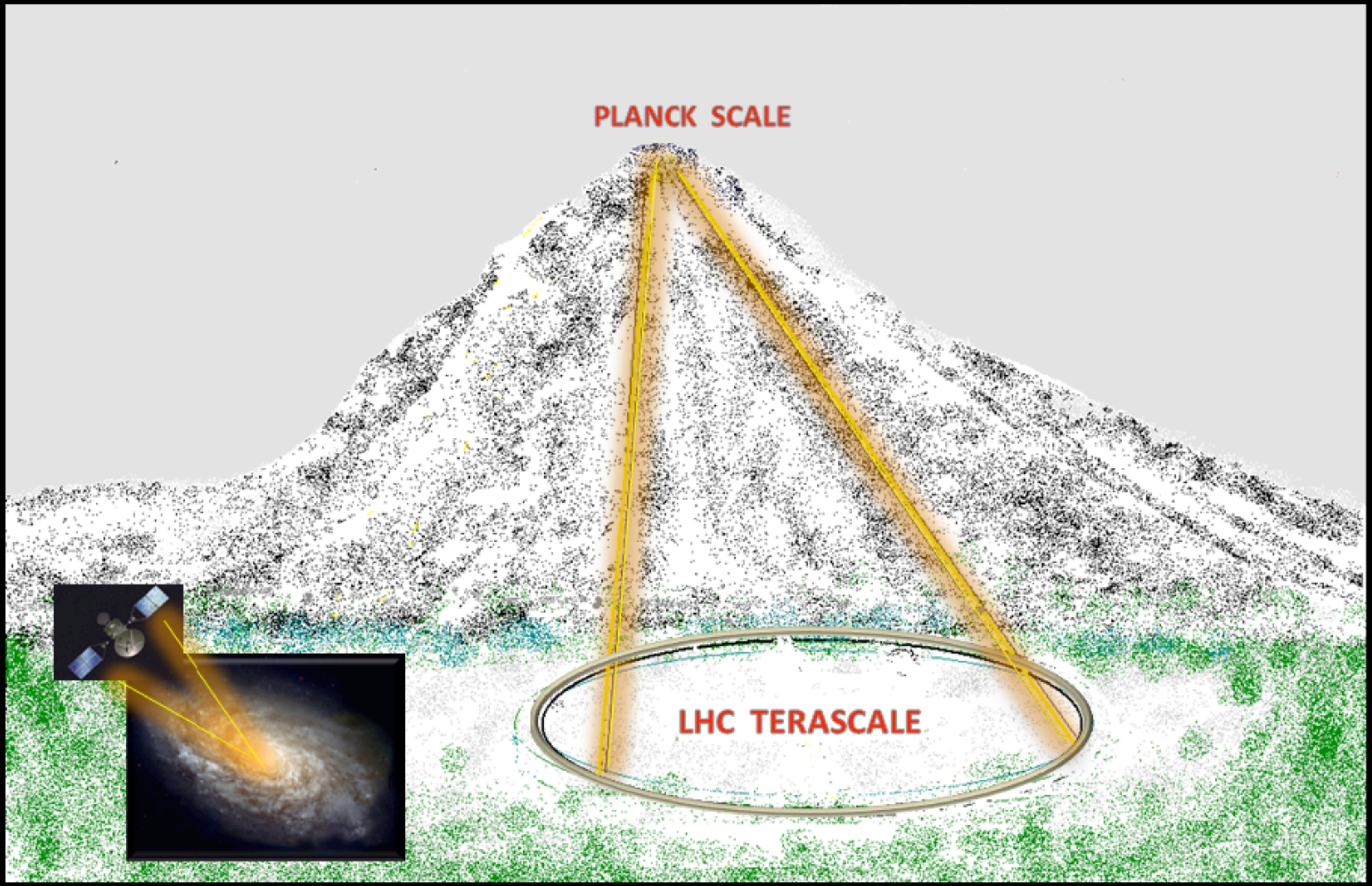
Supersymmetry: LHC, Dark Matter, and the Scale of New Physics



THE MICHIGAN CENTER FOR THEORETICAL PHYSICS
UNIVERSITY OF MICHIGAN COLLEGE OF LITERATURE, SCIENCE AND THE ARTS DEPARTMENT OF PHYSICS

Daniel Feldman

SUSY 2011, Fermilab

Today’s 30 minutes...

- SUGRA, LHC, DM and SIGNATURES
- EWSB in SUGRA and STRINGS
- ORIGIN OF DARK FORCES, HIDDEN SECTOR DM and SUSY
- PAMELA/FERMI/XENON SUSY and the LHC

SUGRA Paradigm

- Naturally incorporate gravity via the gauging of global SUSY
- Mass generation for super-partners via super-Higgs breaking SUSY
- Unification of gauge couplings manifest
- Dynamic triggering of spontaneous electroweak symm. breaking through RGE
- Dark matter candidate consistent with R-parity
- Predictive - unification scale boundary cond. determine TeV scale phenomena
- Testable - colliders and flavor physics, dark matter scattering and annihilation + ...
- Basis for contact with string theory (determine W, K, f) - string phenomenology

$$\mathbf{SUGRA + MSSM} \longrightarrow \mathrm{RGE + REWSB} \longrightarrow \mathcal{L}_{\mathrm{eff}} + \textbf{Testable Physics}$$

Break Super-Symmetry

$$V(\phi_M, \phi_M^*) = e^G \left(G_M K^{M\bar{N}} G_{\bar{N}} - 3 \right) + V_D$$

stable or metastable dS vacuum

$$G(\phi_M, \phi_M^*) = K(\phi_M, \phi_M^*) + \log |W(\phi_M)|^2$$

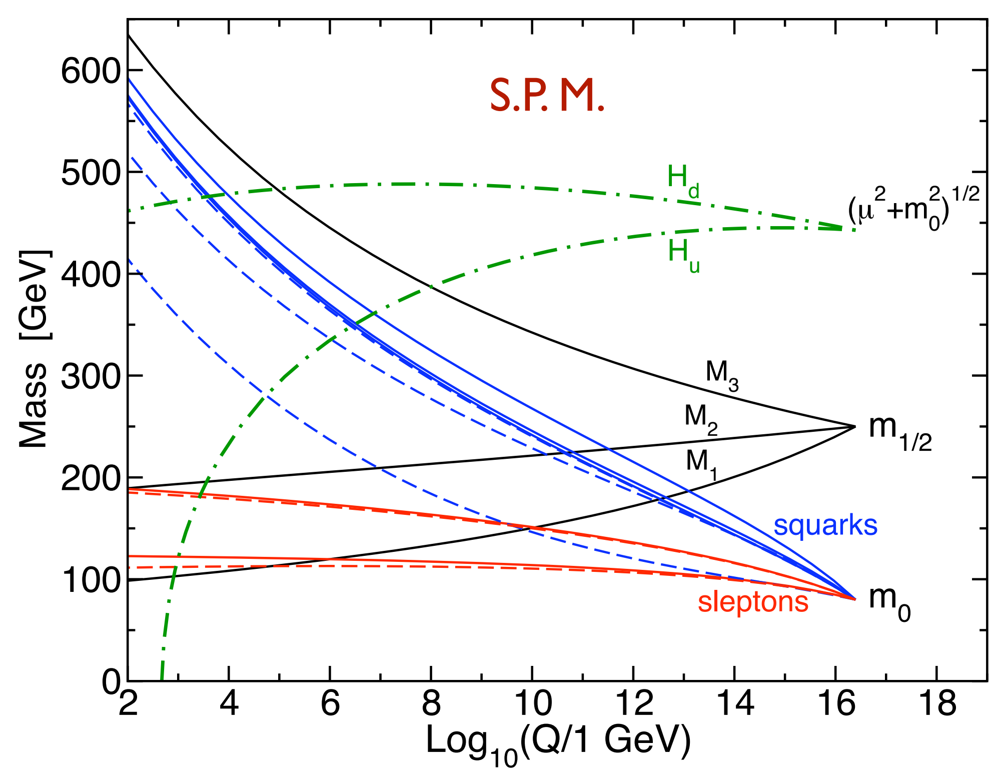
Super Higgs: Gravitino becomes massive : ~~SUSY~~

$$\mathcal{L}_{soft} = \frac{1}{2}(M_a \widehat{\lambda}^a \widehat{\lambda}^a + h.c.) - m_\alpha^2 \widehat{C}^{*\overline{\alpha}} \widehat{C}^\alpha - \left(\frac{1}{6} A_{\alpha\beta\gamma} \widehat{Y}_{\alpha\beta\gamma} \widehat{C}^\alpha \widehat{C}^\beta \widehat{C}^\gamma + B \widehat{\mu} \widehat{H}_1 \widehat{H}_2 + h.c. \right)$$

$$C^\alpha = Q_L, u_L^c, d_L^c, L_L, e_L^c, H_1, H_2$$

$$W = \hat{W}(h_m)\mu(h_m)H_1 H_2 + \sum_{\text{gen}} [Y_u(h_m) Q_L H_2 u_L^c + Y_d(h_m) Q_L H_1 d_L^c + Y_e(h_m) L_L H_1 e_L^c]$$

Break EW-Symmetry



Large Hadron Collider

$$\begin{aligned}
gg &\rightarrow \tilde{g}\tilde{g},\ \tilde{q}_i \tilde{q}_j^*, \\
gq &\rightarrow \tilde{g}\tilde{q}_i, \\
q\bar{q} &\rightarrow \tilde{g}\tilde{g},\ \tilde{q}_i \tilde{q}_j^*, \\
qq &\rightarrow \tilde{q}_i \tilde{q}_j, \\
q\bar{q} &\rightarrow \widetilde{C}_i^+ \widetilde{C}_j^-,\ \widetilde{N}_i \widetilde{N}_j, \quad u\bar{d} \rightarrow \widetilde{C}_i^+ \widetilde{N}_j, \\
q\bar{q} &\rightarrow \tilde{\ell}_i^+ \tilde{\ell}_j^-,\ \tilde{\nu}_\ell \tilde{\nu}_\ell^* \quad u\bar{d} \rightarrow \tilde{\ell}_L^+ \tilde{\nu}_\ell
\end{aligned}$$

$+ \ldots$

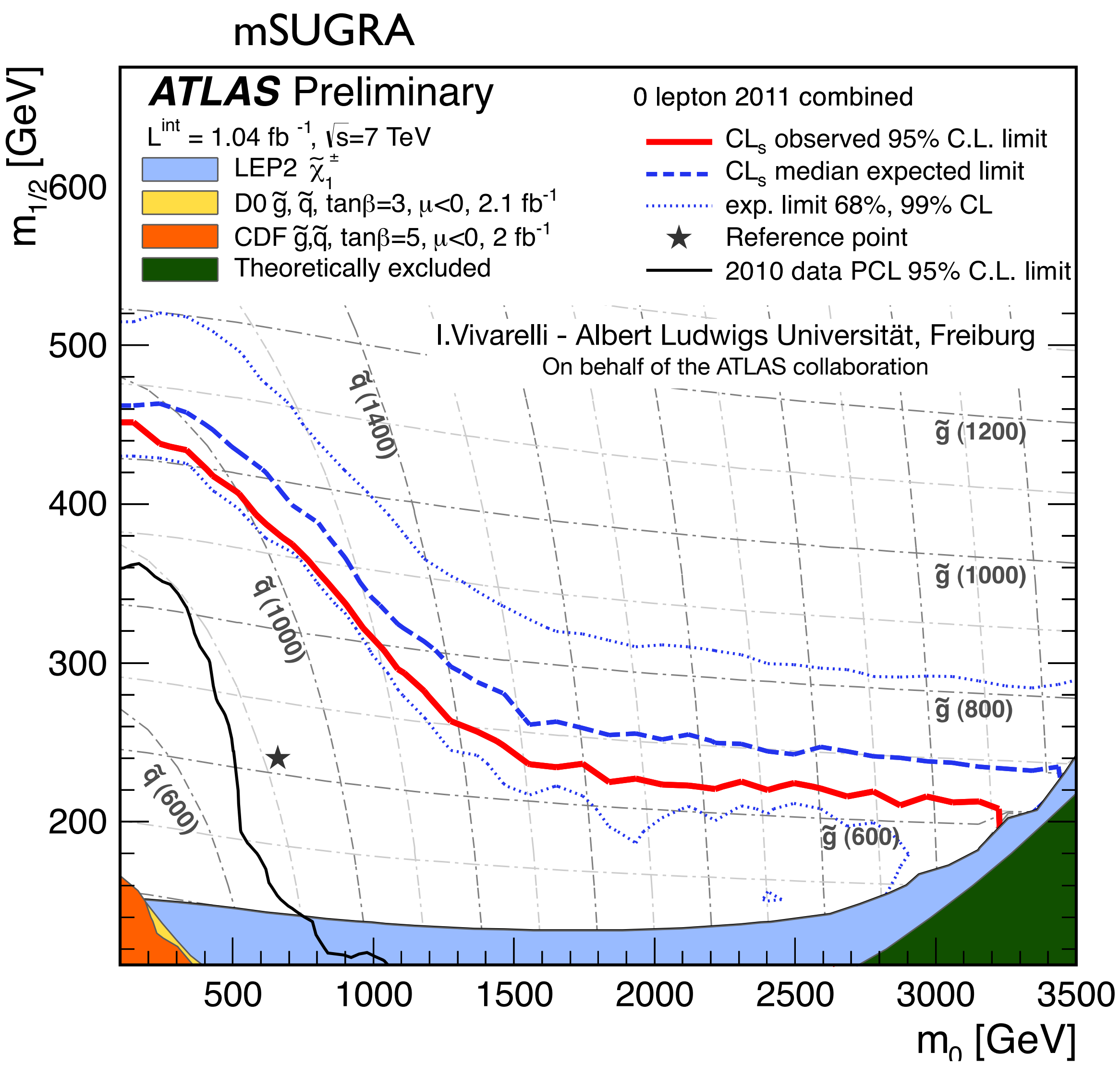
DM within Earth $\tilde{N}_1 q \rightarrow \tilde{N}_1 q$

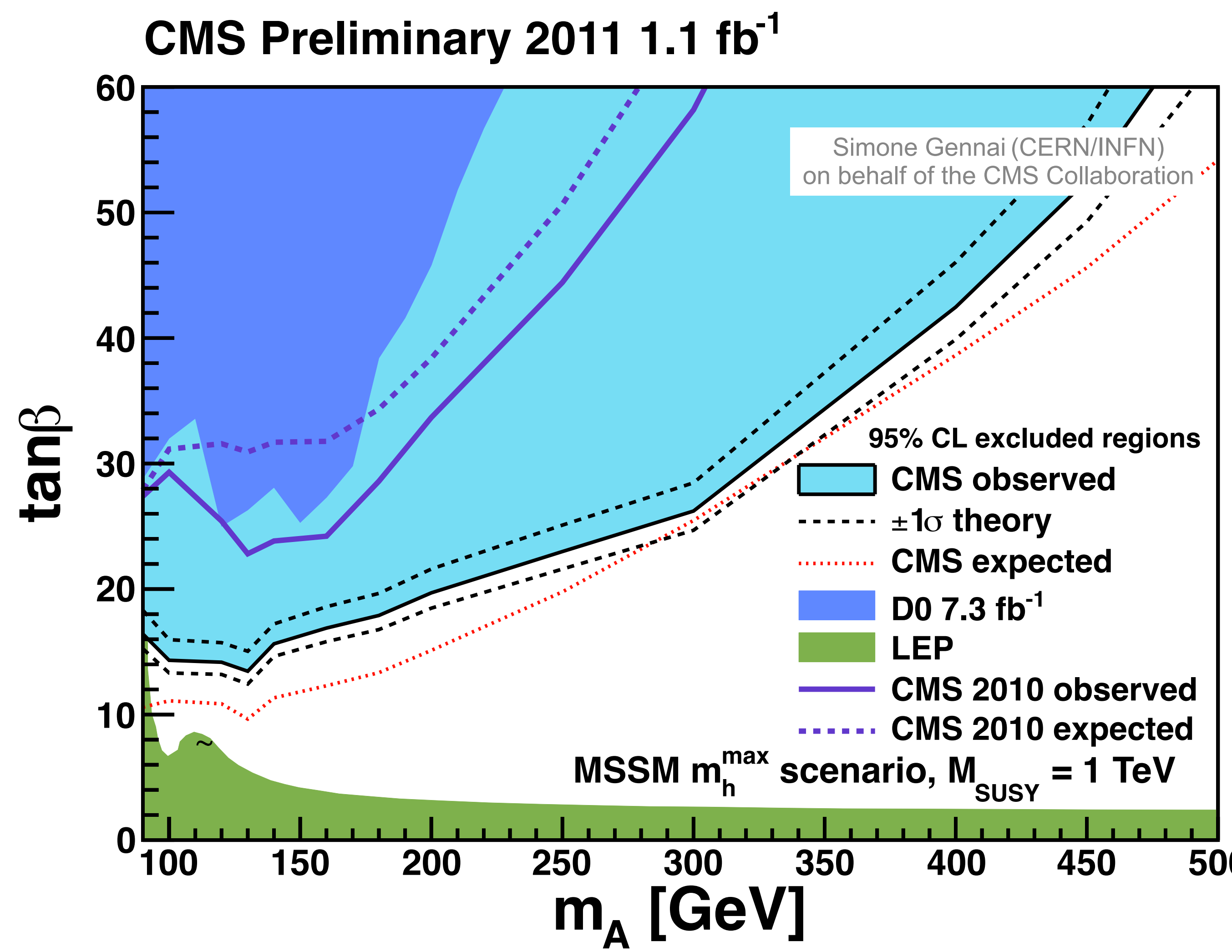
DM in the Galaxy $\tilde{N}_1 \tilde{N}_1 \rightarrow \mathrm{SM\ SM'}$

DM evolution in the Universe Ωh^2

Results From the EPS 2011 Meeting (see also talks ~ today)

$\mathbf{R-odd}\quad(\tilde{q}\tilde{q},\tilde{q}\tilde{g},\tilde{g}\tilde{g}\ldots)$ $\mathbf{R-even}\quad(\mathbf{\Phi=(h,H,A)})$





LHC 2011

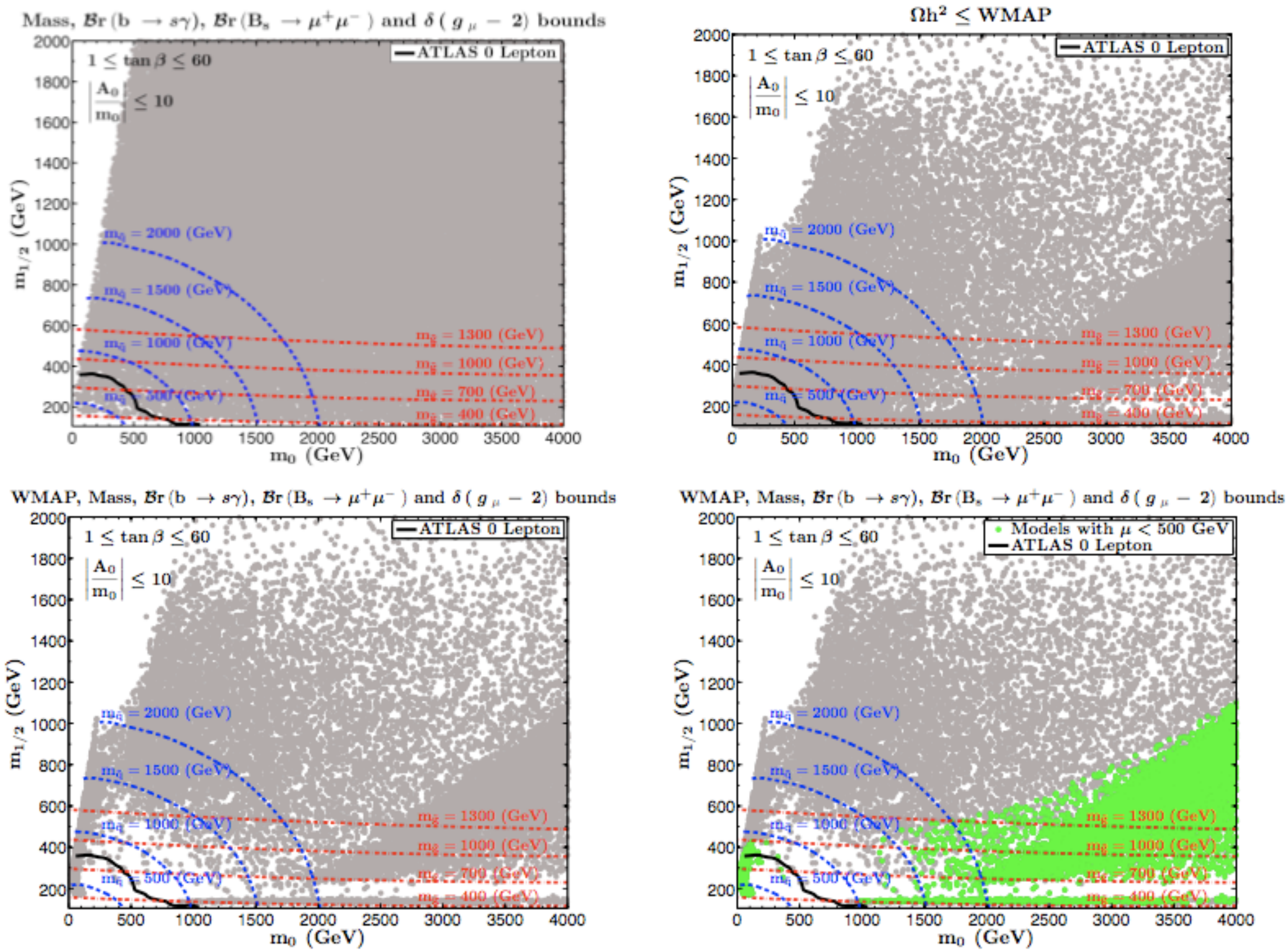
Constraint on gluino $\tilde{g}$ is significantly weaker than the constraint on $\tilde{q}$
Constraint on $\tilde{q}_3$ is significantly weaker (in particular $\tilde{t}$)
Low $M_A \sim M_H$ now highly constrained = big impact on dark matter searches

- Some of these constraints may be clear from theoretical considerations with the <u>gaugino</u> sector sub-TeV to order TeV.

- Viable parameter is **<u>LARGE</u>**, even in the minimal model of soft breaking (which is minimal SUGRA) and **LARGER** in extensions.

