The Sparticle Landscape and Signatures at the LHC

[PN]

LHC New Physics Signatures Workshop
UMich, Jan 6, 2008.

with
Daniel Feldman, Zuowei Liu

arXiv: 0707.1873[hep-ph] (PRL 99: 251802, 2007)
arXiv:0711.4591 [hep-ph]
+ work in progress.

New physics at the TeV scale

Persuasive reasons that there is new physics at the TeV scale, and that the LHC should discover it. A partial list of possibilities

- Higgs/Higgs variants
- SUSY/SUGRA/string motivated
  - Nature of SUSY breaking
  - Nature of EWSB: EB, or HB/FP ?
- Extra/warped dimensions
- TeV scale strings
- Others: Extra Z''s, Stueckelberg extensions, narrow resonances, 4th gen, or something entirely different such as unparticles, ungravity or non-commutatitve geometry.
- endpoint: leptons + jets + γs + missing P_T.

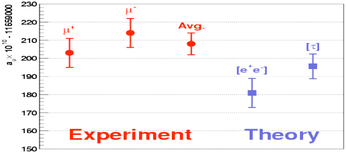
Two approaches: model $\longleftrightarrow$ data

- (A): From model to data
  L(inputs) $\longrightarrow$ lepton +jets +photons+ $\boldsymbol{P_T}$ miss
- (B): From data to model
  Construct the low energy effective Lagrangian starting from data

  Arkani-Hamed, Kane, Thaler, Wang; Bechtle, Desch, Porod, Wienemann; Rauch, Lafaye, Plehn, Zerwas, ..
- Approach (A) is guided by a theoretical preferance, and approach (B) must also assume a theoretical framework, and the parameter space is limited by practical constraints.
- In the analysis here we follow approach (A) and specifically for SUSY/SUGRA models.

SUSY/SUGRA: Looking back
Circa: early eighties - present

- An explanation of EWSB via RG
- Precision LEP data & gauge coupling unification
- A heavy top
- $b - \tau$ unification
- BNL result on $a_\mu = (g_\mu - 2)/2$



$$\Delta a_\mu = 26.8(9.3) \times 10^{-10} \quad 2.9\sigma \quad \text{discrepancy}$$

- Dark matter

Looking forward: Missing link- Sparticles

- If the BNL experiment holds up, i.e., a $\mathbf{2.9\sigma}$ discrepancy is present, then within SUSY/SUGRA it is predicted that some of the **sparticles** have an upper bound and **must be seen at the LHC.**
- The observation of SUSY will come most likely via the observation of the lightest sparticles first. So imperative to pursue what the likely possibilities for the lightest sparticles are.
- More generally the mass hierarchies may shed light on what specific scenarios are operating to give masses to the sparticles.

Landscape of sparticle mass hierarchies

- There are 32 sparticle masses in MSSM. Excluding the light Higgs and using sum rules on the chargino, neutralino, and Higgs sectors and using stirling's formula

$$n! \sim \sqrt{2\pi n}(n/e)^n$$

  one has upwards of 10^{25} mass hierarchies.
- As a comparison one has

$$\textbf{string landscape} \sim 10^{500}$$

  While sparticle landscape does not rise to the level of the string landscape, still the number of possibilities is impressive.
- The number of sparticle mass hierarchies decreases sharply in well motivated models such as in sugra, strings, D brane models.

Nature of soft breaking

- Miminal supergravity model, mSUGRA: $m_0, m_{1/2}, A_0$, $\tan\beta$, $\text{sign}\mu$.
- Sugra models with non-universalities: NUSUGRA with non-universalities in the Higgs sector, third generation sector and gaugino sector $\{|\delta_{H_u}|, |\delta_{H_d}|; |\delta_{q3}|, |\delta_{tb_R}|; |\delta_{M_2}|, |\delta_{M_3}|\} < 1$
- Soft breaking in heterotic string models, and in D brane models.
- Others: Gauge and anomaly mediation, KKLT, large volume compactification, ..

The first four sparticle mass hierarchies

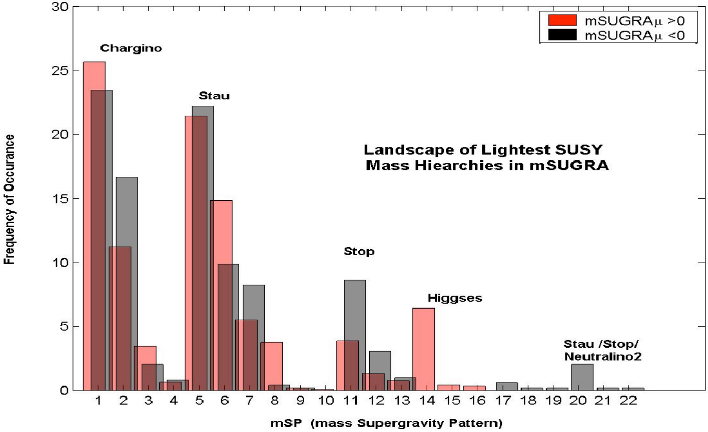
Daniel Feldman, Zuowei Liu, PN: arXiv: 0707.1873[hep-ph] (PRL 99: 251802, 2007); arXiv:0711.4591 [hep-ph]

- We focus on the first four sparticle mass hierarchies aside from the light higgs.
- A Monte Carlo scan of the parameter space of mSUGRA with $\mathbf{3 \times 10^6}$ models shows 'saturation' with 16 minimal sugra patterns **(mSP1-mSP16)** for $\boldsymbol{\mu > 0}$, and 6 additional patterns **(mSP17-mSP22)** for $\boldsymbol{\mu < 0}$.
- A similar scan of NUSUGRA with $\mathbf{3 \times 10^6}$ models also shows 'saturation' with 15 additional NUSUGRA patterns **(NUSP1-NUSP15)**.
- A scan of D brane models with $\mathbf{10^6}$ models gives 6 additional patterns **(DBSP1-DBSP6)**.

