Connecting the LHC & Underlying Theories

- ❑ Can we interpret new physics when it is discovered?
- ❑ Can we relate it to the underlying theory?

Gordon Kane, PK, Jing Shao

0709.4259 & hep-ph/0610038

Earlier approach hep-ph/0312248,

P Binetruy, Gordon Kane, Brent Nelson, Liantao Wang, Ting Wang

Some Overlap with Feldman, Nath, Liu arXiv 0707.1873

LHC New Physics Signatures Workshop

Ann Arbor, Jan 5-11, 2008

Piyush Kumar

U C Berkeley

January 8th, 2008

INTRODUCTION

Suppose LHC reports a signal beyond the SM

- Confident that experimenters and SM theorists will get that right.

WANT TO INTERPRET IT!

Usual approach:

- Is it really supersymmetry? -- If yes, what are the masses of superpartners?
  -- Soft-breaking parameters?
- L(EW)?
- L(High), if there exists a high (microscopic) scale?
- Underlying theory, like String Theory?

"LHC inverse problem"

CHALLENGING!

A) Most of the study has focussed on EW scale issues

Many difficult Issues – Large Number of Parameters, Degeneracies, etc.

Arkani-Hamed, Kane, Thaler, Wang, hep-ph/0512190

Talks in this conference – many techniques being developed, hopeful.

B) Little study of obstacles to naïve extrapolation to high scales

a) from intermediate matter, “S” term, Majorana Neutrinos

Kane, PK, Morrissey, Toharia (PRD75:115018,2007; hep-ph/0612287)

b) from hidden sector effects

Cohen, Roy, Schmaltz (JHEP 0702:027,2007)

Much more work needed.

C) Essentially no systematic study of connection between high scale frameworks and LHC signatures. Complementary to approach A). Will benefit from each other.

in this talk, would like to address C).

Most work in string phenomenology

- -- Construct a particular top-down example with some or many assumptions.
- -- Look at some phenomenology, not really experimental observables.

But now, it seems that string theory can give rise to large classes of quasi-realistic effective field theories.

Argue that:

- -- It makes sense in many cases to analyze realistic classes of string theory vacua to the extent that predictions for the LHC can be made – encourage doing that.
- -- Moreover, one could try to connect patterns of signatures to classes of realistic string vacua

“Realistic” String Theory Vacua

For concreteness, focus on string vacua with low energy SUSY, can similarly define realistic vacua with other ways of explaining the Hierarchy.

- N=1 susy in 4D broken in a controlled approximation.
- Moduli stabilized in a metastable dS vacuum, & stable Hierarchy between the Electroweak and Planck Scales generated.
- Visible sector accommodates the MSSM particle content and gauge group (maybe more) and their properties.
- Mechanism of breaking the Electroweak Symmetry.
- Consistent with all Experimental Constraints.

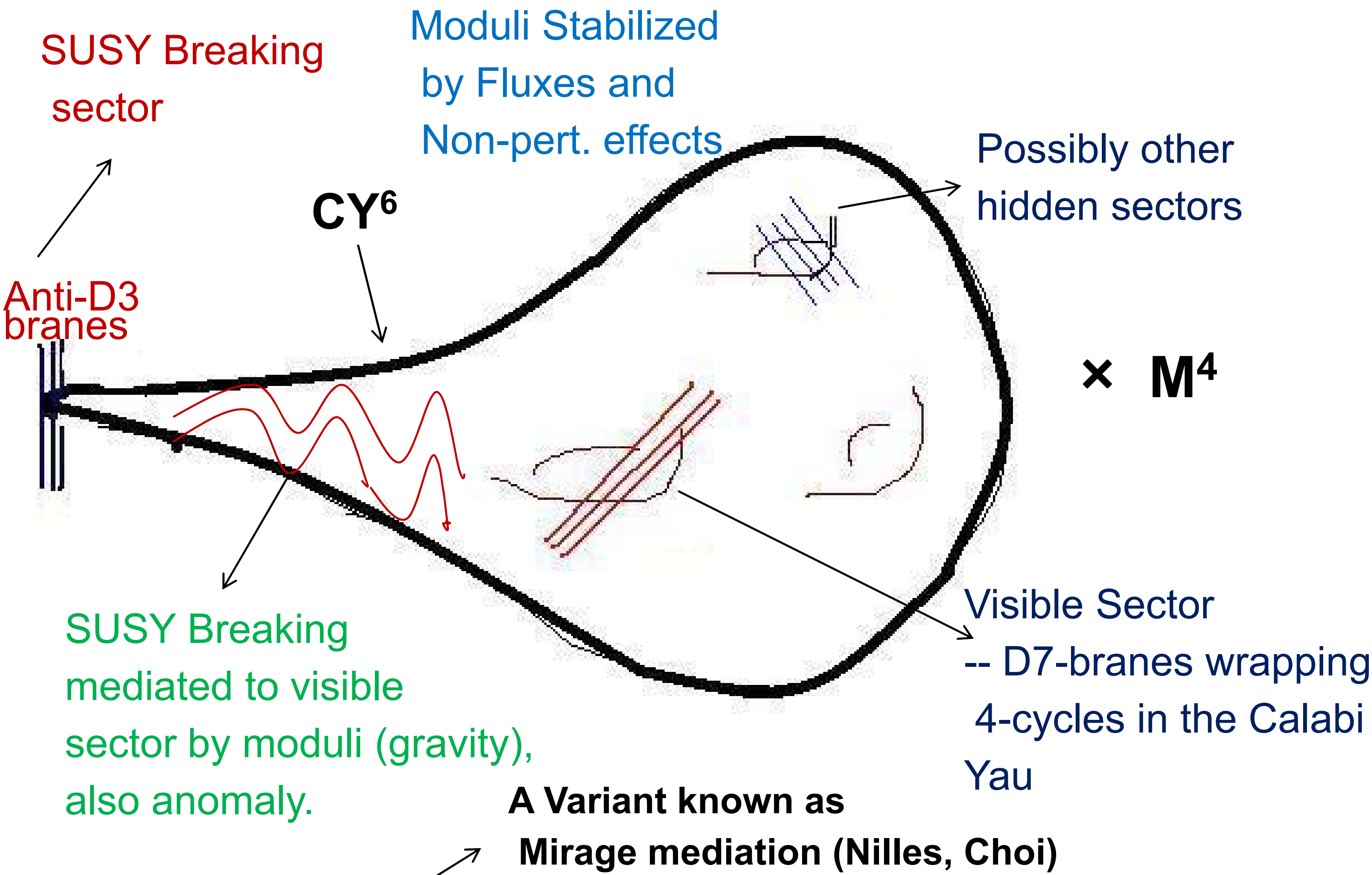
- At present, these criteria satisfied separately in many cases in a more reliable manner, but explicit constructions do not meet all criteria at once.

