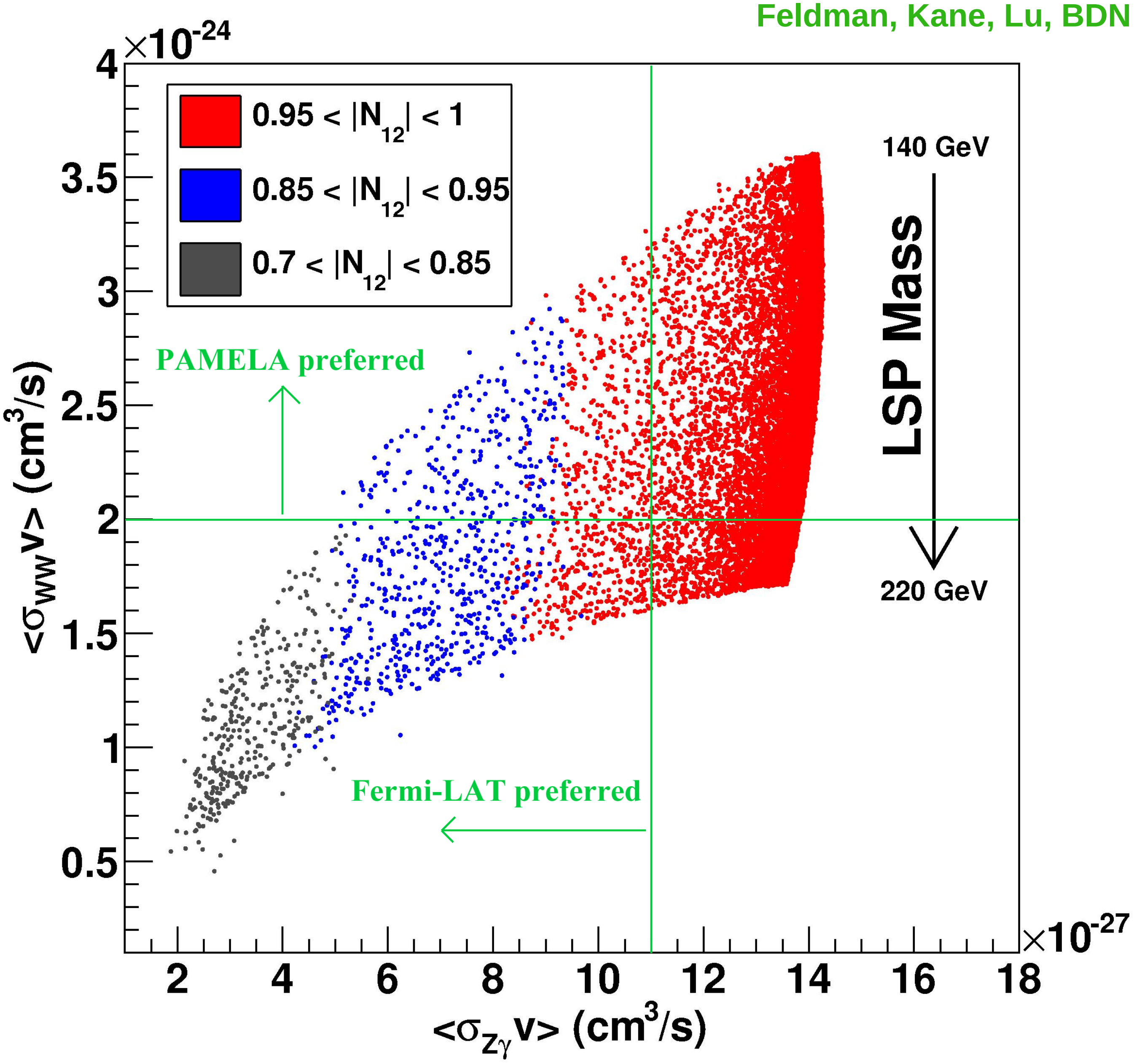
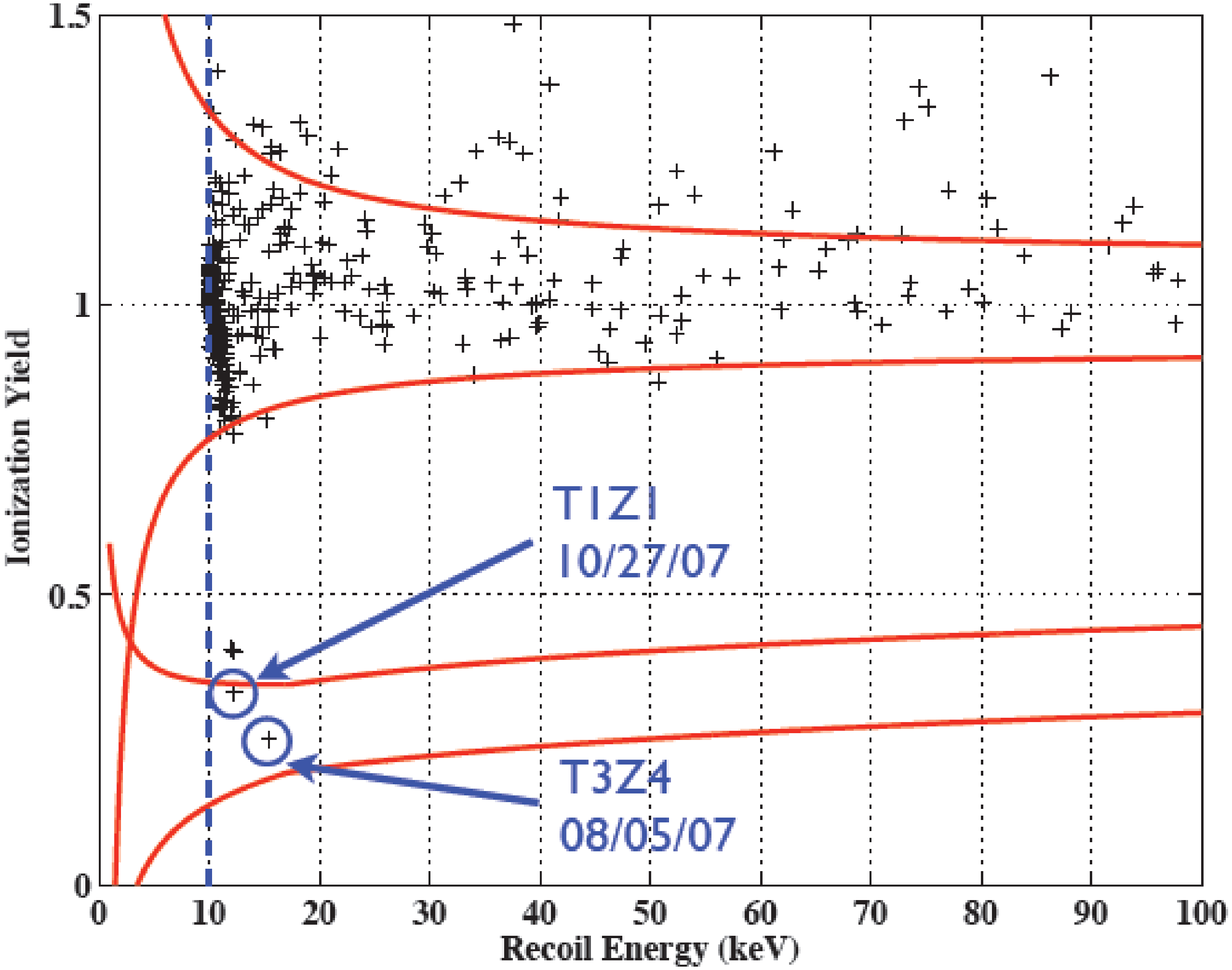
Feldman, Kane, Lu, BDN, arXiv:1002.2430