mSP Label	4 sparticle mSUGRA patterns	$\mu > 0$	$\mu < 0$	#
mSP1	$\widetilde{\chi}_1^0 < \widetilde{\chi}_1^\pm < \widetilde{\chi}_2^0 < \widetilde{\chi}_3^0$	✓	✓	4
mSP2	$\widetilde{\chi}_1^0 < \widetilde{\chi}_1^\pm < \widetilde{\chi}_2^0 < A/H$	✓	✓	
mSP3	$\widetilde{\chi}_1^0 < \widetilde{\chi}_1^\pm < \widetilde{\chi}_2^0 < \widetilde{\tau}_1$	✓	✓	
mSP4	$\widetilde{\chi}_1^0 < \widetilde{\chi}_1^\pm < \widetilde{\chi}_2^0 < \widetilde{g}$	✓	✓	
mSP5	$\widetilde{\chi}_1^0 < \widetilde{\tau}_1 < \widetilde{l}_R < \widetilde{\nu}_\tau$	✓	✓	6
mSP6	$\widetilde{\chi}_1^0 < \widetilde{\tau}_1 < \widetilde{\chi}_1^\pm < \widetilde{\chi}_2^0$	✓	✓	
mSP7	$\widetilde{\chi}_1^0 < \widetilde{\tau}_1 < \widetilde{l}_R < \widetilde{\chi}_1^\pm$	✓	✓	
mSP8	$\widetilde{\chi}_1^0 < \widetilde{\tau}_1 < A/H < A/H$	✓	✓	
mSP9	$\widetilde{\chi}_1^0 < \widetilde{\tau}_1 < \widetilde{l}_R < A/H$	✓	✓	
mSP10	$\widetilde{\chi}_1^0 < \widetilde{\tau}_1 < \widetilde{t}_1 < \widetilde{l}_R$	✓		
mSP11	$\widetilde{\chi}_1^0 < \widetilde{t}_1 < \widetilde{\chi}_1^\pm < \widetilde{\chi}_2^0$	✓	✓	3
mSP12	$\widetilde{\chi}_1^0 < \widetilde{t}_1 < \widetilde{\tau}_1 < \widetilde{\chi}_1^\pm$	✓	✓	
mSP13	$\widetilde{\chi}_1^0 < \widetilde{t}_1 < \widetilde{\tau}_1 < \widetilde{l}_R$	✓	✓	
mSP14	$\widetilde{\chi}_1^0 \lessgtr A/H < A/H < H^\pm$	✓		3
mSP15	$\widetilde{\chi}_1^0 \lessgtr A/H < A/H < \widetilde{\chi}_1^\pm$	✓		
mSP16	$\widetilde{\chi}_1^0 \lessgtr A/H < A/H < \widetilde{\tau}_1$	✓		
mSP17	$\widetilde{\chi}_1^0 < \widetilde{\tau}_1 < \widetilde{\chi}_2^0 < \widetilde{\chi}_1^\pm$		✓	3
mSP18	$\widetilde{\chi}_1^0 < \widetilde{\tau}_1 < \widetilde{l}_R < \widetilde{t}_1$		✓	
mSP19	$\widetilde{\chi}_1^0 < \widetilde{\tau}_1 < \widetilde{t}_1 < \widetilde{\chi}_1^\pm$		✓	
mSP20	$\widetilde{\chi}_1^0 < \widetilde{t}_1 < \widetilde{\chi}_2^0 < \widetilde{\chi}_1^\pm$		✓	2
mSP21	$\widetilde{\chi}_1^0 < \widetilde{t}_1 < \widetilde{\tau}_1 < \widetilde{\chi}_2^0$		✓	
mSP22	$\widetilde{\chi}_1^0 < \widetilde{\chi}_2^0 < \widetilde{\chi}_1^\pm < \widetilde{g}$		✓	1

Frequencies with which patterns appear

Pattern Classes: Chargino (CP), Stau (SUP), Stop (SOP), Higgses (HP), Neutralino (NP).



mSP patterns vs Snowmass and Post-WMAP3 benchmarks

$Snowmass$	mSP
$SPS1a, SPS1b, SPS5$	$mSP7$
$SSP2$	$mSP1$
$SPS3$	$mSP5$
$SPS4, SPS6$	$mSP3$

$Post-Wmap3$	mSP
$A', B', C'.D', G', H', J', M'$	$mSP5$
I', L'	$mSP7$
E'	$mSP1$
K'	$mSP6$

- **Not all the mSP patterns appear in the mSUGRA-Snowmass and Post-WMAP3 benchmarks.**

mSP Label	NUSUGRA patterns	NUH	NU3	NUG
mSP1	$\widetilde{\chi}_1^0 < \widetilde{\chi}_1^\pm < \widetilde{\chi}_2^0 < \widetilde{\chi}_3^0$	$\surd$	$\surd$	$\surd$
mSP2	$\widetilde{\chi}_1^0 < \widetilde{\chi}_1^\pm < \widetilde{\chi}_2^0 < A/H$	$\surd$	$\surd$	$\surd$
mSP3	$\widetilde{\chi}_1^0 < \widetilde{\chi}_1^\pm < \widetilde{\chi}_2^0 < \widetilde{\tau}_1$	$\surd$	$\surd$	$\surd$
mSP4	$\widetilde{\chi}_1^0 < \widetilde{\chi}_1^\pm < \widetilde{\chi}_2^0 < \widetilde{g}$		$\surd$	$\surd$
mSP5	$\widetilde{\chi}_1^0 < \widetilde{\tau}_1 < \widetilde{l}_R < \widetilde{\nu}_\tau$	$\surd$	$\surd$	$\surd$
mSP6	$\widetilde{\chi}_1^0 < \widetilde{\tau}_1 < \widetilde{\chi}_1^\pm < \widetilde{\chi}_2^0$	$\surd$	$\surd$	$\surd$
mSP7	$\widetilde{\chi}_1^0 < \widetilde{\tau}_1 < \widetilde{l}_R < \widetilde{\chi}_1^\pm$	$\surd$	$\surd$	$\surd$
mSP8	$\widetilde{\chi}_1^0 < \widetilde{\tau}_1 < A/H < A/H$	$\surd$	$\surd$	$\surd$
mSP9	$\widetilde{\chi}_1^0 < \widetilde{\tau}_1 < \widetilde{l}_R < A/H$	$\surd$	$\surd$	$\surd$
mSP10	$\widetilde{\chi}_1^0 < \widetilde{\tau}_1 < \widetilde{t}_1 < \widetilde{l}_R$		$\surd$	
mSP11	$\widetilde{\chi}_1^0 < \widetilde{t}_1 < \widetilde{\chi}_1^\pm < \widetilde{\chi}_2^0$	$\surd$	$\surd$	$\surd$
mSP12	$\widetilde{\chi}_1^0 < \widetilde{t}_1 < \widetilde{\tau}_1 < \widetilde{\chi}_1^\pm$	$\surd$	$\surd$	$\surd$
mSP13	$\widetilde{\chi}_1^0 < \widetilde{t}_1 < \widetilde{\tau}_1 < \widetilde{l}_R$	$\surd$	$\surd$	$\surd$
mSP14	$\widetilde{\chi}_1^0 \lessgtr A/H < A/H < H^\pm$	$\surd$	$\surd$	$\surd$
mSP15	$\widetilde{\chi}_1^0 \lessgtr A/H < A/H < \widetilde{\chi}_1^\pm$		$\surd$	$\surd$
mSP16	$\widetilde{\chi}_1^0 \lessgtr A/H < A/H < \widetilde{\tau}_1$	$\surd$		

#: Label	New patterns in NUSUGRA	3rd	Gaugino
4: NUSP1	$\widetilde{\chi}_1^0 < \widetilde{\chi}_1^\pm < \widetilde{\chi}_2^0 < \widetilde{t}_1$	√	√
NUSP2	$\widetilde{\chi}_1^0 < \widetilde{\chi}_1^\pm < A/H < A/H$	√	
NUSP3	$\widetilde{\chi}_1^0 < \widetilde{\chi}_1^\pm < \widetilde{\tau}_1 < \widetilde{\chi}_2^0$		√
NUSP4	$\widetilde{\chi}_1^0 < \widetilde{\chi}_1^\pm < \widetilde{\tau}_1 < \widetilde{l}_R$		√
5: NUSP5	$\widetilde{\chi}_1^0 < \widetilde{\tau}_1 < \widetilde{\nu}_\tau < \widetilde{\tau}_2$	√	
NUSP6	$\widetilde{\chi}_1^0 < \widetilde{\tau}_1 < \widetilde{\nu}_\tau < \widetilde{\chi}_1^\pm$	√	
NUSP7	$\widetilde{\chi}_1^0 < \widetilde{\tau}_1 < \widetilde{t}_1 < A/H$		√
NUSP8	$\widetilde{\chi}_1^0 < \widetilde{\tau}_1 < \widetilde{l}_R < \widetilde{\nu}_\mu$		√
NUSP9	$\widetilde{\chi}_1^0 < \widetilde{\tau}_1 < \widetilde{\chi}_1^\pm < \widetilde{l}_R$		√
2: NUSP10	$\widetilde{\chi}_1^0 < \widetilde{t}_1 < \widetilde{g} < \widetilde{\chi}_1^\pm$		√
NUSP11	$\widetilde{\chi}_1^0 < \widetilde{t}_1 < A/H < A/H$		√
1: NUSP12	$\widetilde{\chi}_1^0 < A/H < A/H < \widetilde{g}$		√
3: NUSP13	$\widetilde{\chi}_1^0 < \widetilde{g} < \widetilde{\chi}_1^\pm < \widetilde{\chi}_2^0 \longleftarrow$		√
NUSP14	$\widetilde{\chi}_1^0 < \widetilde{g} < \widetilde{t}_1 < \widetilde{\chi}_1^\pm \longleftarrow$		√
NUSP15	$\widetilde{\chi}_1^0 < \widetilde{g} < A/H \longleftarrow$		√