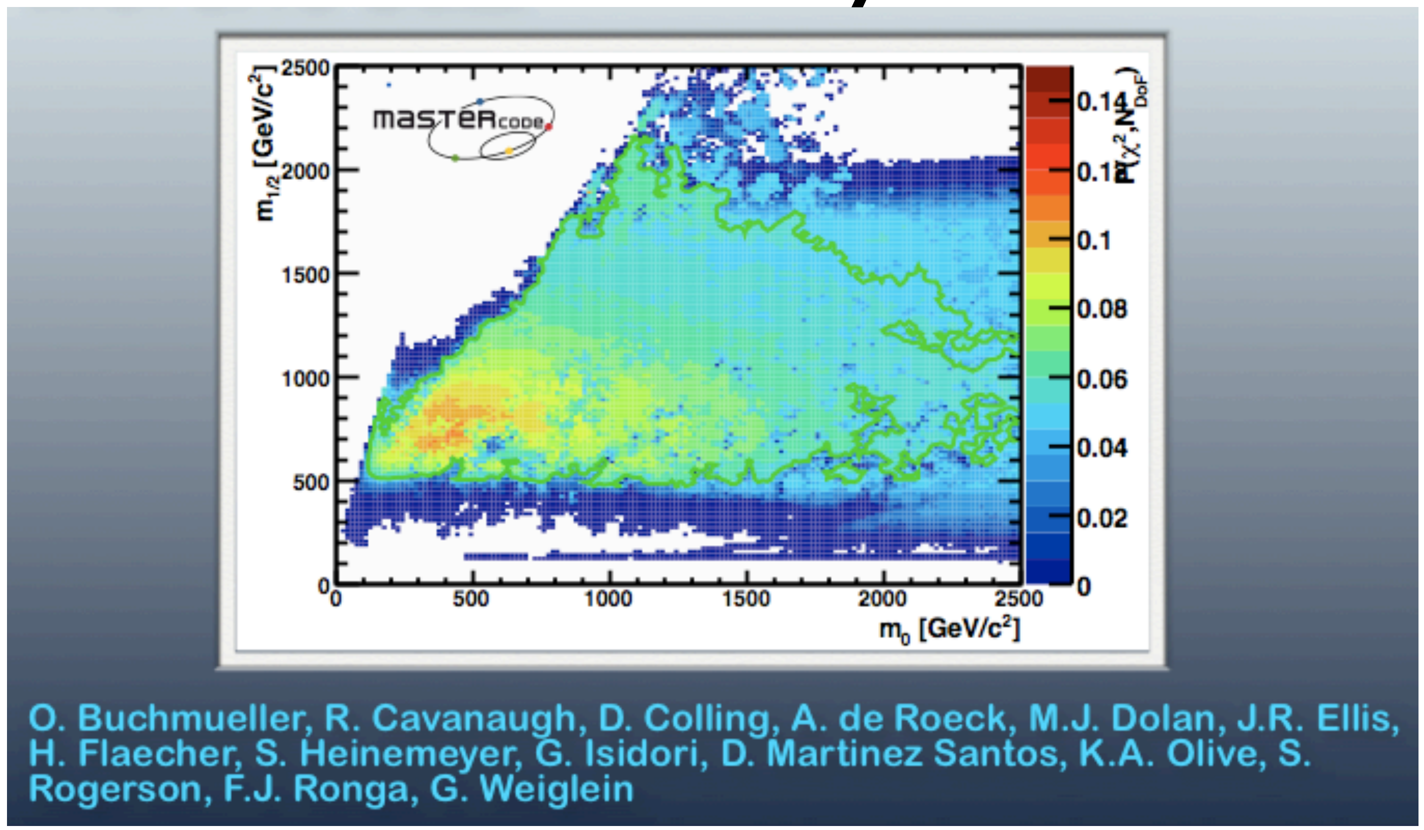
vast parameter space

Akula, Peim, Chen, Liu, Nath, DF 1103.1197, PLB

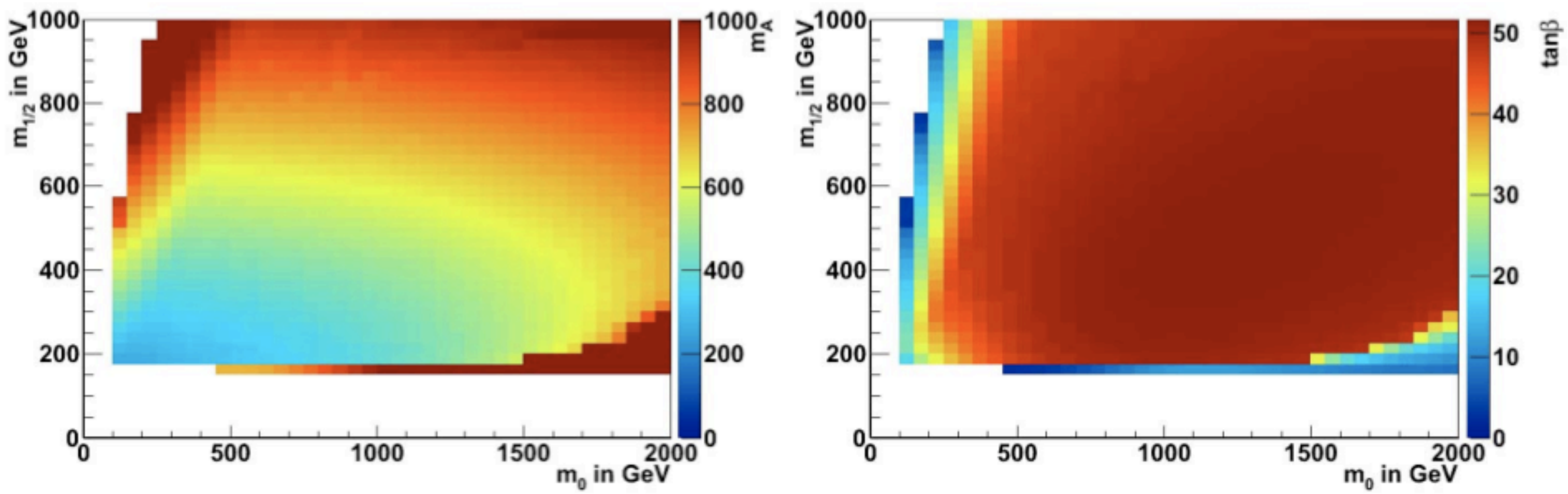


vast parameter space

Sven Heinemeyer's talk



See talk with W. de Boer et al



see: Allanach, Khoo, Lester, Williams

http://www.ep.ph.bham.ac.uk/general/seminars/slides/ben-allanach.pdf

Within the vast parameter space of SUSY models there is generally a Large Landscape of Mass Hierarchies

- Sparticle **Mass Hierarchies**, along with **scale and mass splittings** dictate what types of sparticles can **decay** into one another and can **significantly alter signatures of new physics at the LHC.**

What are the collection of the possible ways the masses can stack up ?

Scanning over the Landscape of mass configurations, what does this imply for the LHC ? Dark Matter ?

Mass Hierarchical Patterns
"Sparticle Landscape"

D. Feldman, Z. Liu, P. Nath	sugra, nusugra, and strings (PRL 2007), (PLB 2008, JHEP 2008)
J. Hewett, J. Gainer, T. Rizzo, et al	pmssm (JHEP 2009)
D. Nanopoulos, J. Maxin, V. Mayes	sugra and strings (PRD 2009)
K. Matchev, P. Konar, M. Park, G. Sarangi	mssm (PRL 2010)
L. Everett, B. Nelson, I. Kim, B. Altunkaynak, Y. Rao	sugra, mirage (arXiv:1011.1439)
P. Langacker	PRL viewpoint
G. Peim, N. Chen, et al	nusugra (PRD 2011)

For a review see: arXiv:0908.3727

Sparticle Mass Hierarchies

Feldman, Liu, Nath: Phys. Rev. Letters 99: 251802, (2007)
Phys.Lett.B662:190-198, (2008), JHEP 0804, 054 (2008)

mSP	Mass Pattern	μ
mSP1	$\widetilde{\chi}^0 < \widetilde{\chi}_1^{\pm} < \widetilde{\chi}_2^0 < \widetilde{\chi}_3^0$	$\mu_{\pm}$
mSP2	$\widetilde{\chi}^0 < \widetilde{\chi}_1^{\pm} < \widetilde{\chi}_2^0 < A/H$	$\mu_{\pm}$
mSP3	$\widetilde{\chi}^0 < \widetilde{\chi}_1^{\pm} < \widetilde{\chi}_2^0 < \widetilde{\tau}_1$	$\mu_{\pm}$
mSP4	$\widetilde{\chi}^0 < \widetilde{\chi}_1^{\pm} < \widetilde{\chi}_2^0 < \widetilde{g}$	$\mu_{\pm}$
mSP5	$\widetilde{\chi}^0 < \widetilde{\tau}_1 < \widetilde{l}_R < \widetilde{\nu}_\tau$	$\mu_{\pm}$
mSP6	$\widetilde{\chi}^0 < \widetilde{\tau}_1 < \widetilde{\chi}_1^{\pm} < \widetilde{\chi}_2^0$	$\mu_{\pm}$
mSP7	$\widetilde{\chi}^0 < \widetilde{\tau}_1 < \widetilde{l}_R < \widetilde{\chi}_1^{\pm}$	$\mu_{\pm}$
mSP8	$\widetilde{\chi}^0 < \widetilde{\tau}_1 < A \sim H$	$\mu_{\pm}$
mSP9	$\widetilde{\chi}^0 < \widetilde{\tau}_1 < \widetilde{l}_R < A/H$	$\mu_{\pm}$
mSP10	$\widetilde{\chi}^0 < \widetilde{\tau}_1 < \widetilde{t}_1 < \widetilde{l}_R$	μ_{+}
mSP11	$\widetilde{\chi}^0 < \widetilde{t}_1 < \widetilde{\chi}_1^{\pm} < \widetilde{\chi}_2^0$	$\mu_{\pm}$
mSP12	$\widetilde{\chi}^0 < \widetilde{t}_1 < \widetilde{\tau}_1 < \widetilde{\chi}_1^{\pm}$	$\mu_{\pm}$
mSP13	$\widetilde{\chi}^0 < \widetilde{t}_1 < \widetilde{\tau}_1 < \widetilde{l}_R$	$\mu_{\pm}$
mSP14	$\widetilde{\chi}^0 < A \sim H < H^{\pm}$	μ_{+}
mSP15	$\widetilde{\chi}^0 < A \sim H < \widetilde{\chi}_1^{\pm}$	μ_{+}
mSP16	$\widetilde{\chi}^0 < A \sim H < \widetilde{\tau}_1$	μ_{+}
mSP17	$\widetilde{\chi}^0 < \widetilde{\tau}_1 < \widetilde{\chi}_2^0 < \widetilde{\chi}_1^{\pm}$	μ_{-}
mSP18	$\widetilde{\chi}^0 < \widetilde{\tau}_1 < \widetilde{l}_R < \widetilde{t}_1$	μ_{-}
mSP19	$\widetilde{\chi}^0 < \widetilde{\tau}_1 < \widetilde{t}_1 < \widetilde{\chi}_1^{\pm}$	μ_{-}
mSP20	$\widetilde{\chi}^0 < \widetilde{t}_1 < \widetilde{\chi}_2^0 < \widetilde{\chi}_1^{\pm}$	μ_{-}
mSP21	$\widetilde{\chi}^0 < \widetilde{t}_1 < \widetilde{\tau}_1 < \widetilde{\chi}_2^0$	μ_{-}
mSP22	$\widetilde{\chi}^0 < \widetilde{\chi}_2^0 < \widetilde{\chi}_1^{\pm} < \widetilde{g}$	μ_{-}

Table: The Sparticle Landscape of Mass Hierarchies in mSUGRA.

NUSP	Mass Pattern	Model
NUSP1	$\widetilde{\chi}^0 < \widetilde{\chi}_1^{\pm} < \widetilde{\chi}_2^0 < \widetilde{t}_1$	NU3,NUG
NUSP2	$\widetilde{\chi}^0 < \widetilde{\chi}_1^{\pm} < A \sim H$	NU3
NUSP3	$\widetilde{\chi}^0 < \widetilde{\chi}_1^{\pm} < \widetilde{\tau}_1 < \widetilde{\chi}_2^0$	NUG
NUSP4	$\widetilde{\chi}^0 < \widetilde{\chi}_1^{\pm} < \widetilde{\tau}_1 < \widetilde{l}_R$	NUG
NUSP5	$\widetilde{\chi}^0 < \widetilde{\tau}_1 < \widetilde{\nu}_\tau < \widetilde{\tau}_2$	NU3
NUSP6	$\widetilde{\chi}^0 < \widetilde{\tau}_1 < \widetilde{\nu}_\tau < \widetilde{\chi}_1^{\pm}$	NU3
NUSP7	$\widetilde{\chi}^0 < \widetilde{\tau}_1 < \widetilde{t}_1 < A/H$	NUG
NUSP8	$\widetilde{\chi}^0 < \widetilde{\tau}_1 < \widetilde{l}_R < \widetilde{\nu}_\mu$	NUG
NUSP9	$\widetilde{\chi}^0 < \widetilde{\tau}_1 < \widetilde{\chi}_1^{\pm} < \widetilde{l}_R$	NUG
NUSP10	$\widetilde{\chi}^0 < \widetilde{t}_1 < \widetilde{g} < \widetilde{\chi}_1^{\pm}$	NUG
NUSP11	$\widetilde{\chi}^0 < \widetilde{t}_1 < A \sim H$	NUG
NUSP12	$\widetilde{\chi}^0 < A \sim H < \widetilde{g}$	NUG
NUSP13	$\widetilde{\chi}^0 < \widetilde{g} < \widetilde{\chi}_1^{\pm} < \widetilde{\chi}_2^0$	NUG
NUSP14	$\widetilde{\chi}^0 < \widetilde{g} < \widetilde{t}_1 < \widetilde{\chi}_1^{\pm}$	NUG
NUSP15	$\widetilde{\chi}^0 < \widetilde{g} < A \sim H$	NUG
DBSP1	$\widetilde{\chi}^0 < \widetilde{\tau}_1 < \widetilde{\nu}_\tau < A/H$	DB
DBSP2	$\widetilde{\chi}^0 < \widetilde{\tau}_1 < \widetilde{\nu}_\tau < \widetilde{l}_R$	DB
DBSP3	$\widetilde{\chi}^0 < \widetilde{\tau}_1 < \widetilde{\nu}_\tau < \widetilde{\nu}_\mu$	DB
DBSP4	$\widetilde{\chi}^0 < \widetilde{t}_1 < \widetilde{\tau}_1 < \widetilde{\nu}_\tau$	DB
DBSP5	$\widetilde{\chi}^0 < \widetilde{\nu}_\tau < \widetilde{\tau}_1 < \widetilde{\nu}_\mu$	DB
DBSP6	$\widetilde{\chi}^0 < \widetilde{\nu}_\tau < \widetilde{\tau}_1 < \widetilde{\chi}_1^{\pm}$	DB

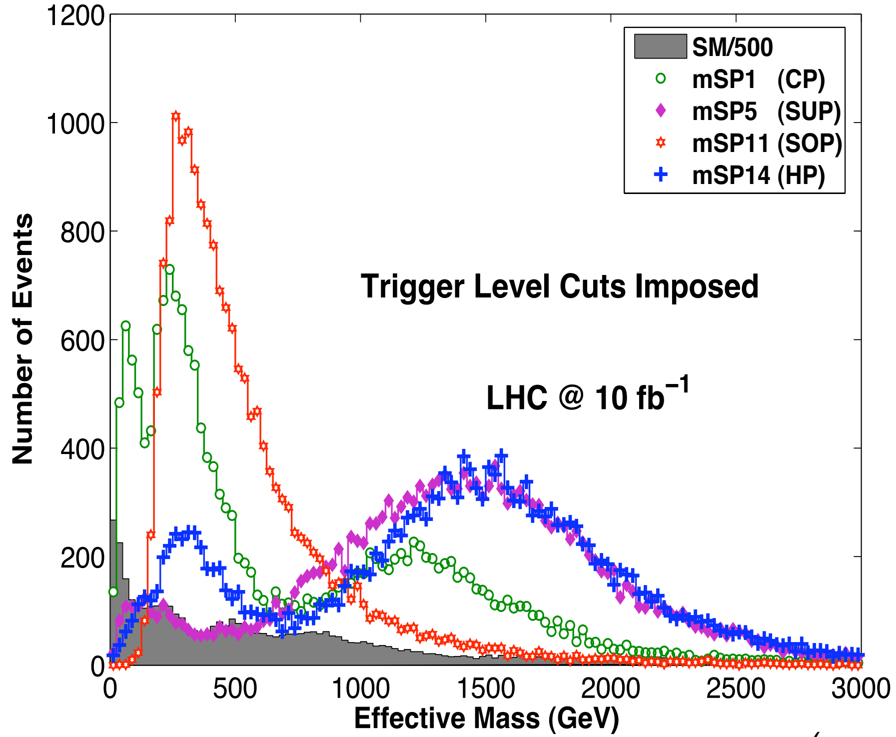
Table: New patterns in NUSUGRA ; no new patterns seen in NUH.

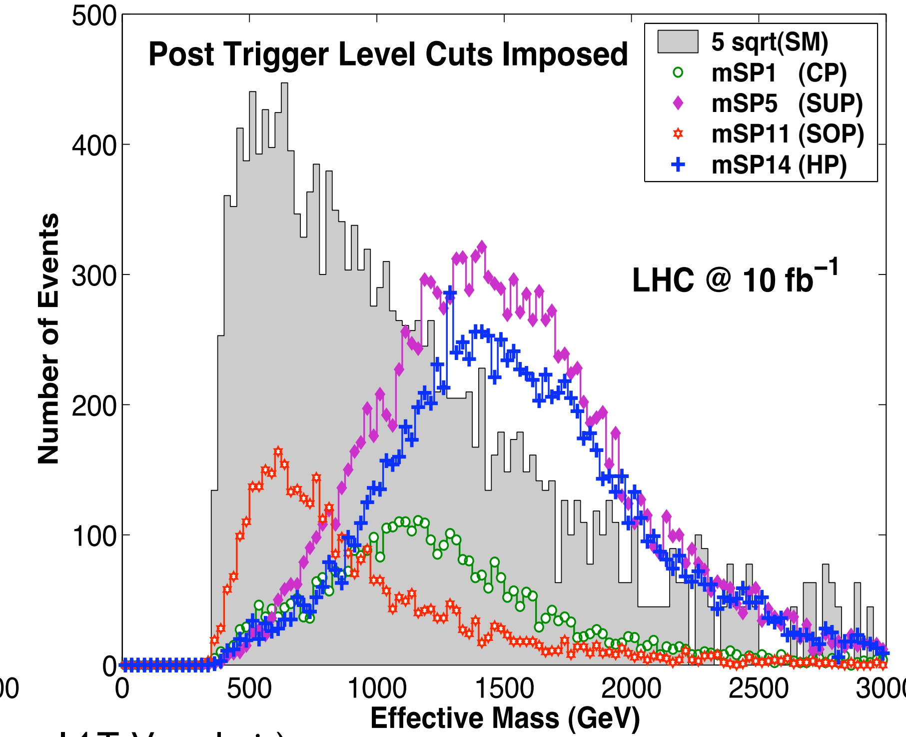
NUG - non-universal gauginos
NUH - non-universal Higgses
NU3 - non-universal 3rd gen squarks

Can we map out the entire landscape? Intensive ...
Larger sugra par. space searches should reveal even more.

However, one really needs to understand the mapping of the mass hierarchies into LHC and Dark Matter Signatures

D. Feldman, Z. Liu and P. Nath, JHEP **0804**, 054 (2008)





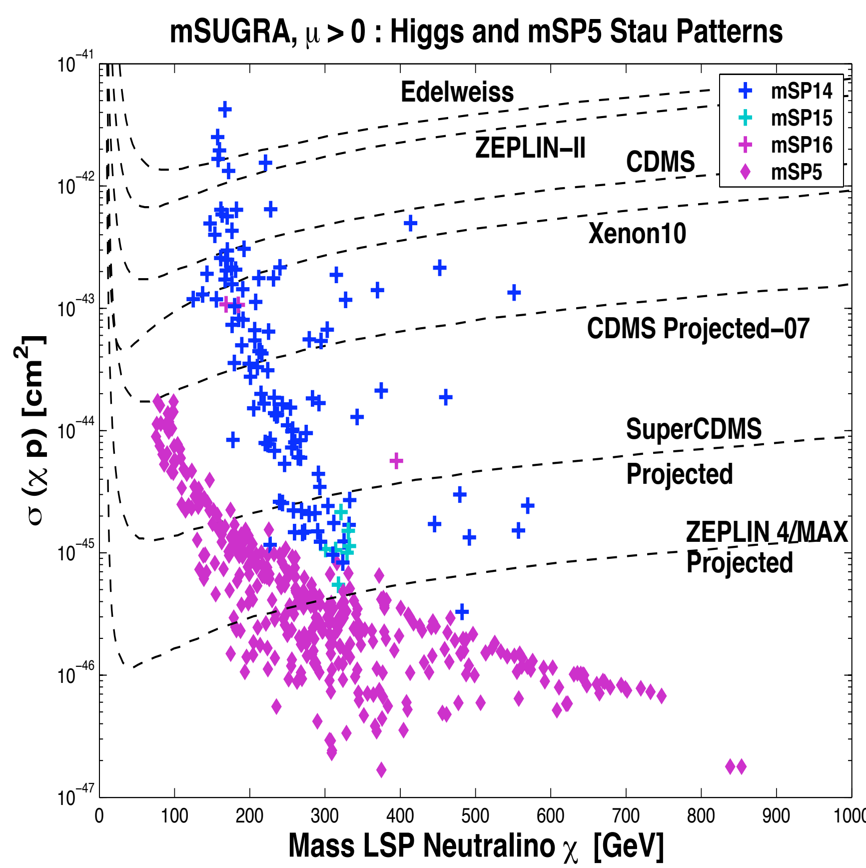
(note: 14 TeV analysis)

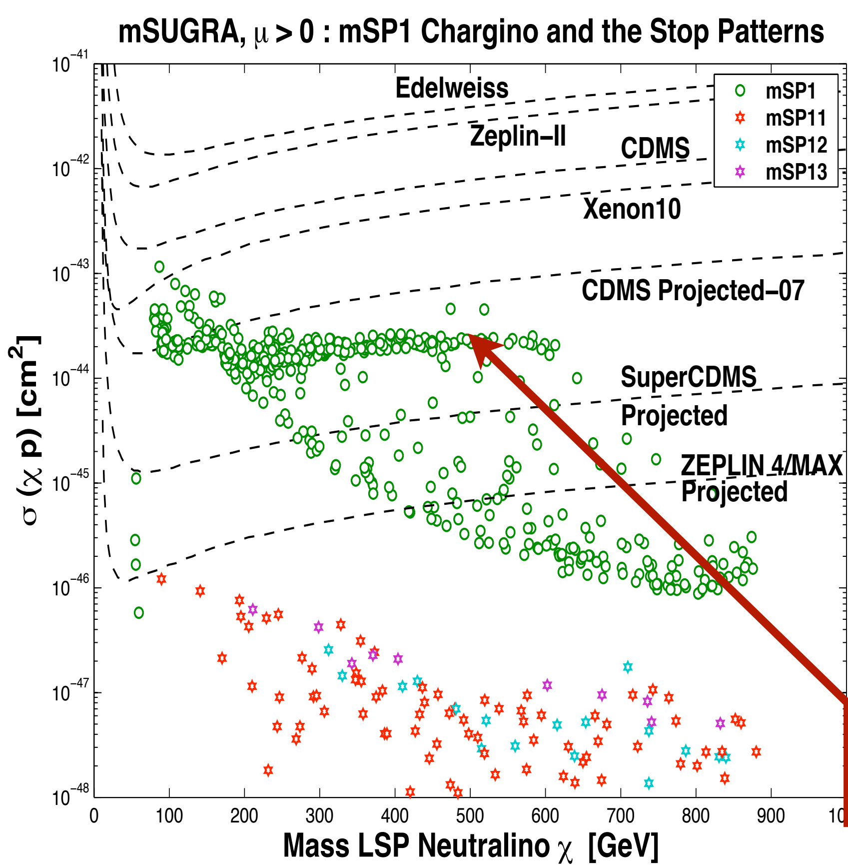
$$m_{\rm eff} = \sum_{i=1}^{4} p_T\,(j_i) + \not{E}_T,$$

some examples
Higgs Patterns
Chargino Patterns
Stau patterns
Stop Patterns

D. Feldman, Z. Liu and P. Nath, Phys. Lett. B **662**, 190 (2008)

arXiv: 0711.4591





Can Separate at the LHC and in Dark Matter Direct Detection

$\tilde{\chi}^0 q \rightarrow \tilde{\chi}^0 q$ scattering

enhancements at large tb low Higgs mass, & largish Higgsino component for a mostly bino LSP.

