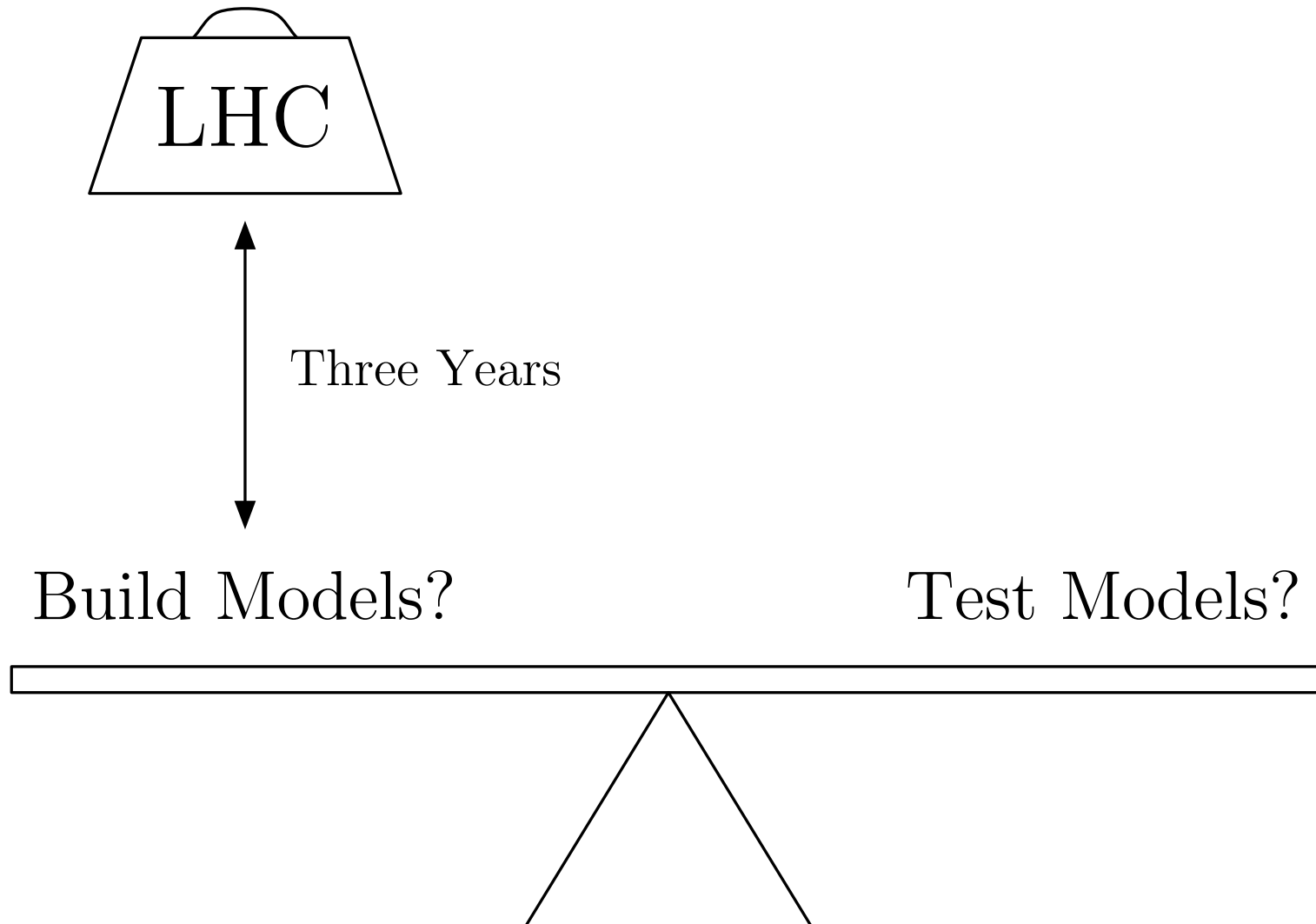


# Confronting a Degenerate MSSM at the LHC

Jesse Thaler

with N. Arkani-Hamed, G. Kane, and L.-T. Wang

# Particle Theory Circa 2005



# Models Still Worth Building

1. “Best SUSY Ever”

*e.g.*  $6 \times$  Nomura, *et al.*

2. Proof of Concept

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

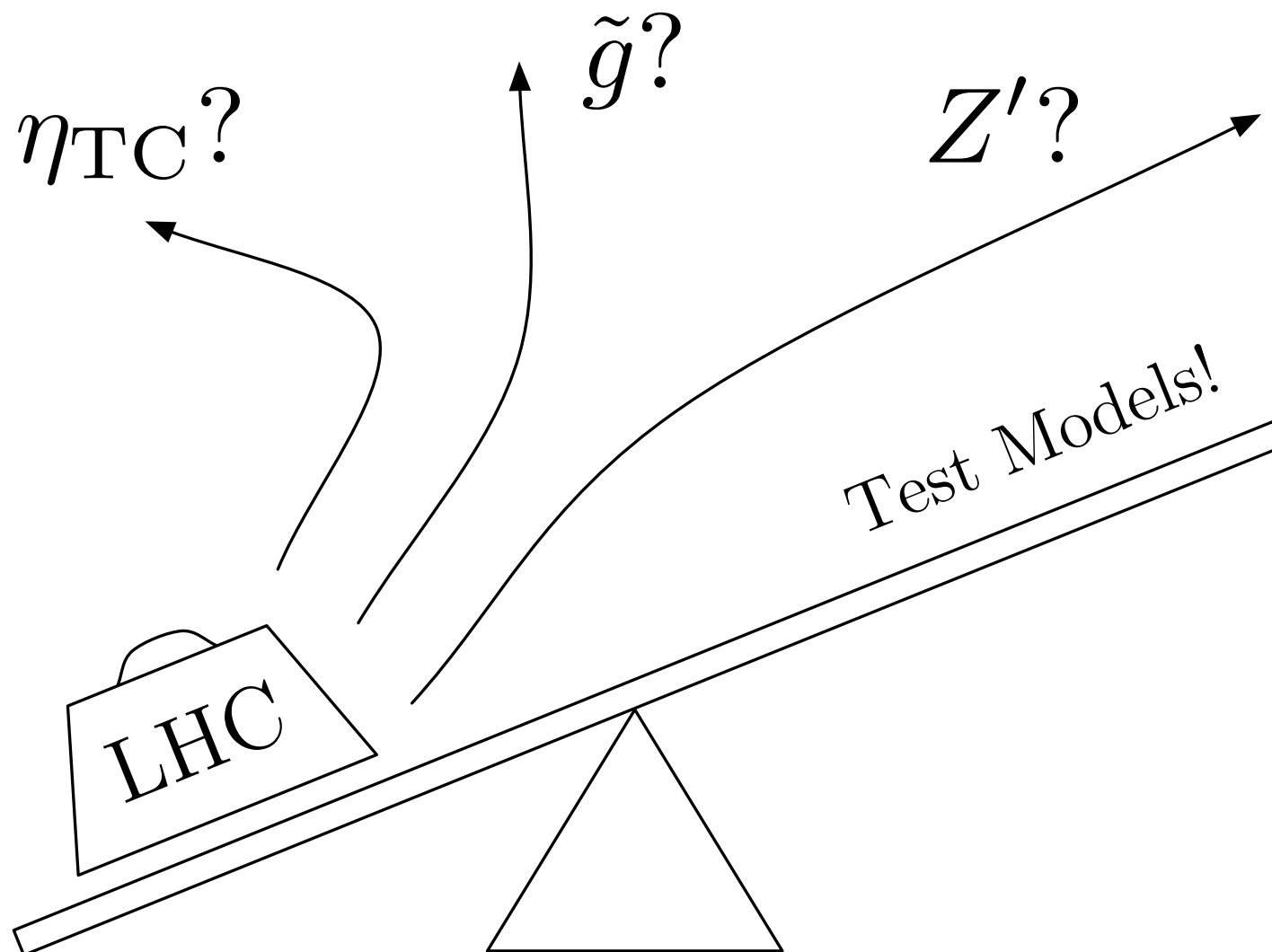
3. Unnatural Theories

*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?

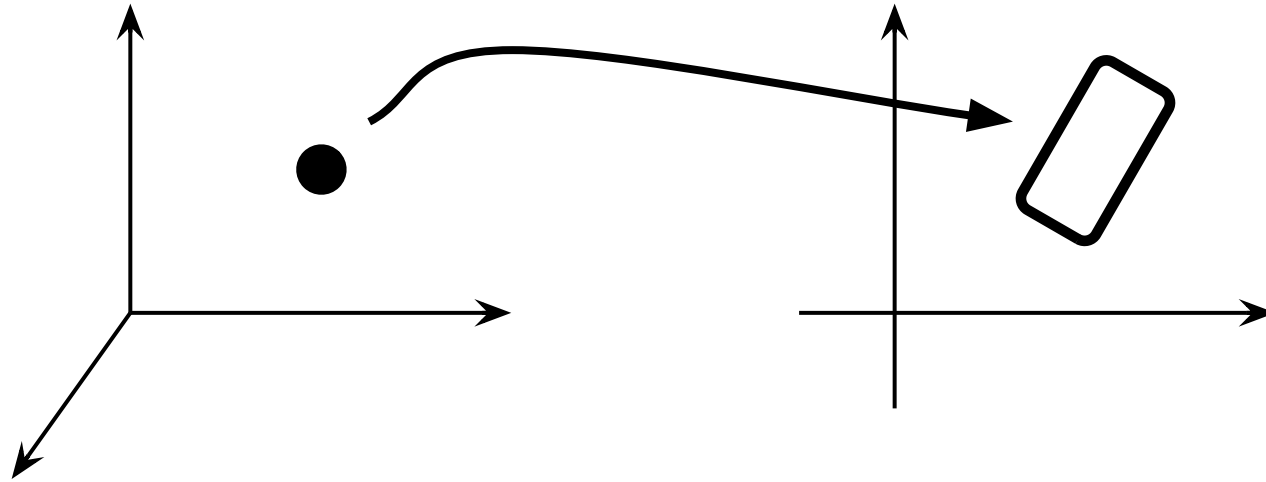
Weak Scale Dark Matter?

$\tan \beta$ ?

# Standard Method

Parameter Space

Signature Space



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

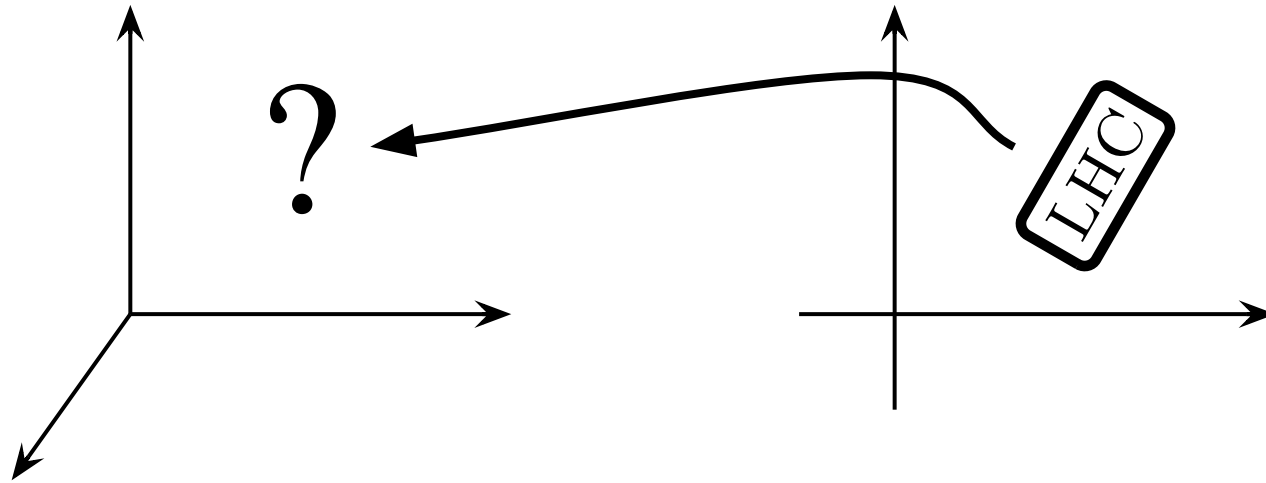
Reduced parameter set (mSUGRA, AMSB, GMSB):

Experimental Data  $\longrightarrow$  Precision Measurements

# The Inverse Problem

Parameter Space

Signature Space

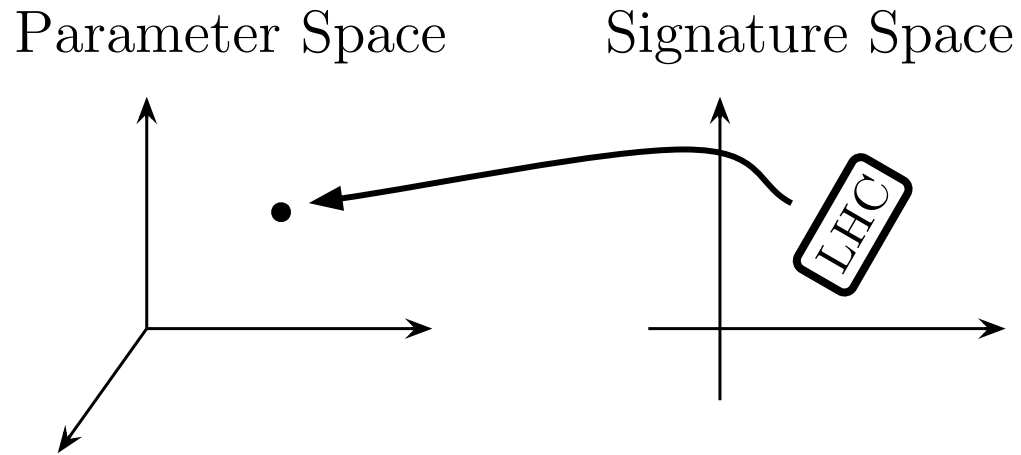


Much more interesting!

