

# I. Looking for SUSY under the LHC Lamppost

(towards a complete classification of SUSY signatures)

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1111.asap

Interpreting LHC Discoveries workshop  
GGI, Florence, November 10, 2011

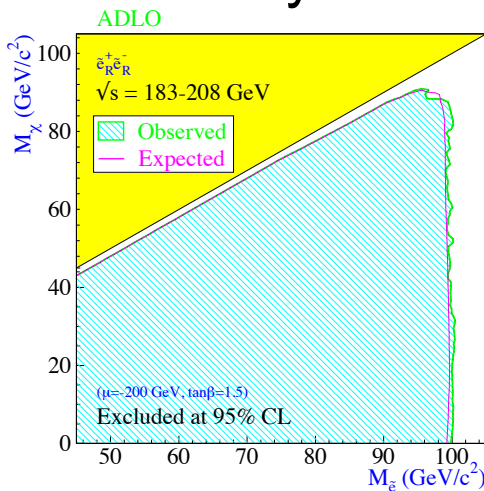
# Outline of this talk

- The latest fashionable models? No.
  - Any given model is surely wrong
- Supersymmetry (SUSY) in general (no prejudice!).
  - theoretical motivations
    - gauge unification
    - hierarchy problem
  - experimental motivations
    - not ruled out
    - dark matter candidate
  - sociological motivations
    - popular, must learn for final exam, competition is doing it...
    - looks like many other models anyway Cheng, KM, Schmaltz 2002
- This talk: a fresh new look at SUSY phenomenology

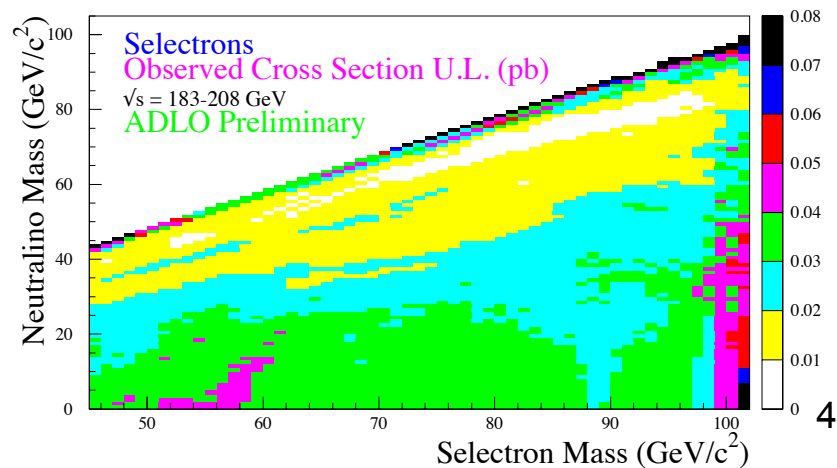
	Theory constructs		Number of parameters	Number of relevant event topologies under study
simplification by assumption	Theory of Everything, e.g. string theory		one?	NA
	SUSY breaking "model"		a few	all
simplification by relevance	General MSSM		way too many	all
	pMSSM	JoAnne's talk	nineteen	all
	a SUSY "hierarchy"	This talk	a few	a few
	"Simplified model"	Jay's talk	a few	one

# What is needed for LHC collider phenomenology?

- Theory models? No.
  - those were important to get funding
  - will become important again after a discovery
- Event topologies (a.k.a. simplified models).
  - specified by a skeleton Feynman diagram (A->B->C->...)
  - relevant parameters: masses, widths, rate
  - not really a new idea:



From LEP2 SUSY WG



# SUSY under the lamppost

- The first LHC discovery may not be in the TDR
- It will be easier to make a discovery if
  - there are many new particles to be discovered ✓
  - the new particles are colored (produced with QCD-type cross-sections) ✓
  - the signal involves (lots of) isolated, high  $P_T$  leptons **How many?**
- Look for new physics under the lamppost
  - also find what new physics away from the lamppost looks like