- However, can consider *frameworks* in which the relevant effects of the underlying mechanisms may be assumed to exist self-consistently.

- One Popular Example of a *Framework* – **KKLT compactifications.**
  Call such Frameworks – **"String-susy Frameworks".**

  Framework can be made more realistic with further developments.

- In this analysis assume an MSSM visible sector, but can be easily relaxed easily.



KKLT FRAMEWORK – Possible to study pheno. implications of this framework. Has been done in the literature. Similarly for others.

In this work, we study four classes of string/M Theory Frameworks with an MSSM visible sector

- (Original) Type IIB KKLT, (KKLT-1) *(Kachru,Kallosh,Linde,Trivedi).*

Choi et al :NPB718:113(2005);PRD75:095012; Kitano, Nomura: PRD73:095004

Pierce, Thaler: JHEP 0609:017,2006, Others.

- Type IIB KKLT with F-term uplifting, (KKLT-2)

Dudas et al JHEP 0702:028,2007 , Nilles et al JHEP 0702:063,2007, others.

- Type IIB LARGE Volume, (LGVol). *(Balasubramanian,Conlon,Quevedo)*
- M Theory on G_2 manifolds, (G_2). *(Acharya,Bobkov,Kane,PK,Shao)*

These Frameworks – Completely specified by a few “microscopic” parameters of the underlying theoretical construction.

Their consequences for the LHC can be readily predicted by standard methods and is testable.

Analysis of the entire microscopic parameter space necessary to compute characteristic predictions for any string-susy framework.

- Write effective 4D Lagrangian of the String-susy model at the compactification scale (~ M_{GUT}),L_{soft} in terms of the "microscopic" parameters.

  -- gives initial conditions for the soft parameters calculating collider scale values.

The remaining steps the same as in any other approach at M_{GUT}

- Use RGEs to run down to EW scale – programs already exist for MSSM and some extensions.

  Examples - **softsusy**, spheno, suspect…

- Impose Experimental constraints.

- Generate events for short distance processes such as superpartner production. (Eg. q + q $\longrightarrow$ ~g + ~g)

  Examples - **Pythia**, madgraph, alpgen, comphep (calchep), herwig

- Hadronize to long distances, quarks and gluons into jets, decay taus.

  Examples - **Pythia**, isajet, herwig,etc.

- Cuts, triggering, combine overlapping jets, detector simulation –

  Examples - **PGS**, ATLFAST, GEANT, etc.

Backgrounds

-- Used PYTHIA and PGS to simulate some SM backgrounds. Estimated the remaining.

Observability Criteria: $N_{sig}/\sqrt{N_{bkg}} > 5$; $N_{sig}/N_{bkg} > 0.1$; $N_{sig} > 5$.

-- Have done a simplified analysis of backgrounds at present.
But since results depend on intrinsic correlations due to theoretical structure, should not change qualitative results at an early stage.

Want to avoid relying on signals for which backgrounds too large, use signals which are likely to be above background.

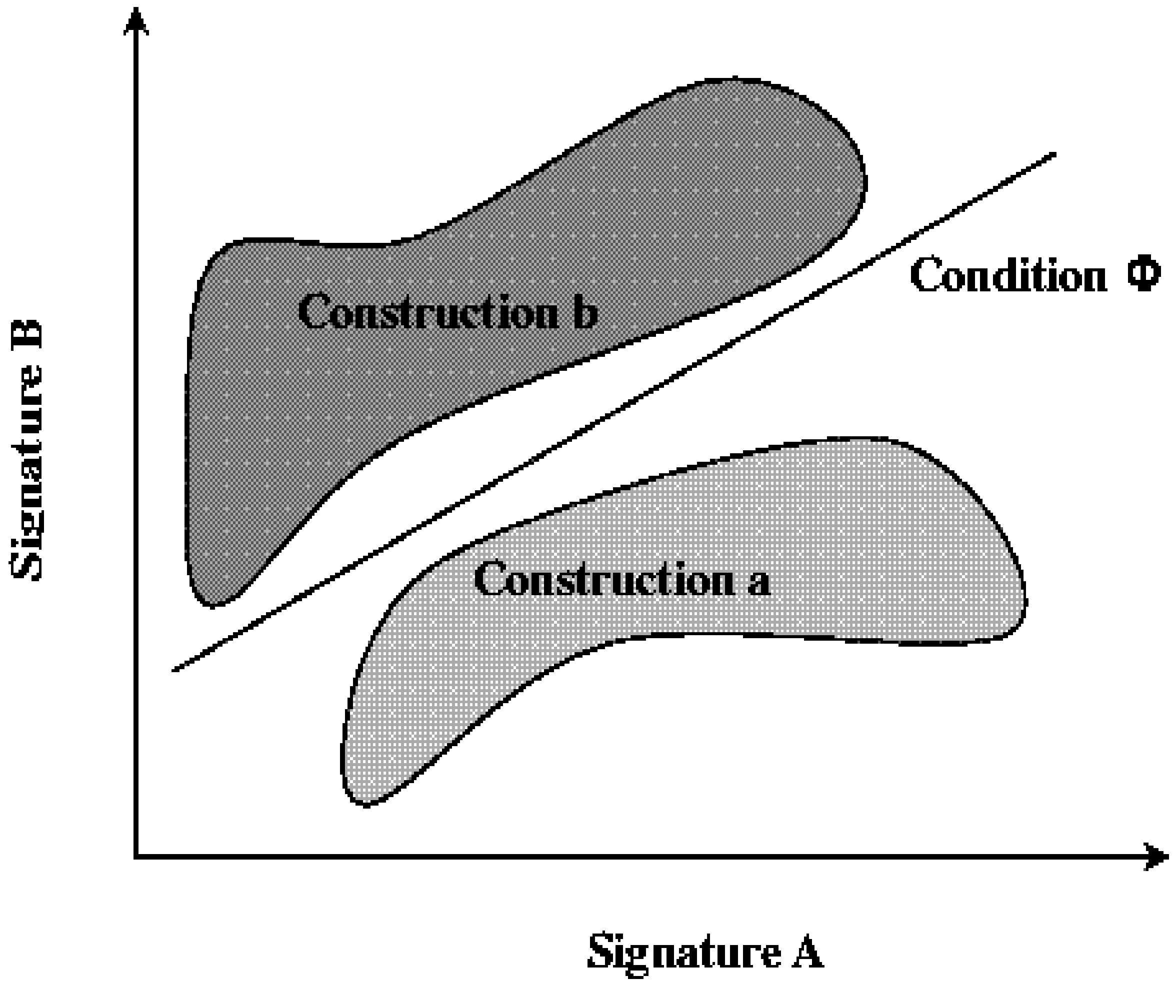
By varying (sampling) the microscopic parameters consistent with all theoretical constraints, one obtains :

