Supersymmetry and the LHC Inverse Problem

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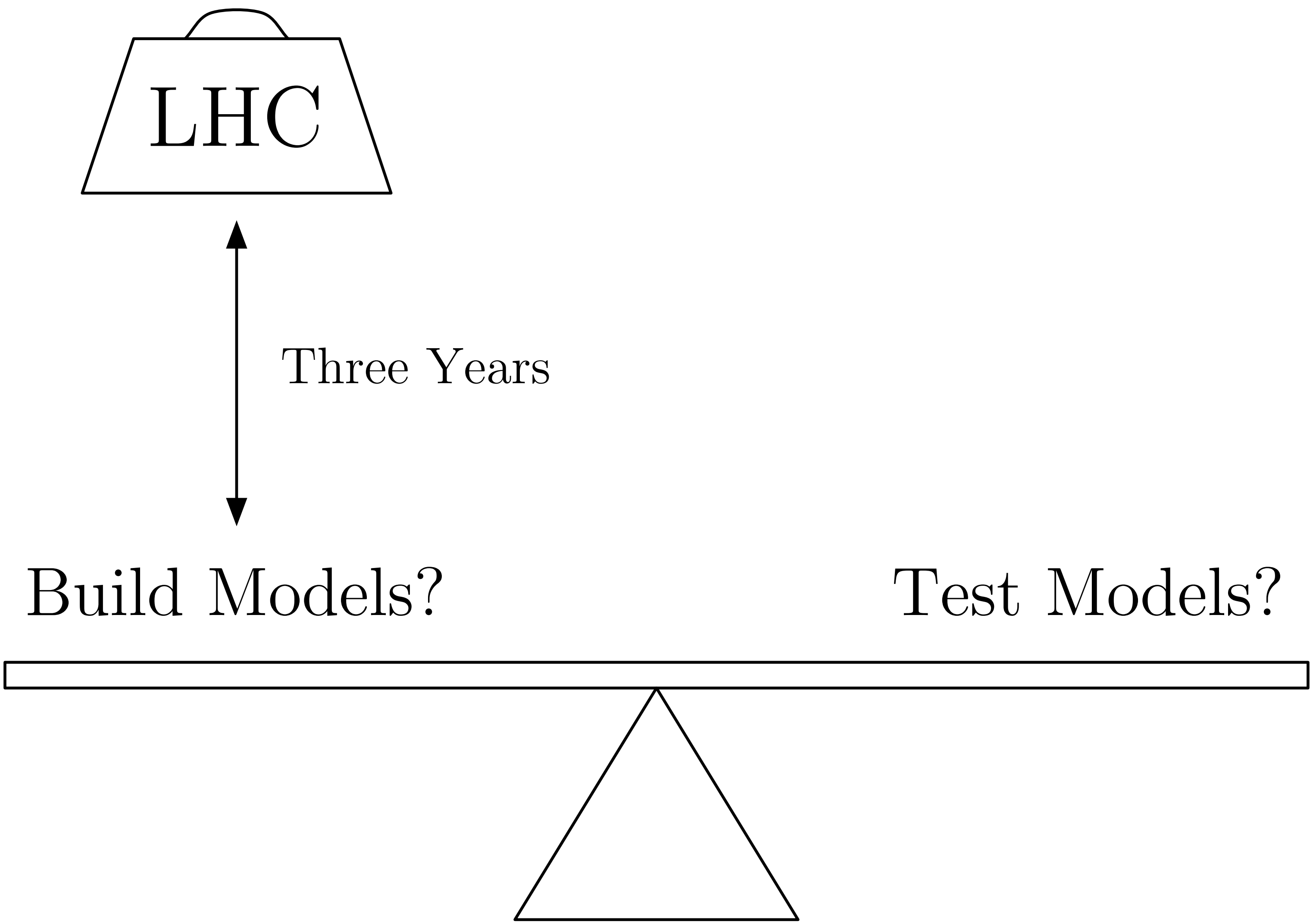
hep-ph/0512190

Particle Theory Circa 2006



Models Still Worth Building

1. "Best SUSY Ever"

   e.g. 6 × Nomura, *et al.*

2. Proof of Concept

   e.g. Twin Higgs (Chacko, Goh, Harnik)

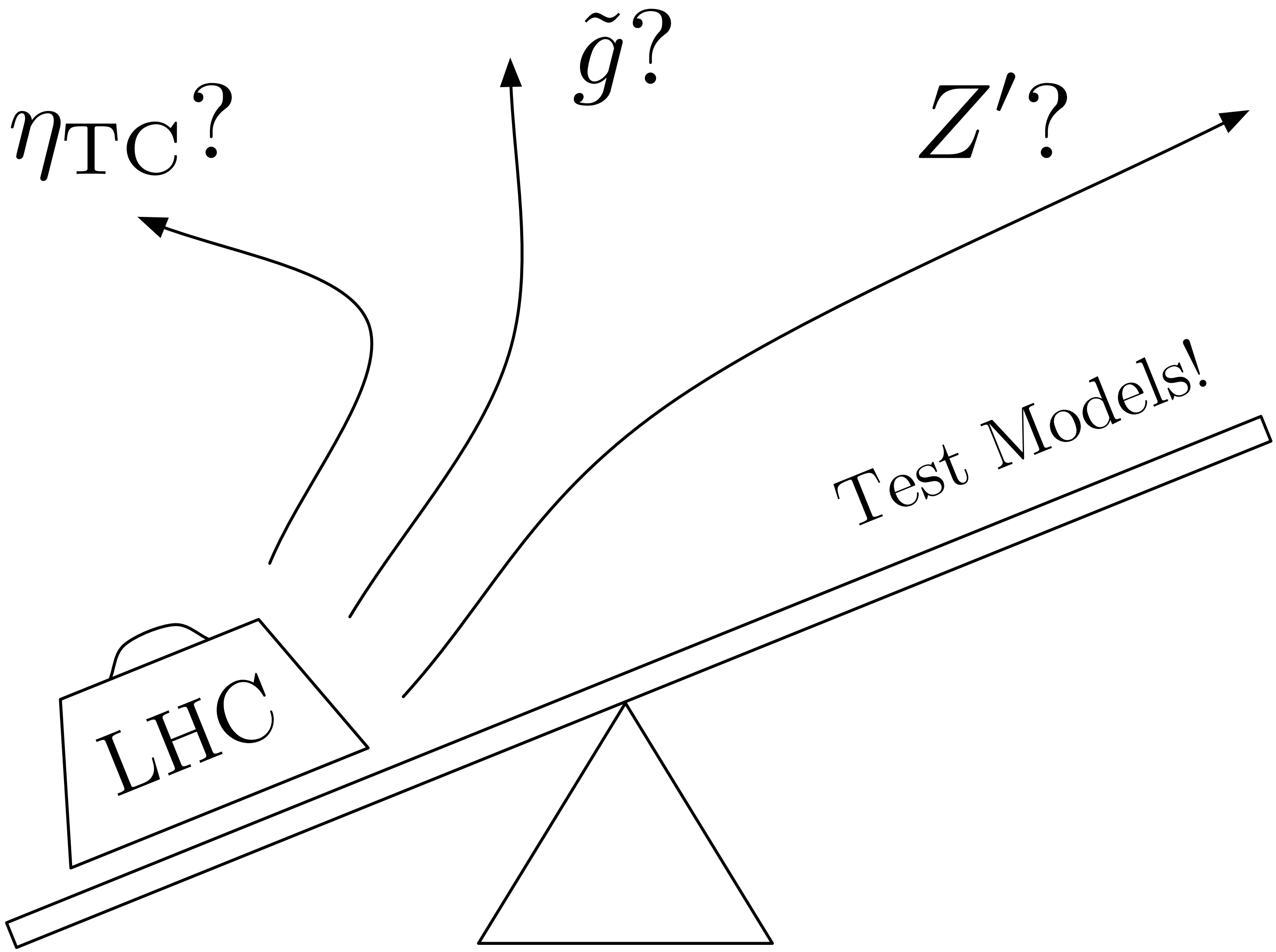
3. Unnatural Theories

   e.g. Minimal Dark Matter (Mahbubani, Senatore)

4. Canonical Models

   e.g. Little M-theory (Cheng, JKT, Wang)

Particle Theory Circa 2008



One Year at the LHC

$$10 \text{ fb}^{-1}$$

Experimental Data $\longrightarrow$ Theoretical Models?

