.

THE LHC INVERSE PROBLEM

-- TOWARD THE UNDERLYING THEORY

Gordy Kane, Michigan Center for Theoretical Physics

University of Indiana, June 2015

- The Standard Model (SM) of particle physics is an awesome theory, truly a relativistic quantum field theory of the particles (quarks and leptons) that make up all we see, and the interactions that act on the particles to form our world

- The SM is an effective theory, with some inputs – surprisingly few from a historical point of view, considering how much it describes – all measured
  - Three gauge couplings for SU(3), SU(2), U(1), but partially unified
  - Some quark and lepton masses
  - Two Higgs sector parameters – the Higgs sector looks like a naïve SM one but obviously is not since that is inconsistent – presumably the observed Higgs boson is the lightest eigenvalue of a decoupling two-doublet supersymmetric Higgs sector
  - θ_{QCD}

- The SM is incomplete – it cannot explain the dark matter or the matter asymmetry or precise gauge coupling unification or the existence of three families of quarks and leptons – it can describe (accommodate) parity violation but not explain it – it has a fundamental quantum hierarchy problem – and more

- Most of the workshop has been about reactions and phenomena within the SM

- Finding out what physics extends the SM and strengthens its foundations also requires data!

- Two approaches:
  - Need discoveries and data to point to the theory – approach of this school, and historical
  - “Guess” correct underlying theory – but even then must test it or will never get consensus
  - 1 to 1.5 lectures on first point, rest on second – I focused on first approach ~ 2002, then moved toward second beginning 2005

Our “guess” for a top-down theory will be a well motivated compactified M-theory – starting at 11D, and at Planck mass in the resulting 4D theory

I’ll try to make it clear why string/M theories are good physics and testable, and predictive

- Data likely to come mainly from LHC, some from dark matter experiments (“indirect detection” (satellites), “direct detection” (scattering of DM on nuclei)), EDMs, g_μ-2, etc

- Suppose some discoveries at LHC – then the problem is how to interpret them, what do they imply – without a theory, hopeless – always many interpretations – need to get low scale theory and then presumably underlying theory at Planck scale

- Suppose we know the theory (supersymmetry, of course) – still degeneracies – we showed that the inverse map of a point in “signature space” consists of a number, possibly large, of isolated islands in “parameter space”, i.e. of different models (different superpartner masses etc)

  [Nima Arkani-Hamed, GK, Jesse Thaler, Liantao Wang, hep-ph/0512190]

- Data is at low scale, collider scale – but underlying theory is at high scale – *must* do RGE running to connect data to theory – always ambiguous since incomplete data at low scale – maybe new physics at in-between scales affects running – can find some techniques to help

  [GK, Piyush Kumar, David Morrissey, Manuel Toharia, hep-ph/0612287]

- Study/test of gaugino masses unification at LHC – given measurements of observables related to gaugino masses are the gaugino masses actually universal at the unification scale? – don't (cannot) actually measure the gaugino masses themselves

  [Boris Altunkaynak, Phillip Grajek, Michael Holmes, GK, Brent Nelson, arXiv:0901.1145]

- The lightest superpartner (LSP) is a good candidate for the dark matter – if superpartners produced at LHC, every superpartner decays into lightest one – it can be a linear combination of wino, bino, photino, zino – the associated relic density depends sensitively on the linear combination – can we determine the LSP mass and wavefunction from LHC data?

  [GK, Eric Kuflik, Brent Nelson, arXiv:1105.3742]

Knowledge of supersymmetry not needed to understand the issues – basically just that every SM particle has a superpartner with same properties, except mass can be different

Supersymmetry and the LHC Inverse Problem

-- Nima Arkani-Hamed, GK, Jesse Thaler, Liantao Wang - ph/0512190 – 55 pages

- Given experimental evidence for physics beyond the SM (!), how can we determine the nature of the underlying theory?
- Assume supersymmetry – study “inverse map” from space of LHC signatures to parameters of susy theory
- Find “degeneracies” – different “models” with same LHC signatures, maybe many
- Major issues – is LSP dark matter? – gaugino masses consistent with grand unification? – large extra dimensions?
- At hadron collider difficult to measure masses and properties of new particles, particularly because two escaping LSPs

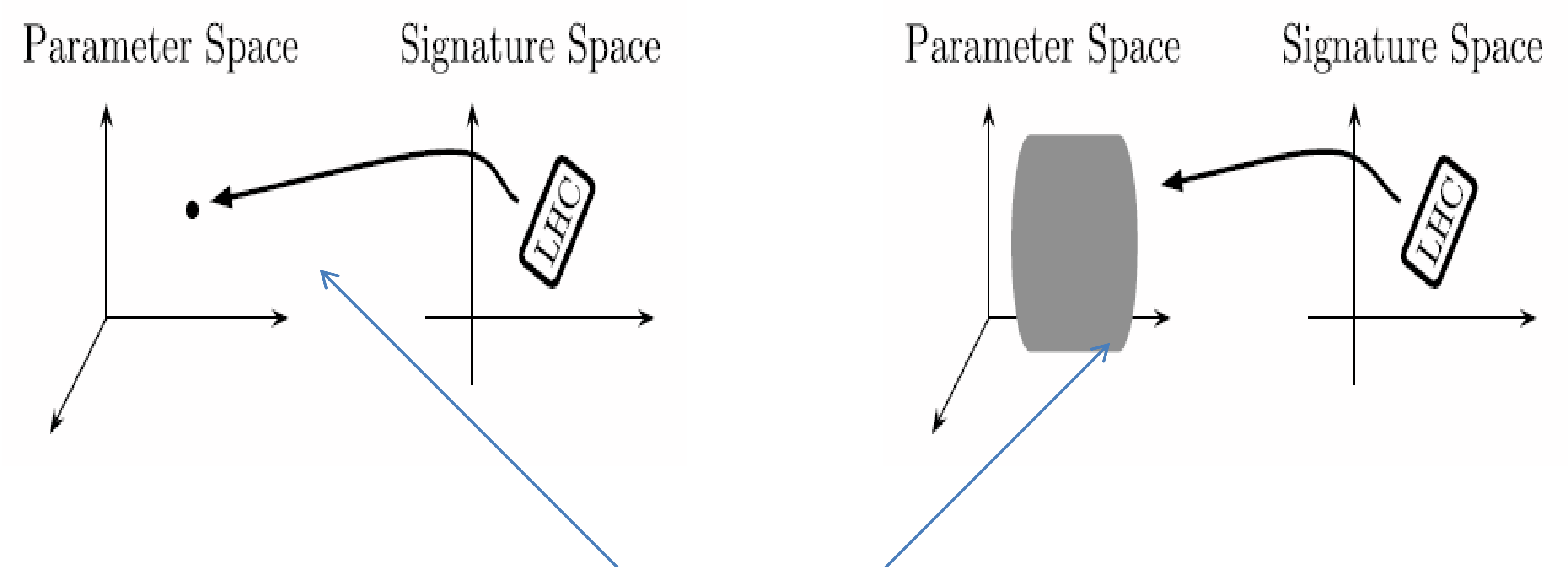
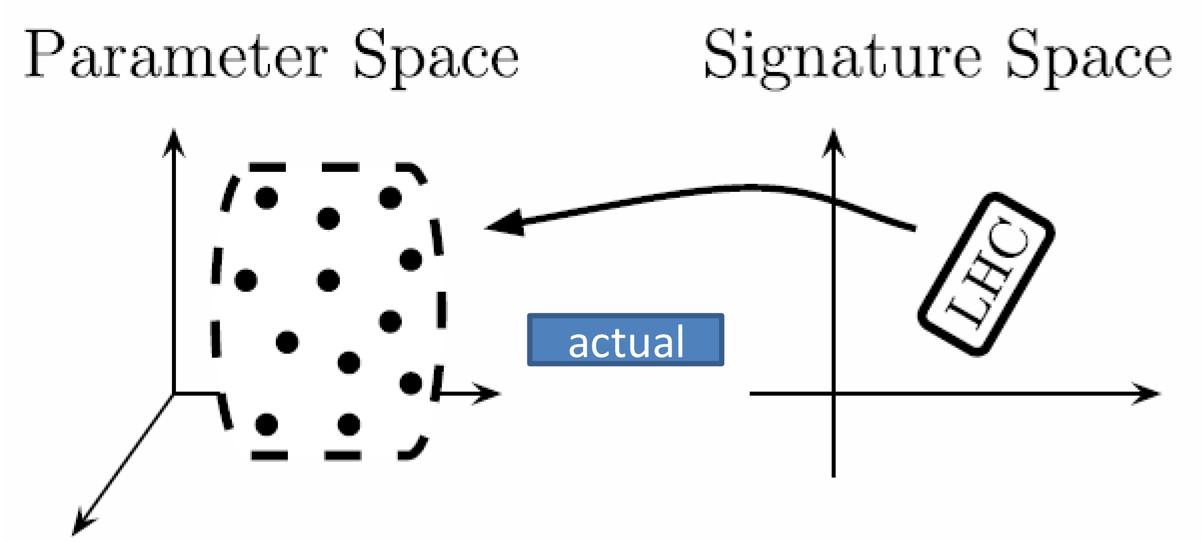


Figure 2: The Inverse Map in the Best and Worst of All Possible Worlds. Ideally, the



actual

- **We find that the inverse map consists of disconnected and perhaps widely separated regions in parameter space → degeneracies**
- **Our study – 3 gaugino masses M1, M2, M3; μ; soft masses of first two families of squarks and sleptons taken degenerate; soft masses of 3rd family; tanβ, so 15 parameters – probably sufficient for almost all outcomes**
- **Many signatures, e.g. event counts with cuts, binning → 1808 observables**
- **Don't need to simulate m models to study this – suppose throw balls into box with N bins – can't see inside, so don't know N – might think need to throw m=N balls in to cover all possible cases – but on average the number of bins with p balls is $N_p \sim m^p/p!N^{p-1}$ – number of doubles is $N_2=m^2/(2N)$ – see how many doubles N_2 there are, and then $N=m^2/(2N_2)$ – need $m \sim \sqrt{N}$ to have at least some doubles, but not $m \sim N$ – we were simulation limited (in 2005)**

- **There are “cliffs” in model space – small distance in parameter space but large differences in signature space – small parameter changes can lead to large changes in the signatures**
- **Consider (well motivated) models where sleptons are heavy – then leptons mainly come from W’s and Z’s arising in electroweakino cascade decays**
- **Two models can have identical LHC signals if**