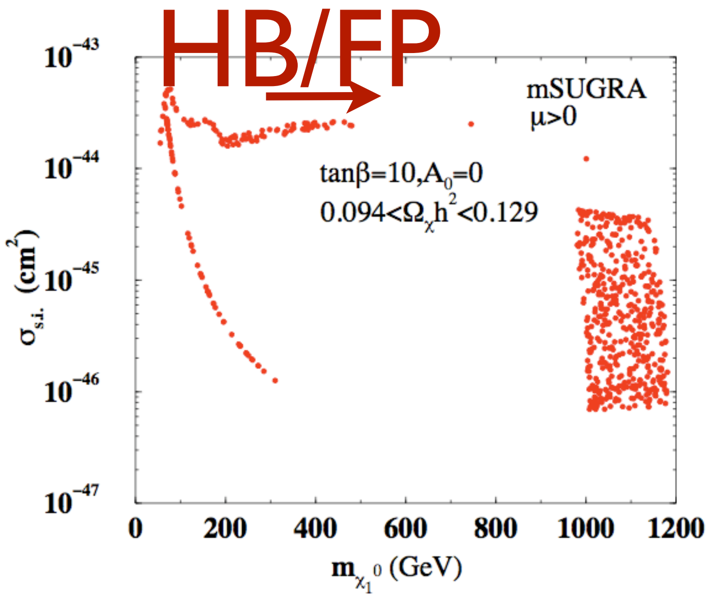
Xenon is now here

HB/FP

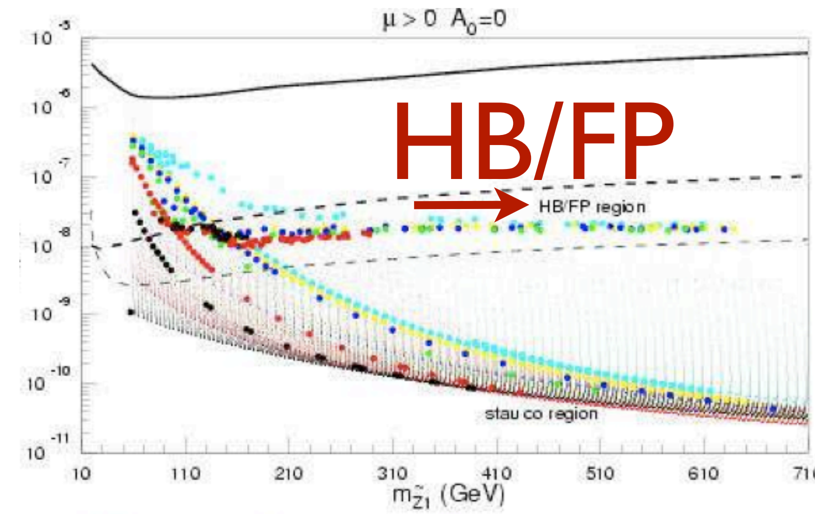
Hyperbolic Branch / Focus Point

hep-ph/9710473 Chan, Chattopadhyay, Nath

hep-ph/9908309 Feng, Matchev, Moroi



Chattopadhyay, Corsetti, Nath
hep-ph/0303201



Baer, Balazs, Belyaev,O'Farrill
hep-ph/0305191

SI cross section on the HB/FP : **Feng, Matchev, Wilczek** hep-ph/0004043

$$\sigma^{\rm SI}_{\chi p}({\rm WALL}) \sim \frac{m_p^2\mu_{\chi p}^2 g_2^2}{324\pi m_h^4 M_W^2}(g_Y n_1 - g_2 n_2)^2 \times (n_4+\alpha n_3)^2(9f_p+2f_{pG})^2 \sim \mathbf{10^{-8}\ pb = 10^{-44}\ cm^2}$$

Chargino WALL on HB/FP

Analytic result : arXiv:0808.1595 **DF, Liu, Nath** arXiv:1001.3408 **Cohen, Phalen, Pierce**

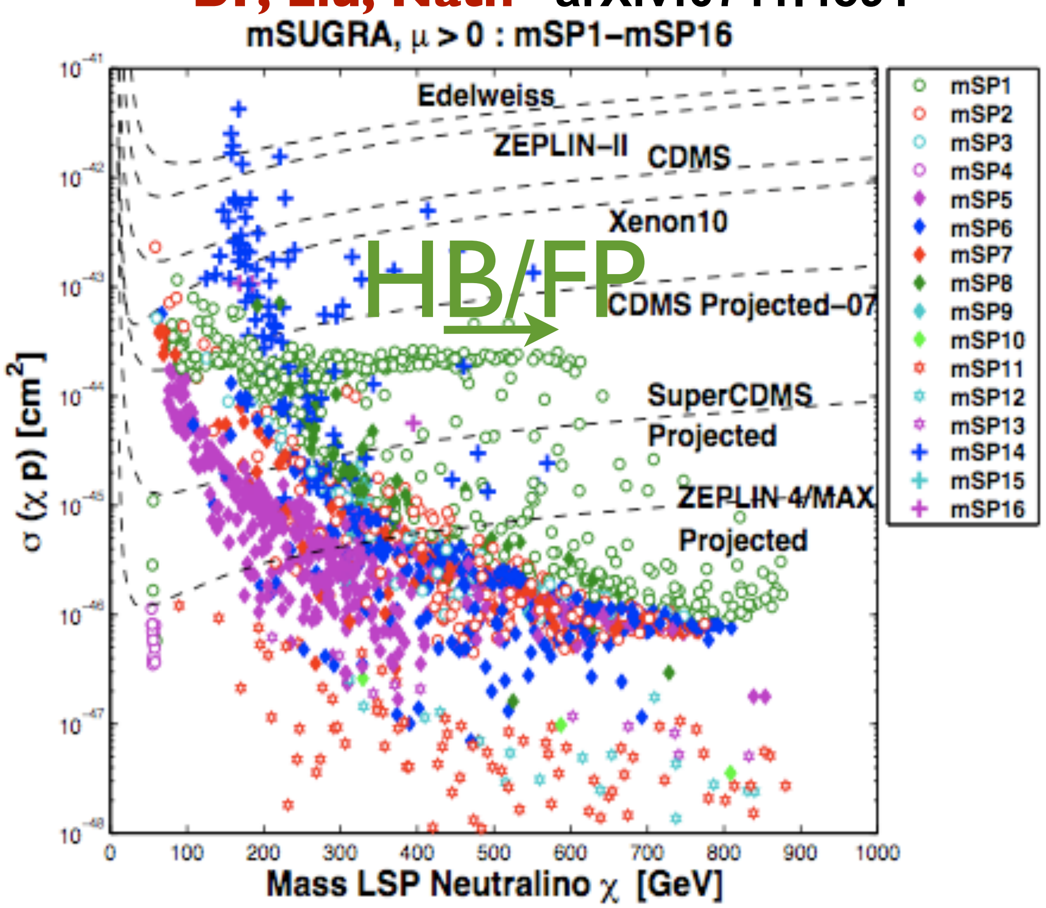
DF, Liu, Nath arXiv:0711.4591

Higgs Patterns msp(14-16)

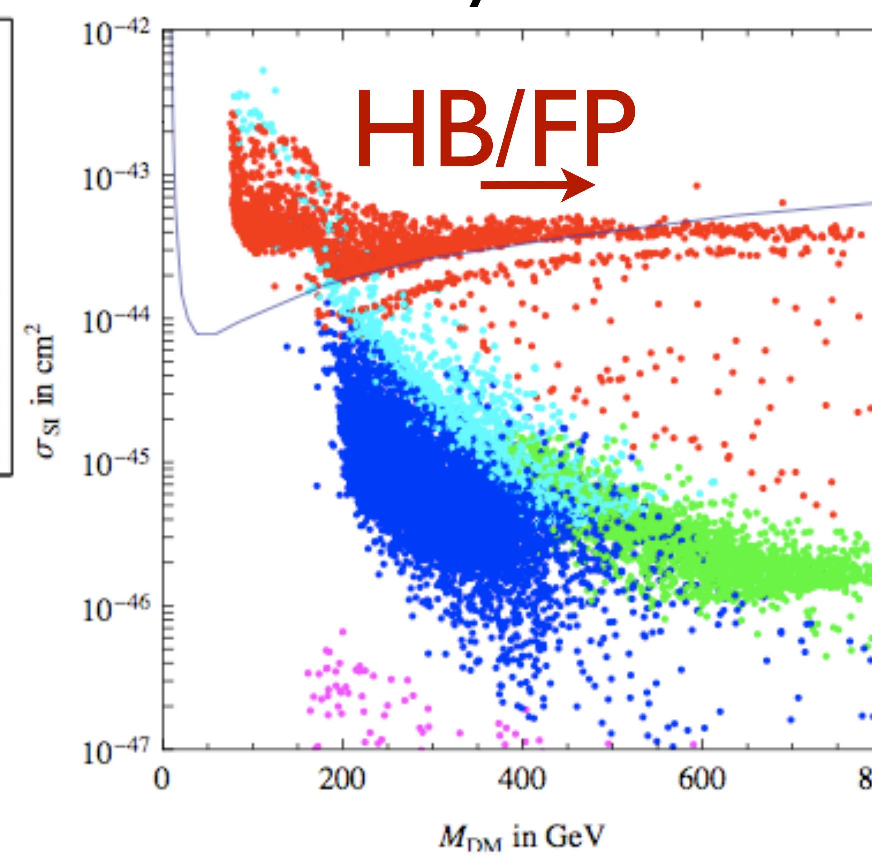
Chargino Patterns msp(1-4)

Stau patterns msp(5-10)

Stop Patterns msp(11-13)



See talk by Aaron Pierce

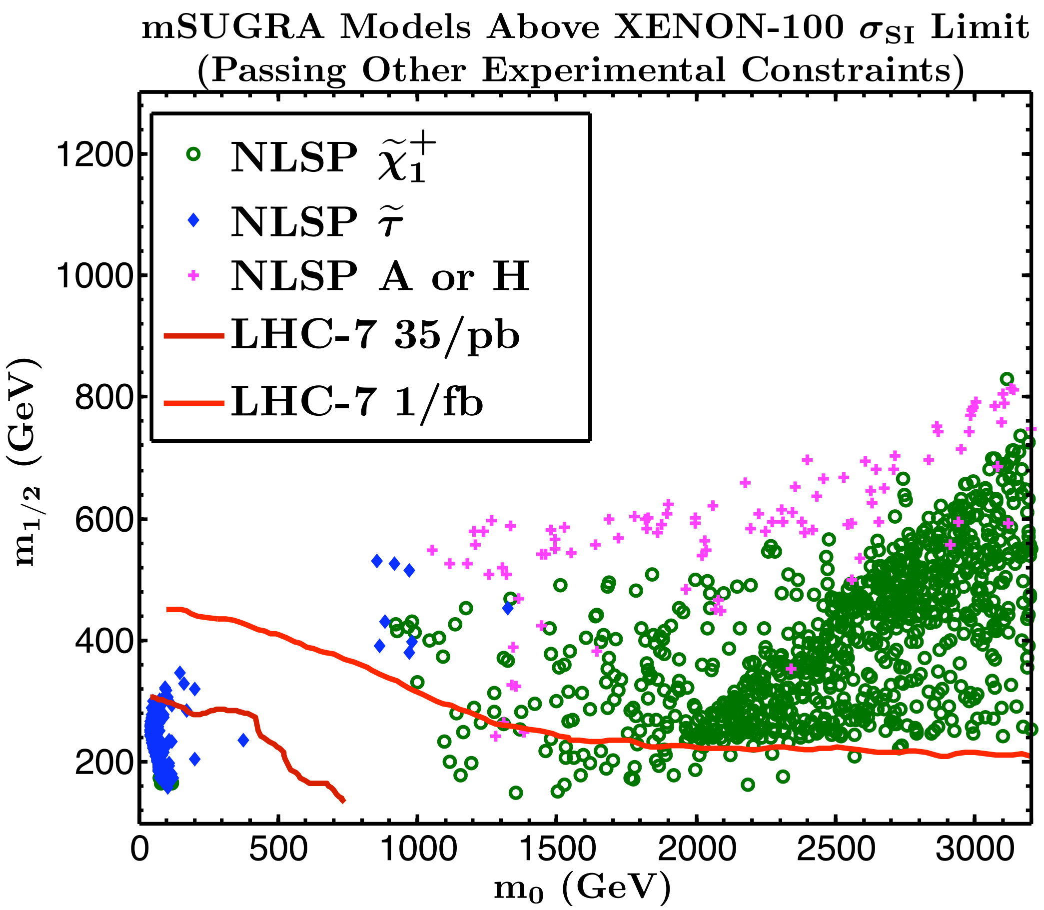


Aukla et al
arXiv:1103.5061

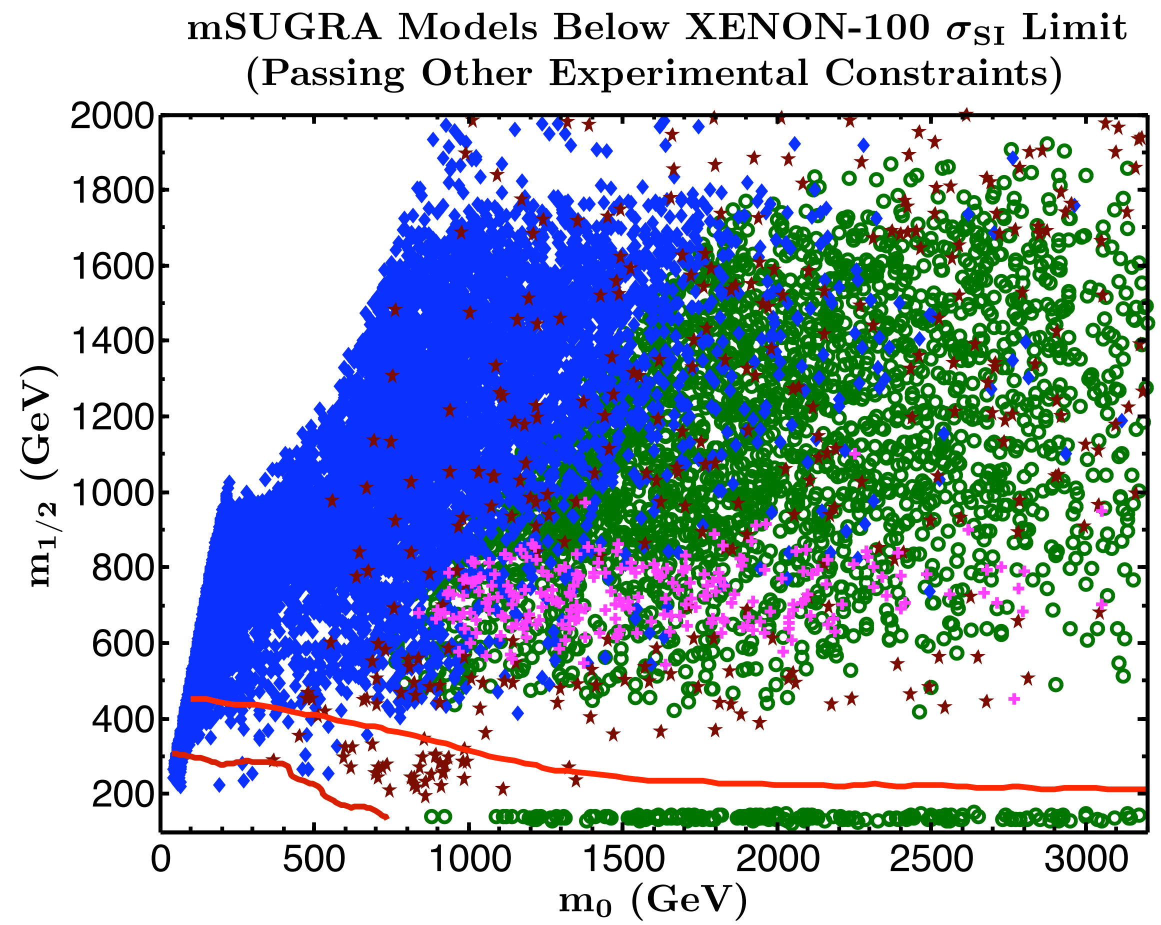
Farina et al
arXiv:1104.3572

NEW CONSTRAINTS: XENON and the LHC

Xenon Constrained*



Xenon Allowed



Sujeet Akula, DF, Zuowei Liu, Pran Nath, and Gregory Peim, arXiv:1103.5061 MPLA, and recent: 1107.3534

Allowed model space is HUGE (and with a denser search more models arise).
No constraint at this time by any experiment above red curve in right plot.

<u>All models shown have consistent bsmumu, bsg, g-2, Relic Density (double sided), and prev. mass limits</u>

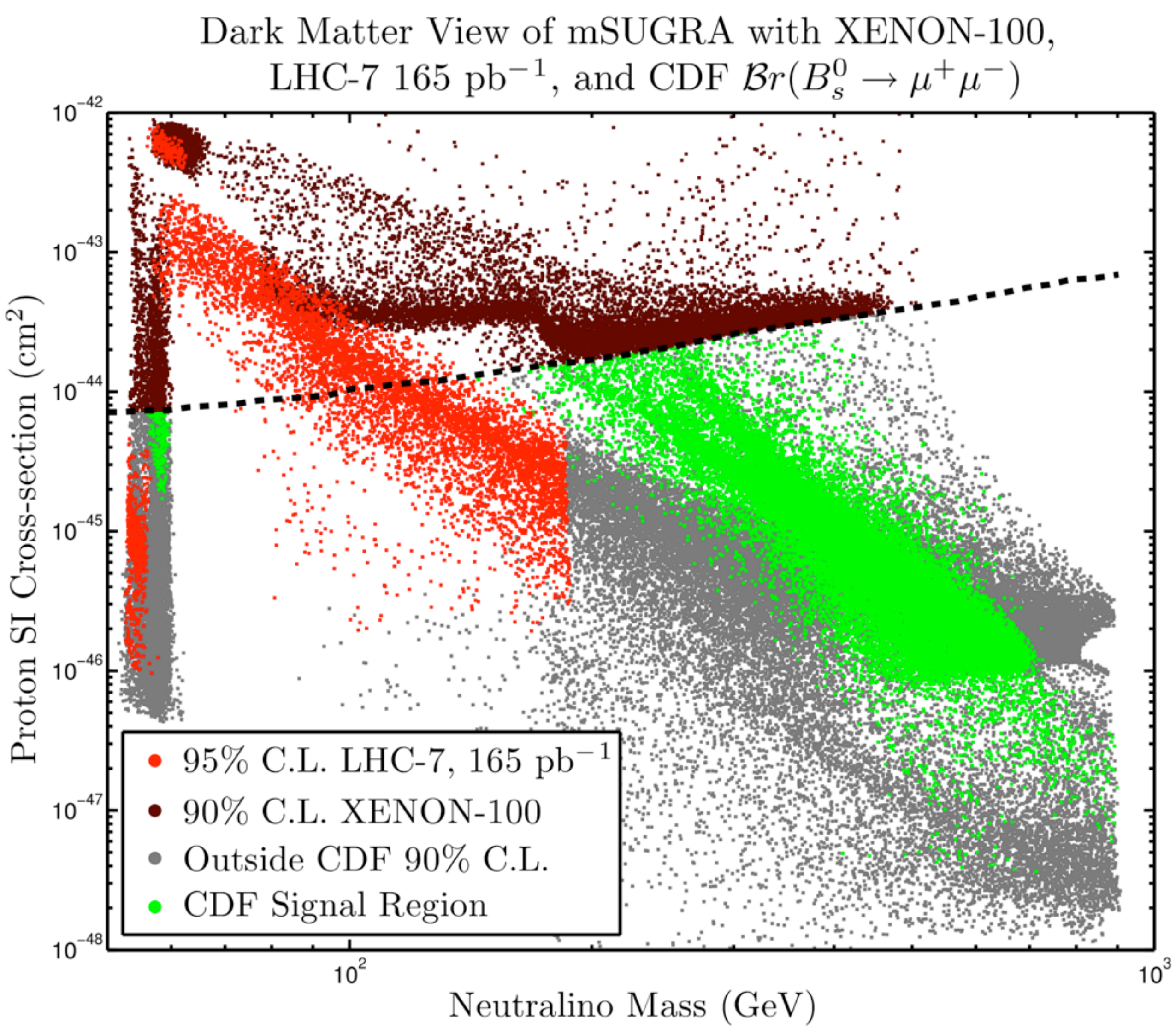
... uncertainties become important
* **(Ellis, Olive, Savage, Giedt et al)**
...note also sensitivity above i.e. regions overlap

- HB/FP region (filled with Chargino Patterns) - part constrained.
- Higgs Patterns in the Bulk - some are removed.
- Note, h-pole extends well beyond 3 TeV .... on the edge ... in or out ...?
- No Stop Patterns constrained by XENON (~total bino), some by LHC (Stop NLSPs =★) in the right plot.

Reality Check : One is looking for <u>one</u> model (represented by ~ pixel in these planes).
ALSO: non-universal soft breaking even more models allowed, see arXiv:1103.5061

However...

- **LHC is ripping into the testable space of Dark Matter experiments.**
- **Xenon constraints are very significant for lower LSP mass as $(1/2)m_{1/2} \sim$ LSP mass**



Akula, DF, Nath, Peim, arXiv:1107.3535, arXiv:1103.5061

..suggests upper limits on scalar masses, if it holds up, and if SUSY is the source, then SUSY can appear at the LHC.

(Recent: **Dutta/Santoso, Kelso/Hooper, Carena et al, Akeroyd, Mahmoudi, Martinez Santos.**) **Early SUSY analysis: (1999-2002) Choudhury, Gaur, Bobeth et al, Buras et al, Arnowitt, Dutta et al, Ibrahim, Nath ...**

Note: Light CP even Higgs-pole Region

densely populated with models (in and out of CDF region)
- important right now for LHC searches

Hints of $B_s^0 \to \mu^+\mu^-$?