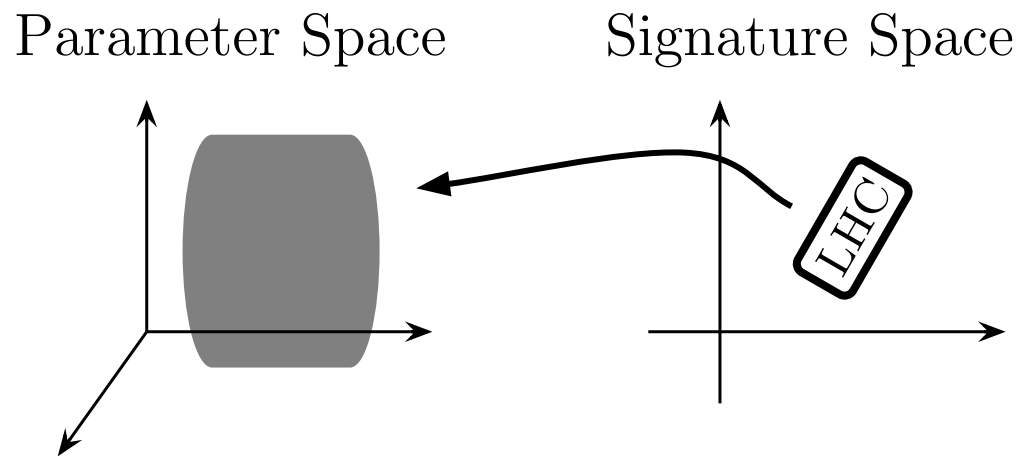
Data  $\xrightarrow{?}$  gaugino unification, dark matter, ...

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

# Best of all Possible Worlds



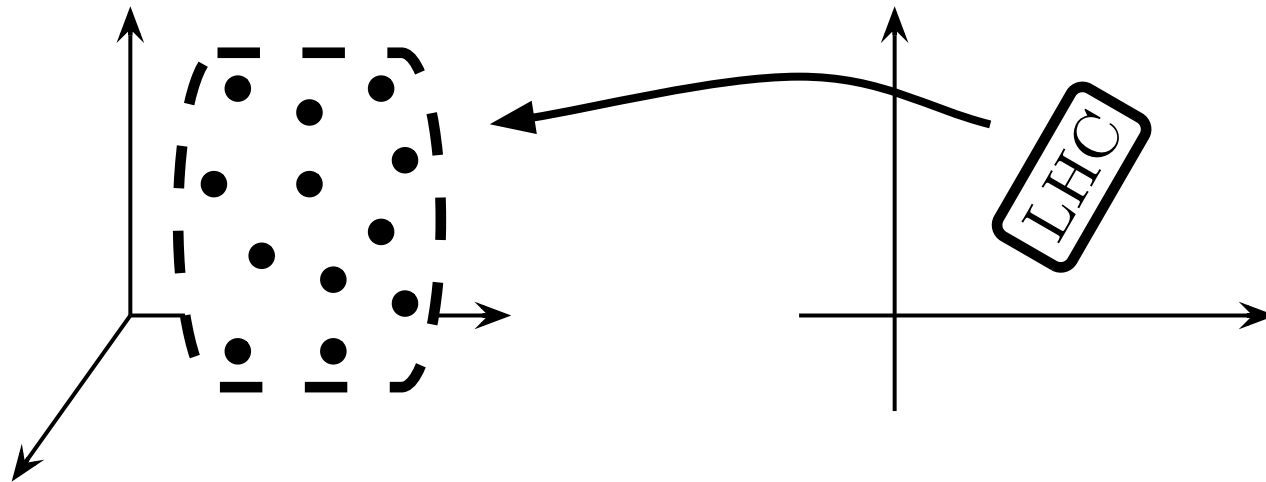
# Worst of all Possible Worlds



# Our Picture of the Inverse Map

Parameter Space

Signature Space



## Degeneracies!

Many small footprints in a large overall region.

# Advertisements

# Do LHC Experimentalists Need Our Help?

No {  
A 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:  $\Lambda_{\text{higher dim}} \sim 5 - 10 \text{ TeV}$

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:

Colored Particles  $>$  Electroweak Particles

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

## So What?

LHC is supposed to be a “discovery” machine...

Eventually, a next generation collider (ILC?)...

But model builders are impatient!

“What will we know  
after one year?”

# Concerns About Uniqueness

Sfitter, Fittino: Observables  $\rightarrow$  SUSY parameters

Without ILC observables, algorithms don't coverge.

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.

# The Inverse Problem: LHC Olympics

Competition as motivation for interpreting data.

The Zeroth LHC Olympics: CERN, July 2005

University of Michigan Blackbox

(Partially Analyzed by University of Washington)

The First LHC Olympics: CERN, January 2006

Three New Blackboxes (Harvard, UMich, UWash)

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

**Back to the Inverse Problem...**

# The Inverse Problem: A Statistical Approach

LHC Data  $\rightarrow$  Theoretical Models

Too many models, impossible to analyze them all!

But, if mapping is not one-to-one, all we need is one degeneracy to prove so.

In fact, “birthday problem” gives us a simple statistical technique to measure the degree of one-to-one-ness!

# Outline: The Degenerate MSSM

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?

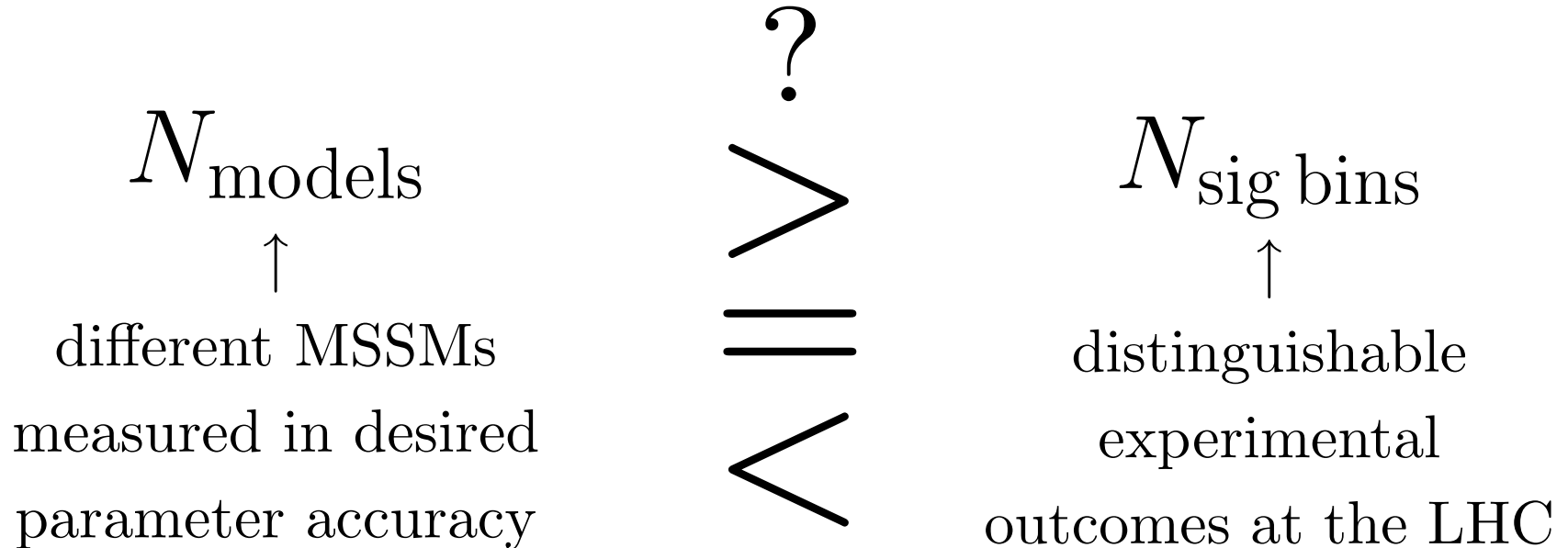
1153 LHC Observables

4. What kind of degeneracies are there?

Flippers, Sliders, and Squeezers

# Statistics of the MSSM

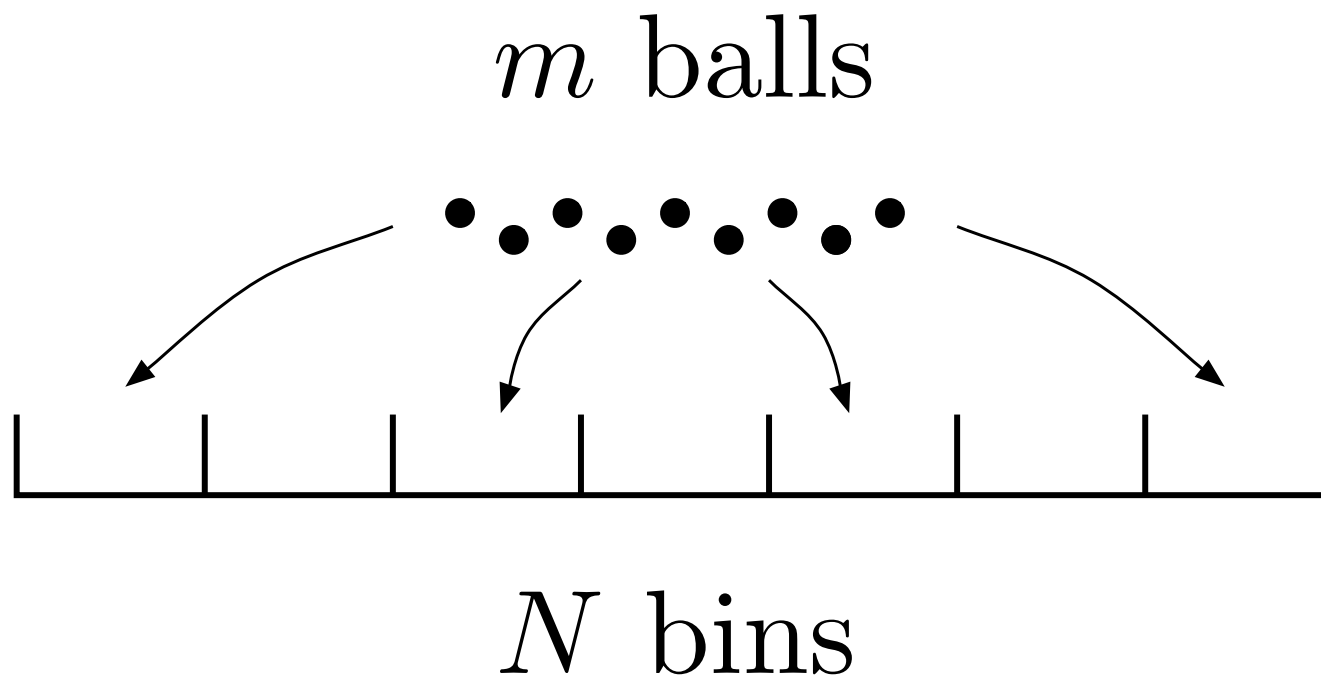
# Simple Statistical Question



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

Guaranteed degeneracies at the LHC.

# How to Count Degeneracies



$$\begin{array}{c} \bullet \quad \bullet \\ \swarrow \quad \searrow \\ \boxed{\phantom{\bullet \quad \bullet}} \end{array} = \frac{1}{2!} \frac{m^2}{N}$$
$$\begin{array}{c} \bullet \\ \downarrow \\ \bullet \quad \bullet \\ \swarrow \quad \searrow \\ \boxed{\phantom{\bullet \quad \bullet}} \end{array} = \frac{1}{3!} \frac{m^3}{N^2}$$

## As of Last Night...

We have simulated  $m = 39137$  MSSMs (and counting...)

Number of pairs with matching LHC signatures = 2120

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

$$N_{\text{models}} \sim 10^8$$

Probability of choosing correct model at LHC = 1%

Equivalently, for every model, there are 99 other (well motivated?) models with the same LHC signatures.

# More Realistically

Demonic Bins:

$x$  of models  $\mapsto \lambda$  of signature bins

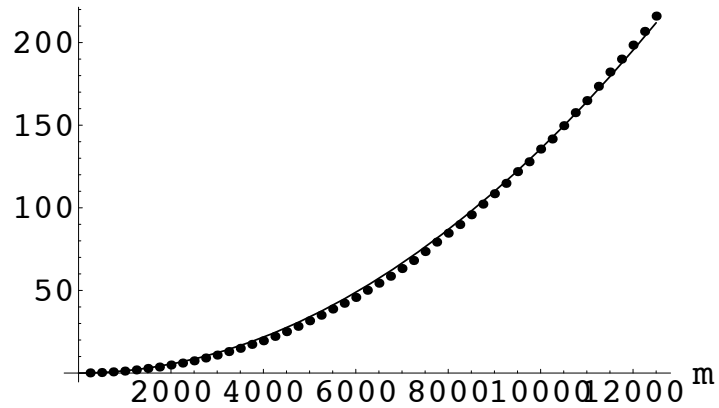
Normal Bins:

$1 - x$  of models  $\mapsto 1 - \lambda$  of signature bins

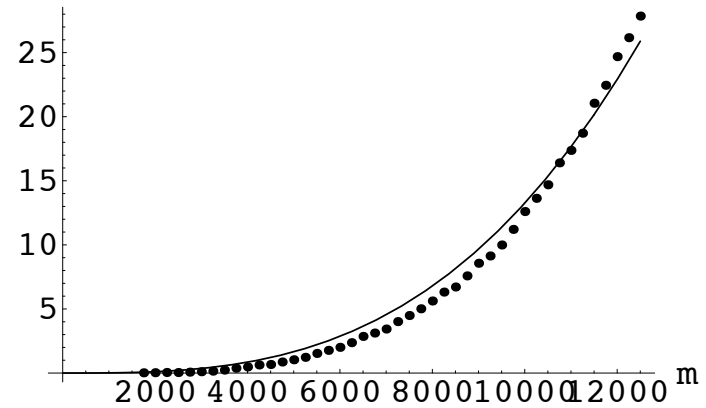
$$k\text{-tuples} = \frac{m^k}{k!N^{k-1}} \left( \frac{x^k}{\lambda^{k-1}} + \frac{(1-x)^k}{(1-\lambda)^{k-1}} \right)$$

