Dark Matter as a Guide to a Gluino Factory at the LHC

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May 27th 2010, Brookhaven Forum

Annihilating Dark Matter in the Halo

Several particle physics models that can simultaneously explain BOTH WMAP $\Omega h^2_{CDM} \sim 0.10$ and PAMELA data
without huge adhoc boost factors put in by hand .

1. **Breit-Wigner Enhancement (BWE)** of dark matter annihilations in the halo Feldman, Liu, Nath, arXiv:0810.5762, Ibe, Murayama, Yanagida, arXiv:0812.0072
2. **Thermal wino like LSP** with a weakly interacting co-annihilating hidden sector HS Feldman,Liu, Nath, Nelson, arXiv:0907.5392
3. **Non-thermal wino LSP** with the relic abundance explained via moduli decay Randall and Moroi, Hisano et al, Kane, Acharya, Watson et al

Common Feature is mass sensitivity:

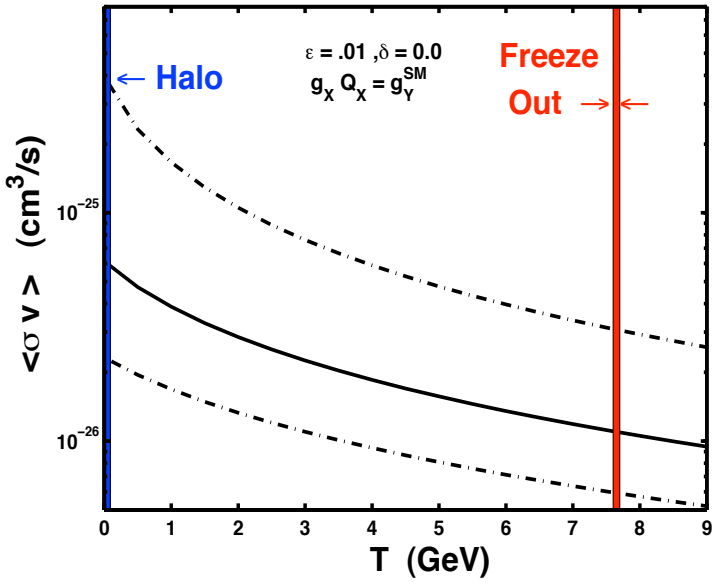
1. BWE sensitive to mass $M_{Z'} \sim 2m_{Dirac}$
2. Thermal wino-like $m_{LSP=\widetilde{\chi}^0} \sim m_{\xi_a}$
3. Non-thermal wino $m_{\widetilde{\chi}^0} \sim m_{\widetilde{\chi}^{\pm}_1}$

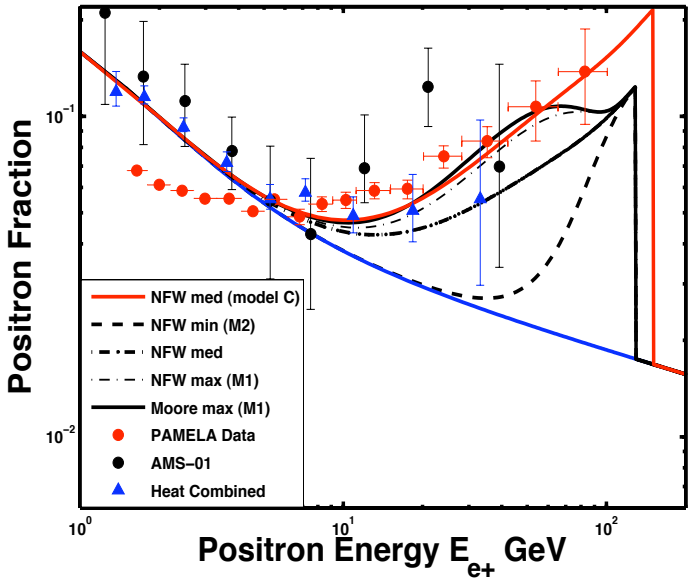
SUSY Models generally lead to a light gluino at the LHC

Boost in the $\langle \sigma v \rangle$ from the Hidden Sector Pole

Breit-Wigner Enhancement Mechanism:

Oct. 2008 Feldman, Liu, Nath, arXiv:0810.5762 Phys. Rev. D 79, 063509 (2009).

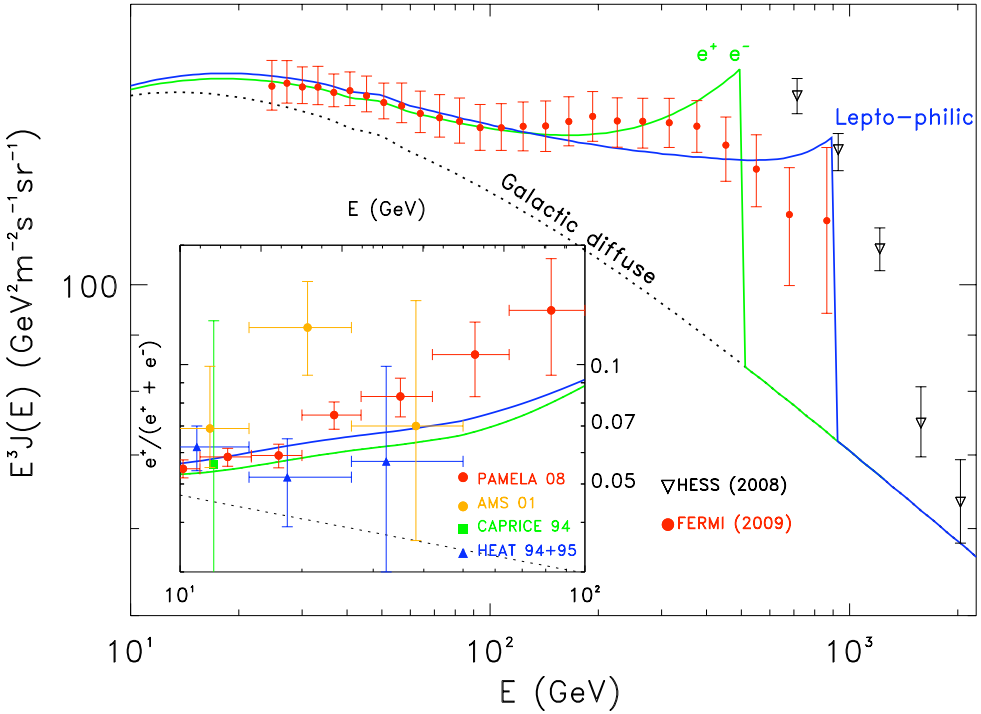




- $\langle \sigma v \rangle_{\rm Halo} \neq \langle \sigma v \rangle_{\rm freeze}, \; and \; specifically \; in \; region \; of \; pole$
- Large boost generated in the halo relative to freezeout. One must peform the integral over the pole in the relic density calculation.
- $\xi^{Z'}_{L,R} = C^{Z'}_{\psi} C^{Z'}_{f_{L,R}} [s - M^2_{Z'} + i\Gamma_{Z'} M_{Z'}]^{-1}, (Dirac \, \mathrm{DM} \; narrow \; Z')$

Breit-Wigner Enhancement - where WMAP constraints are satisfied (FLN hep-ph/0702123 PRD).

