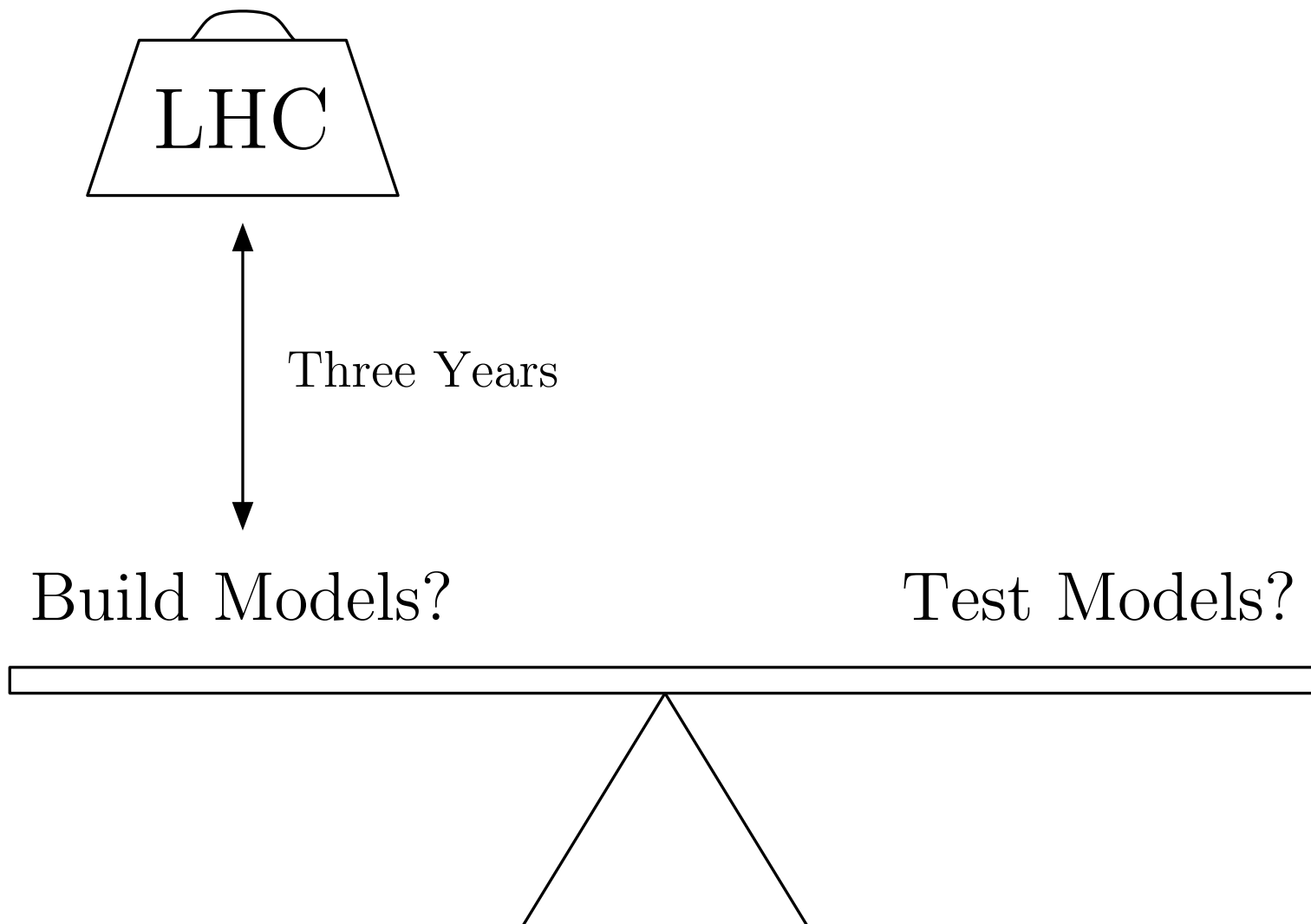


Supersymmetry and the LHC Inverse Problem

Jesse Thaler

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

Particle Theory Circa 2005



Models Still Worth Building

1. “Best SUSY Ever” (or Best Composite Higgs Ever?)

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

2. Proof of Concept

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

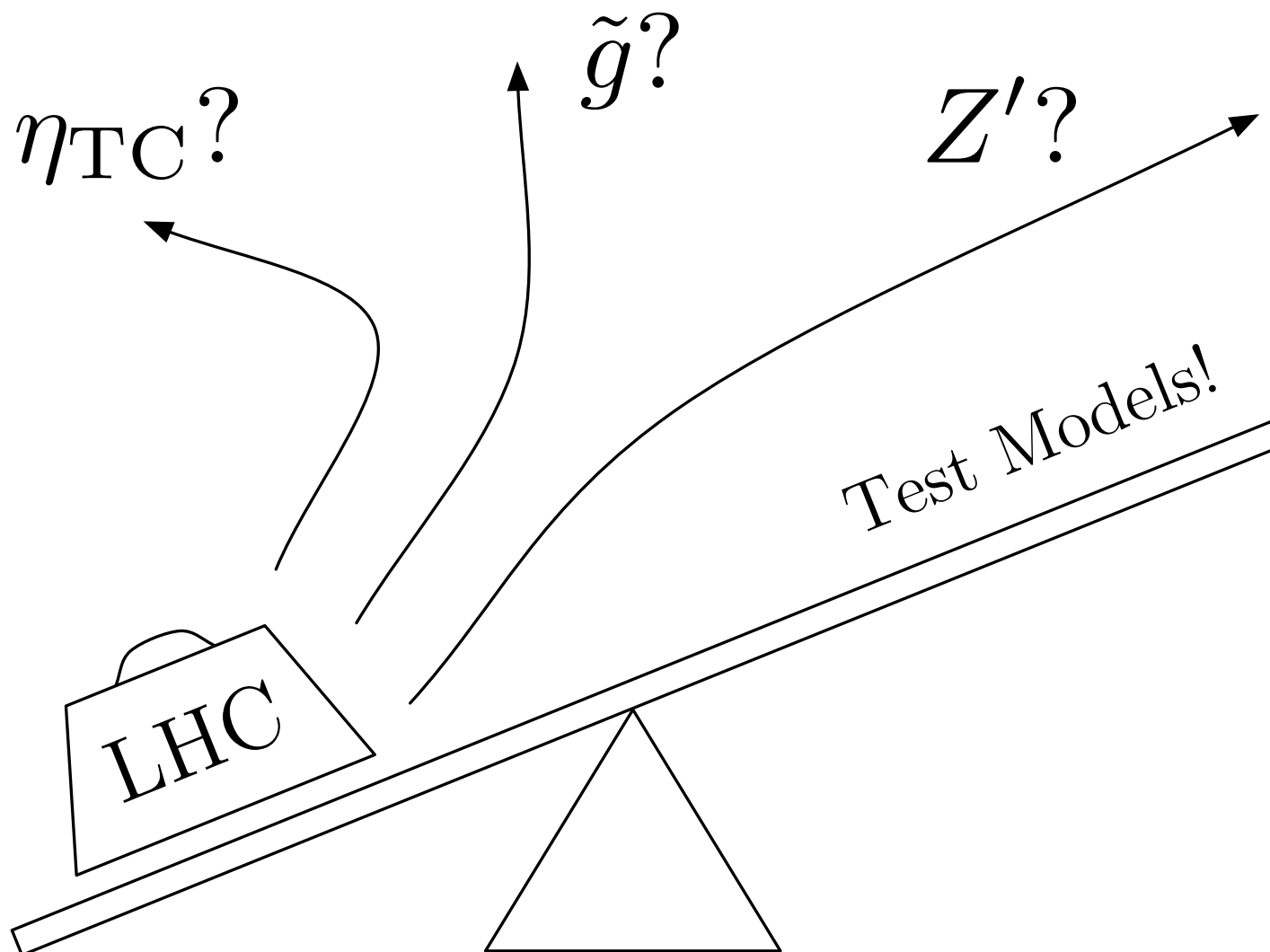
3. Unnatural Theories

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?

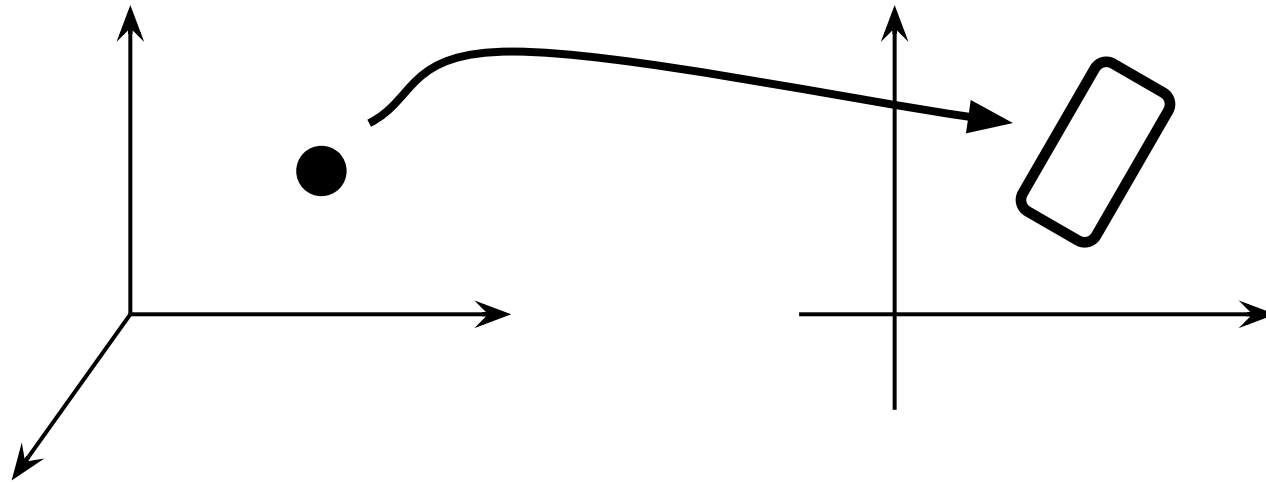
Weak Scale Dark Matter?

$\tan \beta$?

Standard Method For Testing Models

Parameter Space

Signature Space



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

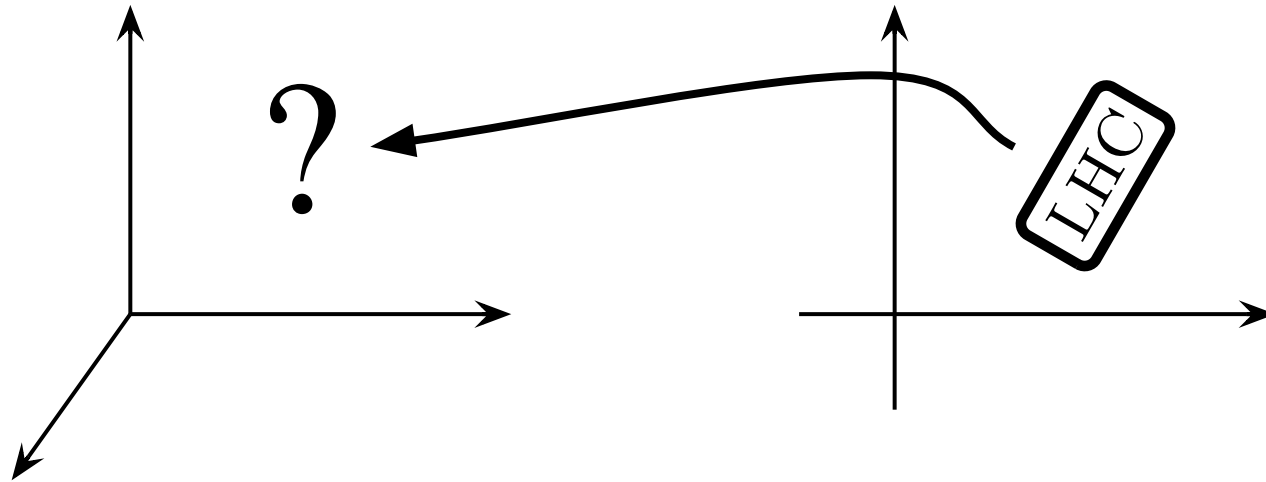
Reduced parameter set (mSUGRA, AMSB, GMSB):

Experimental Data \longrightarrow Precision Measurements

The Inverse Problem

Parameter Space

Signature Space

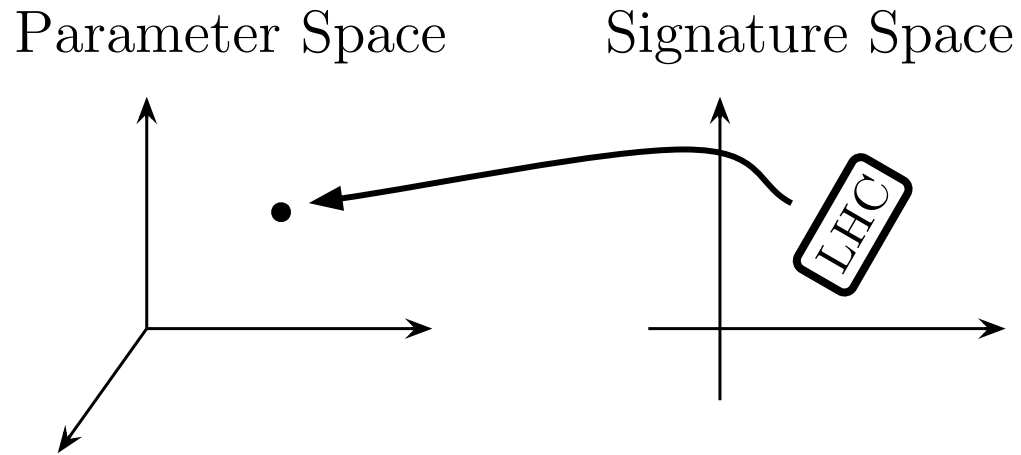


Much more interesting! (One-to-One Map?)