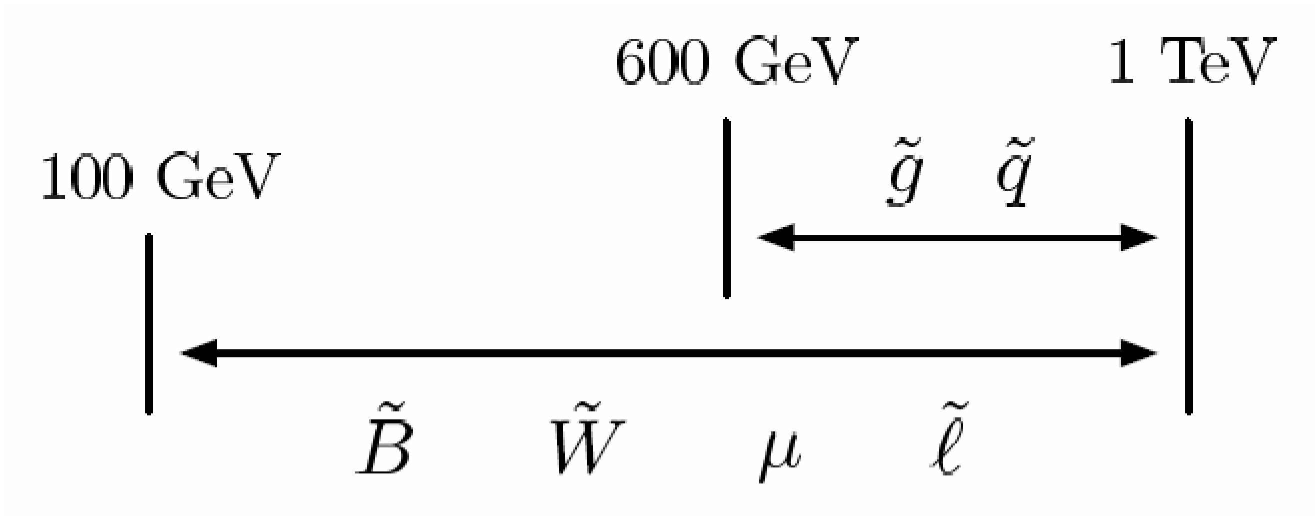
  -- “flippers” – electroweakino mass eigenvalues same but eigenstates different

  -- “sliders” – electroweakino spectrum moved up or down but mass differences fixed

  -- “squeezers” – some splittings small so leptons too soft to see

Used PGS

Parameter ranges:



LSPs have about same mass – masses of squarks and sleptons move a little to compensate switch of wino and higgsino

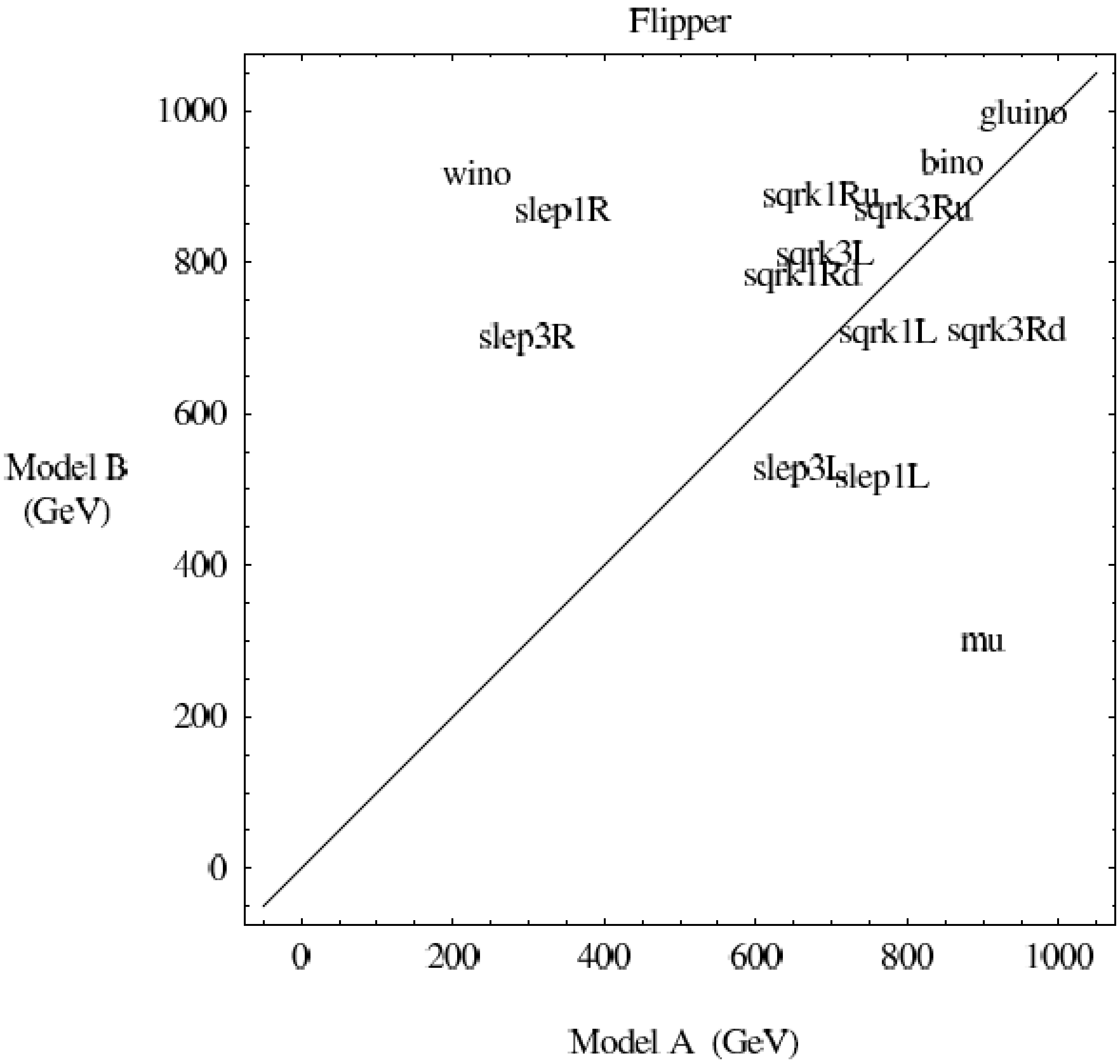


Figure 17: An example of a Flipper, where the masses of the electroweak-inos sta
fixed but their identity changes. In this example a wino LSP is replaced by a higgs

Identities of three electroweakinos differ by cyclic permutation – in both there are two electroweakinos lighter than gluino and squarks so both present in decay chain

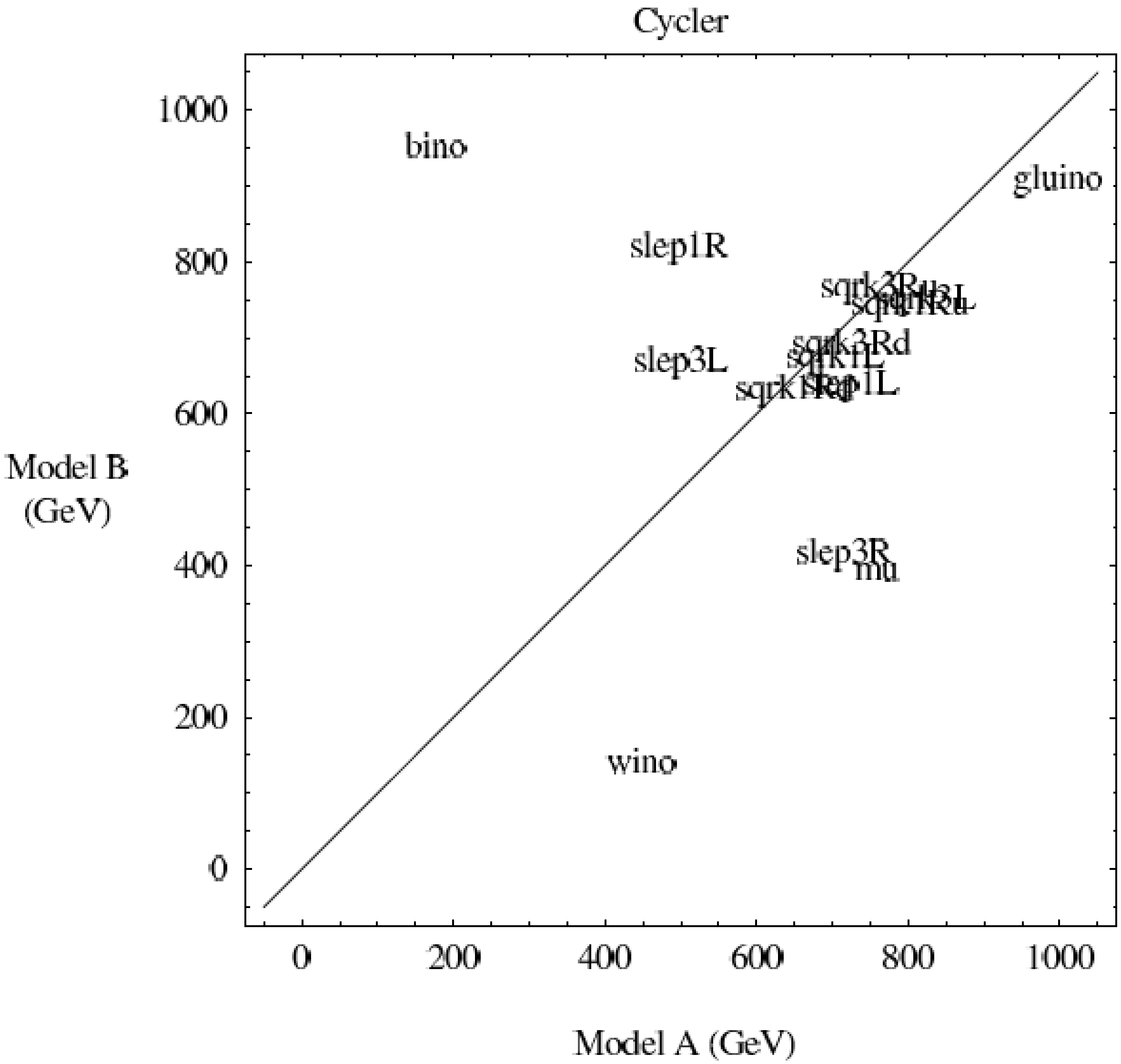
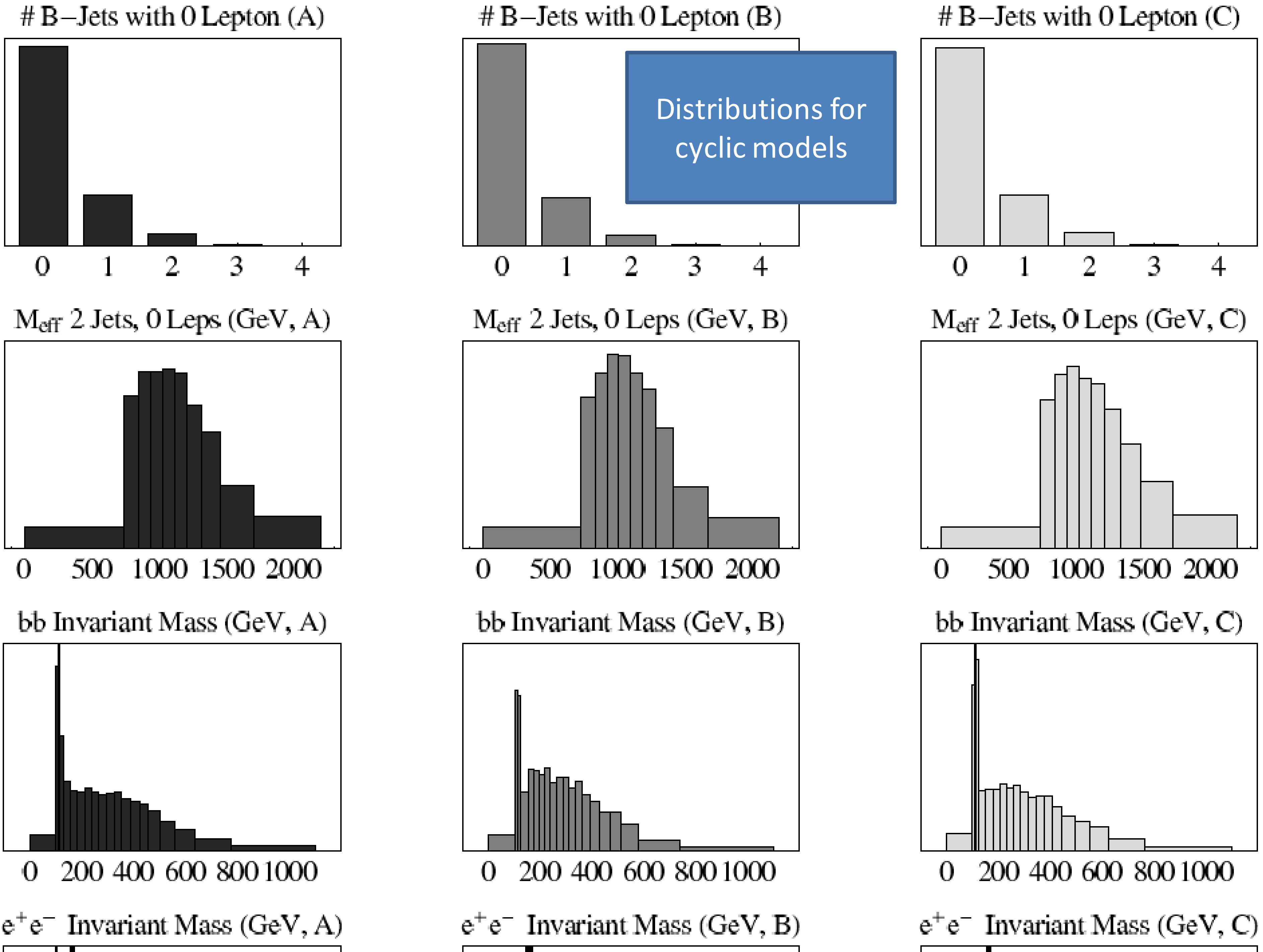