New patterns in D brane models
A new pattern class: the Sneutrino Pattern.

$$\mathbf{DBSP1}: \widetilde{\chi}_1^0 < \widetilde{\tau}_1 < \widetilde{\nu}_\tau < A/H \ ,$$

$$\mathbf{DBSP2}: \widetilde{\chi}_1^0 < \widetilde{\tau}_1 < \widetilde{\nu}_\tau < \widetilde{l}_R \ ,$$

$$\mathbf{DBSP3}: \widetilde{\chi}_1^0 < \widetilde{\tau}_1 < \widetilde{\nu}_\tau < \widetilde{\nu}_\mu \ ,$$

$$\mathbf{DBSP4}: \widetilde{\chi}_1^0 < \widetilde{t}_1 < \widetilde{\tau}_1 < \widetilde{\nu}_\tau \ ,$$

$$\mathbf{DBSP5}: \widetilde{\chi}_1^0 < \widetilde{\nu}_\tau < \widetilde{\tau}_1 < \widetilde{\nu}_\mu \longleftarrow \ ,$$

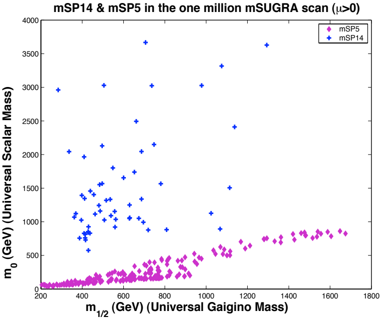
$$\mathbf{DBSP6}: \widetilde{\chi}_1^0 < \widetilde{\nu}_\tau < \widetilde{\tau}_1 < \widetilde{\chi}_1^\pm \longleftarrow \quad .$$

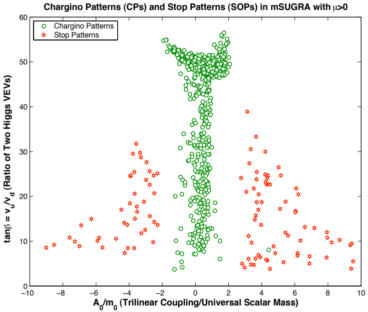
Pattern discrimination

- Parameter space as a discriminant.
- Analysis of lepton and jet signatures.
  - Missing P_T cut distributions.
  - Missing P_T distributions.
  - Higgs production cross sections.
  - The decay $B_s \to \mu\mu$.
- Dark matter cross sections.

Parameter space as a discriminant

Higgs Pattern mSP14 & Stau Pattern mSP5 in $m_0 - m_{1/2}$ plane (left)
Chargino Pattern mSP1 & Stop Pattern mSP11 in $\tan\beta - A_0$ plane (right).
Feldman, Liu, PN: arXiv: 0707.1873[hep-ph] (PRL 99: 251802, 2007)

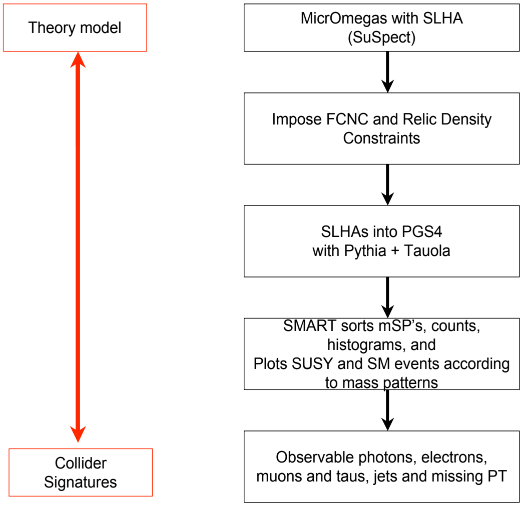




Description of 41 signatures that are analyzed for each parameter point.

41 Signatures	Description	41 Signatures	Description
(1) − 0L	0 Lepton	(22)−0T	0 τ
(2)−1L	1 Lepton	(23)−1T	(23)−1 τ
(3)−2L	2 Lepton	(24)−2T	(24)−2 τ
(4)−3L	3 Lepton	(25)−3T	(25)−3 τ
(5)−4L	4 Lepton and more	(26)−4T	4 τ and more
(6)−0L1b	0 Lepton + 1 b-jet	(27)−0T1b	0 τ + 1 b-jet
(7)−1L1b	1 Lepton + 1 b-jet	(28)−1T1b	1 τ + 1 b-jet
(8)−2L1b	2 Lepton + 1 b-jet	(29)−2T1b	2 τ + 1 b-jet
(9)−0L2b	0 Lepton + 2 b-jet	(30)−0T2b	0 τ + 2 b-jet
(10)−1L2b	1 Lepton + 2 b-jet	(31)−1T2b	1 τ + 2 b-jet
(11)−2L2b	2 Lepton + 2 b-jet	(32)−2T2b	2 τ + 2 b-jet
(12)−ep	e^+ in 1L	(33)−em	e^- in 1L
(13)−mp	μ^+ in 1L	(34)−mm	μ^- in 1L
(14)−tp	τ^+ in 1T	(35)−tm	τ^- in 1T
(15)−OS	Opposite Sign Di-Lepton	(36)−0b	0 b-jet
(16)−SS	Same Sign Di-Lepton	(37)−1b	1 b-jet
(17)−OSSF	Opp Sign Same Flavor Di-Lepton	(38)−2b	2 b-jet
(18)−SSSF	Same Sign Same Flavor Di-Lepton	(39)−3b	3 b-jet
(19)−OST	Opposite Sign Di-τ	(40)−4b	4 b-jet and more
(20)−SST	Same Sign Di-τ	(41)−ptmax	P_T peak value
(21)−TL	1 τ plus 1 Lepton		

From models to LHC signals



Comparison of CMS simulation and of PGS4+SMART

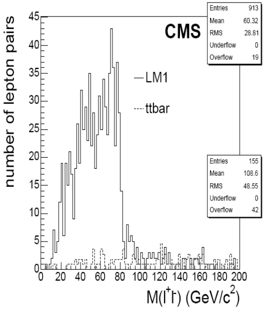
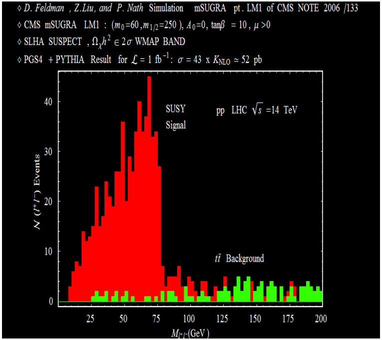


Figure 11: Same flavour opposite sign lepton pair distributions of SUSY and $t\bar{t}$ events for 1 fb^{-1}.



Tau Signal and Background with PGS4 + SMART vs CMS Note

Table: **Comparison of SM background events from (a) our analysis using PGS4 and SMART and from (b) CMS analysis. Other sources of background besides $t\bar{t}$ are for (a): $b\bar{b}$, DiJets, Drell Yan, Z,W and ZZ,WW,ZW , while for (b) they are listed as : "QCD" and W+Jets.**

Observable with $N_{\text{Jet}} = 2$	(a) FLN N_B @ 12.67 fb^{-1}	(b) CMSnotes N_B @ 12.67 fb^{-1}
N_B(OS 2τ)	406	543 ± 112
% from $t\bar{t}$	25	20
% Other Sources	75	80

The analysis shows that our simulations of backgrounds is nearly as good as the CMS simulations (CMS NOTE: 2006/096).