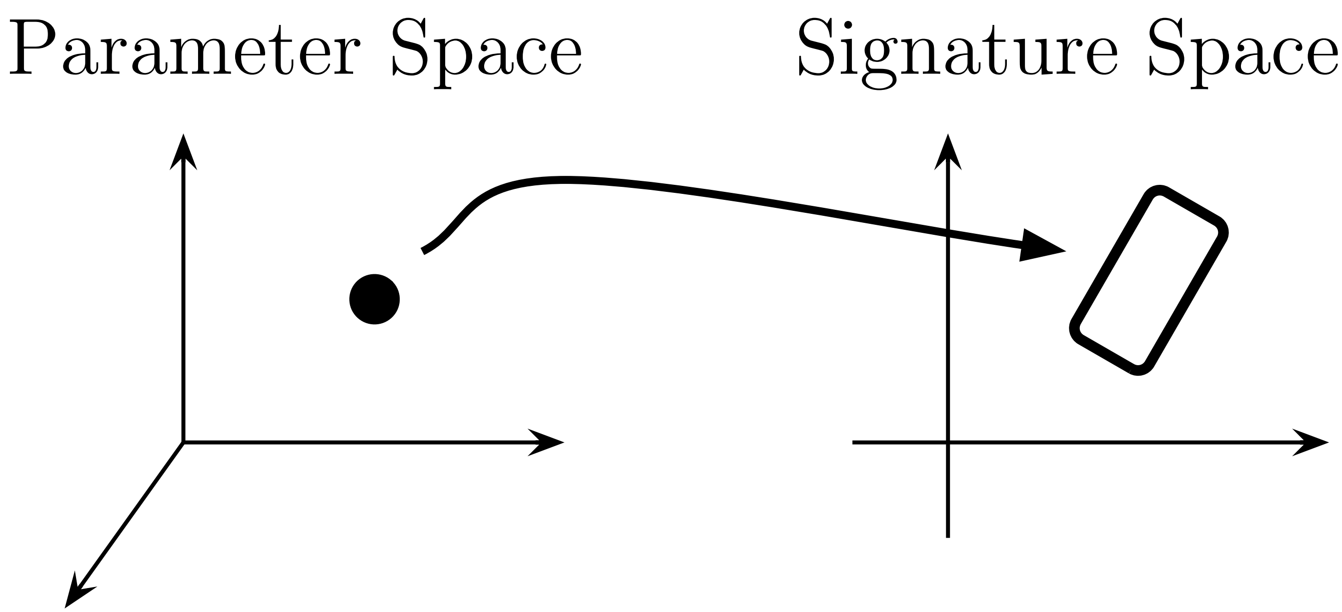
Assume it is the MSSM. Without forcing constraints on soft parameters, can we "rule in":

Gaugino Unification?

Weak Scale Dark Matter?

$\tan\beta$?

Standard Method For Testing Models

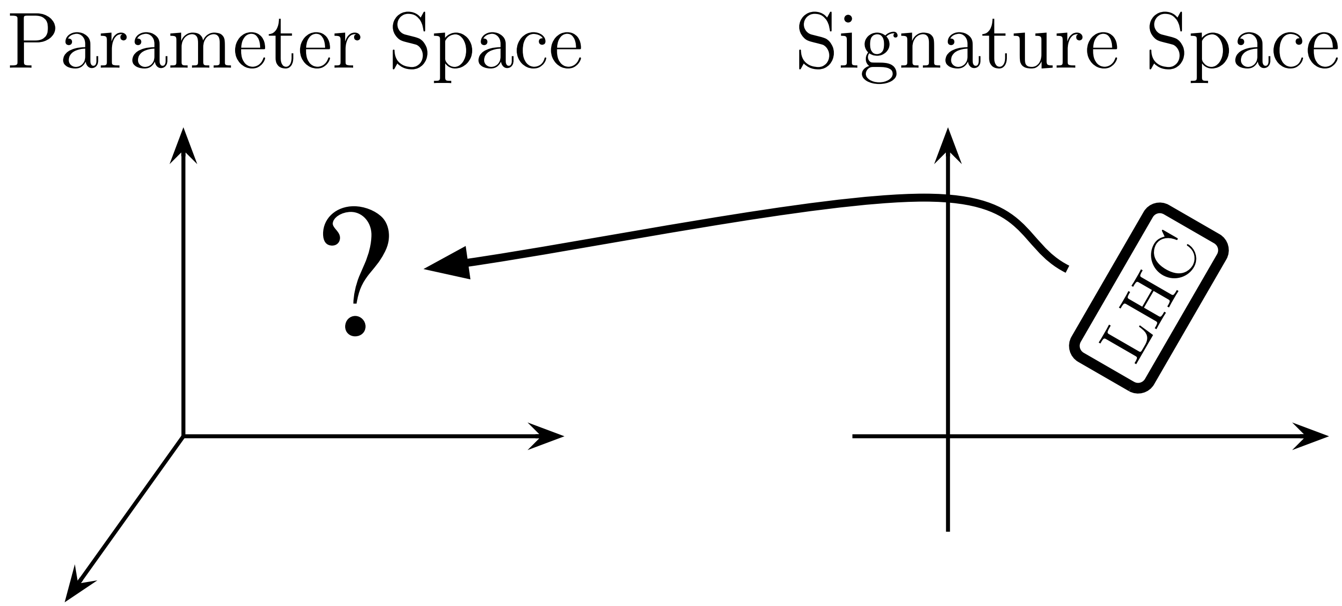


TDR, Benchmark studies, LEP/Tevatron bounds, etc.

Reduced parameter set (mSUGRA, AMSB, GMSB):

Experimental Data $\longrightarrow$ Precision Measurements

The Inverse Problem

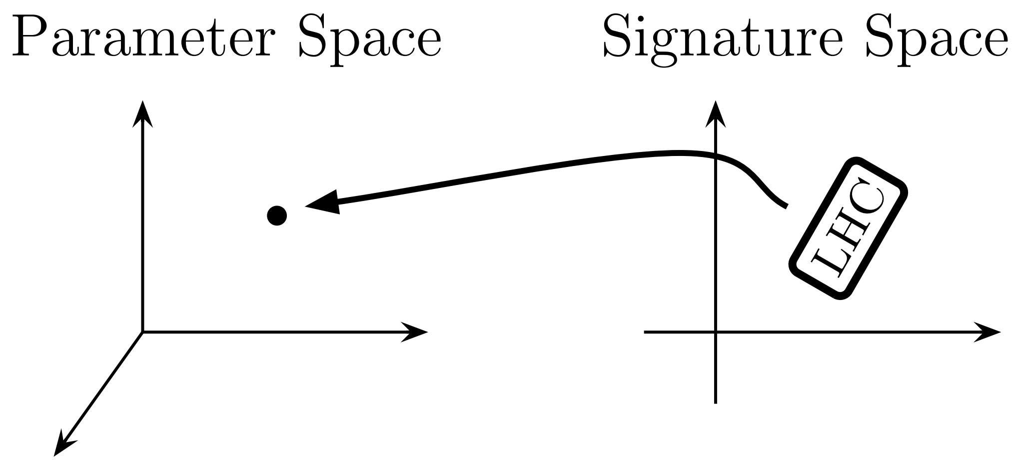


Much more interesting! (One-to-One Map?)

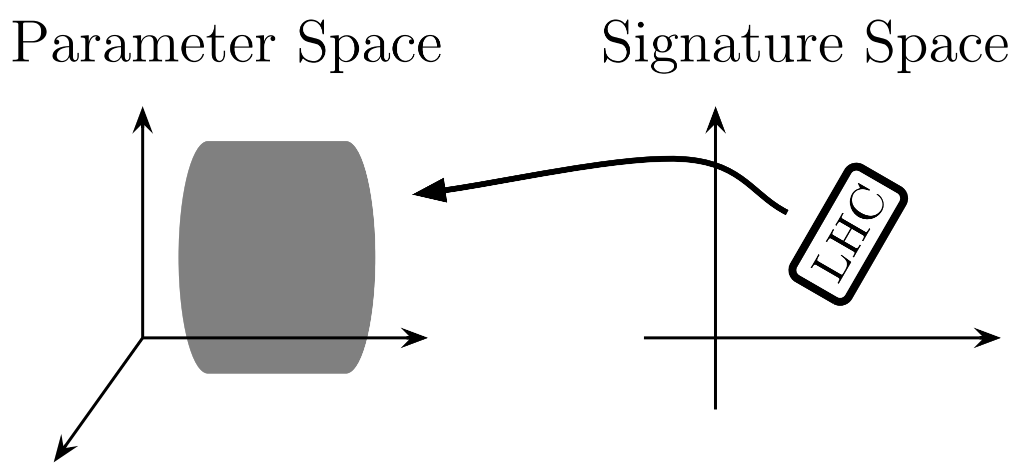
$$\text{Data} \xrightarrow{?} \text{gaugino unification, dark matter, ...}$$

Much more important! (500 GeV ILC in 10 years?)

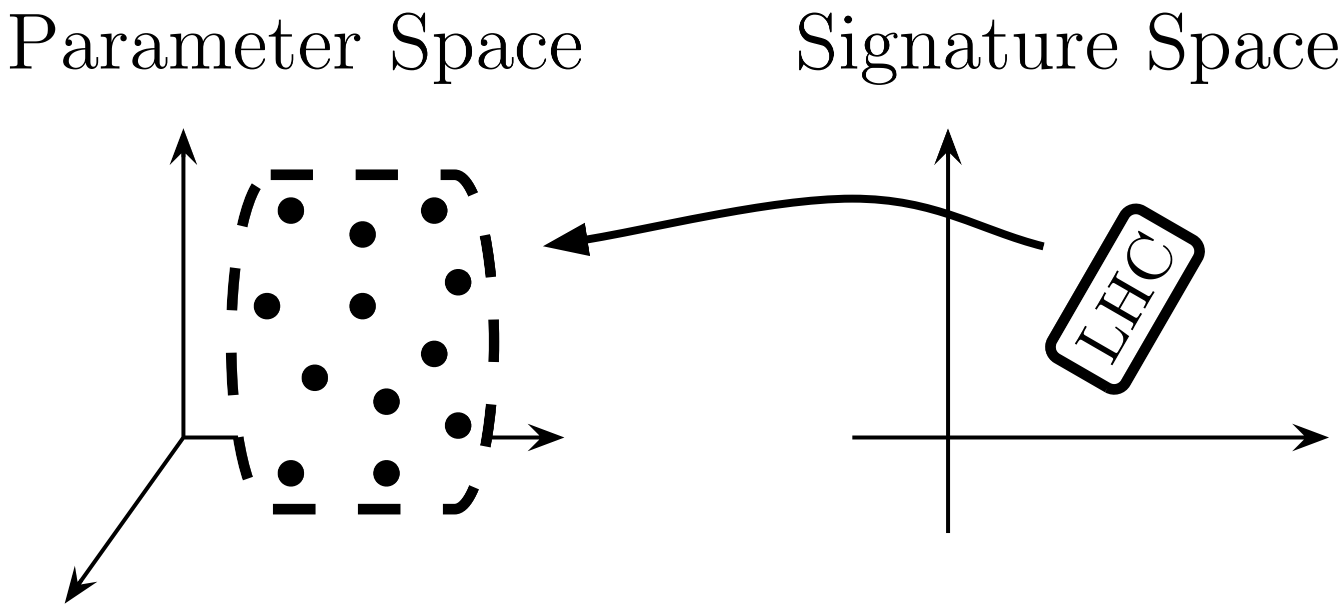
Best of all Possible Worlds



Worst of all Possible Worlds



Our Picture of the Inverse Map



Degeneracies!