$$N_{\text{models}} = 775000$$

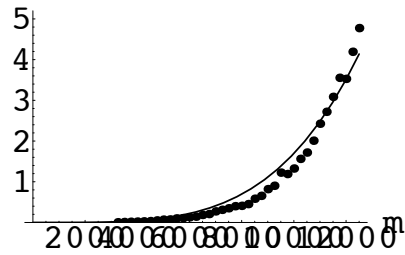
Doubles



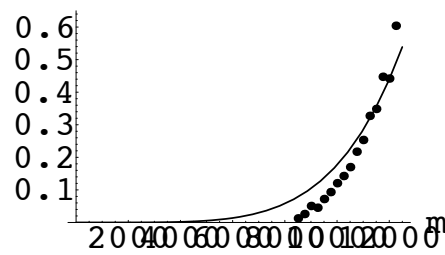
Triples



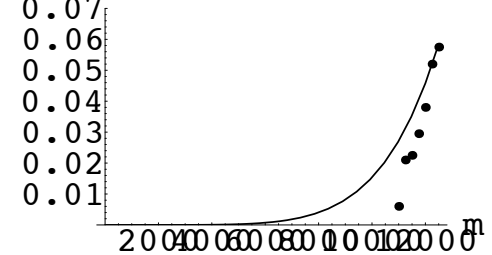
Quadruples



Quintuples



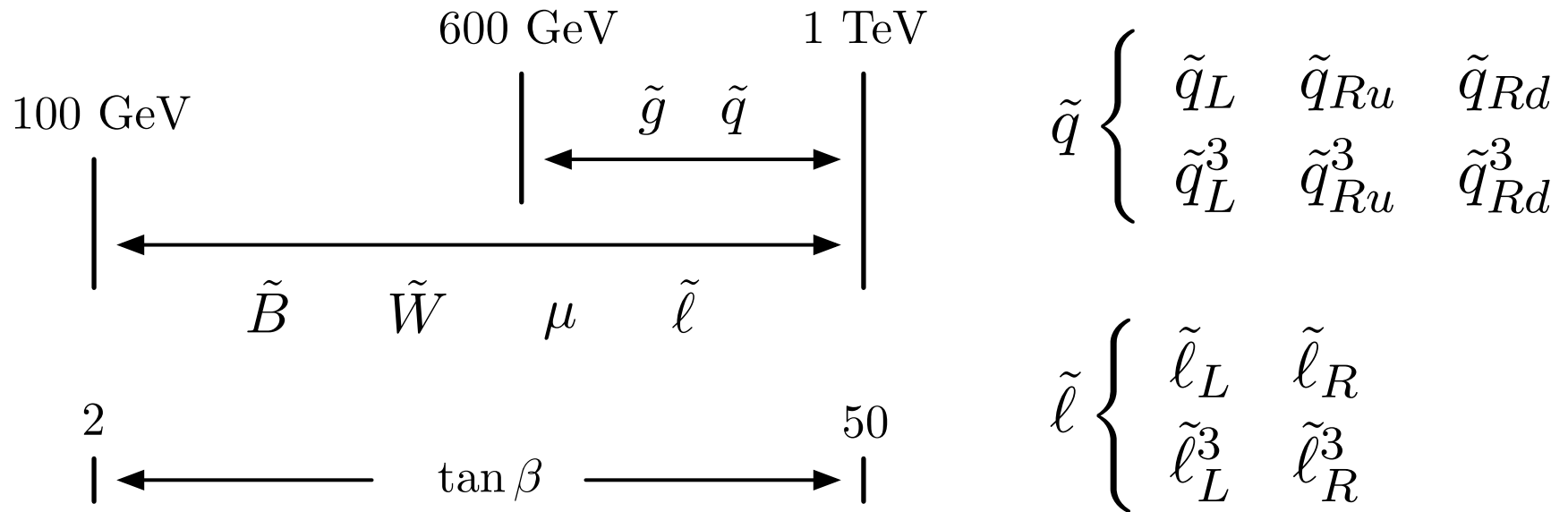
Sextuples



2.8% of models map to 0.07% of signature bins

**What Kind of Models?**

# Choosing 39,137 MSSMs



Constraints: Nothing more than 50 GeV decoupled

Max Colored > Max Electroweakino > Max Slepton

No slepton LSP.

# Some Peculiarities

Non-decoupling constraint tends to decouple particles!

Very rarely three light inos.

Very rarely cascade decays ino-slepton-ino.

Most leptons in final states from  $W$  and  $Z$ .

Future run with guaranteed cascade decays.

(Is the degeneracy story different when the spectra looks more like mSUGRA, AMSB, GMSB?)

# Generating 39,137 MSSMs

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

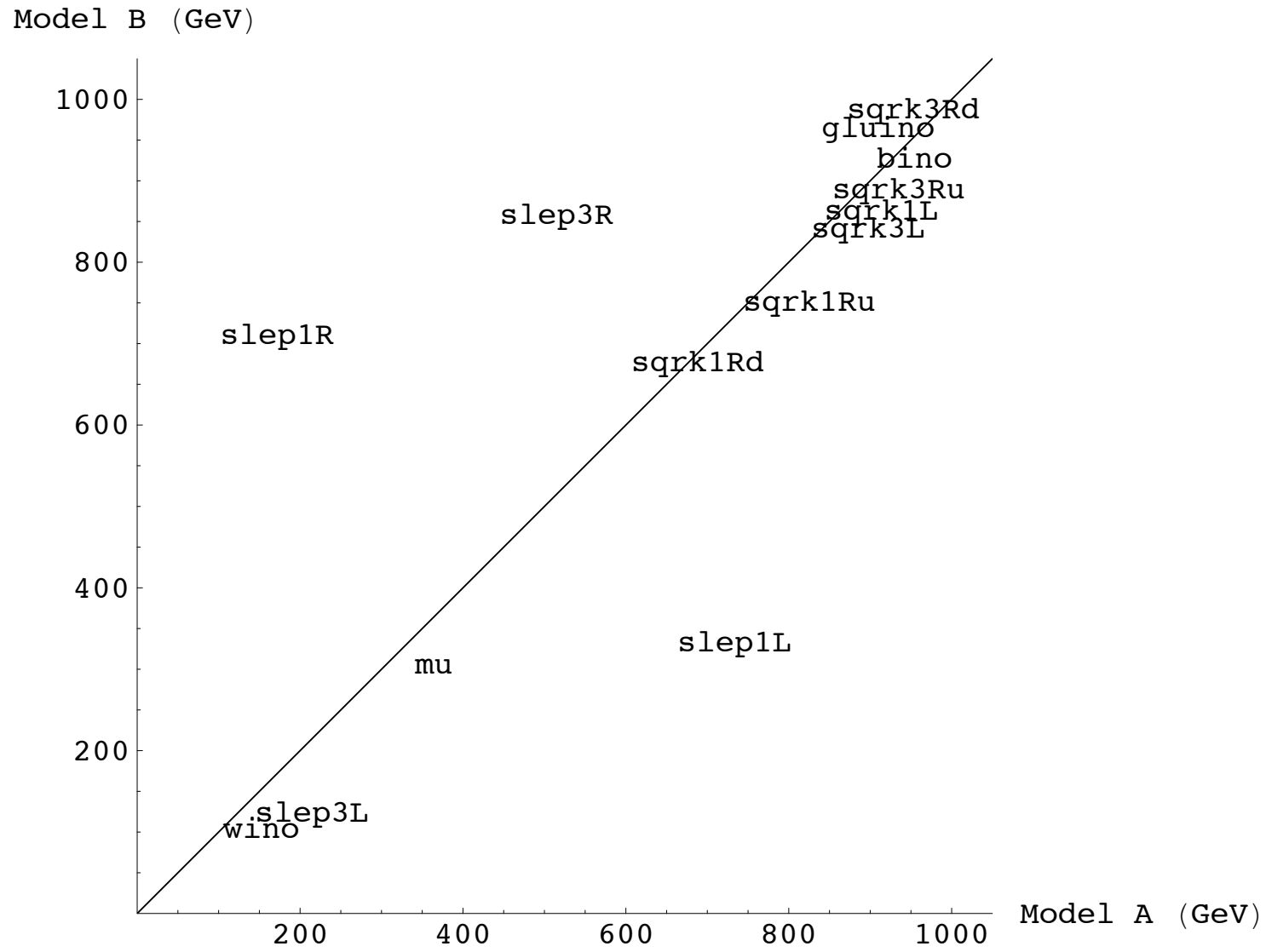
1 Model / CPU / hr

PYTHIA → 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 Pair: 2005 vs. 32444



**What Kind of Data?**

# LHC Observables

Triggers:  $\cancel{E}_T > 125 \text{ GeV}$

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

Categorize all events by the number of:

j, bj, e,  $\mu$ , hadronic  $\tau$ ,  $\gamma$

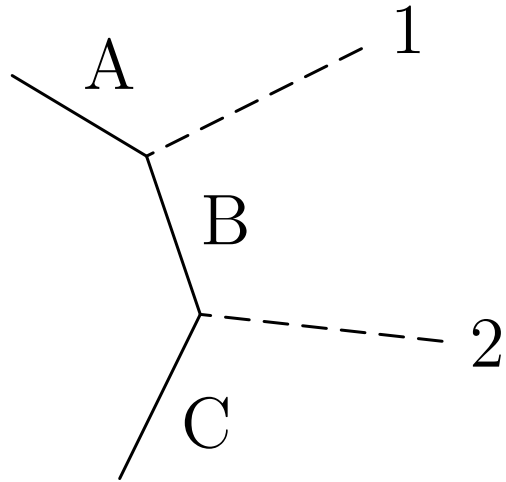
Count NEV, everything else ratios.

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

# Kinematic Histograms

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

Edges/endpoints of distributions.



Offshell B (Endpoint):

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

Onshell B (Edge):

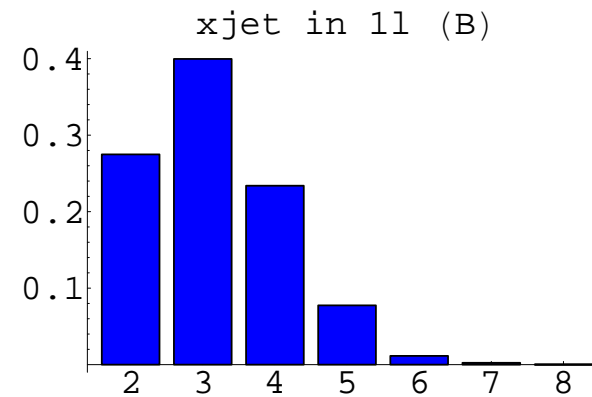
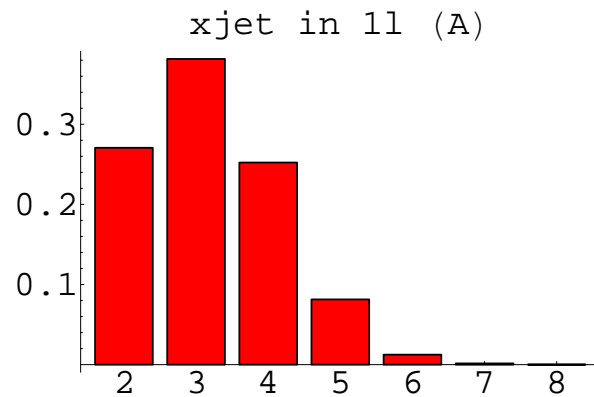
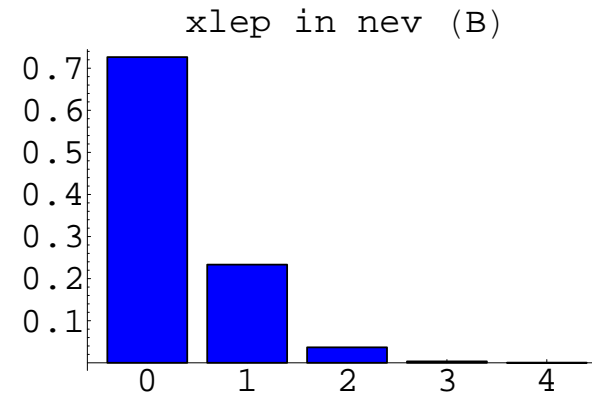
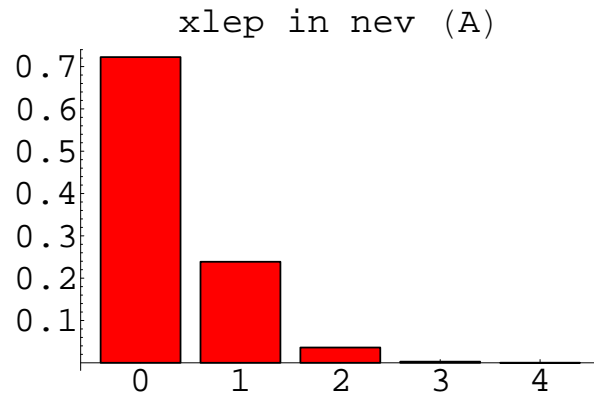
$$m_{\text{inv}}^{12} = \sqrt{(m_A^2 - m_B^2)(m_B^2 - m_C^2)/m_B^2}$$

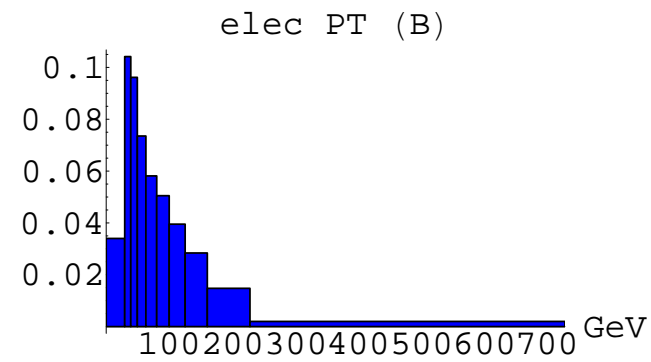
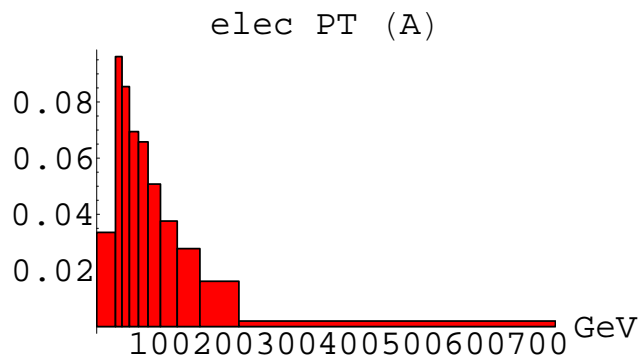
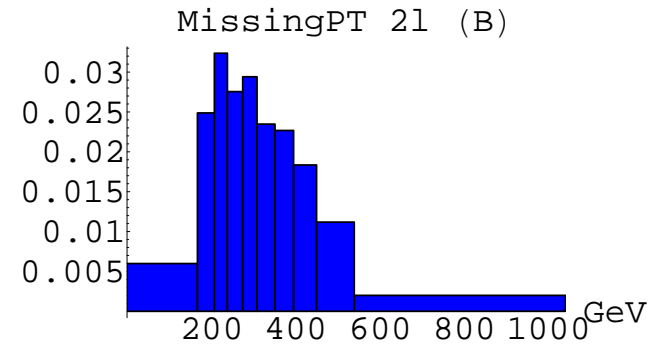
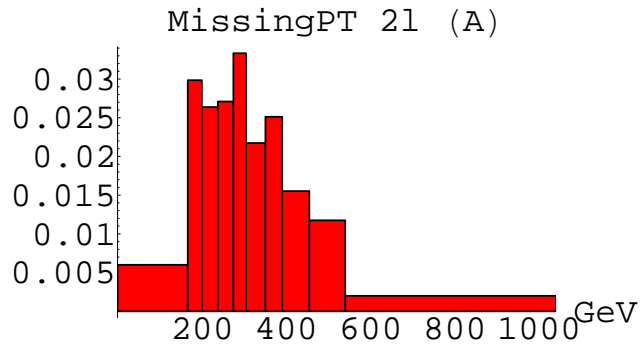
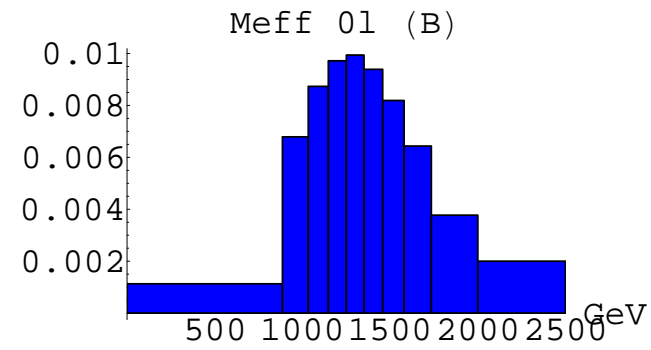
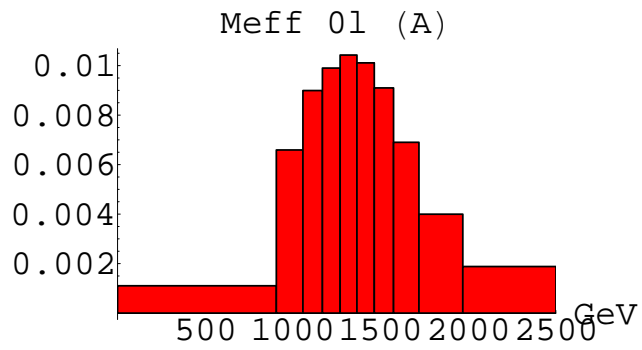
Distributions in quantiles. (Deciles,  $m_{\text{eff}}$ ; 20-tiles,  $m_{\text{inv}}$ )

