New Physics at the LHC

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• Outline

1. What to expect at the LHC

   Supersymmetry, compositeness

2. How well can we untangle the structure of new physics

   Example: MSSM

3. Conclusion and future directions

LHC: $p\ p$ collider. 2007.

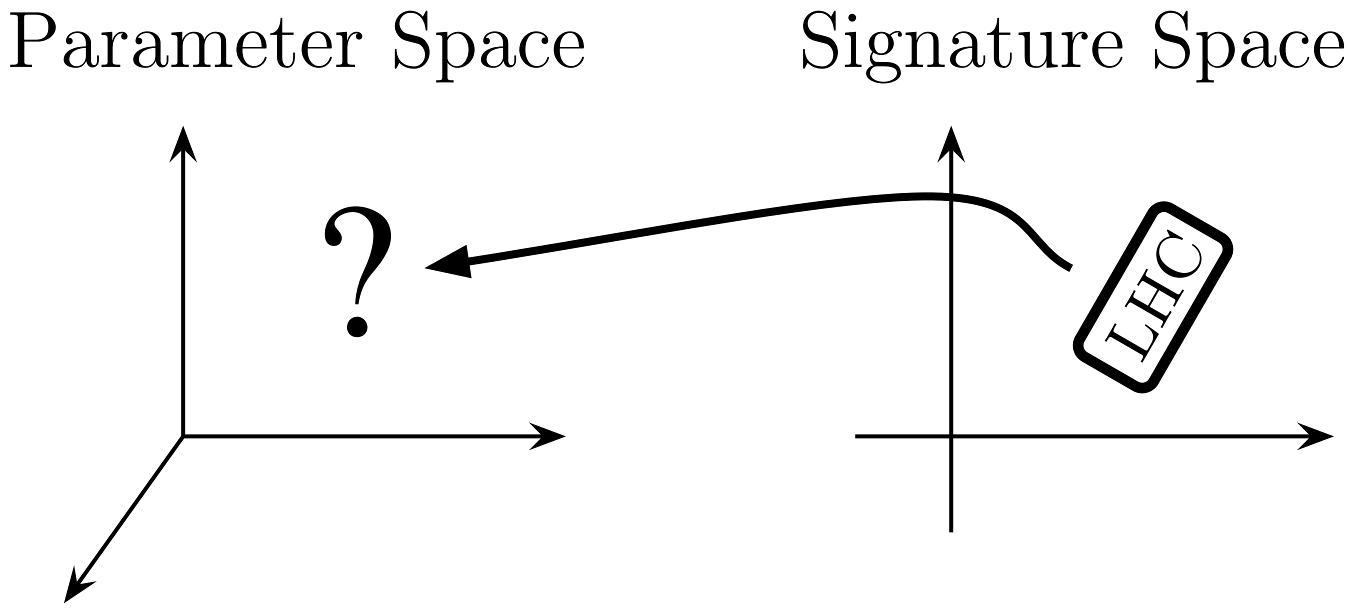
Energy: $E_{\mathrm{cm}} = 14$ TeV

New physics 100 GeV - several TeV $\sim 4\pi \times \Lambda_{\mathrm{EW}}$!

If there is new physics responsible for the stability of the weak scale, it has to come in at $4\pi \times \Lambda_{\mathrm{EW}}$

At the LHC: Fully explore such new physics and start to understand the mystery of the weak scale.

The *inverse* problem: LHC data $\rightarrow \mathcal{L}_{\text{New Physics}}$



General Character of the inverse map (One-to-One?)

How can we extract as much information as possible about the underlying theory from data?

• What to expect

In order to study the inverse problem, it is important to understand what to expect first.

Focus of decades model building and anticipation

new physics $\leftrightarrow$ the mystery of the weak scale

$\longrightarrow$ new (BSM) information about the fundamental theory

- Mystery of the weak scale

1. (big) Hierarchy problem: $\Lambda_{\mathrm{EW}} << M_{\mathrm{Pl}}$

a. How to generate a scale very different from the Planck scale

QCD: Logarithmic running $\rightarrow$ exponential separation of scales.

b. How to stabilize such a scale

Two classes of ideas: supersymmetry, compositeness

• Mystery of the weak scale

2. (little) Hierarchy problem:

Tension between the size of higher dimensional operators and the size of radiative corrections to the electroweak scale.

$$\text{Naturalness of the weak scale} \;:\; \Lambda_{\mathrm{NP}}^2 \sim 16\pi^2 \Lambda_{\mathrm{EW}}^2$$

$$\frac{\mathcal{O}^{(5)}}{\Lambda_{\mathrm{NP}}},\ \frac{\mathcal{O}^{(6)}}{\Lambda_{\mathrm{NP}}^2} \to \text{EWPT, flavor, EDM...} \;:\; \Lambda_{\mathrm{NP}}^2 \sim (16\pi^2)^2 \Lambda_{\mathrm{EW}}^2$$

Little Hierarchy problem ($\mathcal{O}(1\%)$ tuning) is the focus of many model building in the past decade. Many variations of models exist.