a “footprint” of that string-susy-framework in “signature space”

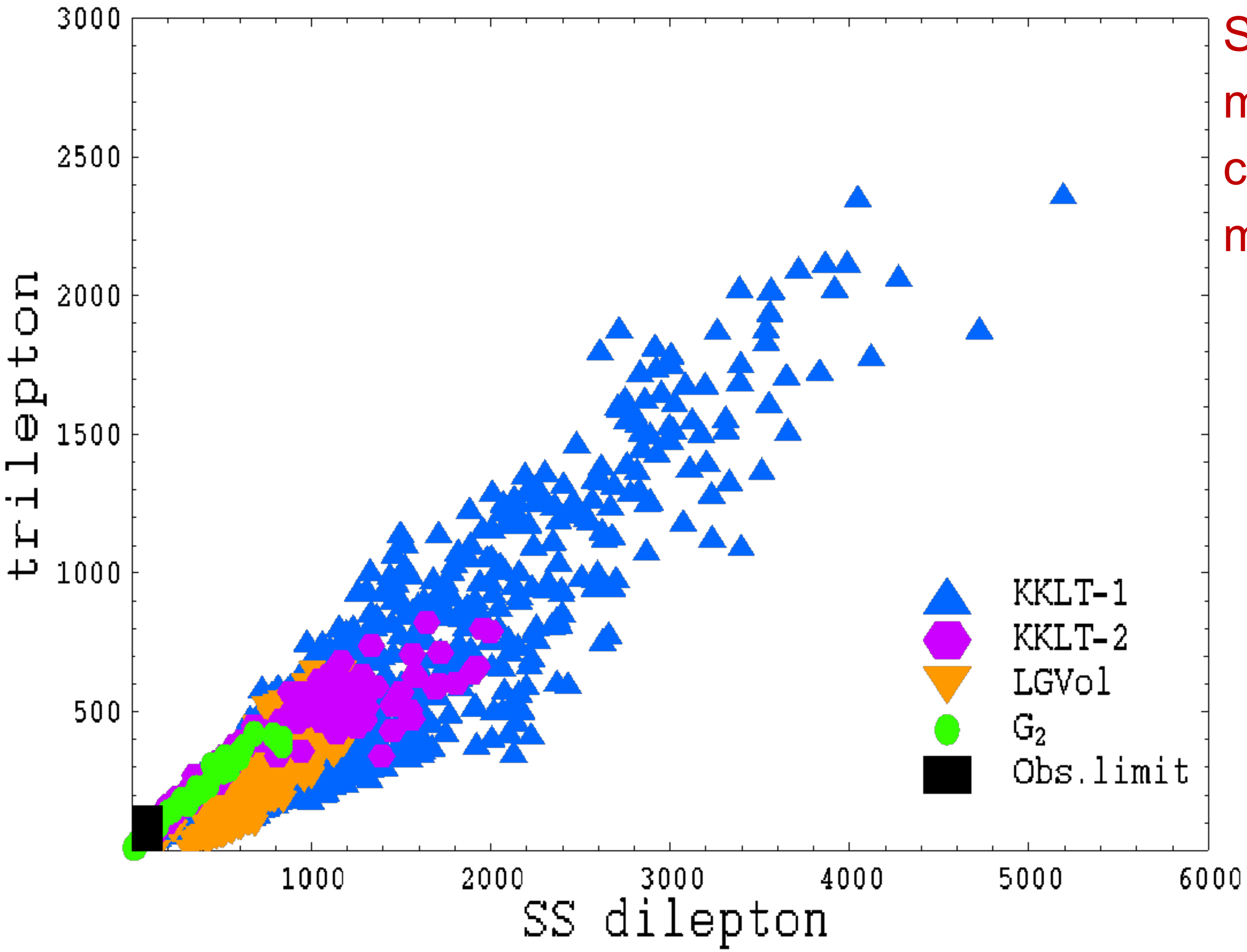
CLAIM 1

- For any string-susy framework, one can meaningfully calculate experimental low scale observables (such as LHC signatures).
- The footprint in signature space is interestingly limited and characteristic of the string-susy framework.

True for all frameworks we have looked at, and is understandable and expected.