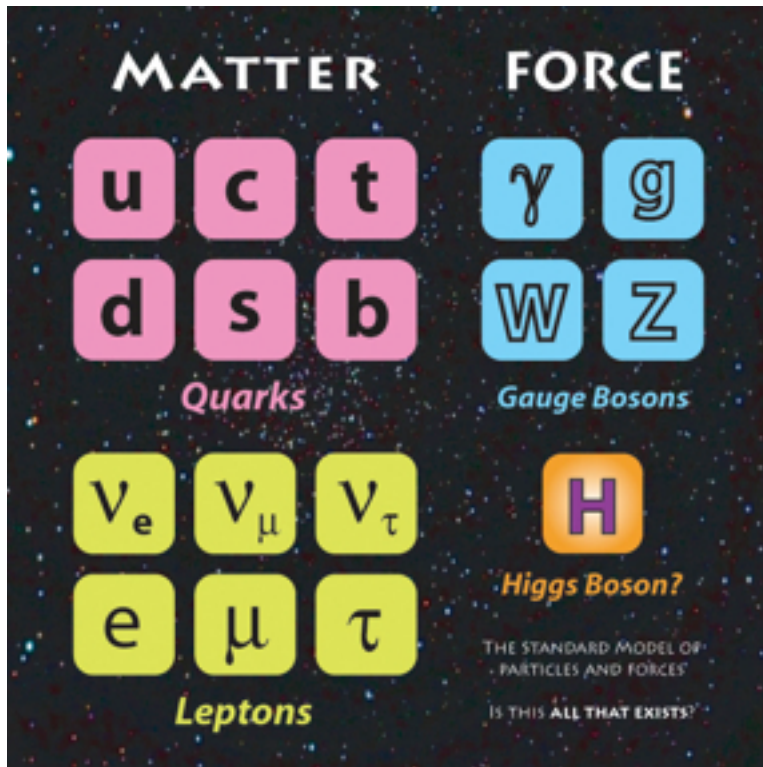


# Main building blocks

- Standard Model

Fermions

Bosons



- Supersymmetry

Bosons

Fermions



- Spins and couplings fully predicted by SUSY
- Masses of the new particles completely unknown

# SUSY signatures depend on

- **Quantitative factors:** require parameter space **scans**.
  - value of SUSY masses themselves
    - size of the cross-sections
    - relative contribution of strong vs. electroweak production
  - SUSY mass splittings
    - phase space suppression factors in the BR's
    - hardness of the SM decay products, efficiency of cuts
- **Qualitative factors:** requires considering **permutations**
  - the hierarchical ordering of the SUSY particles
- The parameter space is infinite, the number of permutations is finite! Let's study all permutations first!

pMSSM scan:  
 $2^{19}=524288$

# Mass parameter space factorization

Parameter space  
of the masses  
of  $n$  particles

All possible  
permutations  
("hierarchies")