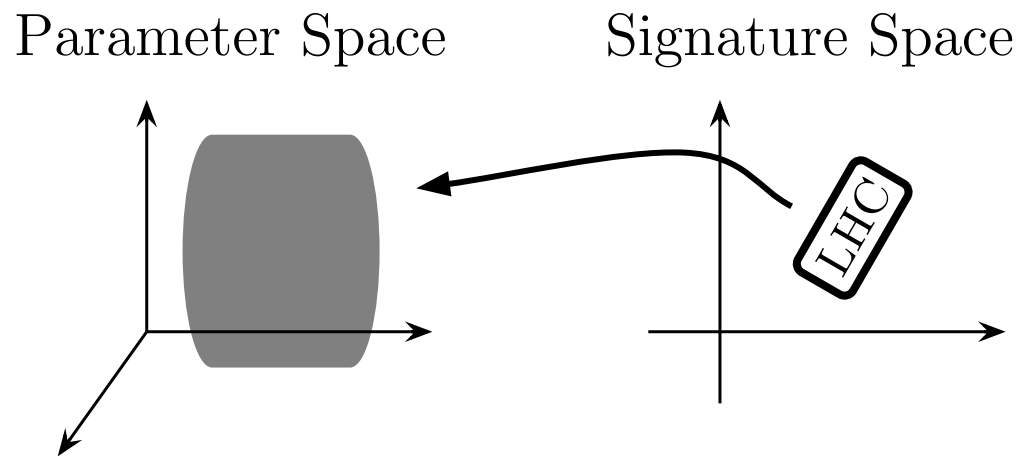
Data $\xrightarrow{?}$ gaugino unification, dark matter, ...

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

Best of all Possible Worlds



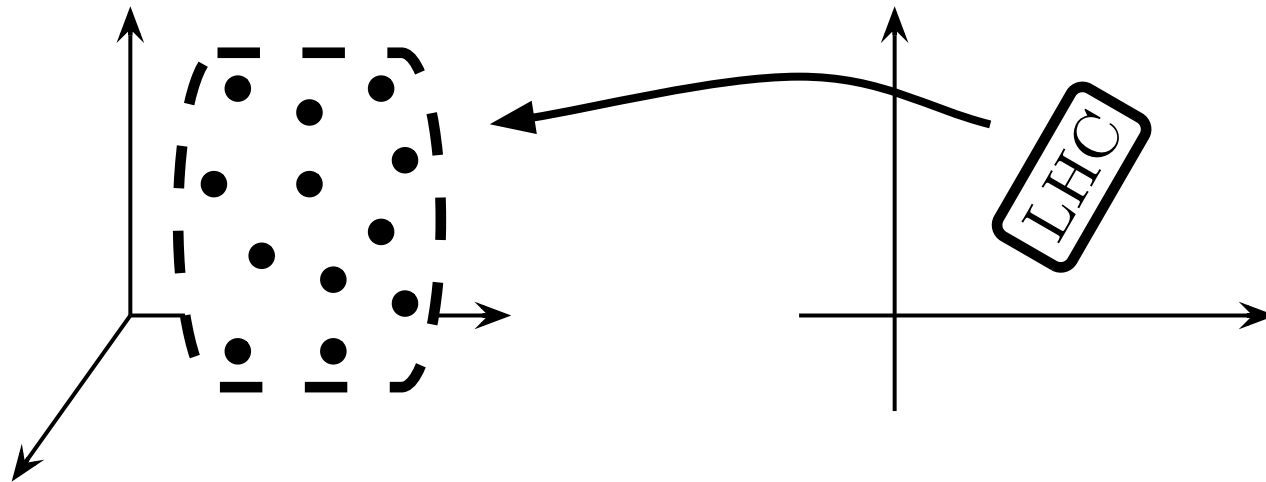
Worst of all Possible Worlds



Our Picture of the Inverse Map

Parameter Space

Signature Space



Degeneracies!

Many small footprints in a large overall region.

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

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 σ_{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: 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?

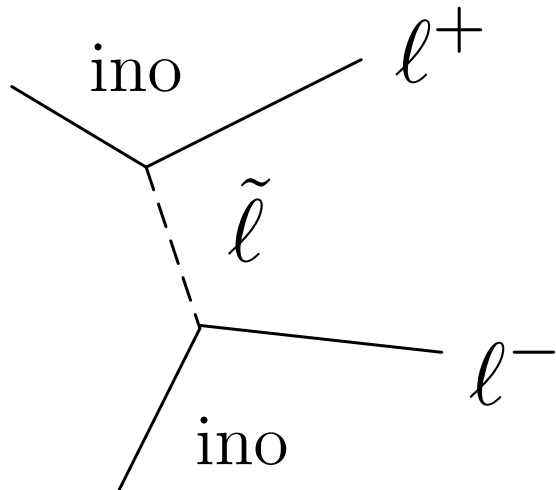
The Birthday Problem!

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?

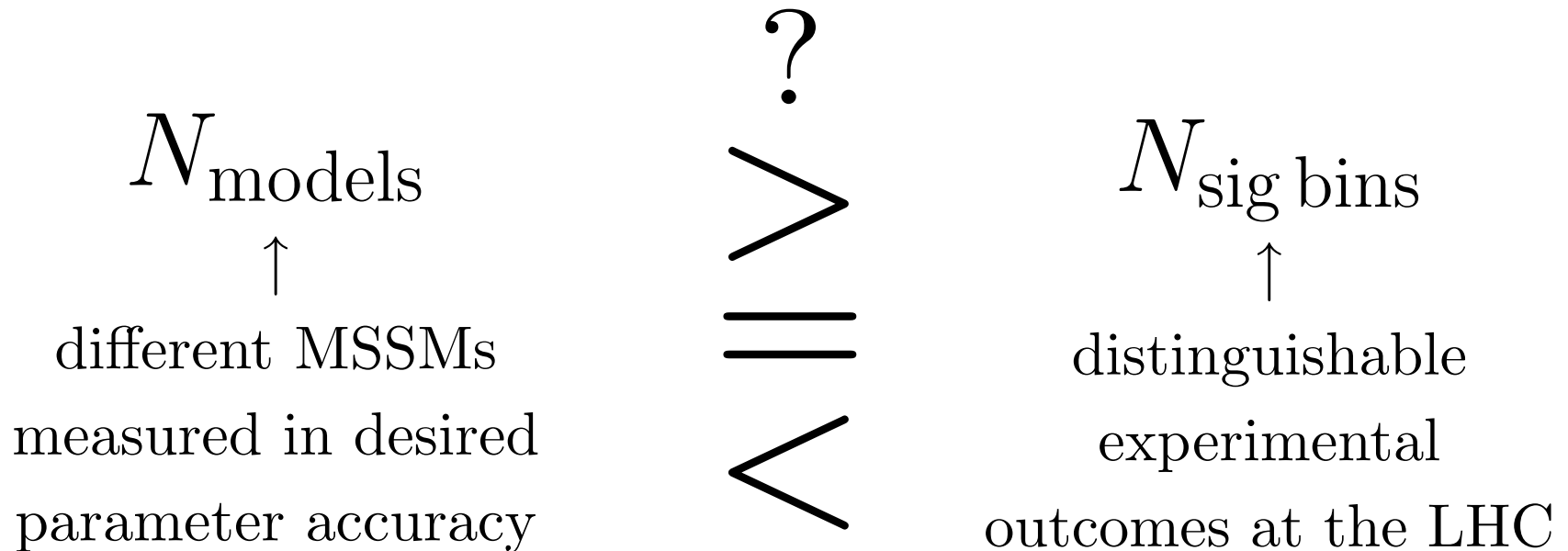
1153 LHC Observables

4. What kind of degeneracies are there?

Flippers, Sliders, and Squeezers

Statistics of the MSSM

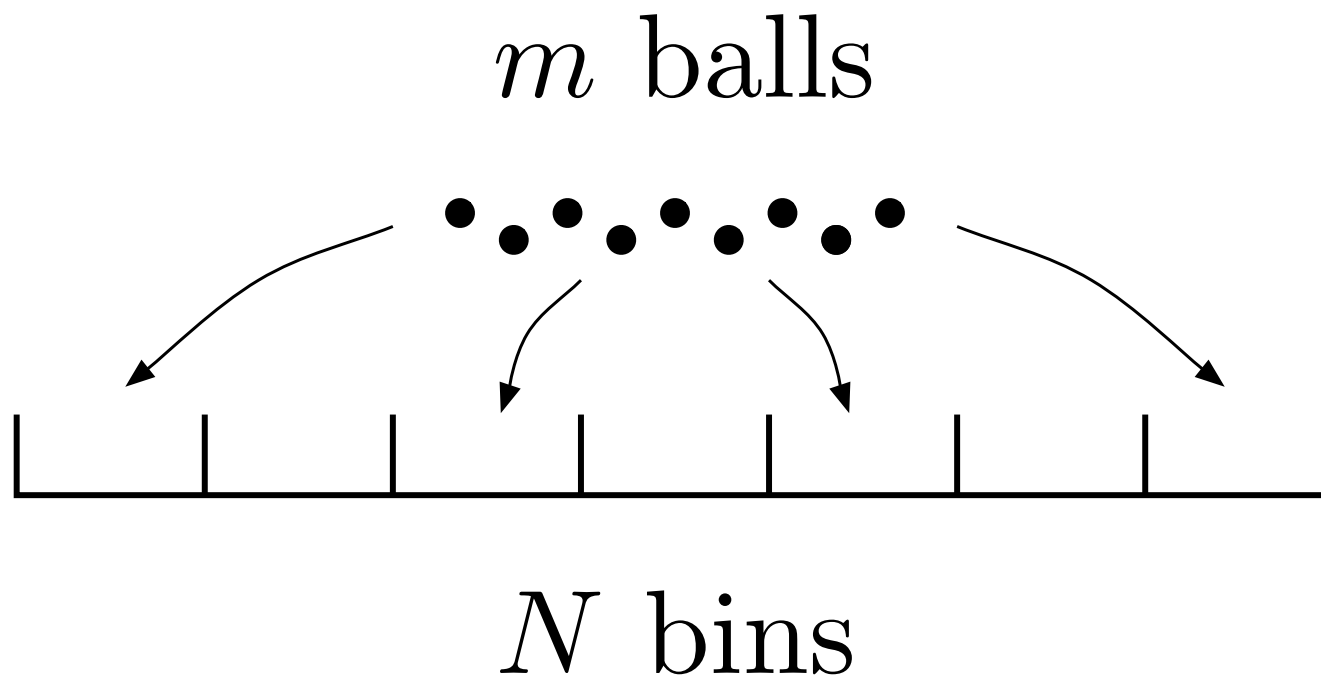
Simple Statistical Question



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

Guaranteed degeneracies at the LHC.

How to Count Degeneracies



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

As of Last Night...

We simulated $m = 39137$ MSSMs (+ 3918 waiting...)

Number of pairs with matching LHC signatures = 364

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

$$N_{\text{models}} \sim 10^8 \text{ (See next slide.)}$$

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 want to know the mean $\tilde{\ell}$ and \tilde{q} masses to 10%.

I can live without knowing $\tan \beta$.

16 of 364 pairs satisfy this criteria $\implies \langle d \rangle \sim 23$.

Other Criteria

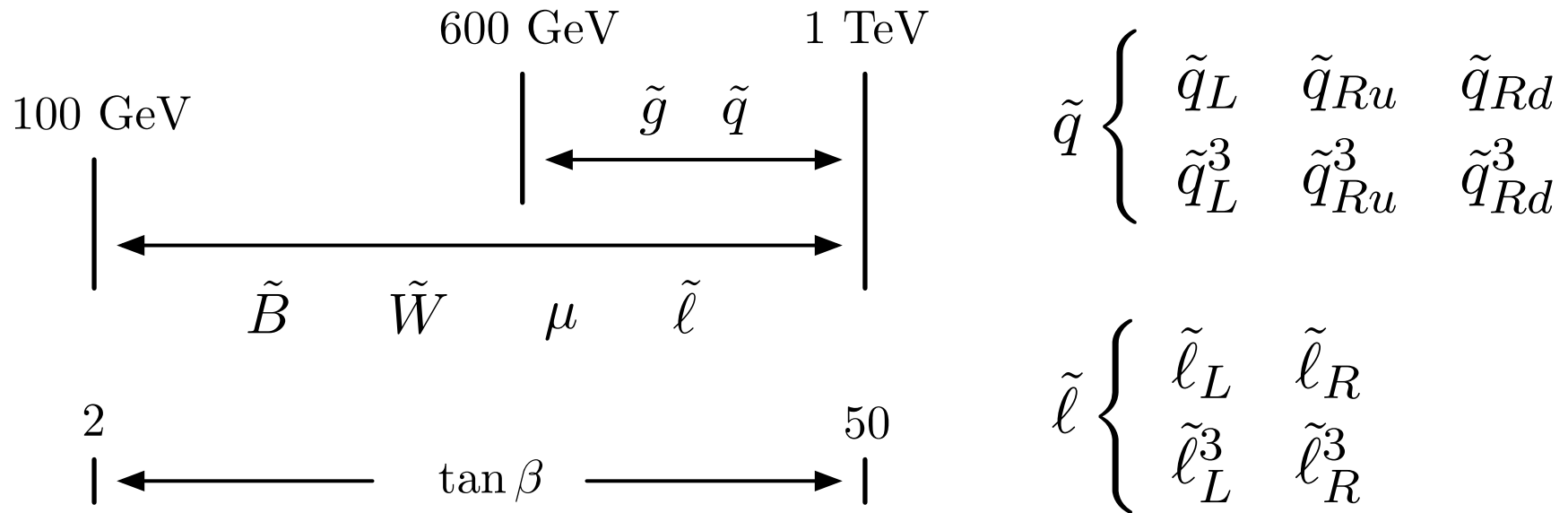
Are there SUSY-like events?	→	$\langle d \rangle = 1$
Match just electroweakino ordering	→	$\langle d \rangle \sim 2.0$
Match all ino ordering	→	$\langle d \rangle \sim 3.5$
Match 7 of 14 parameters (10%)	→	$\langle d \rangle \sim 4.3$
Match 10 of 14 parameters (10%)	→	$\langle d \rangle \sim 182$
Match 12 of 14 parameters (10%)	→	$\langle d \rangle > 364$

For gaugino unification/LSP identity:

Match ino masses (10%)	→	$\langle d \rangle \sim 8.5$
Match ino masses (5%)	→	$\langle d \rangle \sim 52$

What Kind of Models?