Direct Detection Experiments: CDMS II

⇒ December 2009 data release for 14 Ge detectors by CDMS-II Collaboration



CDMS II Collaboration, Science **327** (2010) 1620

- Two events in signal region with (revised) background estimate of $0.8 \pm 0.1\,(\mathrm{stat}) \pm 0.2\,(\mathrm{sys})$ events
- Implies an interaction cross-section $\sigma^{\mathrm{SI}}_{\chi p} \sim 10^{-44}\,\mathrm{cm}^2 = 1 \times 10^{-8}\,\mathrm{pb}$

Fitting to CDMS II

⇒ Differential recoil rate at direct detection experiments given by

$$\frac{dR}{dE} = \sum_i c_i \frac{\rho_\chi \sigma^{\rm SI}_{\chi i} |F_i(q_i)|^2}{2 m_\chi \mu^2_{i\chi}} \int_{v_{min}}^{\infty} \frac{f(\vec{v},t)}{v} d^3v \,,$$

with $F_i(q_i)$ being a nuclear form factor for i-th target nucleus

- Calculation of integrated event rate depends on experimental configuration

$$R = \int_{E_{\rm min}}^{E_{\rm max}} \frac{dR}{dE} dE\,; \quad ({\rm Germanium}) : 10\,{\rm keV} \leq E_{\rm recoil} \leq 100\,{\rm keV}$$

Altunkaynak, Holmes and BDN, arXiv:0804.2899

Point	A	B	C	D	E
$m_{\chi^0_1}$ (GeV)	138	190	175	112	230
δ_2	0.65	0.62	-0.6	0.82	-0.47
δ_3	-0.35	-0.3	-0.3	-0.35	-0.3
B%	3.0%	70.2%	0.3%	5.4%	40.9%
W%	0.4%	0.4%	95.8%	0.5%	53.0%
H%	96.6%	29.4%	3.9%	94.1%	6.1%
$\sigma^{\rm SI}_{\chi p} \times 10^{45}$ (cm^2)	11.9	44.4	41.3	35.3	74.8
$N_{\rm Ge}$ (184 kg-days)	0.51	1.36	1.30	1.65	1.90

Holmes and BDN, arXiv:0912.4507

DM Hints - Lessons Thus Far

⇒ **Wino-like LSP preferred, but probably not 100% wino**

- Pure wino better for PAMELA (no boost factor) but tension with anti-protons and photons without help from halo model and/or diffusion parameters
- Higgsino or Bino component of 5-10% (at least) needed to avoid photon and anti-proton constraints – but need $\mathcal{O}(5)$ boost factors to get PAMELA
- If CDMS-II is seeing a signal, will need even more substantial Higgsino component for large enough cross section

All scenarios (probably) require non-thermal relic production mechanisms

High-Scale Theoretical Motivation

What Can Cause Non-Universalities?