Overall scale  
and mass splittings

$\mathbf{R}^n$

=

$\mathbf{S}_n$

$\otimes$

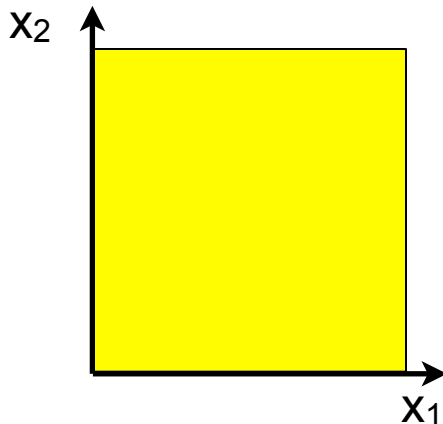
$\mathbf{R}^n / \mathbf{S}_n$

infinite

finite

infinite

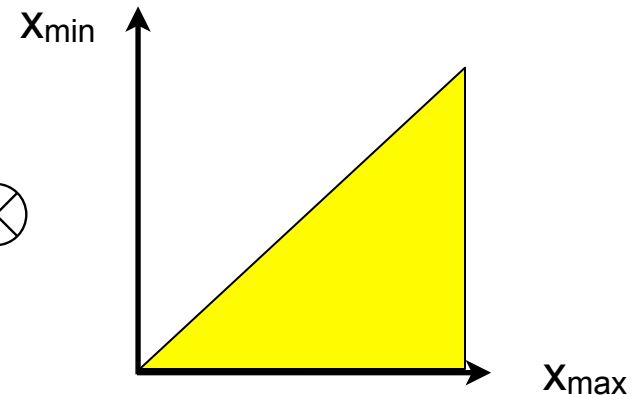
- Example:  $n=2$



=

$(x_1, x_2)$   
or  
 $(x_2, x_1)$

$\otimes$



Let us study this part!  
Konar, KM, Park, Sarangi 2010

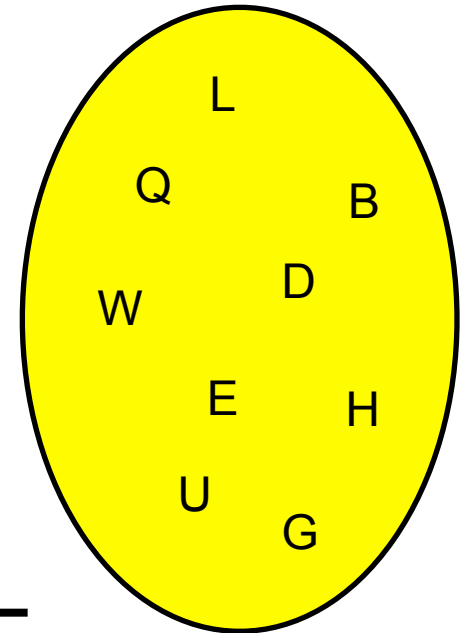
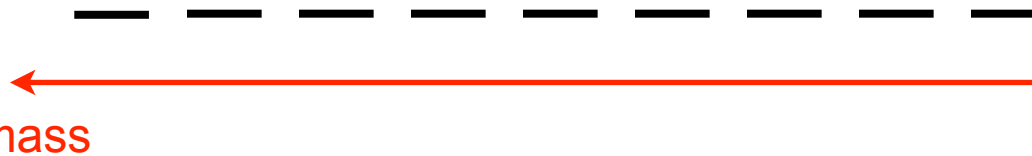
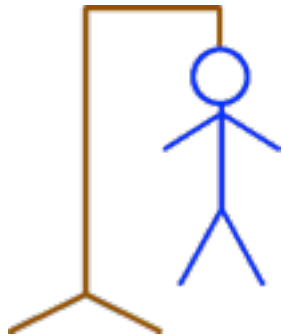


# The SUSY parameter space

- The relevant parameters are the physical masses
  - taken directly at the weak scale, no need to run any RGE's

TABLE I: The set of SUSY particles considered in this analysis, shorthand notation for each multiplet, and the corresponding soft SUSY breaking mass parameter.