Signature analyses

- With PGS4 we use the L1 triggers based on CMS specifications. Our detector parameter card is the standard LHC card.
- Signature plots are with cuts:

$$P_T > 10 \text{ GeV},\ P_T^{jet} > 60 \text{ GeV}, P_T^{miss} > 200 \text{ GeV}$$

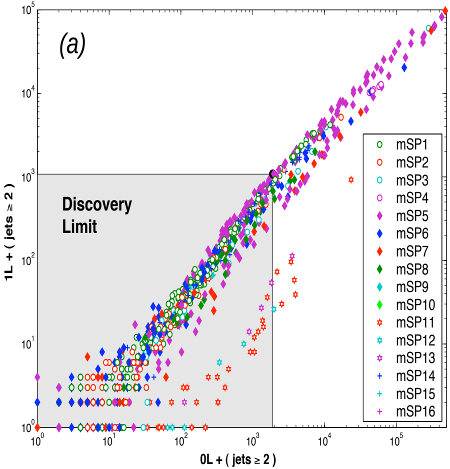
$$|\eta| < 2.4,\ |\eta^{jet}| < 3$$

- Leptonic events without jets are typically small so we focus on events with at least two jets. We analyze $0, 1, 2, 3$ leptonic events (lepton $L = \tau, e, \mu$).
- Discovery limit

$$N_S > 5\sqrt{N_{SM}},\ \text{or}\ N_S > 10$$

Signal vs background

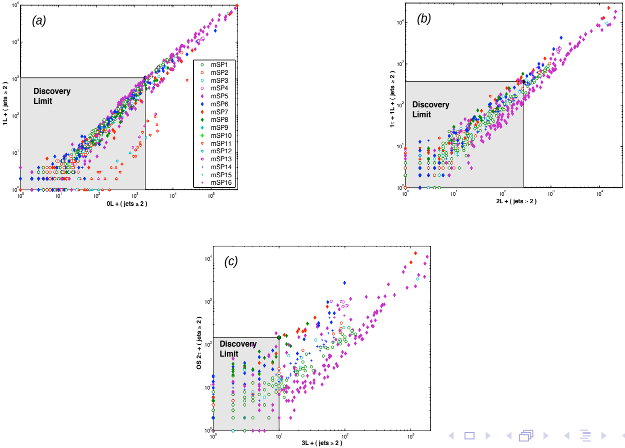
Feldman, Liu, PN arXiv: 0707.1873[hep-ph] (PRL 99: 251802, 2007)



Signal vs background with increasing number of leptons

Analysis with $10 fb^{-1}$.

Feldman, Liu, PN arXiv: 0707.1873[hep-ph]; (PRL 99: 251802, 2007)



Leptons + jets signature analysis for patterns

- Consider two patterns: X and Y. One can define a signature vector originating for a given point in the parameter space

$$\xi = (\xi_1, .., \xi_{41}), \quad \xi_i = n_i/N$$

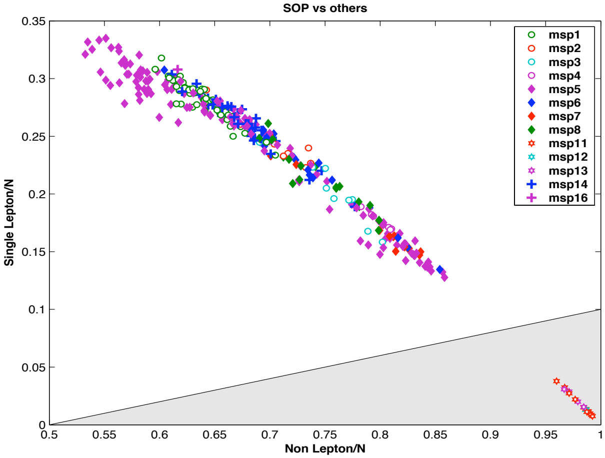
  n_i is no. of events for a given $\mathcal{L}$ for i-th signature; N is the total number of events.
- One can define a (fat) pattern vector $\xi^P = (\Delta\xi_1^P, .., \Delta\xi_{41}^P)$ where $\Delta\xi_i$ is the range for signature i within a pattern.
- One criterion is that two patterns X and Y are distinguishable if at least one element $\Delta\xi_i^X$ does not overlap $\Delta\xi_i^Y$. One assigns the value 1 if the above criterion is satisfied and the value 0 otherwise.
- According to this simple criterion some patterns are distinguishable from others.

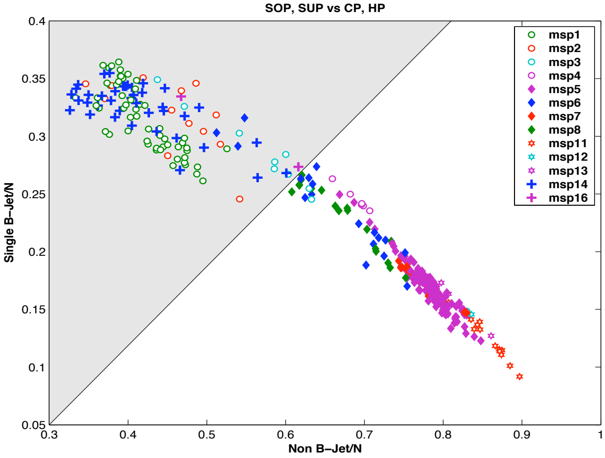
Discriminating patterns by overlap: $(\boldsymbol{\xi}^{\boldsymbol{X}}|\boldsymbol{\xi}^{\boldsymbol{Y}}) = \mathbf{0}(\mathbf{1})$ if there is an overlap of one (none) elements of $\boldsymbol{\xi}^{\boldsymbol{X}}$ and $\boldsymbol{\xi}^{\boldsymbol{Y}}$.

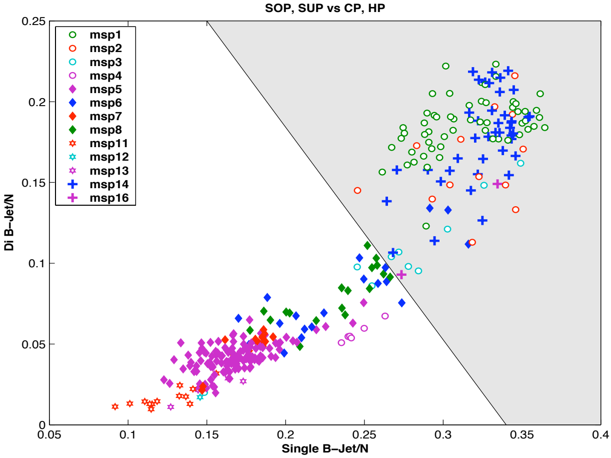
Feldman, Liu, PN in progress.