• Supersymmetry

The big Hierarchy

Scale generation: hidden sector dynamics

Stability: supersymmetry $\rightarrow$ non-renormalization theorem $+$ soft-breaking

Little Hierarchy Problem of supersymmetry breaking

after LEP, B-factories, EDM...

1. FCNC: Generically, there is no "super-GIM" mechanism.

2. CP: Generically, $>>$ Jarlskog, enter at lower loop order

3. m_{Z} vs m_{SUSY}

$$
\begin{aligned}
\Lambda^2_{\mathsf{EW}} &\sim m^2_{\mathsf{Z}} \sim -\mu^2 + m^2_{H_u} + \ldots \\
\mathsf{RGE} \to m_{H_u} &\sim M_{\mathsf{color}}(\tilde{q}, \tilde{g}) \\
M_{\mathsf{color}} &> M_{\mathsf{electroweak}}(\tilde{\ell}, \tilde{W}, \tilde{B})
\end{aligned}
$$

Is there natural mechanism of supersymmetry breaking which is consistent with all these constraints?

- Many SUSY breaking scenarios/models:

  GMSB, AMSB, gaugino-MSB, ...

  Gravity mediation with flavor symmetries.

  special relations between soft parameters

    e.g., focus point, AMSB+moduli...

  Various string theory constructions...

Fine arts of supersymmetry breaking have been developed to deal with the little Hierarchy problem. Many of them very sophisticated.

No clear winner...

Lesson from two decades of model building and experimental search:

If supersymmetry is responsible for the weak scale, its implementation is probably subtle, and/or complicated, and/or strange.

It is interesting to explore radically new ideas in model building.

On the other hand, it is hard to be sure that we are getting closer to the answer by refining our current setups.

Is little hierarchy solved by mechanism or an 1% accident?

Good news: LHC will teach us a lot about it!

• Learning supersymmetry breaking from the LHC

Starting Point:

Low energy effective Lagrangian with the possibility of incorporating all possible supersymmetry breaking models.

$$\mathrm{MSSM} + \mathrm{V(h)}$$

Measurement of parameters in it will lead us toward specific supersymmetry breaking scenarios.

The supersymmetry LHC inverse problem: how well can we extract information about the *general* MSSM Lagrangian from the LHC data

• Non-SUSY: Many models

Common character (bottom-up):

Cutoff $\Lambda \sim \mathcal{O}(10)$ TeV

same spin resonances $\rightarrow$ SM partners: W', T',...

Some ingredients of little hierarchy:

discrete symmetry, $SU(2)_C$, collective breaking.

flavor sequestering/localization

UV completion: possibly some strong dynamicsetion: possibly some strong dynamics

• Non-SUSY: one general framework

1. Large hierarchy:

TC, Randall-Sundrum (Higgsless);   Stability: compositeness

2. Little Hierarchy:

composite Higgs/(little Higgs $\cong$ A^5-Higgs)
many variations: simple group, product group, holographic Higgs...

Z_2 parity: T-parity$\cong$ UED/KK-parity

Localization of fermions in RS $\cong$ elementary/composite mixing

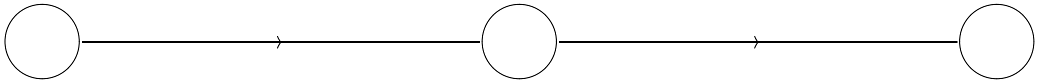
None of them works straightforwardly $\rightarrow$ trick-rich era of model building.

We need information from the LHC!

Starting point: Simple parameterization of low energy effective Lagrangian

- A simple setup:*

Global : SP(4) $f_1 e^{\xi_1}$ SP(4) $f_2 e^{\xi_2}$ SP(4)



Gauged : $SU(2)_1$ $SP(4)_c$ $SU(2)_2$

fermions : $t_1^c,\ b_1^c$ q_L, Q t_2^c, b_2^c

Non-linear σ-model with custodial $SU(2)$.

PGB: $h \subset \xi_1 + \xi_2$ ...

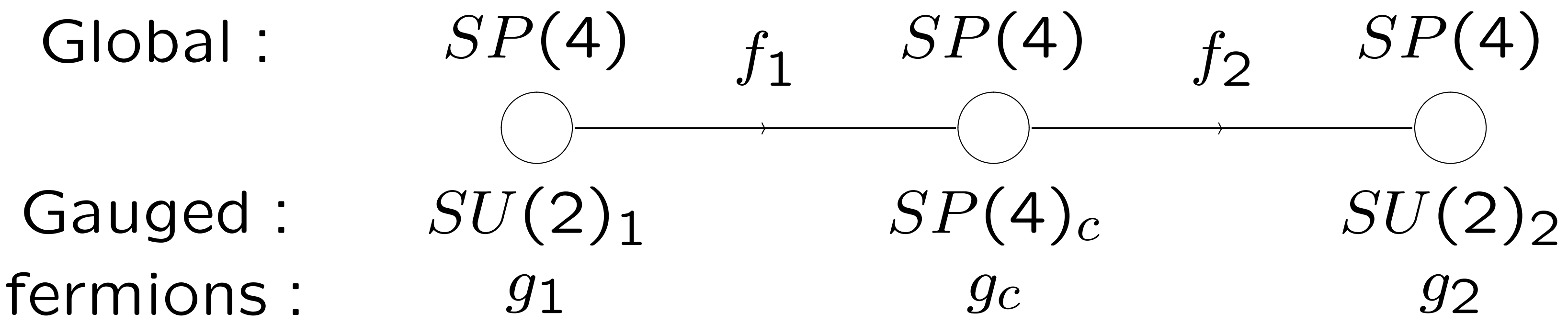
Heavy Gauge Boson: $W' \subset \{SU(2)_1\text{-}SU(2)_2, SU(2)_c\}$ ...