Figure 18: An extreme example of a flipper is a Cycler, where the electrweak-ino undergo a cyclic permutation. In model A, $\tilde{B} < \tilde{W} < \mu$, whereas in model B, $\tilde{W} <$

Distributions for cyclic models



- **Number of degeneracies interesting – not very large – but non-trivial challenge – more study valuable**
- **Good to study degeneracies between different sorts of physics, such as large extra dimensions and MSSM**
- **This work only studied low scale 4D theory**

CONNECTING WEAK SCALE THEORIES TO AN ULTRAVIOLET COMPLETION

[GK, Piyush Kumar, David Morrissey, Manuel Toharia ph/0612287; see also Cohen, Roy, Schmaltz ph/0612100]

- Unification of gauge couplings implies this is possible
- Planck scale is the natural scale for an underlying theory
- Unification of gauge couplings restricts possible forms of new physics above electroweak scale
- But there are obstacles…

- Used some Snowmass points as examples in papers – some excluded already – ignore that issue

- Suppose superpartners are observed at LHC
- As we saw, extracting the parameters of the soft-breaking Lagrangian is not under control
- Experimental errors, islands, etc
- Guessing a high scale theory and running down would be basically under control, but not running up
- If new physics above EW scale is gauge singlets, or complete GUT multiplets, then doesn't change the running up
- Don't know how supersymmetry is broken
- Nevertheless, can write the most general soft-breaking Lagrangian (soft = don't introduce UV divergences)
- The high scale values can be very sensitive to uncertainties in low scale values
- In some cases we found there are particular combinations that ARE stable under RGE evolution, or unaffected by some forms of new physics!

The one-loop renormalization group (RG) equations of the MSSM soft scalar masses have the form [16]

$$(16\pi^2)\frac{dm_i^2}{dt} = \tilde{X}_i - \sum_{a=1,2,3} 8\, g_a^2 C_i^a |M_a|^2 + \frac{6}{5} g_1^2 Y_i\, S, \tag{1}$$

where $t = \ln(Q/M_Z)$, $\tilde{X}_i$ is a function of the soft squared masses and the trilinear couplings, M_a denotes the a-th gaugino mass, and the S term is given by

$$\begin{aligned} S &= Tr(Y\, m^2) \\ &= m_{H_u}^2 - m_{H_d}^2 + tr(m_Q^2 - 2\, m_U^2 + m_E^2 + m_D^2 - m_L^2) \end{aligned} \tag{2}$$

where the first trace runs over all hypercharge representations, and the second runs only over flavors.

- One loop running of S in MSSM is

$$(16\pi^2)\,\frac{dS}{dt} = -2\, b_1\, g_1^2\, S$$

where b_1 =-33/5 is the one loop beta-function coefficient

- S=0 if all soft masses equal

- If S≠0 the high scale values of the soft masses are shifted by

$$\Delta m_i^2(t) = \frac{Y_i}{Tr(Y^2)} \left[\frac{g_1^2(t)}{g_1^2(t_0)} - 1 \right] S(t_0)$$

- If S=0 at one scale it vanishes at all scales (one loop) – often S neglected
- No theoretical motivation for S to vanish
- Since g_1 grows with energy the mass shift grows
- Experimental uncertainty in value set by least well measured scalar mass – unbounded if any scalar mass not measured
- S does not enter directly into running of other soft parameters until 3-loop order
- Can avoid the problem if use instead, for any pair,

$$Y_j m_i^2 - Y_i m_j^2,$$

Study several examples:

- ☐ **Example – SPS-5 with unmeasured Higgs soft mass M_{Hd}**

  -- mSUGRA high scale inputs m_0 =150 GeV, $m_{1/2}$=300 GeV, A_0=-1000 GeV, tanβ=5, sign of μ>0

- ☐ **Example – Complete GUT multiplets – unification scale same but value of unified gauge coupling is changed – running of soft masses changed**
- ☐ **Example – Yukawa effects, more combinations**
- ☐ **Example – Intermediate scale gauge singlet matter, e.g. heavy singlet neutrinos**
- ☐ **Example combining several – reconstruct underlying theory from incomplete data and clever theory**

STUDYING GAUGINO MASS UNIFICATION AT LHC

[Baris Altunkaynak, Phillip Grajek, Michael Holmes, GK, Brent Nelson, arXiv:0901.1145 – 68 pages]

What are most valuable measurements at LHC to learn about underlying theory?

- **Value, origin of μ**
- **tanβ - but doesn’t exist at high scale!**
- **LSP mass and wave function**
- **Arguably, gaugino masses – gaugino mass universality?**
    - **But gaugino masses not directly measurable!!!!!**
    - **M3, gluino mass, has ~ 30% loop corrections that depend on other masses**

$$M_{\tilde{g}} = M_3(Q)\left[1+\frac{\alpha_s(Q)}{4\pi}\left(15-18\log\frac{M_3(Q)}{Q}+\sum_q B_1(M_3,m_{\tilde{q}},m_q)\right)\right]$$

.

$$\mathcal{L} \supset -\left(\tilde{W}^- \; \tilde{H}_d^-\right) \mathcal{M}_C \begin{pmatrix} \tilde{W}^+ \\ \tilde{H}_u^+ \end{pmatrix} + h.c.,$$

Charginos:

$$\mathcal{M}_C = \begin{bmatrix} M_2 & \sqrt{2} M_W s_\beta \\ \sqrt{2} M_W c_\beta & -\mu \end{bmatrix}$$

$$\mathcal{L} \supset -\left(\tilde{B} \; \tilde{W}^3 \; \tilde{H}_d^0 \; \tilde{H}_u^0\right) \mathcal{M}_N \begin{pmatrix} \tilde{B} \\ \tilde{W}^3 \\ \tilde{H}_d^0 \\ \tilde{H}_u^0 \end{pmatrix} + h.c$$

Neutralinos:

$$\mathcal{M}_N = \begin{bmatrix} M_1 & 0 & -M_Z s_W c_\beta & M_Z s_W s_\beta \\ 0 & M_2 & M_Z c_W c_\beta & -M_Z c_W s_\beta \\ -M_Z s_W c_\beta & M_Z c_W c_\beta & 0 & -\mu \\ M_Z s_W s_\beta & -M_Z c_W s_\beta & -\mu & 0 \end{bmatrix}$$

Diagonalize chargino mass matrix:

unitary matrices U and V, such that

$$\mathcal{M}_C^{\rm diag} = U \mathcal{M}_C V^{-1},$$

where

$$U = \mathcal{O}_-,$$
$$V = \begin{cases} \mathcal{O}_+ & \text{if } \det\mathcal{M}_C > 0 \\ \sigma_3 \mathcal{O}_+ & \text{if } \det\mathcal{M}_C < 0 \end{cases},$$

where σ_3 is the diagonal Pauli matrix introduced to make the masses positive and the rotation matrices $\mathcal{O}_\pm$ are given by

$$O_\pm = \begin{pmatrix} \cos\phi_\pm & -\sin\phi_\pm \\ \sin\phi_\pm & \cos\phi_\pm \end{pmatrix},$$

where

$$\tan 2\phi_- = 2\sqrt{2} M_W \frac{-\mu \sin\beta + M_2 \cos\beta}{M_2^2 - \mu^2 - 2M_W^2 \cos 2\beta},$$

and

$$\tan 2\phi_+ = 2\sqrt{2} M_W \frac{-\mu \cos\beta + M_2 \sin\beta}{M_2^2 - \mu^2 - 2M_W^2 \cos 2\beta},$$

The matrix $\mathcal{M}_C$ has two egingstates $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^\pm$ (the charginos)

The Hermitian matrix $\mathcal{M}_N$ can be diagonalised by a unitary transformation of the neutralino fields, so that

$$N^\dagger \mathcal{M}_N N = \mathcal{M}_N^{diag}.$$

$\tilde{\chi}$ has good chance of being the LSP. The lightest neutralinc combination of the original fields:

$$\tilde{\chi}_1^0 = N_{11}\tilde{B}^0 + N_{12}\tilde{W}^0 + N_{13}\tilde{H}_1^0 + U_{14}\tilde{H}_2^0. \tag{5.14}$$

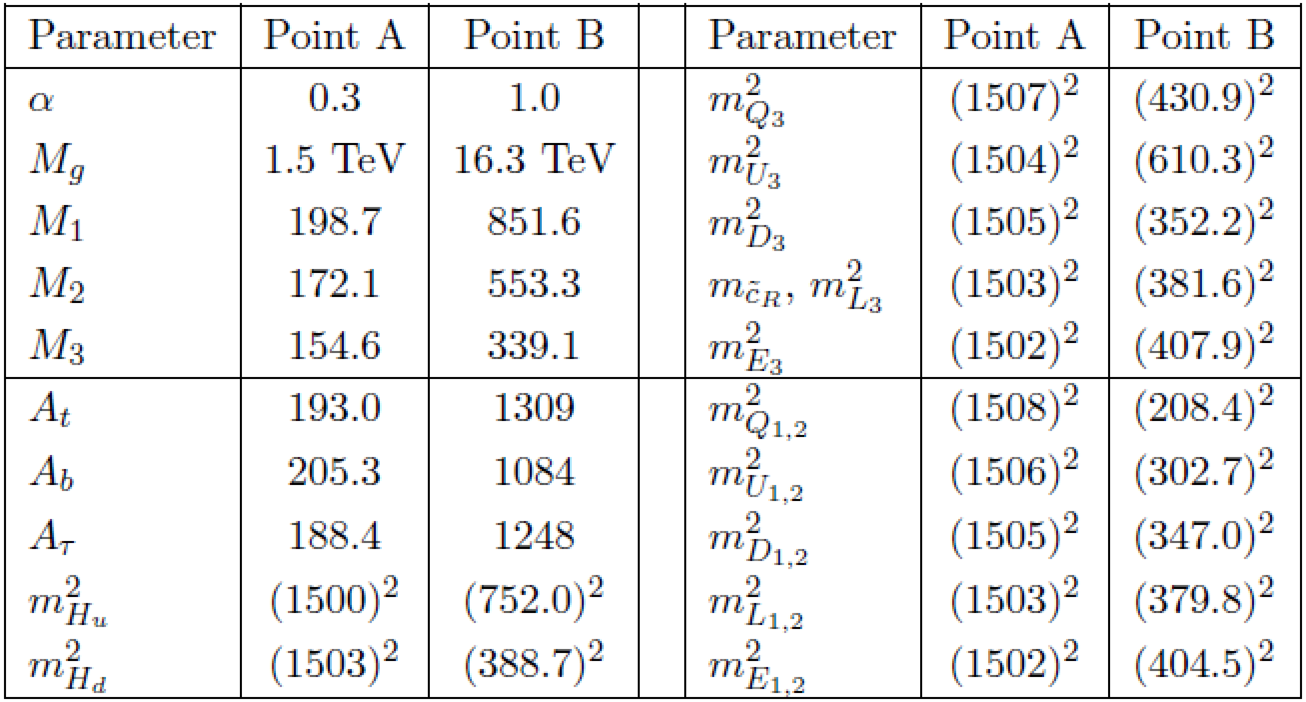
Key point:

- **Data on neutralino and chargino mass eigenstate production is sensitive to M1, M2, μ -- cross sections, decay chains, LSP mass**
- **So can get info on their values**
- **But hard – global fits give poor results**
- **Approach:**
  - **Adopt (motivated) parameterization, aim to measure parameter(s)**

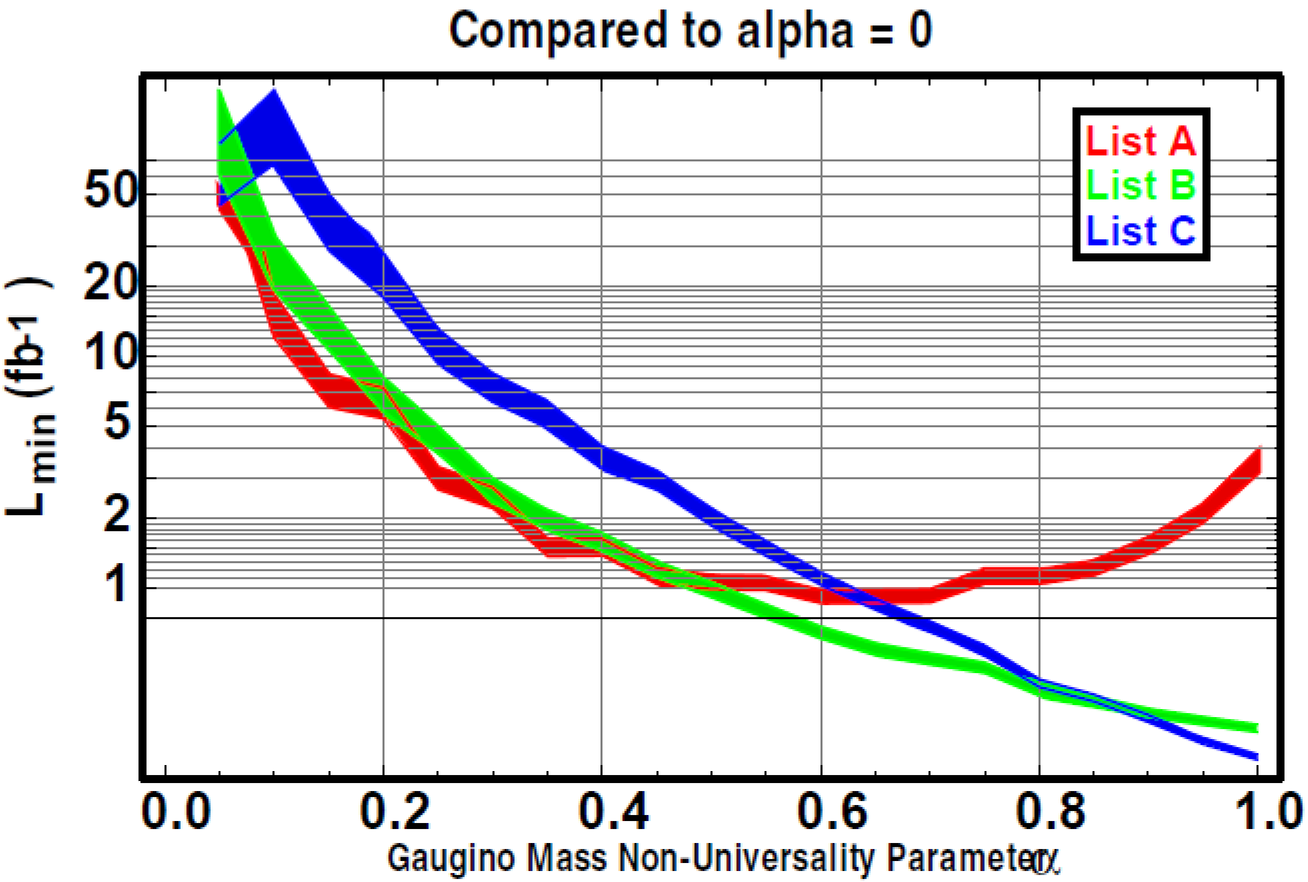
$$M_1 : M_2 : M_3 \simeq (1+0.66\alpha) : (2+0.2\alpha) : (6-1.8\alpha)$$

- **α=0 is high scale gaugino mass universality – various values of α relate to various models**
- **Use essentially same parameter list (15) as for degeneracy analysis**

Benchmark models (A,B,C)



Parameter	Point A	Point B		Parameter	Point A	Point B
α	0.3	1.0		$m^2_{Q_3}$	$(1507)^2$	$(430.9)^2$
M_g	1.5 TeV	16.3 TeV		$m^2_{U_3}$	$(1504)^2$	$(610.3)^2$
M_1	198.7	851.6		$m^2_{D_3}$	$(1505)^2$	$(352.2)^2$
M_2	172.1	553.3		$m_{\tilde{c}R}$, $m^2_{L_3}$	$(1503)^2$	$(381.6)^2$
M_3	154.6	339.1		$m^2_{E_3}$	$(1502)^2$	$(407.9)^2$
A_t	193.0	1309		$m^2_{Q_{1,2}}$	$(1508)^2$	$(208.4)^2$
A_b	205.3	1084		$m^2_{U_{1,2}}$	$(1506)^2$	$(302.7)^2$
A_τ	188.4	1248		$m^2_{D_{1,2}}$	$(1505)^2$	$(347.0)^2$
$m^2_{H_u}$	$(1500)^2$	$(752.0)^2$		$m^2_{L_{1,2}}$	$(1503)^2$	$(379.8)^2$
$m^2_{H_d}$	$(1503)^2$	$(388.7)^2$		$m^2_{E_{1,2}}$	$(1502)^2$	$(404.5)^2$


Compared to alpha = 0
List A
List B
List C
L_{min} (fb-1)
50
20
10
5
2
1
0.0
0.2
0.4
0.6
0.8
1.0
Gaugino Mass Non-Universality Parameter α

α

68 pages – signatures, signature space – measures – degeneracies – simulations -

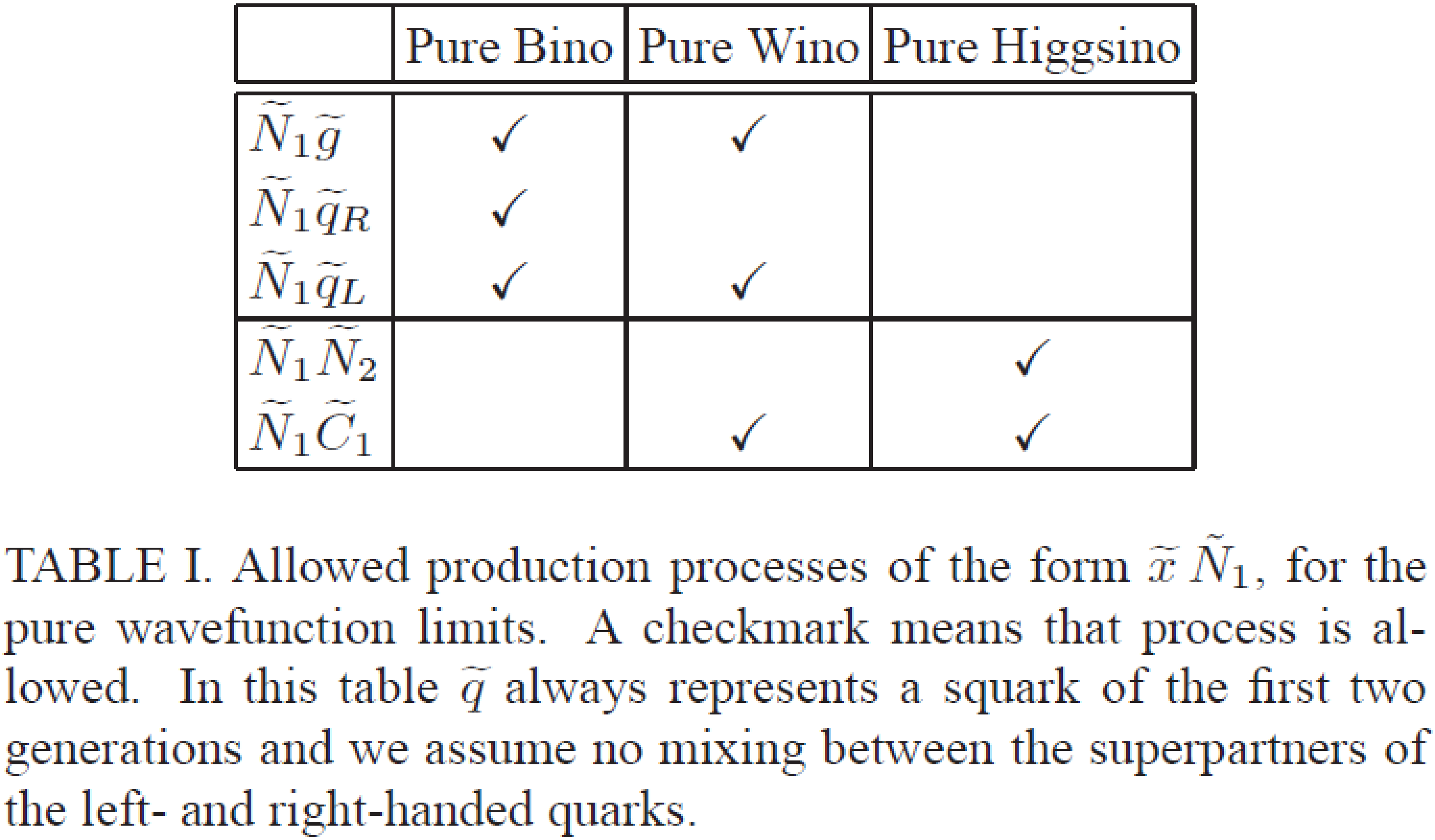
EXTRACTING THE LSP WAVE FUNCTION

[GK, Eric Kuflik, Brent Nelson, arXiv:1105.3742]