Signature B
Construction b
Condition Φ
Construction a
Signature A



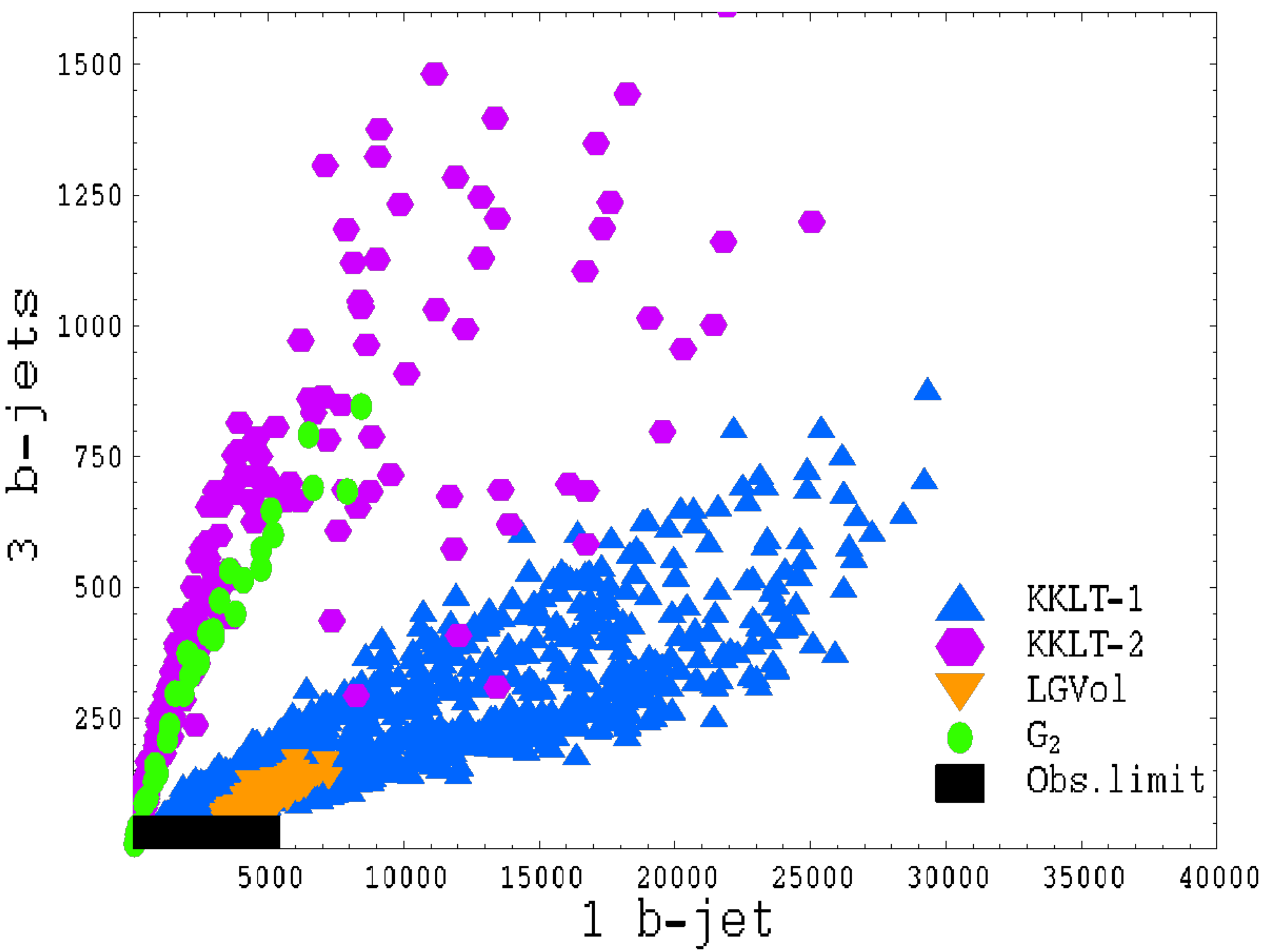
Similar Plots made in the context of other models by Nath et al

Black Region implies signal not observable above background.

Lum = 5 fb^{-1} L2 Trigger -- PGS

2D slices of footprints as microscopic parameters are varied

Pt (Jet) > 200GeV, Pt (Lepton)>10GeV, Missing Et > 100GeV



Can use distributions in addition to counting signatures

Some Generic Features of Footprints

For simplicity, stick to counting signatures.

- Counting Signatures always bounded from above by the maximum cross-section, due to lower limits on superpartner masses. So, 2D footprints with counting signatures bounded along the radial direction.

- Angular Dispersion of the Footprint – Due to variation in the spectrum, Leading to a variation in the BRs, hence signatures.

Exact spread depends upon many factors - structure of the model as well as real-world "detector effects".

CLAIM 2

The patterns of signatures can distinguish among different string-susy-framework predictions.

Origin of Distinguishibility- Correlations

- $s_i = s_i\,(m_j) = s_i\,(m_j\,(\zeta_k)\,)$

- For arbitrary MSSM parameters m_j, very large region in signature space.

However, if non-trivial dependence of m_j on microscopic parameters ζ_k, then MSSM parameters m_j, and hence signatures s_i correlated with each other.

- Therefore, understanding these correlations can help us understand the position and shape of the footprints.

- Try to understand -- A) Footprint in terms of qualitative features of spectra.
  B) Qualitative features in terms of microscopic parameters.

A) In the context of susy, a combination of the qualitative features of the spectra determines the footprint. Some of the most important ones are:

-- universality of tree level gaugino masses?

[Choi and Nilles, hep-ph/072146]

-- relative size of tree level and anomaly mediation gaugino masses?

-- origin, size of μ, Bμ?

-- hierarchy of scalar vs gaugino masses?