Many small footprints in a large overall region.

Motivating the Inverse Problem

Do LHC Experimentalists Need Our Help?

No
- A long-lived gluino at 300 GeV...
- A 2 TeV Z'...
- A Higgs and nothing else...

Yes
- Almost any model of TeV scale physics with a $\mathbf{Z}_2$ symmetry and heavy-ish colored particles.

The L(ittle) H(ierarchy) C Problem

Precision EW: $\Lambda_{\text{higher dim}} \sim 5 - 10$ TeV

Direct Bounds (if not hidden):

$$\tilde{\chi}_0 \gtrsim 100 \text{ GeV}, \quad h \gtrsim 115 \text{ GeV}, \quad \tilde{g} \gtrsim 300 \text{ GeV}$$

Flavor-independent mediation scheme SUSY:

$$\text{Colored Particles} > \text{Electroweak Particles}$$

LHC is a *pp*-collider: Smallish σ_{SUSY} if heavy gluino, huge SM background to “jets plus missing energy.”

Concerns About Uniqueness

Miller, Osland, Gjelsten: Detailed study of SPS 1a

Edges/Endpoints $\rightarrow$ Various Mass Scenerios

Lester, Parker, White: Markov Chain Technique

Some discussion of decay chain ambiguity.

Meade, Reece: Model-Independent Top Partners

Top partner spin? New observables needed.

The Inverse Problem: Two Themes

Theme #1

Statistics and the Inverse Problem

How can we assess degree of one-to-one-ness without simulating every corner of the MSSM?

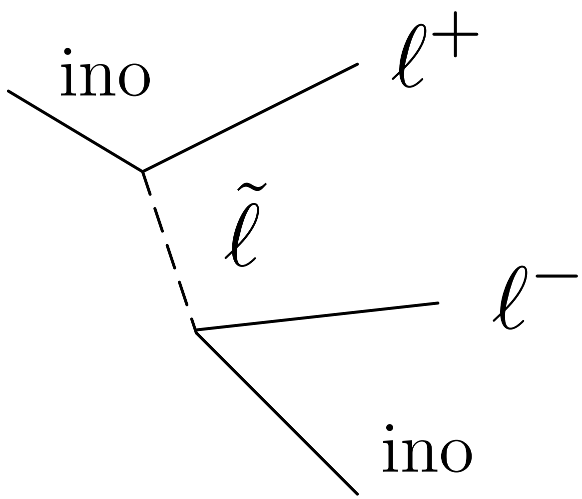
The Birthday Problem!

By assembling a large sample of MSSMs, we can evaluate the effectiveness of existing LHC observables over a wide range of SUSY soft parameters.

Theme #2

SUSY, Sleptons, and the LHC

Most benchmark studies involve the cascade decay:



By studying dilepton invariant mass distributions, one can constrain electroweakinos.

When sleptons are decoupled, you lose this handle!

Outline: The LHC Inverse Problem

1. What is our statistical technique?

   Generalized Pigeon Hole Principle

2. What kind of models are we simulating?

   15 Parameter MSSM Scan

3. What kind of data are we using?

   1808 LHC Observables

4. What kind of degeneracies are there?

   Flippers, Sliders, and Squeezers

Statistics of the MSSM

Simple Statistical Question

$$N_{\text{models}} \quad \overset{?}{\substack{> \\ = \\ <}} \quad N_{\text{sig bins}}$$

$\uparrow$ different MSSMs measured in desired parameter accuracy

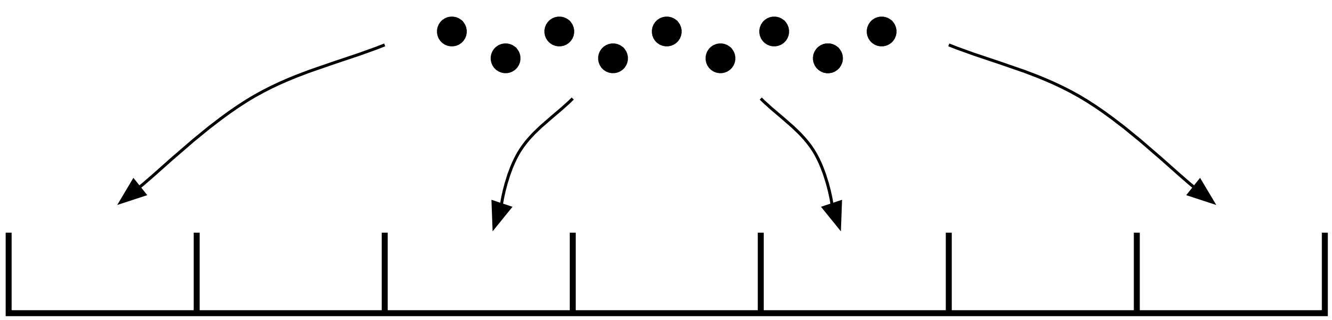
$\uparrow$ distinguishable experimental outcomes at the LHC

If $N_{\text{models}} > N_{\text{sig bins}} \Rightarrow$ Pigeon hole principle!

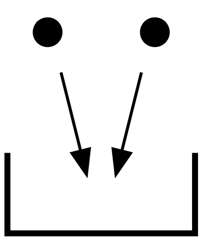
Guaranteed degeneracies at the LHC.

How to Count Degeneracies

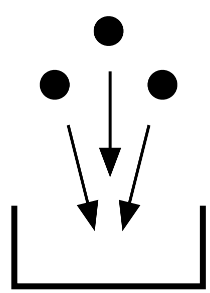
m balls



N bins



$$= \frac{1}{2!}\frac{m^2}{N}$$



$$= \frac{1}{3!}\frac{m^3}{N^2}$$

For This Talk...

We simulated $m = 39137$ MSSMs (+ 3889 in total...)

Number of pairs with matching LHC signatures $= 364$

$$N_{\text{sig bins}} \sim m^2/d \sim 4 \times 10^6$$

$$N_{\text{models}} \sim 10^8 \text{ (From parameter ranges.)}$$

Probability of choosing correct model at LHC is 1 in 25.

Equivalently, for every model, there are 24 other (well motivated?) models with the same LHC signatures.

Criteria Based Analysis

Among 364 pairs of matching LHC models, none are identical models, but some are "good" pairs.

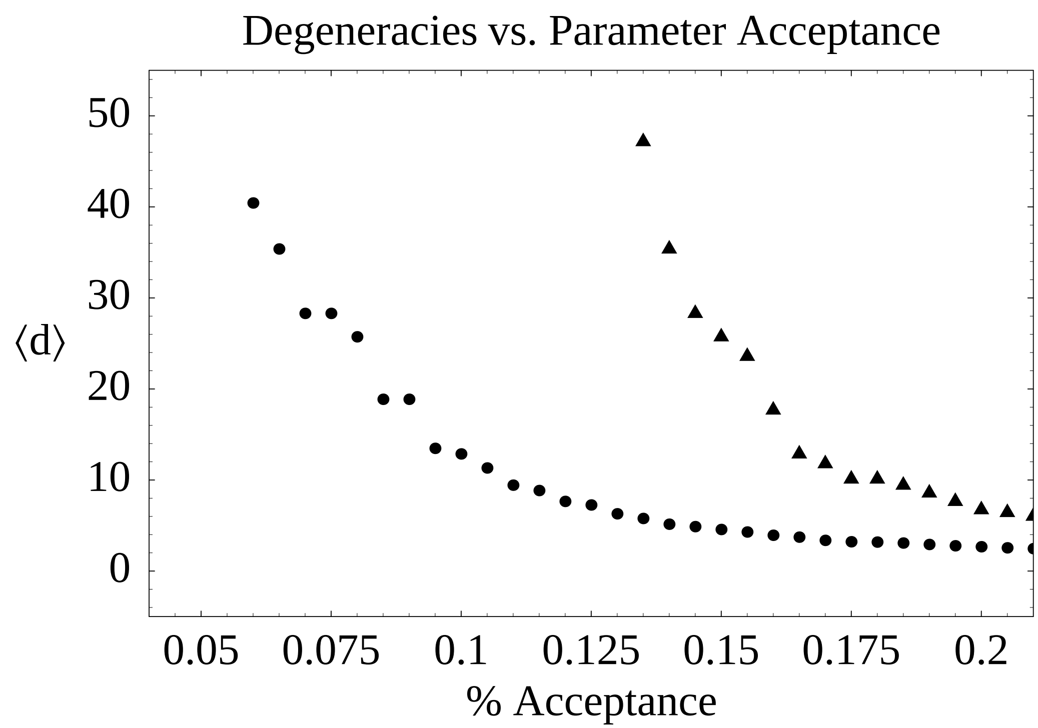
$$\langle \text{degeneracies} \rangle = \frac{\text{number of matching pairs}}{\text{number of ``good'' pairs}}$$

I want to know the $\tilde{B}$, $\tilde{W}$, μ and $\tilde{g}$ masses to 10%.
I can live without knowing $\tan\beta$ or sfermion masses.