Hidden sector, kinetic and mass mixings and a new massive boson, hep-ph/0610133 PRD, hep-ph/0701107 JHEP , hep-ph/0702123 PRD (New Jargon : "Dark Force, Dark Photon, Vector Portal, etc...")



By FERMI-LAT Collaboration 2009 - with S. Profumo ; Astropart.Phys.32:140-151,2009.

- Breit-Wigner can address the relic density
- Stueckelberg and Kinetic Mixings models are lepto-loving

  (see arXiv:0810.5762 , arXiv:1004.0649)
- See O. Adriani et al. Jan 2010, e-Print: arXiv:1001.3522 for an update.

Supersymmetric Hidden Sector

- Can Thermal winos or wino-like DM explain PAMELA and WMAP? Is not $\langle \sigma v \rangle$ too large $\Omega h^2 \propto 1/\int \langle \sigma v \rangle$ too small?
- Degenerate Neutralino-Like Matter with suppressed interactions **Enhance the relic density** for the LSP by as much an order of magnitude or more by adding extra dof to the relic density.
- $n\ U(1)_X$ gauge symmetries in the hidden sector ($Q_{SM}|\mathrm{Hidden}\rangle = Q_X|\mathrm{SM}\rangle = 0$) with new mass terms for the vector superfields.
- $n\ U(1)_X$ weakly mixed (Nath, Feldman, Liu, Nelson, July 2009)
  $n\ U(1)_X$ weakly mixed (Dimopoulos, March-Russell et al. Sept. 2009).

- $U(1)_X^n$ Hidden sector: Stueckelberg Mass Growth

$$\Delta\mathcal{L} = \int d^2\theta d^2\bar{\theta} \sum_{m=1}^{N_S} \left(\sum_{l=1}^{N_V} M_{l,m} V_l + (S_m + \bar{S}_m) \right)^2$$

where $V = \{B, X, X', X'' \ldots\}$ are vector supermultiplets which include the hypercharge gauge multiplet B, and S_m are a collection of [Stueckelberg] chiral supermultiplets $(F_S, \chi_S, \rho + i\sigma)_m$ and $(N_S, N_V > N_S)$ are the number of (axions σ, vectors).

- $n\ U(1)_X$ gives $2n+4$ Majorana states when coupled to MSSM: $(\chi_1^0, (\xi_1^0, \xi_2^0 \ldots \xi_{2n}^0), \chi_2^0, \chi_3^0, \chi_4^0)$ **Feldman, Liu, Nelson, Nath , arXiv:0907.5392, PRD 09**

- $2n+4$ dimensional "neutralino" mass matrix, new states $(\xi_1^0, \xi_2^0 \ldots \xi_{2n}^0)$ clustered in mass (nearly degenerate) and weakly coupled.

- Can also occur via kinetic and mass mixing combination

  Feldman, Körs, Nath 2006, hep-ph/0610133, PRD

- **Multicomponent Dark Matter** arises by

(single $U(1)_X$ in this illustration)

$$\mathcal{W}_{\rm dirac} = M_\psi \Phi^C_{\rm hid} \Phi_{\rm hid}$$

$$\mathcal{L}_{\rm mat} = \int d^2\theta d^2\bar\theta \sum_{i={\rm vis,hid}} \bar\Phi_i e^{2g_Y Q_Y Y + 2g_X Q_X X} \Phi_i$$

$$\text{which couples after diag.}: \ \phi\ \bar\psi\ \chi^0_a + \text{h.c.}$$

2 dark matter components for $m_{\phi,\phi'} > M_\psi + M_{\chi^0_1}$:

- **Dirac**, ψ is stable component of dark matter
- χ^0_1 is stable R-odd **Majorana** dark matter

Up to 4 dark matter components of dark matter:

- **scalars** in $\Phi_{\rm hid}, \Phi^C_{\rm hid}$ carry opposite X charge and can also be stable components of dark matter.

- When coupled to MSSM, Chargino NLSP is typical, with a light gluino that will generally produce rich b-jet signals at the LHC. REWSB most natural on HB/FP where these models tend to sit

- Dirac: Breit-Wigner Enhancement WMAP/PAMELA/FERMI
  Majorana: WMAP/CDMS/XENON can be probed
  $\Omega h^2 \in$ WMAP 2 σ **See: arXiv:1004.0649, to appear in PRD (Feldman, Liu, Nath, Peim)**

Enhancement of Relic Density B_{Co} : $n\ U(1)_X$ gives $2n+4$ Majorana states when coupled to MSSM : $(\chi_1^0, (\xi_1^0, \xi_2^0 \ldots \xi_{2n}^0), \chi_2^0, \chi_3^0, \chi_4^0)$

$$B_{\rm Co} = \frac{\Omega h^2{}_{\rm MSSM\otimes Hidden}}{\Omega h^2{}_{\rm MSSM}} = \frac{\sum_{a,b}\int_{x_f}^{\infty}\langle\sigma_{ab}v\rangle\gamma_a\gamma_b\frac{dx}{x^2}}{\sum_{A,B}\int_{x_f}^{\infty}\langle\sigma_{AB}v\rangle\Gamma_A\Gamma_B\frac{dx}{x^2}},$$

$$\gamma_a = \frac{g_a(1+\Delta_a)^{3/2}e^{-\Delta_a x}}{\sum_b g_b(1+\Delta_b)^{3/2}e^{-\Delta_b x}}, \quad \text{(MSSM)}$$

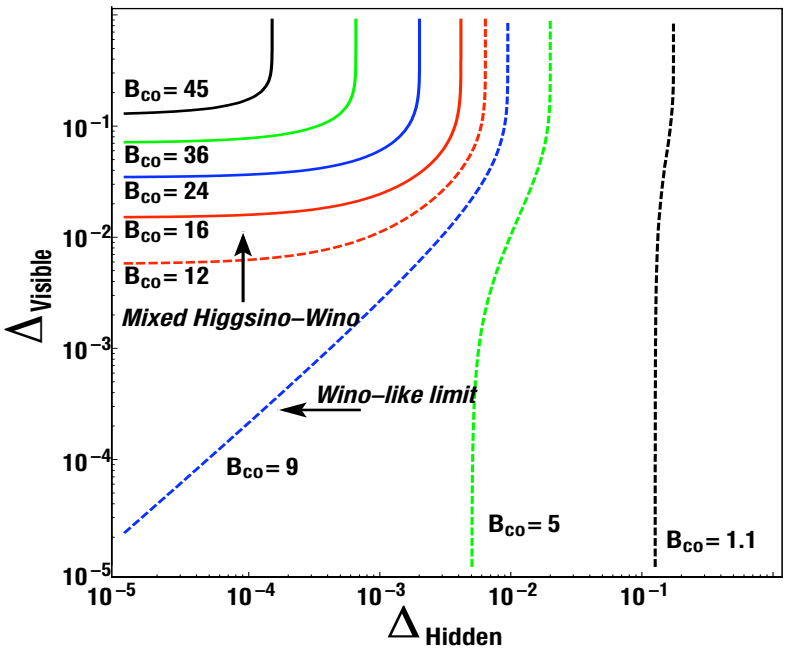
$$\Gamma_A = \frac{g_A(1+\Delta_A)^{3/2}e^{-\Delta_A x}}{\sum_A g_A(1+\Delta_A)^{3/2}e^{-\Delta_A x}} \quad (\text{MSSM}\otimes\text{Hidden}).$$

