What Does LHC Data Have to do with String Phenomenology?

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Executive Summary

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- Many good reasons why these new models should be string-derived (or “motivated” or “inspired”)

- The up-side of this exercise for string phenomenologists and model builders goes well beyond merely trying to make “predictions” for the LHC

What will this data look like?

$\Rightarrow$ What LHC actually looks for (CMS level one triggers):[1]

- EM objects (photons, electrons, muon) $E \gtrsim 15 - 30 \text{ GeV}$
- Taus (single or in pairs) $E \gtrsim 60 - 85 \text{ GeV}$
- 1, 3 or 4-jets with $E \geq 177,\ 86,\ 70 \text{ GeV}$
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- (1) Inclusive multijets with $N_{\mathrm{jets}} \geq 3$
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⇒ With skill we might turn these into (some) physical eigenstate masses and individual cross sections $\times$ branching ratios.

[1] *c.f.* list for CDF in R. Culbertson's talk Wednesday

Challenges at the LHC

But extracting this data requires model-dependent algorithms

⇒ Kinematic distributions can be powerful tools

- For multijet events with $E_T^{\rm miss}$ a useful quantity $M_{\rm eff} = E_T^{\rm miss} + \sum_{\rm jets} E_T^{\rm jet}$

⇒ For events with leptons we might use end-point information, but more model-dependent

- Consider $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \ell^+ \ell^-$: end point in the di-lepton invariant mass distribution for all isolated di-lepton + jets + $E_T^{\rm miss}$ events

$$M_{\ell\ell}^{\rm max} = m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0}$$

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- **But...** if there is a light enough slepton this measures something different!

$$M_{\ell\ell}^{\rm max} = \frac{1}{m_{\tilde{\ell}}} \sqrt{(m^2_{\tilde{\chi}_2^0} - m^2_{\tilde{\ell}})(m_{\tilde{\ell}2} - m^2_{\tilde{\chi}_1^0})} \qquad (1)$$

- Lesson: can always assemble the distribution and extract $M_{\ell\ell}^{\rm max}$, but its utility and meaning is model-dependent

Challenges at the LHC

$\Rightarrow$ Many such invariants can be formed (ℓq, $\ell\ell q$ etc) for different conjectured cascade decays (say squark decays)

- Gluino mass measurement from $\tilde{g} \to \tilde{b}_i b,\ \tilde{b}_i \to \tilde{\chi}^0_2 b$ chain
  - ⋆ Utility tested only in the mSUGRA paradigm
  - ⋆ What if $\tilde{b}$ is heavier than the gluino?
- Squark mass measurement robust when $\mathrm{Br}(\tilde{q}_R \to \tilde{\chi}^0_1 q) \simeq 1$
  - ⋆ True only when LSP is overwhelmingly B-ino (mSUGRA)
  - ⋆ Can bootstrap the mass of the squark only if you know the mass of the LSP (transverse mass distribution)

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EXAMPLE: LHC analysis trying to extract “SUSY mass scale” M_{SUSY} from M_{eff}, “We’ll have a general idea of these values *within a few days*....”

Example: LEP Higgs Search

⇒ We can see this already in the LEP MSSM Higgs search analysis

- Just assigning events to signature categories model-dependent
  - ⋆ Events can be assigned to either associated production mechanism $e^+e^- \to Zh$ versus $e^+e^- \to Ah$
  - ⋆ Some events may fit well in both hypotheses!
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⇒ *Even if we believe there was a signal, we still haven't nailed down the theory!*

Case	m_h	m_A	m_H	$\tan\beta$	C_h^2	C_H^2	ϕ	μ
1	82-110	$< m_h$	115	7-50	0.0	1.0	Y	Y
2	82-110	$\simeq m_h$	115	5-50	0.0	1.0	N	N
3	82-110	115-140	115	6-24	0.0	1.0	N	Y
4	115	$> m_h$	$> m_h$	3-50	1.0	0.0	N	N

Can we extract the soft Lagrangian?

⇒ Never enough observable quantities at hadron machines – need a model context to fill in the gaps

- Consider the simplest MSSM system: the chargino sector

$$M_{\chi^\pm} = \left(\begin{array}{cc} M_2 e^{i\phi_2} & \sqrt{2} M_W \sin\beta \\ \sqrt{2} M_W \cos\beta & \mu e^{i\phi_\mu} \end{array} \right)$$

- Assume measurement of eigenvalues: want to invert

$$m^2_{\chi_1^\pm} + m_{\chi_2^\pm} = M_2^2 + \mu^2 + 2M_W^2$$

$$m^2_{\chi_1^\pm} m^2_{\chi_2^\pm} = M_2^2 \mu^2 + 2M_W^4 \sin^2 2\beta - 2M_W^2 M_2 \mu \sin 2\beta \cos(\phi_2 - \phi_\mu)$$

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- If you try to get more observables by factoring in the branching ratio times cross section you now bring in sneutrino and slepton masses, the mass of the LSP, etc. Always more unknowns than observables at a hadron collider.

⇒ **CHALLENGE**: We'll need to understand the underlying theory *without the soft Lagrangian...*

Inclusive signatures vs. "IPOs"

How can we bypass the soft Lagrangian?

$\Rightarrow$ Need to calculate inclusive signatures, not stop at the soft SUSY breaking parameters

- Soft Lagrangian parameters $\leftrightarrow$ "In-Principle Observables" (IPOs)
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- Extracting specific (exclusive) information requires such crucial information as $\tan\beta$ and μ
- These are dynamically derived quantities and not part of the Lagrangian we receive from the string theorist

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$\Rightarrow$ Can this be done? *It must be done!*

If we want to constrict our favorite model's parameter space, we may need to "do it ourselves"!