$\tilde{u}_L, \tilde{d}_L$	$\tilde{u}_R$	$\tilde{d}_R$	$\tilde{e}_L, \tilde{\nu}_L$	$\tilde{e}_R$	$\tilde{h}^\pm, \tilde{h}_u^0, \tilde{h}_d^0$	$\tilde{b}^0$	$\tilde{w}^\pm, \tilde{w}^0$	$\tilde{g}$
$Q$	$U$	$D$	$L$	$E$	$H$	$B$	$W$	$G$
$M_Q$	$M_U$	$M_D$	$M_L$	$M_E$	$M_H$	$M_B$	$M_W$	$M_G$



# SUSY collider signatures

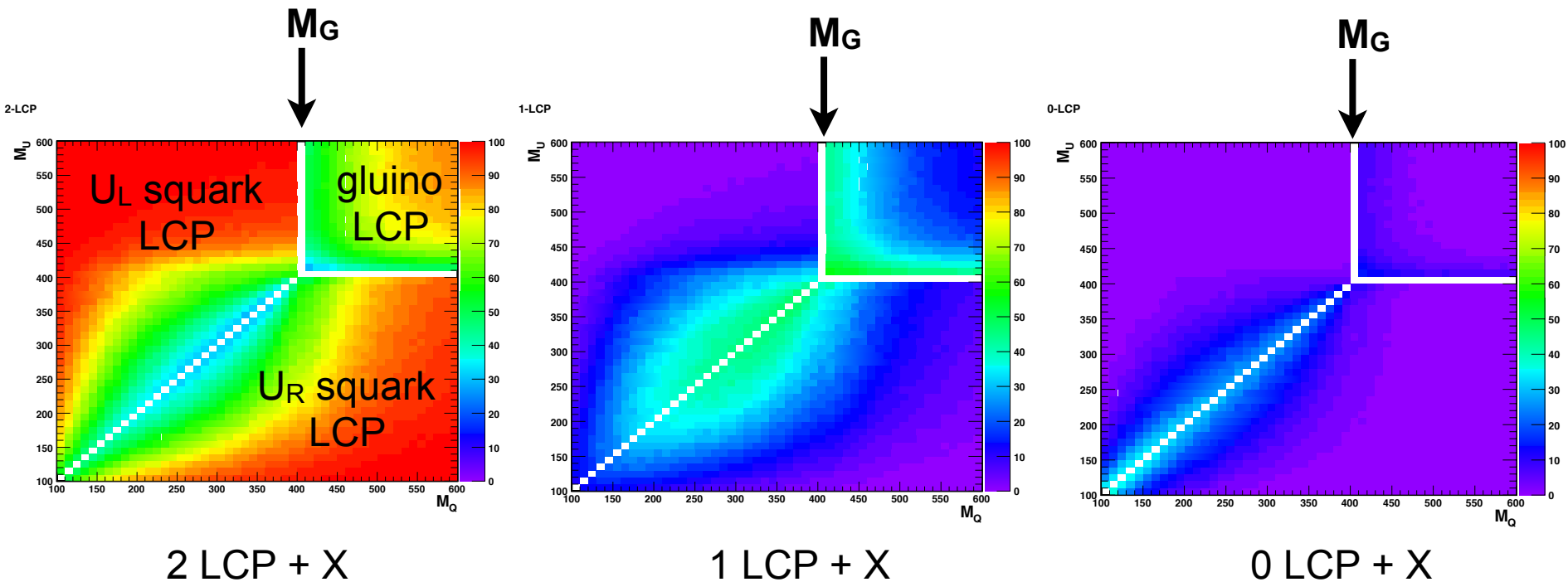
- There are  $9!=362,880$  possible permutations
- First: who is the LSP (lightest superpartner)
  - CHAMP ( $8!=40,320$ ) if LSP=E
  - R-hadron ( $4 \times 8!=161,280$ ) if LSP=G, Q, U or D
  - Missing energy ( $4 \times 8!=161,280$ ) if LSP=L, H, W or B
- Second: who is the LCP (lightest colored particle)
  - most abundantly produced at hadron colliders
- Third factor: what is the dominant decay of the LCP
  - count suppressions by multibody phase space
  - count suppressions from “ino” mixing angles