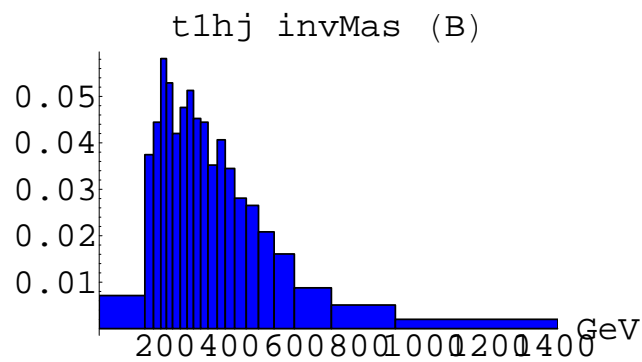
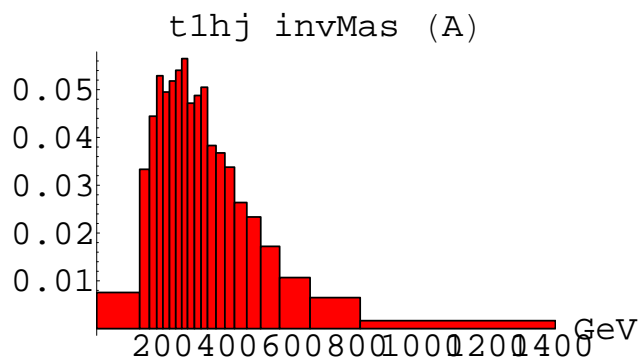
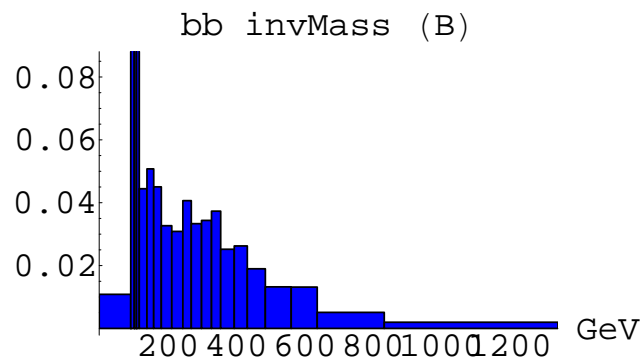
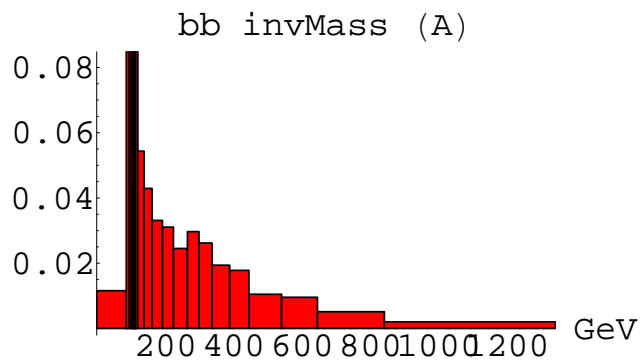
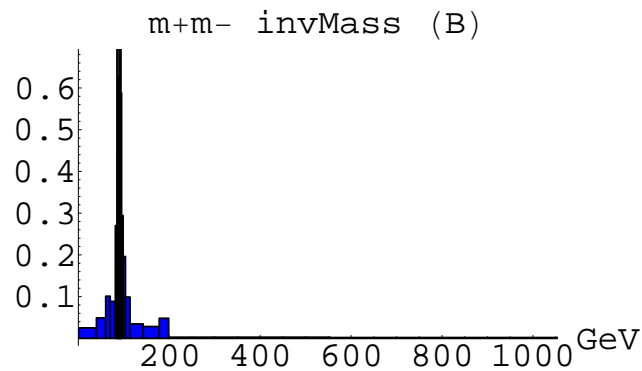
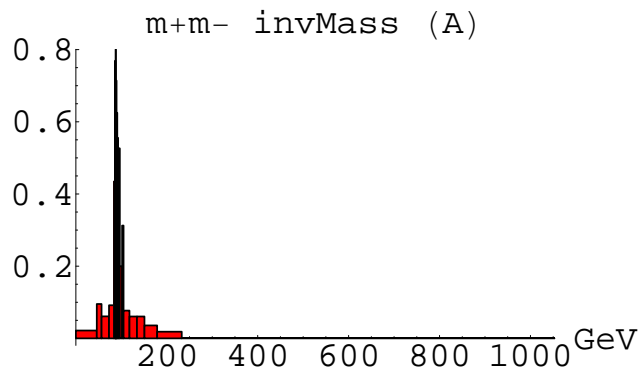
Match distribution, not just endpoint/edge.

# Typical Data: 2005 vs. 32444

$$NEV_A = 30253, \quad NEV_B = 32251$$







# Understanding Degeneracies

# Parameter vs. Signature Distance

Pairwise comparison.

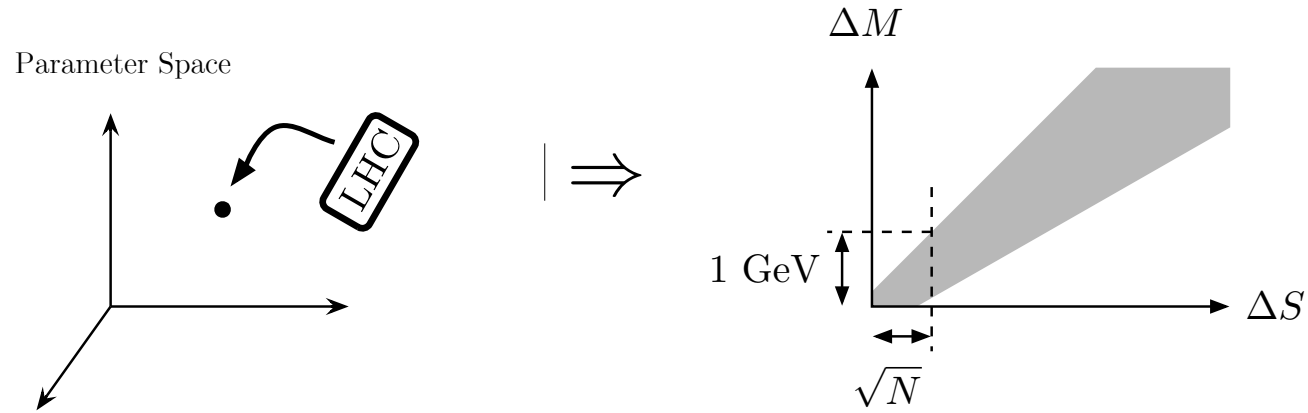
$$\Delta S = \tilde{\chi}_{\text{sig}}^2 = \frac{1}{n_{\text{sig}}} \sum_i \left( \frac{\Delta s_i}{\sigma_i} \right)^2$$

$$\Delta M = \text{“}\chi_{\text{para}}^2\text{”} = \sum_j \Delta m_j$$

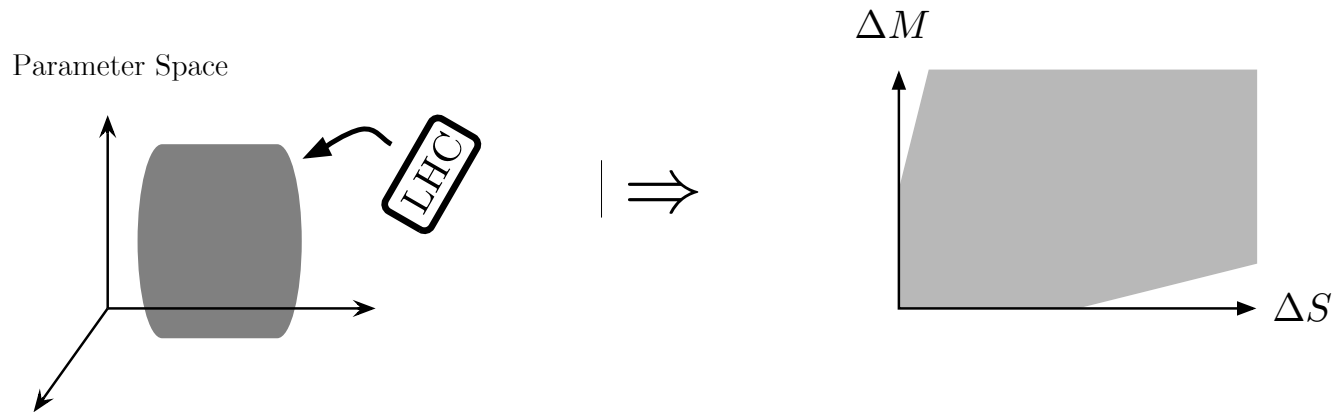
Ignore a signature if for either model, signature is consistent with zero.

Same model over and over again:  $\tilde{\chi}_{\text{sig}}^2 < 0.3$ .