30 of 364 pairs satisfy this criteria $\Longrightarrow \langle d \rangle \sim 12$.

Adjusting the Criteria

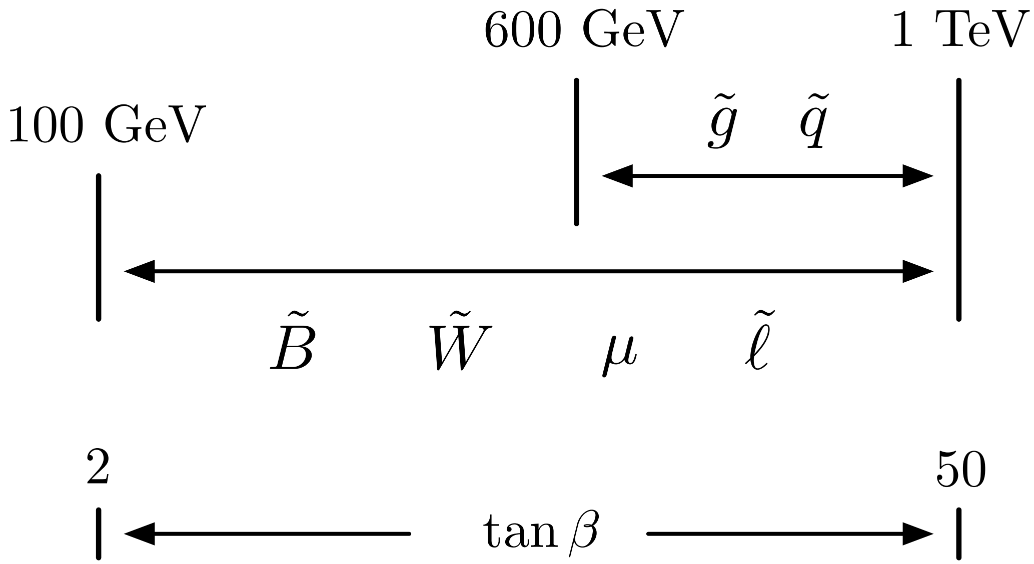
Dots: Gauginos and Higgsinos Triangles: + Squarks



Asymptote at $\langle d \rangle \sim 2 \;\rightarrow\;$ Discrete ambiguities!

What Kind of Models?

Choosing 39,137 MSSMs



$$\tilde{q}\left\{\begin{array}{ccc} \tilde{q}_L & \tilde{q}_{Ru} & \tilde{q}_{Rd} \\ \tilde{q}^3_L & \tilde{q}^3_{Ru} & \tilde{q}^3_{Rd} \end{array}\right.$$

$$\tilde{\ell}\left\{\begin{array}{cc} \tilde{\ell}_L & \tilde{\ell}_R \\ \tilde{\ell}^3_L & \tilde{\ell}^3_R \end{array}\right.$$

Constraints: Nothing more than 50 GeV decoupled

Max Colored > Max Electroweakino > Max Slepton

No slepton LSP.

Generating 39,137 MSSMs

Thanks to “Opus” at UMich, “Sauron” at Harvard:

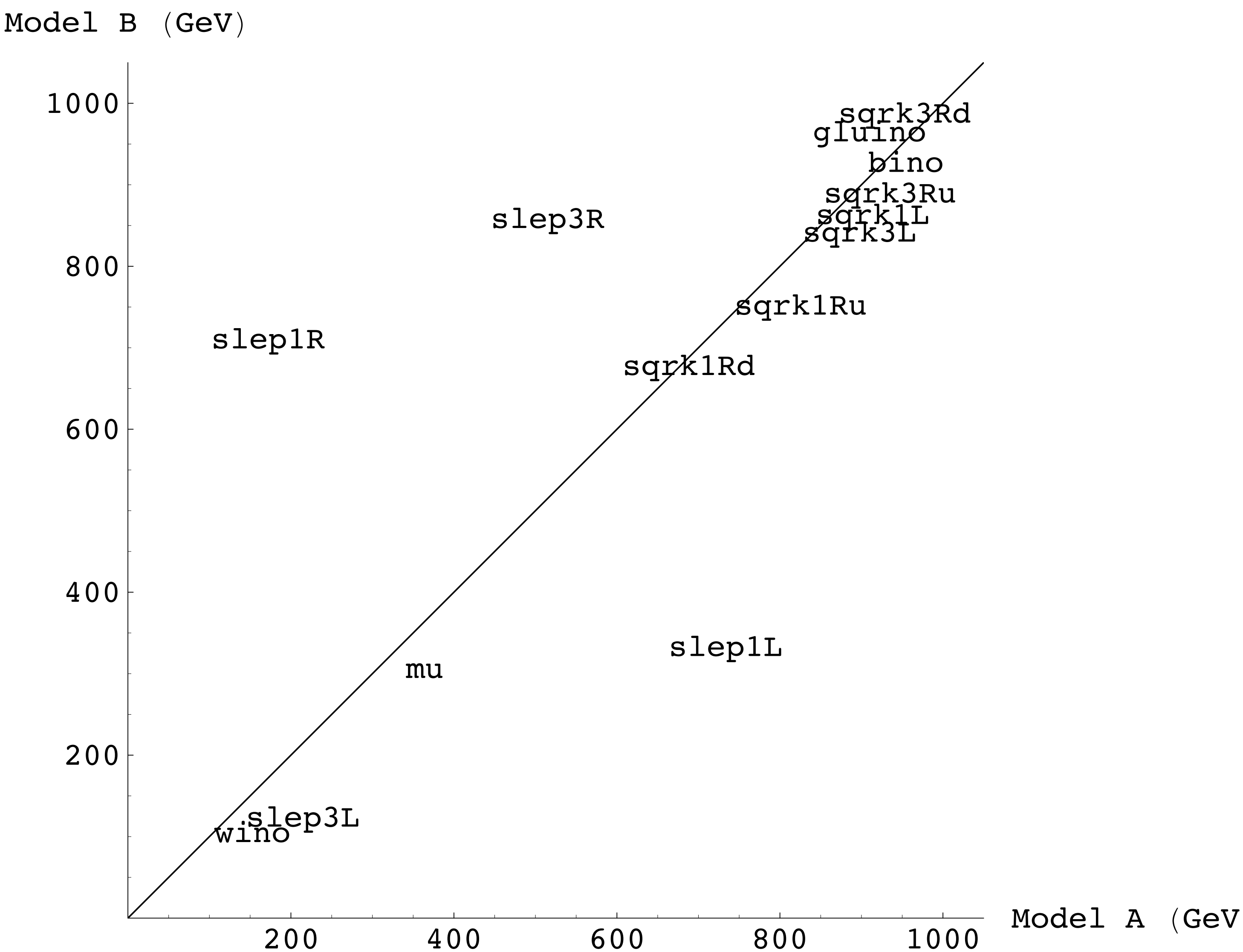
1 Model / CPU / hr

PYTHIA $\rightarrow$ PGS (Pretty Good Simulation)

Two terabytes of storage for raw data like:

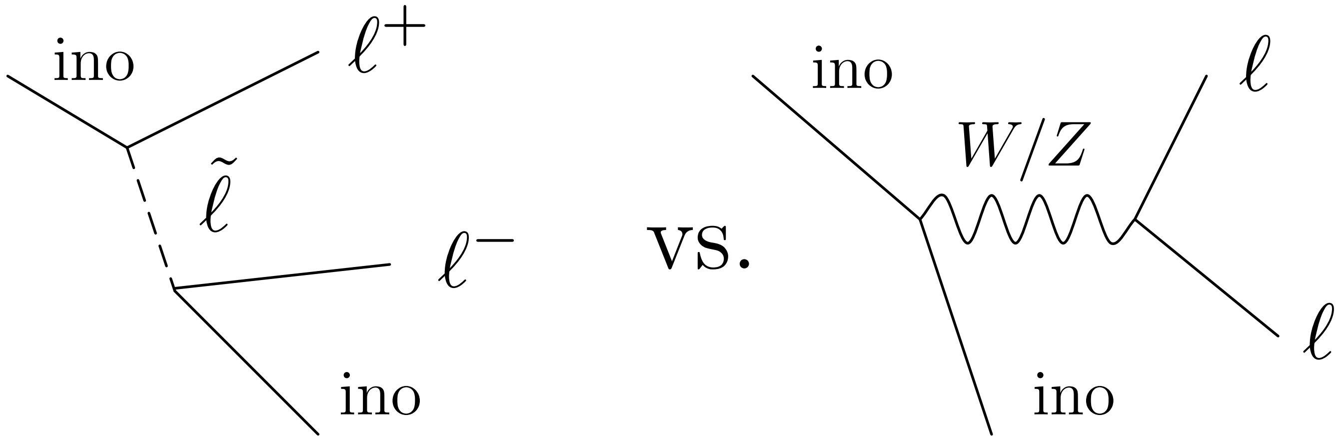
#	typ	eta	phi	pt	jmas	ntrack	btag
1	3	0.816	0.492	36.20	1.00	3.0	0.0
2	4	2.674	5.539	69.72	7.54	0.0	0.0
3	4	1.794	5.499	45.57	5.65	9.0	0.0
4	4	-0.932	1.546	34.33	6.02	9.0	0.0
5	4	1.622	4.151	70.02	23.54	10.0	0.0
6	4	2.636	3.328	22.96	5.84	0.0	0.0
7	4	0.340	2.154	65.68	2.60	9.0	0.0
8	6	0.000	5.441	23.70	0.00	0.0	0.0

A Typical "Good" Pair: 2005 vs. 32444



Sleptons and the LHC

Sleptons often effectively decoupled!