-- nature and content of LSP

-- hierarchy among scalars, e.g. 3^{rd} family vs 1^{st}, 2^{nd} families

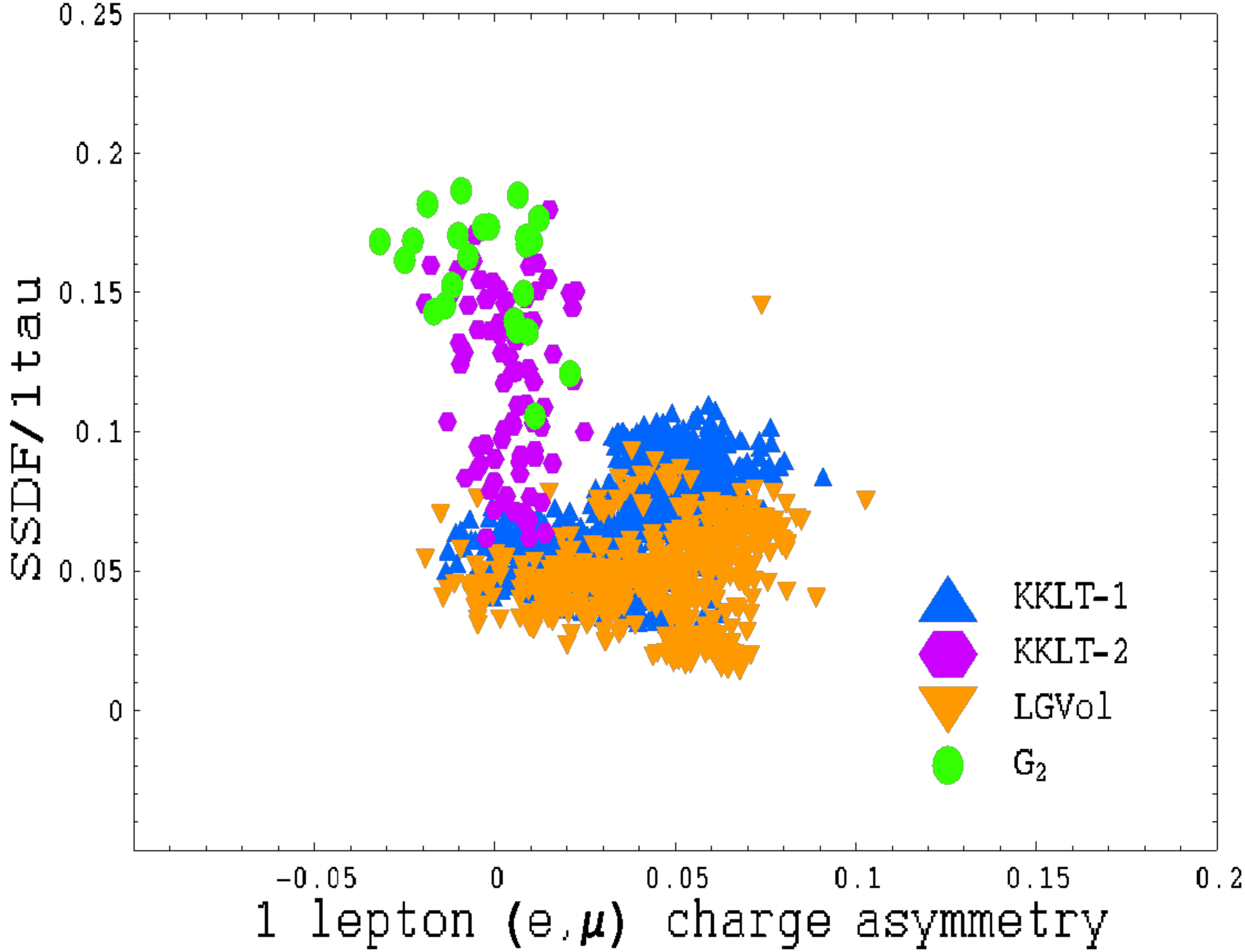
Simple Examples

- For KKLT-1 and LGVol string-susy MSSMs, turns out that squarks are lighter than gluinos. On the other hand, for G_2- and KKLT-2 models, squarks are heavier than gluinos.
  ~q~q or ~q~g production dominant for KKLT-1 and LGVol compared to ~g~g for G2. Leads to a difference in the lepton charge asymmetry.