Fermions: SM $+ \{T,\ (t_1^c - t_2^c)\}$ ...

Extensions to different symmetry structures are straightforward if we discover more/less exotics.

*H. Cheng, J. Thaler, LW to appear

• Limits



UED/T-Parity:	$g_1 = g_2$
Simple group LH:	$g_1,\ g_2 = 4\pi$
Product group LH:	$g_c = 4\pi$
fermion localization:	$f_2 >> f_1$, adjusting fermion mass parameters
holographic higgs:	$g_2 = 4\pi$

More importantly, if the idea of compositeness is correct, we will learn the specific realization of it by measuring parameters at the LHC.

• Possible outcomes from the LHC:

1) Resonances:

hierarchy problem of the weak scale

W', T'-like states, KK-graviton...

$\rightarrow tZ$, hZ, hW, WW, ZZ, $t\bar{t}$...

Z' or some other new gauge bosons

...

'bump' searching, probably not hard to untangle the qualitative features.

- Possible outcomes from the LHC:

2) No resonances

discrete symmetries

Motivated by dark matter, EWPT

Examples: R-parity in SUSY, KK-parity in UED or T-parity in LH

Harder to interpret.

focus of the rest of my talk

• Inverse problems

1. Is it supersymmetry?

2. With in a framework:

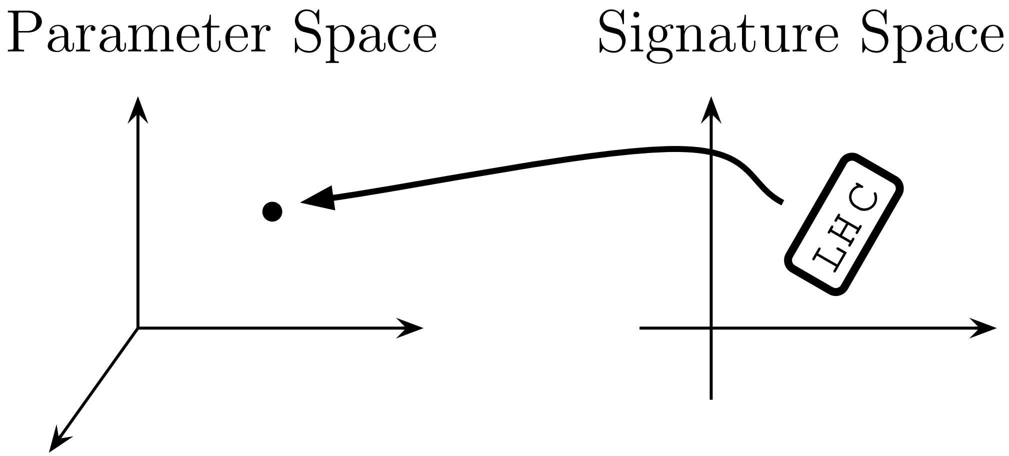
   identities, scales and interactions of the new particles

   How is little hierarchy problem resolved (dismissed?)

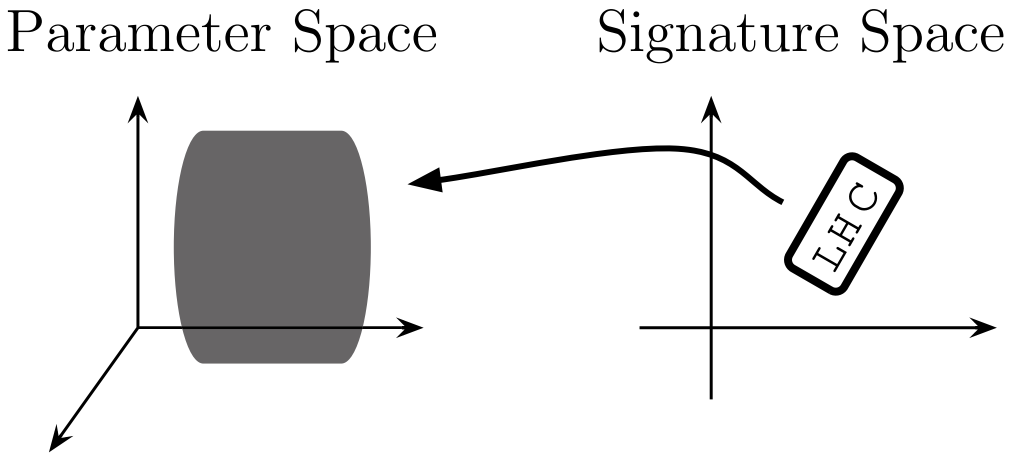
Here, I will focus on 2.