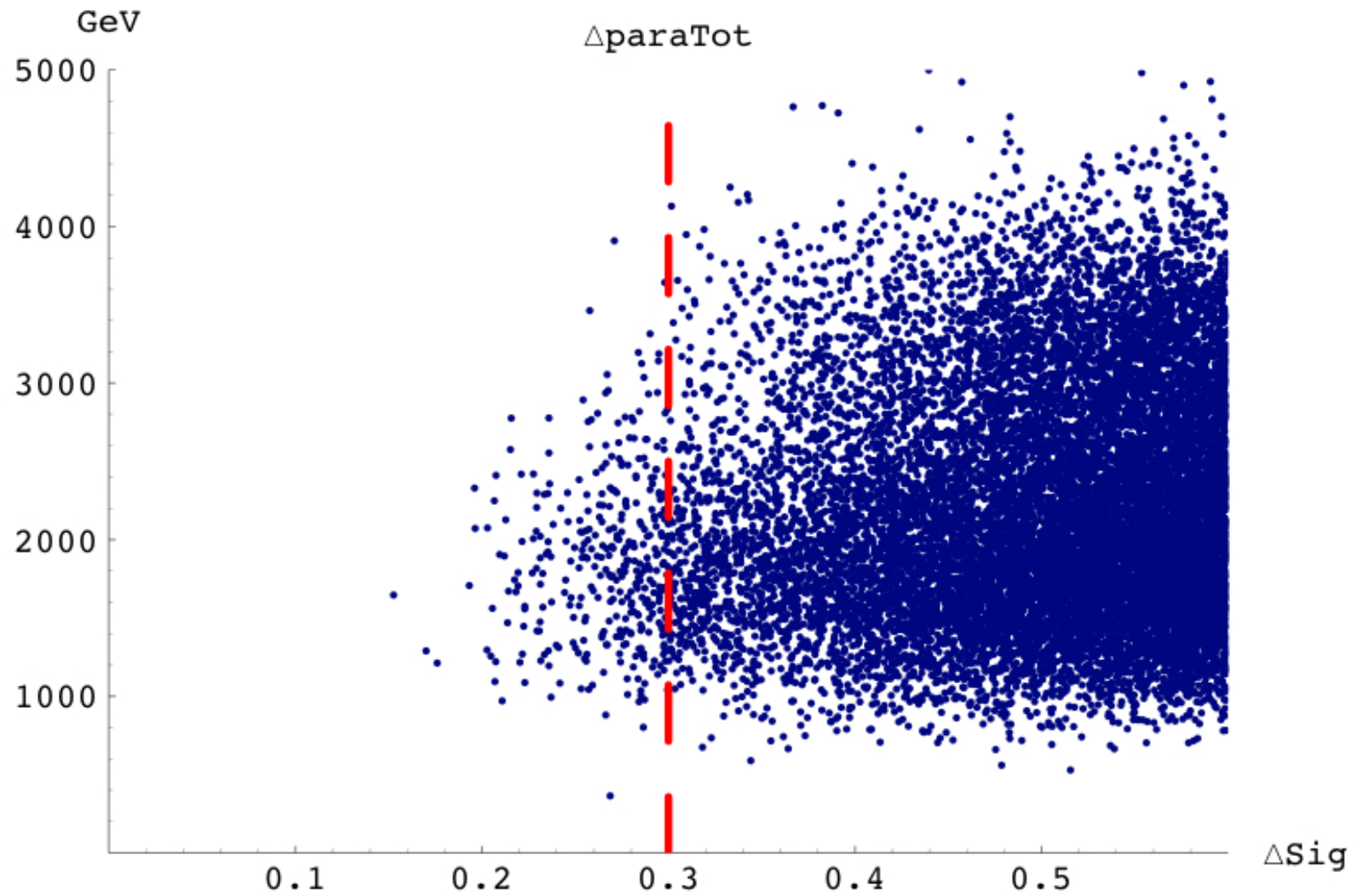
# Best of all Possible Worlds



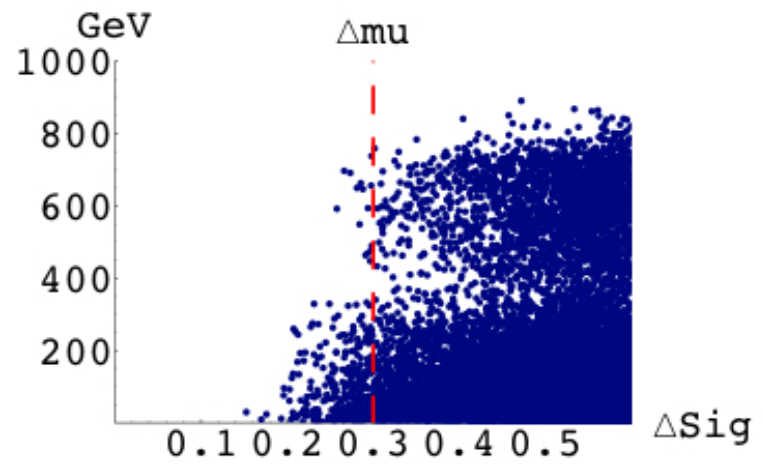
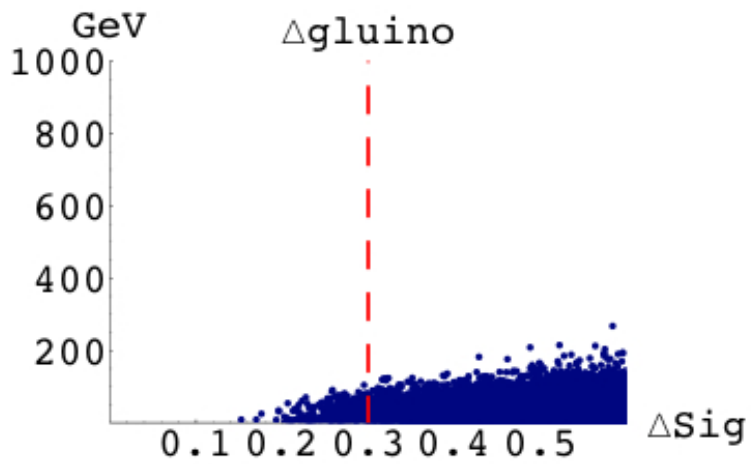
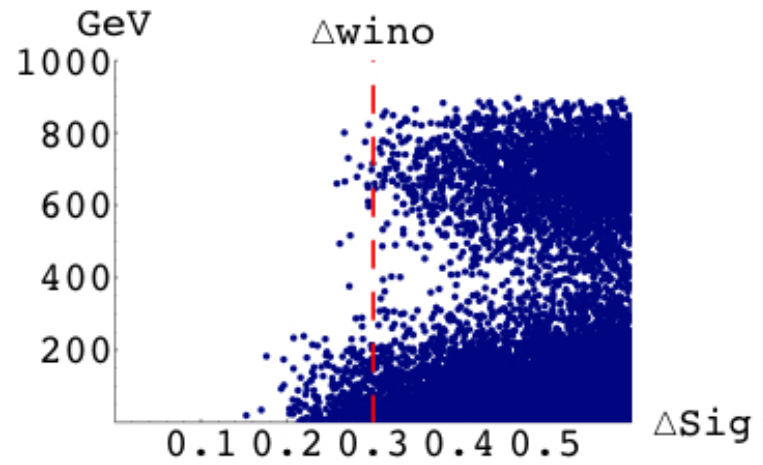
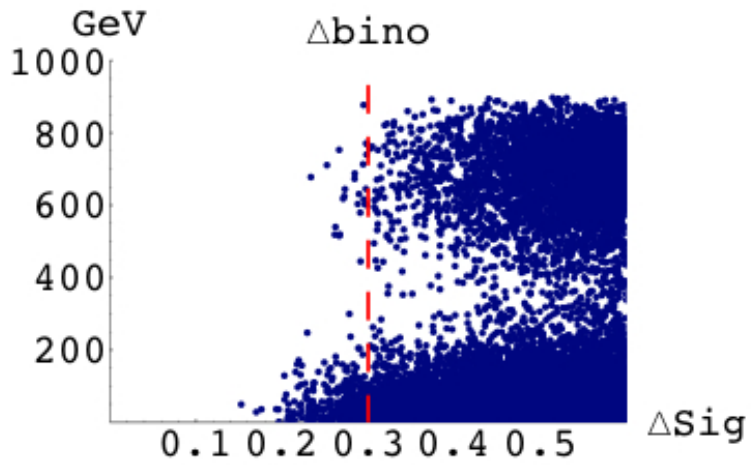
# Worst of all Possible Worlds



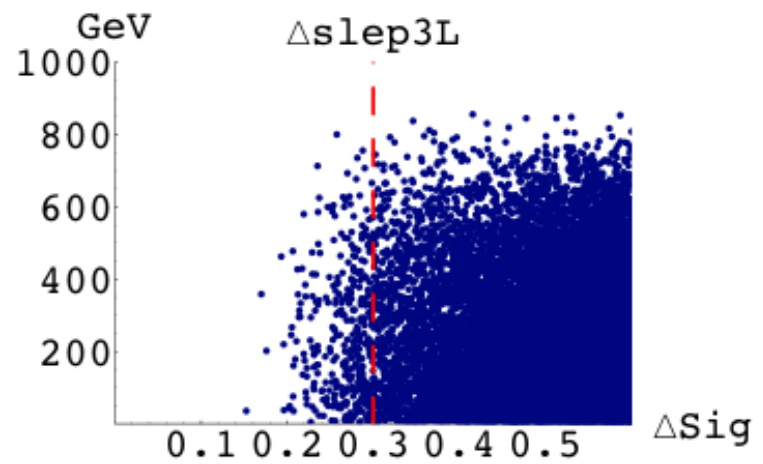
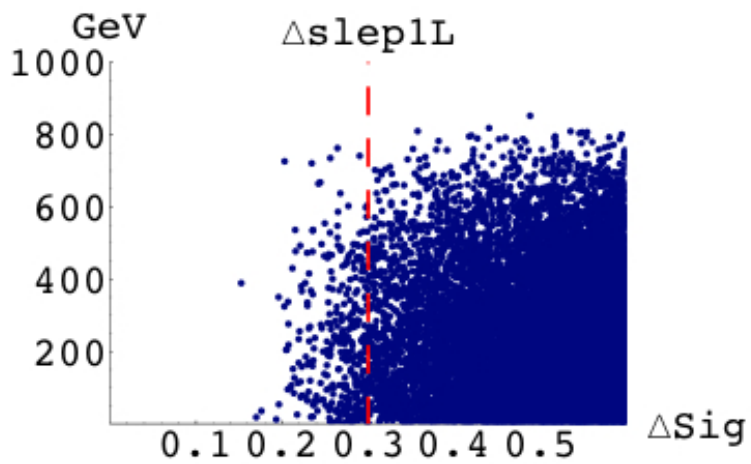
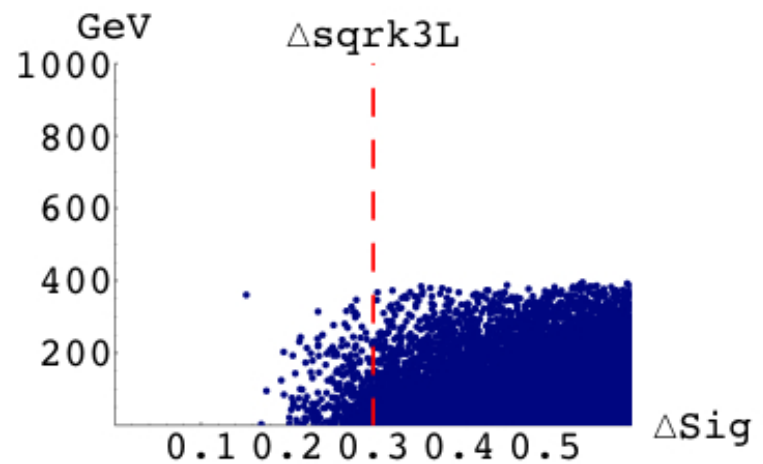
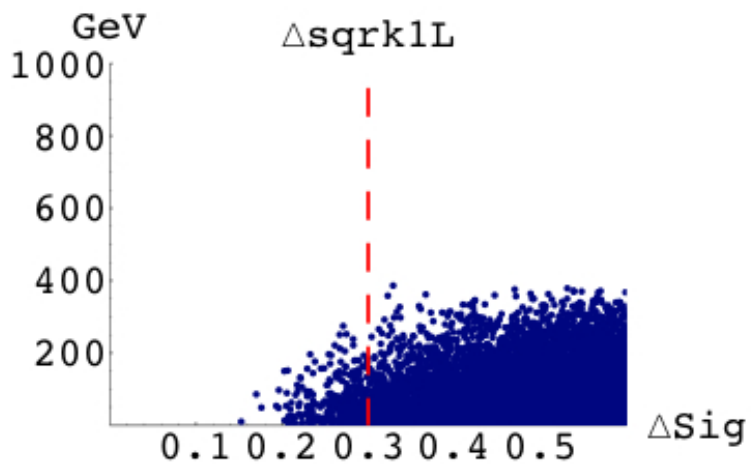
# Total Parameter Distance



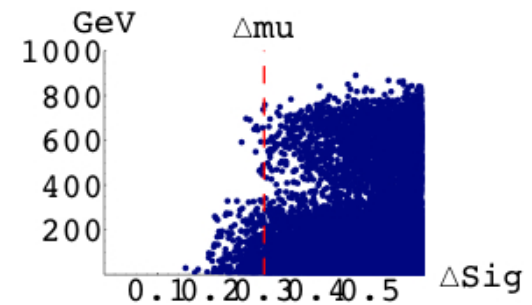
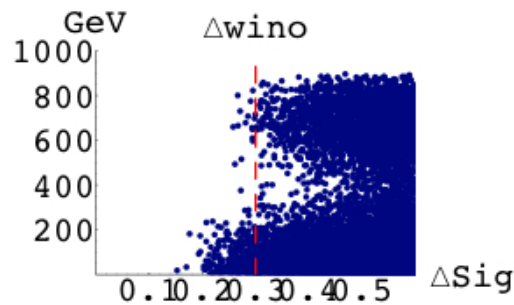
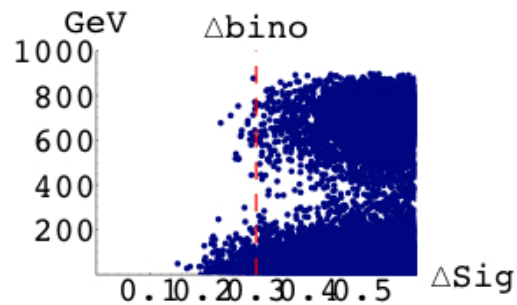
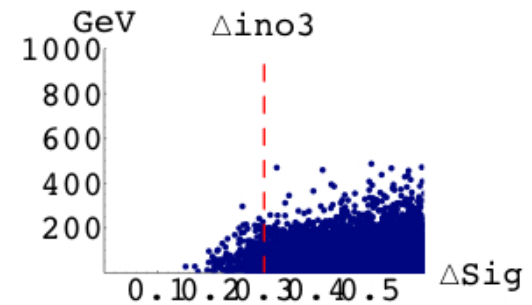
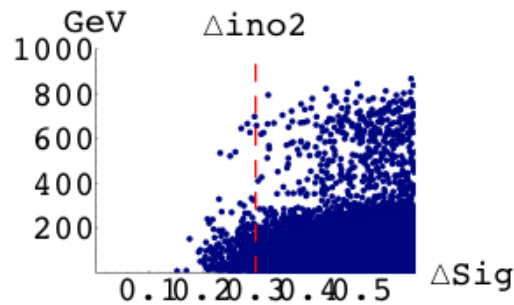
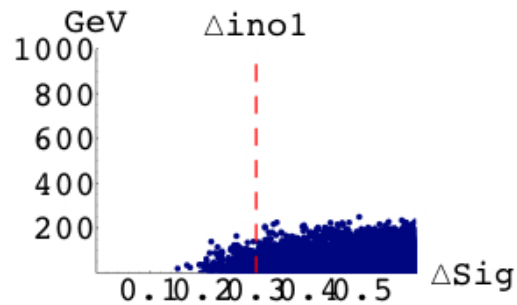
# Inos



# Sfermions



# Eigenvalues Not Eigenvectors



Evidence for discrete choices for ino degeneracies, not large flat directions. (Similar story for squarks, but not sleptons.)

# Types of Degeneracies

We have 39137 models, many degenerate pairs.

Open Question:

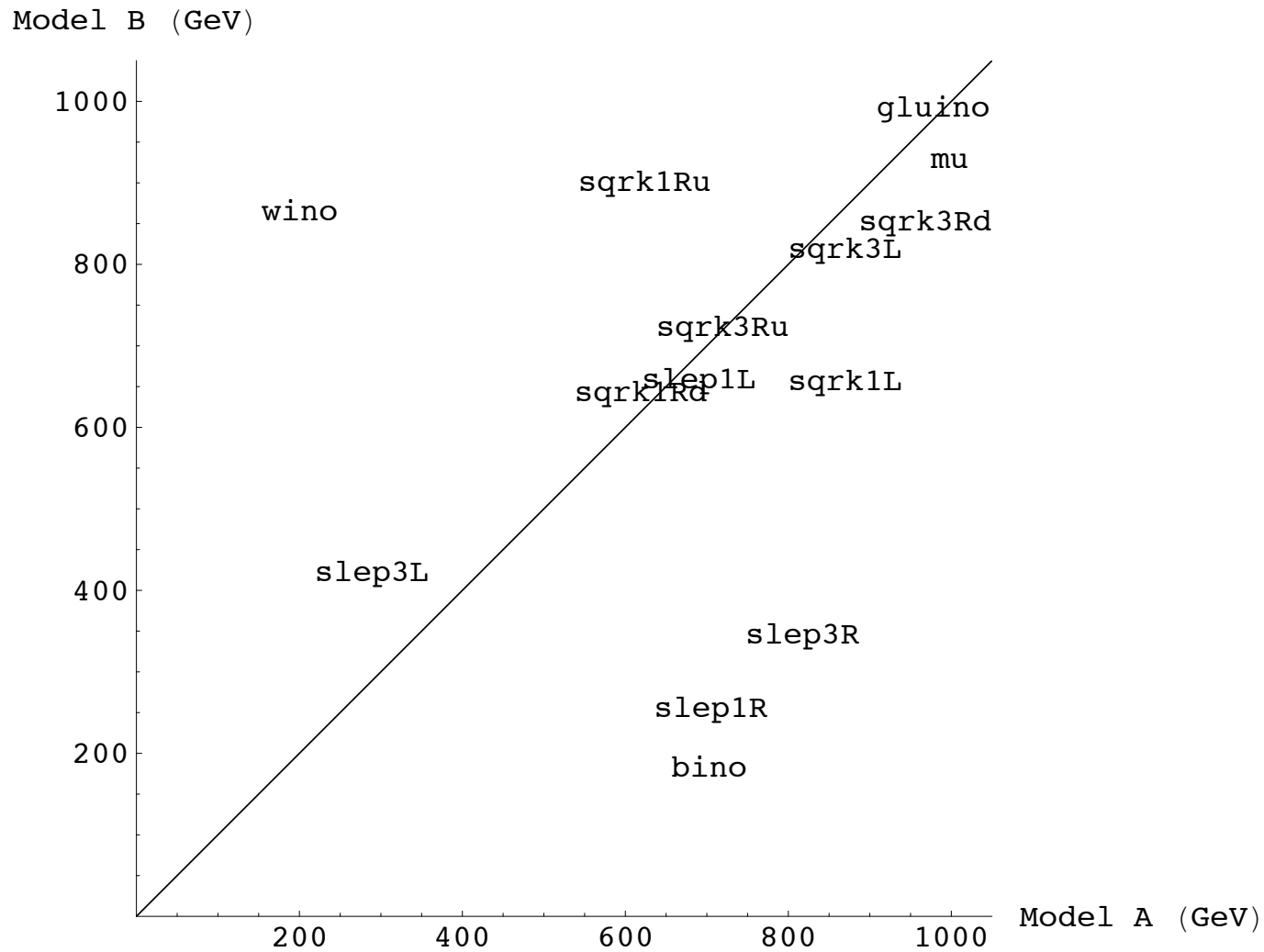
Fundamentally indistinguishable at the LHC?