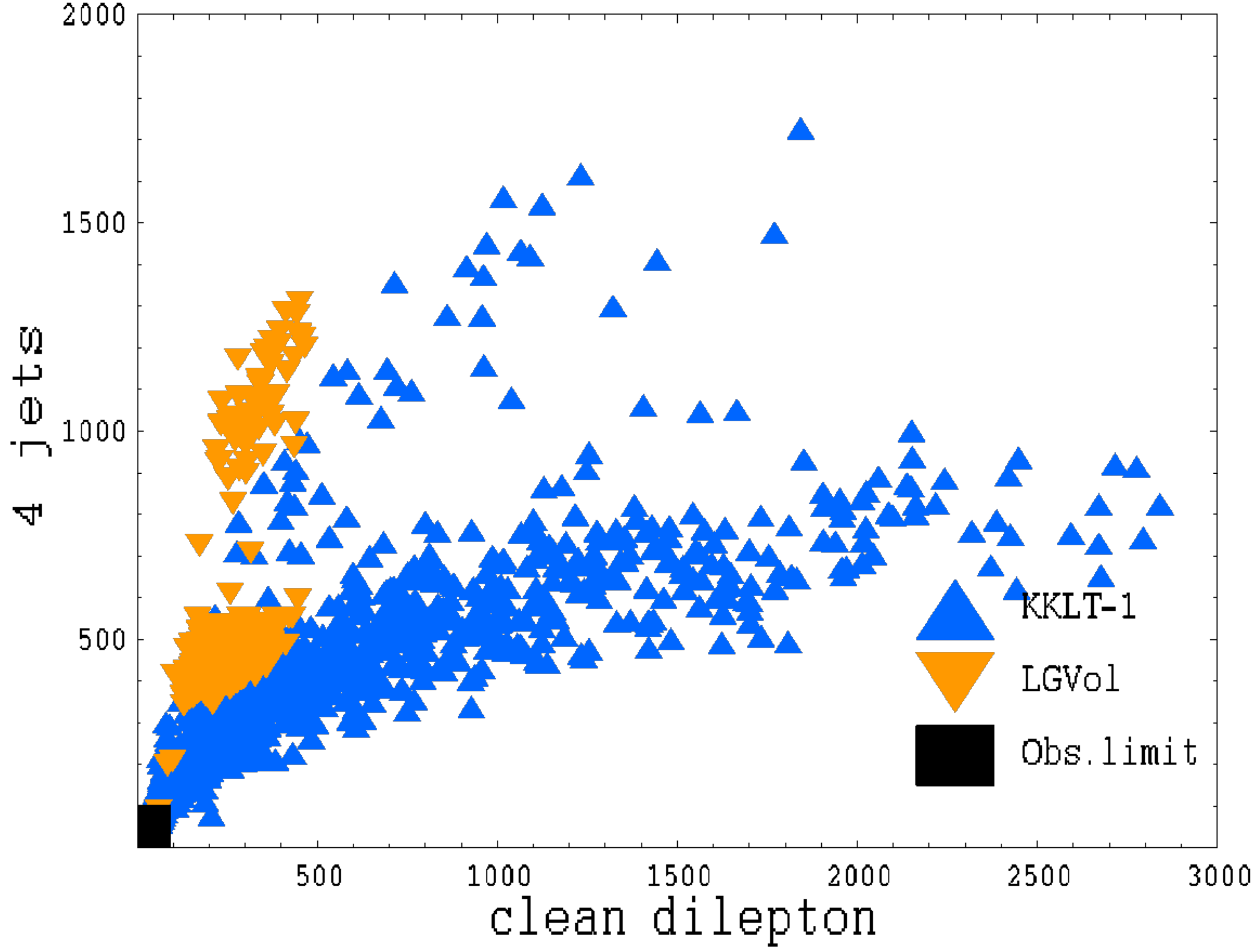
- Gaugino mass ratios are different for different models, which lead to a difference in the jet multiplicity.

  KKLT-1 has a smaller difference between the gluino and LSP compared to that in LGVol and G_2 models. (for the same m_{gluino})

  Using a hard PT(jet) cut (> 200 GeV), very few 4 jet events pass the cuts for KKLT-1 compared to LGVol as these events mostly come from ~g~g production. So, this can partially distinguish.



0.25
0.2
0.15
0.1
0.05
0
SSDF/1tau
-0.05
0
0.05
0.1
0.15
0.2
1 lepton (e,μ) charge asymmetry
KKLT-1
KKLT-2
LGVol
G2



2000
1500
1000
500
4 jets
500
1000
1500
2000
2500
3000
clean dilepton
KKLT-1
LGVol
Obs.limit

- **Qualitative features of the spectra in terms of microscopic parameters.**

Can be understood as well. Explained in papers.

Systematic Way of Distinguishing Models

- Basic Idea

  Look at various 2D signature plots, starting with the first plot, keep track of microscopic parameters and eliminate them if they are not in the overlap region, continue in this way until the number of models in the overlapping region vanishes or reaches a minimum.

- More Technically,

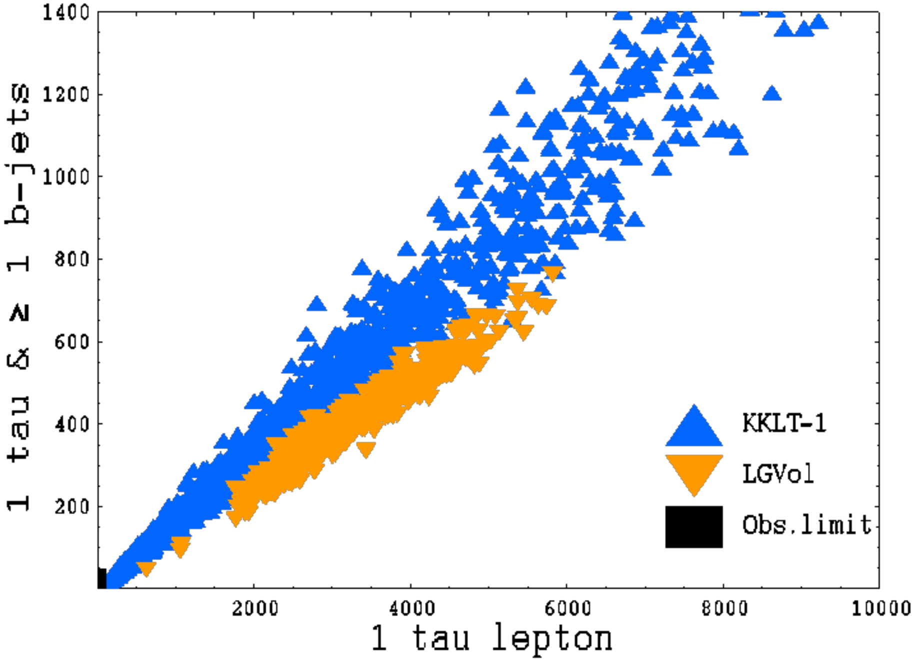
$$(\Delta S_{A_i B_j})^2 = \frac{1}{2}\left[\left(\frac{s_x^{A_i} - s_x^{B_j}}{\sigma_x^{A_i B_j}}\right)^2 + \left(\frac{s_y^{A_i} - s_y^{B_j}}{\sigma_y^{A_i B_j}}\right)^2\right],$$