Choosing 39,137 MSSMs



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:

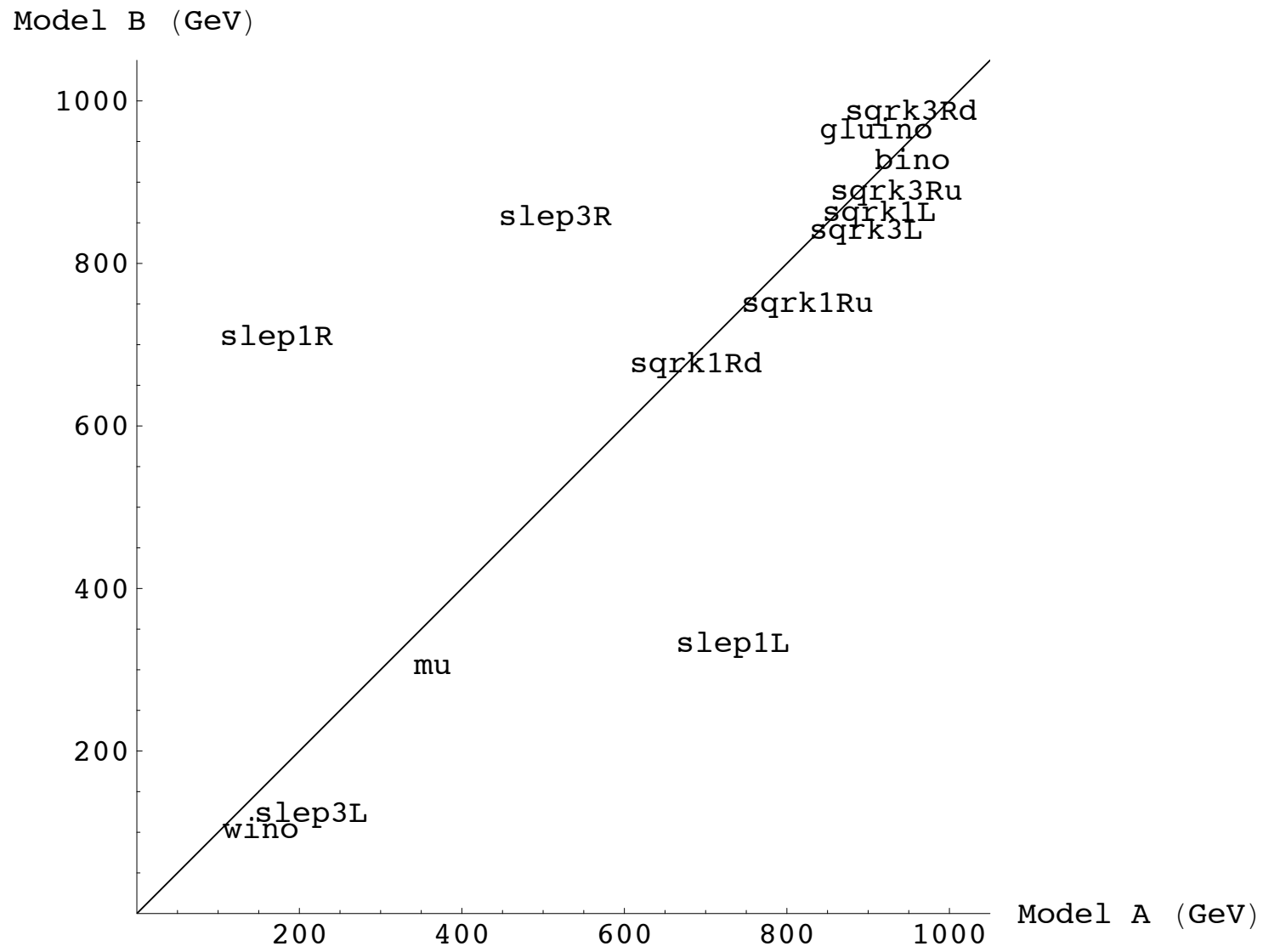
1 Model / CPU / hr

PYTHIA → PGS (Pretty Good Simulation)

Two terabytes of storage for raw data like:

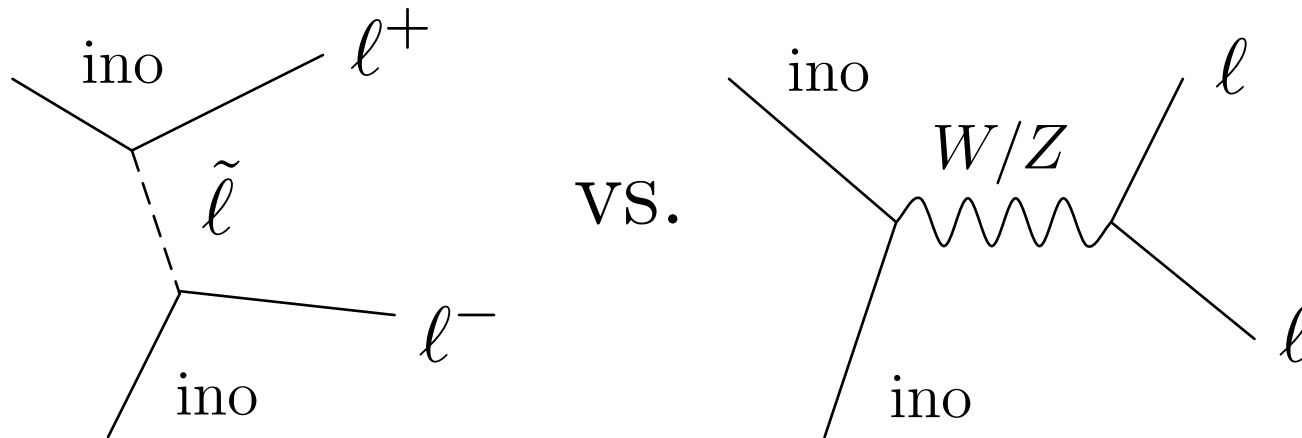
#	typ	eta	phi	pt	jmas	ntrack	btag
1	3	0.816	0.492	36.20	1.00	3.0	0.0
2	4	2.674	5.539	69.72	7.54	0.0	0.0
3	4	1.794	5.499	45.57	5.65	9.0	0.0
4	4	-0.932	1.546	34.33	6.02	9.0	0.0
5	4	1.622	4.151	70.02	23.54	10.0	0.0
6	4	2.636	3.328	22.96	5.84	0.0	0.0
7	4	0.340	2.154	65.68	2.60	9.0	0.0
8	6	0.000	5.441	23.70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

A Typical “Good” Pair: 2005 vs. 32444



Some Peculiarities

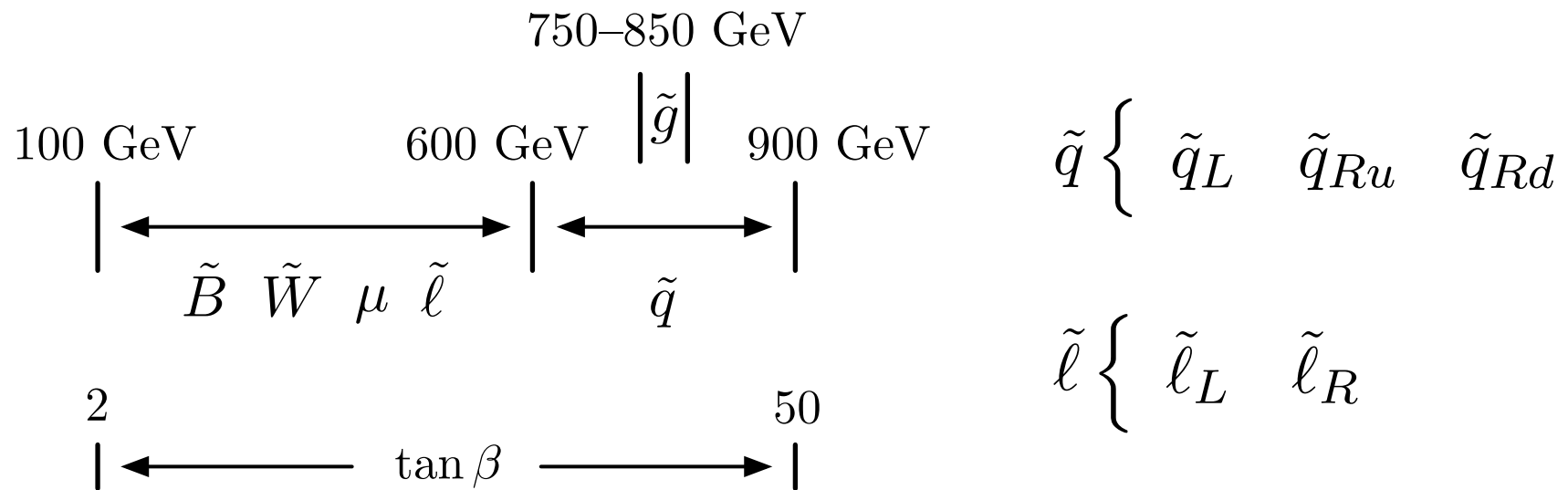
Non-decoupling constraint tends to decouple particles!



Very rarely cascade decays ino-slepton-ino.
Most leptons in final states from W and Z .

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

Preview of Cascade Run



Force cascade decays:

$$\min(\text{electoweakino}) < \text{sleptons} < \max(\text{electoweakino})$$

11964 models so far... interesting degeneracies...

What Kind of Data?

Blackboard Interlude

LHC Observables

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

$$\sum_{3j} P_T > 300 \text{ GeV}, \quad \sum_{3j} P_T > 225 \text{ GeV}$$

Categorize all events by the number of:

j, bj, e, μ , hadronic τ , γ

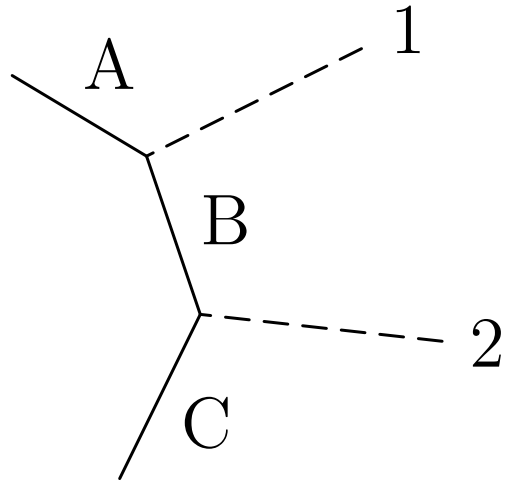
Count NEV, everything else ratios.

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

Kinematic Histograms

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

Edges/endpoints of distributions.



Offshell B (Endpoint):

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

Onshell B (Edge):

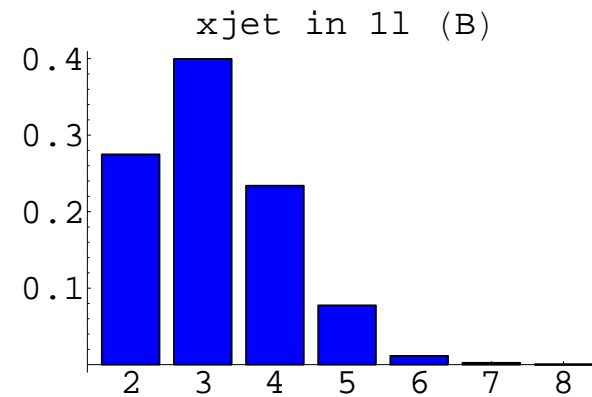
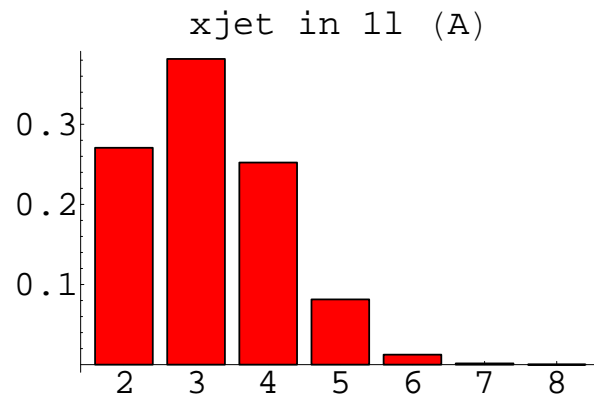
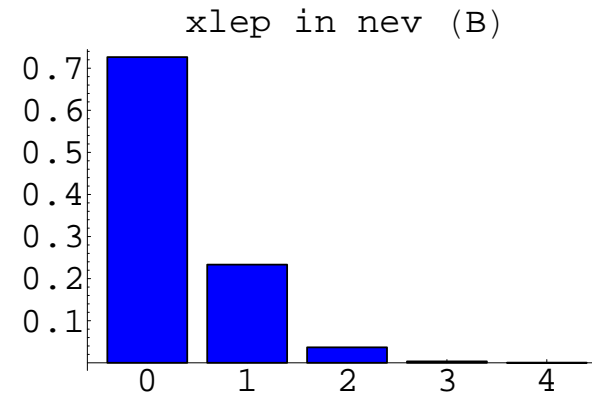
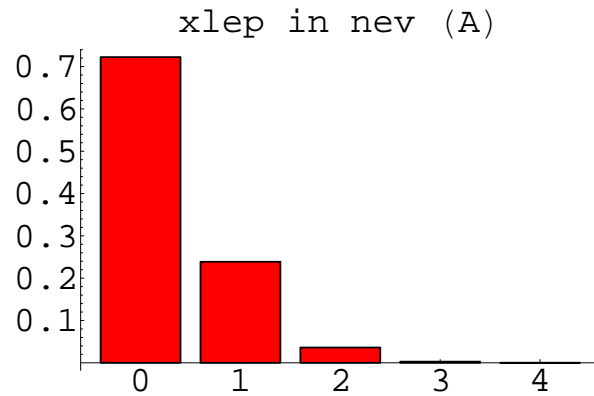
$$m_{\text{inv}}^{12} = \sqrt{(m_A^2 - m_B^2)(m_B^2 - m_C^2)/m_B^2}$$