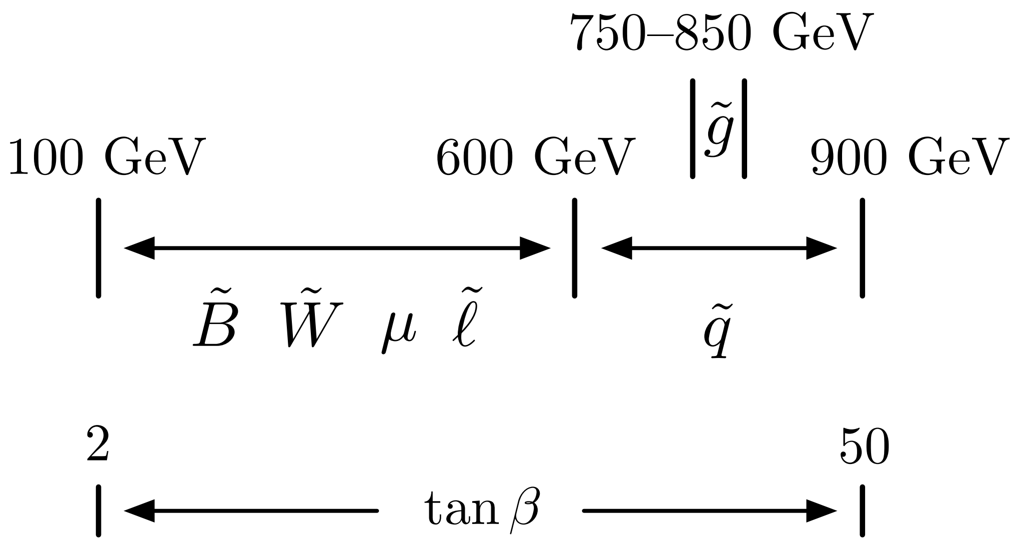


Very rarely cascade decays ino-slepton-ino.

Most leptons in final states from W and Z.

(What about mSUGRA or GMSB?)

Cascade Run



$$\tilde{q} \left\{ \; \tilde{q}_L \quad \tilde{q}_{Ru} \quad \tilde{q}_{Rd} \right.$$

$$\tilde{\ell} \left\{ \; \tilde{\ell}_L \quad \tilde{\ell}_R \right.$$

Force cascade decays:

min(electoweakino) $<$ sleptons $<$ max(electoweakino)

With 27196 models:

Virtually no degeneracies...

What Kind of Data?

Blackboard Interlude

LHC Observables

Triggers: $\not{E}_T > 125$ GeV

$$\sum_{3j\ w/\ 0\ell} P_T > 300 \text{ GeV}, \qquad \sum_{3j\ w/\ 1^+\ell} P_T > 225 \text{ GeV}$$

Categorize all events by the number of:

j, bj, e, μ, hadronic τ, γ

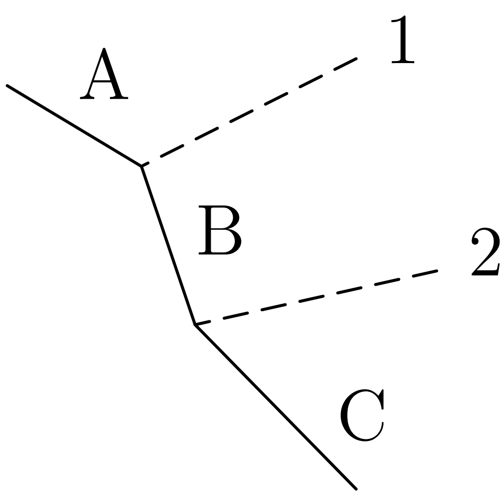
Count NEV, everything else ratios.

Errors: $\sqrt{N}$ error (times scale factor) plus percent error (1%, except 15% for NEV).

Kinematic Histograms

$$m_{\text{eff}} = \sum |p_T|, \qquad m^2_{\text{inv}} = (\sum p_\mu)^2$$

Edges/endpoints of distributions.



Offshell B (Endpoint):

$m^{12}_{\text{inv}} = m_A - m_C$

Onshell B (Edge):

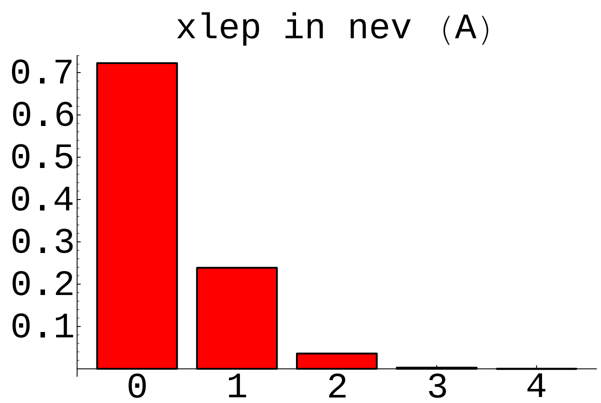
$m^{12}_{\text{inv}} = \sqrt{(m_A^2 - m_B^2)(m_B^2 - m_C^2)/m_B^2}$

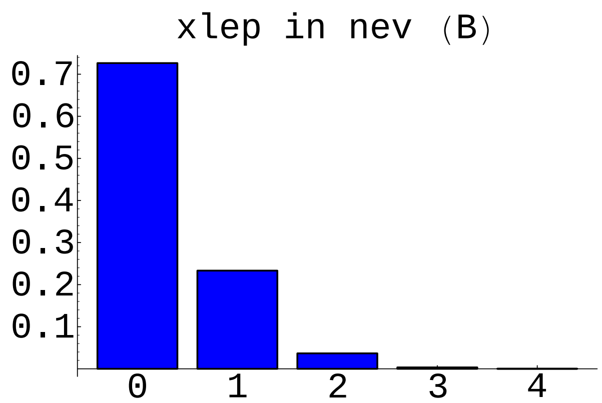
Distributions in quantiles. (Deciles, m_{eff}; 20-tiles, m_{inv})

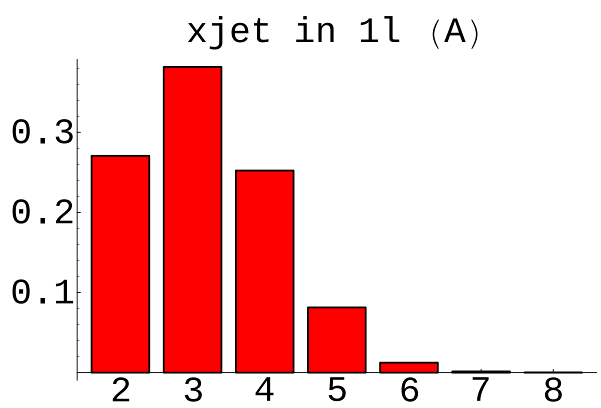
Match distribution, not just endpoint/edge.