Information about the structure of the model will help 1.

Best of all Possible Worlds



Worst of all Possible Worlds



• Study the LHC inverse problem: MSSM

Low energy supersymmetry is the most compelling candidate for physics beyond the Standard Model

perturbative gauge coupling unification
$\longrightarrow$ deep connection to fundamental theory at high scale

It has rich structures which is typical for a model of new physics responsible for the weak scale

spectacular signals, challenging to interpret

• MSSM parameter space at the LHC: $D_{\mathrm{para}} \sim 20$

Largest cross section, important links in decay chains...

$$M_{\tilde{g}} \quad M_2 \quad M_1 \quad \mu$$

$$m_{\tilde{q}_L}^{1,2} \quad m_{\tilde{q}_R}^{1,2} \quad m_{\tilde{t}_{1,2}} \quad m_{\tilde{b}_{1,2}} \quad A_t \quad A_b$$

$$m_{\tilde{\ell}_L}^{1,2} \quad m_{\tilde{\ell}_R}^{1,2} \quad m_{\tilde{\tau}_{1,2}}$$

$$\tan\beta$$

$$m_h \quad m_A \quad m_H$$

• Signature space: what do we observe at the LHC?

jet, b-flavored jet, $e^{\pm}$, $\mu^{\pm}$, $\tau^{\pm}$, γ, $\not{E}_T$,

$\rightarrow$ $\mathcal{O}(10)$objects per event

P_{μ}^{i},

flavor, charge

Typical SUSY signal:

$$\begin{aligned} pp &\rightarrow \text{[colored superpatners]} + \text{jets} \\ &\rightarrow \text{more jets} + \text{(leptons/photon)} + \not{E}_T \end{aligned}$$

• MSSM signature space at the LHC

1. Number counting: (145 used in our study)

$n_j \times$ jet	b-jet non-b-jet
$+$	
$n_\ell \times$ lepton	ℓ all flavor and charge combo: e.g. $2\ell \rightarrow$21 comb.
$+$	
$n_\gamma \times \gamma$	

More inclusive: Nev, $\mathrm{N}_{1\ell}$, ...

For example: lepton counting contain information such as

color/electroweak, additional source of lepton besides W/Z

2. Kinematical distributions

$\sum P_T$: sum over any combination of interests

$\not{E}_T,\ P_T$ leading lepton, jet, b-jet...

M_{eff} many combinations:

3 hardest jets, 2 hardest b-jets....

m_{inv}: many combinations of objects

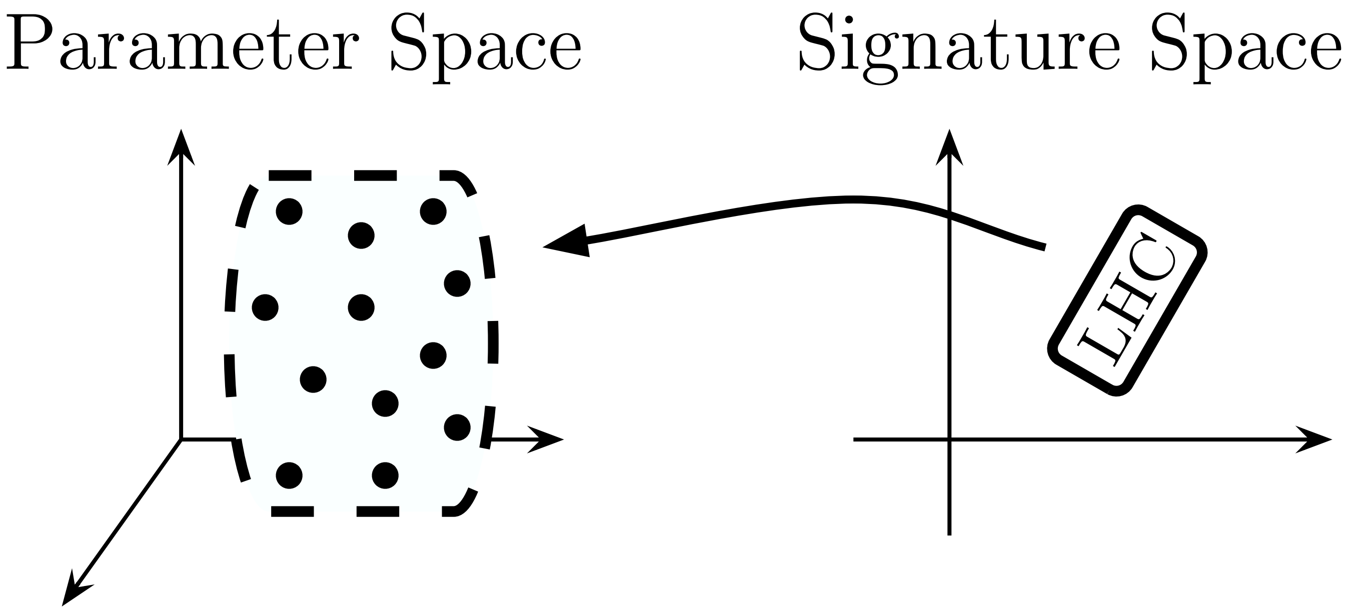
$m_{\text{inv}}(i, j, ...),\ i,\ j = \ell,\ b,$ jet

e.g. $m_{\ell+,\ell-},\ m_{bb},\ m_{q\ell\ell},\ m_{q\ell},\ m_{qq\ell\ell}\ldots$

Most of Distributions charge/flavor specific, $\mathcal{O}(10)$ bins each

Total: $\mathcal{O}(10^3)$ observables, 1808 used in our study

- The Character of the Inverse Map*



Degeneracies!