In supergravity, gaugino masses have a very simple form:

$$m_{\lambda_a} = \sum_n \frac{g_a^2}{2} \frac{F^n}{M_{\rm PL}} {\rm Re}[\partial_n f_a] \; ; \quad f_a = f_a(Z^n)$$

where f_a are gauge kinetic functions which depend on SM gauge singlets Z^n

⇒ *So what are some mechanisms for producing non-universal gaugino masses?*

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1. Grand Unified Theories
2. Independent Gauge Kinetic Functions
3. Loop Effects

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1. Grand Unified Theories
2. Independent Gauge Kinetic Functions
3. Loop Effects

⇒ An example of the last item is the mirage pattern of gaugino masses

$$M_1 \; : \; M_2 \; : \; M_3 \; \simeq \; (1 + 0.66\alpha) \; : \; (2 + 0.2\alpha) \; : \; (6 - 1.8\alpha)$$

Choi & Nilles, **JHEP 0704** (2007) 006

Manifestations of the Mirage Pattern

The mirage pattern (competition between tree and anomaly-mediated contributions to soft masses) appears in a number of phenomenologically successful string constructions:

- Kähler stabilized heterotic string models

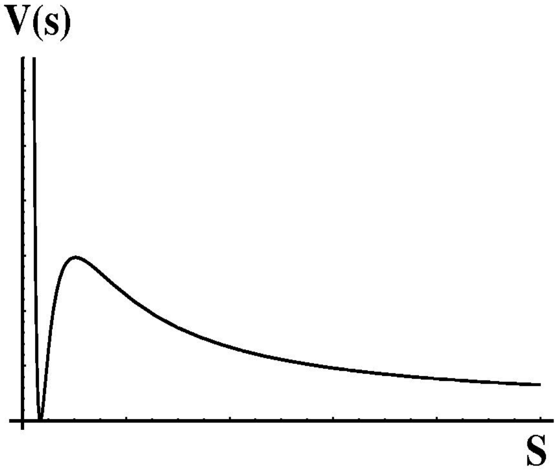
Binetruy, Gaillard, Wu, **NPB 481** (1996) 109
Gaillard and BDN, **IJMP A22** (2007) 1451

- Type-IIB flux compactifications with anti-D_3 branes

Kachru, Kallosh, Linde, Trivedi, **PRD 68** (2003) 046005
Choi, Falkowski, Nilles, Olechowski, **NPB 718** (2005) 113

- M-theory compactified on fluxless G_2 manifolds

Acharya, Kane, et al.,
PRL 97(2006) 191601
PRD 76 (2007) 126010
PRD 78 (2008) 065038



$\Rightarrow$ Common features:

- Single modulus stabilized by gaugino condensation
- Kähler potential for this modulus substantially altered from tree-level value
- Tuning of cosmological constant ($\langle V \rangle$) to zero by adjusting parameters

LHC Implications

General Methodology

- For each point studied 100,000 events generated with `PYTHIA` + `PGS4` with the level 1 trigger only

  ⇒ Typically this is about 5 fb^{-1} of signal

- A single SM sample was generated, including 5 fb^{-1} of top, bottom, dijets and gauge boson production (both single and double production)

  ⇒ This background sample was suitably weighted to be included with each of our "signal" samples

- Initial object-level cuts to keep an object in the event record

Object	Minimum p_T	Minimum $\|\eta\|$
Photon	20 GeV	2.0
Electron	20 GeV	2.0
Muon	20 GeV	2.0
Tau	20 GeV	2.4
Jet	50 GeV	3.0

⇒ After object-level cuts we impose event-level cuts – an example:

- $\not{E}_T > 150 \text{ GeV}$
- Transverse sphericity $S_T > 0.1$
- $H_T = \not{E}_T + \sum_{\text{Jets}} p_T^{\text{jet}} > 600 \text{ GeV}$ (400 GeV for events with 2 or more leptons)