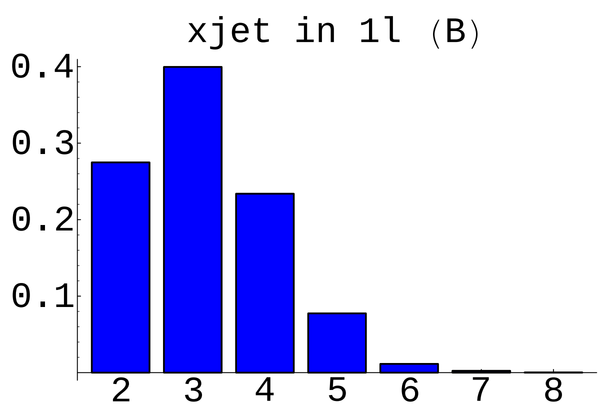
Typical Data: 2005 vs. 32444

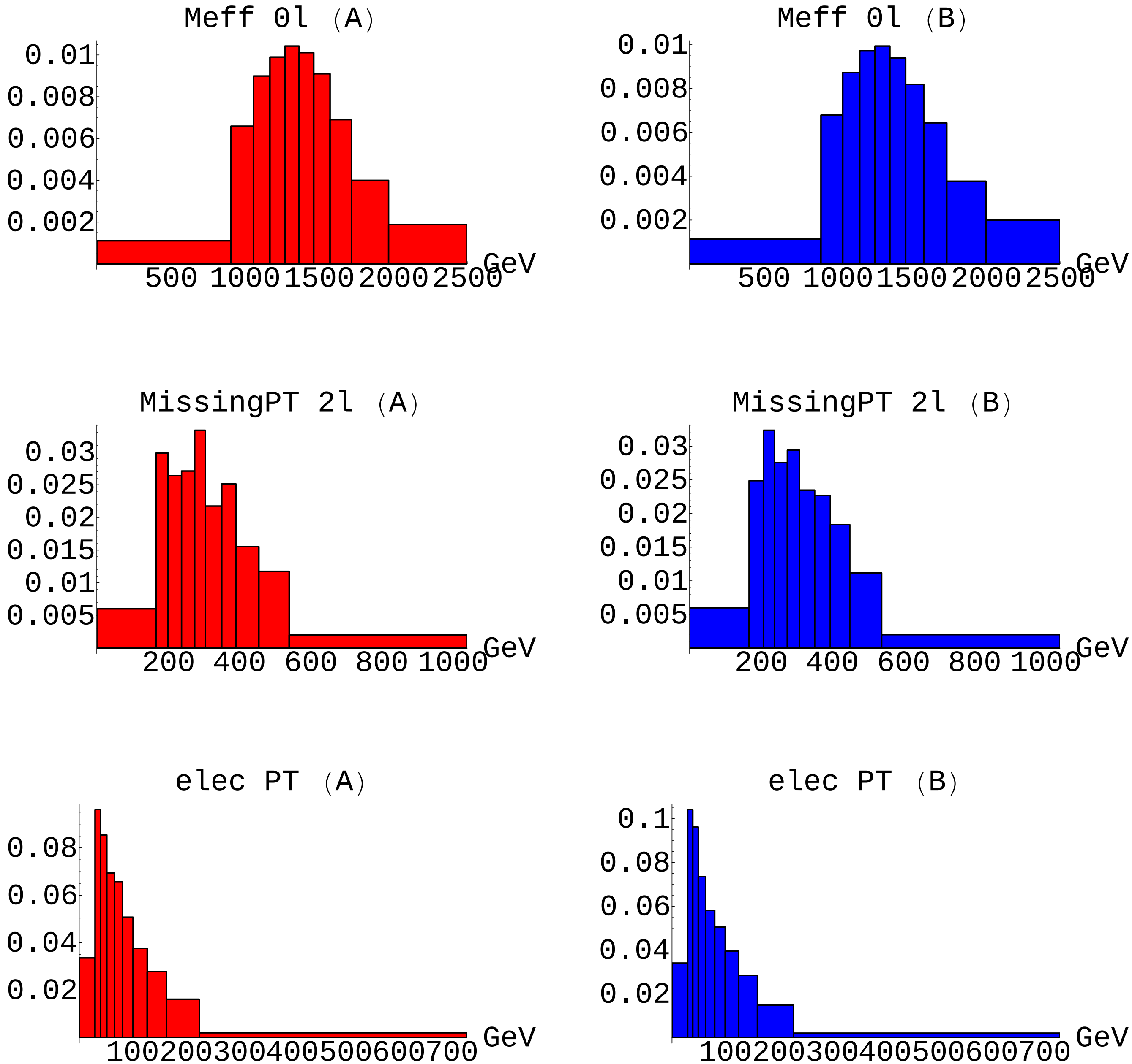
$$\text{NEV}_A = 30253, \quad \text{NEV}_B = 32251$$



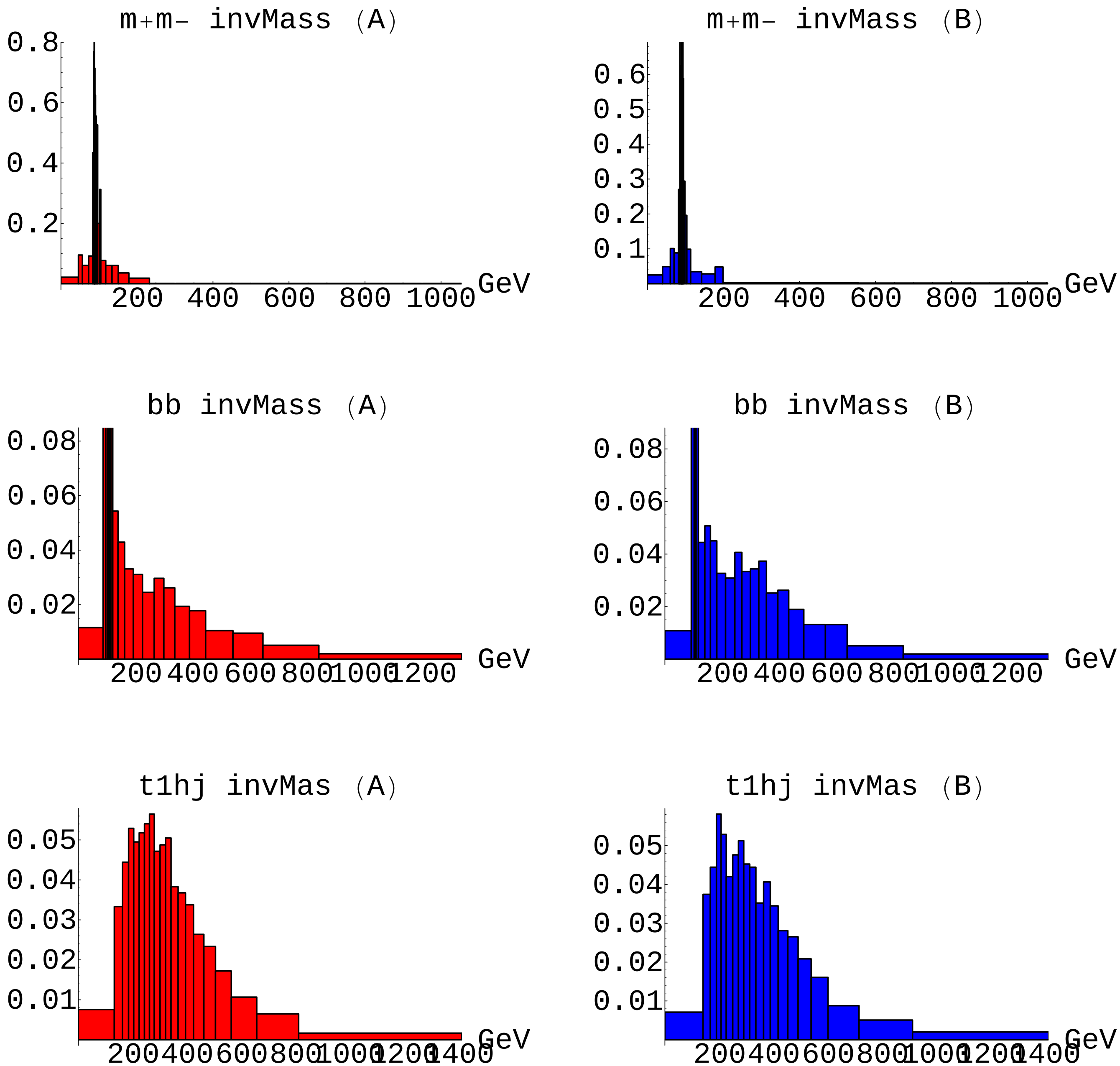








Meff 0l (A)
0.01
0.008
0.006
0.004
0.002
500 1000 1500 2000 2500
GeV
Meff 0l (B)
0.01
0.008
0.006
0.004
0.002
500 1000 1500 2000 2500
GeV
MissingPT 2l (A)
0.03
0.025
0.02
0.015
0.01
0.005
200 400 600 800 1000
GeV
MissingPT 2l (B)
0.03
0.025
0.02
0.015
0.01
0.005
200 400 600 800 1000
GeV
elec PT (A)
0.08
0.06
0.04
0.02
100 200 300 400 500 600 700
GeV
elec PT (B)
0.1
0.08
0.06
0.04
0.02
100 200 300 400 500 600 700
GeV


m+m− invMass (A)
0.8
0.6
0.4
0.2
200 400 600 800 1000
GeV
m+m− invMass (B)
0.6
0.5
0.4
0.3
0.2
0.1
200 400 600 800 1000
GeV
bb invMass (A)
0.08
0.06
0.04
0.02
200 400 600 800 1000 1200
GeV
bb invMass (B)
0.08
0.06
0.04
0.02
200 400 600 800 1000 1200
GeV
t1hj invMas (A)
0.05
0.04
0.03
0.02
0.01
200 400 600 800 1000 1200 1400
GeV
t1hj invMas (B)
0.05
0.04
0.03
0.02
0.01
200 400 600 800 1000 1200 1400
GeV

Confronting Degeneracies

Types of Degeneracies

We have 39137 models, many degenerate pairs.