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- Top-down string models just too “hard”
  - ⋆ Non-minimal particle content/gauge-groups
  - ⋆ Complicated moduli spaces
  - ⋆ Unknown thresholds and 4D dynamical effects
  - ⋆ Yukawa coupling “predictions” hard to make

⇒ If we simply need more examples – and more *variety* of examples – as **exercises**, why bother?

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$\Rightarrow$ **PROGRAM**: Begin with candidate underlying theories. Make motivated assumptions as needed. Calculate inclusive signatures. Vary the assumptions.

Moduli stabilization and SUSY breaking

$\Rightarrow$ Moduli which couple to MSSM fields $\rightarrow$ a defining property of string-motivated 4D effective theories

- Often assume stabilization and allow all to participate in SUSY breaking
- Vacuum energy problem often solved by fiat

$$V = K_{I\overline{J}} F^I \overline{F}^{\bar{J}} - \tfrac{1}{3} M \overline{M} \qquad K_{I\overline{J}} \equiv \partial^2 K / \partial Z^I \partial \overline{Z}^{\bar{J}}$$

Require $\langle V \rangle = 0$ once SUSY is broken $[\langle F \rangle \neq 0]$

$$\begin{aligned} F^A &= -\frac{1}{\sqrt{3}} \overline{M} K_{a\bar{a}}^{-1/2} \sin\theta \rightarrow \sqrt{3} m_{3/2} K_{a\bar{a}}^{-1/2} \sin\theta, \\ F^B &= -\frac{1}{\sqrt{3}} \overline{M} K_{b\bar{b}}^{-1/2} \cos\theta \rightarrow \sqrt{3} m_{3/2} K_{b\bar{b}}^{-1/2} \cos\theta \end{aligned}$$

Moduli stabilization and SUSY breaking

Explicit stabilization mechanisms may suggest otherwise! Heterotic example:

- Finding a solution for the dilaton

  $\Rightarrow$ Assume a superpotential arises for S and T through gaugino condensation

$$W(S,T) = \Omega(S)\eta(T)^{-6} \qquad \langle\Omega\rangle \neq 0$$

  $\Rightarrow$ Two solutions for the dilaton field:

$$(1)\ F^S = (\Omega_s - K_s\Omega) = 0$$
$$(2)\ F^S \neq 0 \text{ and } (s+\bar{s})\Omega_{ss} = 2\Omega^* \left[1 - |(t+\bar{t})G_2(t,\bar{t})|^2\right]$$

Moduli stabilization and SUSY breaking

- Finding a solution for the Kähler moduli

$\Rightarrow$ When solution (1) prevails $V(T) \propto 3|\Omega|^2 \left[|(t+\bar{t})G_2(t,\bar{t})|^2 - 1 \right]$

$$\left\langle F^T \right\rangle \neq 0 \text{ and } \langle \text{Re } T \rangle \simeq 1.2$$

$\Rightarrow$ When solution (2) prevails $V(T) \propto 3|\Omega|^2 |(t+\bar{t})G_2(t,\bar{t})|^2$

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- Other examples
  - ⋆ Coefficients of GS counterterms
  - ⋆ Modular weights under $SL(2,Z)$ symmetries
  - ⋆ Anomalous $U(1)_X$ traces $\mathrm{Tr} Q_X$
  - ⋆ Matter and gauge fields in $N=1$ intersecting brane constructions

Gauge mediation and string models

$\Rightarrow$ Rarely mentioned together, but consider

- Often find exotics charged under both MSSM groups and other "hidden" groups
- If $F^X \simeq \sqrt{3} m_{3/2} M_{\rm PL}$ (*i.e.* $k = 1$), then gauge and gravity mediation comparable when $M_{\rm mess} = \Lambda_X \simeq 10^{17}$ GeV

$$\frac{m_{\rm gauge}}{m_{\rm grav}} \approx \frac{k}{16\pi^2} \frac{M_{\rm PL}}{M_X} \approx 1$$

Gauge mediation and string models

⇒ Yet the *minimal* GMSB model rarely appears

- Standard GMSB assumption: messengers are complete multiplets of SU(5)

- String models: triplets of $SU(3)$ and doublets of $SU(2)$ most common

- Messenger hypercharges are generally *not* those of SM analogs

⇒ **MORAL**: A broadening of parameter/theory space that was artificially restricted

- Other examples
  - ⋆ Variants on AMSB models
  - ⋆ Exotic neutrino sectors[2]
  - ⋆ Exotic flavor symmetries[3]
  - ⋆ Modular weights after integrating out anomalous U(1)'s

[2] *c.f.* P. Langacker talk Monday.

[3] *c.f.* S. Raby talk Thursday.

These variations have real impacts

- Kähler stabilization example
  $\Rightarrow$ Makes use of first class of heterotic moduli stabilizations
  $\Rightarrow$ Now one condensate can stabilize dilaton with $\langle V \rangle = 0$ and $g_{\rm STR} = \mathcal{O}(1)$

$$(K_{s\bar{s}})^{-1} \left| K_s - \frac{3}{2b_+} \right|^2 = 3 \quad \rightarrow (K_{s\bar{s}})^{-1/2} = \sqrt{3} \frac{\frac{2}{3}b_+}{1 - \frac{2}{3}b_+ K_s}$$