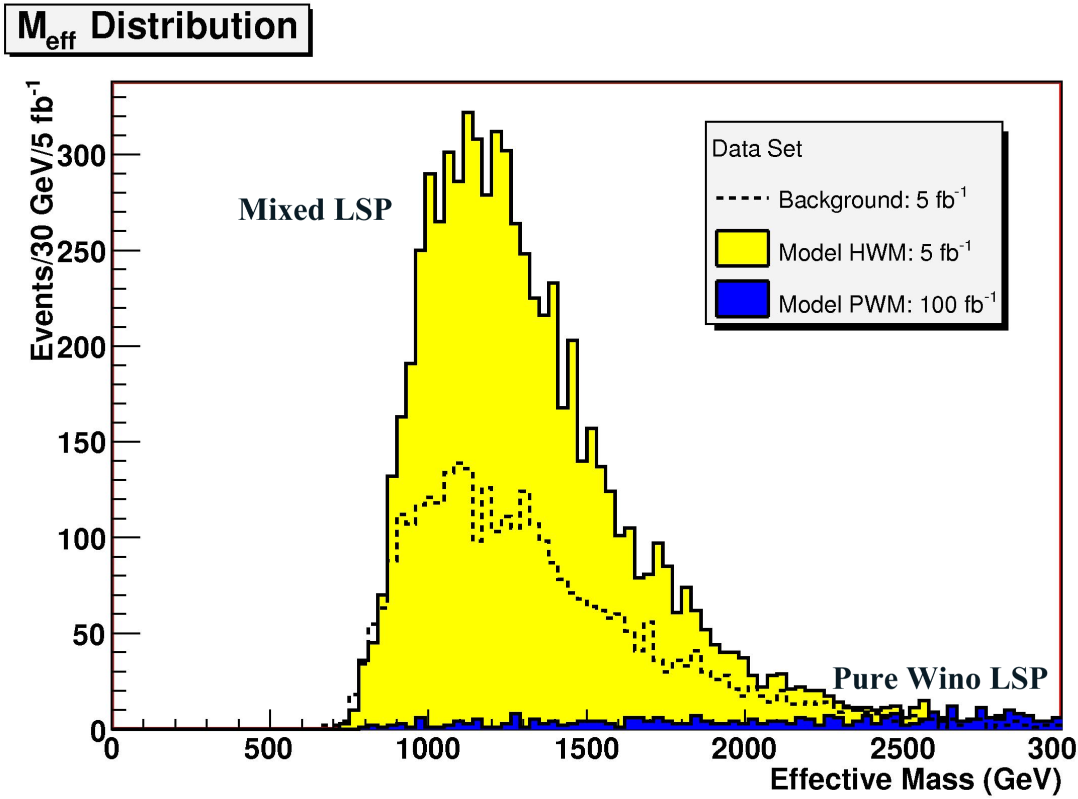
Benchmark Models I: PAMELA Examples

Feldman, Liu, Nath, BDN, reference

Mass	Mixed LSP	Pure Wino LSP
$m_{\tilde{N}_1}$	198.9	195.2
$m_{\tilde{N}_2}$	217.0	357.0
$m_{\tilde{N}_3}$	429.9	1025
$m_{\tilde{N}_4}$	451.3	1029
$m_{\tilde{C}_1}$	208.8	195.5
$m_{\tilde{C}_2}$	448.6	1036
$m_{\tilde{t}_1}$	648.5	1516
$m_{\tilde{t}_2}$	866.8	1749
$m_{\tilde{b}_1}$	841.4	1729
$m_{\tilde{b}_2}$	970.2	1902
$m_{\tilde{\tau}_1}$	817.7	1011
$m_{\tilde{\tau}_2}$	822.8	1041
$m_{\tilde{g}}$	707.1	1929

- Big impact of gluino mass in number of multijet events
- Small mass gaps significantly reduce number of leptonic events

	Mixed LSP		Pure Wino LSP	
Signature	Events	$S/\sqrt{B}$	Events	$S/\sqrt{B}$
Multijets	8766	183.74	50	1.05
Lepton + jets	2450	32.25	26	0.34
OS dileptons + jets	110	6.39	4	0.23
SS dileptons + jets	60	11.77	0	NA
Trileptons + jets	14	2.47	0	NA



10 fb^{-1} **at** $\sqrt{s} = 14\,\mathrm{TeV}$

Benchmark Models II: CDMS-II Examples

Holmes and BDN, arXiv:0912.4507

Point	C	D	E
δ_2	-0.6	0.82	-0.47
δ_3	-0.3	-0.35	-0.3
B%	0.3%	5.4%	40.9%
W%	95.8%	0.5%	53.0%
H%	3.9%	94.1%	6.1%
$m_{\widetilde{N}_1}$	175	112	230
$m_{\widetilde{N}_2}$	235	130	239
$m_{\widetilde{N}_3}$	505	252	504
$m_{\widetilde{N}_4}$	513	846	515
$m_{\widetilde{C}_1}$	175	123	234
$m_{\widetilde{C}_2}$	514	846	515
$m_{\tilde{g}}$	952	890	951
$m_{\tilde{t}_1}$	719	544	709
$m_{\tilde{t}_2}$	862	964	865
$m_{\tilde{b}_1}$	809	766	812
$m_{\tilde{b}_2}$	874	943	871
$m_{\tilde{\tau}_1}$	344	338	352
$m_{\tilde{\tau}_2}$	414	752	424
m_h	113	114	113
$\sigma_{\mathrm{SUSY}}^{7\,\mathrm{TeV}}$ (pb)	1.2	2.7	0.4
$\sigma_{\mathrm{SUSY}}^{10\,\mathrm{TeV}}$ (pb)	2.5	5.1	1.3
$\sigma_{\mathrm{SUSY}}^{14\,\mathrm{TeV}}$ (pb)	5.7	10.0	3.7

- All models can produce signals at CDMS II – C & E can fit PAMELA data as well
- Signal simulated: 1 fb^{-1} at $\sqrt{s} = 14\,\mathrm{TeV}$
- Again, healthy multijets but disappearance of leptonic events

Numbers of Events

Point	C	D	E
Multijets	402	436	298
1ℓ + jets	202	310	111
OS 2ℓ + jets	12	45	7
SS 2ℓ + jets	6	16	3
3ℓ + jets	4	6	1