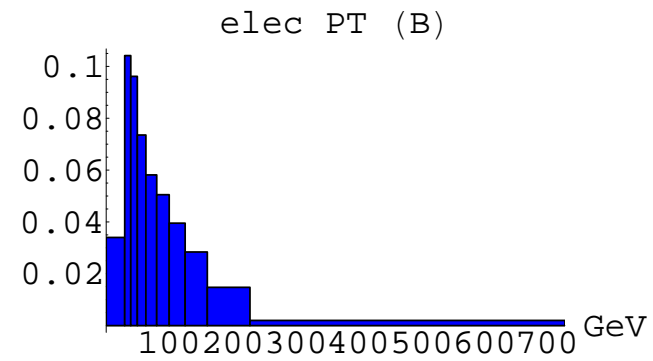
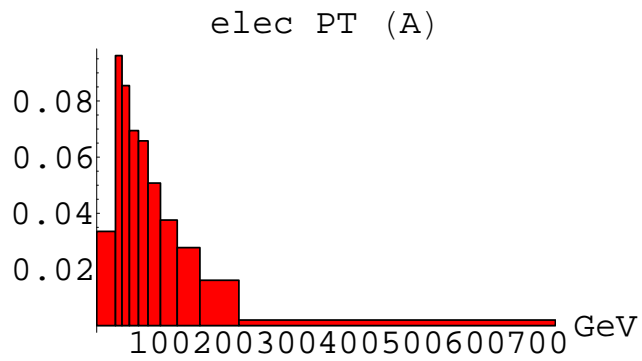
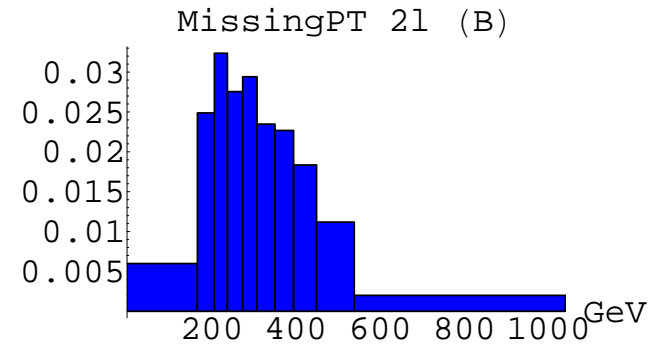
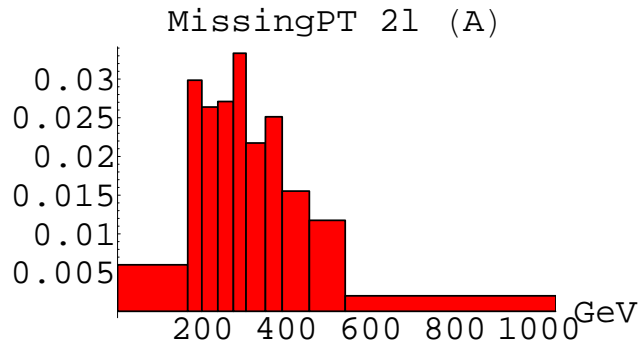
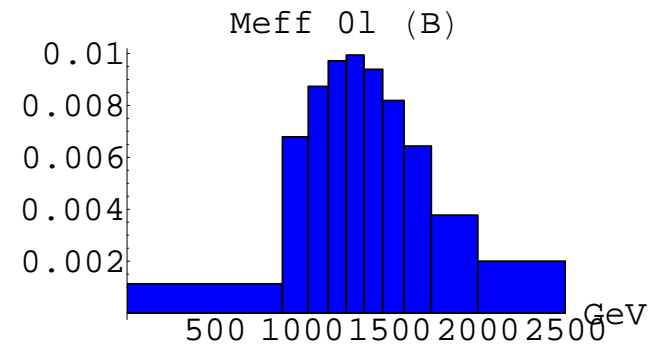
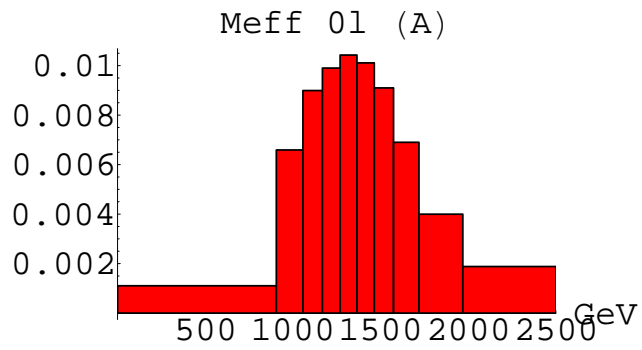
Distributions in quantiles. (Deciles, m_{eff} ; 20-tiles, m_{inv})

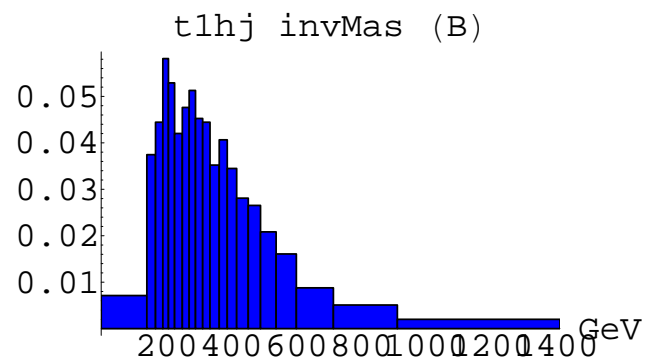
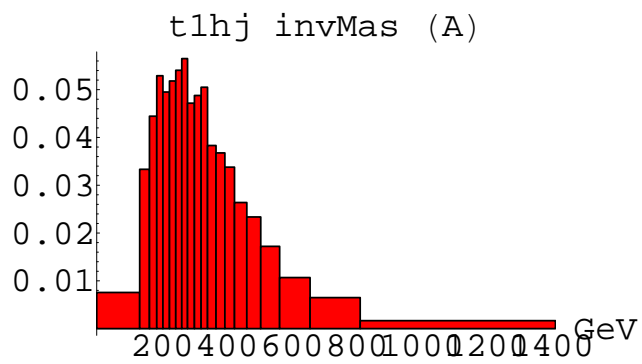
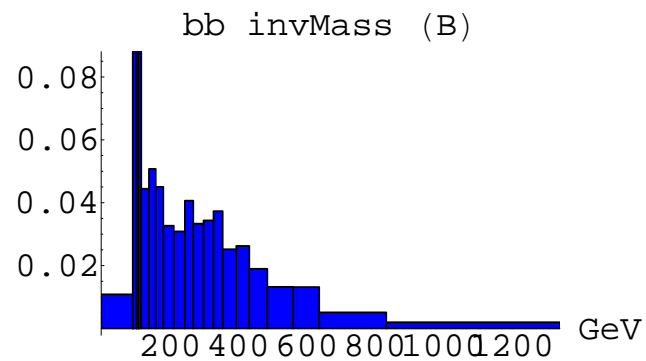
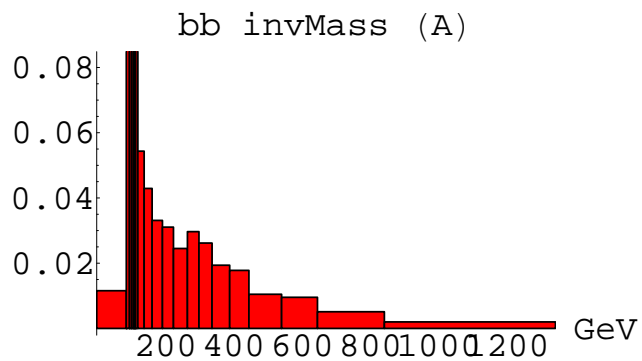
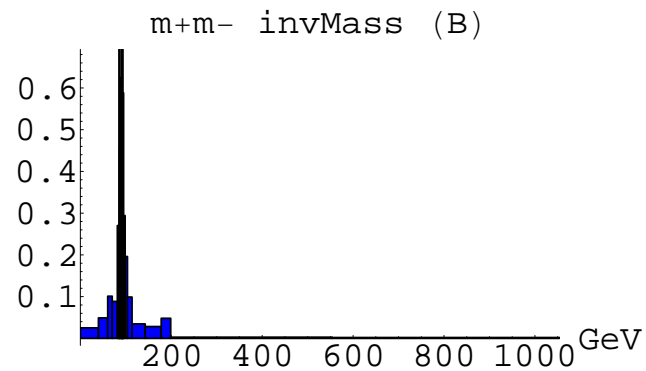
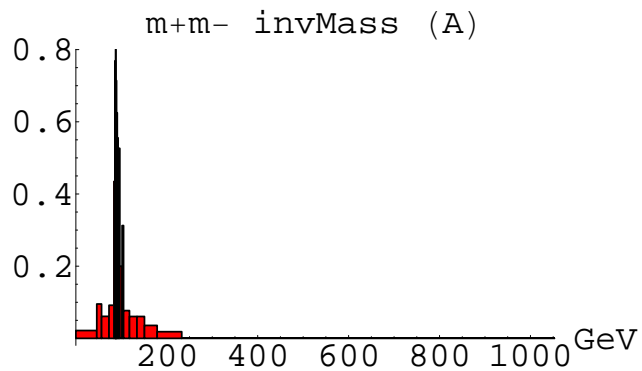
Match distribution, not just endpoint/edge.

Typical Data: 2005 vs. 32444

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







Understanding Degeneracies

Parameter vs. Signature Distance

Pairwise comparison.

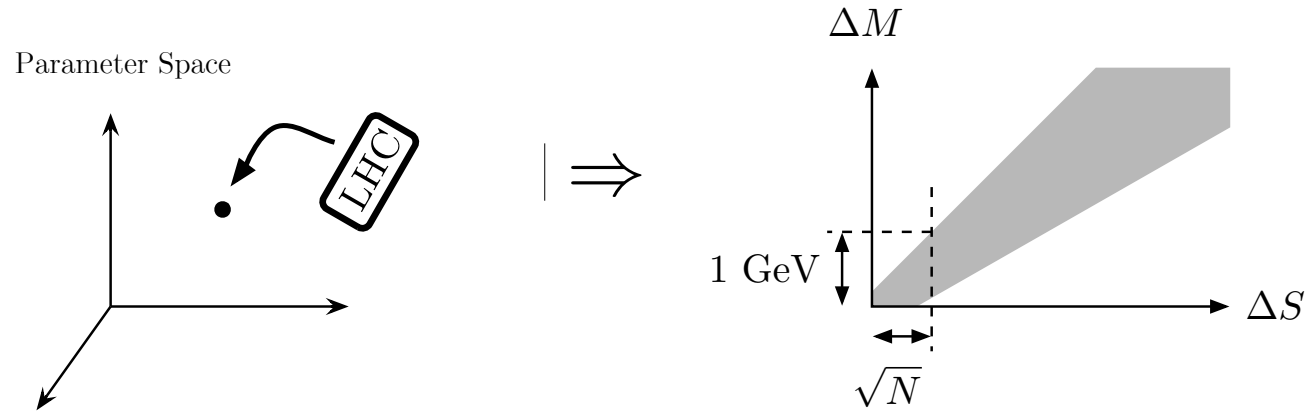
$$\Delta S = \tilde{\chi}_{\text{sig}}^2 = \frac{1}{n_{\text{sig}}} \sum_i \left(\frac{\Delta s_i}{\sigma_i} \right)^2$$

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

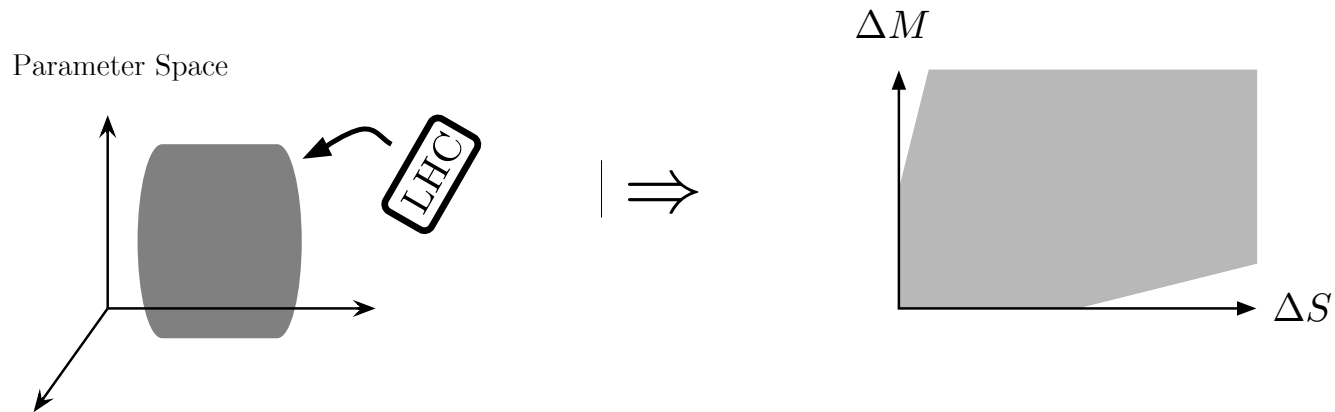
Ignore a signature if for either model, signature is consistent with zero.