- Consider associated production of gluinos (or squarks) with LSP and associated channels – very sensitive to composition of LSP – study event shape variables (some new) – illustrate with benchmark models
- LSP may be stable – if so, very good dark matter candidate – annihilation rate depends strongly on mass, composition
- Scattering rate of LSP on nuclei provides major info – again, very sensitive to composition
- Still very interesting even if not dark matter
- LSP is lightest eigenvalue of neutralino mass matrix – can get mass kinematically, probably, but composition very hard

$$N_1 = N_{11} B + N_{12} W + N_{13} H_d^0 + N_{14} H_u^0$$

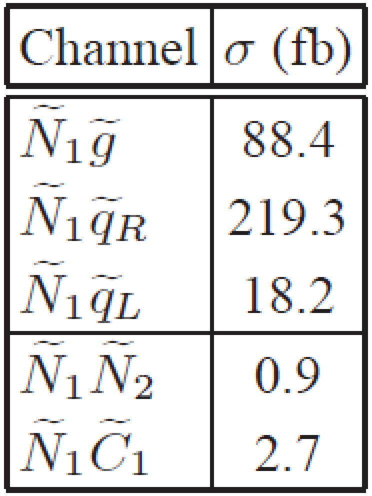
- **Probably hopeless to reconstruct all eigenvalues and eigenstates of neutralino mass matrix**
- **Basic point is that the observables are sensitive to how much wino is in LSP, etc – want to find and study processes that depend on N_{1j}**



	Pure Bino	Pure Wino	Pure Higgsino
$\widetilde{N}_1 \widetilde{g}$	✓	✓	
$\widetilde{N}_1 \widetilde{q}_R$	✓		
$\widetilde{N}_1 \widetilde{q}_L$	✓	✓	
$\widetilde{N}_1 \widetilde{N}_2$			✓
$\widetilde{N}_1 \widetilde{C}_1$		✓	✓

TABLE I. Allowed production processes of the form $\widetilde{x}\,\widetilde{N}_1$, for the pure wavefunction limits. A checkmark means that process is allowed. In this table $\widetilde{q}$ always represents a squark of the first two generations and we assume no mixing between the superpartners of the left- and right-handed quarks.

Production rates:

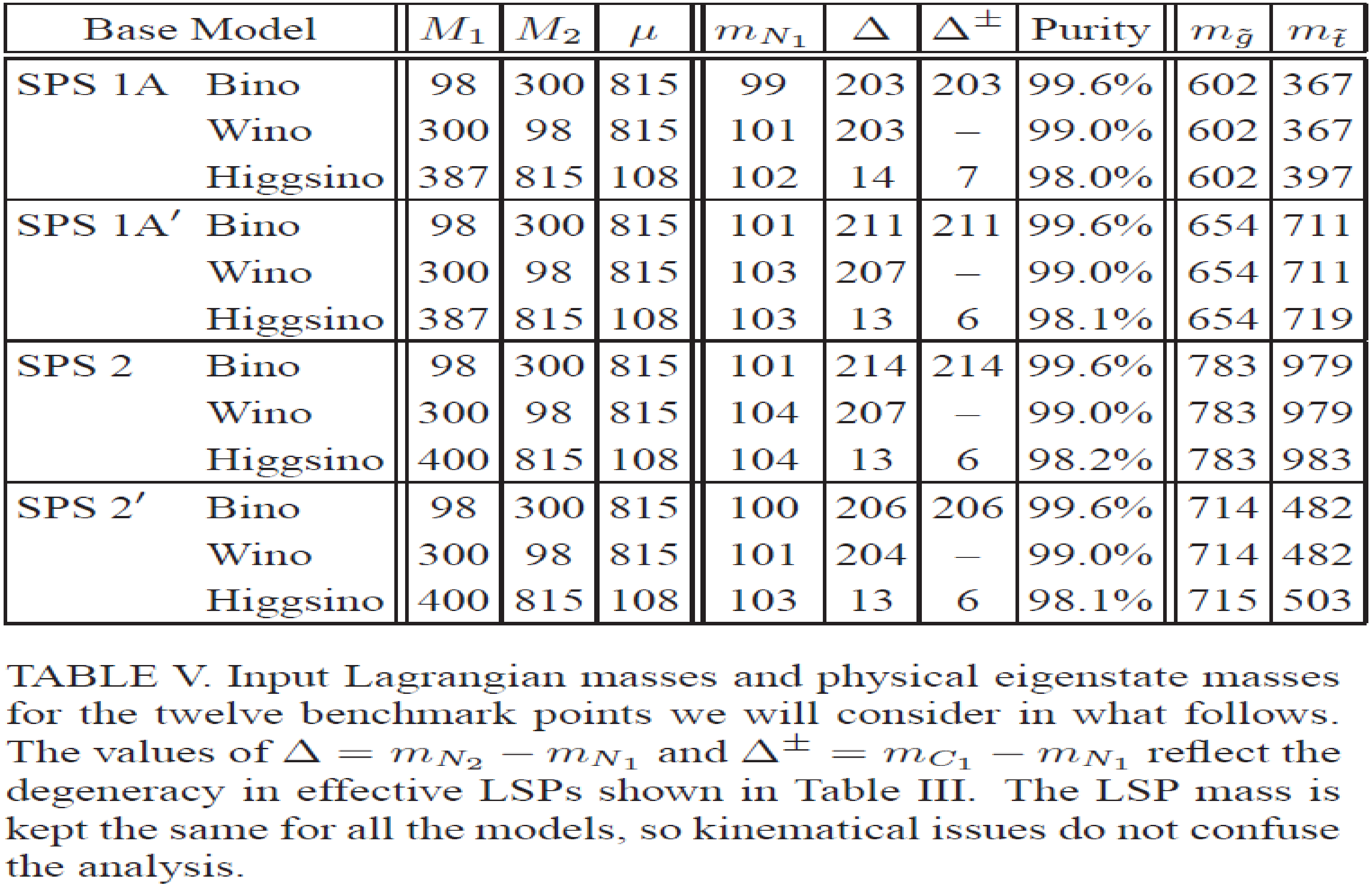


Channel	σ (fb)
$\widetilde{N}_1\widetilde{g}$	88.4
$\widetilde{N}_1\widetilde{q}_R$	219.3
$\widetilde{N}_1\widetilde{q}_L$	18.2
$\widetilde{N}_1\widetilde{N}_2$	0.9
$\widetilde{N}_1\widetilde{C}_1$	2.7

TABLE II. Production cross sections for processes of Table I for the particular example of SPS point 1A. The total supersymmetric production is $\sigma_{\mathrm{SUSY}} = 41.5\,\mathrm{pb}$

- LHC ~ 100 fb^{-1} in 1-2 years

- **So info is there – but other susy channels have larger rates, so “backgrounds” serious – 12 benchmark models, same LSP mass – use degeneracies, flippers, etc to have different type LSPs**



Base Model		M_1	M_2	μ	m_{N_1}	Δ	$\Delta^{\pm}$	Purity	$m_{\tilde{g}}$	$m_{\tilde{t}}$
SPS 1A	Bino	98	300	815	99	203	203	99.6%	602	367
	Wino	300	98	815	101	203	—	99.0%	602	367
	Higgsino	387	815	108	102	14	7	98.0%	602	397
SPS 1A′	Bino	98	300	815	101	211	211	99.6%	654	711
	Wino	300	98	815	103	207	—	99.0%	654	711
	Higgsino	387	815	108	103	13	6	98.1%	654	719
SPS 2	Bino	98	300	815	101	214	214	99.6%	783	979
	Wino	300	98	815	104	207	—	99.0%	783	979
	Higgsino	400	815	108	104	13	6	98.2%	783	983
SPS 2′	Bino	98	300	815	100	206	206	99.6%	714	482
	Wino	300	98	815	101	204	—	99.0%	714	482
	Higgsino	400	815	108	103	13	6	98.1%	715	503

TABLE V. Input Lagrangian masses and physical eigenstate masses for the twelve benchmark points we will consider in what follows. The values of $\Delta = m_{N_2} - m_{N_1}$ and $\Delta^{\pm} = m_{C_1} - m_{N_1}$ reflect the degeneracy in effective LSPs shown in Table III. The LSP mass is kept the same for all the models, so kinematical issues do not confuse the analysis.

- Event shape variables, e. g. sphericity s

$$S^{ab} = \sum_i p_{ai} p_{bi} \, , \qquad a, b = x, y, z \, , \qquad s = \frac{3}{2} \frac{\lambda_1 \lambda_2}{\mathrm{Tr}(S)} \tag{4}$$

also the *recoil* variables, r, which are related to observables such as *thrust*. In this paper we will utilize a triplet of such variables, defined by

$$r = \frac{|\sum_i \vec{p}_i|}{\sum_i |\vec{p}_i|} \tag{6}$$

$$r_T = \frac{|\sum_i \vec{p}_{Ti}|}{\sum_i |\vec{p}_{Ti}|} \tag{7}$$

$$r'_T = \frac{\not{E}_T}{\sum_i |\vec{p}_{Ti}|} \, . \tag{8}$$

In addition to the above, we will also introduce a set of new variables, q,

$$q = \frac{8/\pi}{(\sum_i |\vec{p}_i|)^2} \sum_{i,j<i} |\vec{p}_i \times \vec{p}_j| \tag{9}$$

$$q_T = \frac{2/\pi}{(\sum_i |\vec{p}_{Ti}|)^2} \sum_{i,j<i} |\vec{p}_{Ti}||\vec{p}_{Tj}||(\phi_i - \phi_j)| \, . \tag{10}$$

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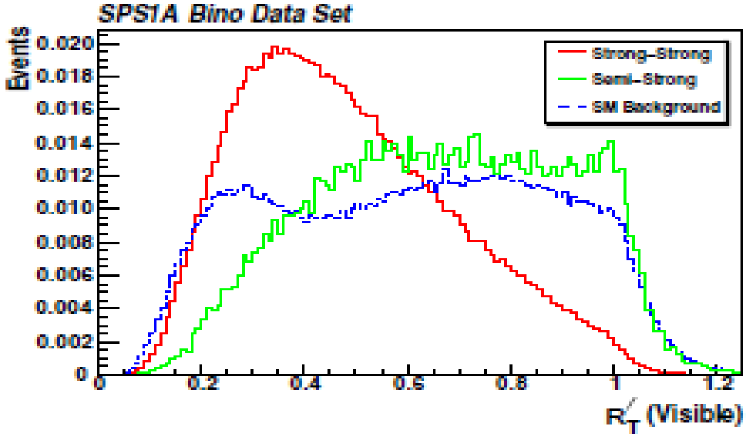
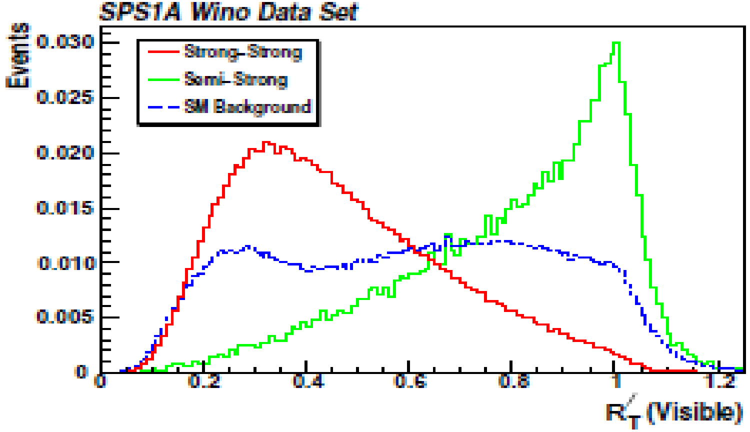
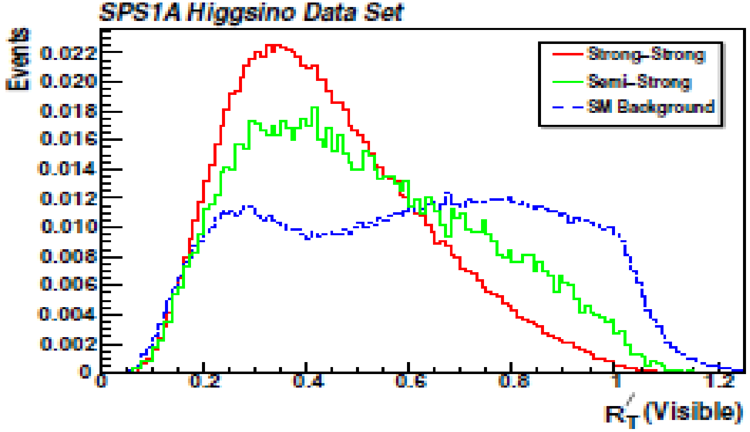