- Here A runs over channels which coannihilate both in the MSSM sector and in the hidden sector (*i.e.*, A =1,..,$n_v + n_h$)
- If Hidden Sector interactions are suppressed, then one gets an **enhancement in the relic density** relative to the MSSM.
- **Degenerate Hidden Sector States act as Spectators!**
- In the Degenerate limit one has for n U(1)s

$$B_{\rm Co} \simeq (1+\frac{d_h}{d_v})^2 \qquad B_{\rm Co}^{\rm MAX} = (1+2n)^2$$

- Here $d_s = \sum_s g_s$, for $s = (v,h)$. arXiv:0907.5392, PRD

Thermal LSP and PAMELA



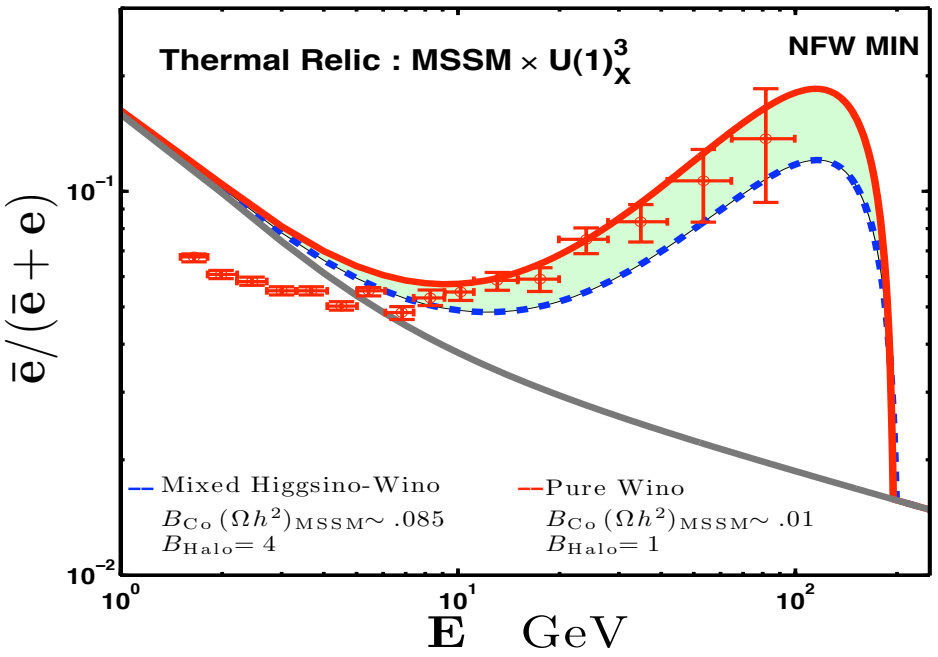
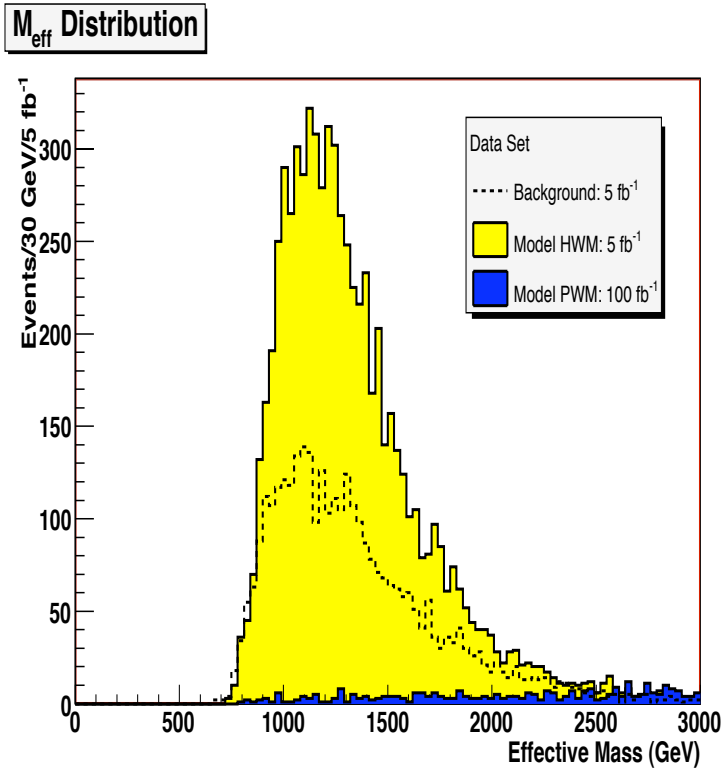


Figure: Left: An illustration of the $B_{\rm Co}$-mechanism with a contour plot of constant $B_{\rm Co}$ in the $\Delta_{\rm Visible}$ vs $\Delta_{\rm Hidden}$ plane for the $U(1)^3$ extended SUGRA model. Right: Fit to PAMELA data; Pure wino co-annihilates significantly more with the chargino i.e. the visible sector (hence reducing its Ωh^2) , while the mixed Higgsino-Wino can be split from the chargino enough to produce Ωh^2 on the edge of WMAP: $\tilde{\chi}^0 = 0.726\lambda_B - 0.616\lambda_W + 0.260\tilde{h}_1 - 0.160\tilde{h}_2 + C_h\Delta\tilde{\chi}^0_h$. $C_h\Delta\tilde{\chi}^0_h$ is the component in the hidden sector and is found to be rather small ($|C_h| < 1\%$ for $n = 3$)

Note: For mixed Higgsino-Wino model $m_{\tilde{g}} \sim 710$ GeV

Note: $\sigma(\rm SI) \sim 6 \times 10^{-44}{\rm cm}^2$, $m_{\tilde{\chi}^0} \sim 200$ GeV with $\Omega h^2 \sim 0.09$.

arXiv:0907.5392, PRD 09



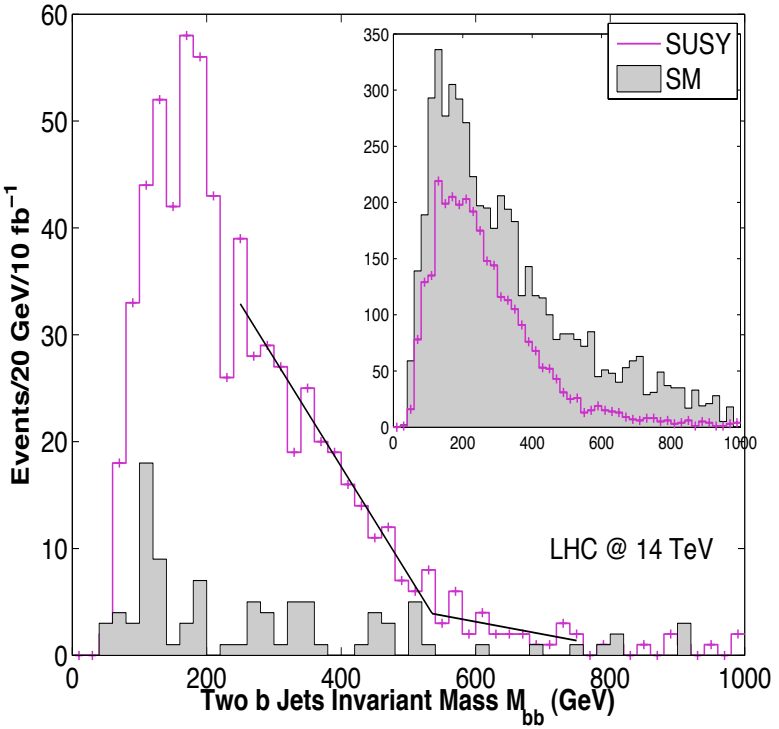


Figure: Left:Higgsino-wino mixed model(HWM) for 5 fb^{-1} (yellow) along with SM (dashed) after 250 GeV MET cut, with 4 hardest jets having $P_T \geq (200, 150, 50, 50)$ GeV. Right: Multi bjets from gluino decay. Increase D.L. with lepton veto and 400 GeV MET cut, and at least 2 jets with $P_T \geq 60$ GeV besides the tagged b-jets.