Many $(O)10-100$ small footprints in a large overall region.
Interesting structures of degeneracy.

*N. Arkani-Hamed, G. L. Kane, J. Thaler, LW: hep-ph/0512190

Degeneracies have structures.

Important information about how to find degeneracies.

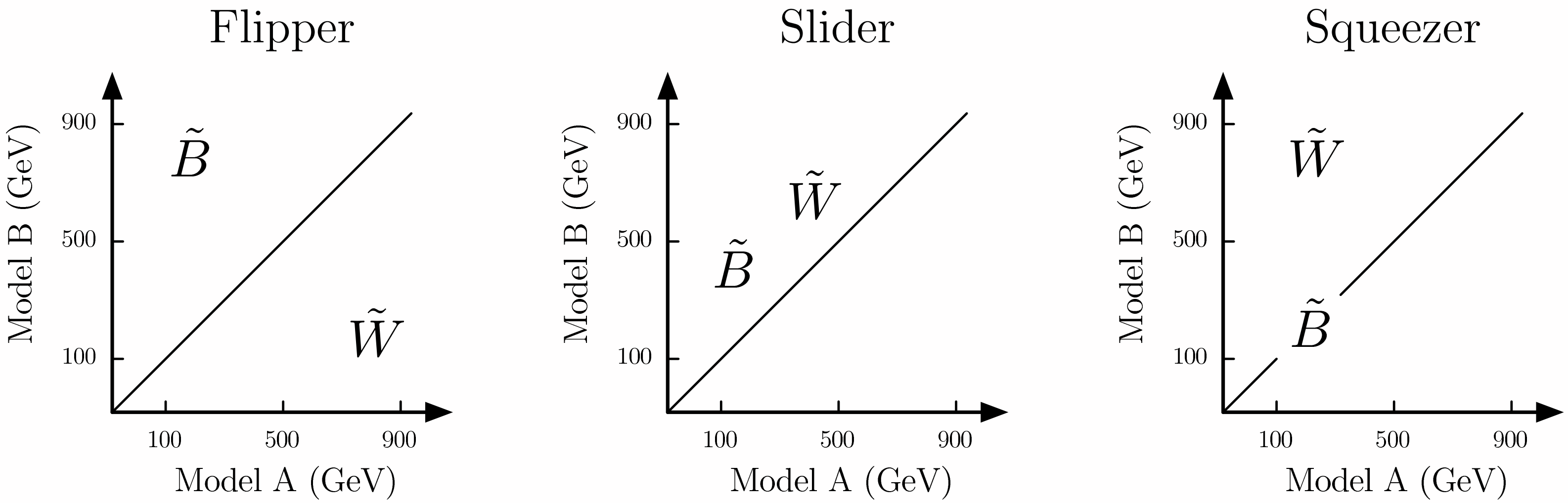