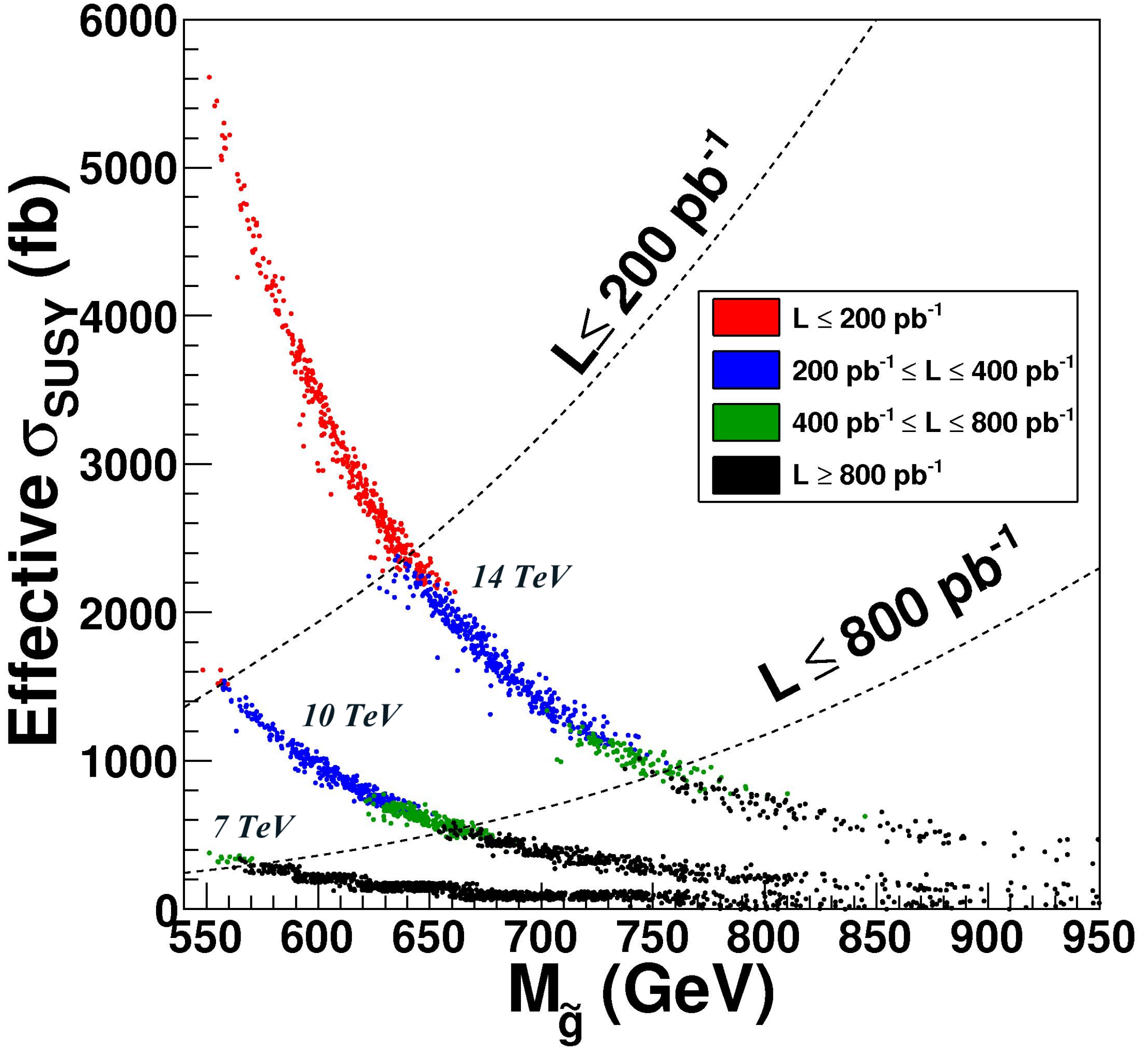
Significance $S/\sqrt{B}$

Point	C	D	E
Multijets	26.9	29.1	19.9
1ℓ + jets	8.2	12.5	4.5
OS 2ℓ + jets	2.0	7.4	1.2
SS 2ℓ + jets	2.3	6.0	1.1
3ℓ + jets	1.6	2.5	0.4

General PAMELA-consistent Models

⇒ General rule: Discovery of DM-motivated models needs a light gluino

Feldman, Kane, Lu, BDN, arXiv: 1002.2430



- High wino-content (for PAMELA) implies small mass gap between $\widetilde{C}_1/\widetilde{N}_2$ and LSP
- Result: major reduction in expected leptonic SUSY signatures
- Increasing Higgsino content to match CDMS (and photon data) requires a light gluino
- Result: multijet signals may be our only handle

⇒ We will need to learn how to do more with less!
Must look for new signatures targeted to non-universalities in gaugino sector

Summary

- Dark matter hints strongly disfavor pure Bino LSP (i.e. mSUGRA)
- PAMELA needs wino predominance; CDMS/photons want strong Higgsino admixture
- Such models find a natural home in many (all?) semi-realistic string constructions
- Likely that mass gaps between $\widetilde{C}_1/\widetilde{N}_2$ and LSP small, so leptonic signatures a bust
- Will need to learn to do more with jet-based signatures and hope the gluino is lighter than in mSUGRA models

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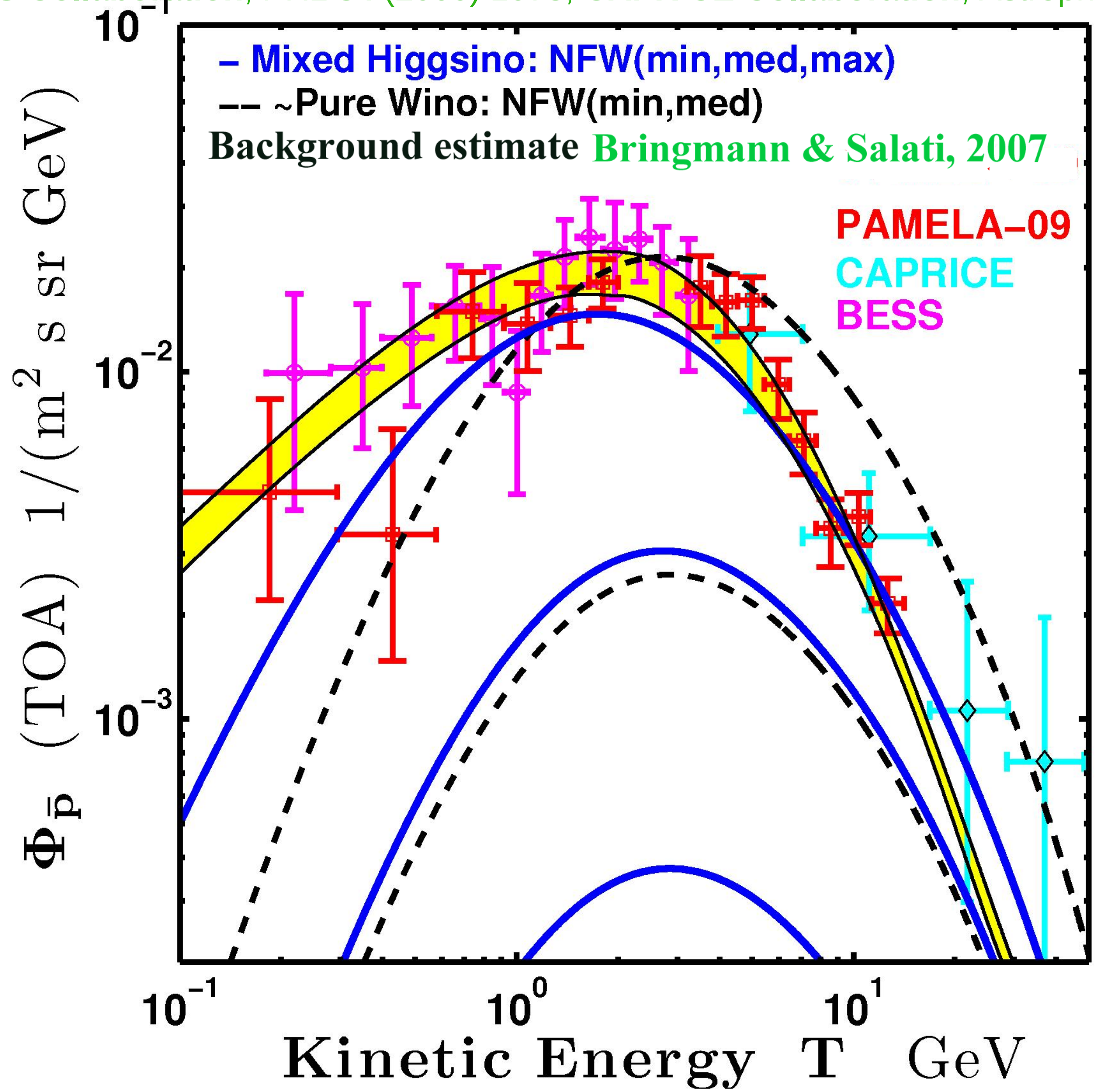
$\Rightarrow$ *Gaugino sector is truly a window on the high-energy world:*
we may be on the verge of revolutionary discoveries!