New clever observables?

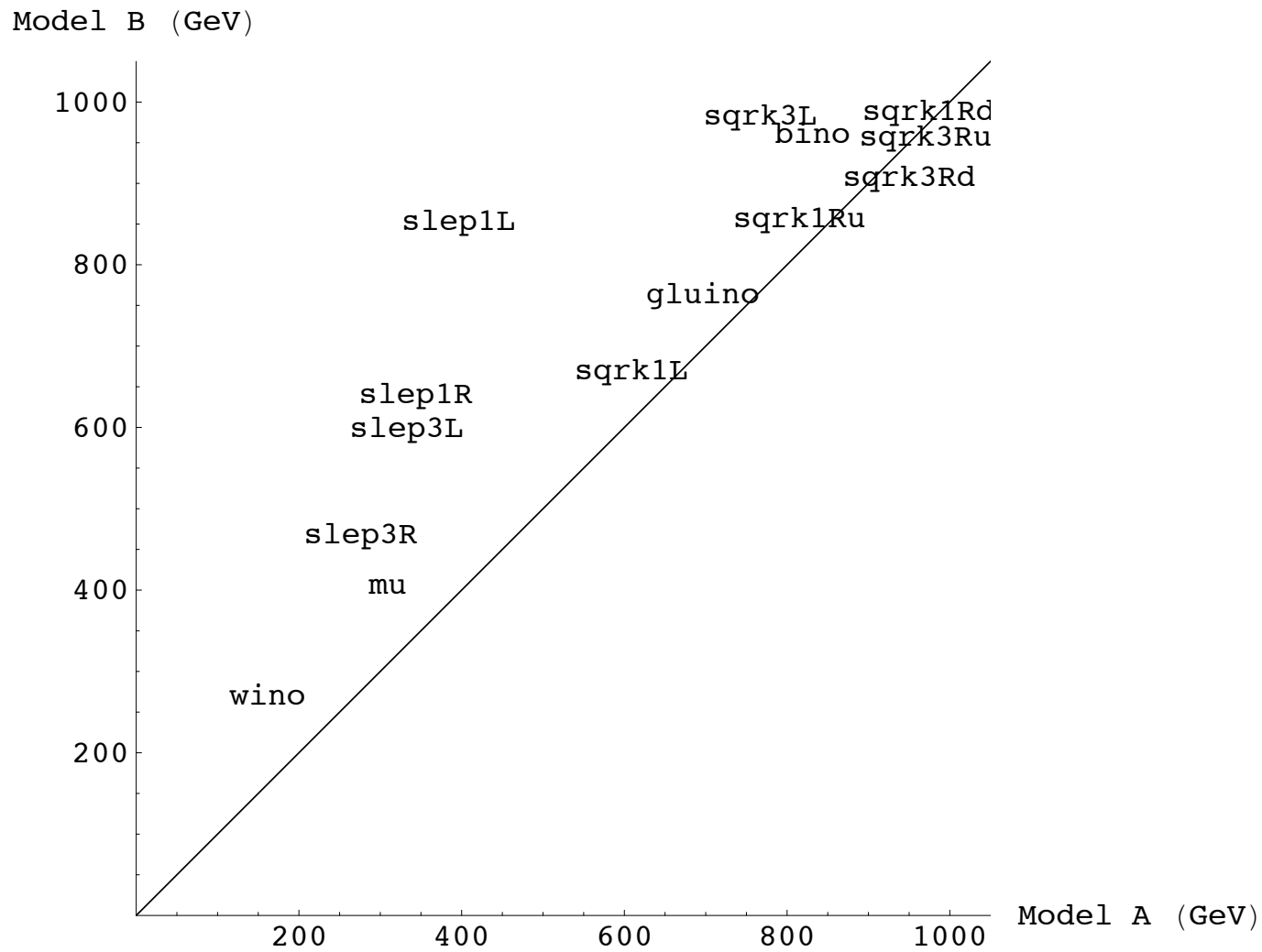
First Step: Catalog...