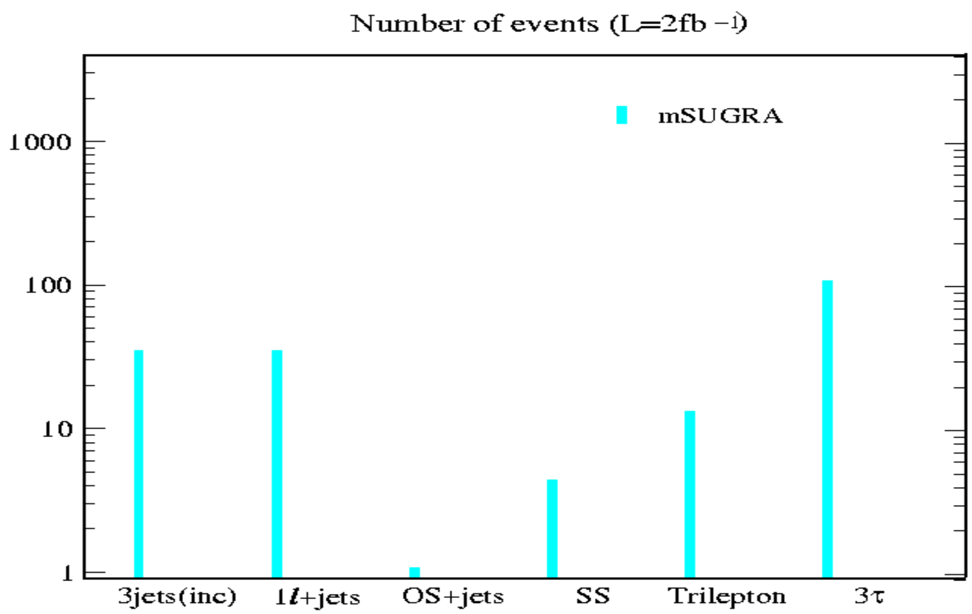
  $\Rightarrow$ Suppression of dilaton contribution to soft terms $(a_{\rm np} \simeq b_+)$

$$\left| \frac{M_a}{m_0} \right| = \sqrt{3} a_{\rm np} \frac{g_a^2(\Lambda_{\rm UV})}{g_{\rm STR}^2}$$

- Gauge mediation example
  $\Rightarrow$ LSP is not a gravitino $\rightarrow$ large $E_T^{\rm miss}$ still a good signature!
  $\Rightarrow$ Incomplete $SU(5)$ multiplet messengers leads to non-universal (but family-independent) soft masses

Tevatron Signatures

⇒ mSUGRA Point B of hep-ph/0106204



- $m_{1/2} = 250$ GeV ; $m_0 = 100$ GeV
- $\tan\beta = 10$; $m_h = 112$ GeV
- $m_{\tilde{g}} = 582$ GeV ; $m_{\tilde{\tau}_1} = 269$ GeV

Inclusive signals (all have large $E_T^{\rm miss}$)

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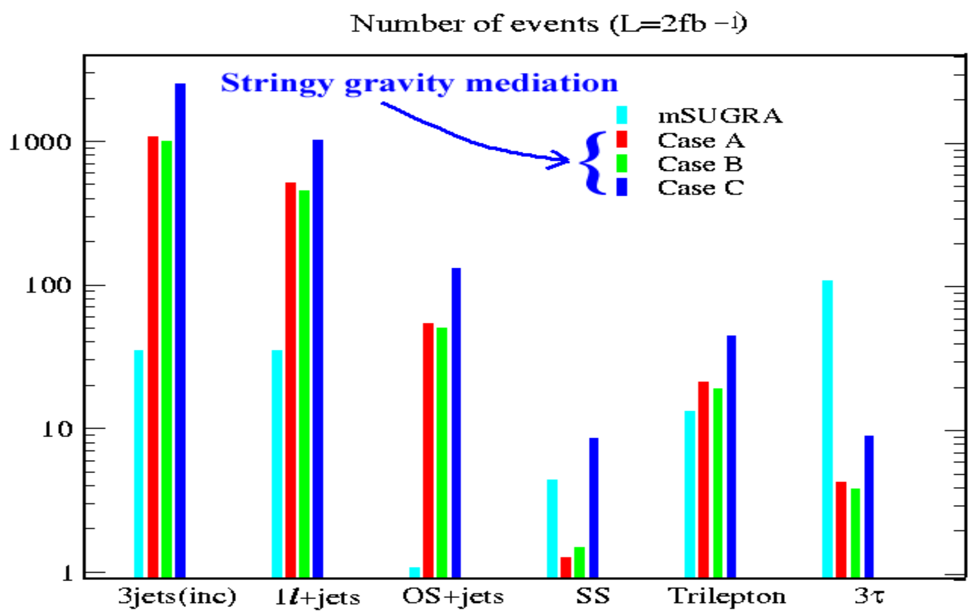
Tevatron Signatures

⇒ Dilaton domination + Kähler stabilization



- Possible $\mathcal{G}_+$: (A) E_6, (B) $SU(5)$, (C) $SU(3)$
- $\tan\beta = 10,\ 5,\ 5$
- $m_{3/2} = 1.5,\ 3.2,\ 4.3$ TeV
- $m_{\tilde{g}} = 330 - 470$ GeV
- $\widetilde{W}_3\%|_{\rm LSP} = 2.5,\ 0.6,\ 4.6\%$
- $\mu_{\rm NLO} = 245,\ 631,\ 481$ GeV