Search for $B_s^0 \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ Decays with CDF II

The data in the B_s^0 search region are in excess of the background predictions. A fit to the data determines $\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (1.8^{+1.1}_{-0.9}) \times 10^{-8}$ including all uncertainties. Although of moderate statistical significance, this is the first indication of a $B_s^0 \to \mu^+\mu^-$ signal.

from : arXiv:1107.2304v1 [hep-ex]

$$4.6 \times 10^{-9} < \mathcal{B}r(B_s^0 \to \mu^+\mu^-) < 3.9 \times 10^{-8} \quad \text{90\% C.L.}$$

7 fb^{-1} of integrated luminosity

CMS 1.14 fb^{-1} at $\sqrt{s} = 7$ TeV

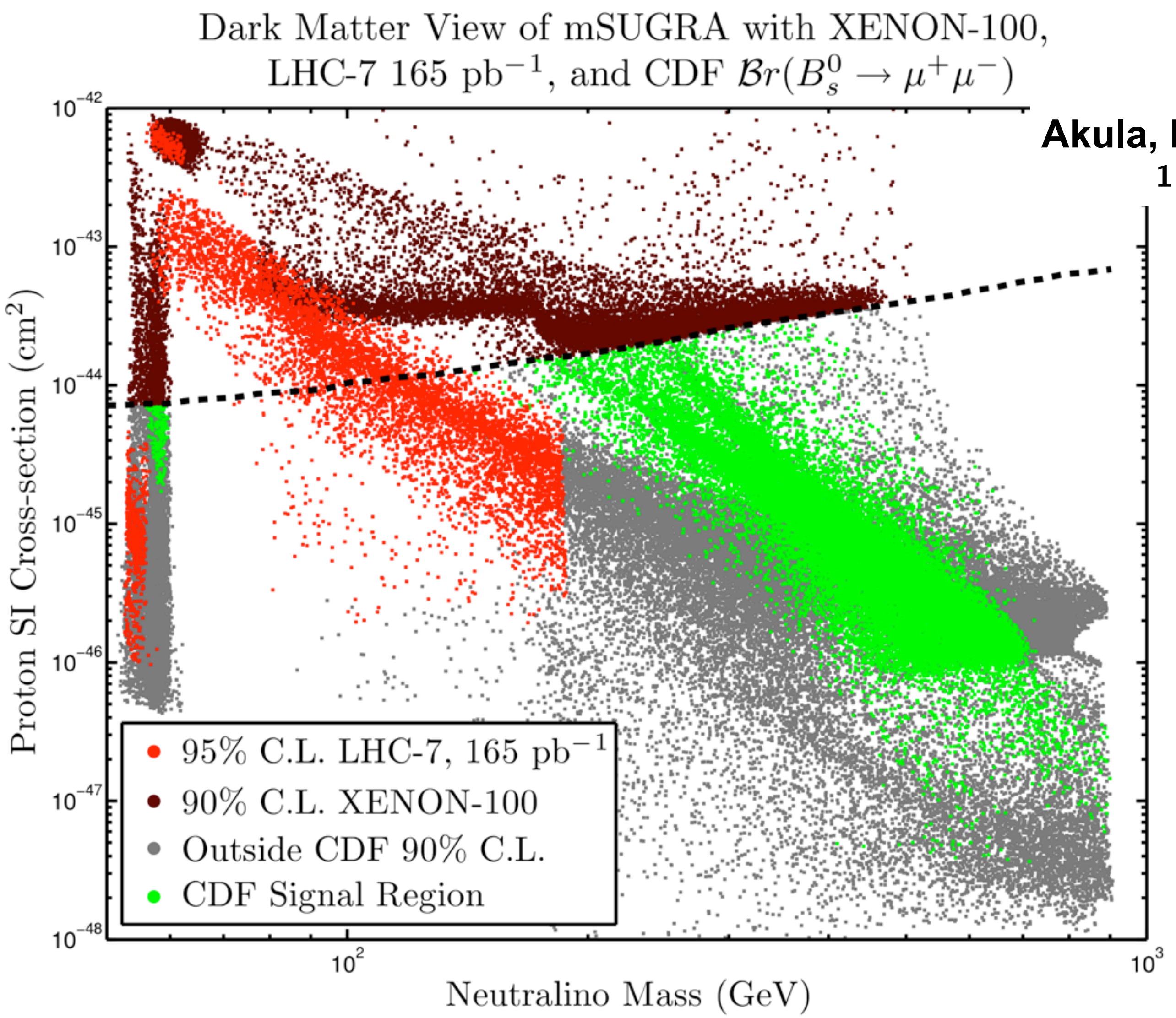
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) < 1.9 \times 10^{-8} \quad (95\%\ \text{C.L.})$$

	Barrel		Endcap	
	$B^0 \to \mu^+\mu^-$	$B_s^0 \to \mu^+\mu^-$	$B^0 \to \mu^+\mu^-$	$B_s^0 \to \mu^+\mu^-$
ε_{tot}	$(3.6 \pm 0.4) \times 10^{-3}$	$(3.6 \pm 0.4) \times 10^{-3}$	$(2.1 \pm 0.2) \times 10^{-3}$	$(2.1 \pm 0.2) \times 10^{-3}$
N^{exp}_{signal}	0.065 ± 0.011	0.80 ± 0.16	0.025 ± 0.004	0.36 ± 0.07
N^{exp}_{comb}	0.40 ± 0.23	0.60 ± 0.35	0.53 ± 0.27	0.80 ± 0.40
N^{exp}_{peak}	0.25 ± 0.06	0.07 ± 0.02	0.16 ± 0.04	0.04 ± 0.01
N_{obs}	0	2	1	1

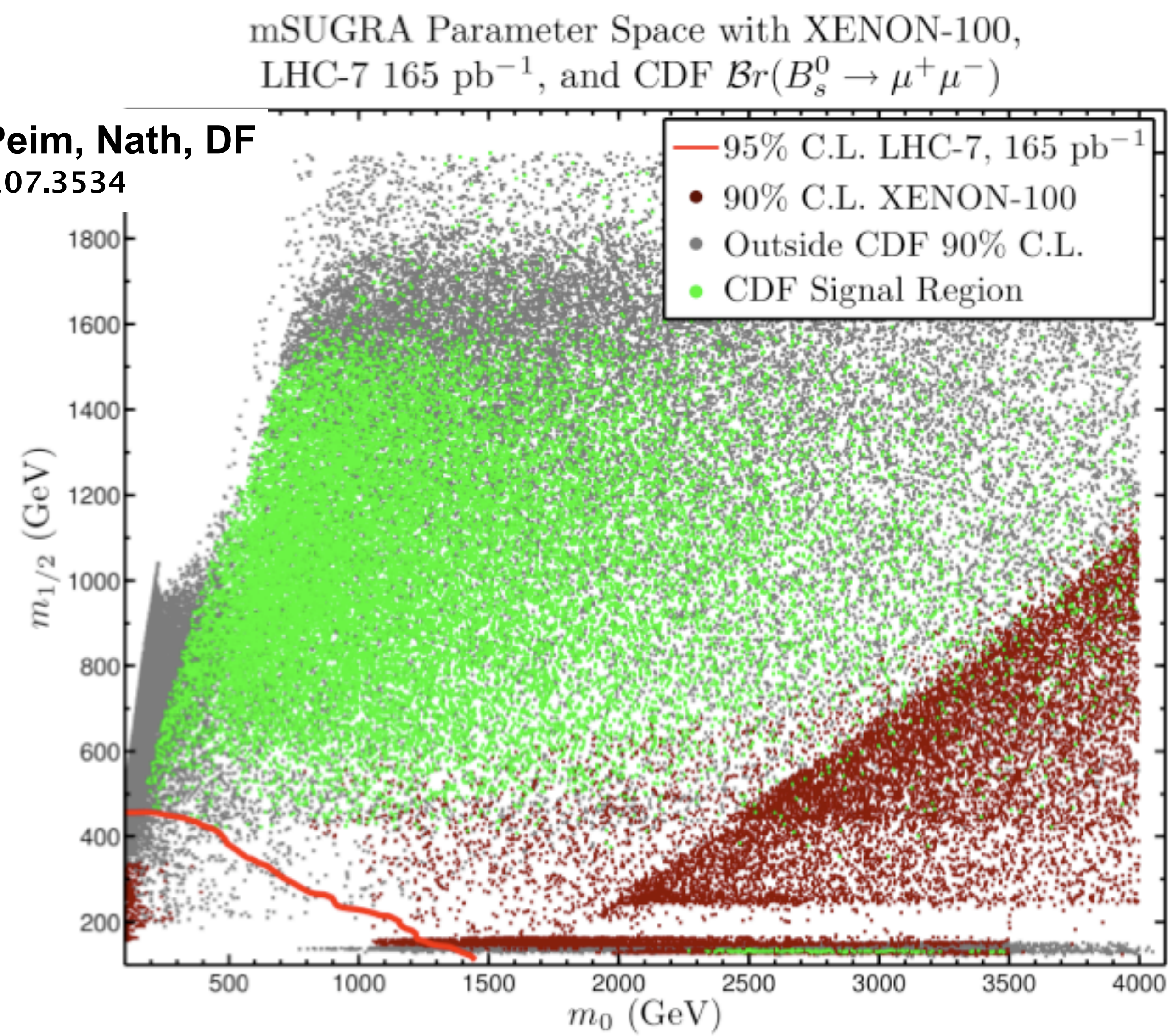
LHCb preliminary results (EPS 2011, 300/pb)

$BR(B_s \to \mu^+\mu^-) < 1.3 \times 10^{-8}$ (1.6×10^{-8}) @ 90 (95)% CL

Interesting comparison



Akula, Peim, Nath, DF
1107.3534



Grey = allowed and also Green = allowed

Large parameter space is untouched, but LSP mass in mSUGRA has a considerable constraint. HOWEVER, With **NU** soft-breaking **constraints weaken** substantially

arXiv:1103.5061. IN FACT, NON-UNIVERSAL GAUGINO MASSES ARISE IN MANY MODELS OF SOFT-BREAKING.

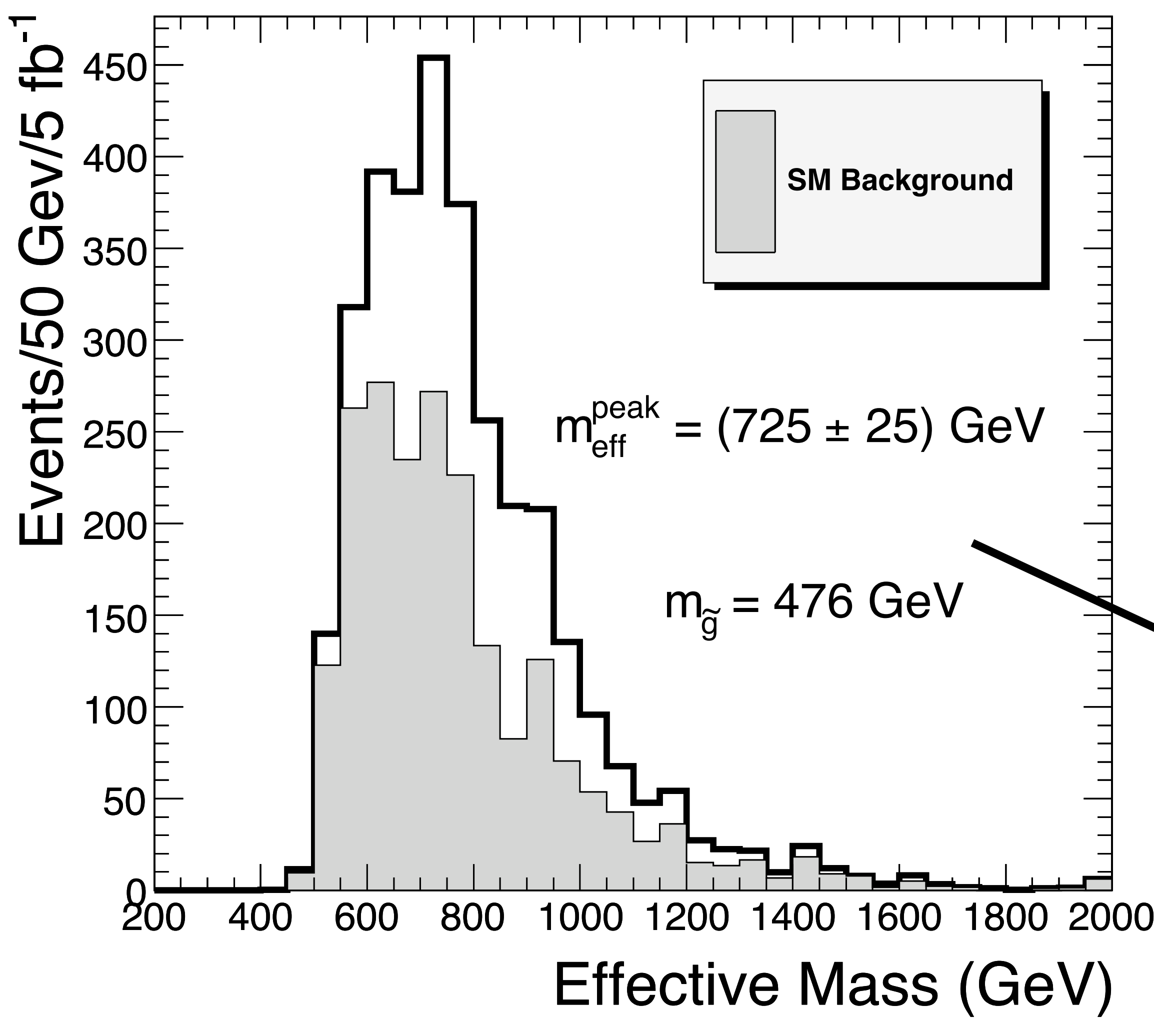
XENON and LHC constrain similar spaces when including the 1 fb^{-1} result.

Observe larger m0 in these plots, and that mu < ~ 500 GeV in mSUGRA is by XENON at 90% C.L.
Higgsino content larger - this is only **PART** of the hyperbolic branch. arXiv:1107.3535, arXiv:1103.5061

Higgs-Pole and Dark Matter on the Hyperbolic Branch

Higgs Pole: P. Nath and R. L. Arnowitt, Phys. Rev. Lett. 70, 3696 (1993); A. Djouadi, M. Drees and J. L. Kneur, Phys. Lett. B 624, 60 (2005); Recent work, Utpal Chattopadhyay, D. Das, D. K. Ghosh and M. Maity, Phys. Rev. D 82, 075013 (2010).

LHC and Dark Matter: DF, Katie Freese, Brent Nelson, Pran Nath, Gregory Peim 1102.2548, PRD



CUT C_1 : $n(\ell)=0$, $p_T(j_1)\geq 150$ GeV, $p_T(j_2,j_3,j_4)\geq 40$ GeV

$$\tilde{g}\to q_i\bar{q}'_i\tilde{\chi}_1^{\pm} \text{ and } \tilde{g}\to q_i\bar{q}_i\tilde{\chi}_2^0$$

$$\tilde{\chi}_1^{\pm} \to \not{E}_T + 2 \text{ fermions}$$

$$\tilde{\chi}_2^0 \to \not{E}_T + 2 \text{ fermions}$$

Theory

$$2m_{\tilde{\chi}_1^0}\simeq m_{\tilde{\chi}_1^{\pm}}\simeq m_{\tilde{\chi}_2^0}\simeq \frac{1}{4}m_{\tilde{g}}$$

$m_{\tilde{g}}$	m_h	$m_{\tilde{\chi}_1^0}$	$m_{\tilde{\chi}_1^{\pm}}$	$m_{\tilde{q}}$	$m_{\tilde{t}_1}$	$m_A\simeq m_H$
476	119	60	117	2959	1668	2608

LHC

$\sigma_{\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0}/\sigma_{\text{total}}$; $47\%\pm 2.5\%$

$\sigma_{\tilde{g}\tilde{g}}/\sigma_{\text{total}}$; $28\%\pm 3.3\%$

$\sigma_{\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}}/\sigma_{\text{total}}$; $23\%\pm 1.3\%$

$$m_{\text{eff}}^{\text{peak}}/m_{\tilde{g}} = 1.52\pm 0.055$$

$$m_{\text{eff}} = \sum_{i=1}^{4} p_T(j_i) + \not{E}_T,$$

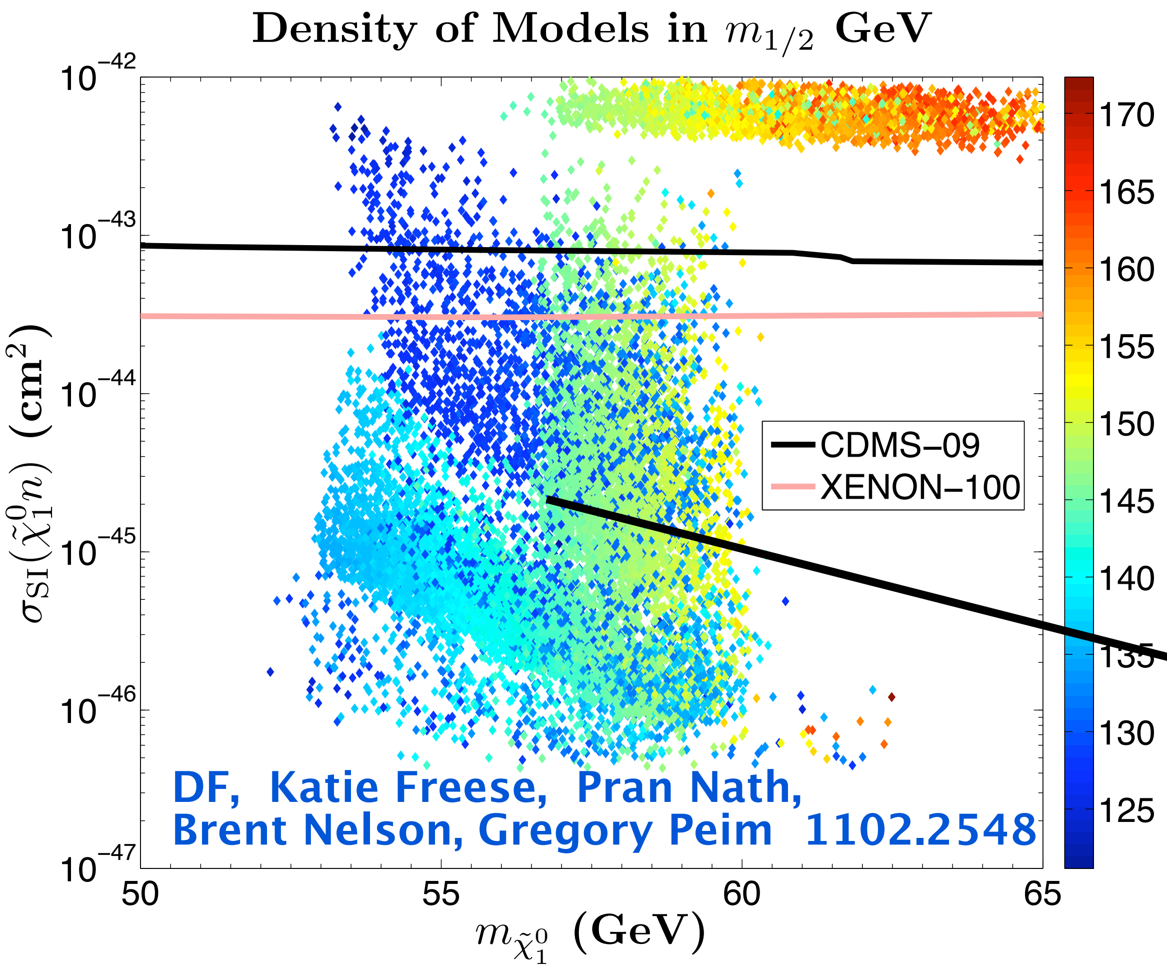
Dark Matter

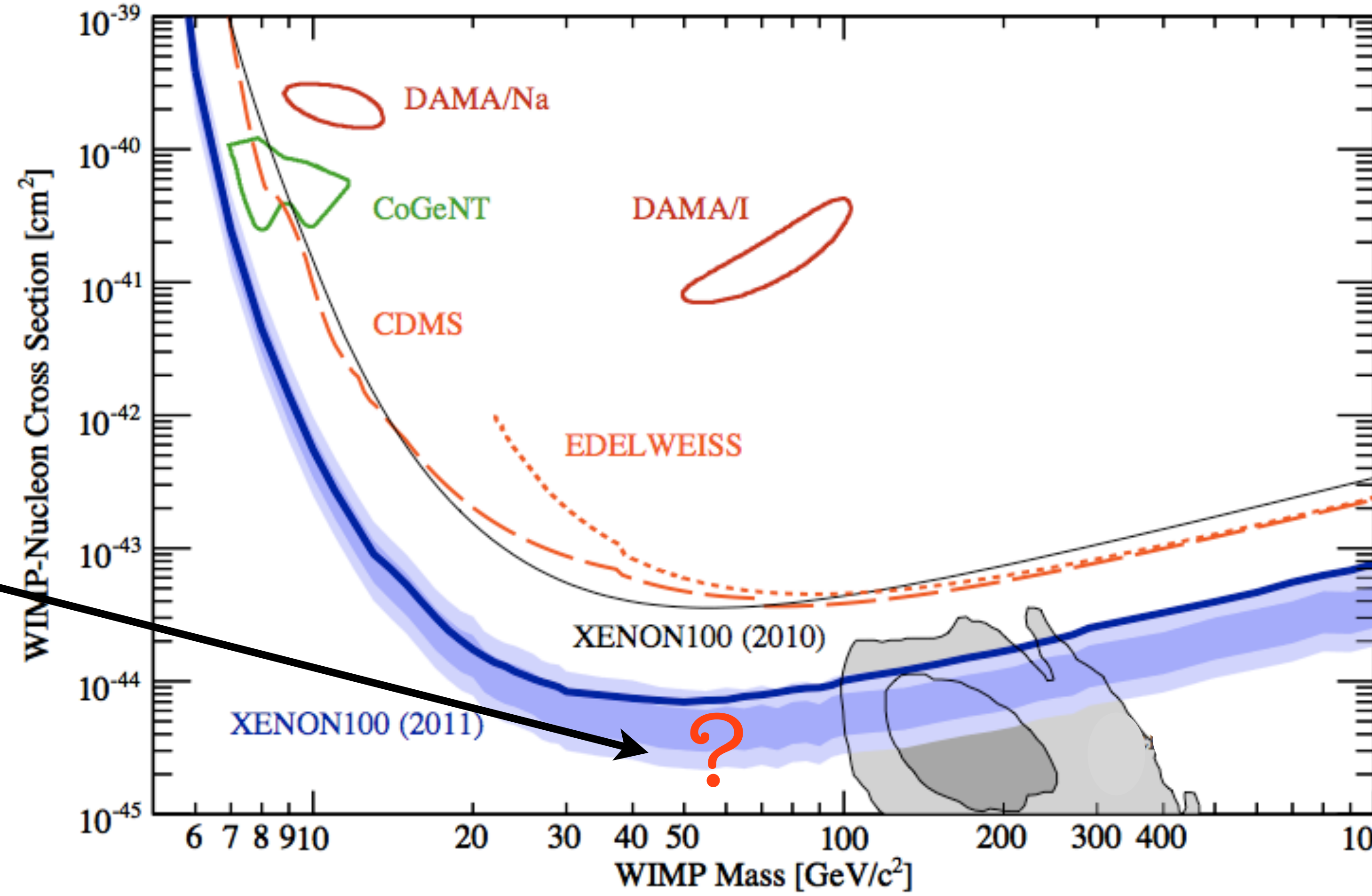
$$\Omega_{\text{CDM}}h^2 = 0.1120\pm 0.0056 \quad \text{(today)}$$

$$\tilde{\chi}_1^0\tilde{\chi}_1^0\to h\to b\bar{b},\tau\bar{\tau},c\bar{c}\ldots \quad (2m_{\tilde{\chi}_1^0}\lesssim m_h)$$