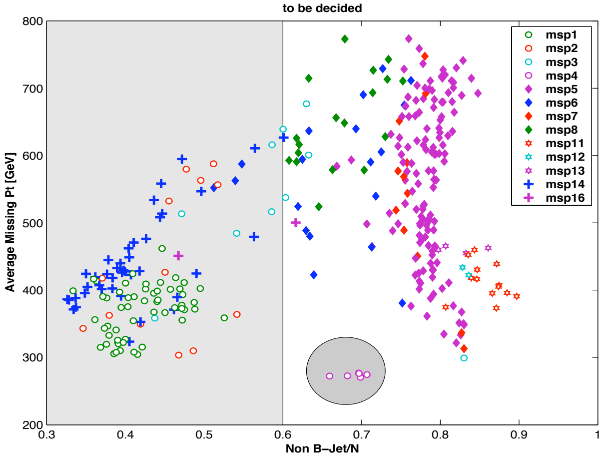
SP																						
m5	0	0	0	0	1	0	1	1	0	1	0	1	1	1	0	1	1	1	1	1	0	1
m1	0	0	0	0	0	0	1	0	0	1	0	1	1	1	0	0	1	1	1	1	0	1
m3	0	0	0	0	1	0	1	1	0	0	0	1	1	1	1	0	1	1	1	1	1	1
m7	0	0	0	0	1	0	1	1	0	1	0	1	1	1	1	0	1	1	1	1	0	1
m11	1	0	1	1	0	0	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1
m6	0	0	0	0	0	0	1	0	0	0	0	1	1	1	0	0	1	1	1	1	0	1
m12	1	1	1	1	1	1	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1
m13	1	0	1	1	1	0	0	0	1	1	0	1	1	1	1	1	1	1	1	1	1	1
N1	0	0	0	0	1	0	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1
m4	1	1	0	1	0	0	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1
m18	0	0	0	0	1	0	1	0	1	1	0	1	1	1	1	1	1	1	1	1	1	1
N13	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1
m20	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1
m10	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1
m17	0	0	1	1	1	0	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1
N3	1	0	0	0	1	0	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1
m19	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1
N5	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1
N8	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1
N10	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1
N4	0	0	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1
N9	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0

Table 10: No overlap of fuzzy signature vectors gives 1 and an overlap gives 0.

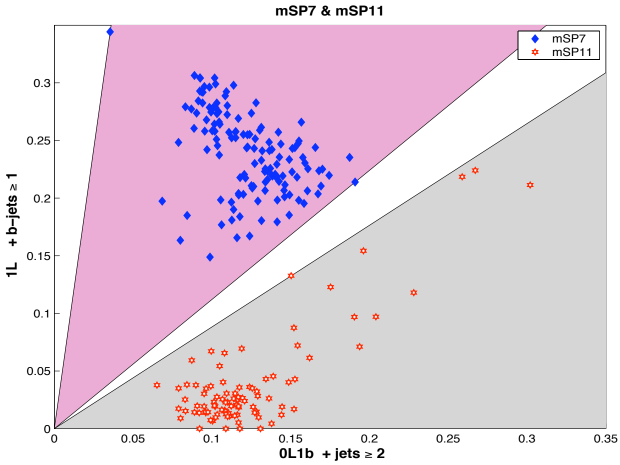

SOP vs others
Single Lepton/N
Non Lepton/N
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0.5
0.55
0.6
0.65
0.7
0.75
0.8
0.85
0.9
0.95
1
msp1
msp2
msp3
msp4
msp5
msp6
msp7
msp8
msp11
msp12
msp13
msp14
msp16


SOP, SUP vs CP, HP
Single B–Jet/N
Non B–Jet/N
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
msp1
msp2
msp3
msp4
msp5
msp6
msp7
msp8
msp11
msp12
msp13
msp14
msp16


SOP, SUP vs CP, HP
Di B−Jet/N
Single B−Jet/N
0.25
0.2
0.15
0.1
0.05
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
msp1
msp2
msp3
msp4
msp5
msp6
msp7
msp8
msp11
msp12
msp13
msp14
msp16

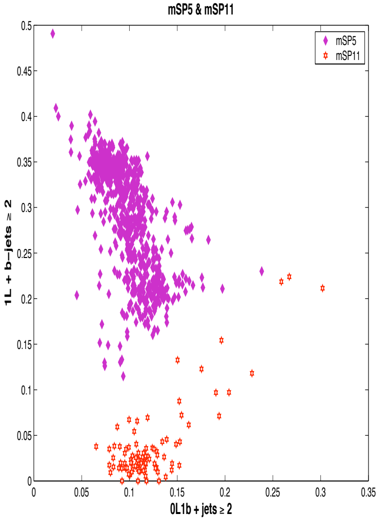

to be decided
Average Missing Pt [GeV]
Non B–Jet/N
800
700
600
500
400
300
200
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
msp1
msp2
msp3
msp4
msp5
msp6
msp7
msp8
msp11
msp12
msp13
msp14
msp16

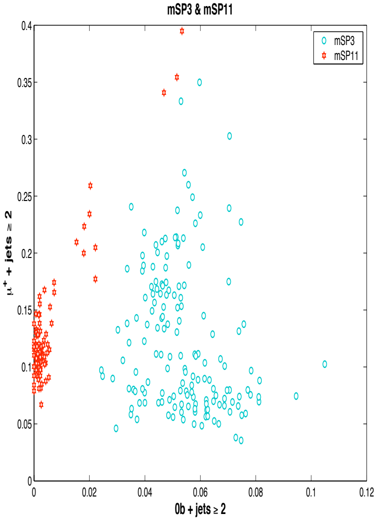
$(1L + b\text{-jets} \geq 1)$ vs $(0L1b\text{-jets} \geq 2)$ for mSP7l& mSP11



$(\mu^+$+jets$\geq 2)$ vs $(0b$+jets $\geq 2)$ for mSP3 & mSP11 (right)

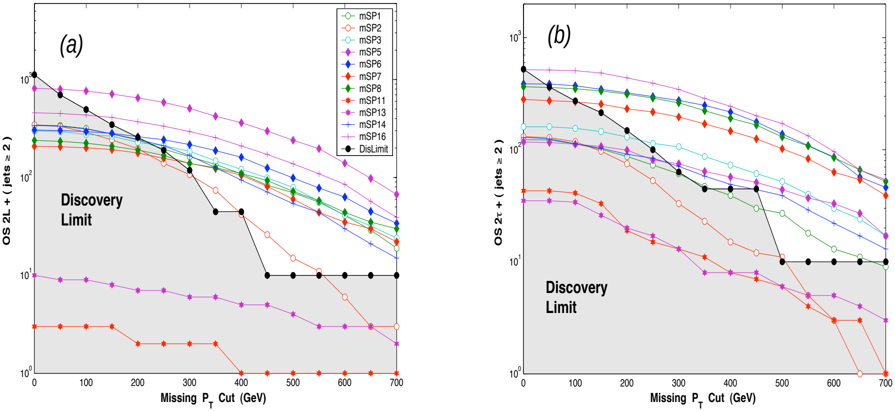
$(1L + b$-jets$\geq 2)$ vs $(0L1b$+jets $\geq 2)$ for mSP5 & mSP11 (left)



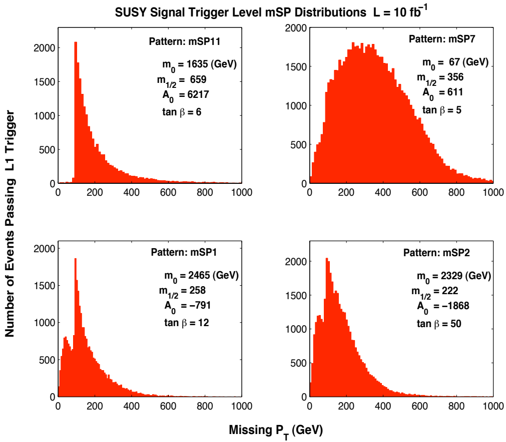


(a) OS Di-Leptons + (jets ≥ 2) vs P_T^{miss} cut
(b) OS Di-taus + (jets ≥ 2) vs P_T^{miss} cut
for a sample of mSPs.