• Classification of degeneracies

Electroweak-ino

flipper: Mass, but not mass eigenstate

slider: only measure mass differences

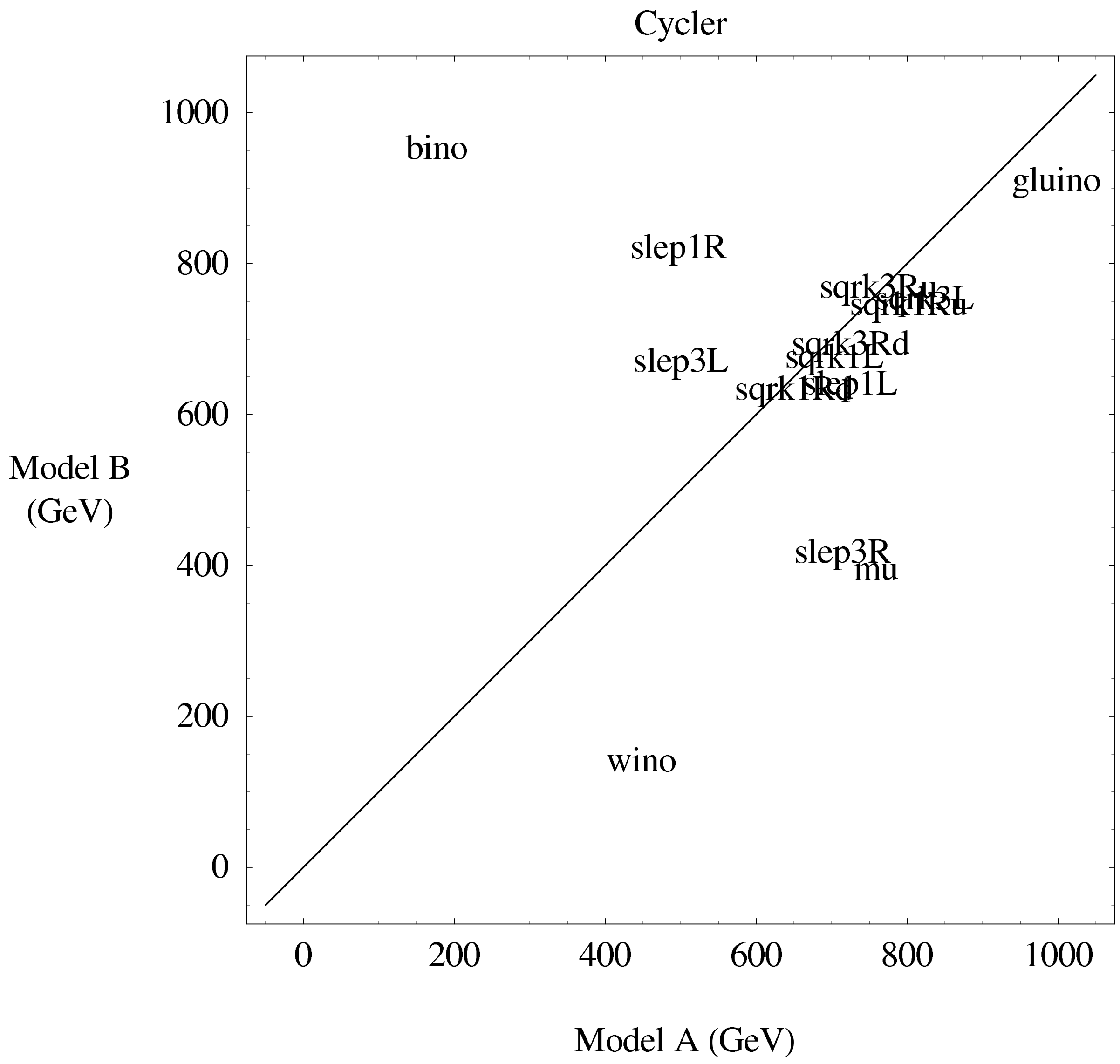
squeezer: can not measure soft stuff



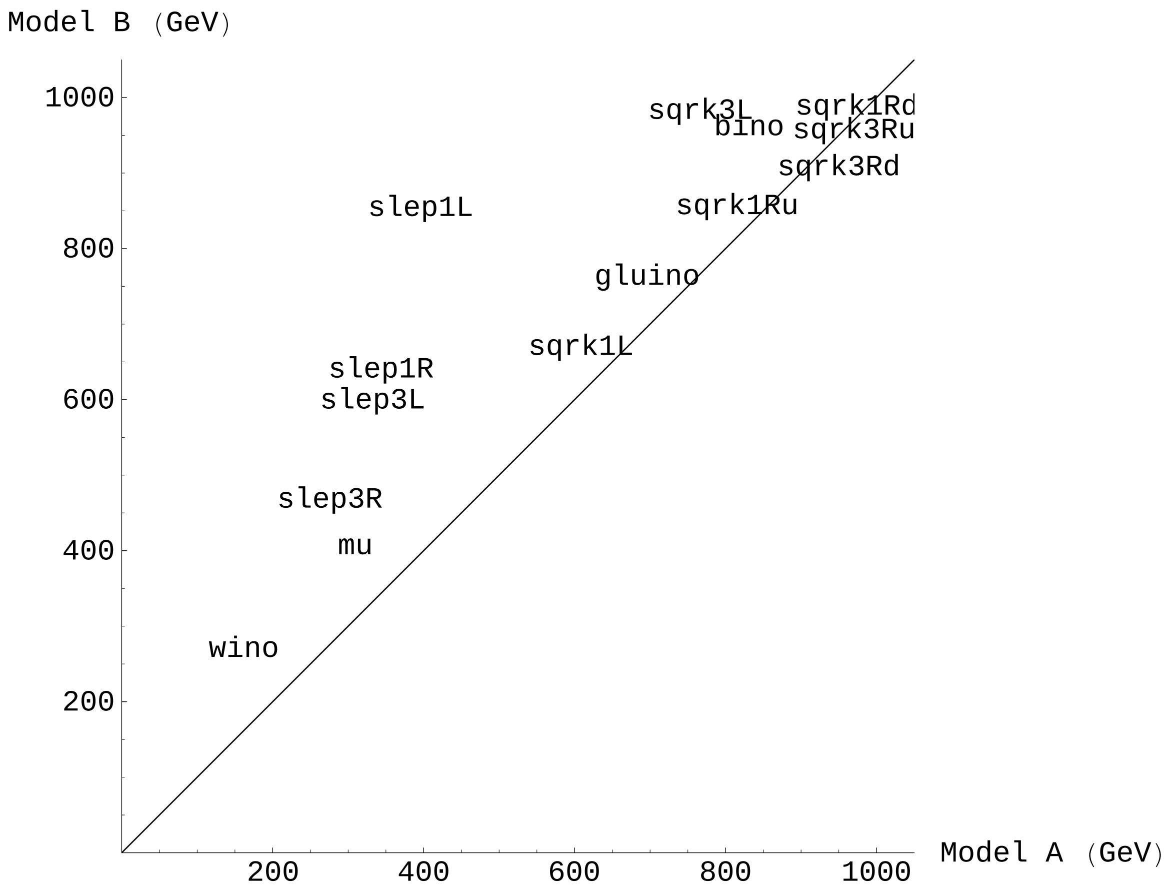
sfermion: LR split...