LHC CAN OBSERVE THIS NOW WITH ~(1-5) fb^{-1} IF IT EXISTS

Higgs-Pole and Dark Matter on the Hyperbolic Branch





Measure Edge Position

→ Dark Matter Mass

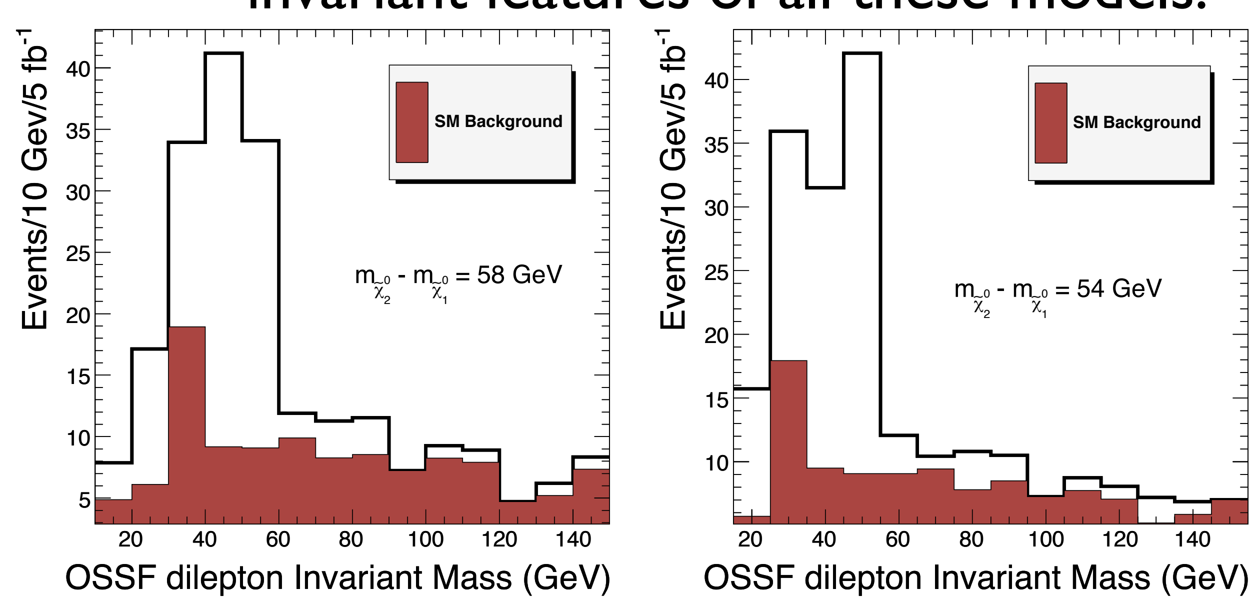
due to gaugino mass scaling

- h-res : Most Sensitive region to SI bounds ~ (50 - 65) GeV
- squarks > few TeV , gluino < 550 GeV ($M_a = m_{1/2}$)

- Dilepton edge **(Baer/Tata/Paige/Chen '95)**

Specifically, 2L will be seen or excluded 1102.2548

2 sample models which capture the ~invariant features of all these models:



$m_{\tilde{\chi}_1^0}$ predicted to be 60 GeV and 55 GeV

Very Low Mass Dark Matter and SI scattering

- No CoGeNT Solution in models with only MSSM spectra with radiative breaking via RGE flow (this is SUGRA with non-universal soft breaking) upper limit on cross section obtained.

Low Mass Neuralino Scattering and (Dama+Cogent) Compatible Size $\sigma_{SI} \in\sim (3 \cdot 10^{-41} - 10^{-40})\text{cm}^2$ with MSSM field Content?

1. **MSSM - REWSB from SUGRA (non-universal)**
   Feldman, Liu, Nath, [arXiv:1003.0437 PRD]
   ♦ B-physics, Higgs Search Limits, Chargino Mass, RD,
   $\longrightarrow \sigma_{SI} \lesssim 5 \times 10^{-42}\text{cm}^2 \quad M_{\tilde{\chi}^0} \in (5-15), [M_{\tilde{\chi}^0} > 30 \text{ GeV}$ (after all constraints)]
2. **MSSM - Weak scale with EWSB**
   Kuflik, Pierce, Zurek, [arXiv:1003.0682 PRD]
   ♦ B-physics, Higgs Search Limits, Chargino Mass, Z width
   $\longrightarrow \sigma_{SI} \lesssim 5 \times 10^{-42}\text{cm}^2$ in relevant region $M_{\tilde{\chi}^0} \in (5-15)$ GeV
3. **MSSM - Weak scale with EWSB**
   Vasquez, Belanger, Boehm, Pukhov, Silk, [arXiv:1009.4380]
   ♦ B-physics, Higgs Search Limits, Chargino Mass, Z width, RD
   $\longrightarrow \sigma_{SI} \lesssim 4 \times 10^{-42}\text{cm}^2$ *also finds* $M_{\tilde{\chi}^0} > 28$ GeV

MSSM attempts with Majorana LSP fail : bsgamma, bsmumu, **Higgs LHC/Tevatron**

NMSSM probes : J. Gunion, T. Tait, D. Hooper, A. Belikov, P. Draper, T. Liu, C. Wagner, L.T. Wang , H. Zhang et al

Theory can allow for many different possibilities. Many different mass hierarchies arise.

Well motivated theories do lead to ~ sub-TeV gauginos with scalars that are rather 'heavy'.

- SUSY scalars several TeV, 10s of TeV, or more - Gaugino three body decays and radiative decays
- Gluino decays into 2 jets + Dark Matter $\tilde{g} \to q\bar{q}\tilde{\chi}_1^0$
- Gluino decays into 1 jet + Dark Matter $\tilde{g} \to g\tilde{\chi}_1^0$
- Gluinos decay into n jets + Dark Matter via Chargino & heavier Neutralino cascades

$$\tilde{g} \to q\bar{q}\tilde{\chi}_{k>1}^0$$

$$\tilde{g} \to q_d\bar{q}_u\tilde{\chi}_{m=1,2}^+ + \text{h.c.}$$

Gluino decays

- Haber/Kane '82
- Barbieri, Gamberini, Giudice, Ridolfi
- Baer, Tata, Woodside

<u>Recent Realization</u> : GNLSP in SUGRA

GNLSP out of the Sparticle Landscape

- One of the interesting possibilities that arises within the landscape of possible sparticle mass hierarchies is that the gluino $(\tilde{g})$ is the next to the lightest supersymmetric particle (NLSP) where neutralino dark matter produces the correct relic abundance of such matter consistent with the WMAP observations.

NUSP	Mass Pattern
NUSP13	$\widetilde{\chi}^0 < \tilde{g} < \widetilde{\chi}_1^{\pm} \lesssim \widetilde{\chi}_2^0$
NUSP14	$\widetilde{\chi}^0 < \tilde{g} < \widetilde{t}_1 < \widetilde{\chi}_1^{\pm}$
NUSP15	$\widetilde{\chi}^0 < \tilde{g} < A \sim H$

Table: Hierarchical sparticle mass patterns for the four lightest sparticles, where $\tilde{\chi}^0 \equiv \tilde{\chi}_1^0$ is the LSP neutralino, and where the gluino is the NLSP that arises in the NUSUGRA models. Mass patterns given in FLN arXiv:0711.4591, Phys.Lett.B662:190-198, (2008)

singlet + nonsinglet F breaking in E6, SO(10), SU(5)

- - Will refer to this subclass of NUSUGRA where **Relic Density constraints are satisfied** as the **GNLSP** class of models.

$$\sigma_{\rm eff} = \sum_{i,j} \gamma_i \gamma_j \sigma_{ij} \simeq \sigma_{\tilde{g}\tilde{g}} \gamma_{\tilde{g}}^2 + 2\sigma_{\tilde{g}\tilde{\chi}_1^0} \gamma_{\tilde{g}} \gamma_{\tilde{\chi}_1^0} + \sigma_{\tilde{\chi}_1^0 \tilde{\chi}_1^0} \gamma_{\tilde{\chi}_1^0}^2 \simeq \sigma_{\tilde{g}\tilde{g}} \gamma_{\tilde{g}}^2$$

SUSY: Jets + Missing E_T

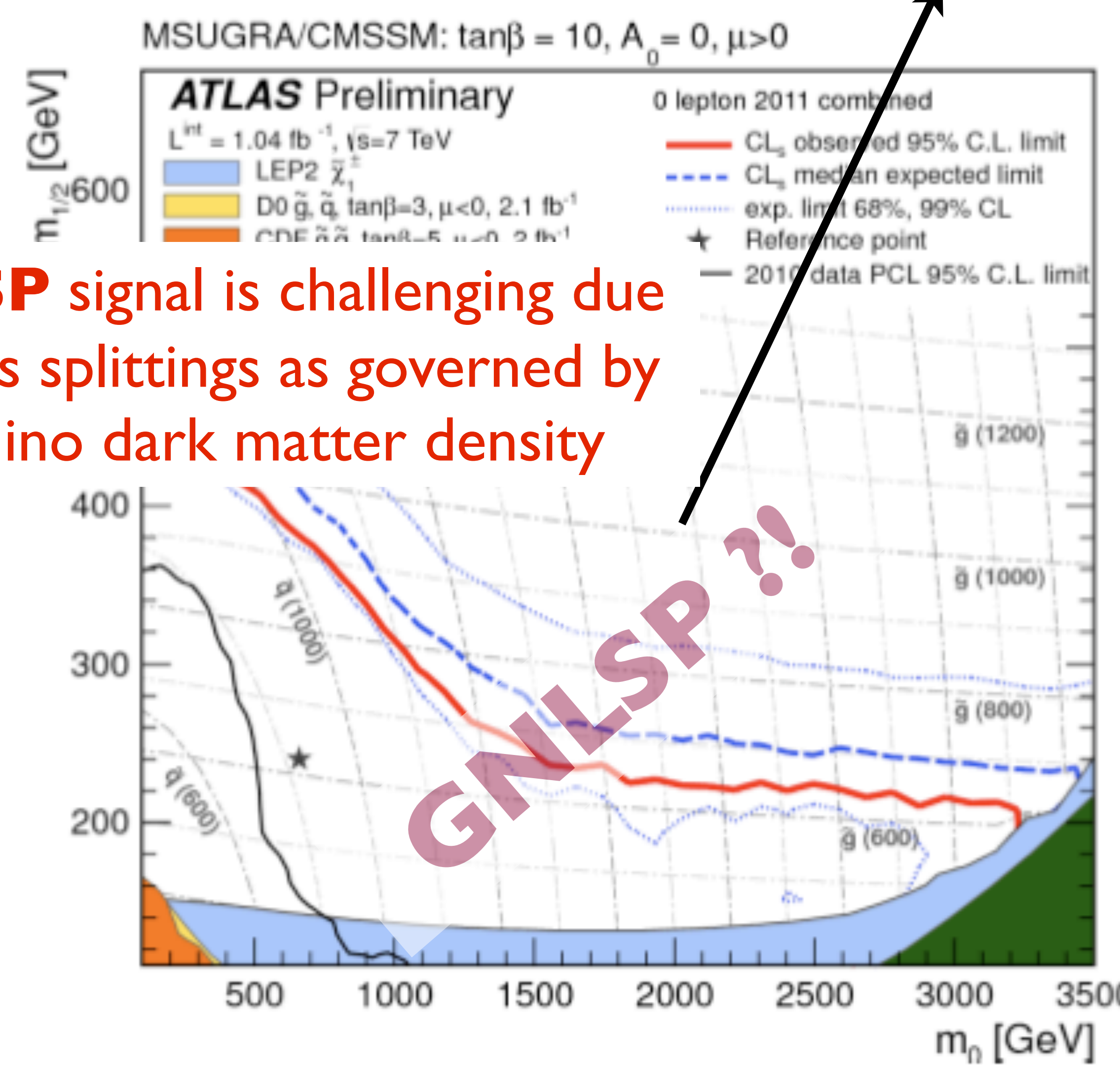
$\tilde{q} \rightarrow q\tilde{\chi}_1^0$

$\tilde{g} \rightarrow qq\tilde{\chi}_1^0$

(DF's invasion of this slide)

- ATLAS:
  - → $m_{eff} = H_T$ + Missing E_T
  - → Optimize cut on m_{eff} and Missing ET for each jet multiplicity
  - → Combine 5 channels

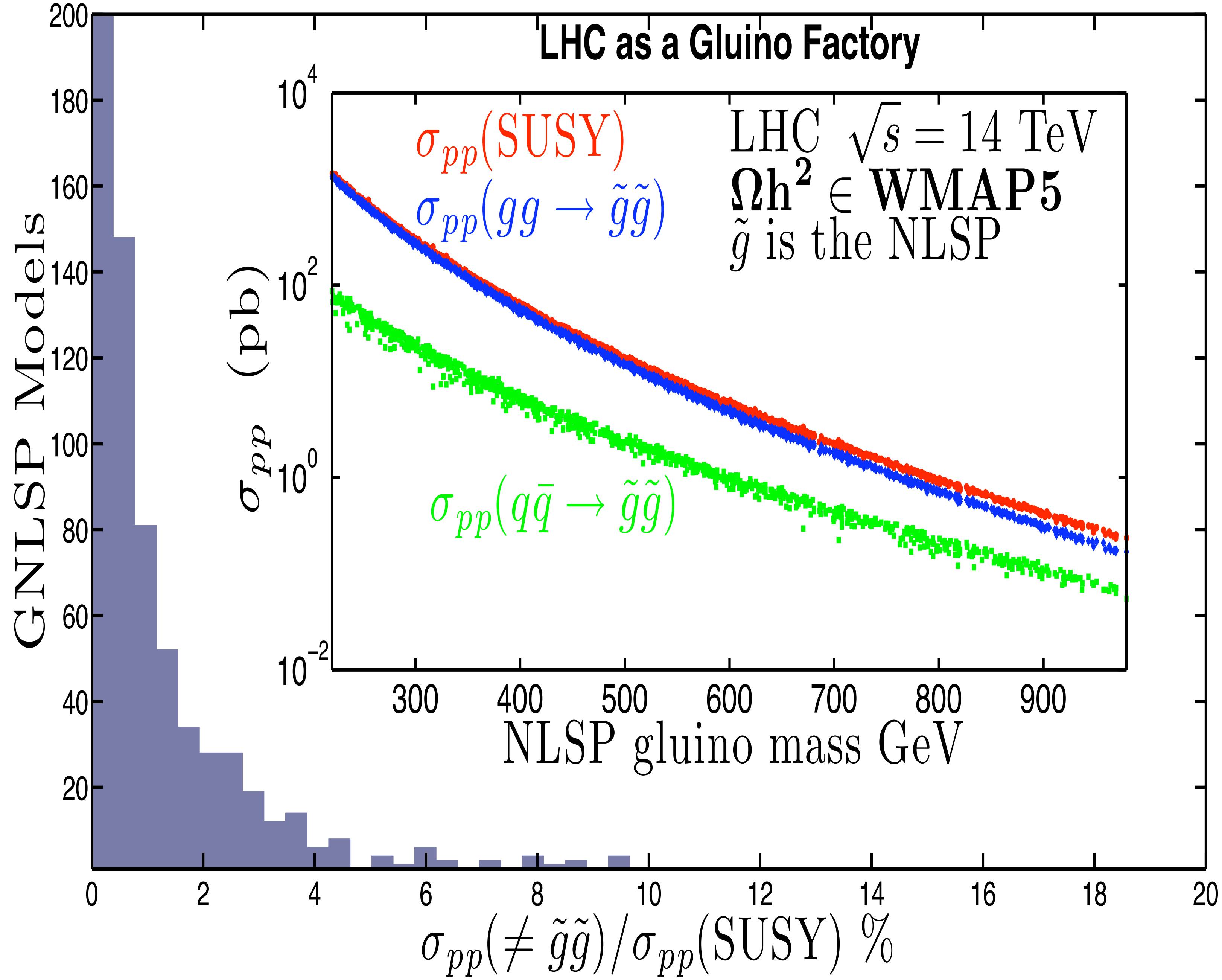
Signal Region	≥ 2 jets	≥ 3 jets	≥ 4 jets	High mass
E_T^{miss}	> 130	> 130	> 130	> 130
Leading jet p_T	> 130	> 130	> 130	> 130
Second jet p_T	> 40	> 40	> 40	> 80
Third jet p_T	–	> 40	> 40	> 80
Fourth jet p_T	–	–	> 40	> 80
$\Delta\phi(\text{jet}, E_T^{miss})_{min}$	> 0.4	> 0.4	> 0.4	> 0.4
E_T^{miss}/m_{eff}	> 0.3	> 0.25	> 0.25	> 0.2
m_{eff} [GeV]	> 1000	> 1000	> 500/1000	> 1100



GNLSP signal is challenging due to mass splittings as governed by neutralino dark matter density

Lepton-Photon 2011

LHC as Gluino Factory; FLN arXiv:0905.1148, PRD 09



Signal is challenging due to mass splittings as governed by neutralino dark matter density

Present constraint
LHC-7 1/fb on GNLSP ~ 400-450 GeV
(see 1011.1246) PRD 2011

$$\Delta_{co} = (m_{\tilde{g}} - m_{\tilde{\chi}})/m_{\tilde{\chi}}$$
$$\in (10 - 20)\%$$

GNLSP via RGE

DF, Liu, Nath
0711.4591,0802.4085, 0905.1148, 1011.1246

Alwall, Wacker, Nojiri, Maltoni et al
-Emphasized ISR (and FSR) and matching
-matching of jets from parton showers and matrix elements.
see e.g. **0803.0019**
-Work by the **Bartol Group**
(see talk by T. Li)
- See also **Martin 1105.4304**

Overwhelming dominance of the $\tilde{g}\tilde{g}$ production process for the GNLSP. Actually, a large number of events pass triggers .... Gluino ~Detailed Balance $\Omega h^2 \leftrightarrow LHC\ \ subprocess$

Gluino-Neutralino Coannhilation (GNLSP) satisfies Relic Density Constraints.
GNLSP is a motivated example of a simplified model.

Paradigm Re-Shift

- Everything discussed so far has been in the framework of effective theories working in the limit that Planck Scale interactions can be ignored.
- However, the supergravity Lagrangian does contain interactions of gravitinos, moduli, modulinos, ...
- These fields couple to everything (due to gravitational interactions) and their interactions can have important cosmological consequences.
- Including such interactions, our picture of Weak Scale SUSY can be altered.
- In fact ...

- 30 years ago is was deduced that if the gravitino, $M_{3/2}$, coupled to SM fields, then $M_{3/2} \gtrsim 10\ \mathrm{TeV}$ is need to avoid constraints on its decay from cosmology; (destruction of light elements) (Weinberg 1982).

$$\Gamma_\phi = \alpha\ M_\phi^3/M_P^2\ , \qquad T_R \sim \sqrt{\Gamma_\phi M_P} \qquad M_\phi \sim M_{3/2}$$

- SUGRA and STRINGS scalar soft breaking masses/couplings generically of size :

$$(\hat{m}_\alpha, \hat{A}_{\alpha\beta\gamma}, \hat{B}_{\alpha\beta}) \sim \mathcal{O}(M_{3/2}) \qquad \text{(Arnowitt/Cham/Nath '82)}$$

- Weinberg G-problem is re-interpreted in terms of **moduli masses**

Early Realization In context of the Polonyi field: Coughlan, Fischler, Kolb, Raby, Ross, Ovrut, Steinhardt

- implications ... Remark: this assumes minimal field content
  - Moduli mass $\gtrsim$ (10 -30) TeV, (BBN)
  - Moduli mass $\gtrsim$ (30 -50) TeV, (WMAP) (being revisited)
  - Assumes energy density is completely converted into radiation
  - Both bounds above are model dependent (coupling size, mass LSP, cross section etc)

Mass parameters in gaugino mass matrix can be suppressed:

- Examples of gaugino mass suppression in SUGRA/STRINGS:

I. (Arnowitt/Cham/Nath '83) SUGRA GUTS - Gaugino masses at 1 Loop
II. (Randall Sundrum '99) AMSB - Gaugino masses at 1 loop
III. (DeCarlos/Casas/Munoz '93), (Gaillard/Bineutry/Wu/Nelson '98,'99) (Conlon,Quevedo '06), (Acharya, Bobkov. Kane, Kumar, Shao '07, Achayra et al 2011) (common feature: non-pertub super potential and multiple moduli)

Remark: -Suppression can happen with multiple moduli.
-Can also generate a smaller **mu** parameter than scalar mass at GUT scale - For a review see Ibanez et al 97 .