arXiv:0907.5392, PRD 09

EARLY LHC $\Longleftrightarrow$ PAMELA

HWM has $m_{\tilde{g}} \sim 710$ GeV and $m_{\tilde{\chi}^0} \sim 200$ GeV $\sim m_{\tilde{\xi}_a}$ with $m_{\tilde{\chi}_1^\pm} \sim 210$ GeV.

Compressed spectrum 2nd,3rd Gen squarks $> m_{\tilde{g}} <$ TeV

$m_{\tilde{g}} \geq (M_{bb}^{\rm inv})^{\rm kink} + m_{\tilde{\chi}^0}$

PAMELA positrons and Non-Thermal Wino Dark Matter with Heavy Scalars and a light gluino

- Moduli fields (scalars in the HS) generic to Supergravity (SUGRA) in Unified models with softly broken SUSY **[Nath, Arnowitt, Chamseddine, 1982 (SUGRA)]**

Wino LSP

- Focus here on Decoupled Scalars $(10-100)\mathrm{TeV}$ with Tree+Anomaly Gaugino mass contributions in string motivated SUGRA models:

  Kane, Nelson, Lykken, Mrenna, Wang, 2003 (Heterotic String Models)

  Kane, Acharya, Bobkov, Shao, Kumar, Watson, 2007, 2008 (G_2 models)

  See arxiv 1002.2430 for list of other models

Moduli Decay Non-Thermal Wino:

- Relic density can be explained via moduli decay which re-populates the LSPs well after freezeout temperatures. **(Randall, Moroi)**
- Need a $T_R \sim O(10-100)\ \mathrm{MeV}$ for heavy moduli **(see i.e Gondolo, Gelmini)**
- Calculable from Boltzmann eq: **(Feldman, Kane, Nelson, Lu Ran, 1002.2430, PLB 2010)**

$$\Omega_{\tilde{W}} h^2 \simeq 0.32 \frac{1}{\alpha\sqrt{c_M}} \left(\frac{3\times 10^{-7}\mathrm{GeV}^{-2}}{\langle\sigma v\rangle}\right)\left(\frac{m_{\tilde{W}}}{200\mathrm{GeV}}\right)\left(\frac{m_{3/2}}{100\mathrm{TeV}}\right)^{-3/2}$$

where the moduli decay is $\Gamma_M = c_M M^3/\Lambda^2$, α parameterizes deviations from the reduced planck mass $\Lambda = \overline{M}_{\mathrm{pl}}/\alpha$ and c_M is the moduli decay coupling.

$m_{\rm wino} \in (170 - 190)$ GeV
$m_{\rm gluino} \in (550 - 750)$ GeV
$m_{\rm gravitino} \in (20 - 40)$ TeV

$\mathcal{B}r(\tilde{g} \to X)$	G_2^1	G_2^2	G_2^3	G_2^4	G_2^5
$\tilde{g} \to b\overline{b}\widetilde{W}$	14.2	6.7	11.3	12.6	19.5
$\tilde{g} \to q\overline{q}\widetilde{W}$	21.0	7.6	14.6	16.6	10.0
$\tilde{g} \to t\overline{t}\tilde{N}_2$	-	45.2	14.5	4.5	14.6
$\tilde{g} \to t\overline{b}\tilde{C}^- + h.c.$	18.9	16.9	20.9	25.2	24.6
$\tilde{g} \to q_u\overline{q}_d\tilde{C}^- + h.c$	41.5	15.4	29.0	33.8	24.9

G_2^m	$\sigma(\tilde{g}\tilde{g})$ (fb)	$\sigma(\widetilde{W}\widetilde{C}_1)$ (fb)	$\sigma(\widetilde{C}_1^{\pm}\widetilde{C}_1^{\mp})$ (fb)	$\sigma_{\rm SUSY}$ (fb)	$\sigma_{\rm eff}$ (fb)	$N(4j)$	$\frac{N}{\sqrt{B}}\|_{4j}$
G_2^1	1613	996	301	2910	1645	416	13.3
G_2^2	210	874	270	1350	308	67	2.1
G_2^3	648	877	246	1773	736	217	7.0
G_2^4	459	742	232	1432	537	154	5.0
G_2^5	182	696	208	1087	250	64	2.0

Table: Shown is $\sigma_{\rm SUSY}({\rm fb})$, the theoretical cross section before passing through the detector simulation, $\sigma_{\rm eff}({\rm fb})$, the effective cross section after events have passed the L1 triggers with $\mathcal{L} = 1\ {\rm fb}^{-1}$ at $\sqrt{s} = 10$ TeV. Observable counts in the number of multijets are also shown $N(4j)$ along with signal to square root background ratios. The missing energy cut is ≥ 200 GeV and we have imposed a transverse sphericity cut of $S_T \geq 0.25$.

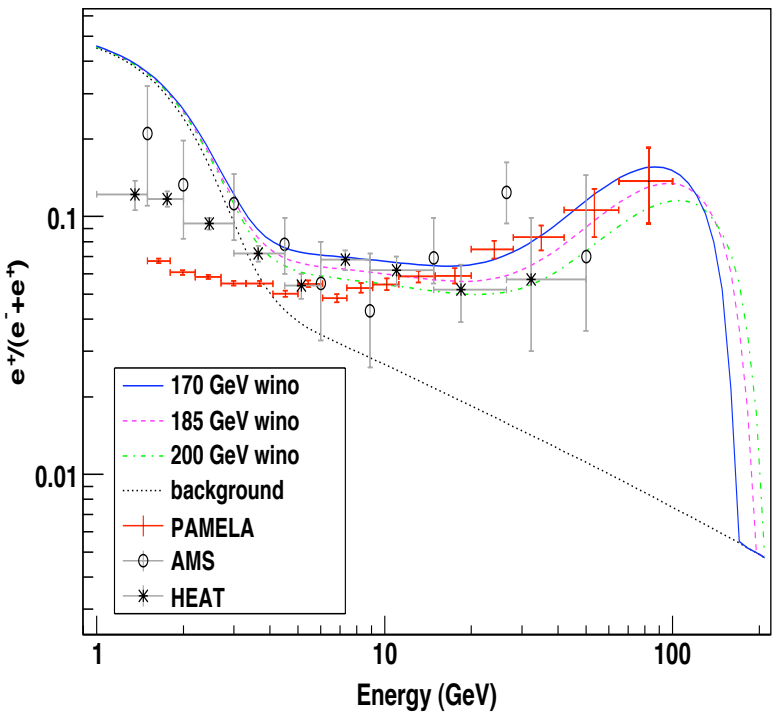
Kane,Lu Ran, Feldman, Nelson 1002.2430, PLB 2010