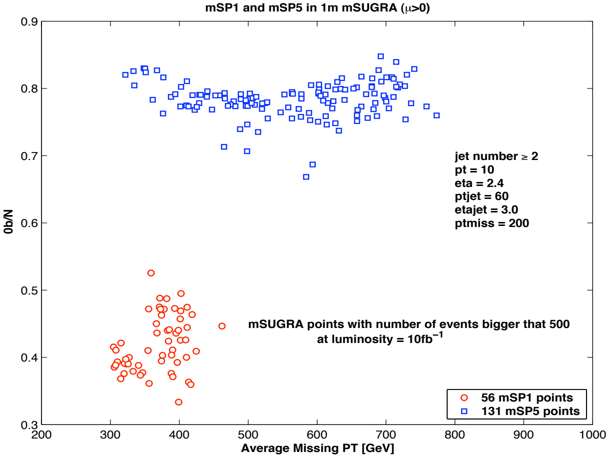
Feldman, Liu, PN arXiv: 0707.1873[hep-ph] (PRL 99: 251802, 2007)



P_T^{miss} distributions for Chargino Patterns (mSP1, mSP2), Stau Pattern (mSP7), and Stop Pattern (mSP11).



Number of events without b-jet /Total Number of Events vs the average missing P_T for Chargino Pattern mSP1 and Stau Pattern mSP5.



Higgs Production Cross section as a pattern discriminant

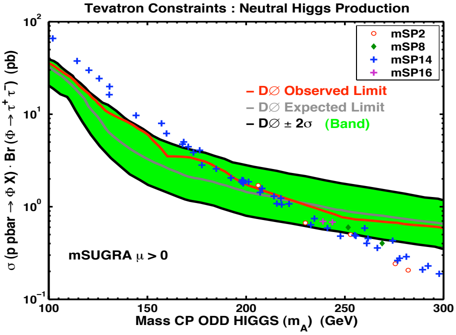
$$\sigma_{\Phi\tau\tau(p\bar{p})} = [\sigma(p\bar{p} \to \Phi) BR(\Phi \to 2\tau)]$$

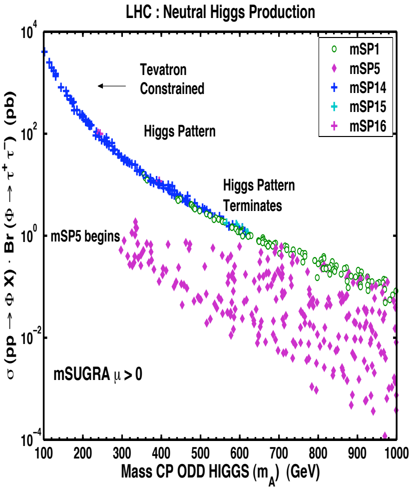
$$\sigma_{\Phi\tau\tau(pp)} = [\sigma(pp \to \Phi) BR(\Phi \to 2\tau)]$$

- The largest cross sections arise from the Higgs Patterns, followed by the Chargino Patterns and then by the Stau Patterns.
- The Tevatron data is beginning to constrain the Higgs Patterns

Pattern discrimination via Higgs production x-section Tevatron constraints (left) and x-sections at the LHC (right)

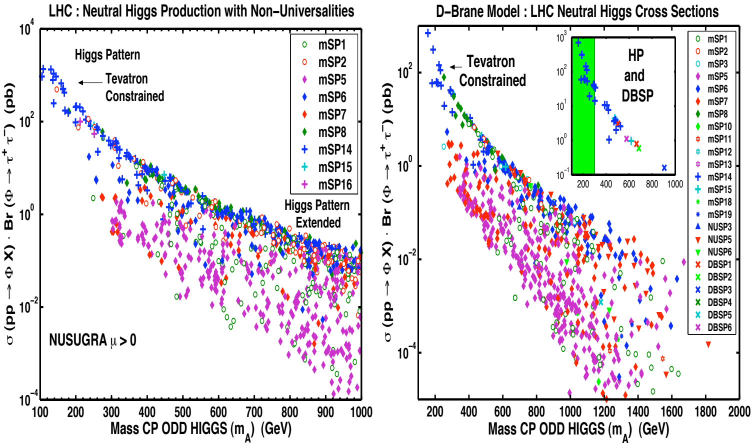
Feldman, Liu, PN, arXiv:0711.4591 [hep-ph]





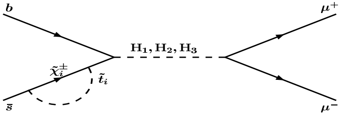
Pattern discrimination via Higgs production x-section NUSUGRA (left) and D Branes (right)

Feldman, Liu, PN, arXiv:0711.4591 [hep-ph]

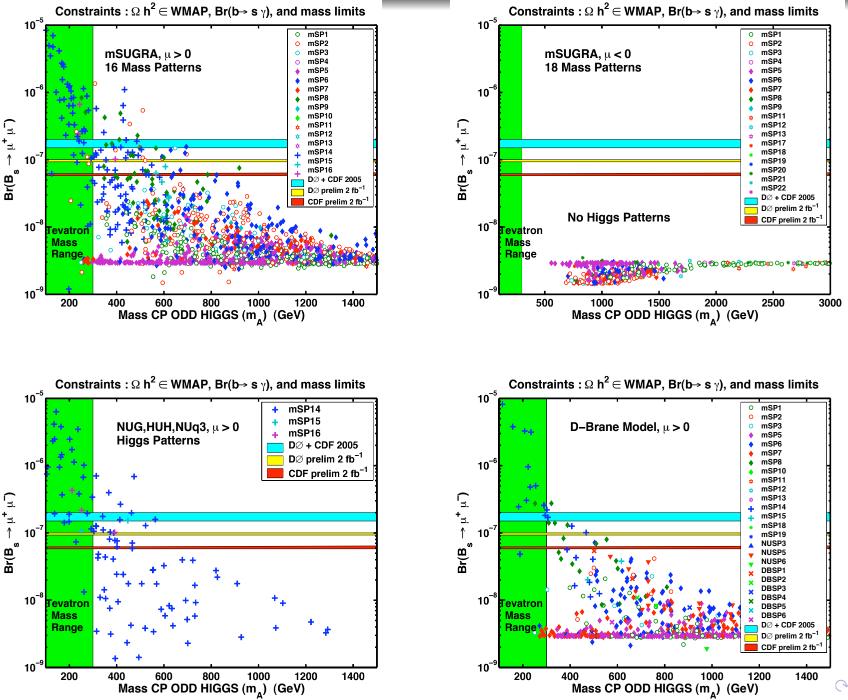


$B_s \longrightarrow \mu^+\mu^-$ and Patterns

Feldman, Liu, PN, arXiv:0711.4591 [hep-ph]



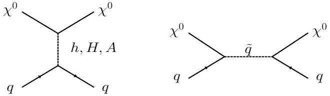
- The process $B_s \longrightarrow \mu^+\mu^-$ is dominated by the neutral Higgs exchange and is enhanced by a factor of $\tan^6\beta$.
- Some patterns with $\mu > 0$, specifically the Higgs Patterns, are beginning to be constrained by the data from the Tevatron. The constraint is relatively ineffective for $\mu < 0$ models.