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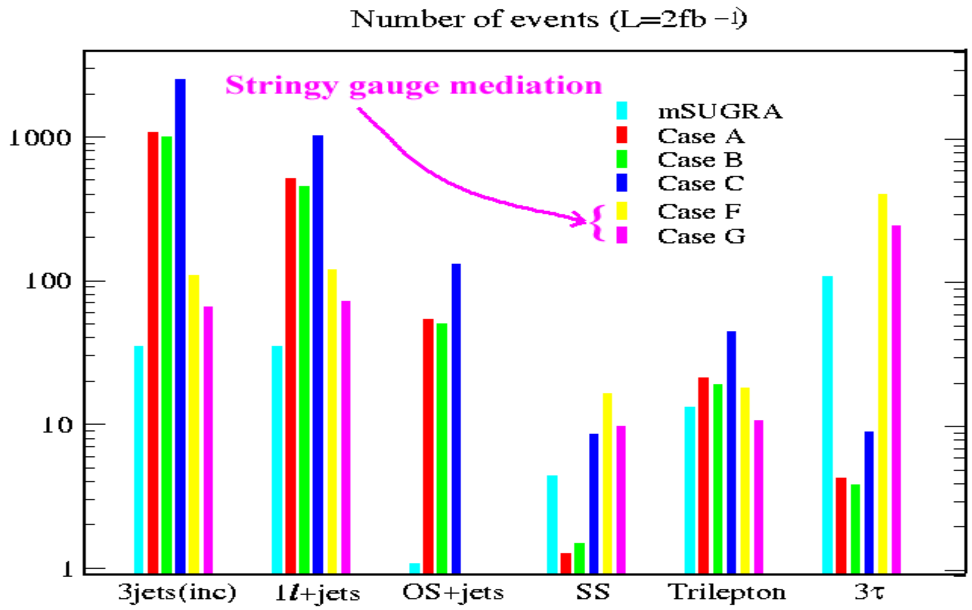
⇒ Gauge and gravity mediation



- $m_{3/2} = 120,\ 130$ GeV ; $\tan\beta = 10,\ 20$
- $M_X = 8 \times 10^{16}$ GeV ; $N_L = 4,\ 3$
- $m_{\tilde{\tau}_1} = 153,\ 135$ GeV

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New signatures to look for

A stringy variant on minimal AMSB signatures

- Imagine a very well motivated form for the gauge kinetic function

$$f_a = \sum_i \alpha_a^i \phi^i + \sum_j \frac{b_a^j}{16\pi^2} f(\varphi^j)$$

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$\Rightarrow$ This is the form of almost all string constructions at weak coupling
$\Rightarrow$ Let $\langle \phi^i \rangle = \langle \varphi^j \rangle = \mathcal{O}(1)$ but $\langle F^i \rangle = 0$
$\Rightarrow$ Gaugino masses suppressed and determined by combination of superconformal anomaly contribution and F^j contribution

New signatures to look for

A stringy variant on minimal AMSB signatures

- Imagine a very well motivated form for the gauge kinetic function

$$f_a = \sum_i \alpha_a^i \phi^i + \sum_j \frac{b_a^j}{16\pi^2} f(\varphi^j)$$

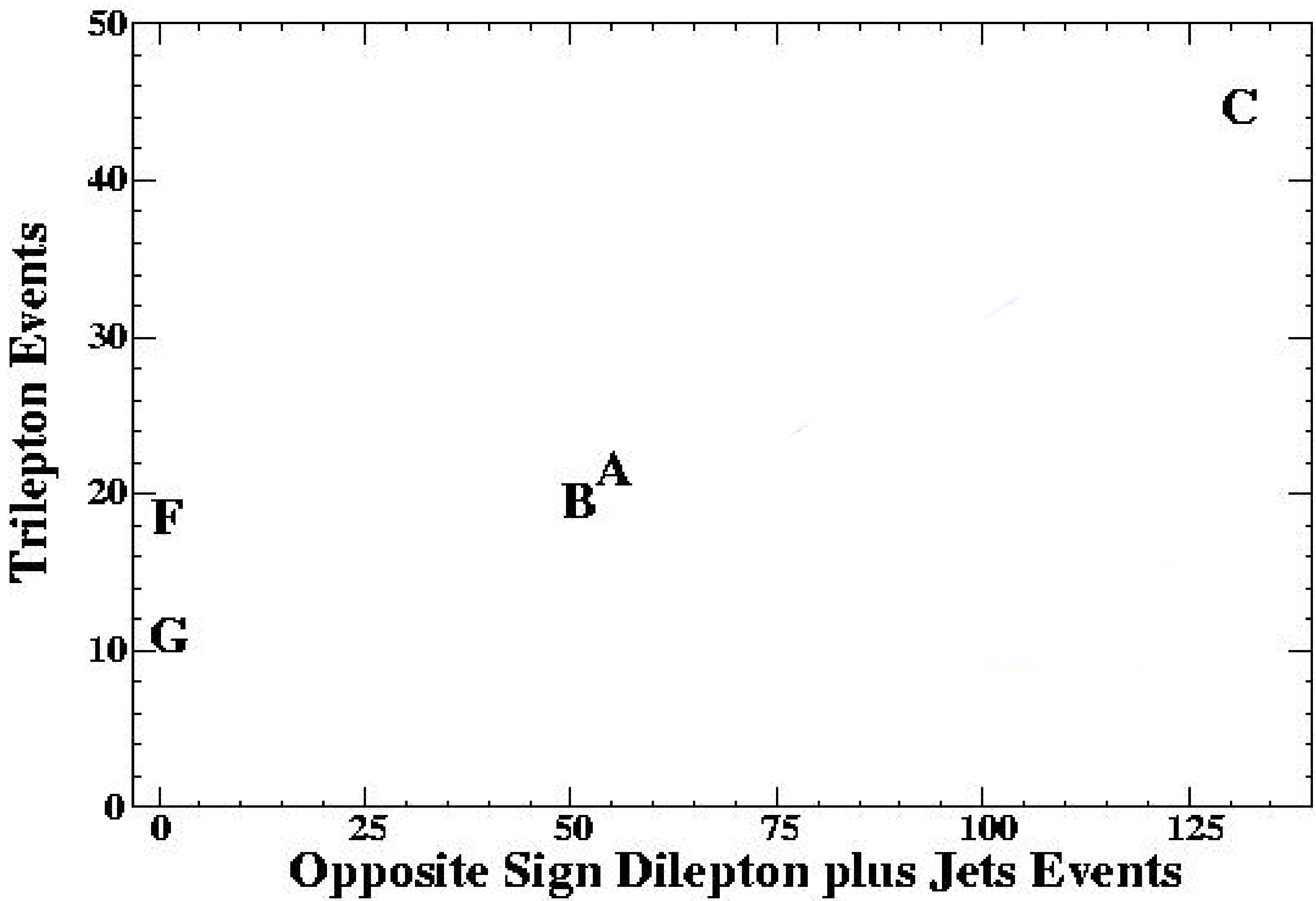
$\Rightarrow$ This is the form of almost all string constructions at weak coupling
$\Rightarrow$ Let $\langle \phi^i \rangle = \langle \varphi^j \rangle = \mathcal{O}(1)$ but $\langle F^i \rangle = 0$
$\Rightarrow$ Gaugino masses suppressed and determined by combination of superconformal anomaly contribution and F^j contribution