Electroweakino Sector: Flippers, Sliders, and Squeezers

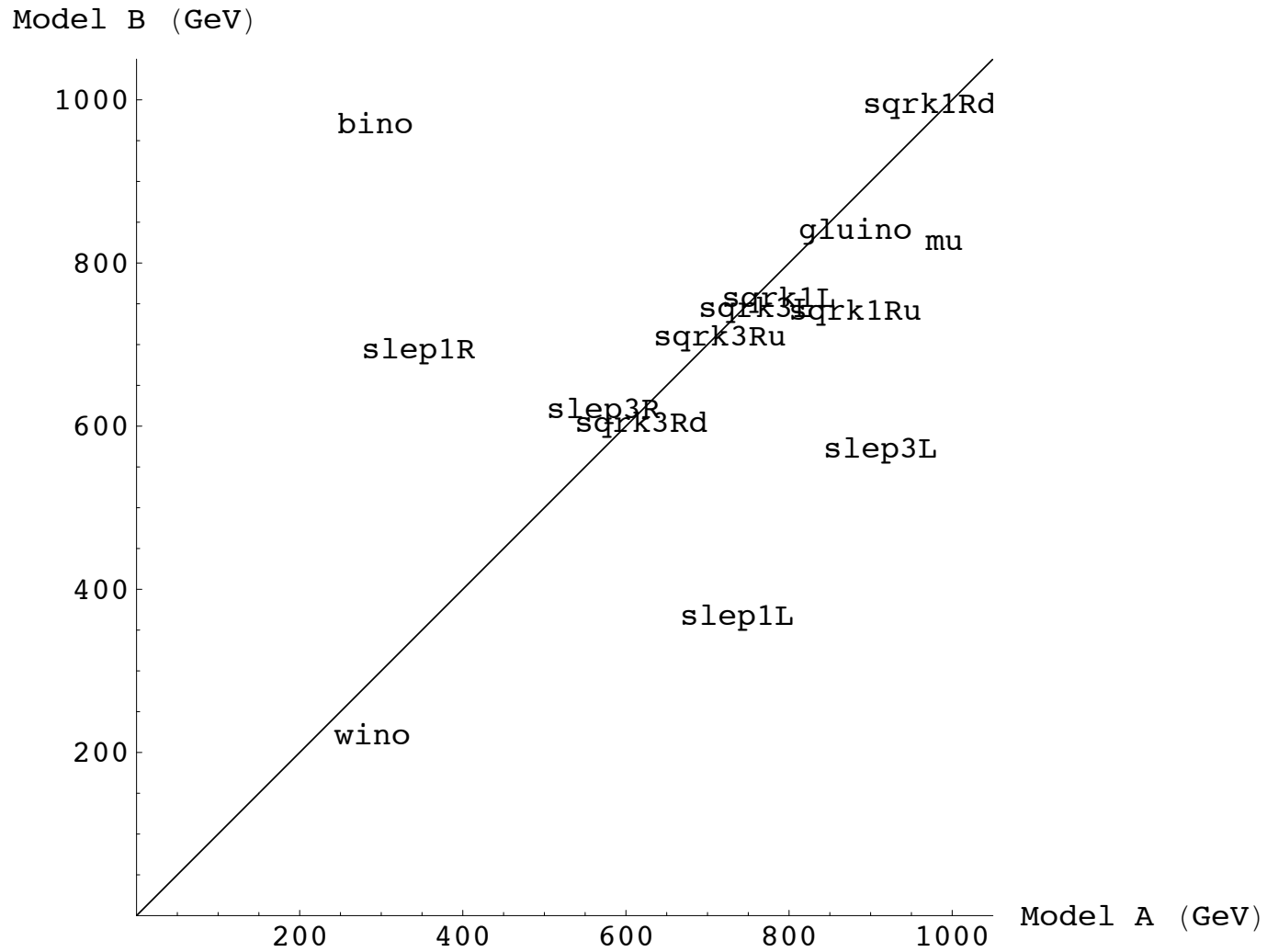
# Flippers: 17653 vs. 20026



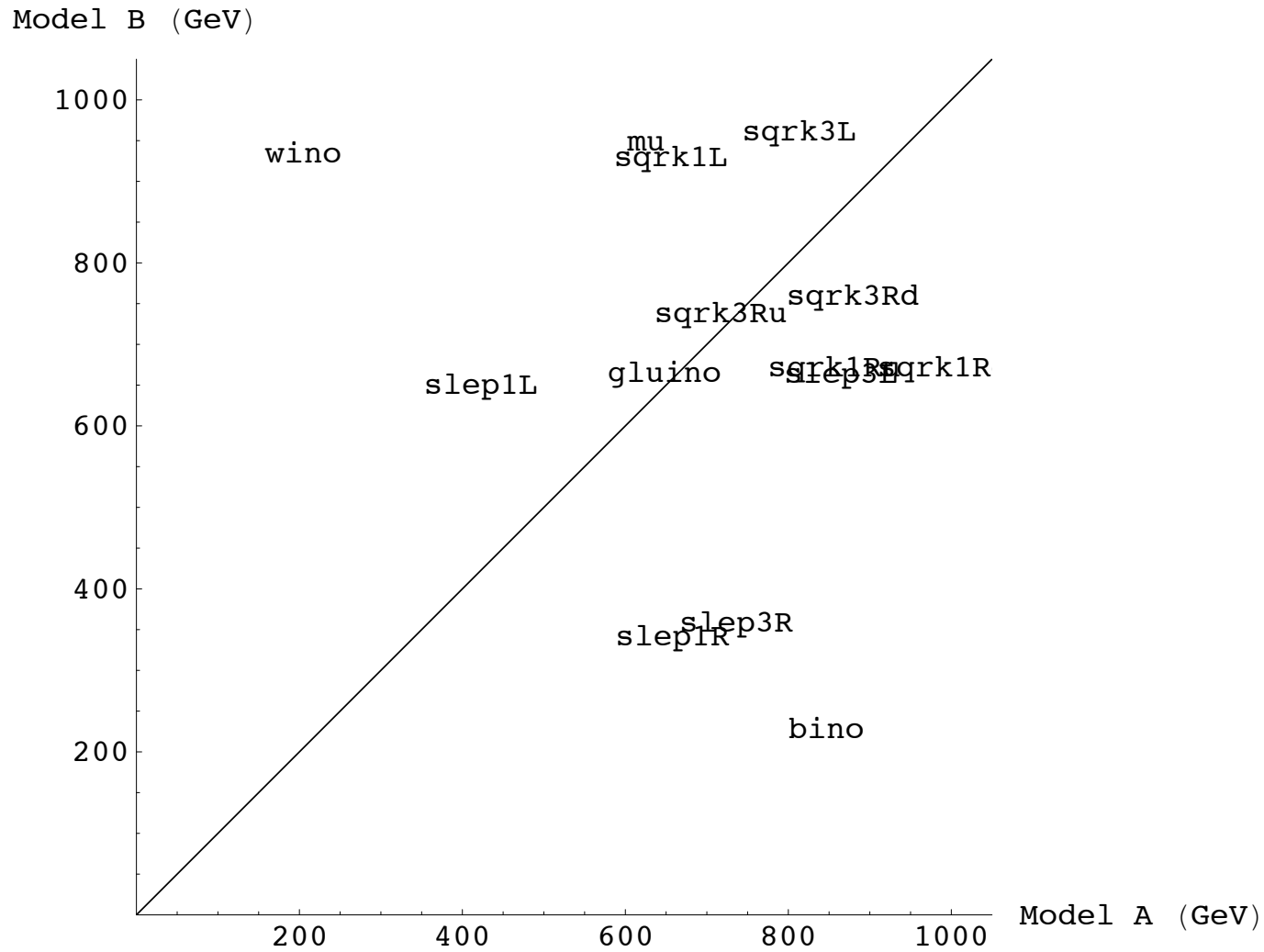
# Sliders: 24230 vs. 25628



# Squeezers: 24119 vs. 35520

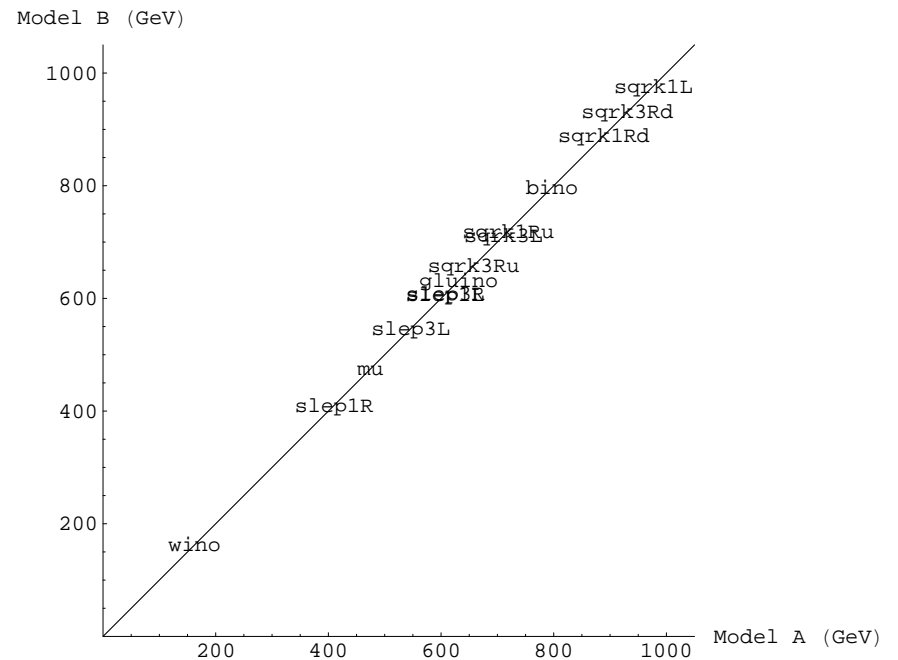
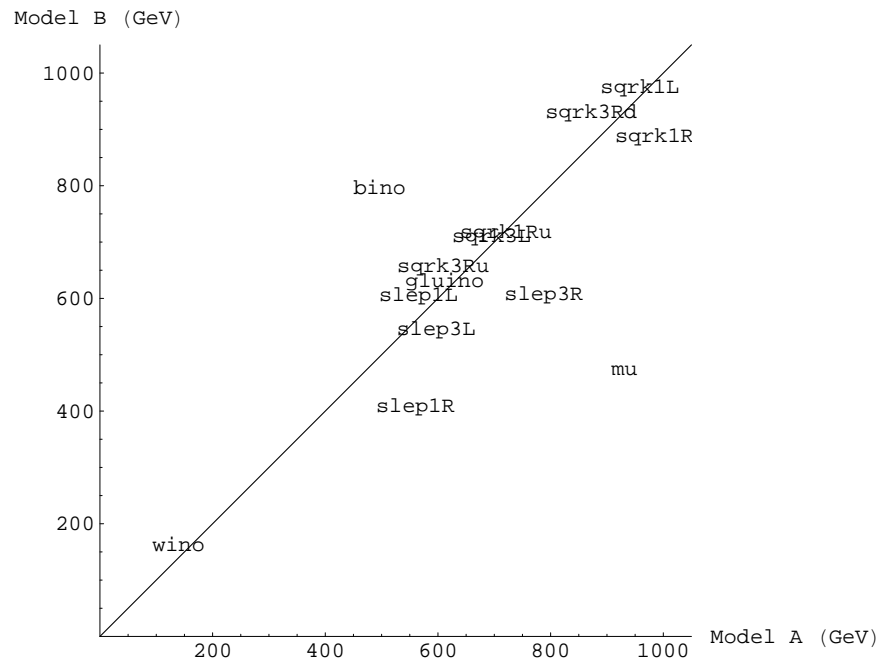


# And So On...: 17544 vs. 27775

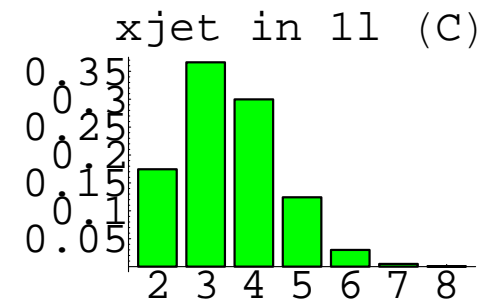
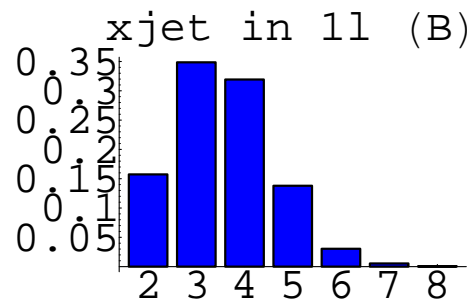
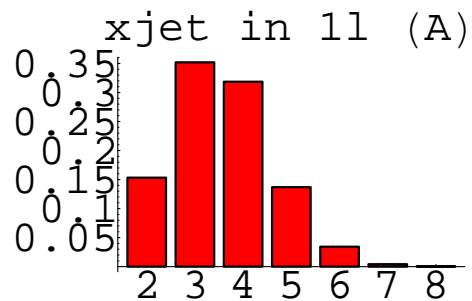
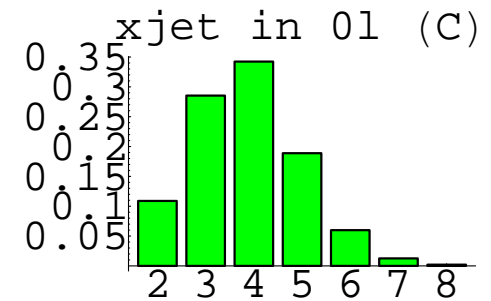
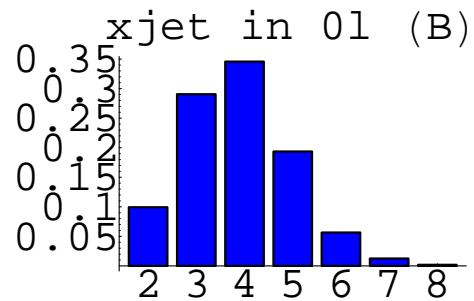
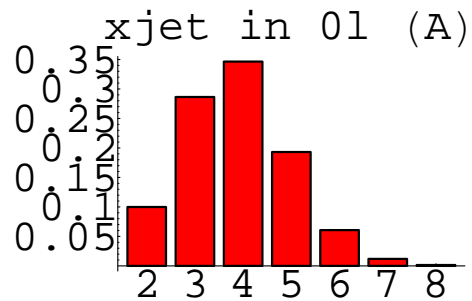
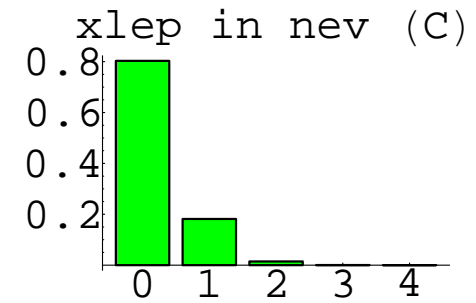
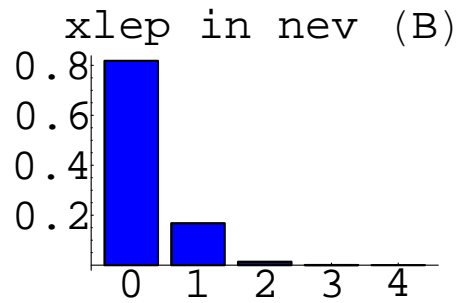
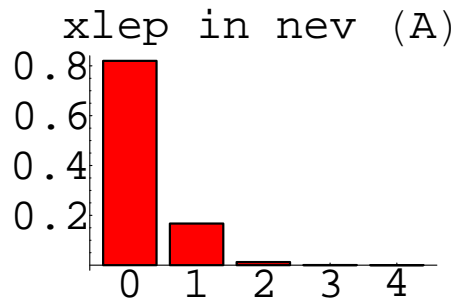


# “Are There Really Degeneracies?”

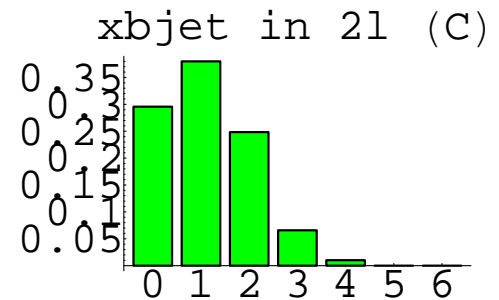
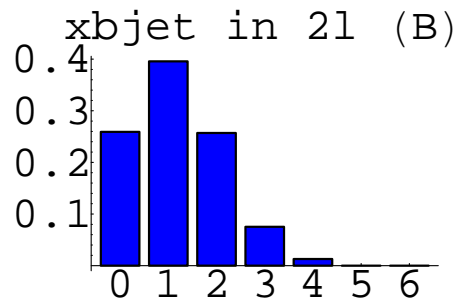
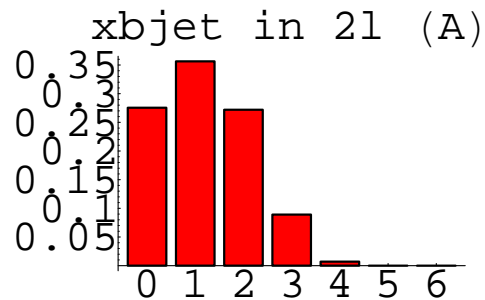
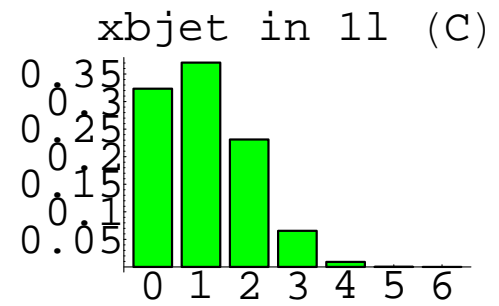
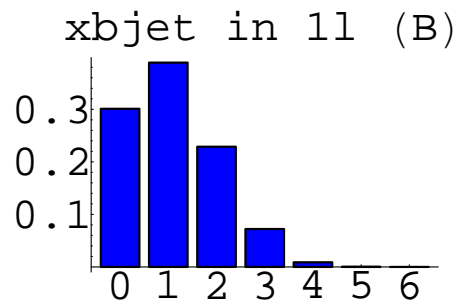
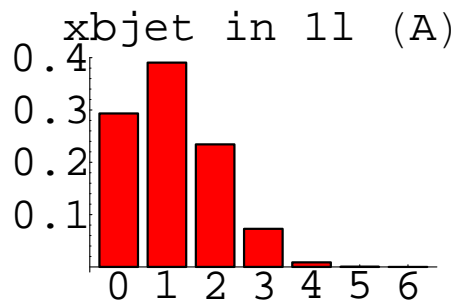
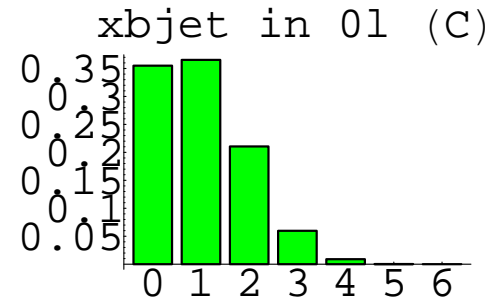
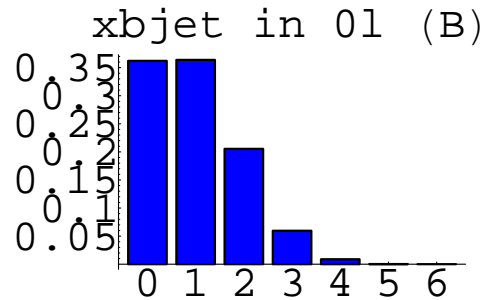
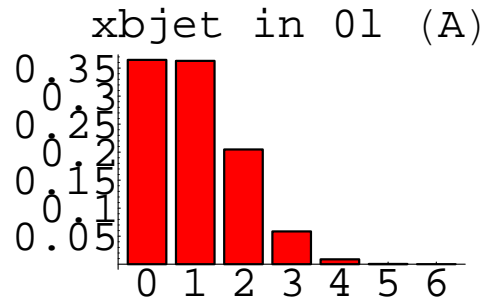
Case Study: MSSM 26 vs. 6226 vs. 26



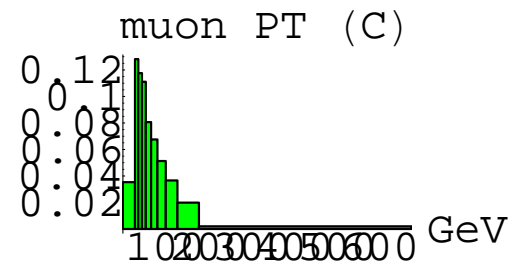
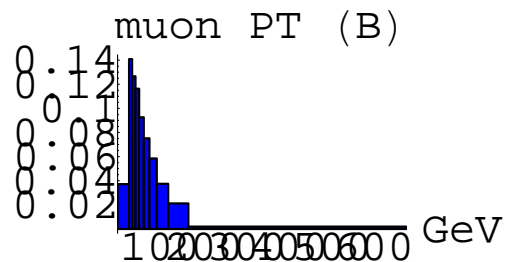
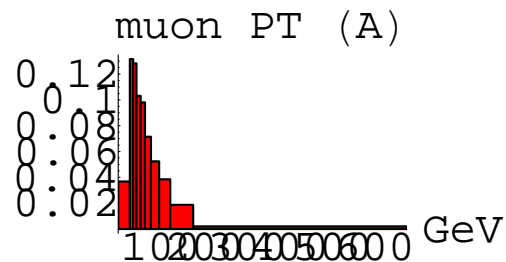
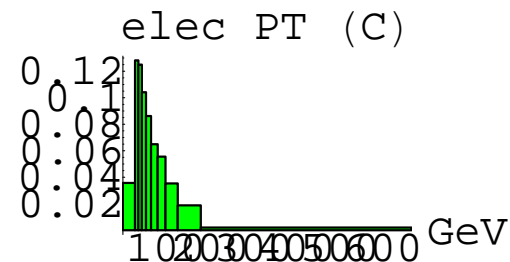
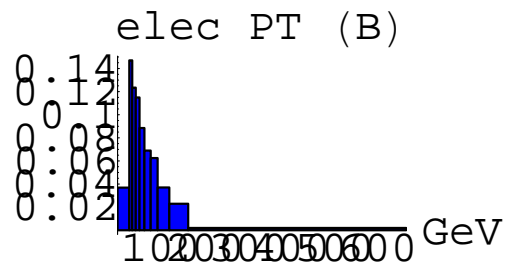
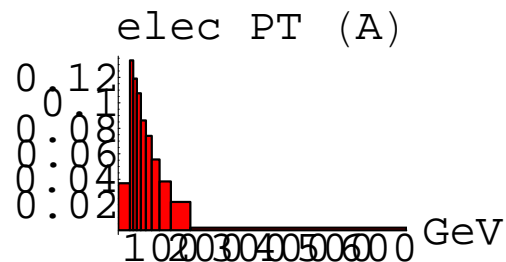
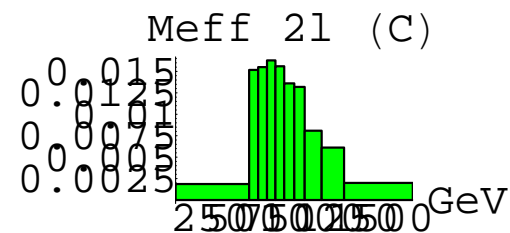
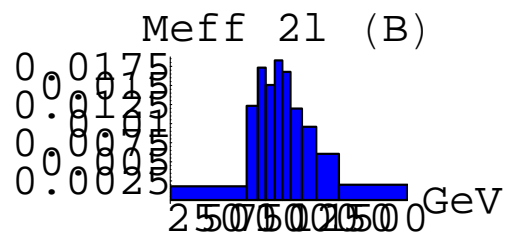
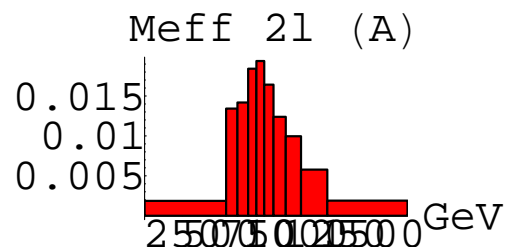
# A = B or B = C ?