SPS1A Bino Data Set
Events
0.020
0.018
0.016
0.014
0.012
0.010
0.008
0.006
0.004
0.002
0
0.2
0.4
0.6
0.8
1
1.2
Strong–Strong
Semi–Strong
SM Background
R_T' (Visible)


SPS1A Wino Data Set
Events
0.030
0.025
0.020
0.015
0.010
0.005
0
0.2
0.4
0.6
0.8
1
1.2
Strong–Strong
Semi–Strong
SM Background
R_T' (Visible)


SPS1A Higgsino Data Set
Events
0.022
0.020
0.018
0.016
0.014
0.012
0.010
0.008
0.006
0.004
0.002
0
0.2
0.4
0.6
0.8
1
1.2
Strong–Strong
Semi–Strong
SM Background
R_T' (Visible)

Using event-shape variables have demonstrated ability to find sub-dominant susy production processes which are sensitive to the wavefunction of the LSP

Now switch to top-down approach – test theories, as in historical approach

How do we predict what will be found? Test ideas?

Much talk about “naturalness”

Opposite of naturalness is having a theory! – Naturalness is what you try when you have given up on finding an underlying theory that predicts masses – with a theory, get predictions for superpartner masses

If one's impression of string theory came from some popular books and articles and blogs, or from theorists who hadn't actually studied string/M-theory projected onto 4 D, one might be suspicious of taking string theory explanations seriously

Wrong to claim that string theory is not testable

Most of what is written on this is very misleading, even by experts(!) – string theorists do not think much about it ("string theorists have temporarily given up trying to make contact with the real world" - 1999)

String/M-theory is too important to be left to string theorists

Surprisingly, some people have claimed that because string theories are naturally formulated at Planck scale high energies or short distances they cannot be tested! – Obviously collisions will never probe energy scales such as 10^{15} TeV (Planck energy)

Equally obviously you don't have to be somewhere to test something there – always relics

-- big bang – expanding universe, He abundance and nucleosynthesis, CMB radiation

-- no signal faster than speed of light

-- don't have to be present 65 million years ago to test whether asteroid impact was a major cause of dinosaur extinction

Also, once you have a theory it suggests new tests – e.g. Maxwell's equations → light outside visible spectrum, radio waves

String/M theory must be formulated in 10 (11) D to be a possible quantum theory of gravity, and obviously must be projected to 4D (“compactified”) for predictions, tests

String theorists who study black holes, AdS/CFT, amplitudes, gravity etc in general do not know the techniques to study or evaluate compactified string/M-theories in 4 D

Supersymmetric SM addresses the problem of dark matter (and more) – contains good candidate, and relic density can be right – if we did not know about dark matter, supersymmetric SM would make us think of it and look for it – the SSM "*addresses*" the problem of dark matter

If we did not know about gravity, or forces like QCD and the electroweak force, or quarks and leptons, or families of particles, or supersymmetry, or axions, string theory would make us think of them and look for them – *"addresses"* them

Curled up dimensions contain information on our world – particles and their masses, symmetries, forces, dark matter, superpartners, more

Several branches of string/M theory – heterotic, Type IIA, …M-theory – no theoretical principle yet leads to one of them, but predictions are different

Also not yet known what gauge, matter groups to compactify to – predictions are different

Try out motivated examples for branch, curled up dimensions – calculate predictions, test – lots of useful, relevant results – many theoretical constraints, limited possibilities, few parameters – lots of examples now

Three new physics aspects:

- “Generic”
- “Gravitino”
- “Moduli”

GENERIC:

- **Probably not a theorem (or at least not yet proved), might be avoided in special cases**
- **One has to work at constructing non-generic cases**
- ***No (or very few) adjustable parameters, no tuning***

GRAVITINO

-- In theories with supersymmetry the graviton has a superpartner, gravitino – if supersymmetry broken, gravitino mass ($M_{3/2}$) splitting from the massless graviton is determined by the form of supersymmetry breaking

– Gravitino mass sets the mass scale for the theory, for all superpartners, for some dark matter

MODULI – from *compactified* string/M theories get not only quantum field theories, but new physics

-- To describe sizes and shapes and metrics of small manifolds the theory provides a number of fields, called “moduli” fields

-- In compactified M-theory, supersymmetry breaking generates potential for all moduli

-- Moduli fields have definite values in the ground state (vacuum) – jargon is “stabilized” – then measurable quantities such as masses, coupling strengths, etc, are determined in that ground state – *if not stabilized, laws of nature time and space dependent*

-- Moduli fields (like all fields) have quanta (also called moduli), with masses fixed by fluctuations around minimum of moduli potential

-- Moduli dominate after inflation, oscillate, stabilize – we begin there

PAPERS ABOUT M-THEORY COMPACTIFICATIONS ON G_2 MANIFOLDS (11-7=4)

Earlier work 1995-2004 (stringy, mathematical) ; Witten 1995

- Papadopoulos, Townsend th/9506150, compactification on 7D manifold with G_2 holonomy → resulting quantum field theory has N=1 supersymmetry
- Acharya, hep-th/9812205, non-abelian gauge fields localized on singular 3 cycles
- Atiyah and Witten, hep-th/0107177, analyze dynamics of M-theory on manifold of G2 holonomy with conical singularity and relations to 4D gauge theory
- Acharya and Witten, hep-th/0109152, chiral fermions supported at points with conical singularities
- Witten, hep-ph/0201018 – shows embedding SU(5)-MSSM ok, solves doublet-triplet splitting in 4D supersymmetric GUT, discrete symmetry sets $\mu=0$
- Beasley and Witten, hep-th/0203061, generic Kahler form
- Friedmann and Witten, th/0211269, SU(5) MSSM, scales – Newton's constant, GUT scale, proton decay – no susy breaking
- Lukas, Morris hep-th/0305078, generic gauge kinetic function

Particles!

Basic framework established – powerful, rather complete

Some Discrete Assumptions

- **Compactify M-Theory on manifold with G_2 holonomy in fluxless sector – well motivated and technically robust**

- **Compactify to gauge matter group SU(5)-MSSM – can try others, one at a time – MSSM always there – most important results don't depend on extension or not**

- **Use generic Kahler potential and generic gauge kinetic function**

- **Assume needed (singular) mathematical manifolds exist – considerable progress recently – Simons Center workshops, Donaldson et al, etc**

- **CC issues not relevant - solving it doesn't help learn our vacuum, and not solving it doesn't stop learning our vacuum**

We started in 2005 – since LHC coming, focused on moduli stabilization, supersymmetry breaking, etc → LHC physics, Higgs physics, dark matter etc

[Acharya, Bobkov, GK, Piyush Kumar, Kuflik, Shao, Watson, Lu, Zheng, Ellis – over 20 papers, over 500 arXiv pages]

- **Indeed we showed that in compactified M theory supersymmetry automatically was spontaneously broken via gaugino and chiral fermion condensation**
- **Simultaneously moduli stabilized, in de Sitter vacuum**
- **Calculated the supersymmetry soft-breaking Lagrangian → radiative EWSB – Higgs potential stable - precise M_h (in decoupling sector) – approximate gluino and wino masses, etc**

Get 4D effective supersymmetric field theory – in usual case coefficients of all operators are independent, so many coefficients – here all coefficients calculable and connected

NO adjustable parameters – some quantities not yet precisely calculable

MAIN RESULTS, PREDICTIONS FOR M-THEORY SO FAR, and in progress

- **Moduli stabilized – vevs $\lesssim$ 1/10 M_{pl}, masses multi TeV √**
- **Calculate gravitino mass approximately ~ 50 TeV (factor 2 or so)**
- **Scalars (squarks, higgs sector, sleptons) ~ gravitino mass (2006) PREDICTION, LHC**
- ➢ **Gaugino masses suppressed (by volume ratios), ~ factor 40 PREDICTION, LHC**
- **HIERARCHY PROBLEM SOLVED √**
- ➢ **Non-thermal cosmological history via moduli decay at late time (but still before BBN) PREDICTION**
- ➢ **Moduli decay provides baryogenesis *and* DM, and their ratio PREDICTION (not finished)**
- **Axions stabilized, give solution to strong CP problem √**
- **Anticipated Higgs boson mass *and* BR (SM-like) PREDICTION √**
- **SM quark and lepton charges, Yang-Mills 3-2-1 forces, parity violation, accommodated**
- **Gauge coupling unification, proton decay all right**
- **No flavor problem, weak CPV ok**
- **EDMs calculable, smallness explained (could have been wrong) PREDICTION √**
- **$\mu \approx$ few TeV – included in theory, approximately calculable**
- **$\tan\beta$ approximately calculable ~ 5-10 PREDICTION**
- ➢ **LHC predictions – gluinos (~ 1.5 TeV, 3rd family decays enhanced)**
  -- wino, bino ~ ½ TeV , BR(wino → bino + Higgs) ≈ 100%
- ➢ **Need future collider for higgsinos, scalars PREDICTION**
- **Hidden sector DM under study**

Important theoretical connection between moduli and gravitino: Lightest eigenvalue of MODULI mass matrix generically ≈ GRAVITINO mass [Douglas, Denef 2004; Scrucca et al 2006; Acharya Kane Kuflik 2010]

(top down simple argument, scalar goldstino generically has gravitino mass, and mixes with moduli, so lightest eigenvalue of moduli mass matrix < lighter eigenvalue of any 2x2 submatrix, i.e. about gravitino mass)

MODULI COSMOLOGY

- **Moduli couple gravitationally to everything**
- **Moduli decay (when width ~ H) – dilutes any previous population of DM by factor $(T_{freezeout}/T_{decay})^3$ if entropy conserved in process**

  [because T~ 1/a and volume ~ a^3]

- **So thermal freezeout occurs, typically at T ~ 20 GeV, *but resulting DM diluted by ~10^9 when moduli decay at T ~ 20 MeV, shortly before nucleosynthesis***

  [first noticed by Moroi, Randall hep-ph/9906527 – generic in string/M theories]

- **Moduli have BR to superpartners, axions ~ ¼ so regenerate DM → "non-thermal cosmological history"**

Possible bonus – Since moduli decay suppresses initial baryon asymmetry (~ 1) to give actual baryon asymmetry (10^{-9}), ***and moduli decay also*** **gives DM, perhaps can explain both** ***and ratio*** ***[important – highest dimension of non-renormalizable operators for Affleck-Dine known to be 9]***

[GK, Shao, Watson, Yu arXiv: 1108.5178]

- ☐ **Solve hierarchy problem fully!** – input Planck scale and derive physics at TeV scale(s)

- ☐ Two basic physics scales – supersymmetry broken (F terms generated) at about 10^{14} GeV, and gravitino mass ($M_{3/2}$) is ~ 50 TeV – IMPORTANT TO DISTINGUISH

- ☐ Three suppressions from gravitino mass to smaller scales (scalars, trilinears not suppressed):

  * Theory predicts gaugino masses (gluino, wino, bino, LSP) suppressed to ~ TeV because no contribution from F_{chi}

  * "μ" incorporated into theory, not a free parameter, suppressed order of magnitude from gravitino mass by moduli vevs

  * Radiative Electroweak Symmetry Breaking solutions common, lightest higgs boson $M_h << M_{3/2}$, **explains Higgs mechanism, EW Symmetry Breaking**

GAUGINO MASSES GENERICALLY SUPRESSED!