- LSP will have increased W-ino content, but need not be in the minimal AMSB regime

- Mass difference between $\tilde{\chi}_1^{\pm}$ and LSP need not be $\sim 140\mathrm{MeV}$

- New signature: four jets plus two isolated, high impact-parameter (but soft) charged pions

Distinguishing Models?



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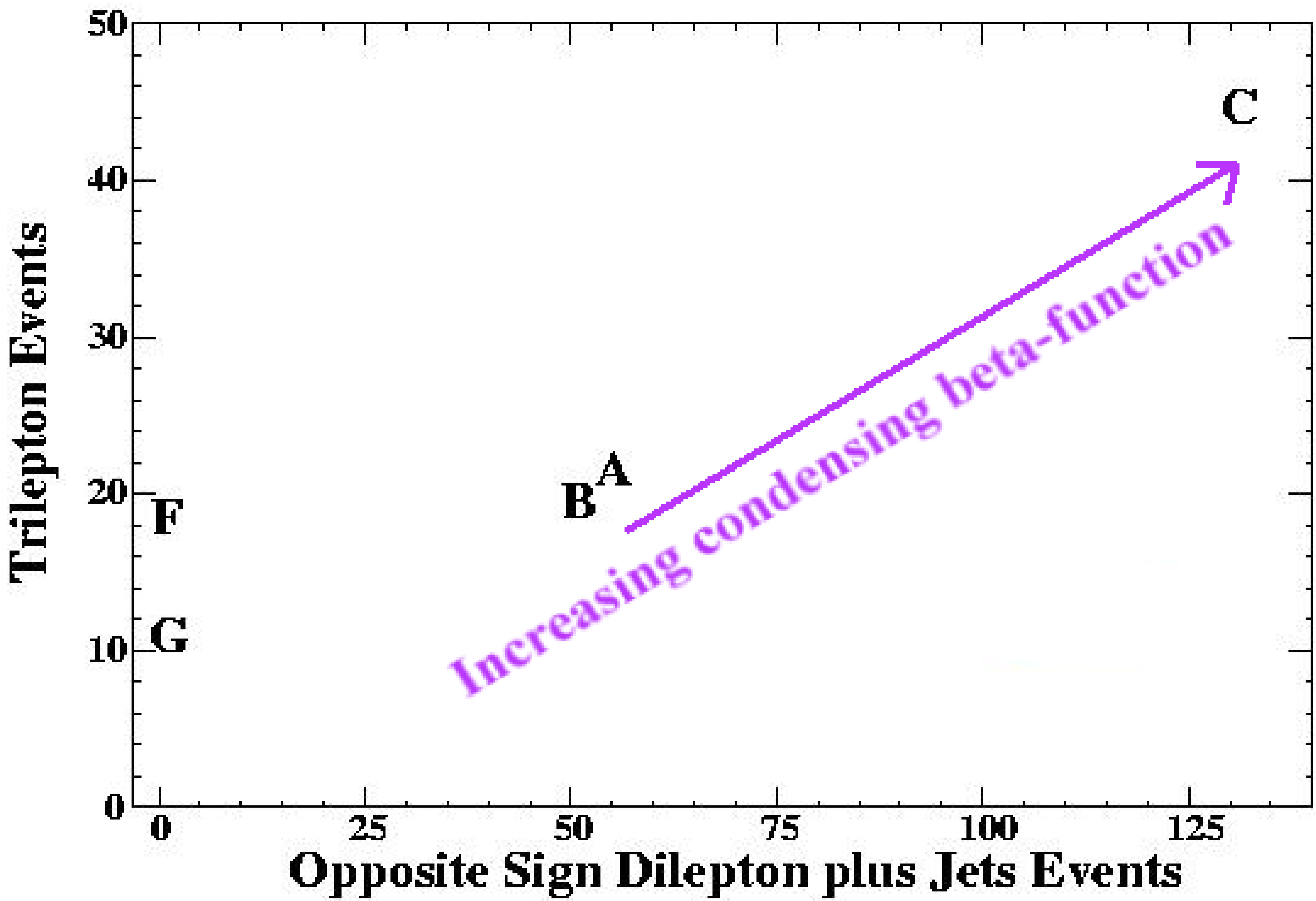