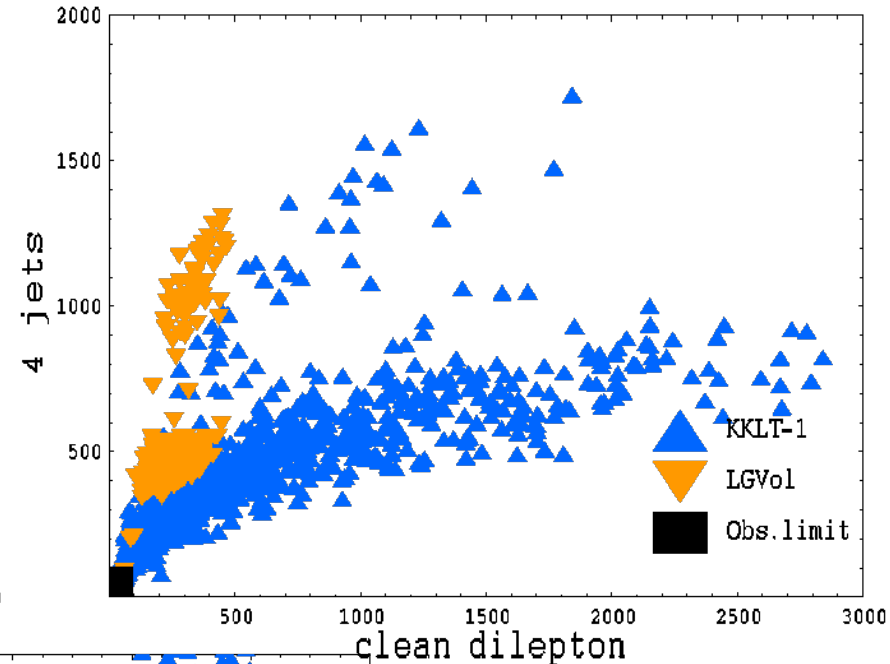
- Two points A_i € A and B_j € B degenerate in 2D signature space (x,y)

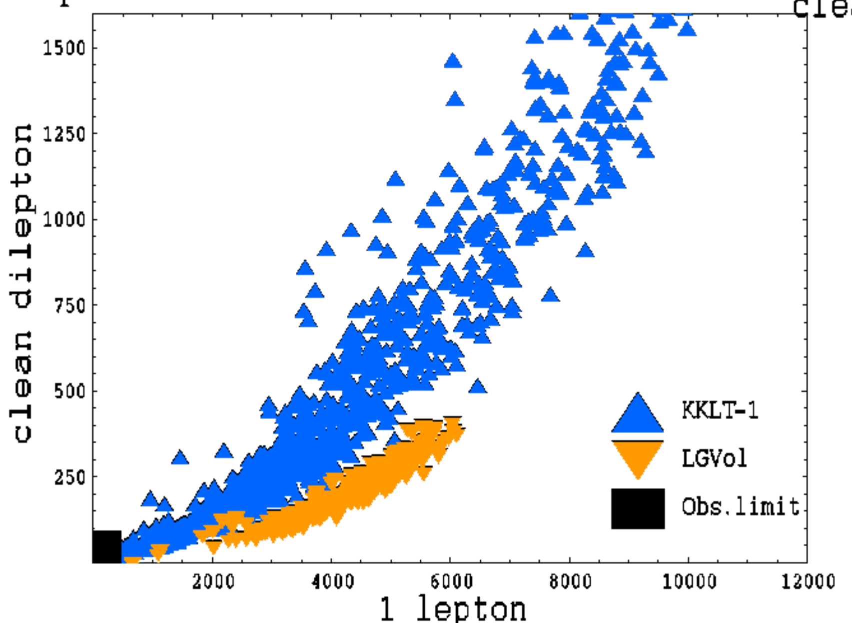
  if $(\Delta S_{AiBj})^2$ smaller than the statistical fluctuation $(\Delta S_0)^2$.

Example – KKLT-1 and LGVol

- Use Trial-and-Error method to select “good” signature plots – converges fast







All signatures include large MET and >= 2 jets

- KKLT (500 models) -- 119 ⟶ 4 ⟶ 0
  LARGE Volume (500 models) -- 237 ⟶ 17 ⟶ 0

The above implies that the number of models in the overlap quickly decreases if one uses "good" signatures. The precise number depends on how densely the parameter space is sampled.

To test robustness, we use 1000 more KKLT-1 models and repeat the Procedure. We find :

- KKLT (1500 models) -- 451 ⟶ 37 ⟶ 6
  LARGE Volume (500 models) -- 477 ⟶ 289 ⟶ 69

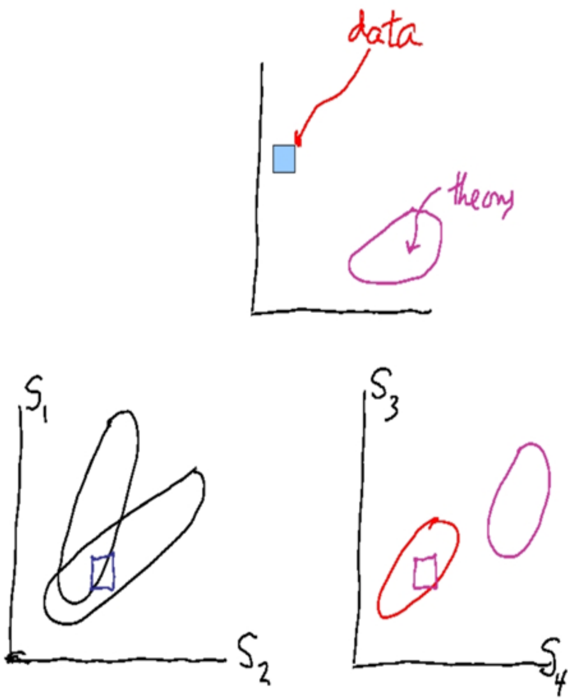
However, if use different combinations of the same signatures *in addition*, we find

"Six Questions for the LHC" – à la Lykken et al in the context of these models.

- KKLT (1500 models) -- 451 ⟶ 37 ⟶ 6 ⟶ 4 ⟶ 1 ⟶ 0
  LARGE Volume (500 models) -- 477 ⟶ 289 ⟶ 69 ⟶ 11 ⟶ 1 ⟶ 0

When there is data

Will favor some frameworks and exclude others



Zoom in on frameworks which are consistent with data.