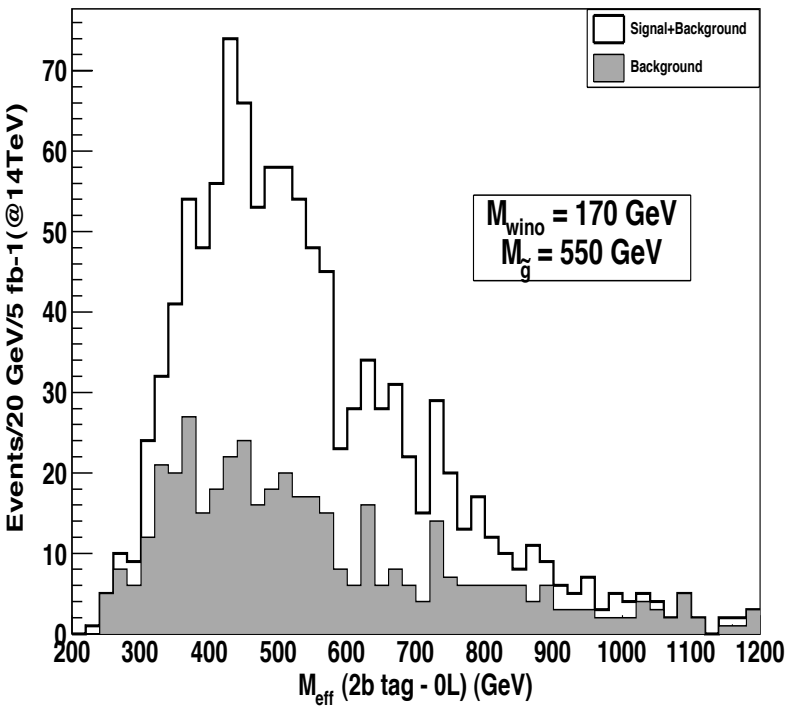
(here LSP is a wino, $\widetilde{N}_1 = \widetilde{W}$,
and notation change from previous slides $\widetilde{N}_i = \chi_i^0, \widetilde{C}_j^{\pm} = \chi_j^{\pm}$)

light gluino and light EW gauginos, decoupled scalars, 3 body decays of gluino, large jet signatures and models fit PAMELA

Kane, Lu Ran, Feldman, Nelson 1002.2430, PLB 2010

LHC (PGS) $\Longleftrightarrow$ PAMELA (Galprop)

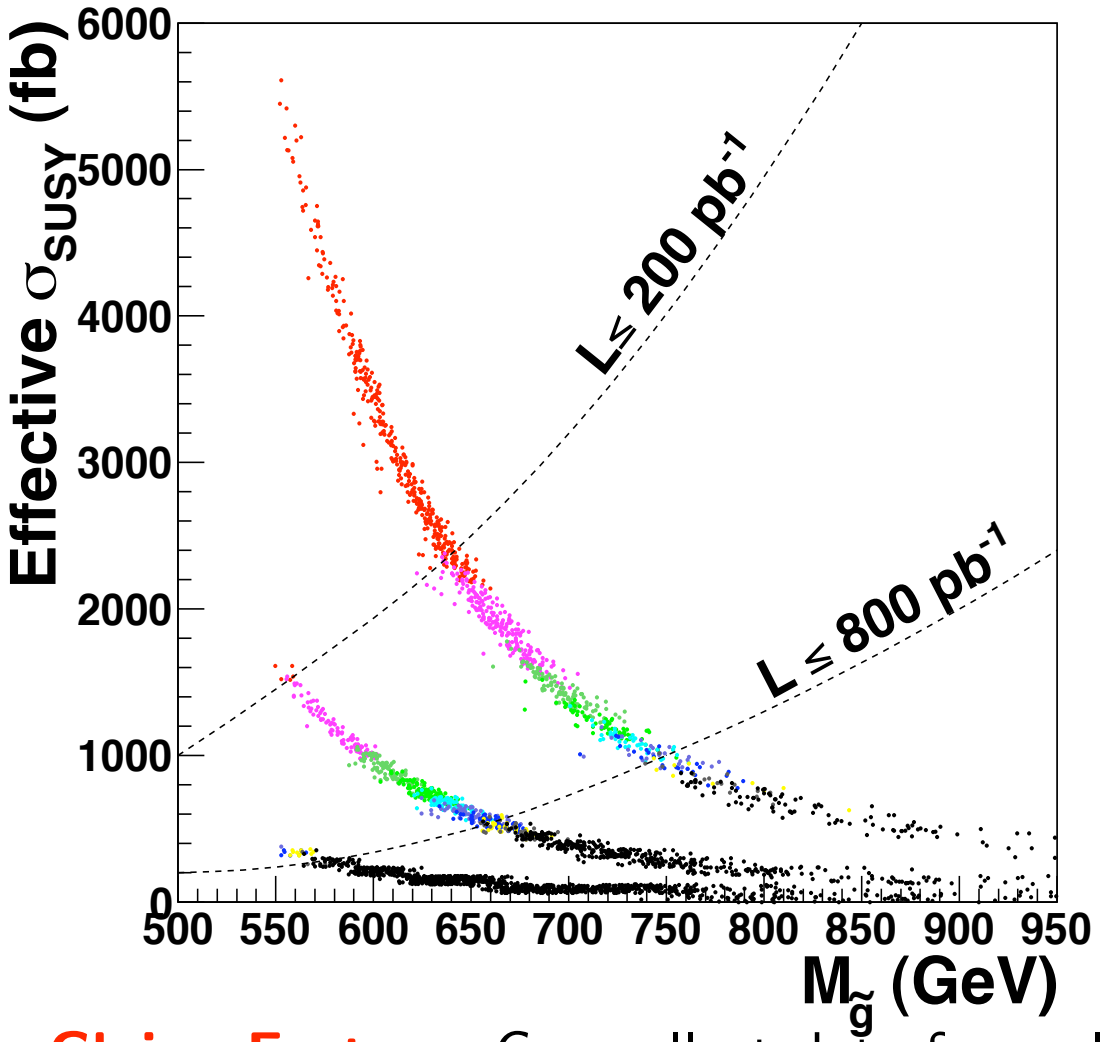




- Models are dominantly wino-like with lighter gluinos
- Dominant production $pp \to [(\tilde{g}\tilde{g}), (\widetilde{W}\widetilde{C}_1), (\widetilde{C}_1^{\pm}, \widetilde{C}_1^{\mp})]$.
- $\tilde{g}$ Decays: $\tilde{g} \to [(\widetilde{N}_2 t\bar{t}), (\widetilde{W} b\bar{b}), (\widetilde{W} q\bar{q}), (\widetilde{C}_1^- \bar{b}t + \text{ h.c.}), (\widetilde{C}_1^- \bar{d}u + \text{ h.c.})]$
- Secondary decays $\widetilde{N}_2 \to \widetilde{C}_1 W^* \to (\widetilde{C}_1 l\nu_l), (\widetilde{C}_1 q\bar{q})$ and $\widetilde{C}_1 \to \widetilde{W} W^* \to (\widetilde{W} l\nu_l), (\widetilde{W} q\bar{q})$
- Tertiary SM $t \to Wb$ and $W \to [(q_u \bar{q}_d), (l\nu_l)]$.
- Typically requires no more than 2-3 branchings
  $=$ predictive $+$ large jet signatures from the light gluino.