Distinguishing Models at the LHC

- (A) Generic mSUGRA
  [Battaglia et al., *Eur. Phys. J.* **C22** (2001) 535]
- (B) Focus point mSUGRA (SPS2)
  [Allanach et al., *Eur. Phys. J.* **C25** (2002) 113]
- (C) Minimal GMSB (SPS8)
  [Allanach et al., *Eur. Phys. J.* **C25** (2002) 113]
- (F) Kähler stabilization in heterotic strings
  [Gaillard & BDN, *Nucl. Phys.* **B588** (2000) 197]
- (H) Heterotic strings at strong coupling
  [Lukas, Ovrut and Waldram, *Nucl. Phys.* **B532** (1998) 43]
- (I) Type IIB on orientifolds with parallel branes and early unification
  [Abel, Allanach, Ibáñez, Klein and Quevedo, *JHEP* **12** (2000) 026]
- (J) Type IIB on orientifolds with intersecting branes
  [Ibáñez, Muñoz and Rigolin, *Nucl. Phys.* **B553** (1999) 43]
- (K) Minimal $SU(5)$ with gaugino mediation
  [Baer, Belyaev, Krupovnickas and Tata, *Phys. Rev.* **D65** (2002) 075024]
- (L) GUT-Inspired minimal $SO(10)$ model
  [Blažek, Dermíšek and Raby, *Phys. Rev.* **D65** (2002) 115004]

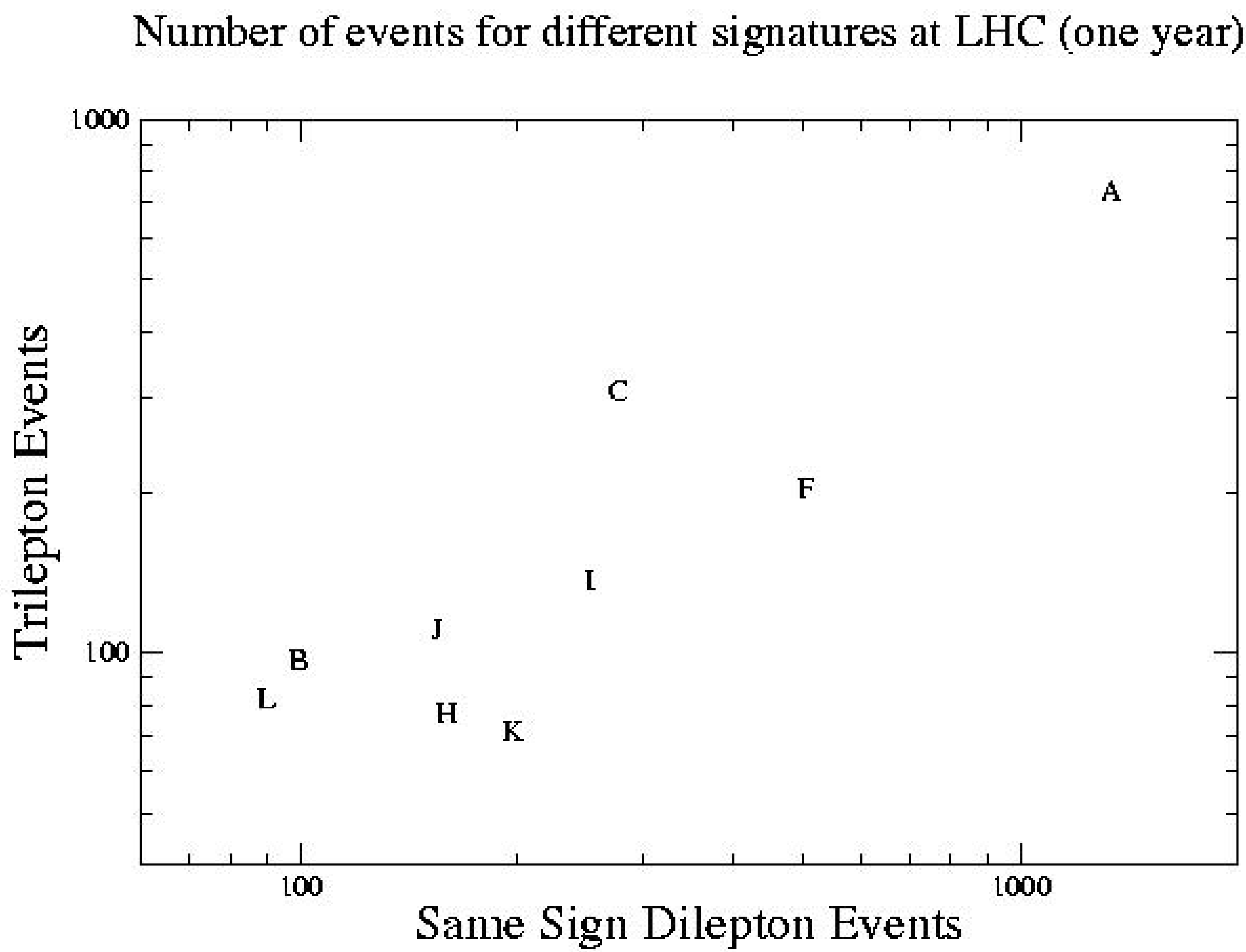
Distinguishing Models at the LHC

⇒ Distinguishing models at the LHC is in principle possible using *only inclusive signatures*

Channel	SM	A	B	C	F	H	I	J	K	L
Jets ($\times 10^3$)	100.0	59.5	0.7	4.2	31.7	6.6	5.0	7.2	7.0	1.1
1ℓ ($\times 10^3$)	13.0	17.1	0.5	1.8	7.3	1.7	1.8	1.8	1.9	0.5
OS ($\times 10^3$)	7.0	5.7	0.2	1.1	2.0	0.6	0.8	0.8	0.6	0.2
SS	20	1332	99	277	504	160	252	155	197	90
3ℓ	60	737	97	310	204	77	137	111	71	82
$m_{\rm eff}^{\rm peak}$ (GeV)	-	812	1140	1310	838	1210	1210	1340	1290	1210

Table 1: **Number of events in excess of the Standard Model prediction for different signatures.** For each channel the Standard Model baseline is given in the first column. Subsequent columns give the excess beyond this baseline.