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

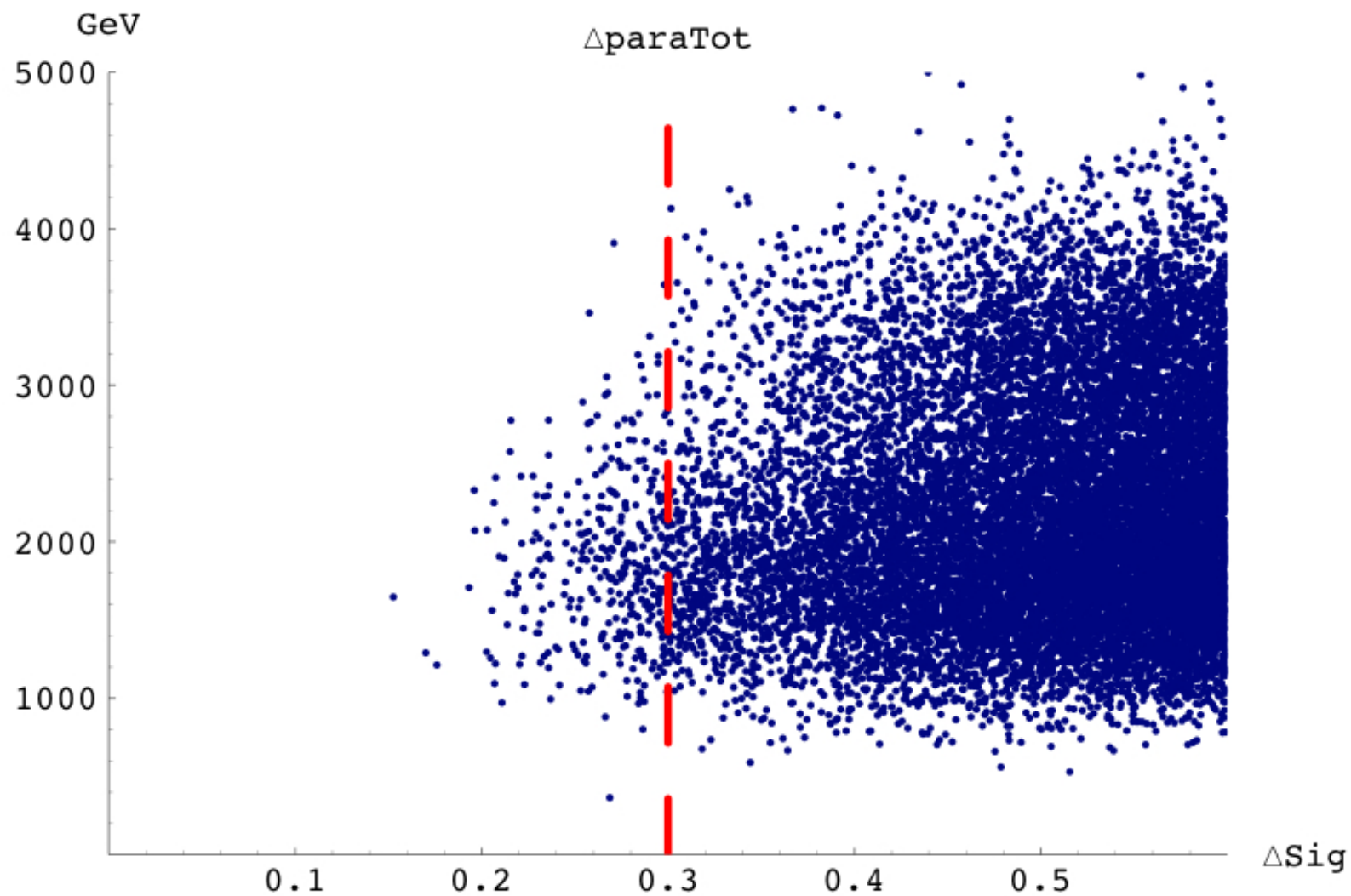
Best of all Possible Worlds



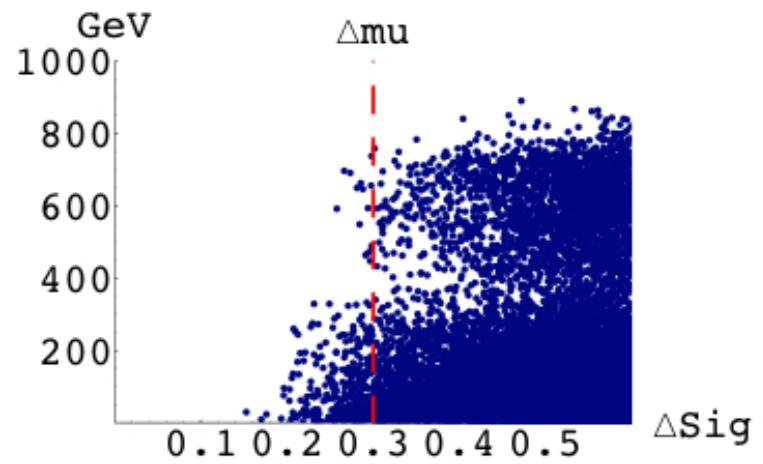
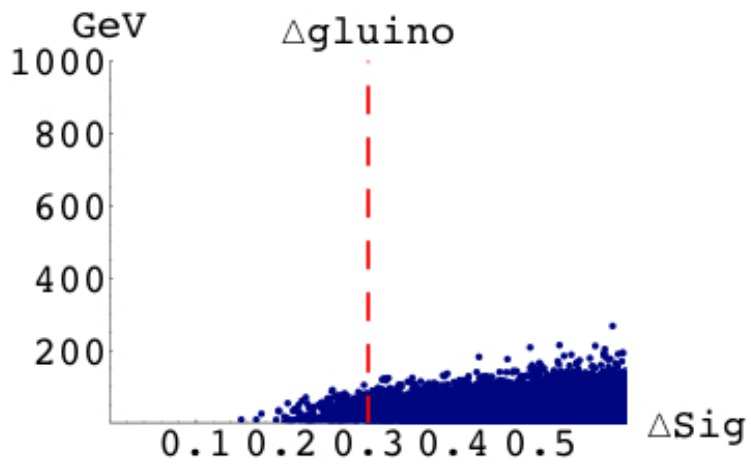
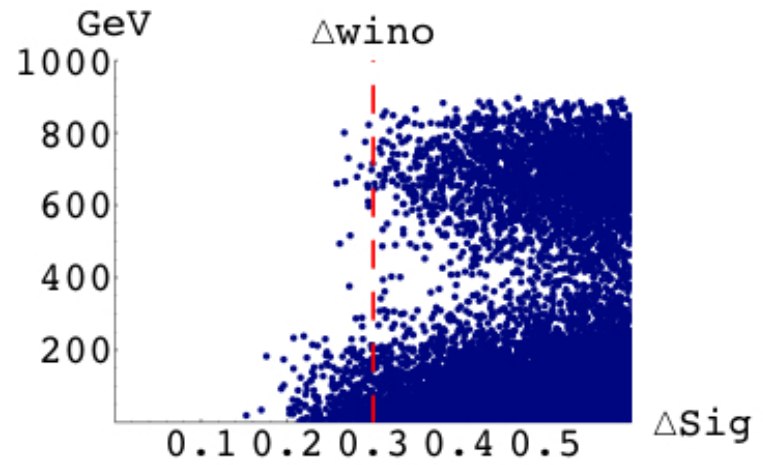
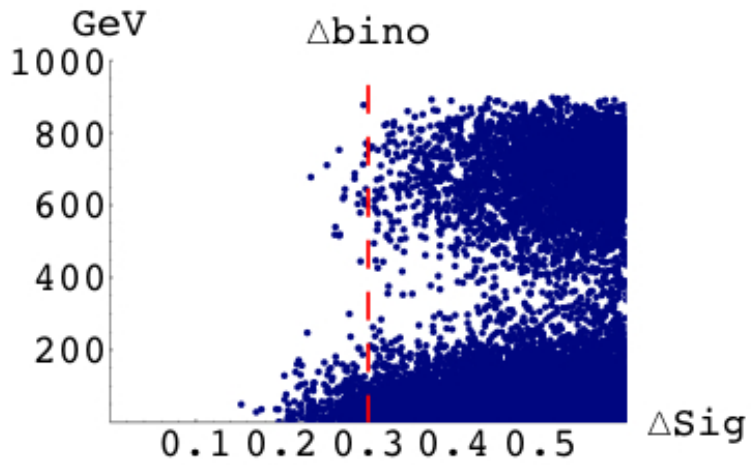
Worst of all Possible Worlds



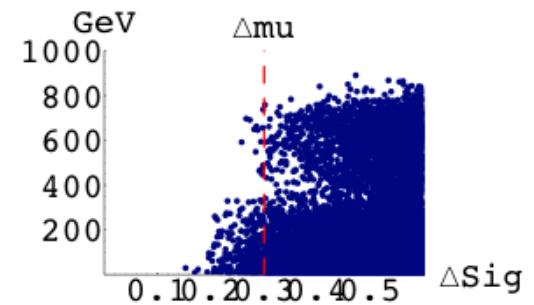
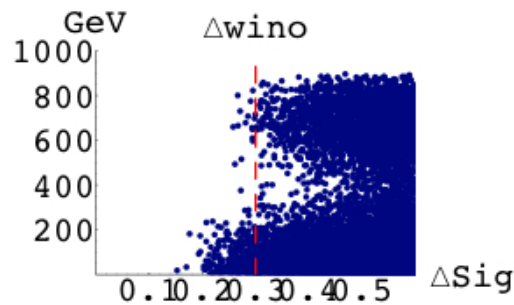
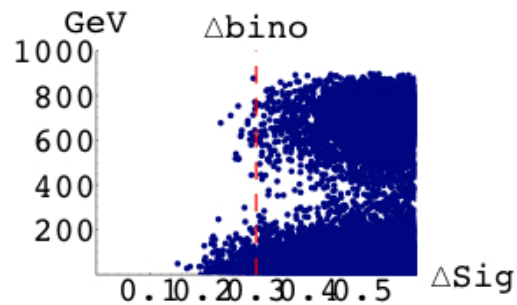
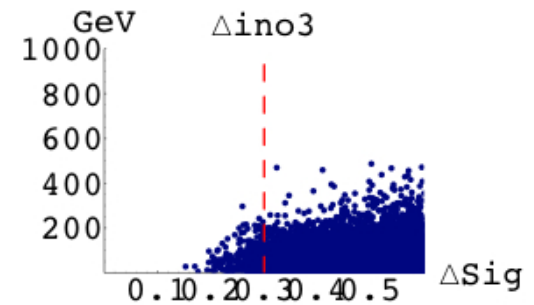
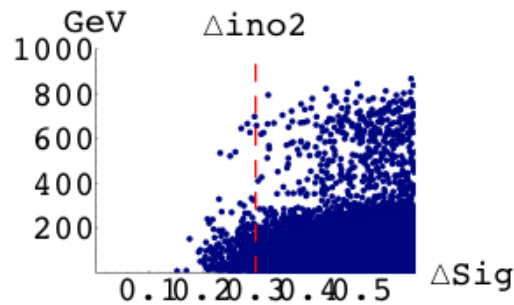
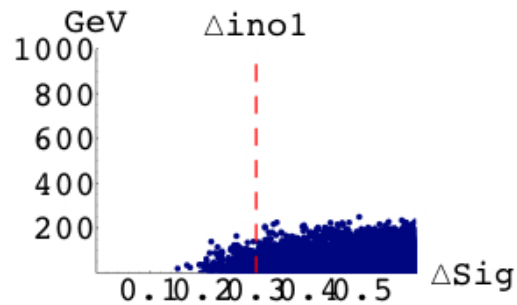
Total Parameter Distance



Inos



Eigenvalues Not Eigenvectors



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

Confronting Degeneracies

Types of Degeneracies

We have 39137 models, many degenerate pairs.

Open Question:

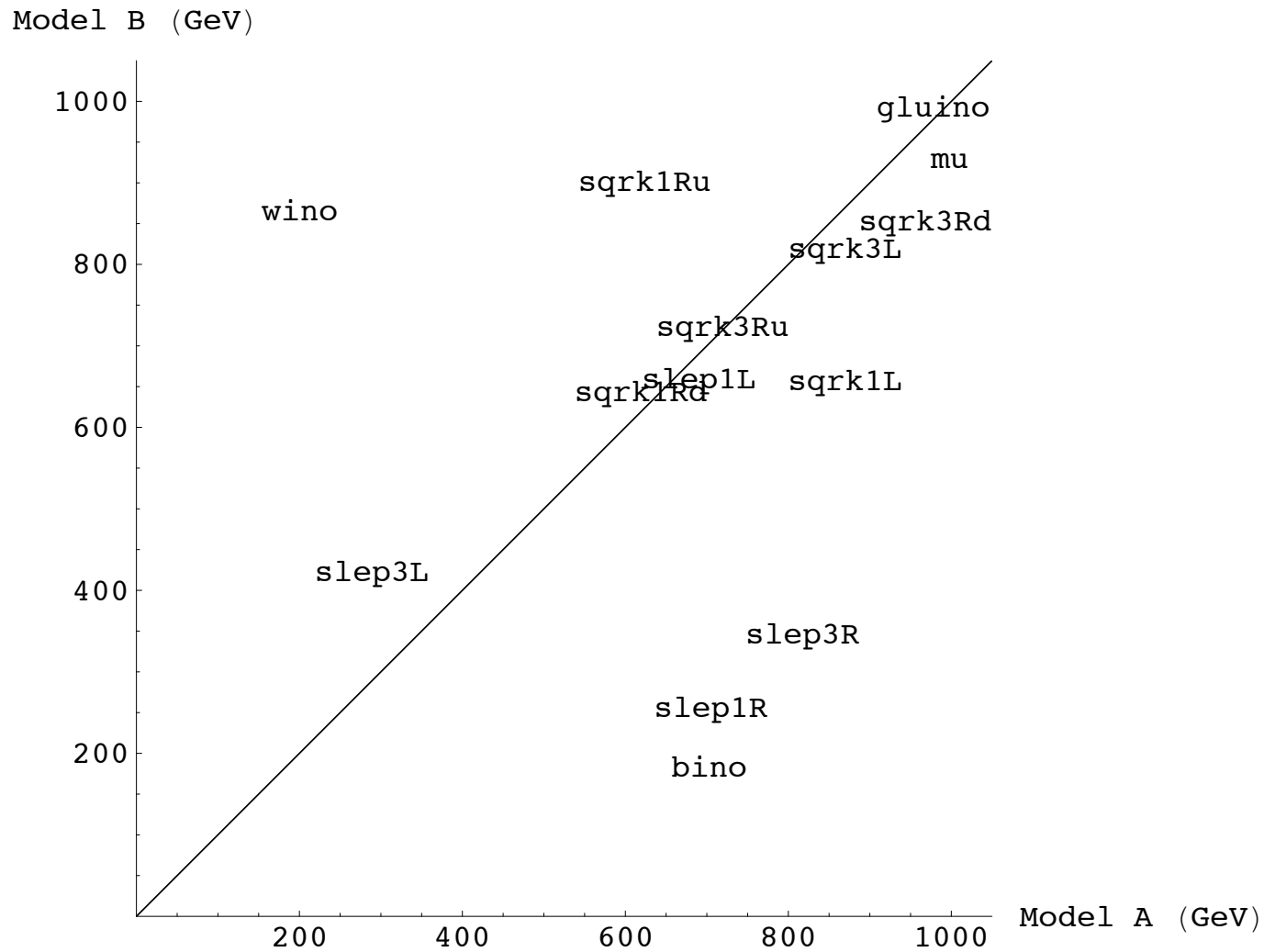
Fundamentally Indistinguishable @ LHC?