Back-Up Slides

What About Anti-protons?

BESS Collaboration, PRL **84** (2000) 1078; **CAPRICE Collaboration**, Astrophys. J. **561** (2001) 787



⇒ Greater tension for pure wino LSP; OK for NFW “min” and “med” halo profiles

Gamma Ray Signals

⇒ Halo profiles especially important in this situation

- Annihilation rates scale like the *square* of the density
- We observe the entire line-of-sight to the galactic center – therefore need to know the halo *profile* $\rho_\chi(r)$
- Many possible profiles suggested in literature; each can be summarized by one parameter $\overline{J}(\Delta\Omega)$

$$\overline{J}(\Delta\Omega) \equiv \frac{1}{\Delta\Omega}\int_{\Delta\Omega} d\Omega'\, J(\psi')\,; \quad J(\psi) = \frac{1}{8.5\,\mathrm{kpc}}\int_{\mathrm{l.\,o.\,s.}} ds(\psi)\left(\frac{\rho_\chi(r)}{0.3\ \mathrm{GeV}\,/\mathrm{cm}^3}\right)^2$$

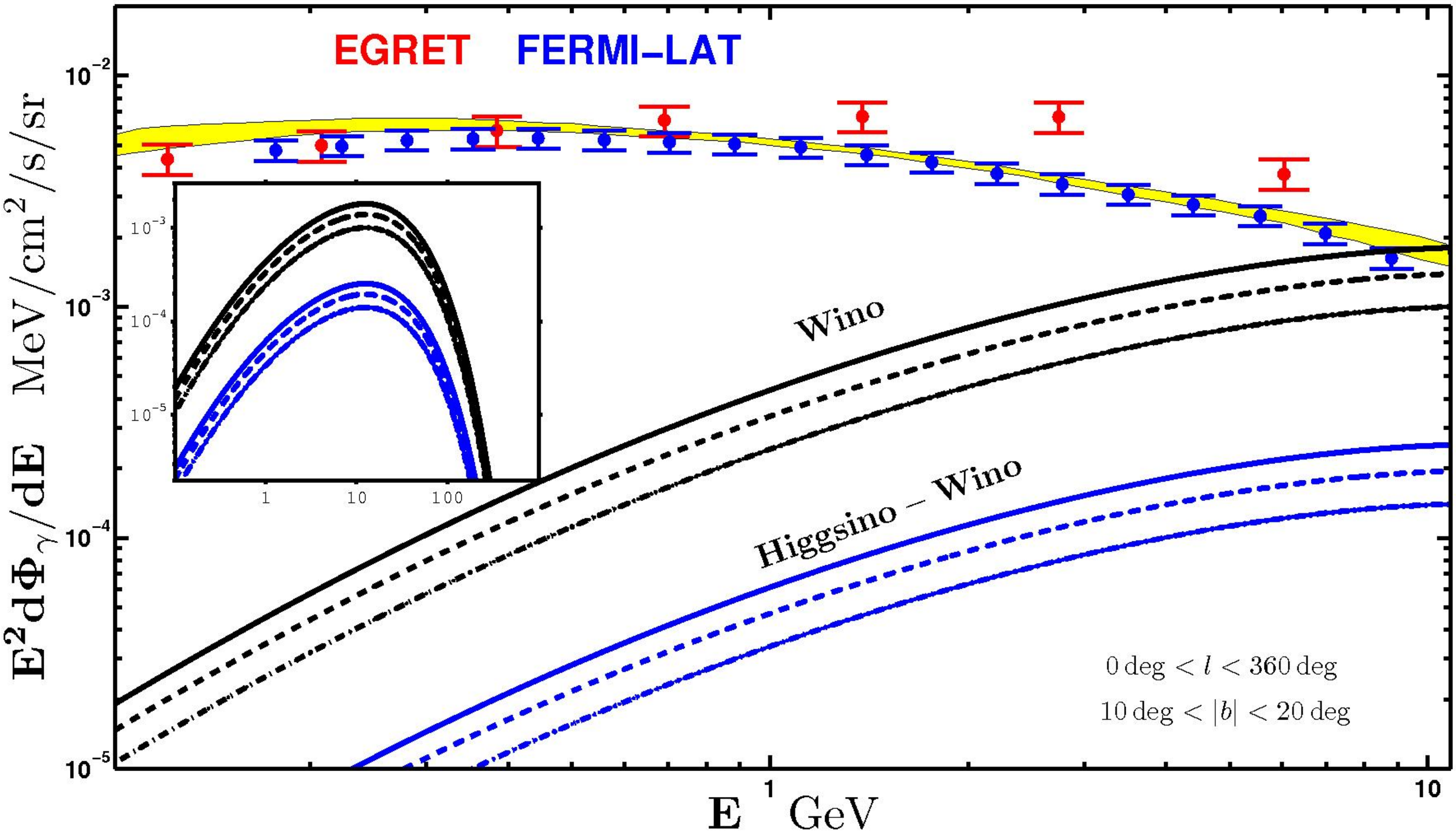
⇒ Two types of signal: continuous spectrum and mono-energetic lines