Remark: $\bar{p}$ is fine. See additional slides

LHC as a Gluino Factory : Low Lums $7, 10, 14$ TeV - EARLY LHC



- **LHC as a Gluino Factory**. Can collect data from gluino decays to look for EW SUSY production. Kane, Lu Ran, Feldman, Nelson 1002.2430, PLB 2010

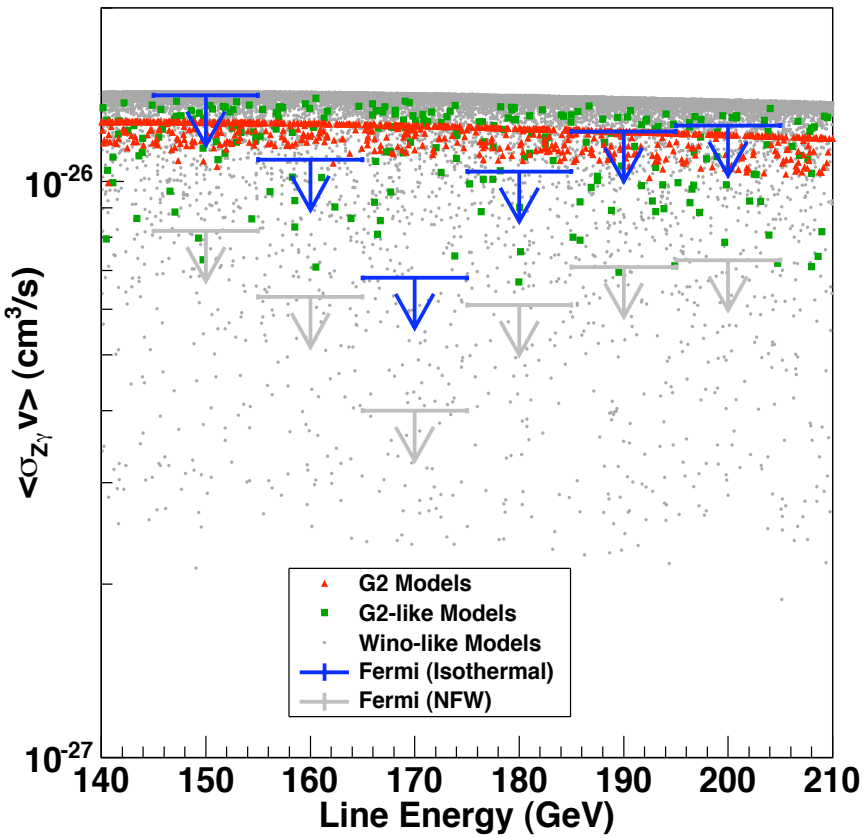
Recent related work : Gian Giudice, Tao Han, Kai Wang, Lian-Tao Wang, arXiv:1004.4902

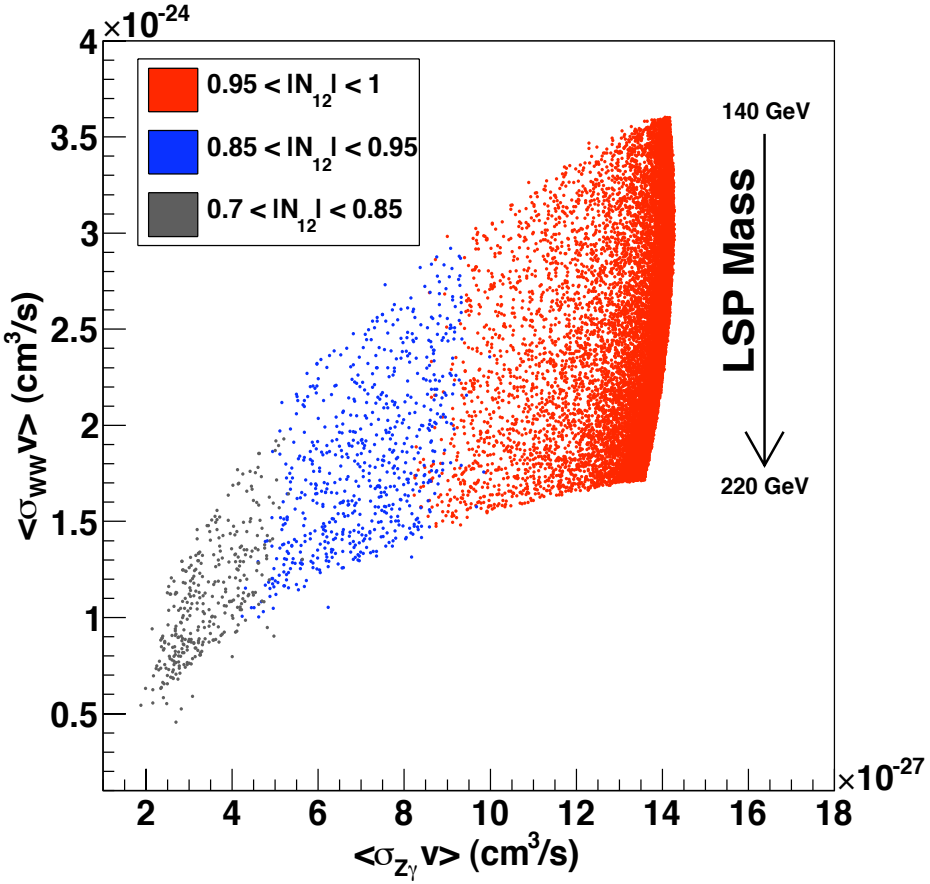
Gluino as dominate mode also in : FLN arXiv:0905.1148, PRD 09

Kane,Lu Ran, Feldman, Nelson 1002.2430, PLB 2010

Data from: Fermi LAT Search for Photon Lines from 30 to 200 GeV and Dark Matter Implications.

Phys.Rev.Lett.104:091302,2010.

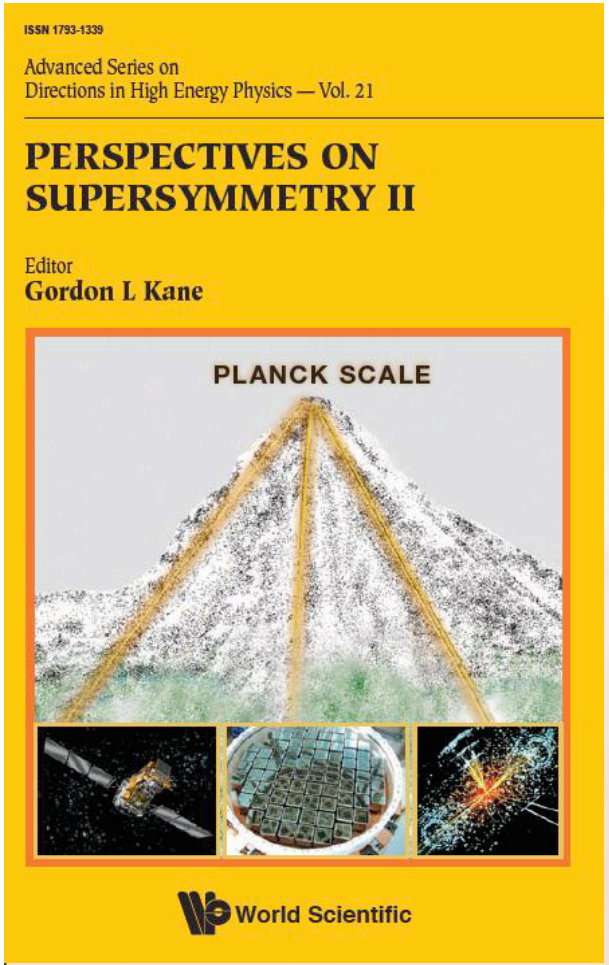




- Wino-LSP being probed. Admixture of Higgsino can support large $< \sigma v >_{WW}$ and has smaller $< \sigma v >_{\gamma Z}$. The constraint on $< \sigma v >_{\gamma Z}$ is the strongest constraint on SUSY models from astrophysics to date.