New Clever Observables?

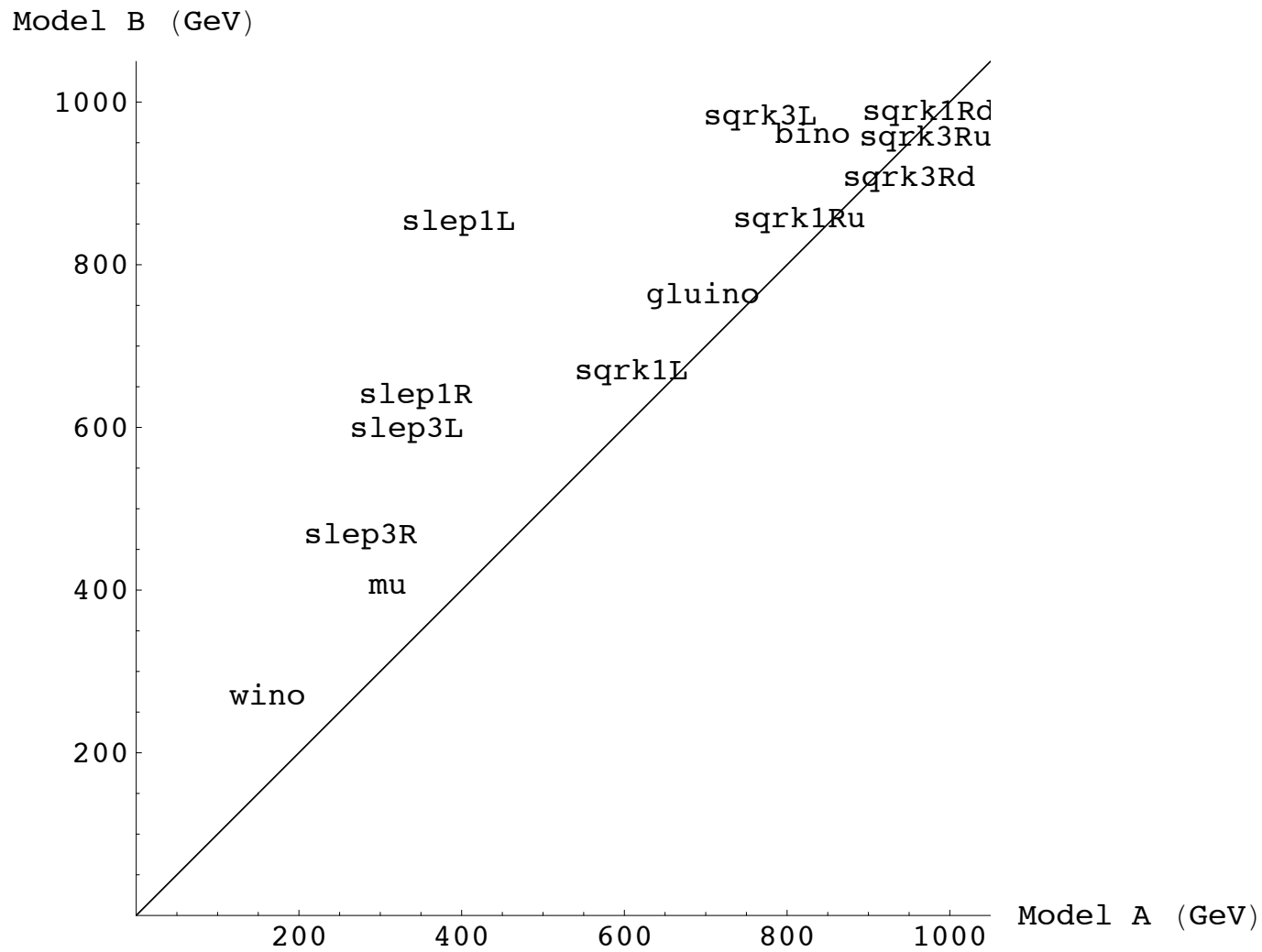
First Step: Catalog...