$$\frac{d\Phi_\gamma}{dE_\gamma} = 0.94\times 10^{-13}\sum_i \frac{dN_\gamma^i}{dE_\gamma}\left(\frac{\langle\sigma_i v\rangle}{10^{-29}\,\mathrm{cm}^3\,\mathrm{s}^{-1}}\right)\left(\frac{100\ \mathrm{GeV}}{m_\chi}\right)^2 \overline{J}(\Delta\Omega)\Delta\Omega$$

- Typical sensitivities require $\Phi_{\mathrm{min}} \sim 10^{-10}$ photons/cm^2/sec
- Plain vanilla NFW profile gives $\overline{J}(10^{-5}\,\mathrm{sr}) = 1.3\times 10^4$
- Much less for isothermal core-type profiles

Continuous Spectrum from Galactic Center

EGRET Collaboration, Astrophys. J. **481** (1997) 205
Fermi-LAT Collaboration, arXiv: 0907.0294



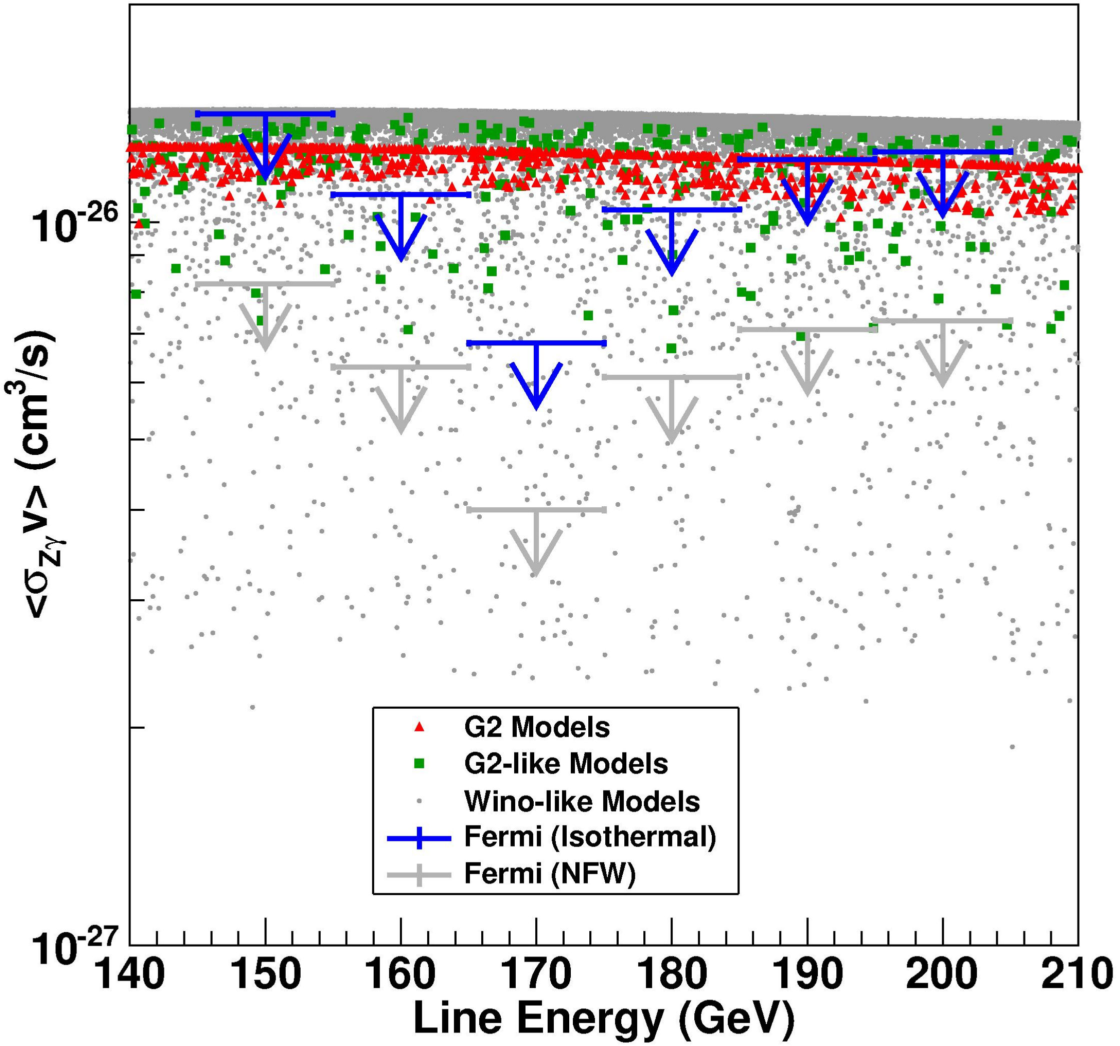
⇒ Not much constraint on any profile from galactic center

- Profiles here: Einasto, NFW, isothermal (top to bottom)

⇒ More substantial constraints on pure-wino case coming from dwarf galaxies?