Open Question:

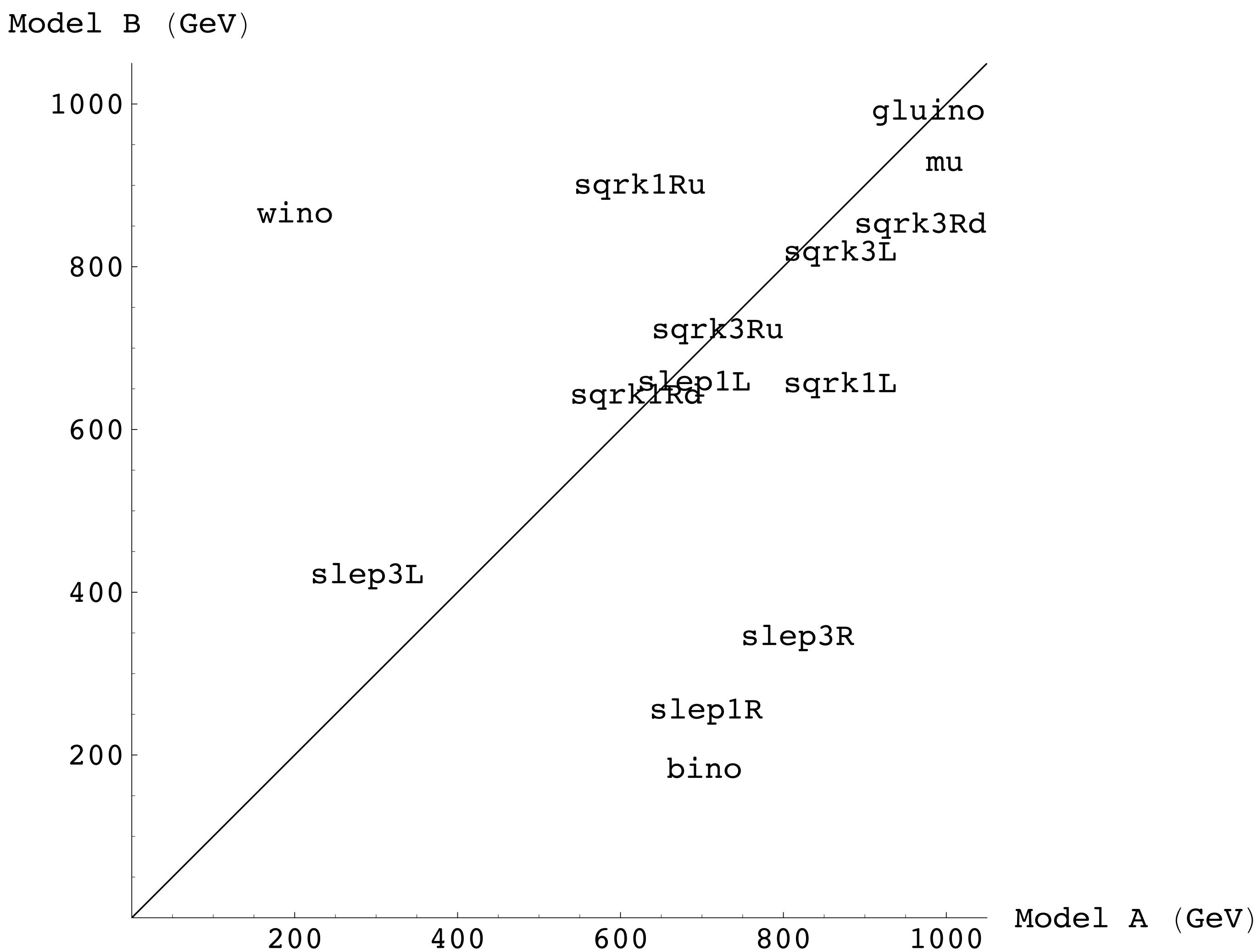
Fundamentally Indistinguishable @ LHC?

New Clever Observables?

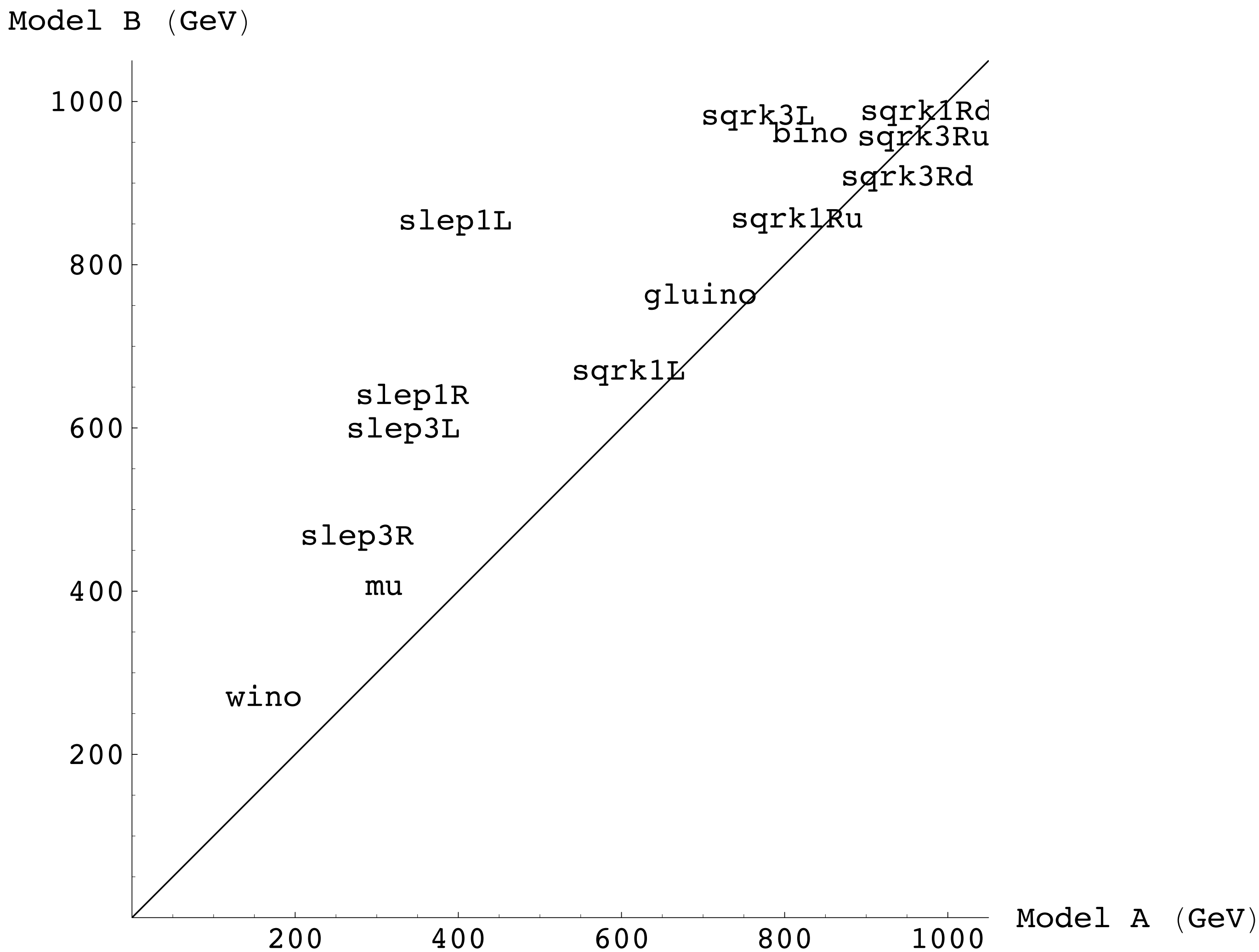
First Step: Catalog...