Electroweakino Sector: Flippers, Sliders, and Squeezers

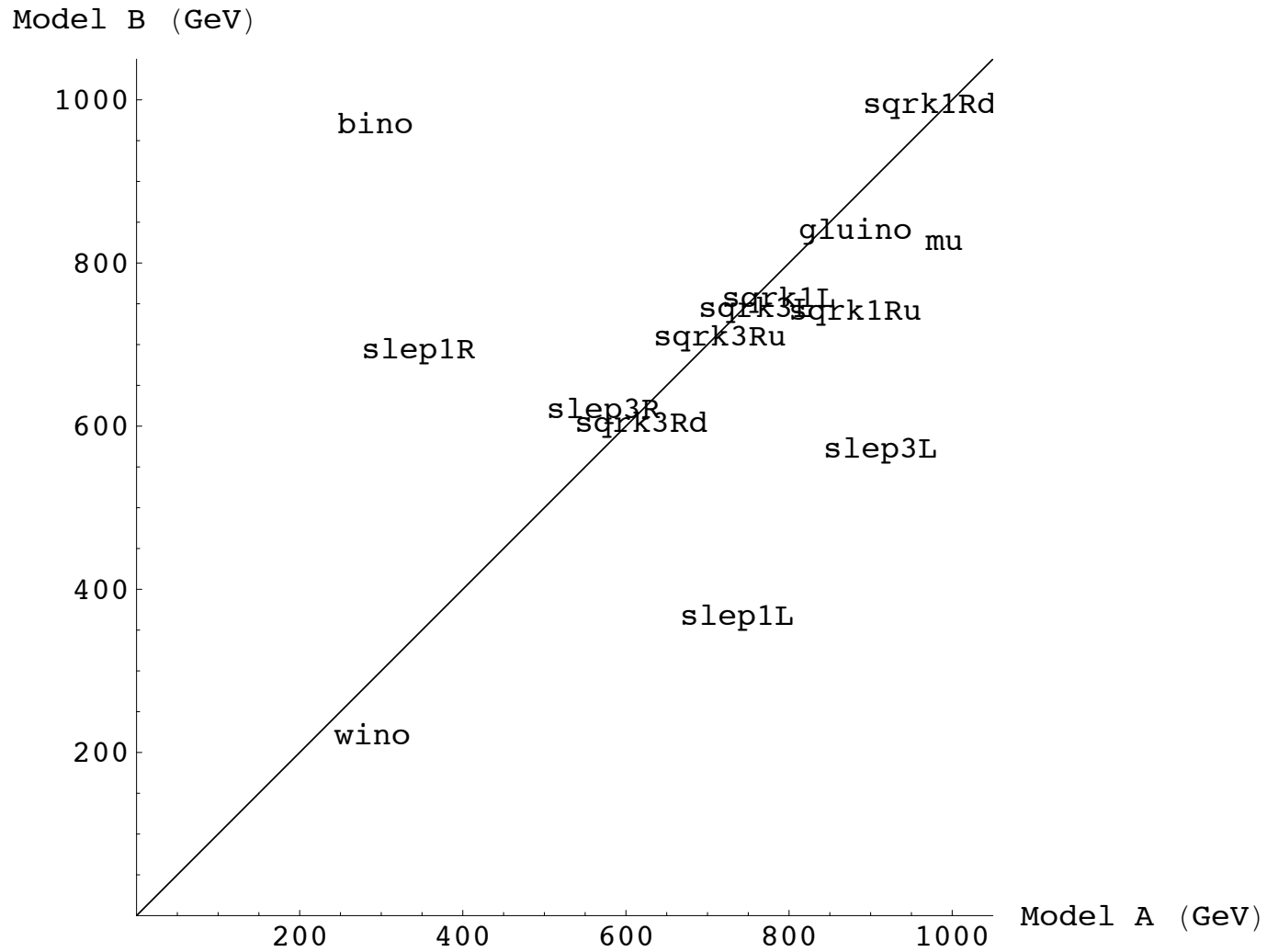
Flippers: 17653 vs. 20026



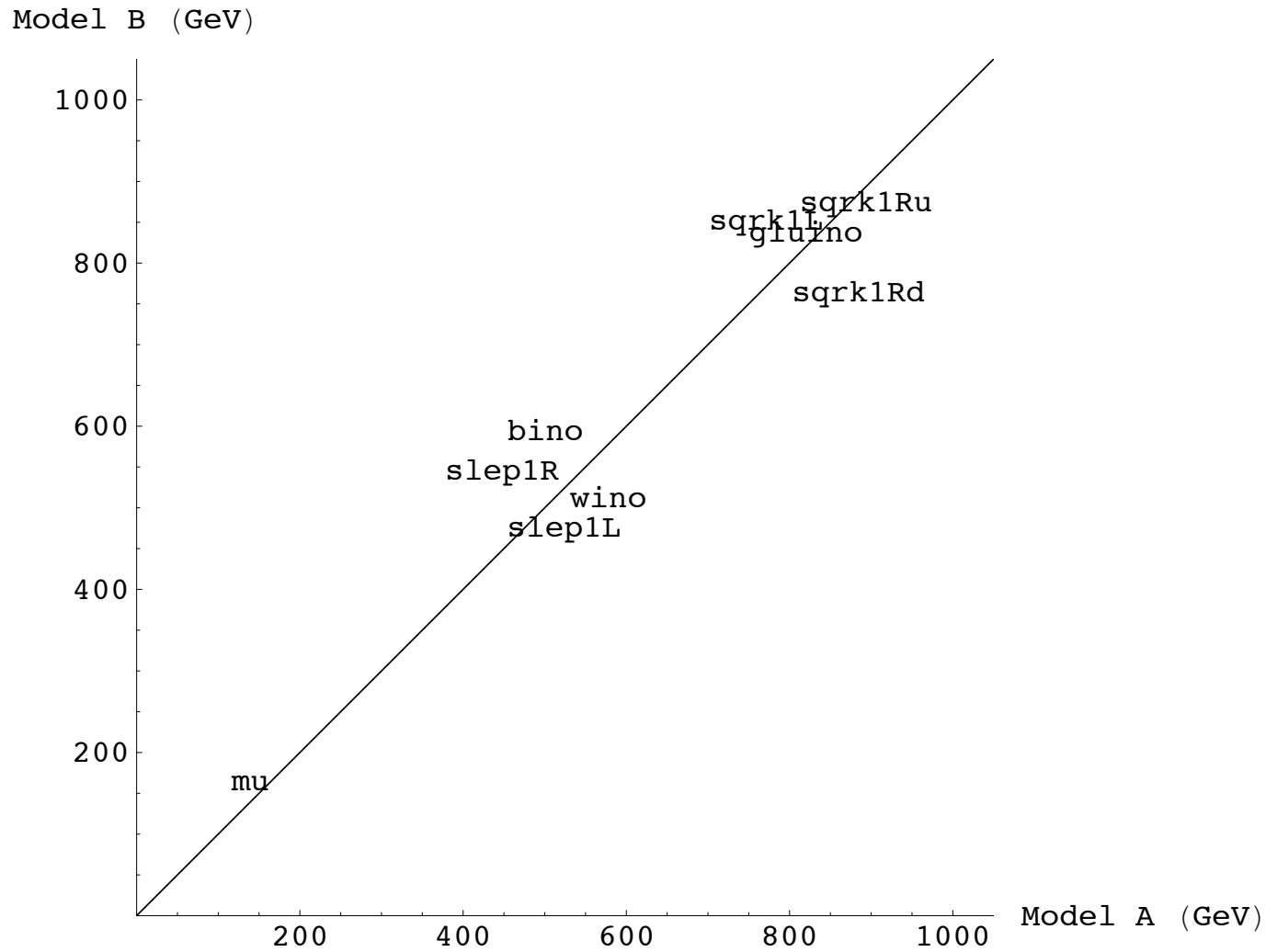
Sliders: 24230 vs. 25628



Squeezers: 24119 vs. 35520

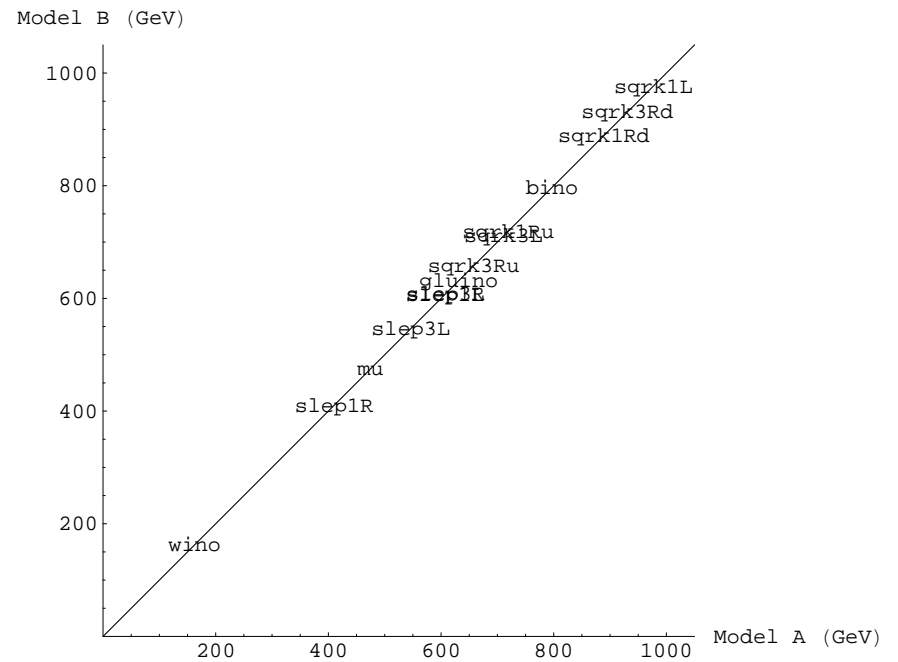
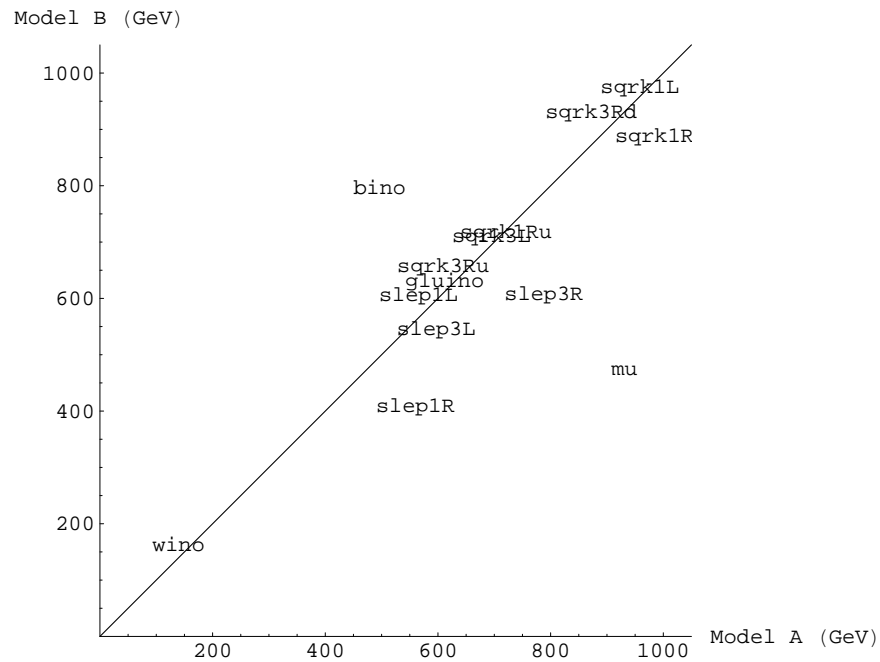


Left/Right Swap: From Cascade Run

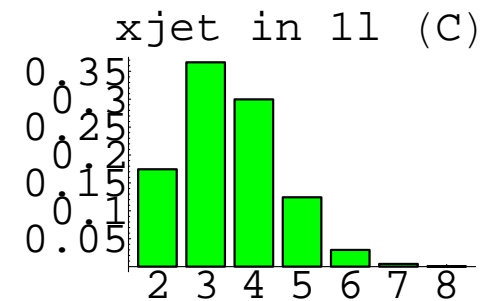
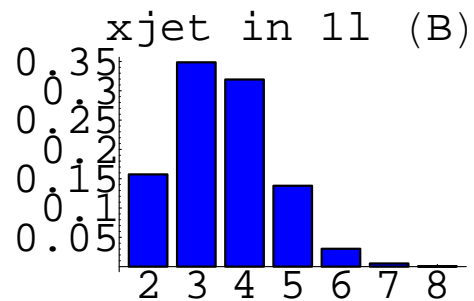
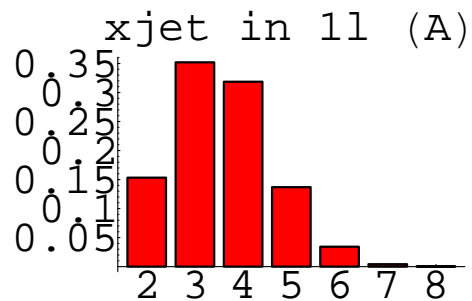
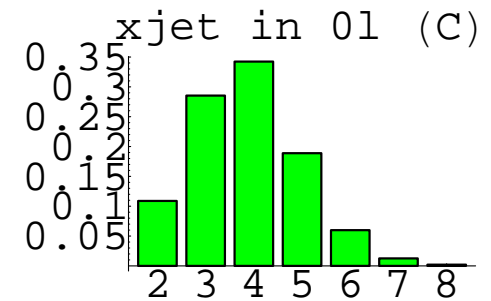
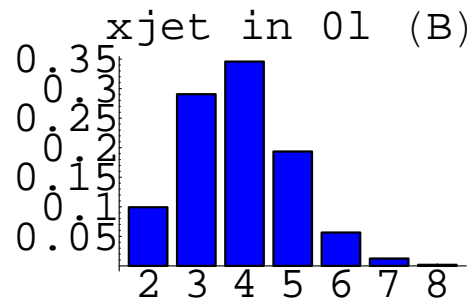
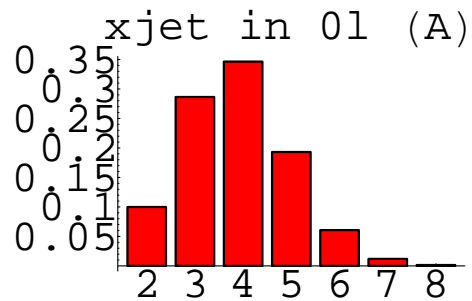
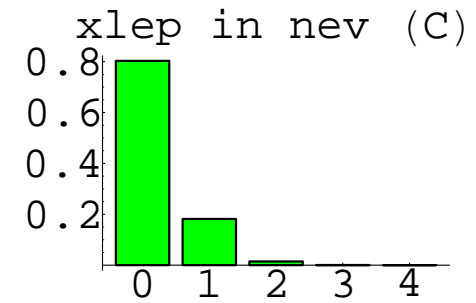
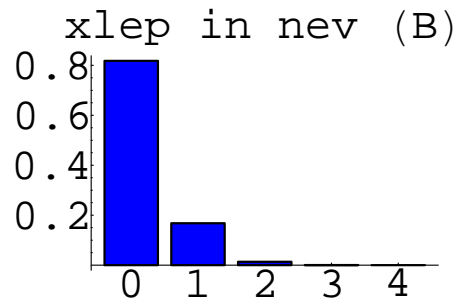
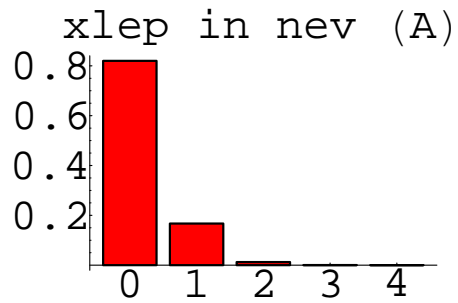


“Are There Really Degeneracies?”

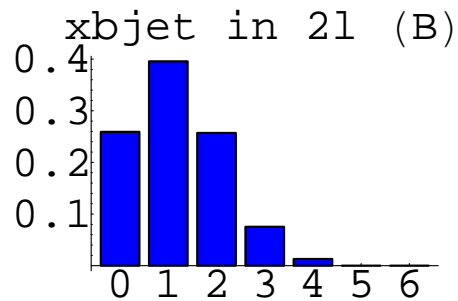
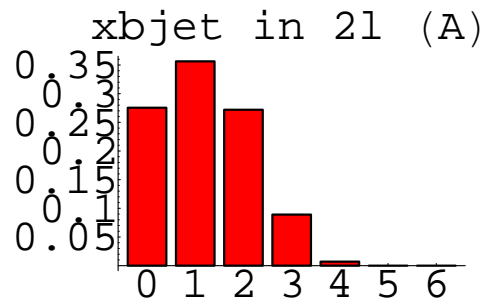
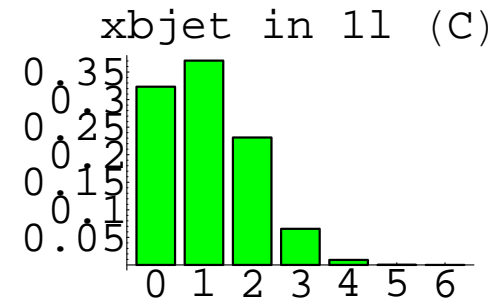
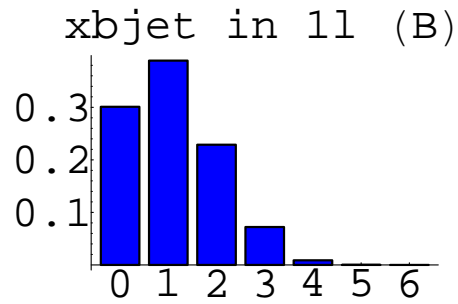
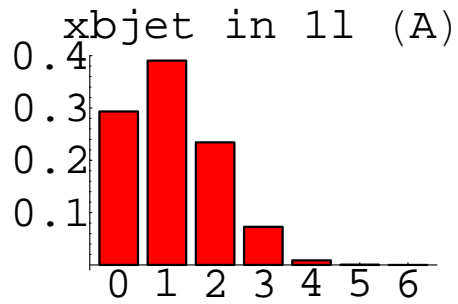
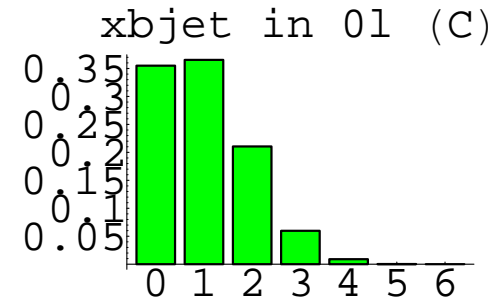
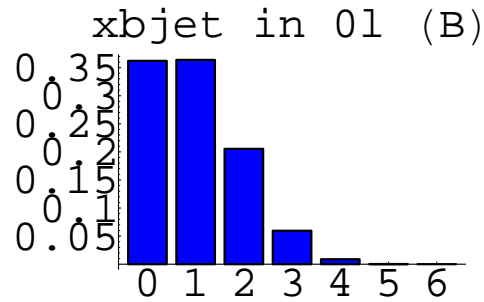
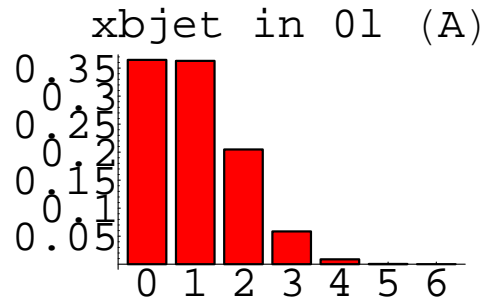
Case Study: MSSM 26 vs. 6226 vs. 26



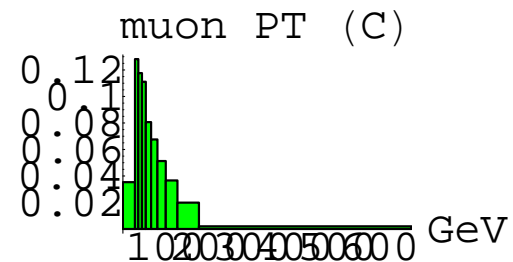
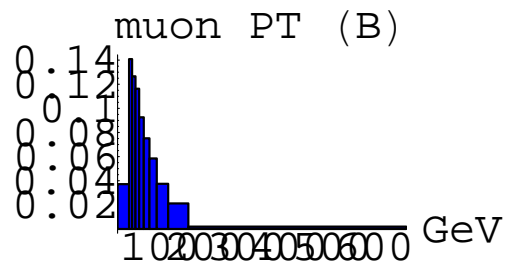
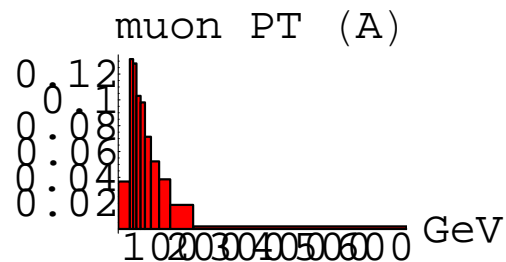
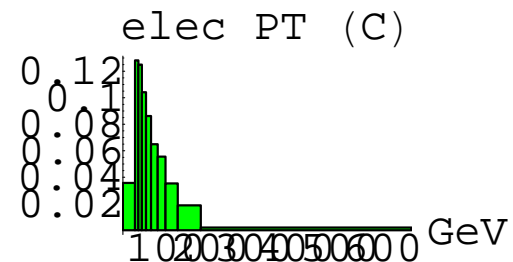
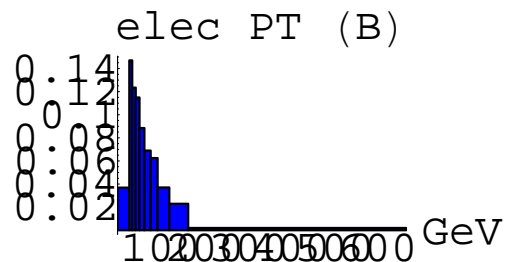
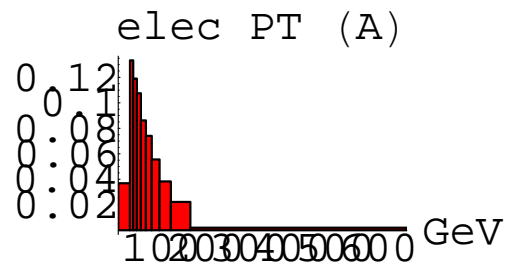
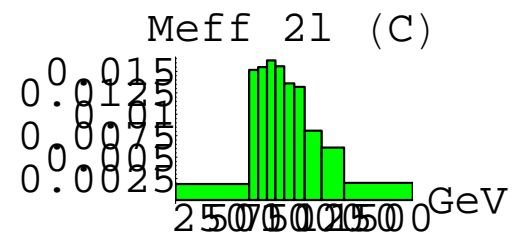
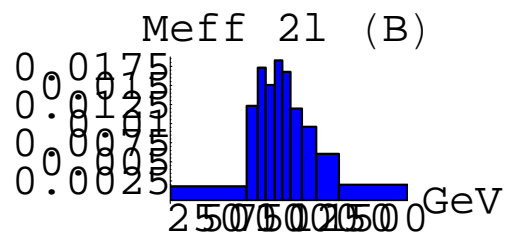
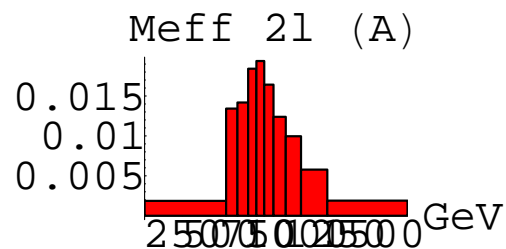
A = B or B = C ?