Monochromatic Signals

$\Rightarrow$ Monochromatic gamma ray signals a “smoking gun” for dark matter



- Loop-induced diagrams provide annihilation into $\gamma\gamma$ and γZ final states
- Monoenergetic signals with $E_{\gamma\gamma} = m_\chi$ and $E_{\gamma Z} = m_\chi - M_Z^2/4m_\chi$
- Easy to pick out over background, but branching fractions reduce rate by factors of 10^3 - 10^4
- Pure-wino models capable of getting PAMELA correct in trouble!

Fermi-LAT Collaboration, arXiv: 1001.4531

What Can Cause Non-Universalities?

3. Loop Effects

- Gauge coupling automatic when single modulus controls all gauge couplings
- Example: heterotic string models with $f_a = S$ (gauge coupling relation...)
- Non-universalities now arise only at the loop level

$$\mathcal{L} \sim \int \mathrm{d}^2\theta f_a \left(W^\alpha W_\alpha\right)_a \rightarrow \int \mathrm{d}^2\theta \left(S + \frac{1}{16\pi^2} X_a \right) \left(W^\alpha W_\alpha\right)_a$$

- If $\langle F^X \rangle \sim 16\pi^2 \langle F^S \rangle$ non-universalities are $\mathcal{O}(1)$ in gaugino sector

Testing for the Mirage Pattern

$\Rightarrow$ Our goal is to ask how well we can determine α at the LHC using only **actual observations**

- Most importantly, can we demonstrate $\alpha \neq 0$?
- Want to do this independent of any particular model
- Not going to assume reconstruction any sparticle masses

$\Rightarrow$ Basic idea: use an ensemble of signatures wisely chosen to perform a fit of Monte Carlo to "data"

- We break the problem into a "base model" specified by the parameters

$$\left\{ \begin{array}{c} \tan\beta,\ m^2_{H_u},\ m^2_{H_d} \\ M_3,\ A_t,\ A_b,\ A_\tau \\ m_{Q_{1,2}},\, m_{U_{1,2}},\, m_{D_{1,2}},\, m_{L_{1,2}},\, m_{E_{1,2}} \\ m_{Q_3},\, m_{U_3},\, m_{D_3},\, m_{L_3},\, m_{E_3} \end{array} \right\}$$

and a value of α which determines the three gaugino masses (with overall scale set by M_3)

$\Rightarrow$ Choose a random "base model" and construct "alpha-line" based off this point

- Each line: $-0.5 \leq \alpha \leq 1.0$ for the parameter α in steps of $\Delta\alpha = 0.05$

Signature List C

- Here we allow as much as 30% correlation between any two signatures

	Description	Min Value	Max Value
	Counting Signatures		
1	N_ℓ [≥ 1 leptons, ≤ 4 jets]		
2	$N_{\ell^+\ell^-}$ [$M_{\text{inv}}^{\ell^+\ell^-} = M_Z \pm 5\ \text{GeV}$]		
3	N_B [≥ 2 B-jets]		
	[0 leptons, ≤ 4 jets]		
4	$M_{\text{eff}}^{\text{any}}$	1000 GeV	End
5	$M_{\text{inv}}^{\text{jets}}$	750 GeV	End
6	$\not{E}_T$	500 GeV	End
	[0 leptons, ≥ 5 jets]		
7	$M_{\text{eff}}^{\text{any}}$	1250 GeV	3500 GeV
8	r_{jet} [3 jets $>$ 200 GeV]	0.25	1.0
9	p_T(4th Hardest Jet)	125 GeV	End
10	$\not{E}_T / M_{\text{eff}}^{\text{any}}$	0.0	0.25
	[≥ 1 leptons, ≥ 5 jets]		
11	$\not{E}_T / M_{\text{eff}}^{\text{any}}$	0.0	0.25
12	p_T(Hardest Lepton)	150 GeV	End
13	p_T(4th Hardest Jet)	125 GeV	End
14	$\not{E}_T + M_{\text{eff}}^{\text{jets}}$	1250 GeV	End

Signature “List” C

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6	$\not\!\!E_T$	500 GeV	End
	[0 leptons, ≥ 5 jets]		
7	$M_{\mathrm{eff}}^{\mathrm{any}}$	1250 GeV	3500 GeV
8	r_{jet} [3 jets $>$ 200 GeV]	0.25	1.0
9	p_T(4th Hardest Jet)	125 GeV	End
10	$\not\!\!E_T/M_{\mathrm{eff}}^{\mathrm{any}}$	0.0	0.25
	[≥ 1 leptons, ≥ 5 jets]		
11	$\not\!\!E_T/M_{\mathrm{eff}}^{\mathrm{any}}$	0.0	0.25
12	p_T(Hardest Lepton)	150 GeV	End
13	p_T(4th Hardest Jet)	125 GeV	End
14	$\not\!\!E_T + M_{\mathrm{eff}}^{\mathrm{jets}}$	1250 GeV	End

Signature “List” C

- Some signatures designed to detect changes in the softness of decay produces in cascade decays
- Particularly effective is the ratio $r_{\mathrm{jet}} \equiv \frac{p_T^{\mathrm{jet3}}+p_T^{\mathrm{jet4}}}{p_T^{\mathrm{jet1}}+p_T^{\mathrm{jet2}}}$