With light slepton: LR+ino combination flippers

1. flipper:

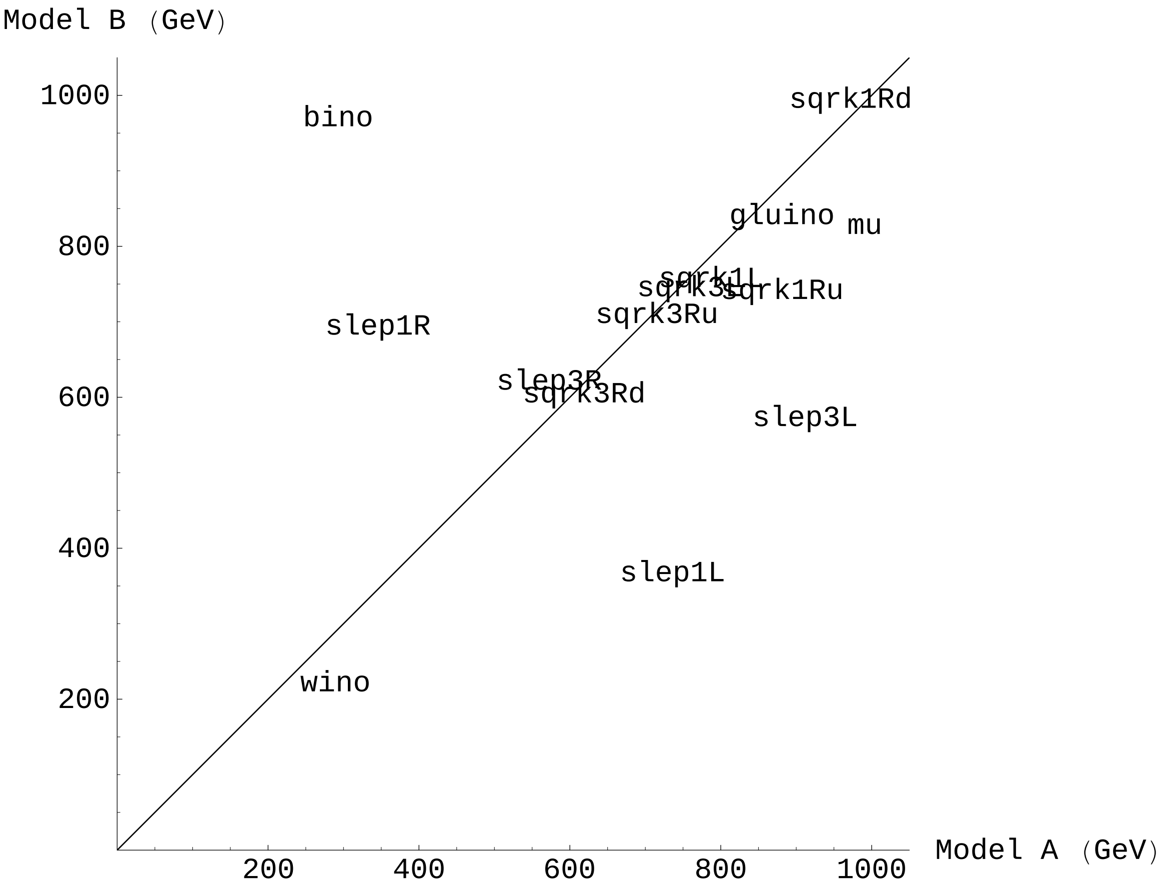

Cycler
bino
gluino
slep1R
sqrk3Ru
sqrk3Rd
slep3L
slep1L
slep3R
mu
wino
Model B
(GeV)
Model A (GeV)
0
200
400
600
800
1000

Slider:



Model B (GeV)
1000
800
600
400
200
sqrk3L
bino
sqrk1Rd
sqrk3Ru
sqrk3Rd
slep1L
sqrk1Ru
gluino
sqrk1L
slep1R
slep3L
slep3R
mu
wino
200
400
600
800
1000
Model A (GeV)

Squeezers:



Model B (GeV)
1000
800
600
400
200
bino
sqrk1Rd
gluino
mu
sqrk1L
sqrk3L
sqrk1Ru
sqrk3Ru
slep1R
slep3R
sqrk3Rd
slep3L
slep1L
wino
200
400
600
800
1000
Model A (GeV)

- Why are there degeneracies?