Electroweakino Sector: Flippers, Sliders, and Squeezers

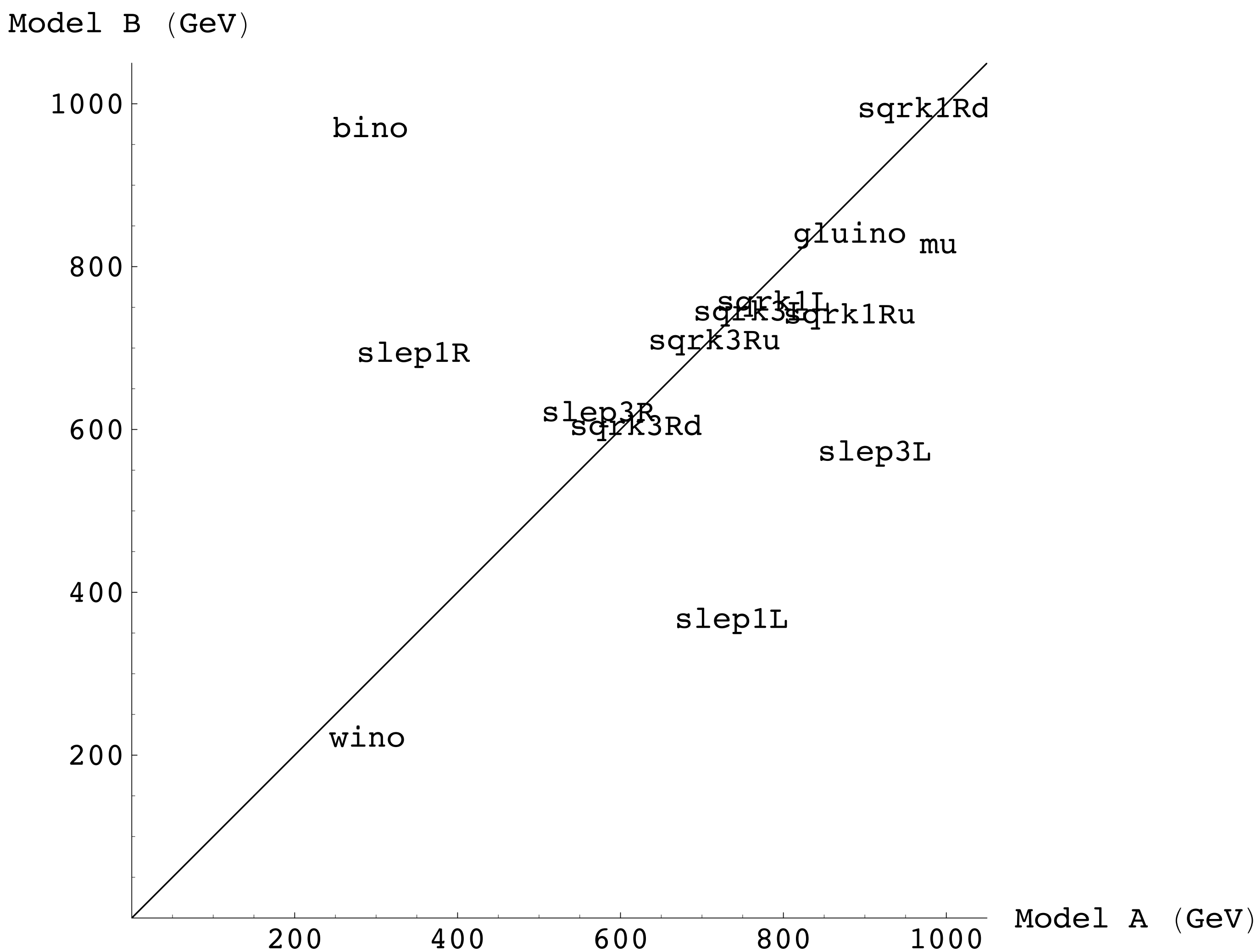
Flippers: 17653 vs. 20026



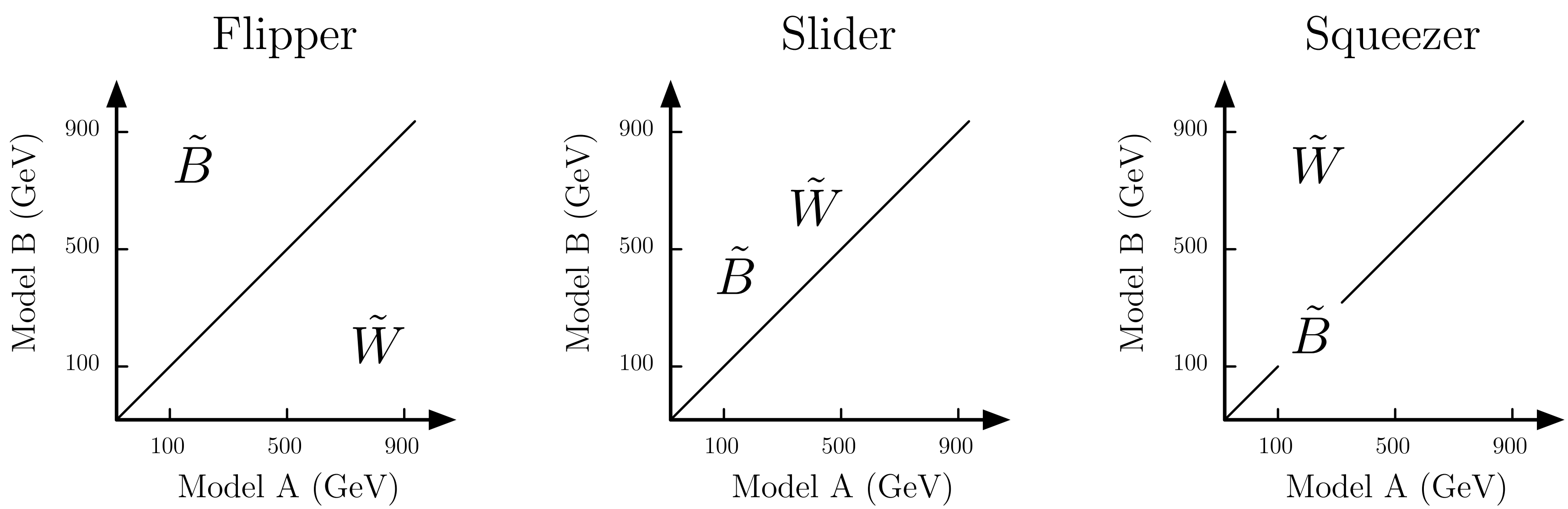
Sliders: 24230 vs. 25628



Squeezers: 24119 vs. 35520



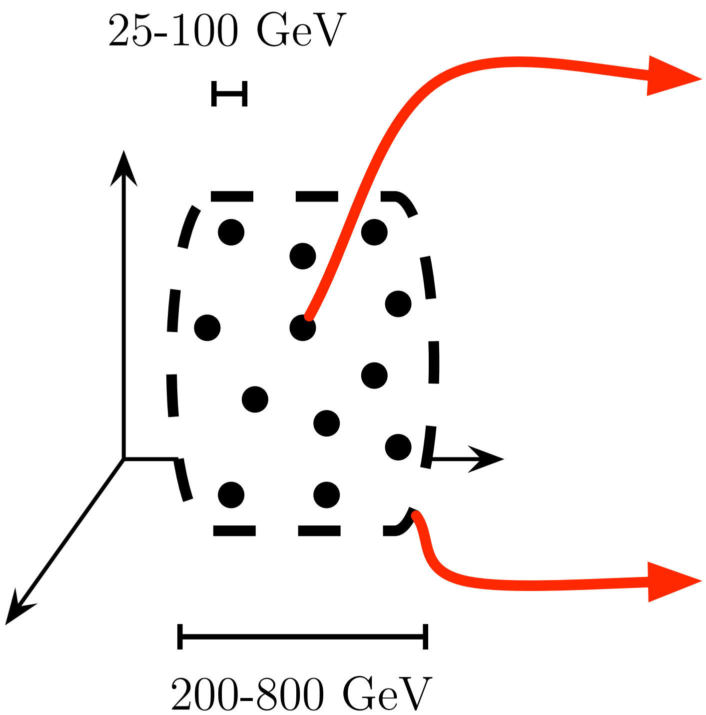
A Challenge for the LHC



After evidence for physics beyond the standard model, can we disentangle these (and other?) degeneracies?

The Outlook

If You Have a Favorite Theory...



If LHC data is consistent with mSUGRA, you will measure mSUGRA parameters very accurately...

...but there are qualitatively different MSSMs consistent with the same experimental data.

200 GeV can change gaugino unification, LSP identity, etc.

Two Themes

Statistics and the Inverse Problem

We now have a handle on the very important question of the map between LHC data and theoretical models.

SUSY, Sleptons, and the LHC

Using this statistical technique, we have learned that without sleptons in decay chain, large ambiguities in electroweakino sector.

Lessons from the Degenerate MSSM

To nail the MSSM at the LHC, we must drastically increase the number of independent LHC signatures.

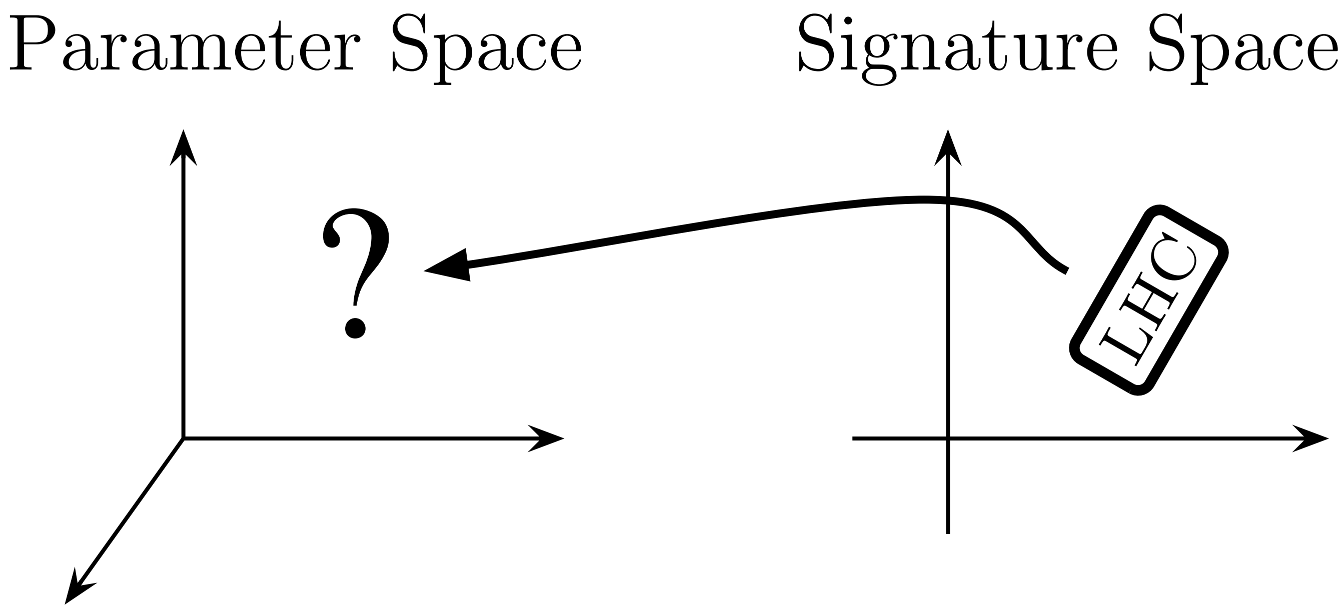
(Is this still true at 300 fb^{-1}? With SM background?)

Easy to check if a new signature works: calculate $\langle d \rangle$.

Statistical techniques useful for diagnosis, but once we have data, how will we actually "rule in" models?

The LHC Inverse Problem

Very little work in this direction.



MSSM vs. NMSSM vs. UED vs. T-parity LH ?

An Invitation to the LHC Olympics

Competition as motivation for interpreting data.

The Second LHC Olympics: CERN, February 2006

Three Blackboxes by Harvard, UMich, UWash

Plus Cornell, Johns Hopkins, Princeton

The Third LHC Olympics: August 2006

New Blackboxes and New Teams

Our tools: experience, intuition, consensus, and luck.