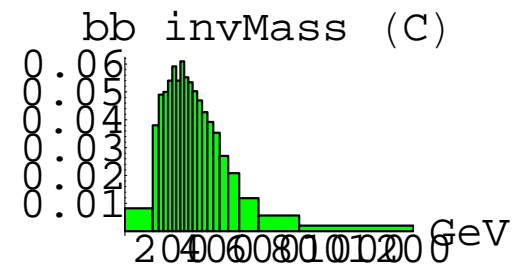
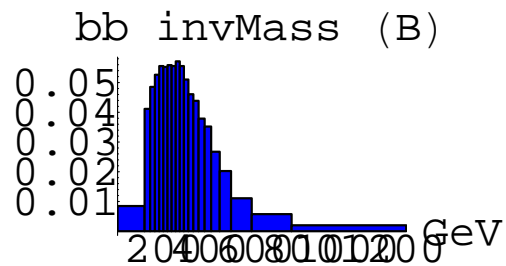
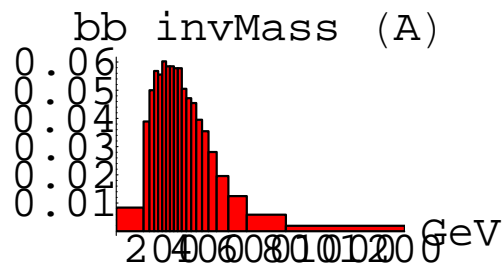
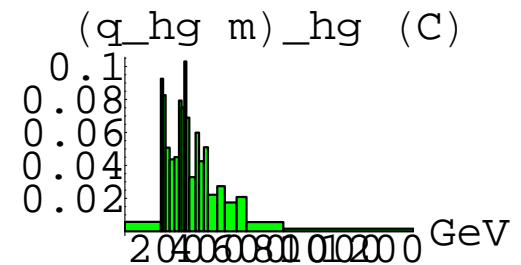
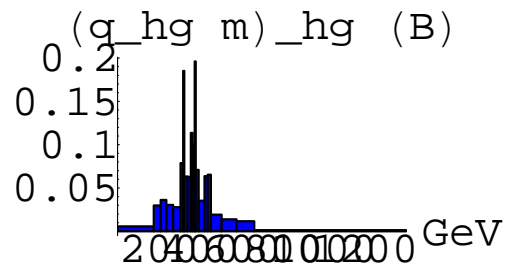
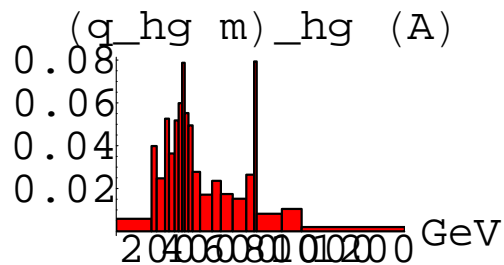
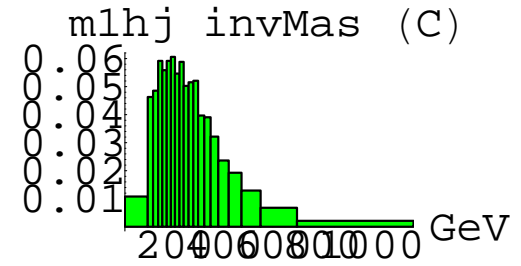
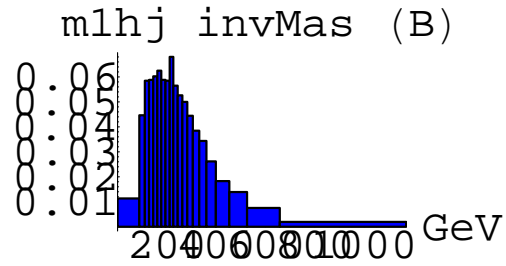
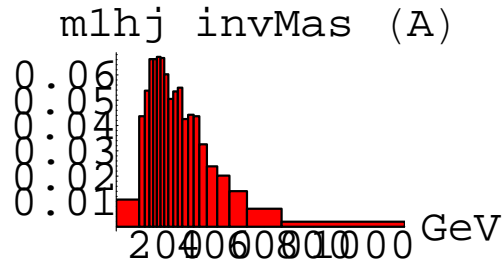
$$\tilde{W} < \tilde{B} < \mu \text{ or } \tilde{W} < \mu < \tilde{B} ?$$



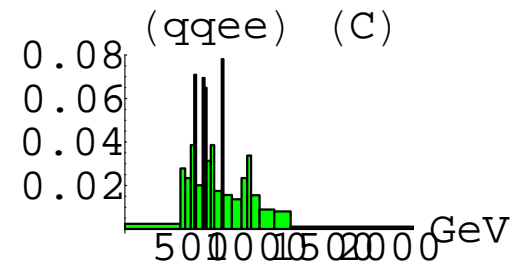
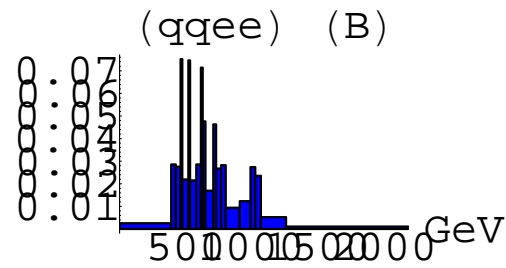
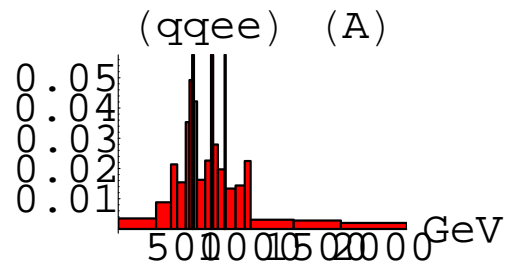
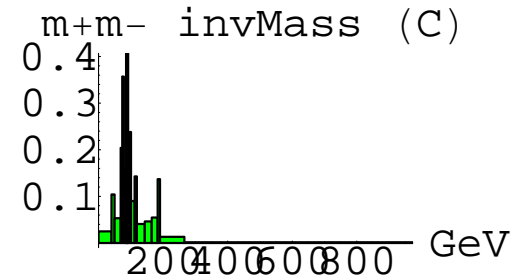
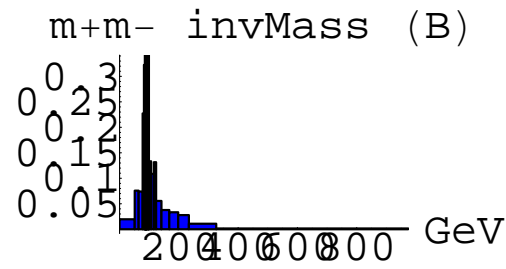
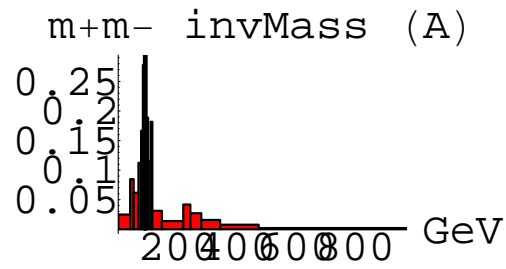
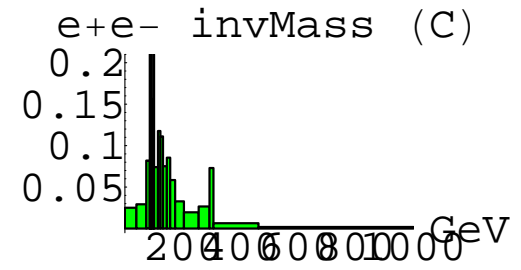
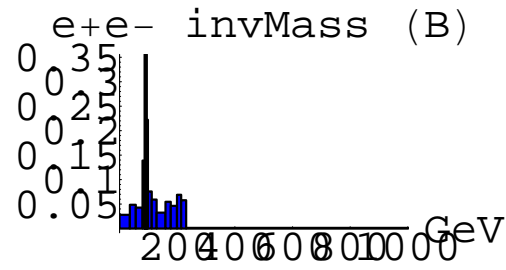
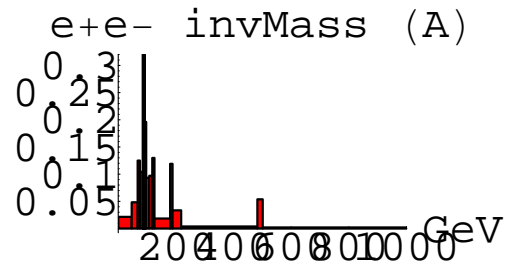
# Wait Until ILC?



**A = B or B = C (or A = C) ?**

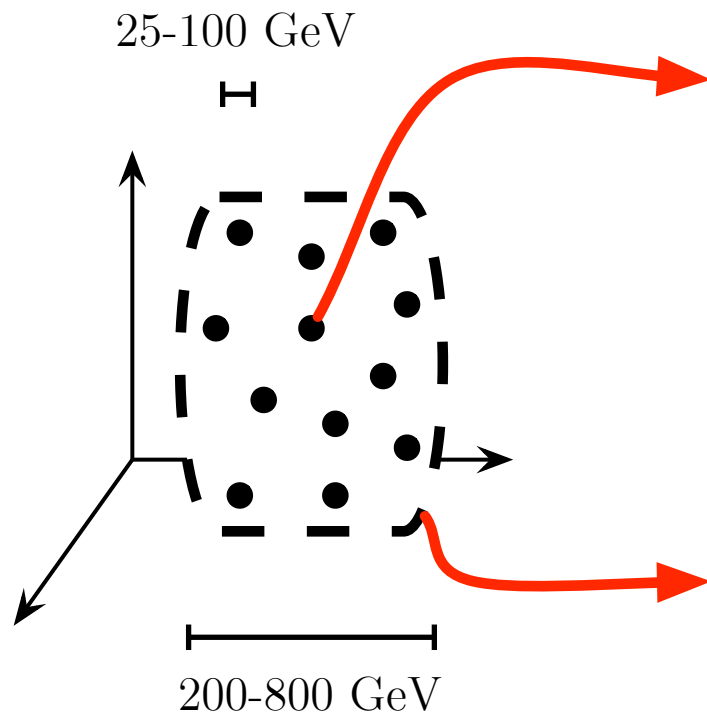


# The Answer is $A = B$



# The Outlook

# If You Have a Favorite Theory...



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

...but there at least  $\mathcal{O}(100)$  other (well-motivated?) MSSMs consistent with the same experimental data.

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

# Reconciling Two Different Attitudes

SUSY at LHC is easy!

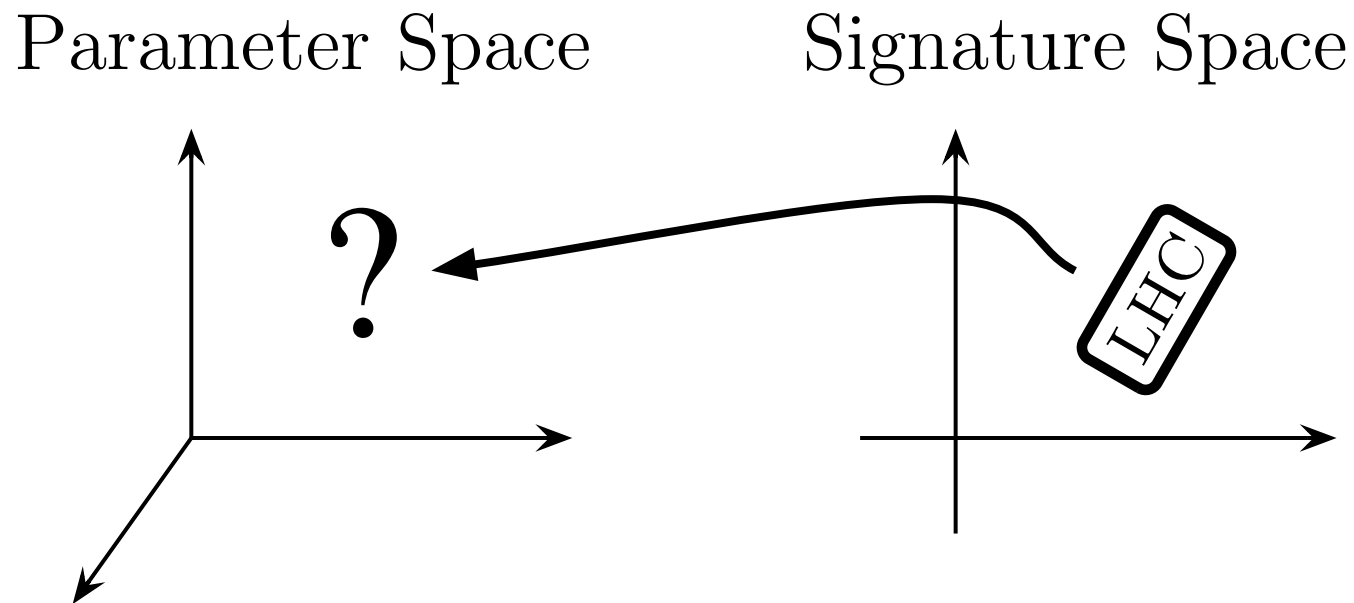
If a constrained model is consistent with LHC data, then you can make reasonably accurate measurements at  $10 \text{ fb}^{-1}$  (assuming no SM background).

SUSY at LHC is hard!

There are  $\mathcal{O}(100)$  different models that also match the data, and there is no systematic way to find them. Do they come from nice UV theories?

# Lessons from the Degenerate MSSM

Very little work in this direction.



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

# 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 for leptophilic models? At  $300 \text{ fb}^{-1}$ ?  
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?