$$x \dots x \mathcal{C} y \dots y \mathcal{L}$$

# Strong production cross-section

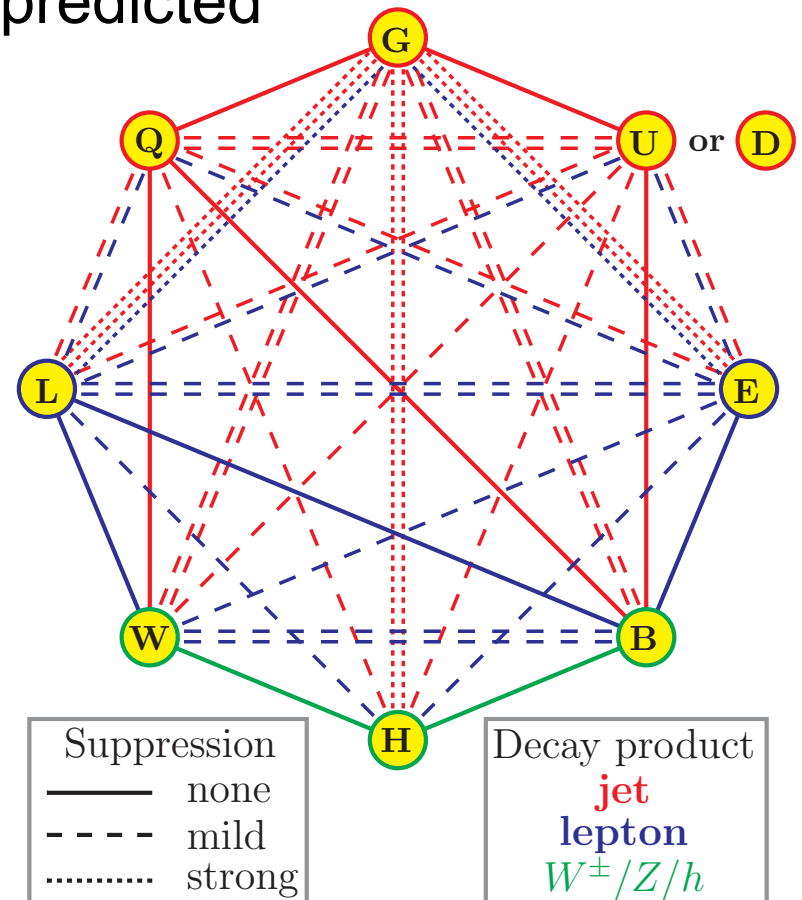
Konar, KM, Park, Sarangi 2011

- Does the LCP cross-section really dominate?
  - compare the inclusive production of gluinos and squarks