Use advanced techniques with more luminosity. (complementary)

Try to understand these Frameworks better from a theoretical perspective.

Minimize assumptions in Framework. Bring them in contact with more expt. observables.

Note with this method can include non collider observables as well.

Also emphasized in Pran's Talk

For eg. - Dark Matter, $(g-2)_\mu$, Rare Decays ($B_s \rightarrow \mu\mu$), Other astrophysical and Cosmological Observables, etc.

RESULTS

- New approach to relating collider data and phenomenology, model building, and underlying theory.

- Different classes of realistic string frameworks give limited footprints.

- LHC signatures of a particular framework sensitive to at least some of the underlying structure of the theory.

- Different string frameworks can be distinguished by systematically adding and studying pattern of signature space plots and distributions, and qualitatively understanding why.

Future Directions

Perfect Opportunity for theorists, phenomenologists and experimentalists to collaborate.

- **Theoretical** :

-- Need to construct more robust & reliable string theory frameworks in the sense defined in the introduction, as well as make existing ones more realistic.

-- Not just different corners of M Theory, but also different constructions within one corner, such as different ways of compactifying, different mechanisms for ~~susy~~ and moduli stabilization, different ~~susy~~ mediation mechanisms, different gauge & matter visible sectors, etc. All will lead to different predictions in general.

Phenomenological

- Need much more study of useful and interesting signatures.

- In the steps from high-scale string frameworks to LHC signatures, various kinds of effects not considered properly.

  For example, uncertainties arising from:

  RG Evolution

  expt. constraints

  simulations – event generation, parton showering, hadronization, detector simulation.

  Backgrounds

More sophisticated analysis of these in the spirit of Lykken et al will be extremely useful.

EXTRA SLIDES

Technically, could pursue this approach in any theory.

Use String theory since

– only plausible candidate for quantum gravity. More importantly, in addition, it addresses all particle physics issues.

a) Some corners of the M theory Moduli space already reasonably well understood.

b) Many features of the SM can be naturally obtained in string theory – non-abelian gauge fields, chiral fermions, hierarchical yukawas, etc.

c) Recently, considerable progress in dynamical issues as well -- moduli stabilization and SUSY.

d) As we will see, a given string theory model gives very limited and characteristic predictions for particle physics.

-- currently several known frameworks within string theory, so possible to compare.

Example – Characteristic Features of KKLT-1 Framework

(kachru,kallosh,linde,trivedi)

-- Type IIB N =1, D=4 compactification with all moduli stabilized in the SUGRA regime.

-- Fluxes stabilize complex. structure and dilaton moduli. Obtain W_0.

-- Non-pert. corrections to W stabilize the kahler moduli.

-- Obtain SUSY AdS vacua.

-- Use anti-D3 branes to break SUSY as well as tune the C.C.

-- mechanism for generating O (TeV) $m_{3/2}$ -- by requiring a flux superpotential (W_0) << 1.
(to solve the Hierarchy Problem)

$m_{3/2} \sim W_0 / V$ **(in Planck units)**

Described by Microscopic Parameters : { ($W_0/V = m_{3/2}$), α, n_l, n_q, n_h }; (tanβ)

Similarly for other frameworks

In my opinion,

- In the absence of a deep dynamical principle selecting a particular vacuum or class of vacua, the most useful approach is to compute predictions for many classes of realistic string vacua and try to learn information about the theory from experimental data .
- Doing so crucial to learning how or if string theory is relevant to the real world.

Note degeneracy issue from point of view of string theory – underlying (string) theory will have some not-yet-determined parameters (that affect collider results) at its natural scale ~ M_{pl} – the low scale effective theory will have many parameters, e.g. the 105 parameters of L_{soft} – but all those are calculable from the underlying theory – if express the (~ 20) collider parameters in terms of the high scale underlying theory parameters, many degeneracies are eliminated

Of course, don't know the correct underlying theory (yet)

In general not possible to reconstruct lots of superpartner masses, particularly at low integrated luminosity, over next few years

But the signatures do depend on masses, and so the patterns of signatures reflect the masses

1) Why String Phenomenology at all? -- Do not yet have non-perturbative and background independent definition of String/M theory.-- Poor understanding of the full M theory landscape.-- “Can get anything from every string theory” -- Just wait?

2) No, because,
Some corners of the M theory Moduli space already reasonably well understood Many features of the SM can be naturally obtained in string theory - non-abelian gauge fields, chiral fermions, hierarchical yukawas, etc.Recently, considerable progress in dynamical issues as well -- moduli stabilization and SUSY. Actually a given string theory model gives very limited and characteristic predictions

3) ***I think string theorists will learn a lot about string theory by studying its phenomenology as well as the theory***

There are many string theories – unlikely to find relevant ones?

No, choices of string theories to study is not random – select those that can give SM-like spectra, softly-broken N=1 supersymmetry, inflation, dark matter, etc.

Other Examples – Very Brief

- LARGE Volume Vacua
  (Balasubramanian, Conlon, Quevedo.)

  – Also Type IIB, but now $W_0 \sim O(1)$.
  -- SUSY broken predominantly by fluxes.
  -- Vacua in different region of moduli space compared to KKLT-1.

- Fluxless M Theory Vacua
  (Acharya, Bobkov, Kane, PK, Shao)
  Phys. Rev. Lett. 2006;hep-th/0701034

  -- N=1, D=4 compactifications (G_2 holonomy)
  -- Stabilize moduli and generate Hierarchy by strong gauge dynamics.
  -- Obtain metastable dS vacua consistent with standard gauge unification.

Both described by a few microscopic parameters.

Next Slide – How to go from string Vacua to LHC Signatures

So, Good to look at Alternative Approaches

Our Approach

To combine both top-down and bottom-up approaches

Carry out more traditional effective theory low scale analyses and this approach in parallel, will complement each other.

For distributions, sometimes more useful to use quantiles (deciles) to represent them.