- How can EWSB be broken naturally with huge scalar masses ?

$$M_{3/2} \simeq M_{\phi,mod} \simeq m_{\text{Soft Higgs}} \sim (100 - 1000) M_Z \ ?$$

- Suggests the "moduli-Higgs Hierarchy problem*"

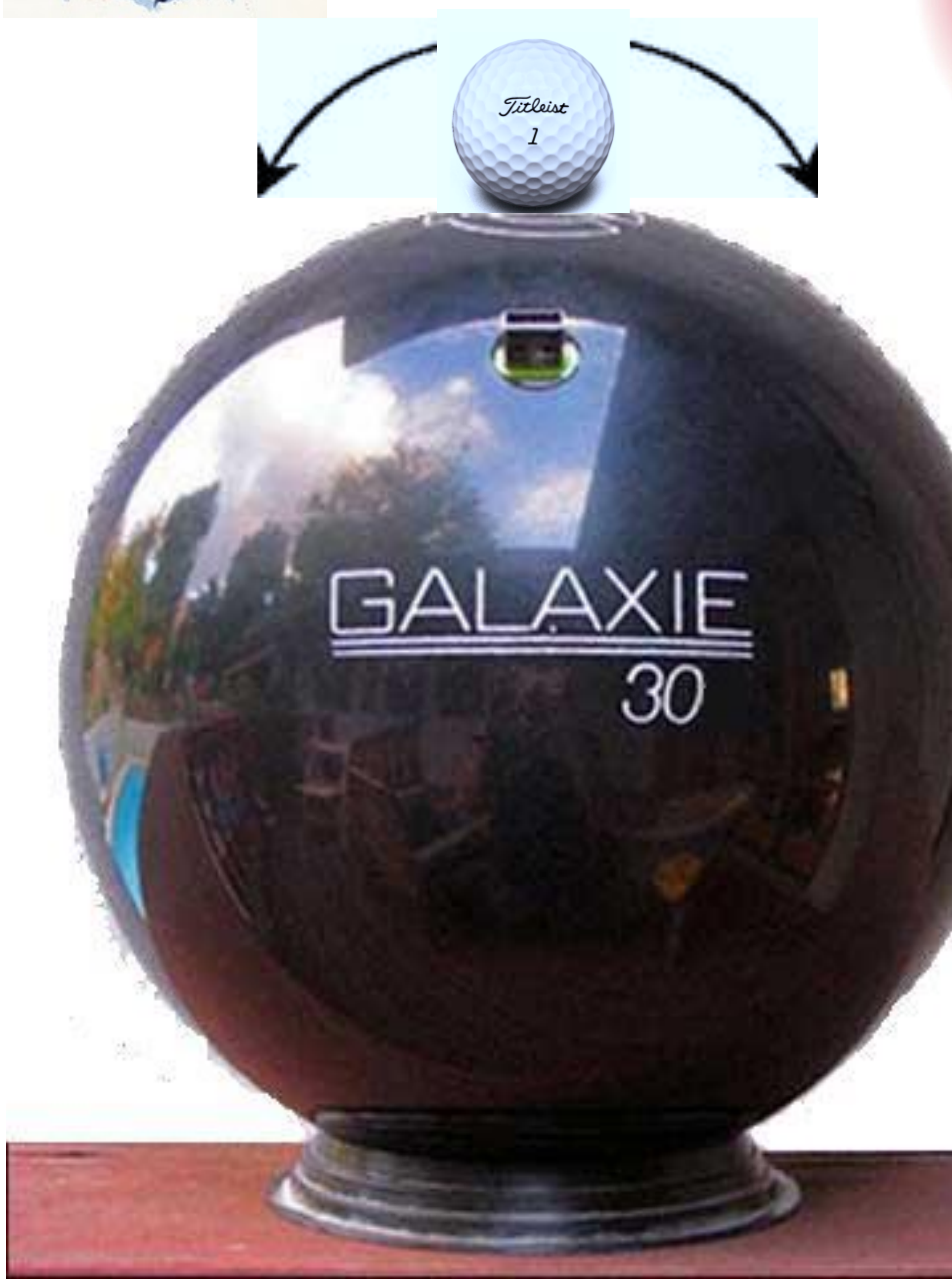
*(DF at Upenn SVP meeting 2011)

- String motivated models within the sugra paradigm do suggest a new approach to rather natural EWSB with $(10\text{-}50)$ TeV scalars. **Feldman, Kane, Kuflik, Lu arXiv:1105.3765** to appear in Phys. Lett. B

... the solution is built into REWSB

Moduli-Higgs Little Hierarchy

EWSB



246 GeV $\sim \frac{30}{100}$ TeV

Higgs Mechanism:
Gauge boson absorbs
massless Goldstone boson

local (gauge)-symmetry breaking

$$M_V = g\langle\phi_{\rm higgs}\rangle$$

Gauge
Coupling

30 TeV

Super Higgs Mechanism:
Gravitino absorbs
massless Goldstino

local (super)-symmetry breaking

$$M_{3/2} = \frac{1}{M_P}\langle F_{\phi_{\rm modulus}}\rangle$$

Gravity
Coupling

$$M_P = M_{Planck}/(\sqrt{8\pi})$$

$$M_{Planck} = \tfrac{1}{7}(6\times6\times6)^{(\pi\cdot e)}\ \text{GeV}$$

$$\mathbf{M_\phi \sim M_{3/2}}$$

Moduli Stabilized

- Soft Parameters, well known to trace out trajectories :

$$m^2_{H_u}(t) = M_0^2 f_{M_0}(t) + A_0^2 f_{A_0}(t) + M_3^2(0) f_3(t) + M_3(0) A_0 f_{\text{mix}}(t) + \ldots$$

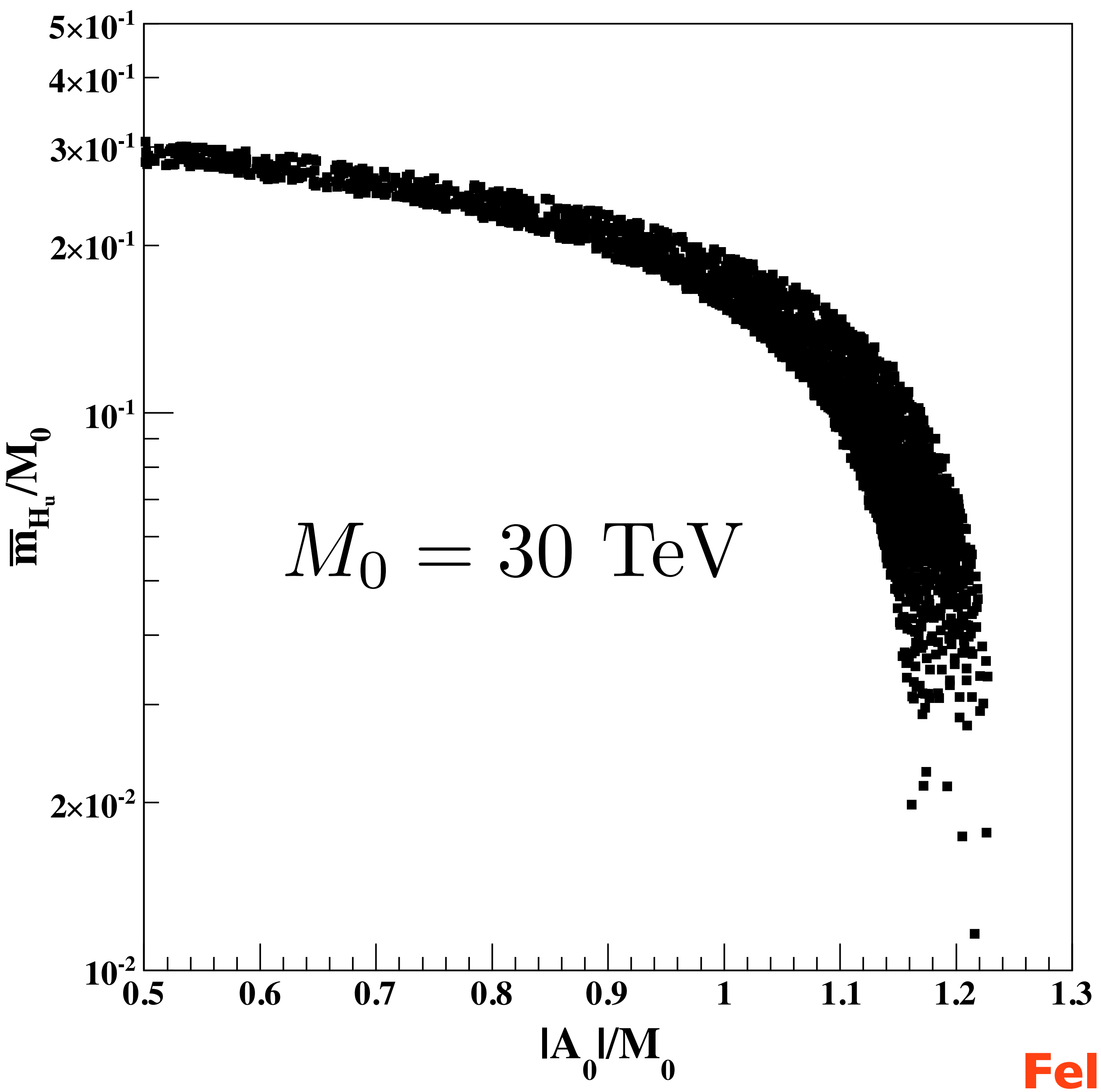
New Result : $M_0 \sim (10-50)$ TeV **can lead to rather natural EWSB** $M_0 \sim (10-50)$ TeV, f_{M_0} is positive and f_{A_0} is positive (it is formally a magnitude $|A_0|^2$ above) and (last 2 terms are small corrections) leading to:

$$m^2_{H_u}(t) \simeq M_0^2 \left[\frac{1}{2}(3\delta(t) - 1)\right] - A_0^2 \left[\frac{1}{2}(\delta(t) - \delta^2(t))\right] + small_{cor}$$

$$f_{M_0}(t) = \frac{1}{2}(3\delta(t) - 1), \quad f_{A_0}(t) = \frac{1}{2}(\delta(t) - \delta^2(t)).$$

- For heavy scalars when EWSB happens $f_{M_0} \sim f_{A_0} \sim 1/10$.
- **Intersection Point (IP)** = near intersection, of the 2 terms in square brackets, suppresses large size of $M_0 = M_{3/2} \simeq A_0$, with $M_0 \sim (10-50)$ TeV **Feldman, Kane, Kuflik, Lu arXiv:1105.3765**
- $\delta(t)$ (top yukawa) receives corrections from QCD/stop-gluino loops

Full 2-loop (RGEs) for the soft supersymmetry breaking masses and couplings, with radiative corrections to the gauge and Yukawa couplings etc.



$$M_{3/2} = M_0 \sim |A_0|$$

$$m^2_{H_u} \simeq (f_{M_0} - f_{A_0}) M^2_{3/2} \simeq 10^{-2} M^2_{3/2}$$

Intersection of RG Coefficients
"Intersection Points"

More Generally:

$M_{3/2} = 10$ TeV, $|A_0|/M_{3/2} \sim 0.9$, $\mu_{\min} \sim 300$ GeV

$M_{3/2} = 30$ TeV, $|A_0|/M_{3/2} \sim 1.2$, $\mu_{\min} \sim 900$ GeV

Large Suppression of mu

Gauginos are sub-TeV

Feldman, Kane, Kuflik, Lu arXiv:1105.3765

Figure: $M_{3/2} = M_0 = 30$ TeV and $\mu \in (0.9, 2)$ TeV with largest suppression occurring for $|A_0|/M_0 \simeq 1.2$

- **The IP will drive down the μ term** :

$$\begin{aligned}
\mu^2 &= -M_Z^2/2 + \frac{\bar{m}_{H_d}^2 - \bar{m}_{H_u}^2 \tan^2\beta}{\tan^2\beta - 1} \\
B\mu &= \frac{1}{2}\sin 2\beta(\bar{m}_{H_u}^2 + \bar{m}_{H_d}^2 + 2\mu^2) \\
\bar{m}_{H_i}^2 &= m_{H_i}^2 - T_i/v_i \ , \quad M_Z^2 = M_{Z,\text{bare}}^2 + \Re\Pi_{ZZ}^T(M_Z^2)
\end{aligned}$$

- Because $m_{H_d}^2$ barely runs, its value is really just $M_{3/2}^2$ while $B = \text{few} \times M_{3/2}$ in our model space. For $\tan\beta$ not too large, using $\bar{m}_{H_d}^2 \gg \bar{m}_{H_u}^2$ the solution for the reduced μ is

$$\mu^2 \approx \bar{m}_{H_u}^2 \frac{1}{(B^2/\bar{m}_{H_d}^2) - 1} \sim \bar{m}_{H_u}^2/2 = \mathcal{O}\left(\frac{1}{10^2}\right) M_{3/2}^2$$

- Reduction via RG running (Intersection Point) and from the tadpole corrections tadpole + tree 'tracks' the solution at the point where the loop corr. is minimized.

- Analytic solution for $\tan\beta \in (4, 15)$ - larger values do arise.

- Even lowers values of μ are obtained.

Let me now emphasize,

- There is a built in cancellation in sugra and string motivated models, or an Intersection Point (IP) of two terms in the running of the square of the up type Higgs mass which suppresses μ.

- $\mu_{min} \sim (0.3 - 1)$ TeV for $M_{3/2} \sim (10 - 30)$ TeV $\sim |A_0|$

- "lets put the trilinear coupling to zero" then you essentially miss this massive suppression
- For the scalars of size (10-50) TeV the reduced value of μ is when scalars and trilinears are of the same magnitude as the gravitino mass, as is suggested by string motivated models of soft breaking.

- **The IP represents a new approach to the little hierarchy problem for models which are cosmologically viable** : μ is of natural size about (0.3-3) TeV, for $M_0 = (10 - 50)$ TeV when $|A_0|/M_0$ is close to unity.

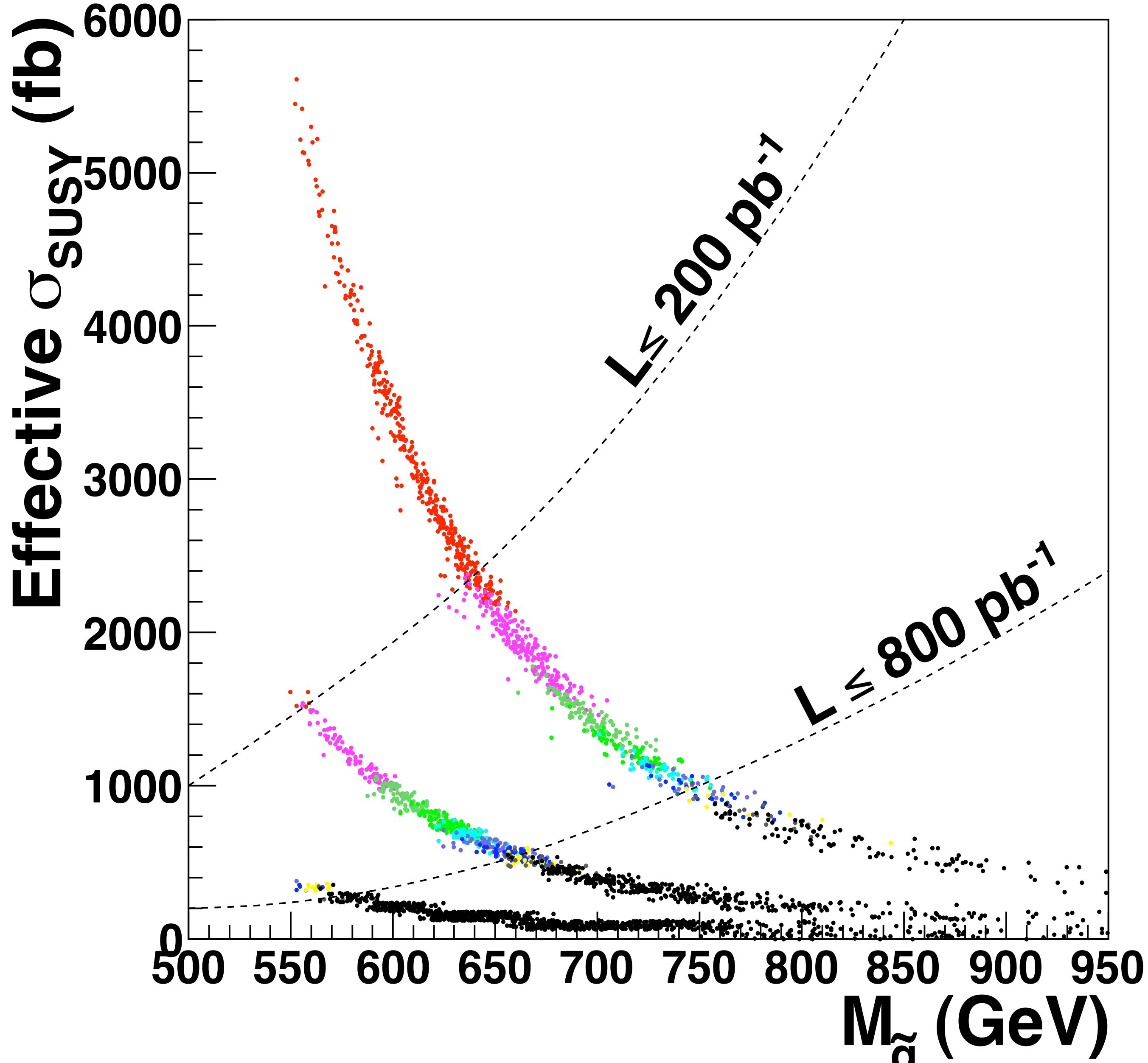
What does this mean for the LHC ?

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

14 TeV

10 TeV

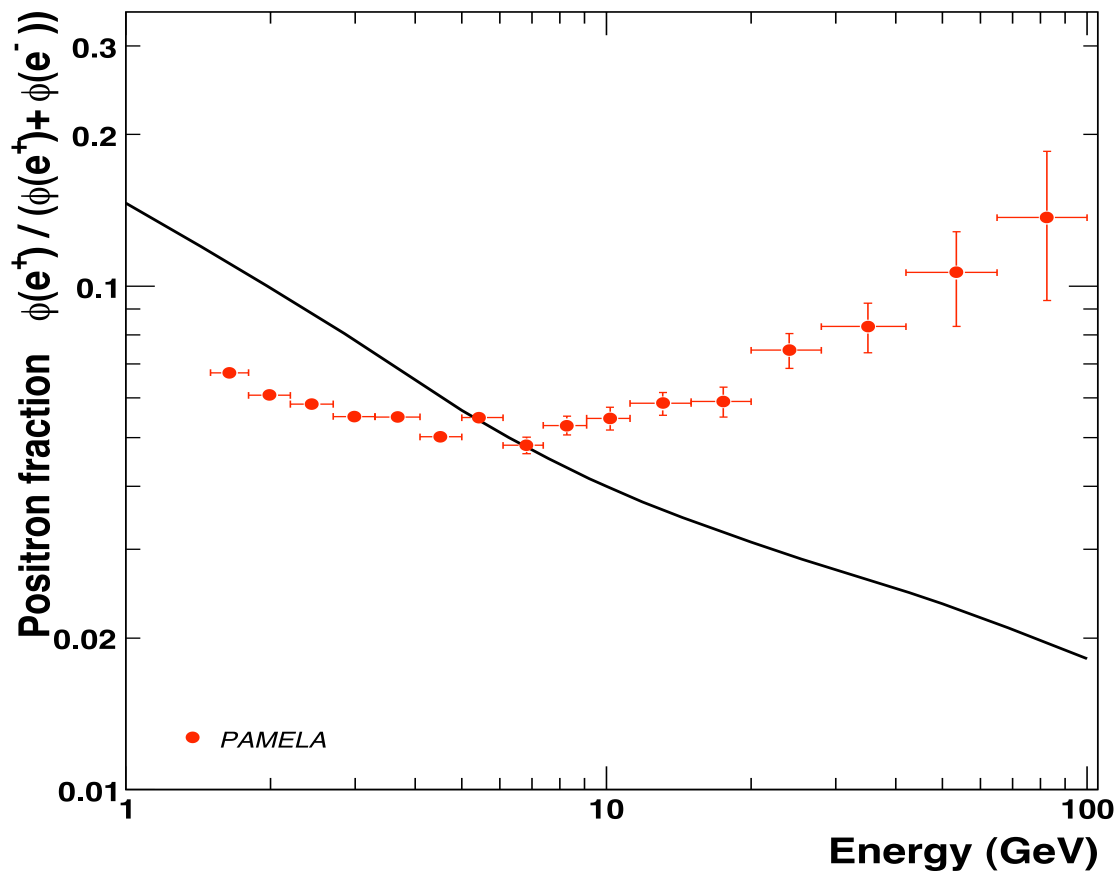
7 TeV



- **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

PAMELA - Galactic Positrons - What's the connection?



"Observation of an anomalous positron abundance in the cosmic radiation"
By PAMELA Collaboration, e-Print: arXiv:0810.4995 [astro-ph] (**Nature**)
and
e-Print: arXiv:0810.4994 [astro-ph], (**PRL**).

Puzzle: DM explanation must be consistent with WMAP.
WMAP-PAMELA "Inverse-Problem" (literally)

$$\Omega_{CDM} h^2 \propto [\int < \sigma v >]^{-1}$$

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. **Thermal Higgsino LSP!** Not constrained by Photons and can produce PAMELA ! Chen,Feldman,Liu, Nath, Peim arXiv:1010.0939
4. **Non-thermal wino LSP** with the relic abundance explained via moduli decay Randall and Moroi 99, Kane et. al (Kane, Lu, Watson 09)

Common Feature is mass sensitivity:

1. BWE sensitive to mass $M_{Z'} \sim 2m_{Dirac}$
2. Thermal wino-like and Higgsino-like $m_{LSP=\widetilde{\chi}^0} \sim m_{\xi_a}$
3. Non-thermal wino $m_{\widetilde{\chi}^0} \sim m_{\widetilde{\chi}^\pm_1}$

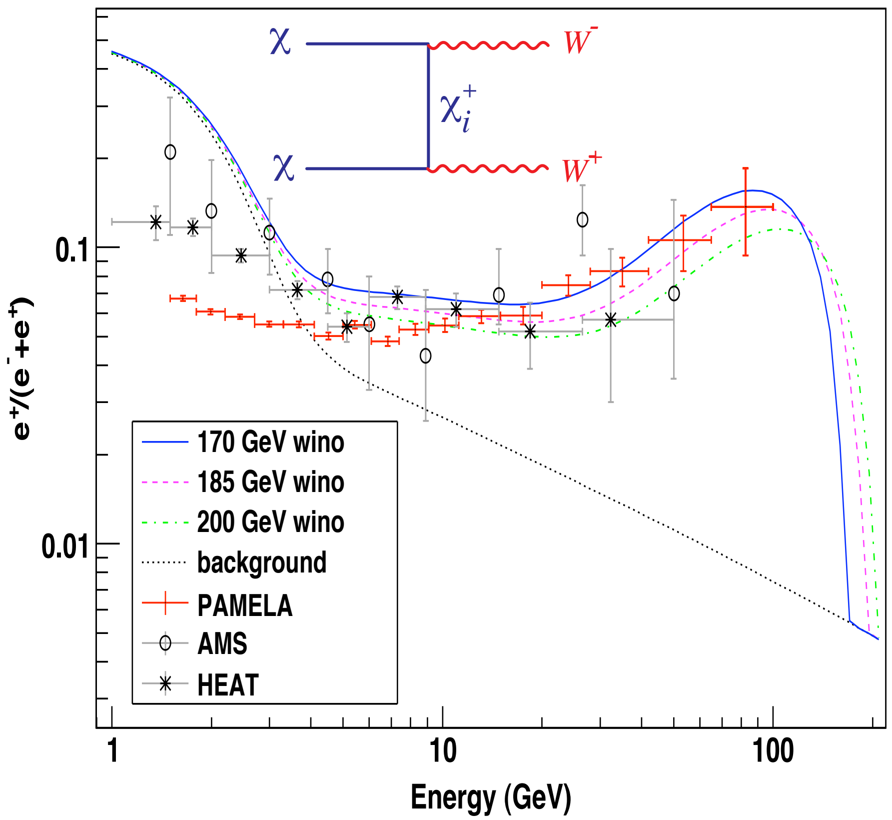
SUSY Models can lead to a light gluino at the LHC