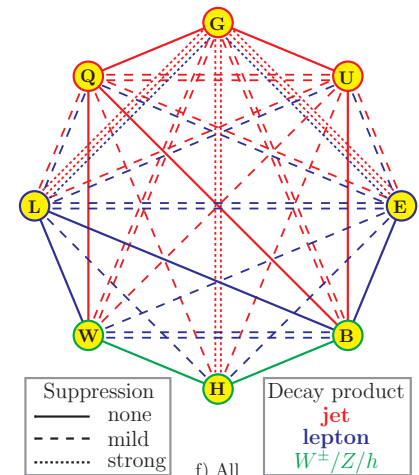
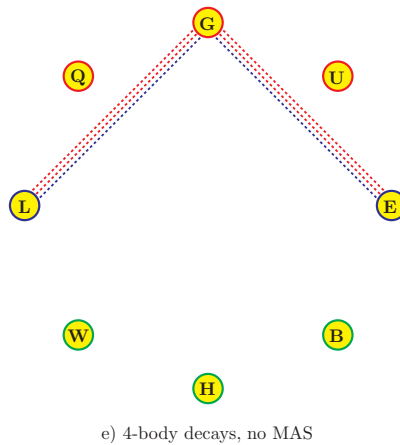
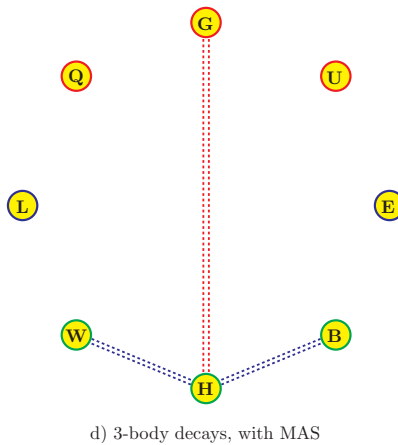
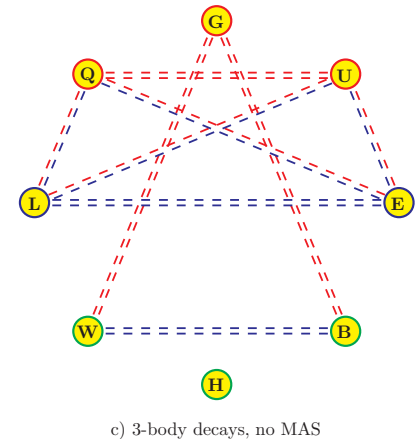
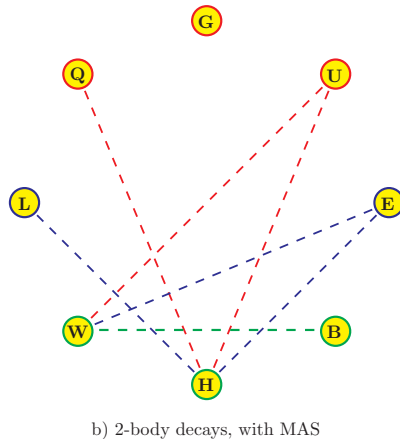
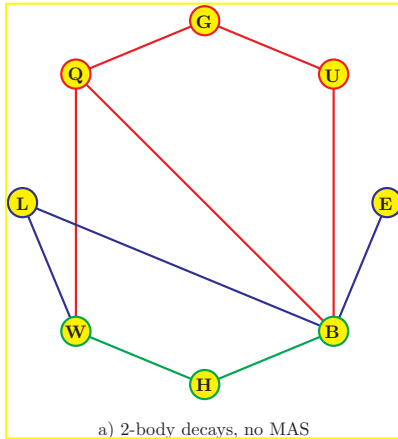


# SUSY decay modes

- Couplings already determined by SUSY
  - mixing angles are typically small; degeneracies are rare
  - branching ratios uniquely predicted