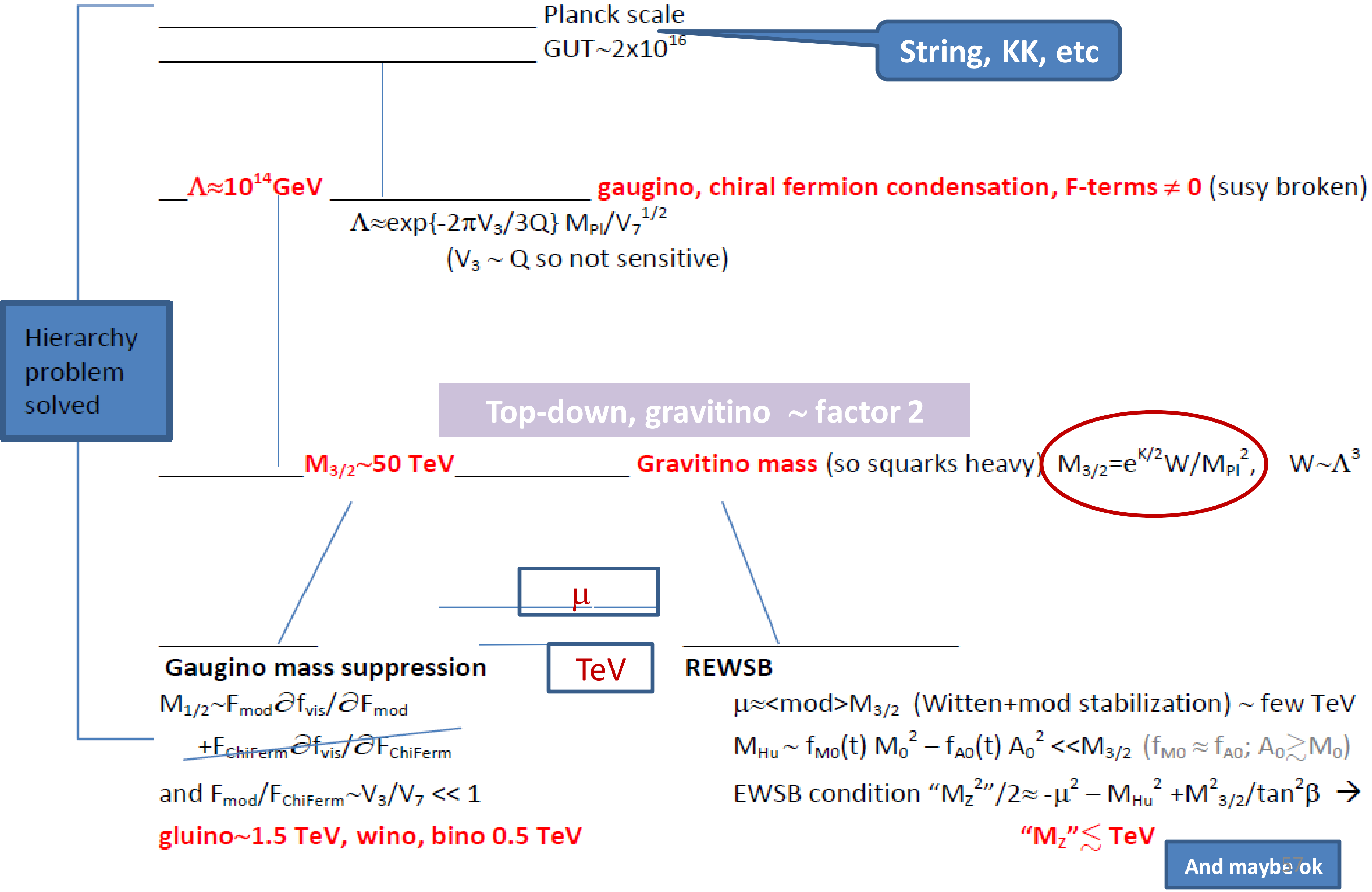
$$M_{1/2} = K_{mn}\, F_m\, \partial_n\, f_{SM}$$

Visible sector gauge kinetic function

f_{SM} doesn't depend on hidden sector chiral fermions, so term proportional to $F_{\text{chiral meson}}$ simply absent – $F_{\text{moduli}}/F_{\text{chiral meson}} \sim V_3/V_7 << 1$

Scales

M-THEORY COMPACTIFIED ON G2 MANIFOLD, TO MSSM



Planck scale

GUT~2×10^{16}

String, KK, etc

$\Lambda\approx10^{14}$GeV **gaugino, chiral fermion condensation, F-terms $\neq 0$** (susy broken)

$\Lambda\approx\exp\{-2\pi V_3/3Q\}\, M_{Pl}/V_7^{1/2}$

($V_3 \sim Q$ so not sensitive)

Hierarchy problem solved

Top-down, gravitino ~ factor 2

$M_{3/2}$~50 TeV **Gravitino mass** (so squarks heavy) $M_{3/2}=e^{K/2}W/M_{Pl}^2$, $W\sim\Lambda^3$

μ

TeV

Gaugino mass suppression

$M_{1/2}\sim F_{mod}\partial f_{vis}/\partial F_{mod}$

~~$+F_{ChiFerm}\partial f_{vis}/\partial F_{ChiFerm}$~~

and $F_{mod}/F_{ChiFerm}\sim V_3/V_7 \ll 1$

gluino~1.5 TeV, wino, bino 0.5 TeV

REWSB

$\mu\approx\langle mod\rangle M_{3/2}$ (Witten+mod stabilization) ~ few TeV

$M_{Hu}\sim f_{M0}(t)\, M_0^2 - f_{A0}(t)\, A_0^2 \ll M_{3/2}$ ($f_{M0}\approx f_{A0}$; $A_0 \gtrsim M_0$)

EWSB condition "M_Z^2"$/2\approx -\mu^2 - M_{Hu}^2 + M_{3/2}^2/\tan^2\beta$ →

"M_Z"$\lesssim$ TeV

And maybe ok

LHC

Here is where supersymmetry is “hiding” at LHC

Squark masses ~ gravitino mass ~ few tens of TeV

GAUGINO MASSES ~ TeV

arXiv:1408.1961 [Sebastian Ellis, GK, Bob Zheng]

arXiv:1506.xxxxx [Sebastian Ellis, Bob Zheng w/backgrounds, etc]

$M_{gluino} \approx 1.5$ TeV,

$M_{bino} \approx 450$ GeV,

$M_{wino} \approx 620$ GeV

all consistent with current data

[lesson from compactified string/M theory is should not have expected superpartners at LHC so far]

$\sigma_{gluino} \approx 20$ fb, $\sigma_{wino\ \ pairs} \approx 20$ fb [20fb x 100 fb^{-1} → 2000 events]

Any bets?

LHC ~2 years

LHC phenomenology

- Only three channels kinematically accessible:

$$p\,p \rightarrow \tilde{g}\;\tilde{g}$$

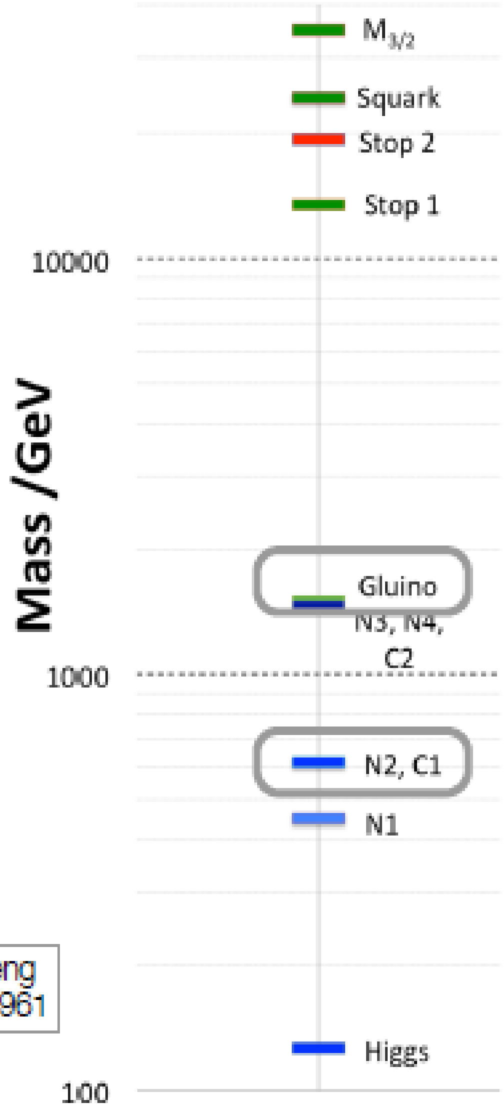
$$p\,p \rightarrow \chi_2^0\;\chi_1^\pm$$

$$p\,p \rightarrow \chi_1^\pm\;\chi_1^\pm$$

- Distinctive branching ratios:

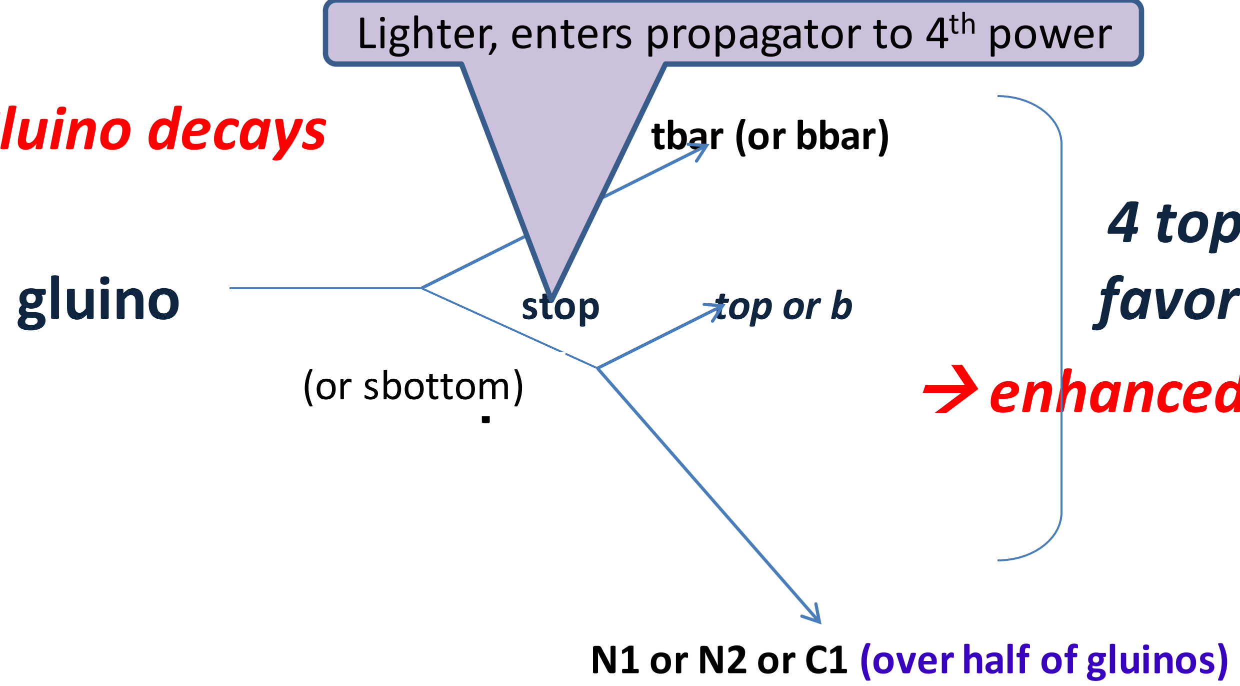
$$\mathrm{BR}(\chi_2^0 \rightarrow \chi_1^0 h) \sim 98\%$$

$$\mathrm{BR}(\chi_2^0 \rightarrow \chi_1^0 Z) \sim 2\%$$



SE, Kane, Zheng
hep-ph/1408.1961

Gluino decays


Lighter, enters propagator to 4th power

gluino

tbar (or bbar)

stop

top or b

(or sbottom)

N1 or N2 or C1 **(over half of gluinos)**

4 tops (or bbbb, or btbt) favored for gluino pair!

→ enhanced 3rd family decays,

Gluino lifetime ~ 10^{-19} sec, decays in beam pipe

Gluino decays flavor-violating: 3rd family/(1st + 2nd) ≈ 1.2 **naively 0.5**

BR (neutral wino → bino + higgs) ≈ 100%

BR (charged wino → bino + W±) ≈ 100%

$$g \longrightarrow bino + t\bar{t} ......20\%$$

$$g \longrightarrow bino + W^{\pm} + b\bar{t}, t\bar{b} ....23\%$$

σ(gluinos, 13 TeV)/
σ(gluinos, 8 TeV)
≈ 40 for 1.5 TeV
gluino (heavy
squarks)

Future colliders

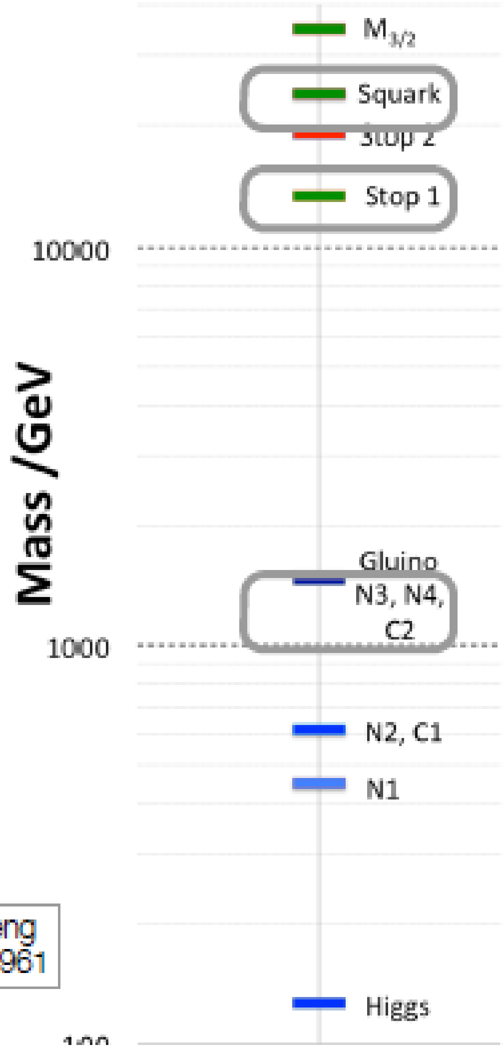
- Heavy squark associated production with light gluino:

$$p\,p \to \tilde{g}\,\tilde{q}$$

$$p\,p \to \tilde{g}\,\tilde{t}\,\bar{t}$$

- Top PDF at 100 TeV collider will be relevant — model as gluon splitting

- Higgsino production possible at a 50 TeV collider



SE, Kane, Zheng
hep-ph/1408.1961

HIDDEN SECTOR DARK MATTER – work in progress

[Acharya, GK, Kumar, Nelson, Zheng]

- In M-theory, curled up 7D space has 3D submanifolds (“3-cycles”) that generically have orbifold singularities and therefore have particles in gauge groups – tens of submanifolds
- We live on one, “visible sector”
- Supersymetry breaking due to ones with large gauge groups
- Gravitational interactions, same gravitino and moduli for all
- Others have their own matter, some stable and DM candidates – can calculate spectra, relic densities
- Calculations underway: already published general relic density calculations with a non-thermal cosmological history, arXiv:1502.05406 (GK, Kumar, Nelson, Zheng)
- Now analyzing actual hidden sectors systematically for M-Theory

The hidden sector with “QCD” scale Λ' ~ TeV will provide dark matter, while other hidden sectors decay to DM hidden sector, or give small contributions to DM abundance – typically several hidden sectors involved

DM includes stable baryon-like particle of G_2 3-cycle hidden sector – could provide full relic density, or less – annihilates to several visible and hidden sector particles – M ~ 1 TeV

FINAL REMARKS (1)

- String/M-theory too important to be left to string theorists

- String/M-theory may seem complicated – but probably it is the simplest framework that could incorporate and explain all the phenomena we want to understand – compactified M-theory promising candidate

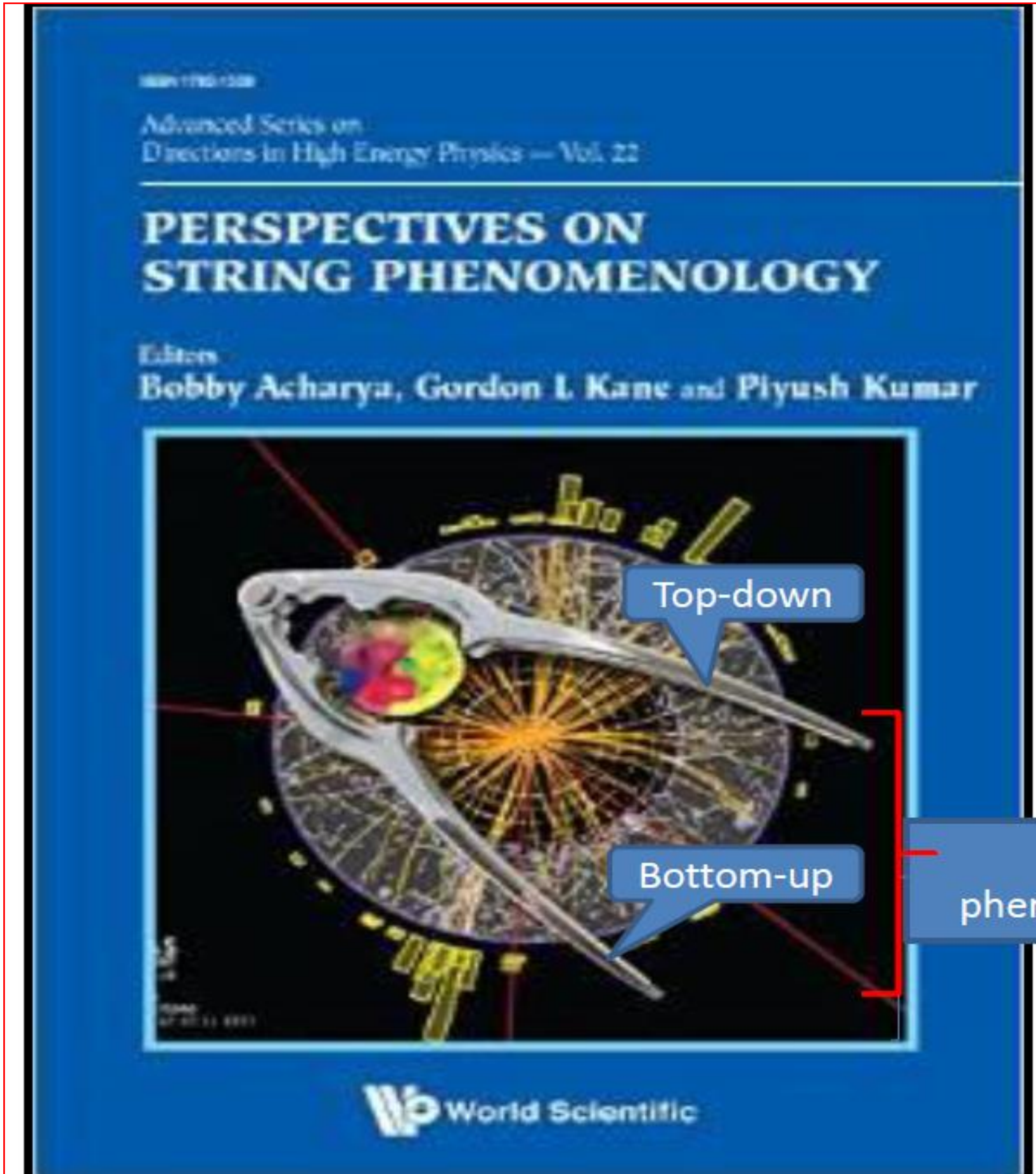
- Landscape? – if so, examples already show not an obstacle to finding descriptions of our world – then study implications for multiverse populations

FINAL REMARKS (2)

- Moduli generically present – probably inevitable in M Theory – imply non-thermal cosmological history

- LHC: gluino ~ 1.5 TeV, wino, bino ~ 0.5 TeV – good signatures

- Hidden sector dark matter candidates generic, probably inevitable – can be up to few TeV, or light – relic densities calculable – signatures calculable


Advanced Series on
Directions in High Energy Physics — Vol. 22

PERSPECTIVES ON
STRING PHENOMENOLOGY

Editors
Bobby Acharya, Gordon L Kane and Piyush Kumar

World Scientific

Top-down

Bottom-up

String phenomenology

Think Nutcracker!

-

COMPACTIFIED M-THEORY (2007)

- **Derive** solution to large hierarchy problem
- Generic solutions with **EWSB derived**
- main F term drops out of **gaugino masses** so **dynamically suppressed**
- **Trilinears > $M_{3/2}$** necessarily
- **μ incorporated in theory**
- Little hierarchy significantly reduced
- **Scalars = $M_{3/2}$ ~ 40 TeV necessarily** , scalars not very heavy
- Gluino lifetime $\lesssim 10^{-19}$ sec, decay in beam pipe
- **$M_h \approx$126 GeV unavoidable**, predicted

SPLIT SUSY (ETC) MODELS

- Assumes **no solution (possible) for large hierarchy problem**
- **EWSB assumed**, not derived
- **Gauginos suppressed by assumed** R-symmetry, suppression arbitrary
- Trilinears small, suppressed compared to scalars
- **μ not in theory** at all; guessed μ ~$M_{3/2}$
- No solution to little hierarchy
- Scalars **assumed** very heavy, whatever you want, e.g. 10^{10} GeV
- Long lived gluino, perhaps meters or more
- **Any M_h allowed**