Constraints : Ω h^2 ∈ WMAP, Br(b→ s γ), and mass limits
mSUGRA, μ > 0
16 Mass Patterns
mSP1
mSP2
mSP3
mSP4
mSP5
mSP6
mSP7
mSP8
mSP9
mSP10
mSP11
mSP12
mSP13
mSP14
mSP15
mSP16
D∅ + CDF 2005
D∅ prelim 2 fb^−1
CDF prelim 2 fb^−1
Tevatron Mass Range
Br(B_s → μ^+ μ^−)
Mass CP ODD HIGGS (m_A) (GeV)
Constraints : Ω h^2 ∈ WMAP, Br(b→ s γ), and mass limits
mSUGRA, μ < 0
18 Mass Patterns
mSP1
mSP2
mSP3
mSP4
mSP5
mSP6
mSP7
mSP8
mSP9
mSP11
mSP12
mSP13
mSP17
mSP18
mSP19
mSP20
mSP21
mSP22
D∅ + CDF 2005
D∅ prelim 2 fb^−1
CDF prelim 2 fb^−1
No Higgs Patterns
Tevatron Mass Range
Br(B_s → μ^+ μ^−)
Mass CP ODD HIGGS (m_A) (GeV)
Constraints : Ω h^2 ∈ WMAP, Br(b→ s γ), and mass limits
NUG,HUH,NUq3, μ > 0
Higgs Patterns
mSP14
mSP15
mSP16
D∅ + CDF 2005
D∅ prelim 2 fb^−1
CDF prelim 2 fb^−1
Tevatron Mass Range
Br(B_s → μ^+ μ^−)
Mass CP ODD HIGGS (m_A) (GeV)
Constraints : Ω h^2 ∈ WMAP, Br(b→ s γ), and mass limits
D−Brane Model, μ > 0
mSP1
mSP2
mSP3
mSP5
mSP6
mSP7
mSP8
mSP10
mSP11
mSP12
mSP13
mSP14
mSP15
mSP18
mSP19
NUSP3
NUSP5
NUSP6
DBSP1
DBSP2
DBSP3
DBSP4
DBSP5
DBSP6
D∅ + CDF 2005
D∅ prelim 2 fb^−1
CDF prelim 2 fb^−1
Tevatron Mass Range
Br(B_s → μ^+ μ^−)
Mass CP ODD HIGGS (m_A) (GeV)

Dark Matter X-Sections and Pattern Discrimination

Feldman, Liu, PN, arXiv:0711.4591 [hep-ph]



- $\sigma(\chi p)$ **(scalar) produces a dispersion among patterns.**
- **A "Wall" consisting of a copious number of parameter points in the Chargino Patterns exist which runs up to the neutralino mass of about 1 TeV with**

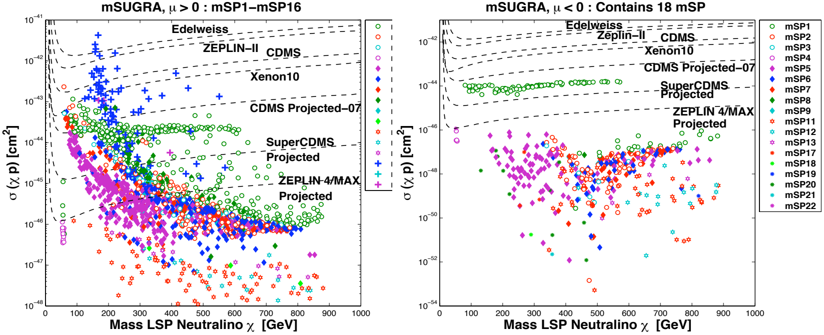
$$\sigma(\chi p) = 10^{-44 \pm .5} \mathrm{cm}^2 \quad \text{(scalar)}.$$

- **The Wall enhances the chances of discovery of cold dark matter in the new generation of experiments such as SuperCDMS, ZEPLIN-MAX, LUX.**

Pattern discrimination in dark matter

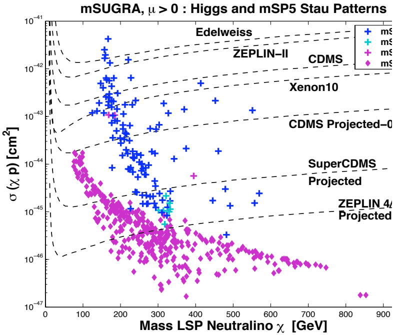
mSUGRA $\mu > 0$ (left) and mSUGRA $\mu < 0$ (right)

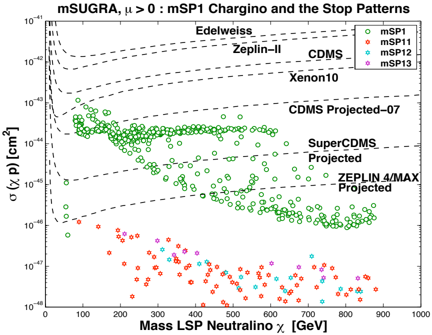
Feldman, Liu, PN, arXiv:0711.4591 [hep-ph]



Pattern discrimination in dark matter for $\mu > 0$
Higgs & Stau Patterns (left)
Chargino & Stop Patterns (right)

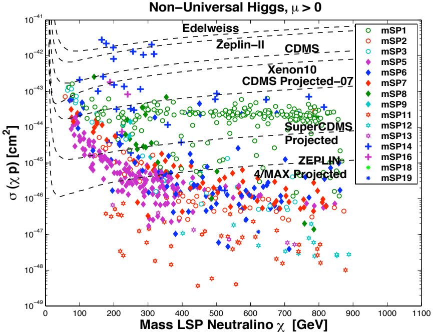
Feldman, Liu, PN, arXiv:0711.4591 [hep-ph]

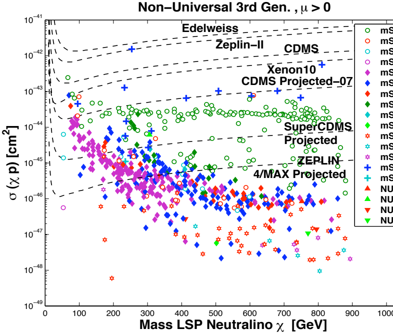




Pattern discrimination in dark matter in NUSUGRA $\mu > 0$ NUH (left) and NUq3 (right)

Feldman, Liu, PN, arXiv:0711.4591 [hep-ph]

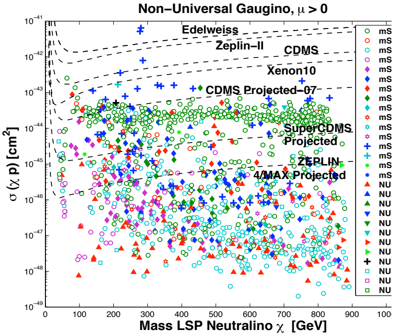


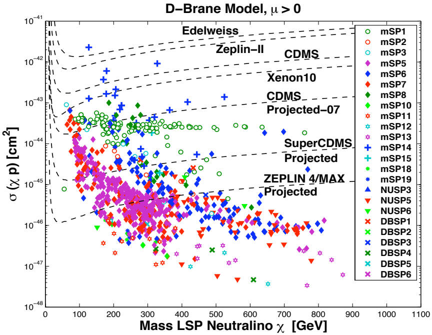


Pattern discrimination in dark matter in NUSUGRA and D Branes ($\mu > 0$)

NUG (left) and D Branes (right)

Feldman, Liu, PN, arXiv:0711.4591 [hep-ph]





Lifting the degeneracies

Feldman, Liu, PN, in progress

Sometimes two points may lead to near identical signatures at the LHC. Consider the following two mSP5 points A and B.

- Point A: $(m_0, m_{1/2}, A_0, \tan\beta) =$ (192.6, 771.3, 1791.1, 8.8),
- Point B (163, 761.3, -775.8, 4.7)

With $10 fb^{-1}$ of integrated luminosity one finds that their 40 signatures have 'pulls' P_i less than 2 where P_i are defined by

$$\mathrm{P}_i = |n_i^A - n_i^B|/\sigma_{AB}$$

$$\sigma_{AB} = \sqrt{1 + (\delta n_i^A)^2 + (\delta n_i^B)^2 + (\delta n_i^{SM})^2}.$$

There are several ways to lift the degeneracies such as including more signatures and increasing the luminosity.