More details in here:

Perspectives on Supersymmetry II



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arXiv:1001.2693v1 [hep-ph] 14 Jan 2010

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Brent Nelson[a]

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Bhaskar Dutta[c] (Dark Matter)
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- Several components of dark matter and Breit-Wigner
- Multiple U(1)s $\rightarrow$ Hidden Sector Co-ann
- Non-thermal possibility for Relic Density from heavy scalar decay, may be generic in string theory

Motivated models that can match observation of Dark Matter signals. Look out for multijets from gluino decays in early LHC data.

Some Extra Slides

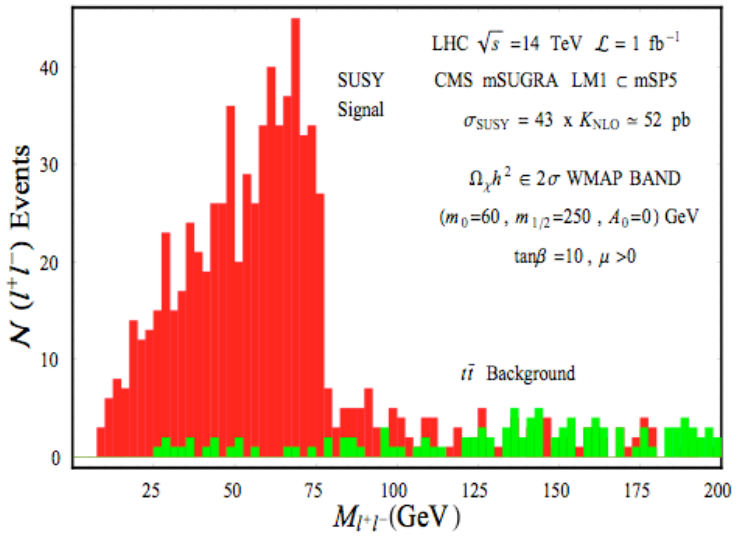
Here are some slides that did not make the 20 minute cut...

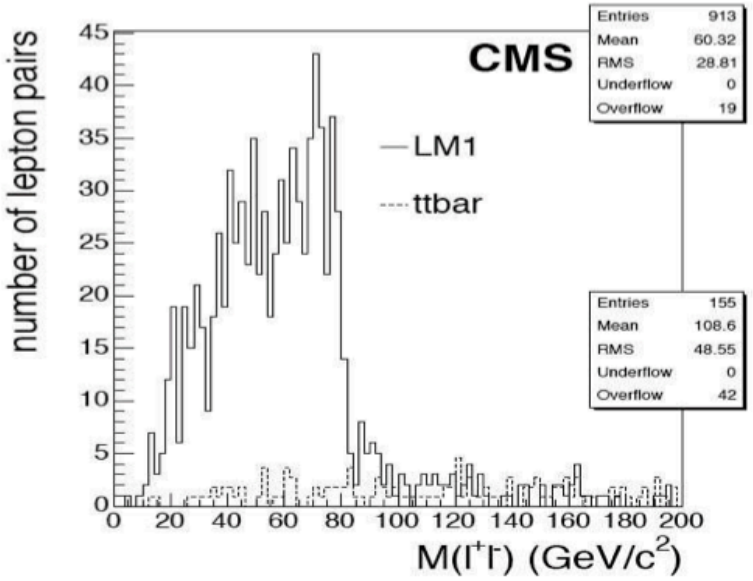
Theorist's LHC Simulation Procedure

- micrOMEGAs[1] + SuSpect (+SUSYHIT)[2] [**REWSB, RD, FC, Mass Limits+Decays**]
- SUSY Les Houches Accord (SLHA) [3] [**Spectrum & Mixings**]
- PYTHIA 6.4.11 + PGS4 [MSEL=39] [4,5] [**SUSY Production**]
- Compare PYTHIA and PROSPINO[6] at LO
- b tagging [7] ϵ_b par is based on CDF Run 2 tight/loose SECVTX tagger
- TAUOLA [8] for τ decays with a DØ tested interface
- Level 1 (L1) triggers (CMS) and CMS Detector Parameters
- SM (QCD,$b\bar{b}$, $t\bar{t}$, DY, Z/W, $Z/W+$ jets, ZZ, WZ, WW)
- SMART (= SUSY Matrix Routine) [**find mSPs, NUSPs etc..., Post Trigger Level Cuts, Count, Histogram, Analyze**]
- $\mathrm{N_{SUSY}} > \mathrm{Max}\left\{5\sqrt{N_{\mathrm{SM}}}, 10\right\}$ [Discovery Limit]

1 **G. Belanger, F. Boudjema, A. Pukhov, A. Semenov**
2 **A.Djouadi, J.L. Kneur, G. Moultaka + M.M. Muhlleitner , M. Spira**
3 **B. Allanach et al. (SLHA Collaboration)**
4 **T. Sjostrand, S. Mrenna , P. Skands**
5 **J. Conway et. al**
6 **J. A. Nielsen**
7 **W. Beenakker, R. Hopker, T. Plehn, M. Spira**
8 **S. Jadach, J. Kuhn, Z.Was**

How Good is our Simulations?
Pretty, Pretty, Pretty Good (PGS4)