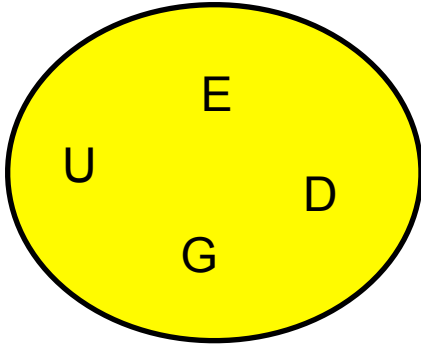


# Counting suppression factors

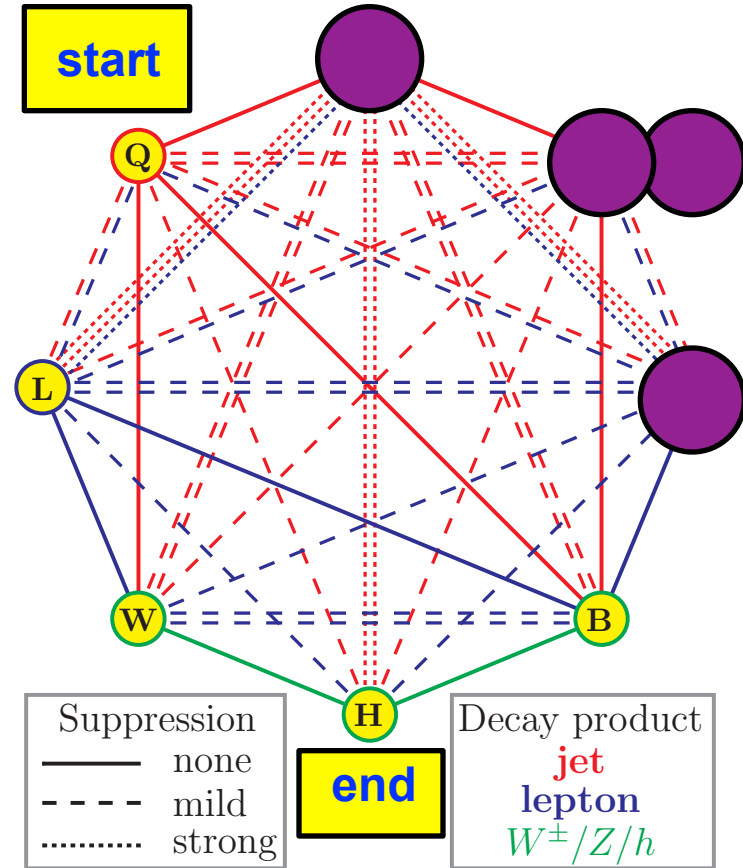


# LCP decays: an example

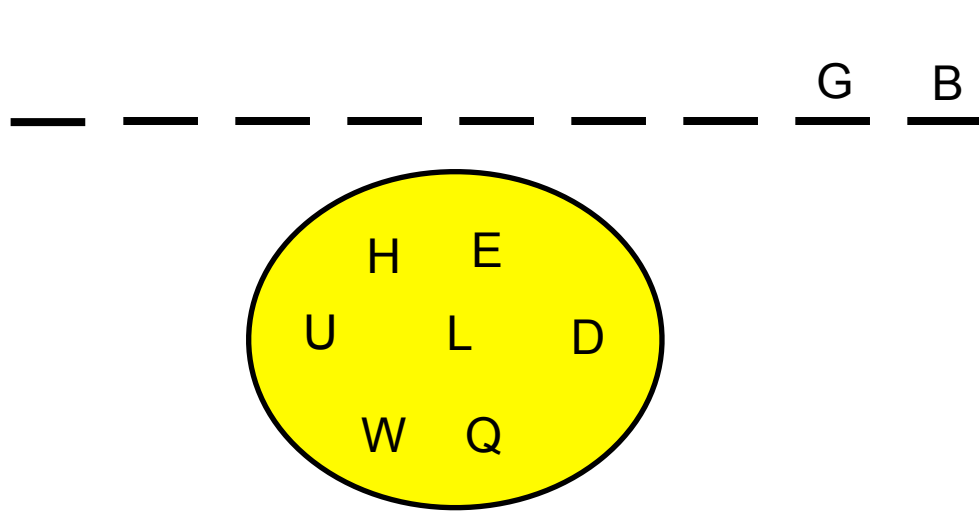
\_\_\_\_\_ Q W B L H



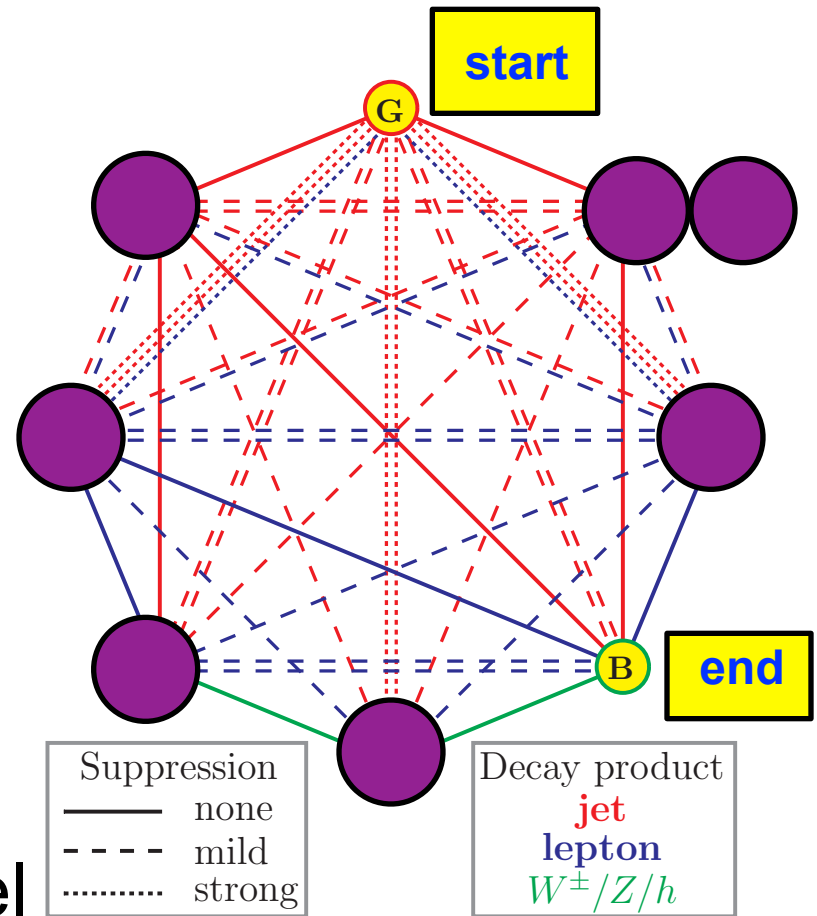
- A variation of the travelling salesman problem
- Several possible paths:
  - QBH, QWH: give jet plus  $V$
  - QBLH, QWLH, give jet plus  $2L$
- Count all such “dominant” signatures for each permutation



# LCP decays: another example

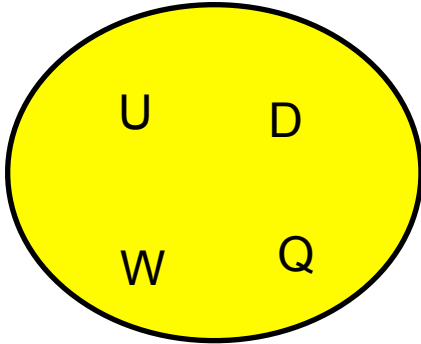


- This example is trivial
- Single unique path:
  - GB: gives 2 jets
- Recall the simplified model from Jay's talk