LHC Signatures



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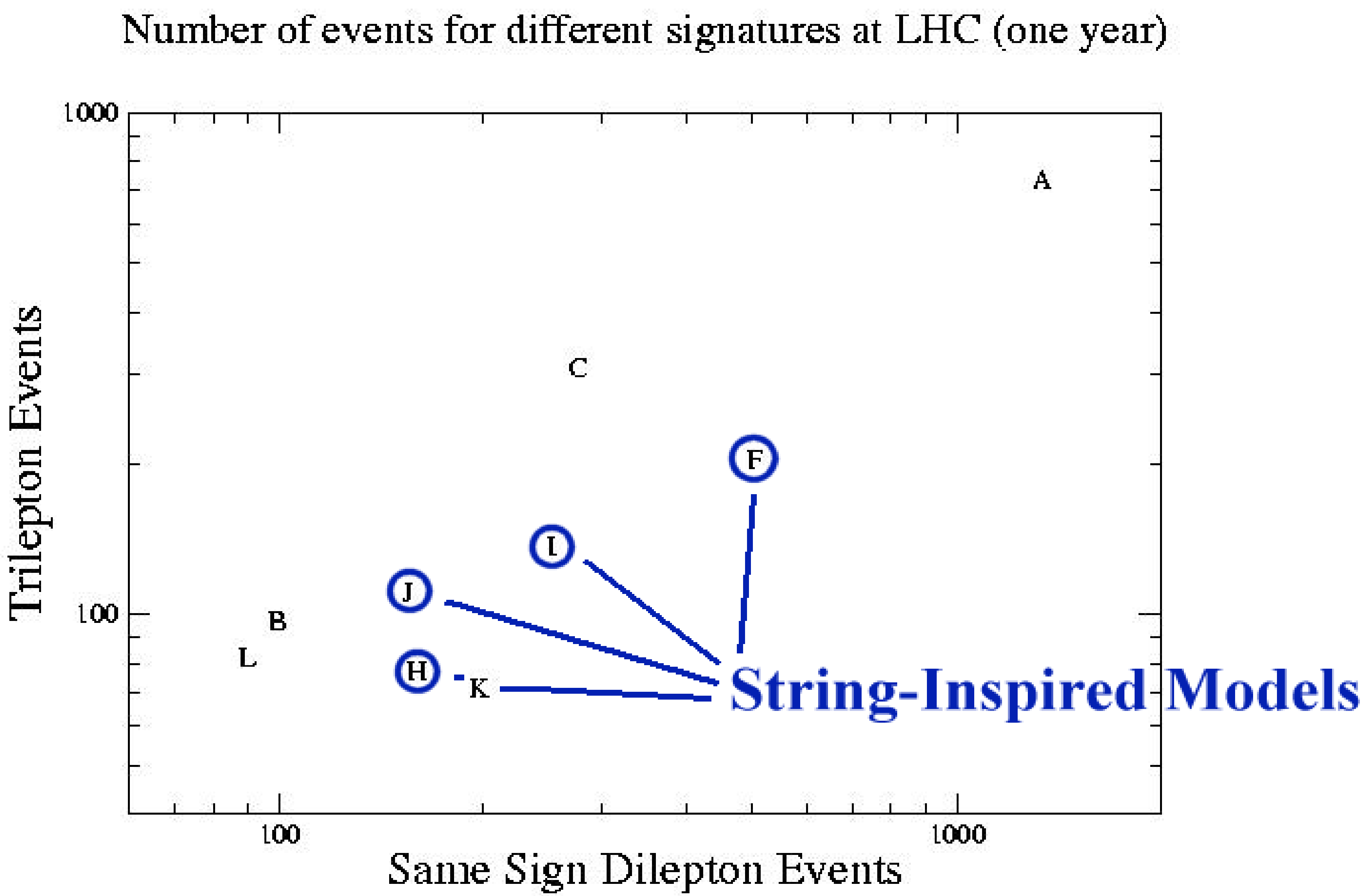
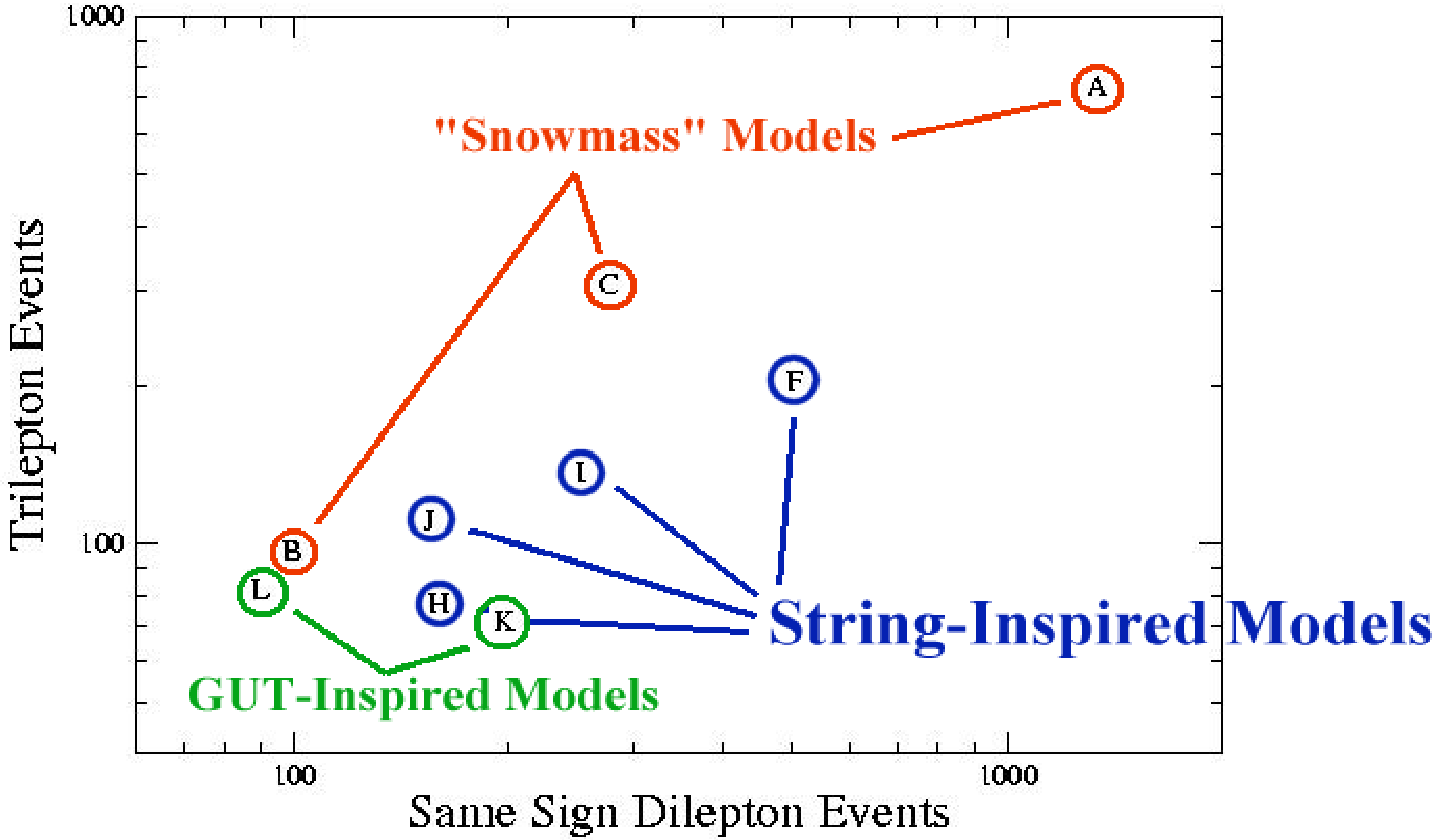