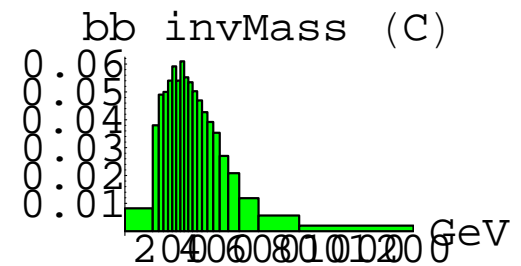
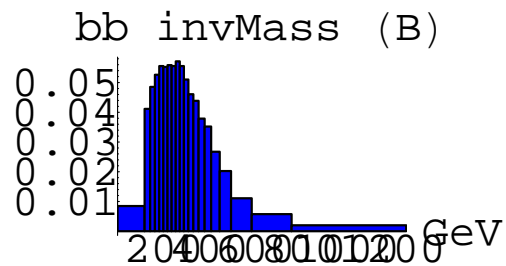
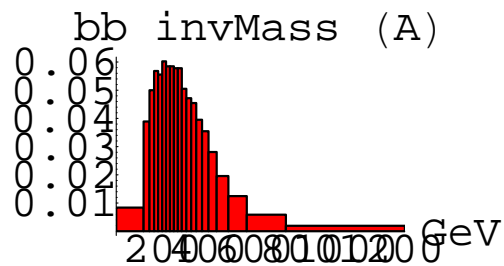
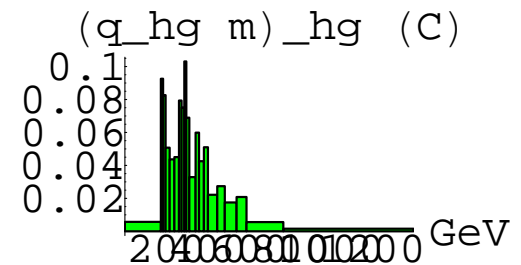
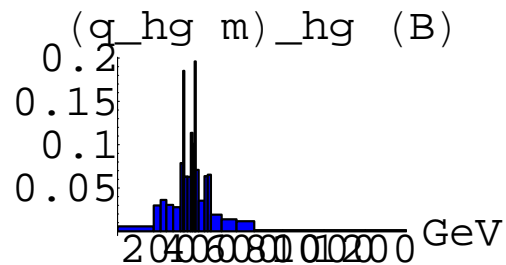
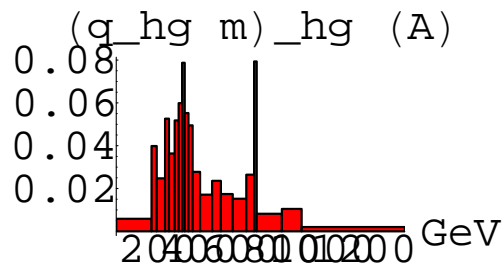
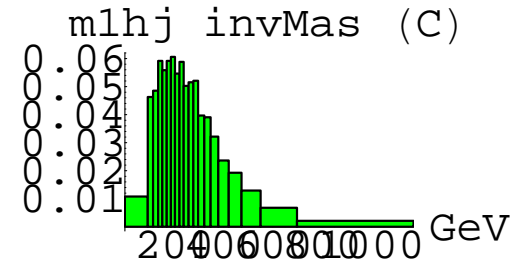
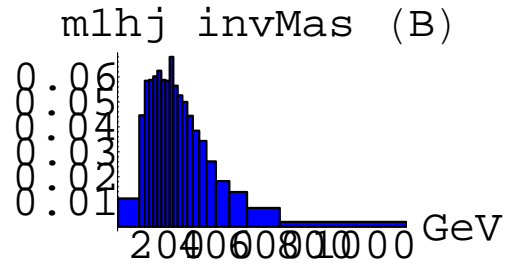
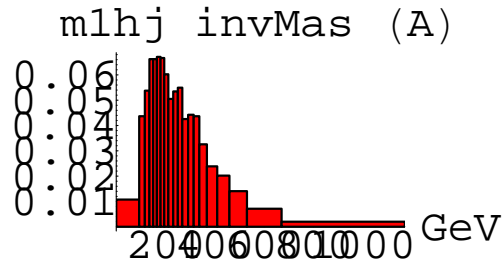
$$\tilde{W} < \tilde{B} < \mu \text{ or } \tilde{W} < \mu < \tilde{B} ?$$



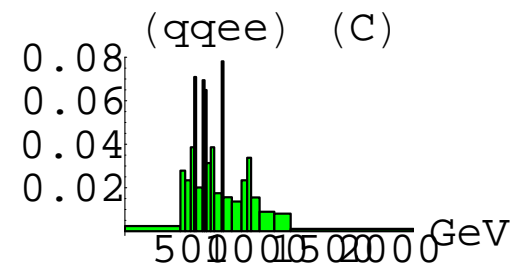
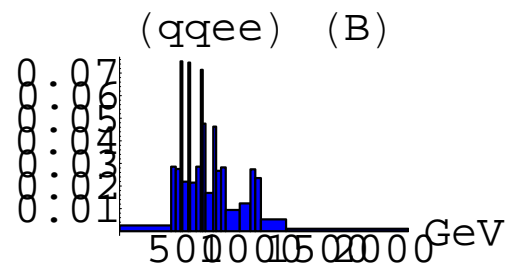
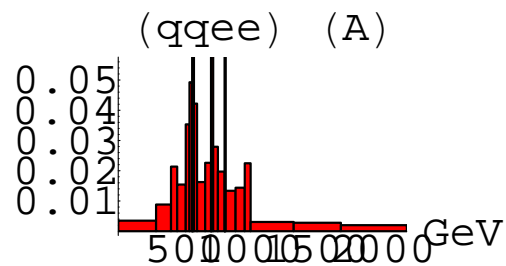
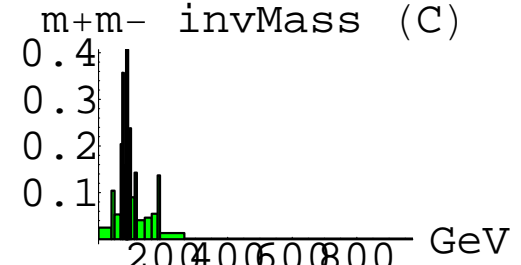
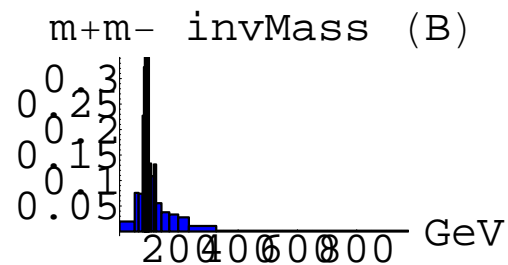
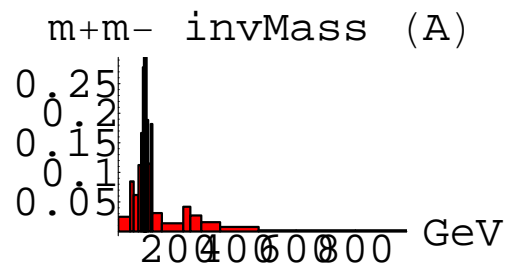
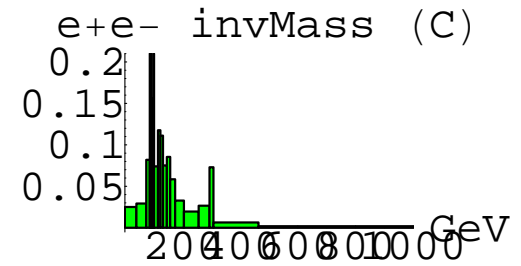
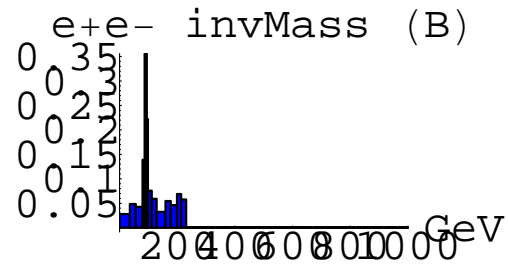
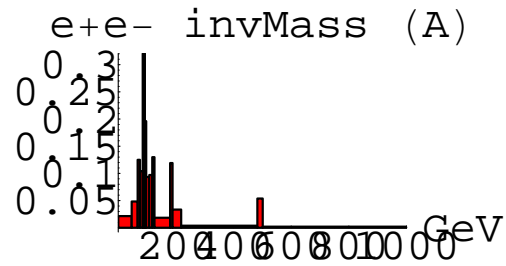
Wait Until ILC?



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

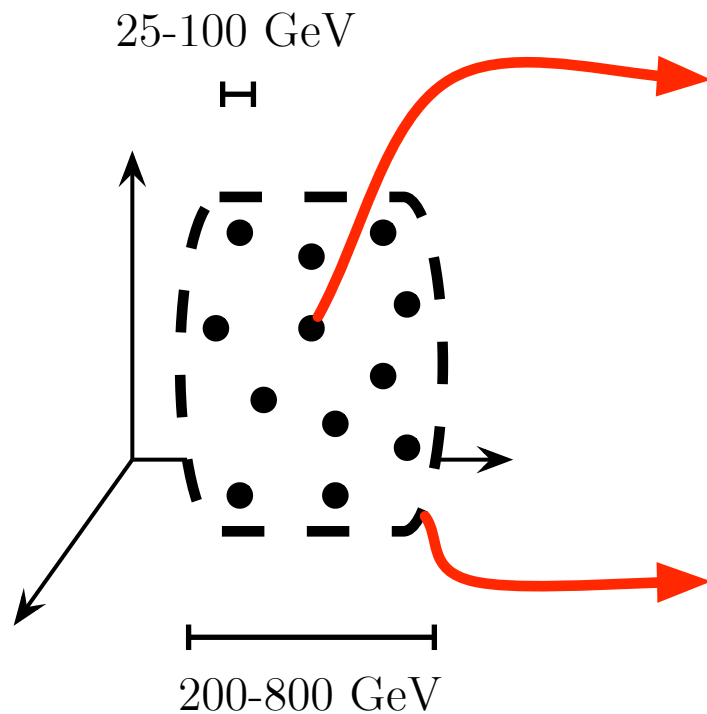


The Answer is $A = B$ (Computer: $B = C$)



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 for leptophilic models? At 300 fb^{-1} ?
With SM background?)

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

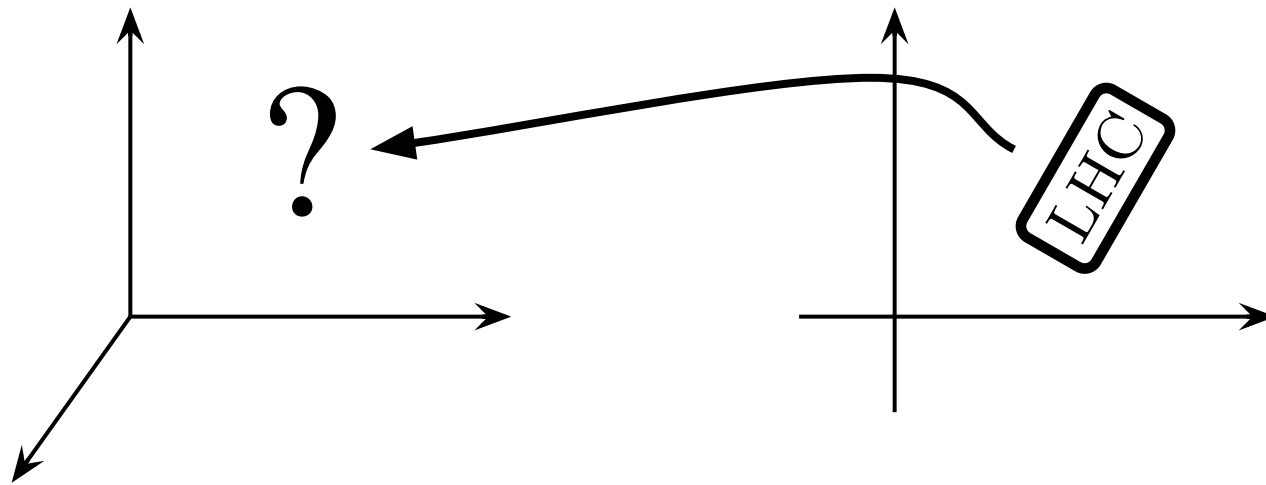
Statistical techniques useful for diagnosis, but once we have data, how will we actually “rule in” models?

The LHC Inverse Problem

Very little work in this direction. This question is perfect for particle physicists trained as model builders.

Parameter Space

Signature Space



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

An Invitation to the LHC Olympics

Competition as motivation for interpreting data.

The First LHC Olympics: CERN, July 2005

University of Michigan Blackbox

(Partially Analyzed by University of Washington)

The Second LHC Olympics: CERN, February 9-10, 2006

Three New Blackboxes (Harvard, UMich, UWash)

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