Colored particle $\rightarrow$ jets + ... :

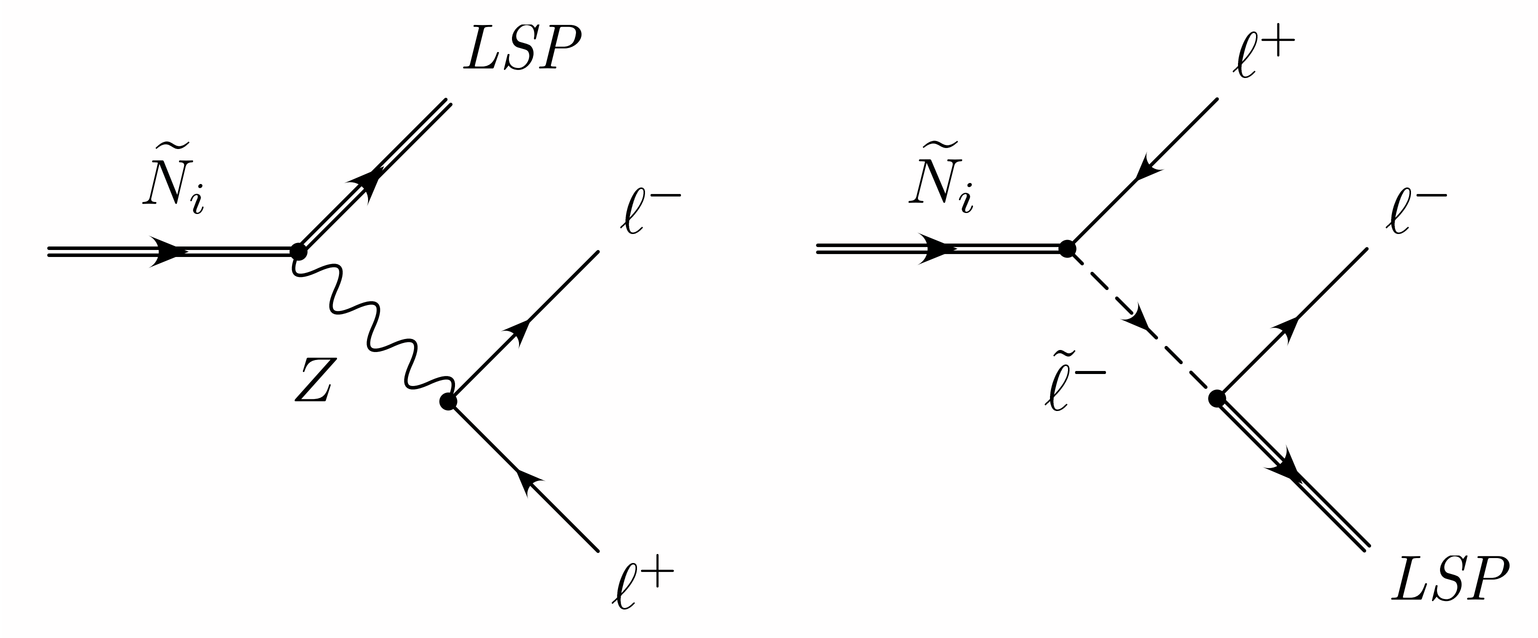
No flavor/charge information from the jets, except b-tag.

Electroweak-ino decay:

most of information in $W/Z \rightarrow$ leptons

h difficult: b-tagging, SUSY background

On-shell slepton in the decay chain will help!



on-shell slepton enhances significantly lepton signatures

More charge and flavor information

More handles on ino identities

However, no really good reason to expect this is generically true

Lessons from MSSM study:

For a generic point in MSSM parameter space,

there are qualitatively different points with very similar experimental outcomes at the LHC.

gaugino masses, μ, LR split, ...

In order to correctly interpret the new physics from the LHC signals, we have to confront them.

Effects of the Standard Model background and luminosity need to be studied more carefully.

Find the degenerate points: the most important first step

Small regions + large distance in between $\longrightarrow$ very hard problem

conventional algorithm won't work

A lot of experience and intuition are needed

go beyond our qualitative classification

signature-parameter correlation in many different scenarios

factor in detector performance...

We have to work hard and be innovative.

New methods to distinguish the degeneracies.

Difficult. Significant progress can be made.

a. New independent observables

Easy to evaluate effectiveness $\leftarrow D_{\text{sig}}$

b. Specific models $\rightarrow$ Specific correlations between observables.

c. Complimentary Effects of other non-LHC observables need to be included.

$g_\mu - 2$, B-decays, EDMs.

direct/indirect detection of Dark matter.

The General LHC Inverse Problem

Extensions of MSSM: NMSSM, $U(1)'$+MSSM, $SU(2)_R$ ...

Compositeness scenario

...

Similar (probably new) degeneracies are expected.

LHC at luminosity $10^{33} cm^{-2} s^{-1}$:

$\longrightarrow$ $\tilde{g}$, $\tilde{q} \sim$ 1 TeV : 1,000 events per month

$\longrightarrow$ Discover supersymmetry up to 2 TeV ($\tilde{g}$) in a year

h, $t\bar{t}$, B_{S}...

We have a lot of work to do!