i	S_i	A	B	$P_i : 10 fb^{-1}$	A	B	$P_i : 400 fb^{-1}$
0	N	743	730	0.1	28616	28456	0.0
1	0L	430	414	0.5	16516	16392	0.5
2	1L	221	230	0.4	8452	8328	0.8
3	2L	78	71	0.6	2992	3156	1.9
4	3L	10	13	0.6	580	540	1.2
5	4L	4	2	0.8$\Longleftarrow$	76	40	3.3$\Longleftarrow$
6	0T	620	610	0.3	23460	23888	1.3
7	1T	112	104	0.5$\Longleftarrow$	4568	4100	4.6$\Longleftarrow$
8	2T	11	14	0.6$\Longleftarrow$	548	432	3.7$\Longleftarrow$
9	3T	0	2	1.2	36	32	0.5
10	4T	0	0	0.0	4	4	0.0
11	TL	38	26	1.5	1384	1276	2.0
12	OS	59	57	0.2	2228	2328	1.4
13	SS	19	14	0.9	764	828	1.6
14	OSSF	40	46	0.6	1640	1712	1.2
15	SSSF	7	9	0.5	348	384	1.3
16	OST	7	8	0.2$\Longleftarrow$	336	272	2.6$\Longleftarrow$
17	SST	4	6	0.6$\Longleftarrow$	212	160	2.7$\Longleftarrow$
18	0L1b	50	59	0.9	2076	2156	1.2
19	1L1b	45	39	0.7	1524	1440	1.5
20	2L1b	9	8	0.2	468	528	1.9
21	0T1b	86	88	0.2	3276	3408	1.5

Table: LHC signatures of two mSUGRA ($\mu > 0$) model points.

i	S_i	A	B	$P_i : 10fb^{-1}$	A	B	$P_i : 400fb^{-1}$
0	N	743	730	0.1	28616	28456	0.0
22	1T1b	21	15	1.0	804	724	2.0
23	2T1b	3	3	0.0	108	76	2.3
24	0L2b	20	20	0.0	472	528	1.7
25	1L2b	11	12	0.2	340	404	2.3
26	2L2b	3	5	0.7	176	132	2.5
27	0T2b	30	29	0.1	796	896	2.4
28	1T2b	4	6	0.6	196	164	1.7
29	2T2b	0	2	1.2	20	28	1.1
30	ep	71	71	0.0	2448	2408	0.5
31	em	47	44	0.3	1708	1564	2.4
32	mp	60	70	0.9	2688	2732	0.6
33	mm	43	45	0.2	1608	1624	0.3
34	tp	60	53	0.7$\Longleftarrow$	2604	2164	6.0$\Longleftarrow$
35	tm	52	51	0.1	1964	1936	0.4
36	0b	597	585	0.3	23236	23036	0.6
37	1b	110	107	0.2	4200	4216	0.2
38	2b	34	37	0.4	1012	1088	1.6
39	3b	1	1	0.0$\Longleftarrow$	156	96	3.8$\Longleftarrow$
40	4b	1	0	0.7	12	20	1.4
41	avgpt	727	717	0.3	708	722	0.4

Table: LHC signatures of two mSUGRA ($\mu > 0$) model points.

Lifting the degeneracies

Feldman, Liu, PN, in progress

2 mSP5 points A', and B'.

- Point = $(\boldsymbol{m_0}, \boldsymbol{m_{1/2}}, \boldsymbol{A_0}, \boldsymbol{\tan\beta})$
- Point A' = (159.3, 732.3, -783.1, 5.6)
- Point B' = (163.5, 753.3, -918.2, 3.3)

With $\boldsymbol{10 fb^{-1}}$ of integrated luminosity one finds that their 40 signatures have 'pulls' $\boldsymbol{P_i}$ less than 2.

i	S_i	A'	B'	P_i	A'	B'	P_i	A'	B'	P_i
				10			100			500
0	N	878	817	1.2	9089	8330	4.7	45479	41135	12.1
1	0L	484	437	1.3	5114	4668	3.7	25897	23427	9.1
2	1L	294	271	0.8	2758	2594	1.8	13669	12414	6.3
3	2L	83	96	0.8	1010	894	2.2	4904	4369	4.5
4	3L	16	11	0.8	193	151	1.8	927	830	1.9
5	4L	1	2	0.4	14	23	1.2	82	95	0.8
6	0T	731	674	1.2	7671	6896	5.2	38213	34138	12.4
7	1T	137	129	0.4	1288	1266	0.4	6528	6296	1.7
8	2T	10	14	0.7	126	162	1.7	693	659	0.8
9	3T	0	0	0.0	4	6	0.5	43	40	0.3
10	4T	0	0	0.0	0	0	0.0	2	2	0.0
11	TL	50	45	0.4	430	409	0.6	2069	2029	0.5
12	OS	66	70	0.3	753	671	1.8	3665	3285	3.7
13	SS	17	26	1.1	257	223	1.3	1239	1084	2.6
14	OSSF	49	52	0.2	549	485	1.6	2710	2389	3.7
15	SSSF	10	13	0.5	120	99	1.2	537	481	1.4
16	OST	5	9	0.9	70	96	1.6	428	402	0.7
17	SST	5	5	0.0	56	66	0.7	265	257	0.3
18	0L1b	61	56	0.4	723	680	0.9	3527	3387	1.4
19	1L1b	48	53	0.4	484	480	0.1	2431	2268	1.9
20	2L1b	15	21	0.8	180	164	0.7	853	778	1.5

Table: Points A' and B' with 10, 100, 500 fb^{-1}.

i	S_i	A'	B'	P_i	A'	B'	P_i	A'	B'	P_i
				10			100			500
21	0T1b	100	110	0.6	1160	1103	1.0	5734	5353	3.0
22	1T1b	22	20	0.3	235	223	0.5	1150	1106	0.8
23	2T1b	4	2	0.6	23	32	1.0	111	129	0.9
24	0L2b	12	13	0.2	165	153	0.5	890	838	1.0
25	1L2b	15	24	1.2	128	129	0.1	625	598	0.6
26	2L2b	1	2	0.4	59	43	1.3	251	227	0.9
27	0T2b	25	32	0.8	303	269	1.2	1481	1379	1.6
28	1T2b	4	6	0.5	50	56	0.5	300	297	0.1
29	2T2b	0	1	0.7	7	8	0.2	28	27	0.1
30	ep	93	83	0.6	863	818	0.9	4251	3957	2.6
31	em	52	51	0.1	533	501	0.8	2618	2358	3.0
32	mp	103	78	1.5	852	787	1.3	4236	3821	3.8
33	mm	46	59	1.0	510	488	0.6	2564	2278	3.4
34	tp	69	80	0.7	710	729	0.4	3564	3504	0.6
35	tm	68	49	1.4	578	537	1.0	2964	2792	1.9
36	0b	717	642	1.7	7258	6588	4.6	36432	32602	11.9
37	1b	126	132	0.3	1420	1358	1.0	7003	6593	2.9
38	2b	29	39	1.0	360	333	0.8	1810	1706	1.4
39	3b	6	2	1.1	47	41	0.5	215	205	0.4
40	4b	0	2	1.1	4	10	1.3	19	29	1.2

Table: Points A' and B' with 10, 100, 500 fb^{-1}.

Conclusions

- The main message is that the study of the sparticle landscape and of patterns can be a useful tool in extrapolating data back to theory.

- The landscape with $\boldsymbol{O(10^4)}$ patterns for the 4 lightest sparticles reduces down just to about 50, in SUGRA and D Brane models, under the WMAP3, LEP and Tevatron constraints. This is a significant progress.

- The partial analysis of lepton and jet events, Higgs production x-sections and $\boldsymbol{B_s\mu\mu}$ already allows one to separate many of these patterns.

- Dark matter cross sections provide additional pattern discrimination and further studies can relate specfic patterns with predictive $\boldsymbol{\sigma(\chi p)}$ and specific LHC signals.

Conclusions-continued

- In the analysis of SUGRA and D brane models one finds the existence of a Wall consisting of a copious number of parameter points in the Chargino Patterns.

- The chances of discovery of dark matter at the Wall are enhanced due to clustering. If the dark matter does indeed originate at the Wall, then the NLSP is a Chargino and mostly likely the first particle to be discovered at the LHC.

- A more complete analysis should include CP phases and the attendant constraints from EDMs.