LHC Signatures

Number of events for different signatures at LHC (one year)



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- No indication of signal/background in our analysis
- No mapping of the entire parameter space for each model[4]
- No indication of experimental error bars (but for inclusive signatures this is less of an issue)

[4] *i.e.* the "footprint" of D. Grellscheid's talk on Wednesday

Finding the Right Model from Data

⇒ One way to distinguish models is a fit to some n-tuple of LHC observables

- Chi-squared method – define a “theory chi-squared”

$$\chi^2_T = \sum_{i=1}^{5} \frac{|a_i^{\rm th}(\vec{x}) - a_i^{\rm obs}|^2}{\sigma_i^2}$$

  - ⋆ $\vec{a}^{\rm obs}$ is an n-tuple of LHC observations
  - ⋆ $\vec{x}$ a vector of input parameter (for example) $\vec{x} = \{m_{1/2}, m_0, \tan\beta, A_0, {\rm sgn}(\mu)\}$
  - ⋆ σ_i^2 is an experimental uncertainty of each value $a_i^{\rm exp}$ that we assign

Finding the Right Model from Data

	mSUGRA $\tan\beta = 10$		mSUGRA $\tan\beta = 40$			
	$\mu > 0$	$\mu < 0$	$\mu > 0$	$\mu < 0$	Model J	Model F
LHC	0.09	0.21	1.70	17.17	3.10	1.7
$a_\mu^{\rm SUSY}$	0.44	1.83	0.03	2.96	0.43	1.0
$\mathrm{Br}(b \to s\gamma)$	1.16	4.96	0.66	11.09	1.00	0.1
Total $\left(\chi_T^2\right)_m$	1.69	7.00	2.39	31.22	4.54	2.8
d.o.f	3	3	3	3	4	5
$M_{\rm eff}^{\rm peak}$ (GeV)	1360	1260	1360	1438	1388	987
$m_{ll}^{\rm peak}$ (GeV)	92	92	92	92	92	58

Table 2: **Breakdown of best-fit $\left(\chi_T^2\right)_m$ for different models.** Each column represents the point in a model's parameter space which minimizes χ_T^2 in the corresponding model. We break down the total $\left(\chi_T^2\right)_m$ into contributions from the five collider signatures ("LHC") as well as contributions from a_μ^{SUSY} and $\mathrm{Br}(b \to s\gamma)$. The kinematic variables $M_{\rm eff}^{\rm peak}$ and $m_{ll}^{\rm peak}$ are also given to show their utility in separating models.

$\Rightarrow$ Once there is data to match (an n-tuple) this technique might single out a favored class of models. Focus more attention there and look for ways to make finer distinctions.

Finding the Right Model from Data

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⇒ But this tool works best when we have a complete "footprint"

- "Closeness" of a model to an experimental observation may be best measured by genetic algorithm (with χ^2_T as "fitness" variable?)

- BIG THREE already have footprints: we need to catch up!

Concluding Thoughts

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- We will likely need this whole table to find the right model: iterative procedure – predictions for yet un-made measurements
- Taking a string model to signatures is daunting
- Back reaction of putting modules together teaches us many things
- Despite the difficulties, taking string models to collider signatures will be a useful exercise in its own right