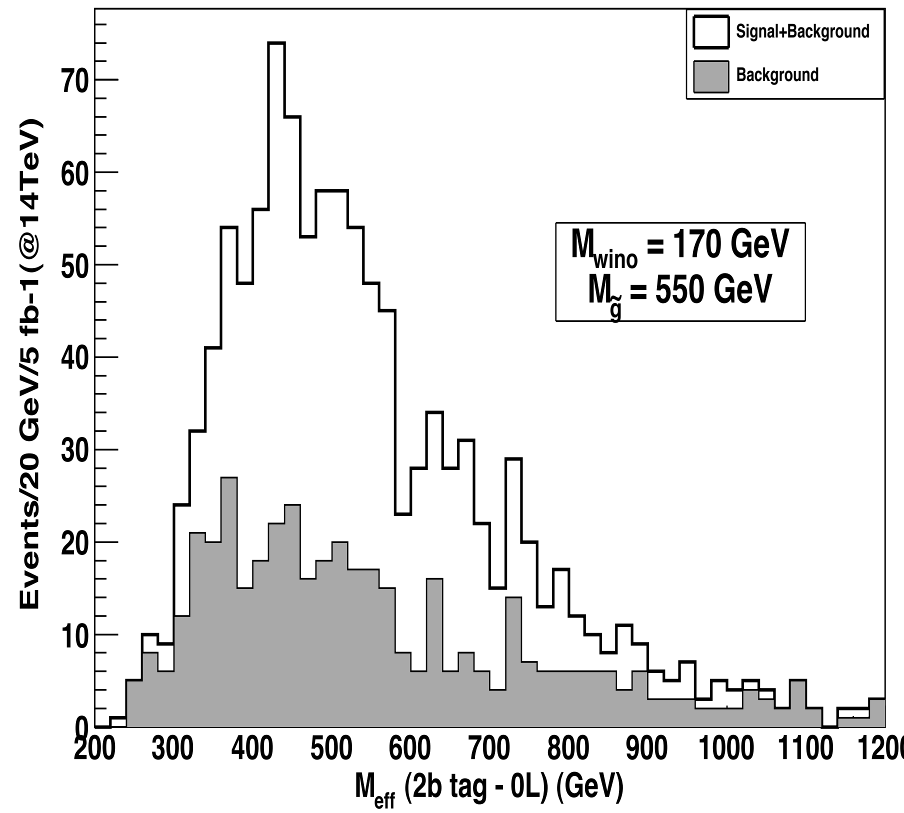
SUSY: Large flux into positrons

Turner, Wilczek, Kamionkowski, Griest, Randall, Moroi, Feng, Matchev, Kane, Wells, Wang, Pierce, Watson, Grajek, Phalen, Hisano, Kawasaki, Khori, Nakayama, Lu, DF, Nath, Liu, Nelson

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

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



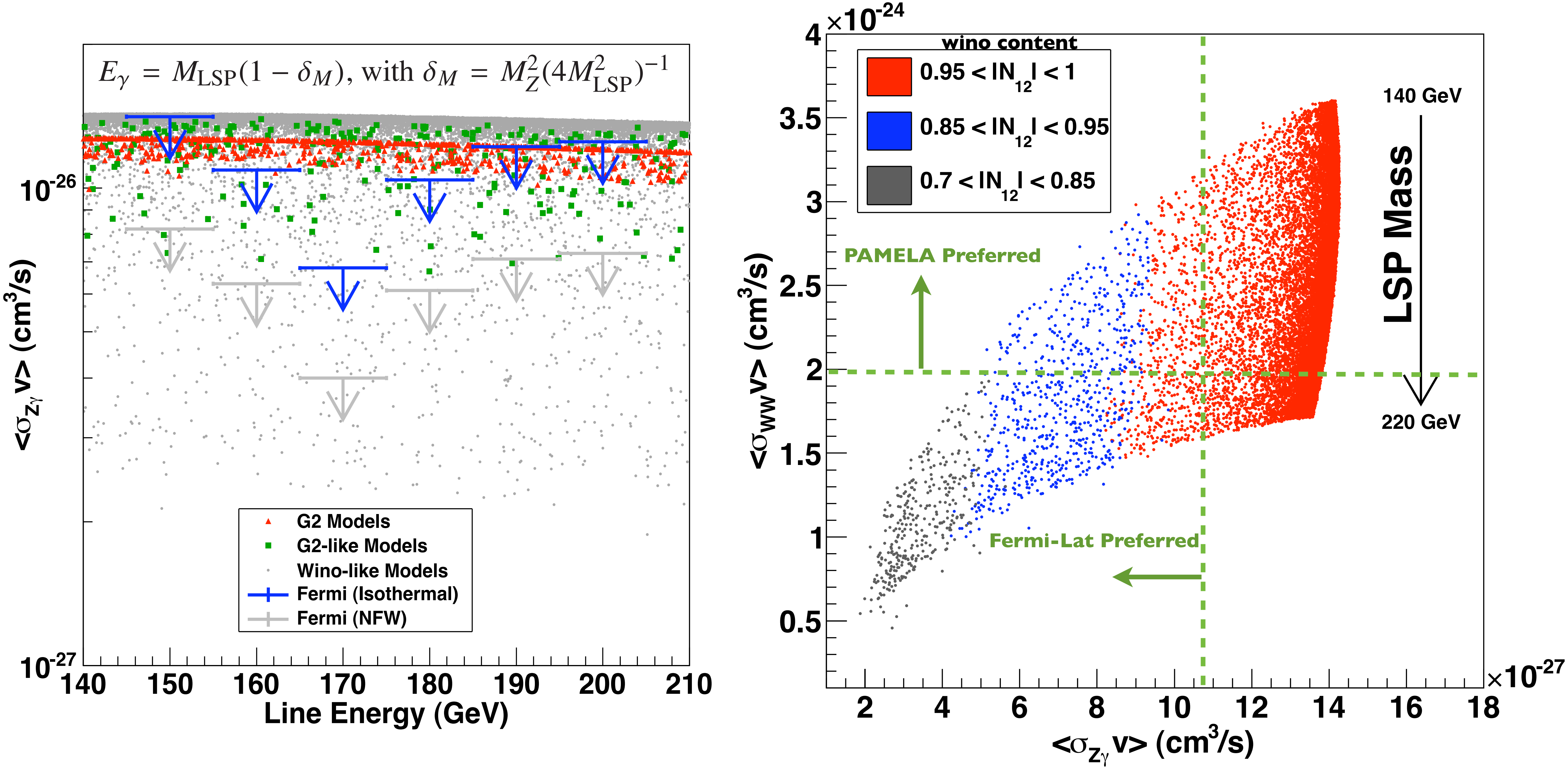


- Models are dominantly wino-like with lighter gluinos
- Dominant production $pp \to [(\tilde{g}\tilde{g}), (\widetilde{W}\widetilde{C}_1), (\widetilde{C}_1^{\pm}, \widetilde{C}_1^{\mp})]$.
- $\tilde{g}$ Decays: $\tilde{g} \to [(\widetilde{N}_2 t\bar{t}), (\widetilde{W} b\bar{b}), (\widetilde{W} q\bar{q}), (\widetilde{C}_1^{-} \bar{b}t + \text{ h.c.}), (\widetilde{C}_1^{-} \bar{d}u + \text{ h.c.})]$
- 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

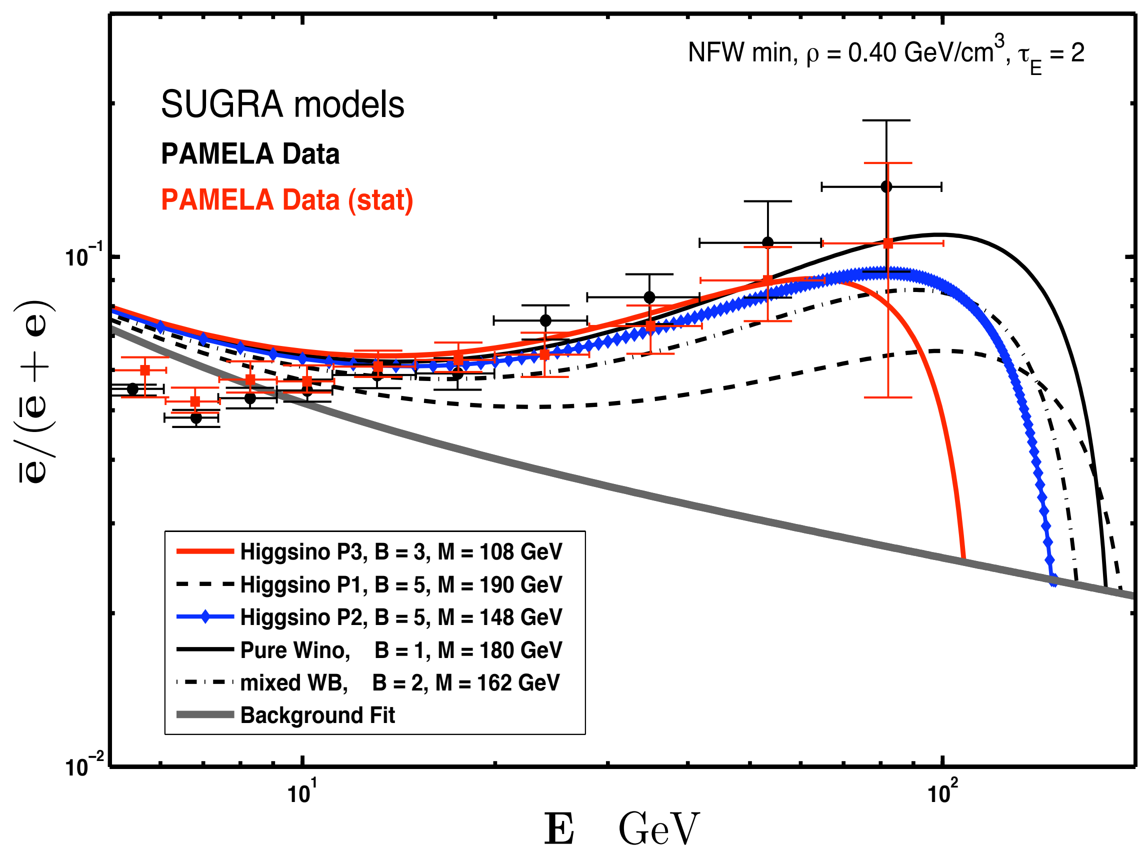
Photons from LSP ann: Bergstrom, Ullio, Bern, Gondolo, Perelstein

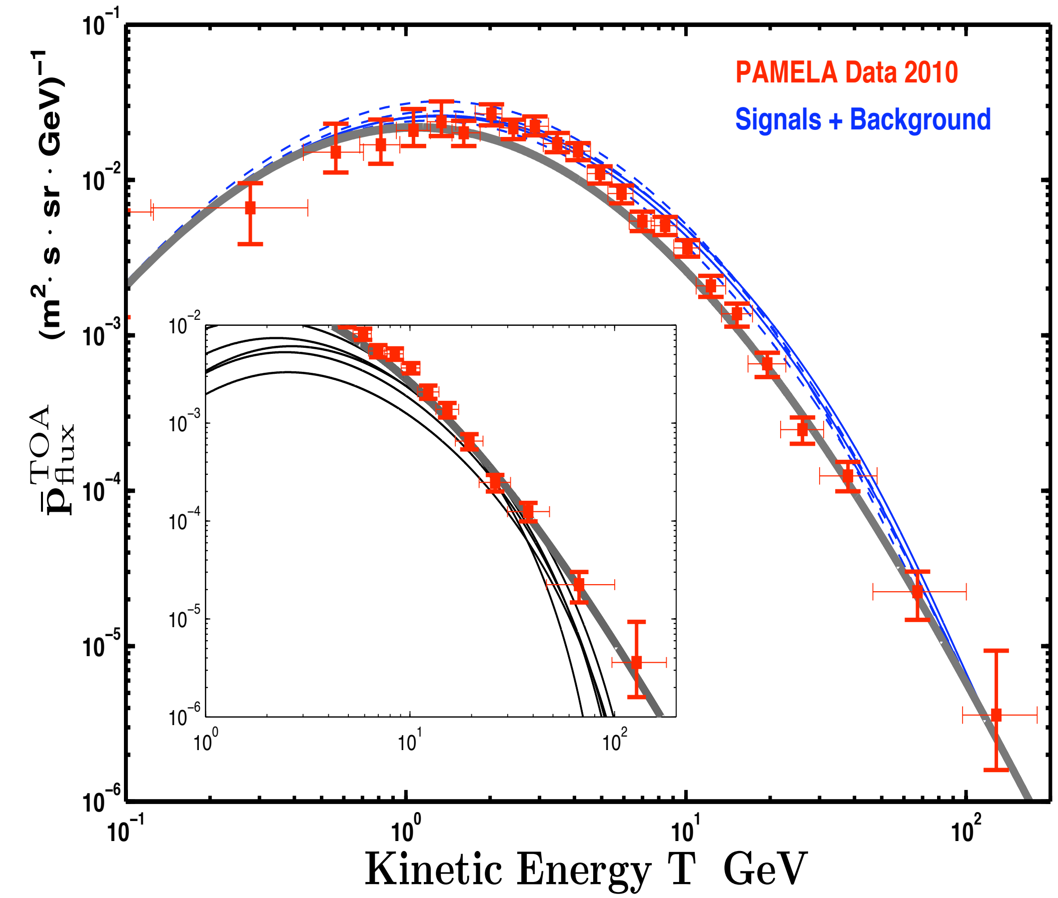
- Wino-LSP being probed. Admixture of Higgsino can support large $<\sigma v>_{WW}$ and has smaller $<\sigma v>_{\gamma Z}$. The constraint on $<\sigma v>_{\gamma Z}$ where monochromatic photons arise via loop diagrams in the neutralino annihilation processes $\chi\chi \rightarrow \gamma\gamma, \gamma Z$. I argue this is the strongest constraint on SUSY models from astrophysics to date.



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

PAMELA and LHC: Higgsino and Mixed Wino





Higgsino ALSO avoids Photon constraint

N. Chen, G. Peim, DF, Z. Liu, & P. Nath arXiv:1010.0939

Relic Density can be **ENHANCED** relative to MSSM
("Boost" in the Relic Density)

LSP is mostly Higgsino or mixed Wino with very weak components in the hidden sector

hep-ph/0610133, arXiv:0907.5392
DF, Boris Kors, Pran Nath, Zuowei Liu, Brent Nelson,

"Stino", "Stueckelino", "String Photini"

... Dark Sectors

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

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

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

- 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 $s = (v,h)$.

Origin of the 'Dark Force' and Hidden Sector Dark Matter with Massive $\mathrm{U(1)_X}$

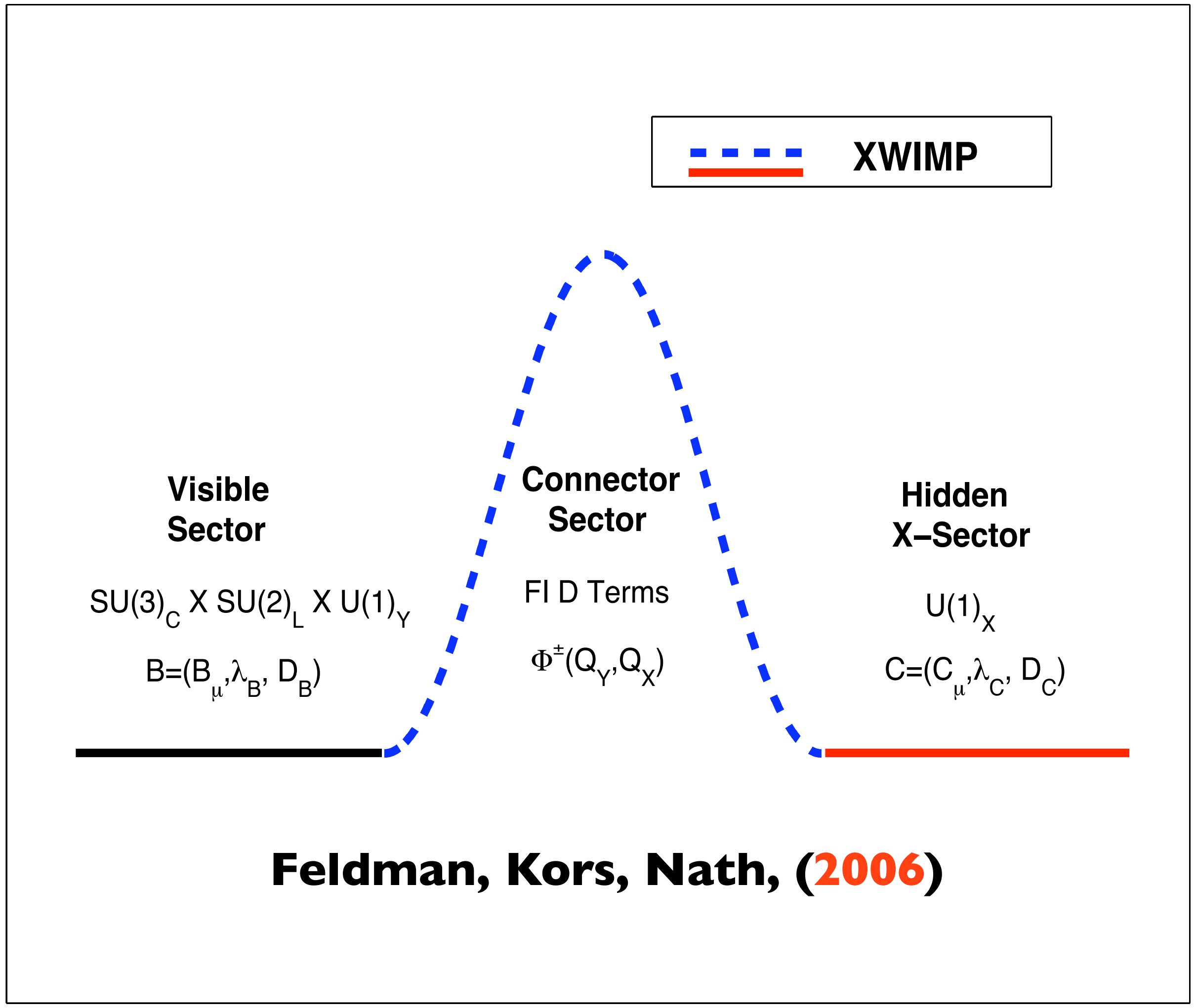


Figure: New matter arises from **Dark sector** and interacts with **visible sector** and interaction made possible through a **connector sector**.

- Include standard gauge Lagrangian and chiral interactions for $U(1)_{X,Y}$ but have **chiral connector fields** $D_\mu\phi^\pm = (\partial_\mu \pm i g_X Q_X C_\mu \pm i g_Y Y_\phi B_\mu)\phi^\pm$
- **FID terms** $\mathcal{L}_{\mathrm{FI}} = \tilde{\xi}_X D_C + \tilde{\xi}_Y D_B$
- $V_{\mathrm{FID}} = \frac{g_X^2}{2}\left(Q_X|\phi^+|^2 - Q_X|\phi^-|^2 + \xi_X\right)^2 + \frac{g_Y^2}{2}\left(Y_\phi|\phi^+|^2 - Y_\phi|\phi^-|^2 + \xi_Y\right)^2$

Feldman, Körs and Nath, Phys. Rev. D 75, 023503 (2007) [arXiv:hep-ph/0610133], 2006

Dual to Stueckelberg Mass Generation in limit of large vev

Hidden dark matter, kinetic & mass mixing + <u>MASSIVE vector</u>

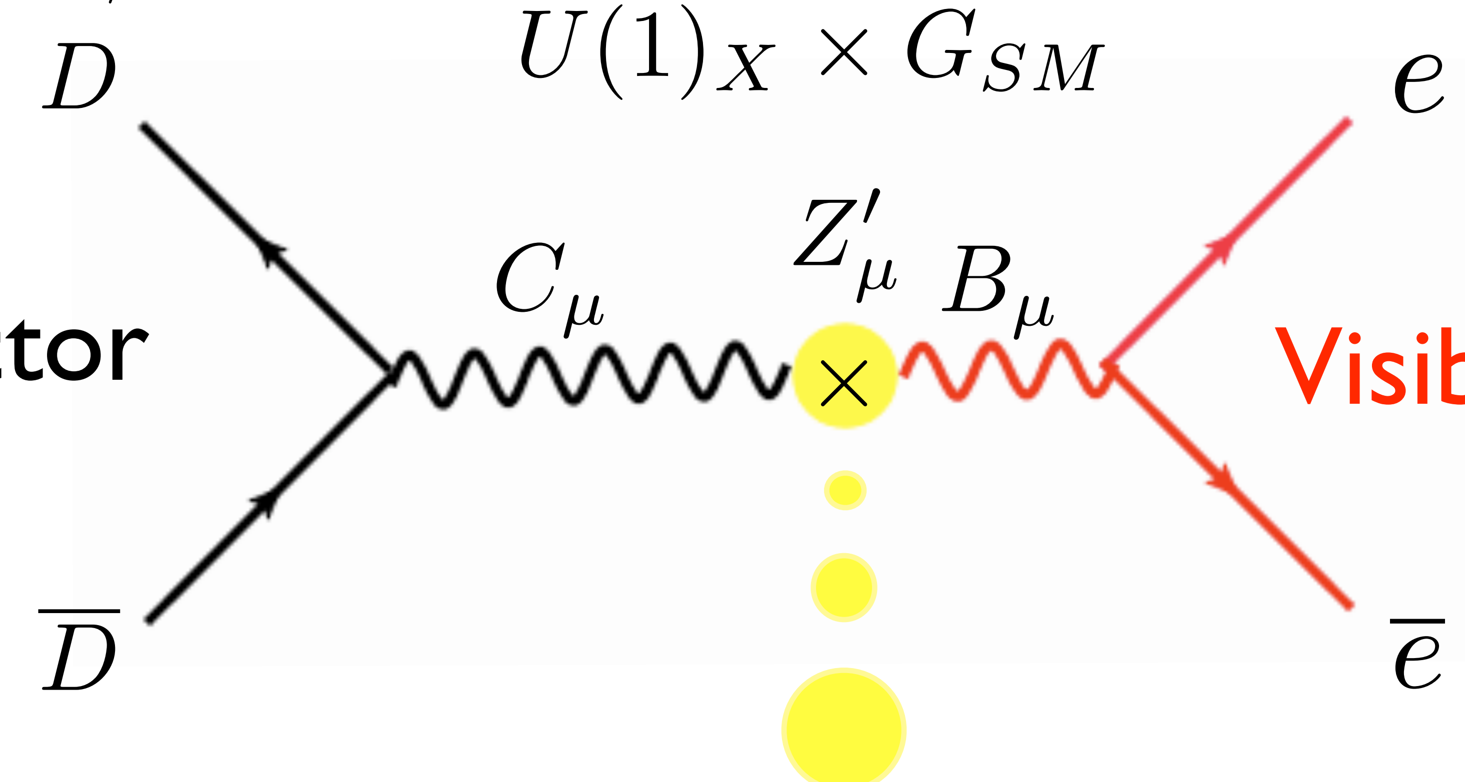
Dark Sectors, Dark Forces : hep-ph/0610133 (FKN) **hep-ph/0702123** (FLN)

Feldman, Kors, Nath, Liu (2006,2007), Cheung, Yuan (2007), Pospelov, Ritz, Voloshin (2007), Arkani-Hamed et al (2008) + ...