OUR SIMULATION WITH PGS

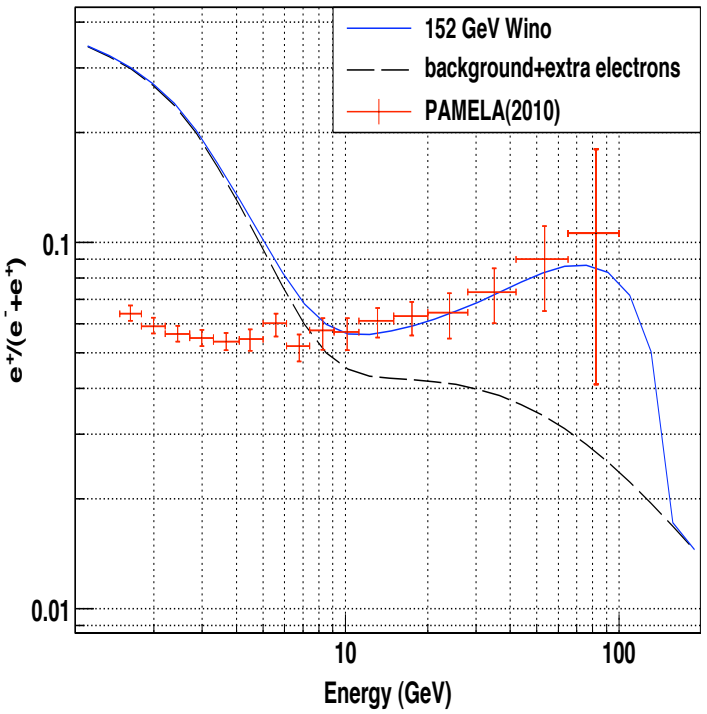
CMS EXPERIMENTAL GROUP LHC SIMULATION

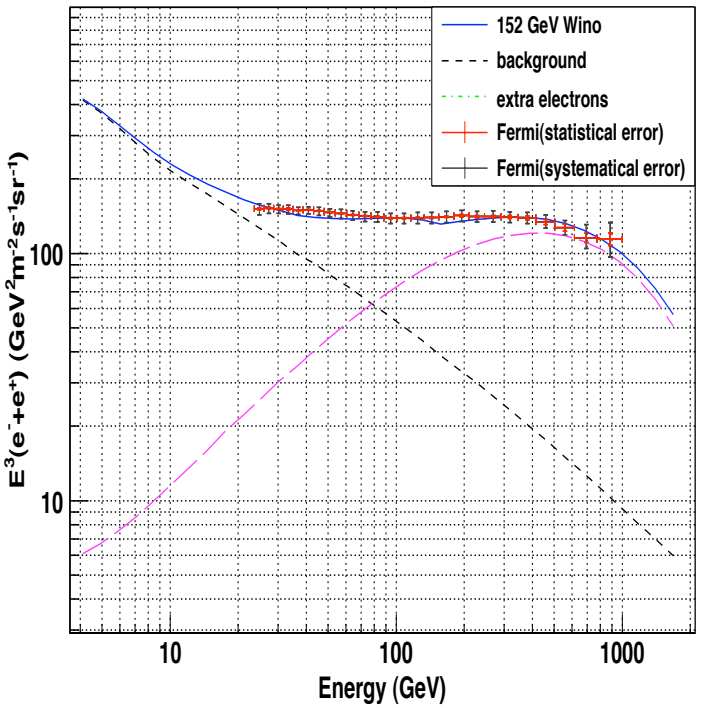
M. Chiorboli, M. Galanti, A. Tricomi, CMS NOTE 2006/133

Signal and backgrounds also checked with: D. J. Mangeol, U. Goerlach, CMS NOTE 2006/096

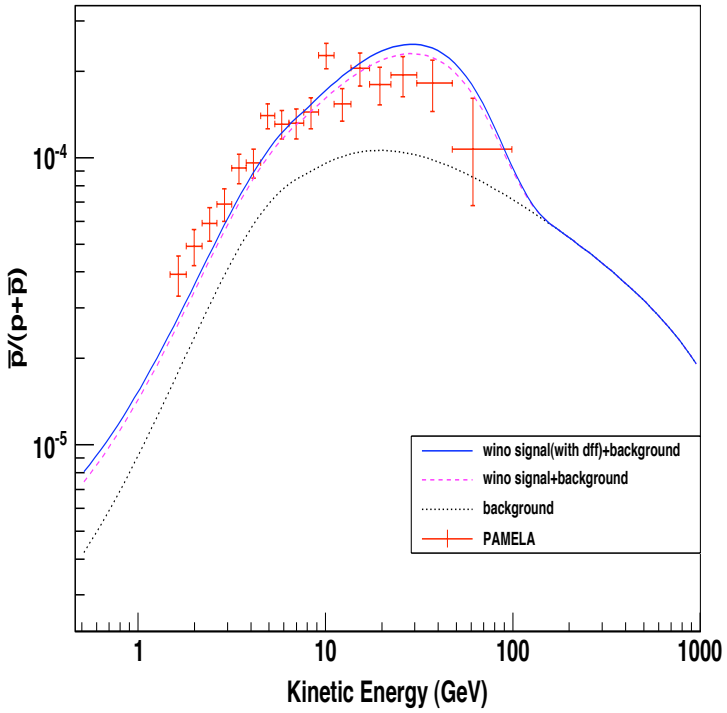
Di-lepton distribution LM9 has been reproduced : W. de Boer, et. al, CMS NOTE 2006/113

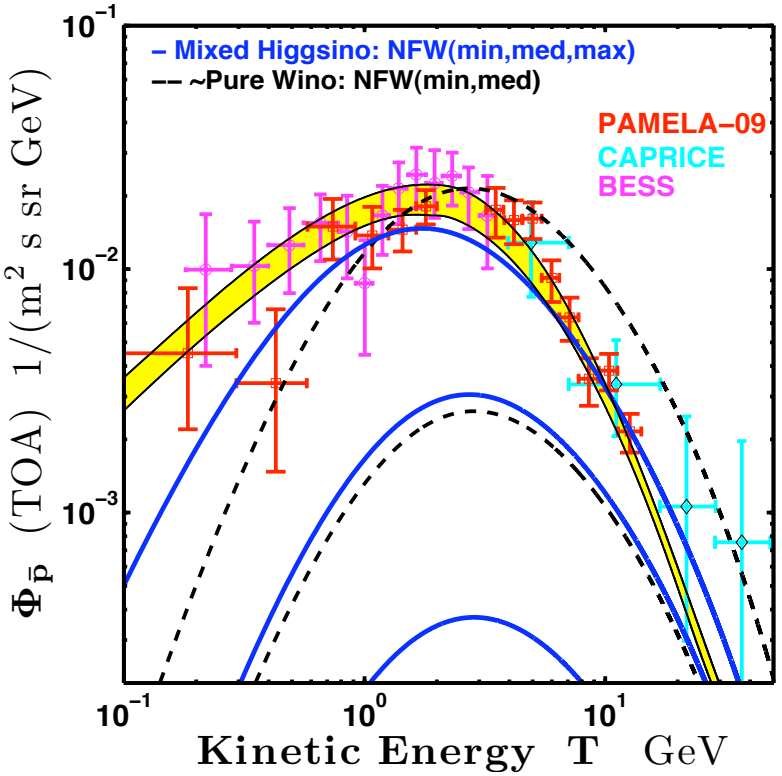
- LM1 is mSUGRA $\in mSP5$
- But it is one of many mass patterns (albeit a good standard candle) (see FLN Phys.Rev.Lett.99:251802,2007, e-Print: arXiv:0707.1873)





- Left: Pure Wino 152 GeV, GALPROP best fit to all data B/C etc
  Right: Fermi can be fit with an additional electron injection
- See Lu Ran's, talk at Madison Pheno.





- $\bar{p}/(p+\bar{p})$ flux ratio from Phys.Lett.B681:151-160,2009 (GALPROP with dN/dE from PYTHIA/DarkSUSY)
  Message: background in previous works used old data.
- $\bar{p}$ flux from Phys.Rev.D80:075001,2009 (dN/dE from HERWIG matches PYTHIA/DarkSUSY, Semi-analytical fits for Halo and Diffusion Models)
  Message: Analysis is also very sensitive to the assumed halo/diff model. Small admixture of Higgsino gives large effect on reducing $\bar{p}$ (and γ)