$$\text{Dirac Fermion Dark Matter} = \chi \equiv D$$

$$Q_{SM}|Hidden\rangle = Q_X|SM\rangle = 0$$

Hidden Sector



Visible Sector

Stueck Mass

$$\Delta\mathcal{L}_{\rm StKM} = -\frac{1}{4}C_{\mu\nu}C^{\mu\nu} - \frac{\delta}{2}B_{\mu\nu}C^{\mu\nu} - \frac{1}{2}(M_1 C_\mu + M_2 B_\mu + \partial_\mu\sigma)^2 + g_X J^\mu_X C_\mu + \mathcal{L}_{\rm g.f.}$$

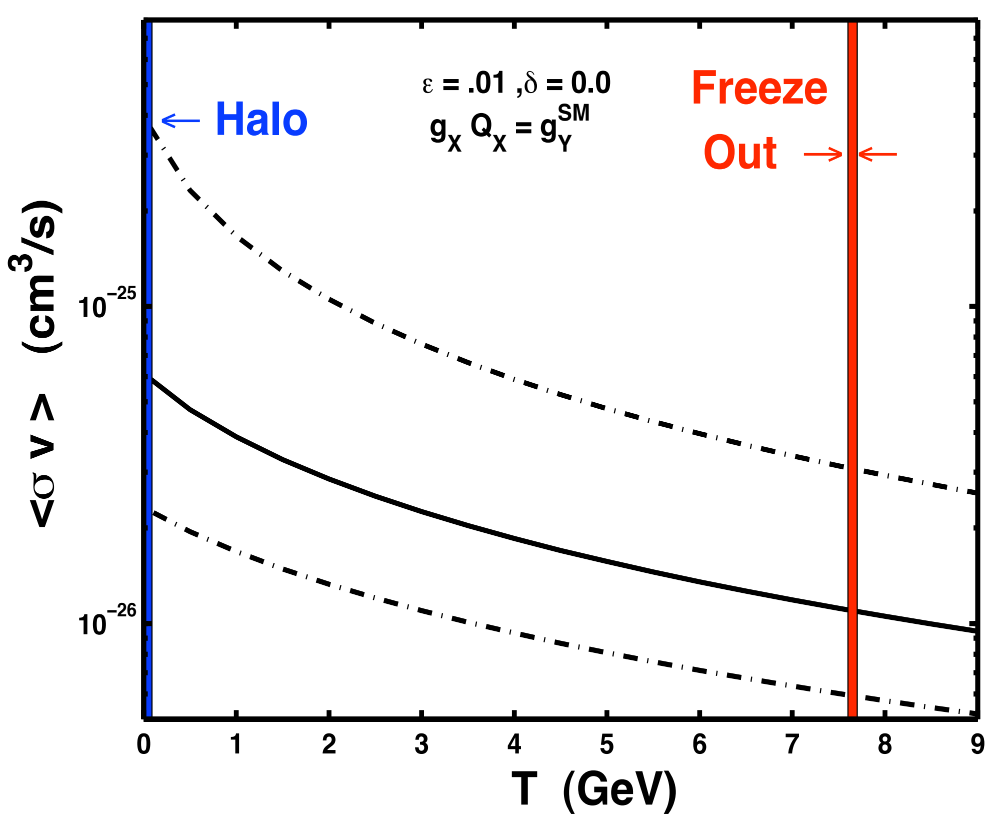
$M_2/M_1 \to 0$ then A_μ coupling $\to 0$

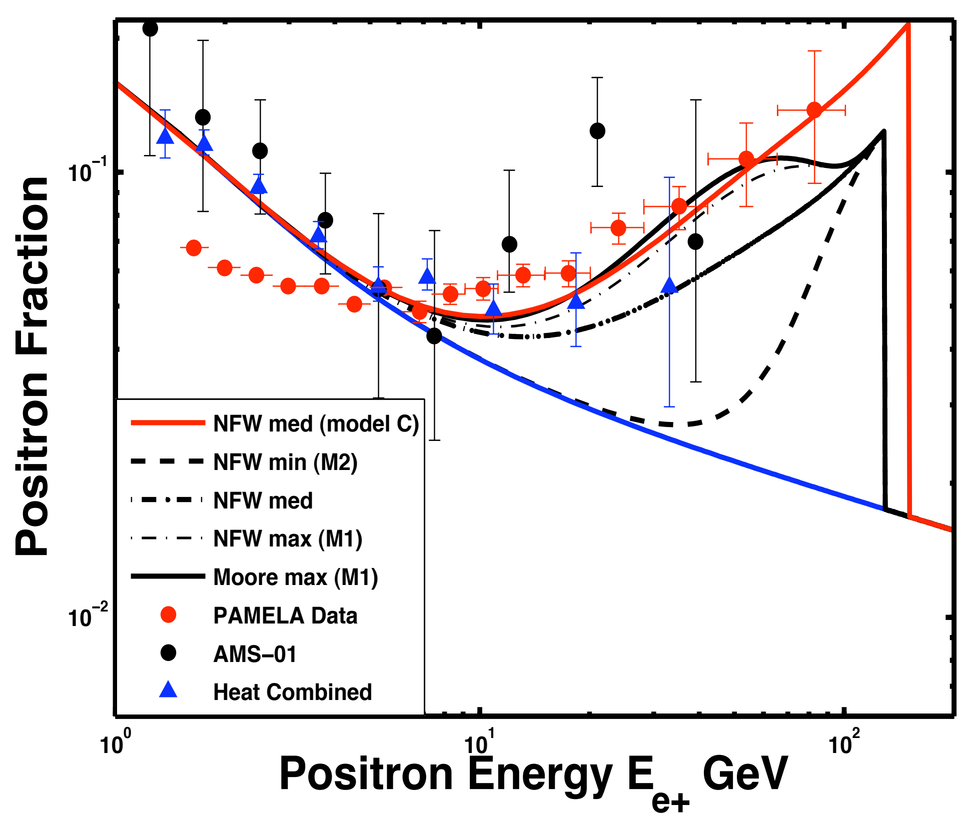
Conserved Vector Current $g_X Q_X J^\mu_X C_\mu$

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).





- $\langle \sigma v \rangle_{\text{Halo}} \neq \langle \sigma v \rangle_{\text{freeze}},$ *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.
- $\xi^{Z'}_{L,R} = C^{Z'}_{\psi} C^{Z'}_{f_{L,R}} [s - M^2_{Z'} + i\Gamma_{Z'} M_{Z'}]^{-1}, (Dirac\,\text{DM}\,narrow\;Z')$

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...")

D Zero Probing Narrow Stueckelberg Resonances

D0 Collaboration (Abazov et al.). FERMILAB-PUB-10-300-E, Aug 2010, e-Print: arXiv:1008.2023 [hep-ex]

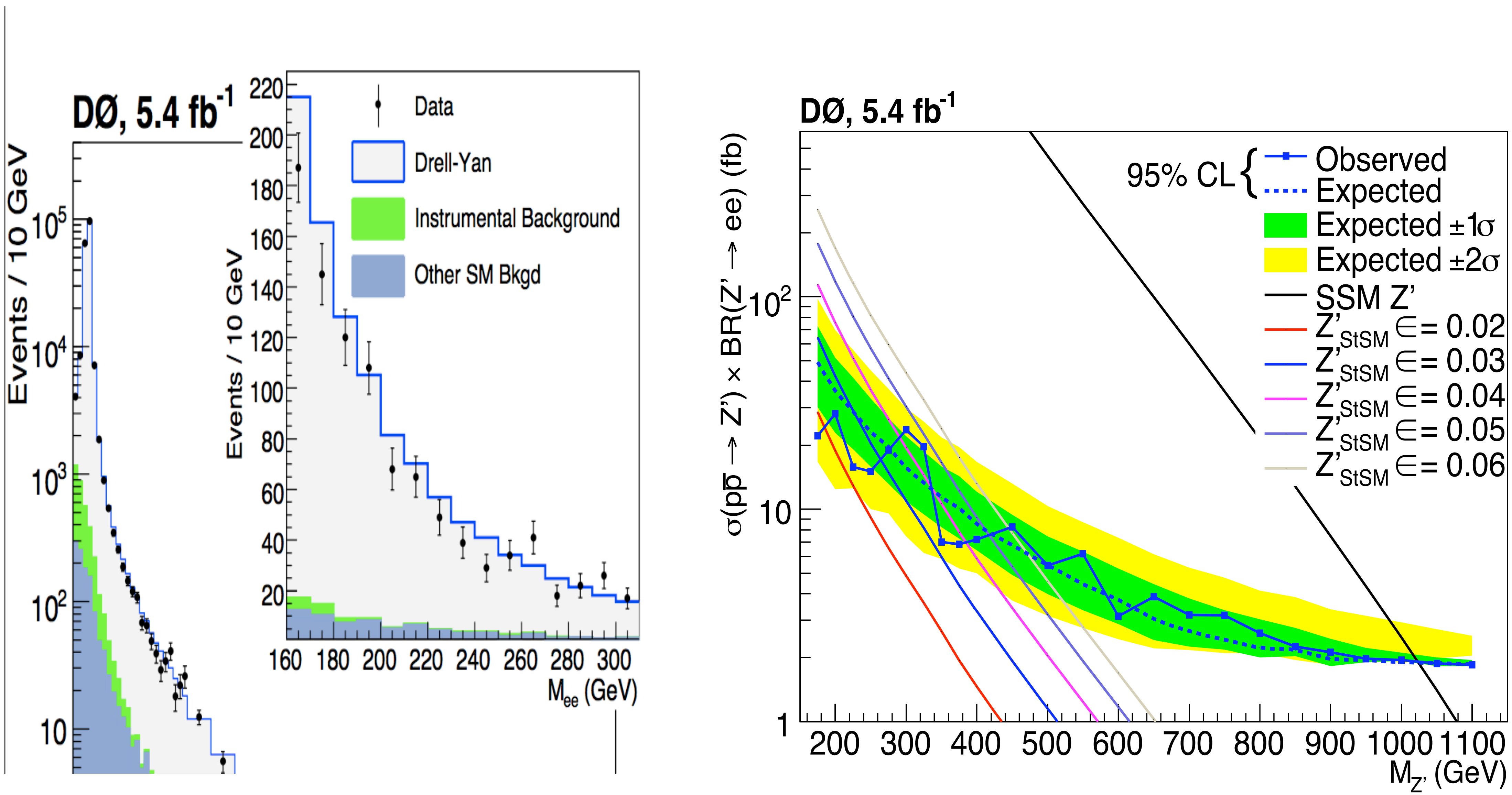


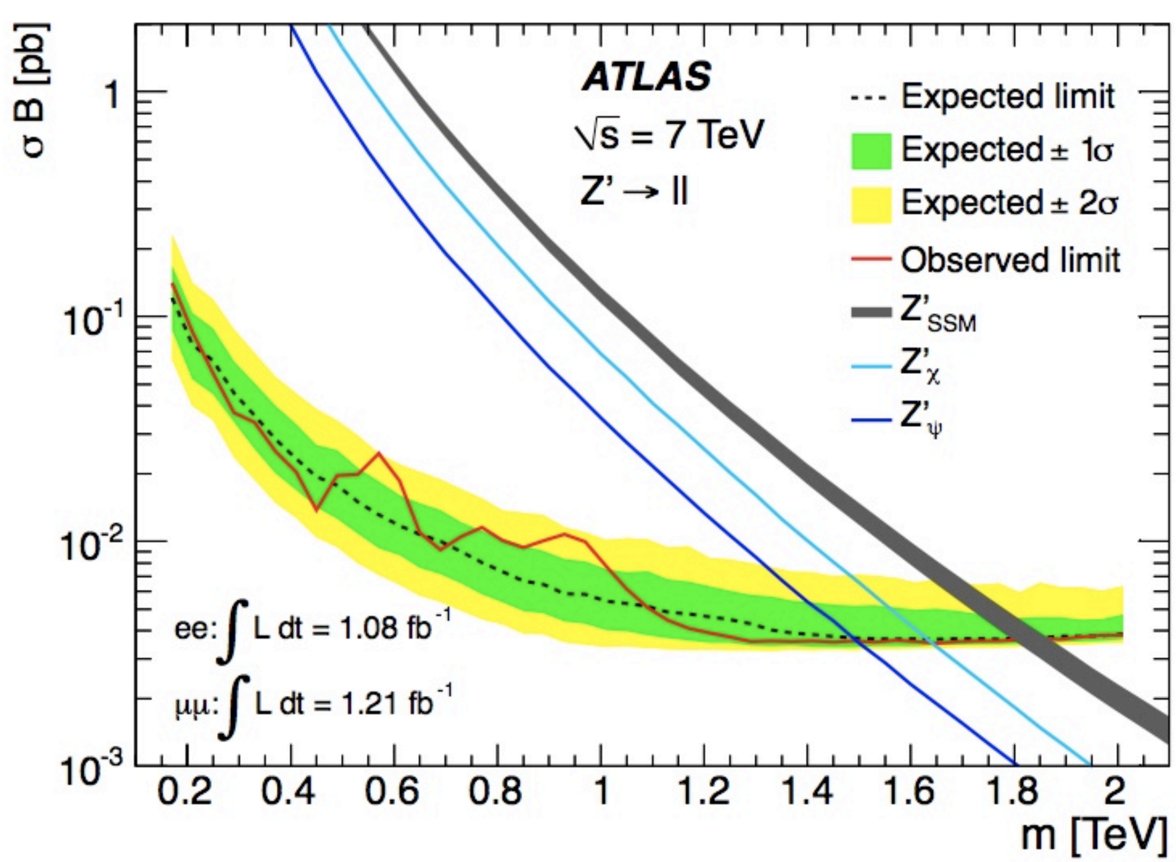
Figure: Tevatron Probing Stueckelberg Extensions.

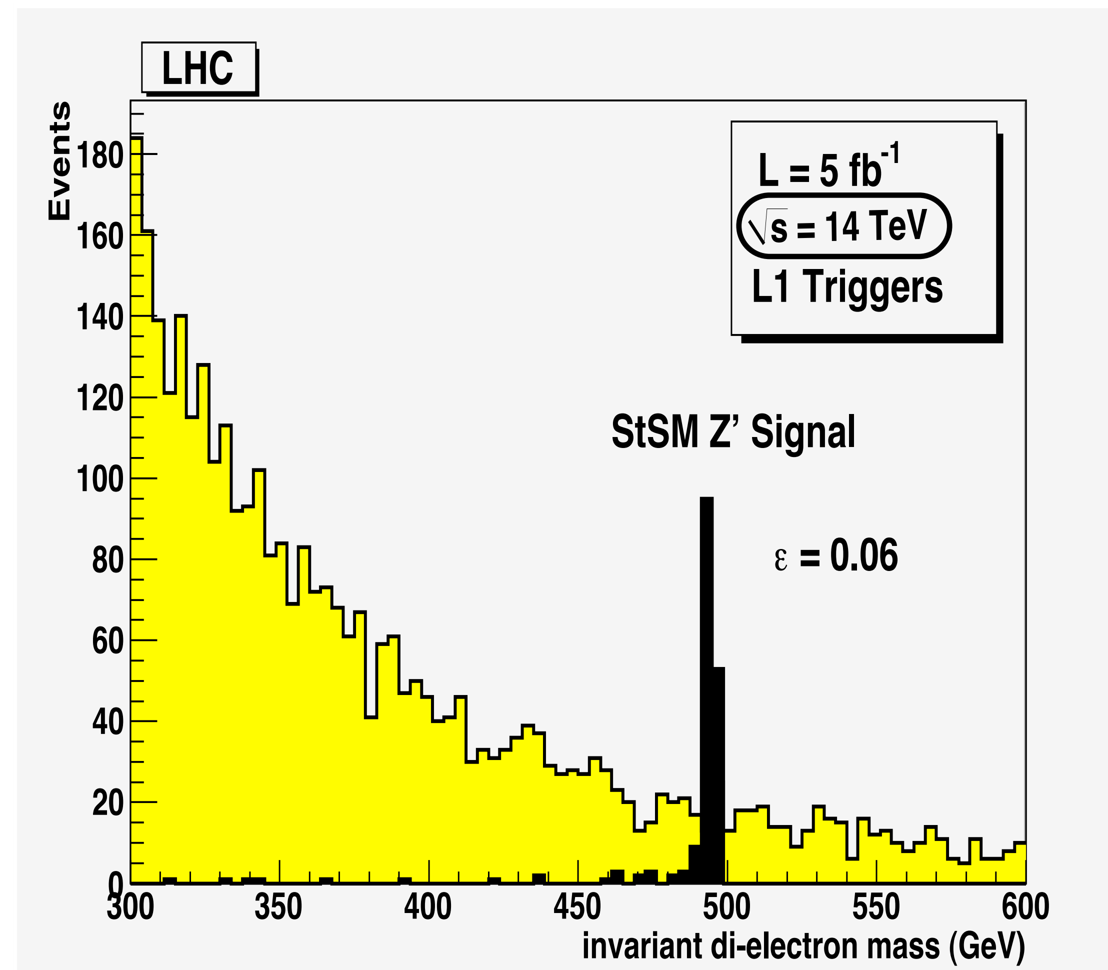
See FLN, PRL hep-ph/0603039

Narrow Resonances at the LHC
Stueckelberg Resonances - Lower Mass

$\mathbf{MSSM \times U(1)_X}$

LHC 7 TeV , arXiv:1108.1582





White Paper BSM-LHC Hidden Sector Signatures
(DF, Z.Liu, L.T. Wang, K. Zurek)

http://arxiv.org/abs/1001.2693

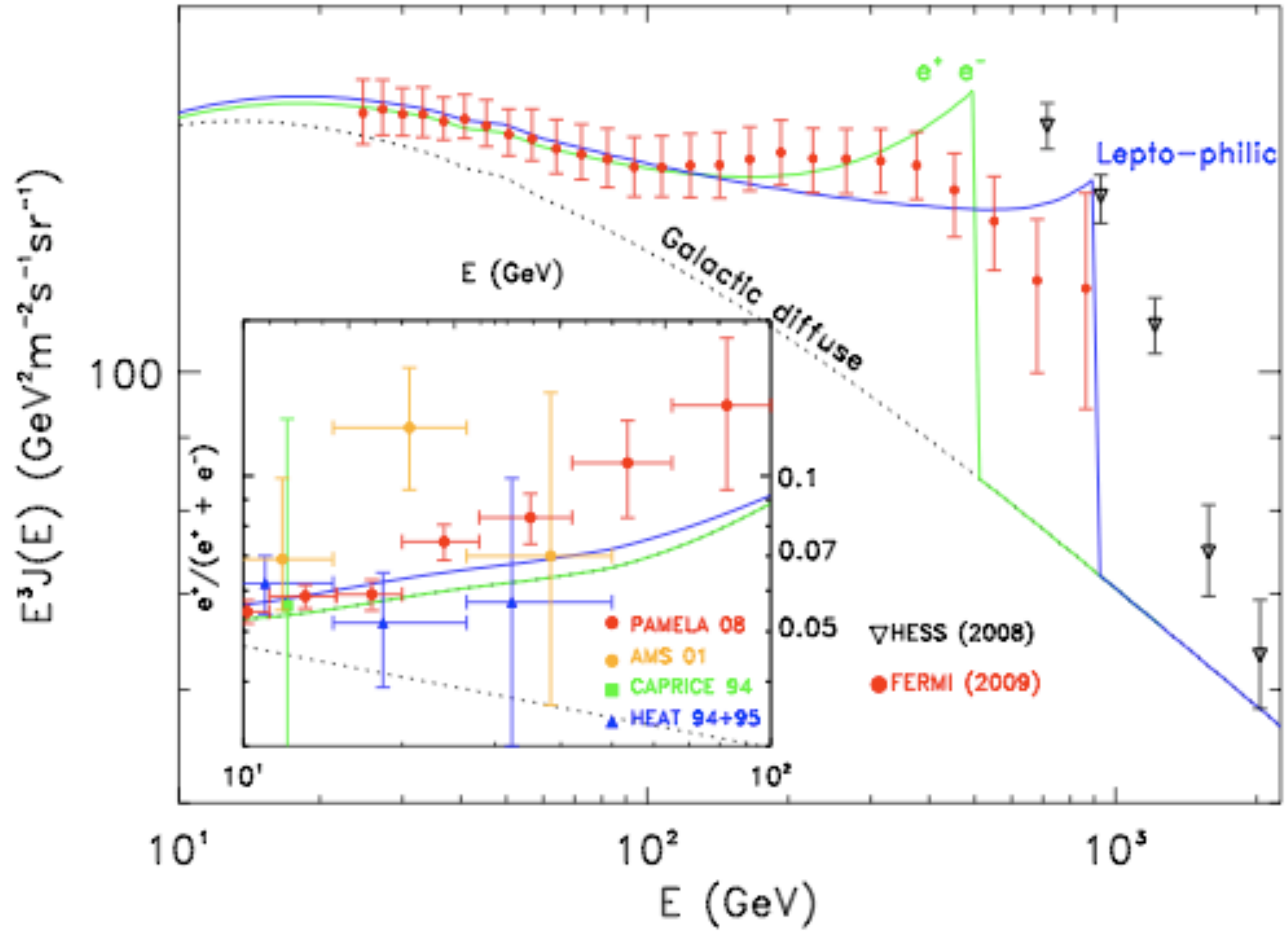
"Summary" - can read it online

- Huge parameter space of SUSY models exist even after all the recent experimental results. But, significant dents in the parameter space are evident.
- Look at possible Sparticle Mass Hierarchies to help sort out signatures and models.
- Connection between Flavor physics, Dark Matter and Colliders - leads to Multi-Probes of New physics: (remarkable - very different experiments reaching comparable sensitivities).
- Dark matter direct detection + LHC constraints + bsmumu ... HB/FP being tested...
- Higgs pole region, unified gaugino masses, can infer dark matter mass, (in or out ?)
- No CoGeNT with MSSM neutralino ... Higgs searches, bsgamma, bsmumu remove this possibility.
  -Upper limit on SI cross section with lower limit on mass for neutralino dark matter.
- Gluino NLSP (GNLSP) well motivated simplified model - degeneracy gives relic density
  -need to add these models in new physics searches.

- New Solution for Electroweak Symmetry breaking Breaking - Intersection points
  - drives down the mu term very heavy scalars, Large Trilinears and Large Scalar mass with ratio close to unity, with sub-TeV to TeV scale gluino
  = Solution to cosmic moduli problem with rather natural EWSB.
- Look for rich n-jet signatures of gluinos - LHC will test this.
- PAMELA wino, mixed wino and higgsino (higgsino weaker photon signal - wino can give signal)

- Extended Gauge Symmetries of the SM and MSSM - Stueckelberg Mechanism.
- Origin of Hidden sector dark matter (aka Dark Force) - massive $U(1)_{\mathbf{hidden}}$ mass & kinetic mixing.
- Narrow Stueckelberg Resonances at colliders - Dark Forces at colliders.
- Breit-Wigner Enhancement in galactic halo consistent with Relic Density and produces PAMELA.
  See recent talk : http://hepg.sdu.edu.cn/THPPC/conference/z0-factory-2011/liuzuowei.pdf
- Extended MSSM - can lead to Enhancement in Relic Density - can also explain PAMELA.

Extra Slide...



By FERMI-LAT Collaboration
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)