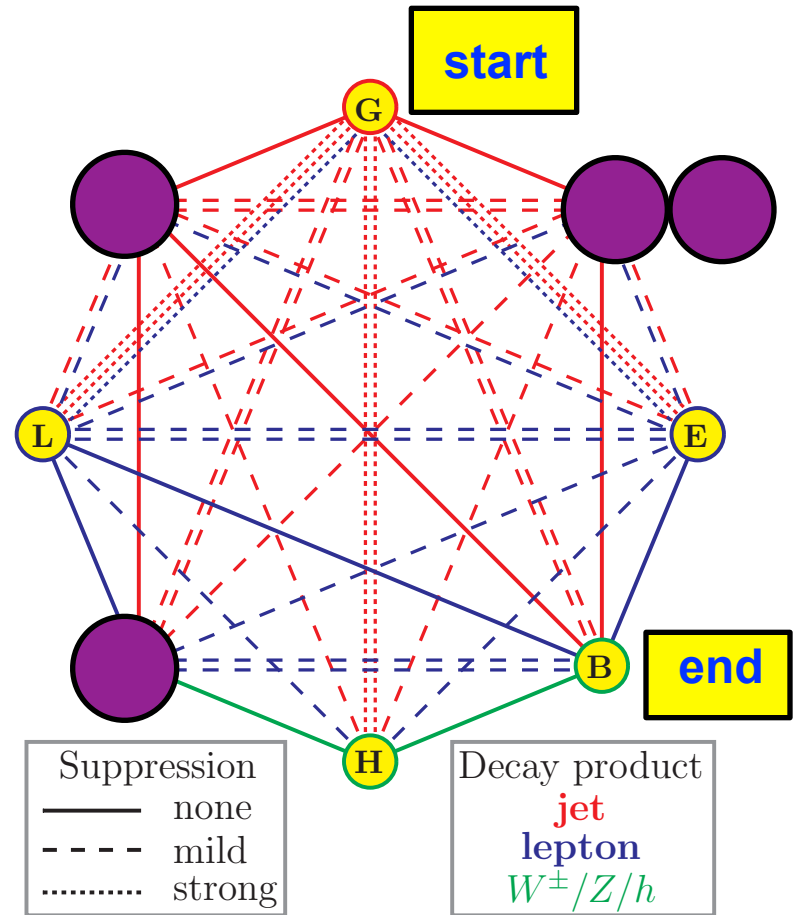


# LCP decays: yet another example

\_\_\_\_\_ G H L E B



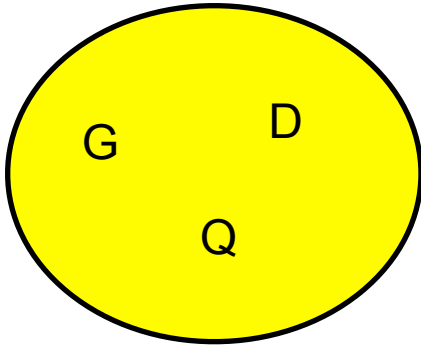
- This example is also trivial
- Single unique path:
  - GB: gives 2 jets
  - G to L is a 4 body decay
  - G to E is a 4 body decay
  - G to H is a 3 body decay with mixing angle suppression



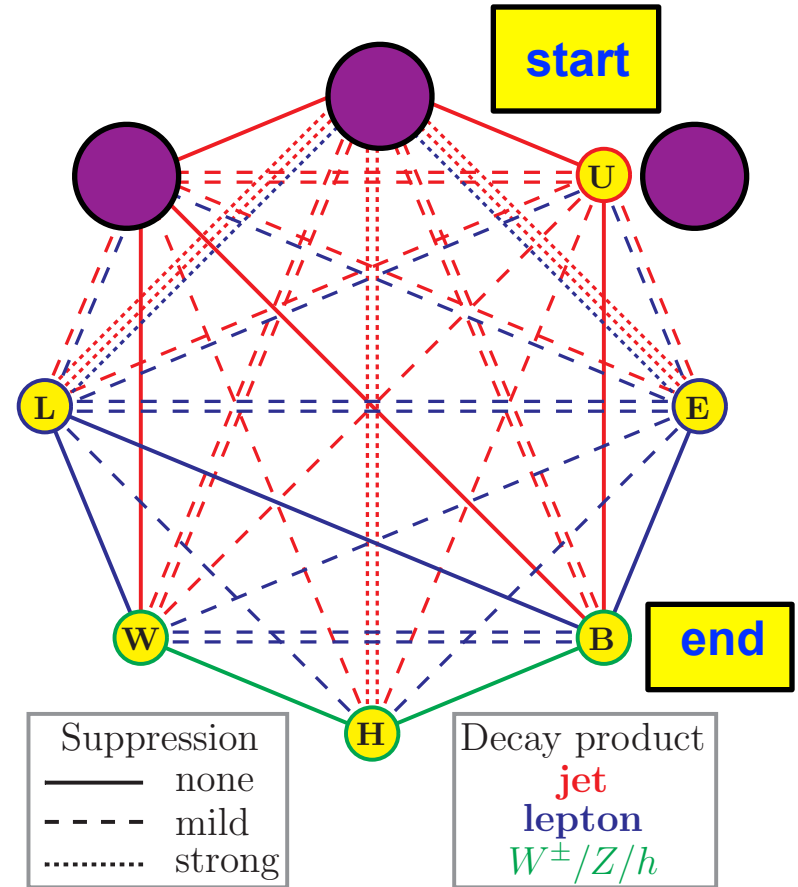


# LCP decays: yet another example

\_\_\_\_\_ U H L W E B

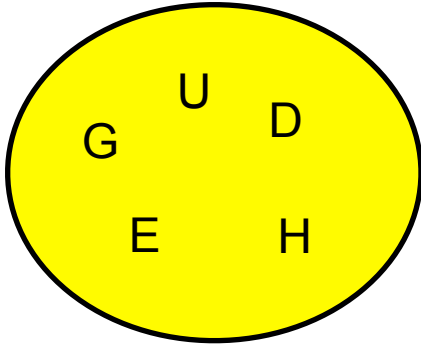


- MSUGRA-like example
- Single unique path:
  - UB: gives 1 jet
  - U to L is a 3 body decay
  - U to E is a 3 body decay
  - U to W suppressed by mixing
  - U to H suppressed by mixing

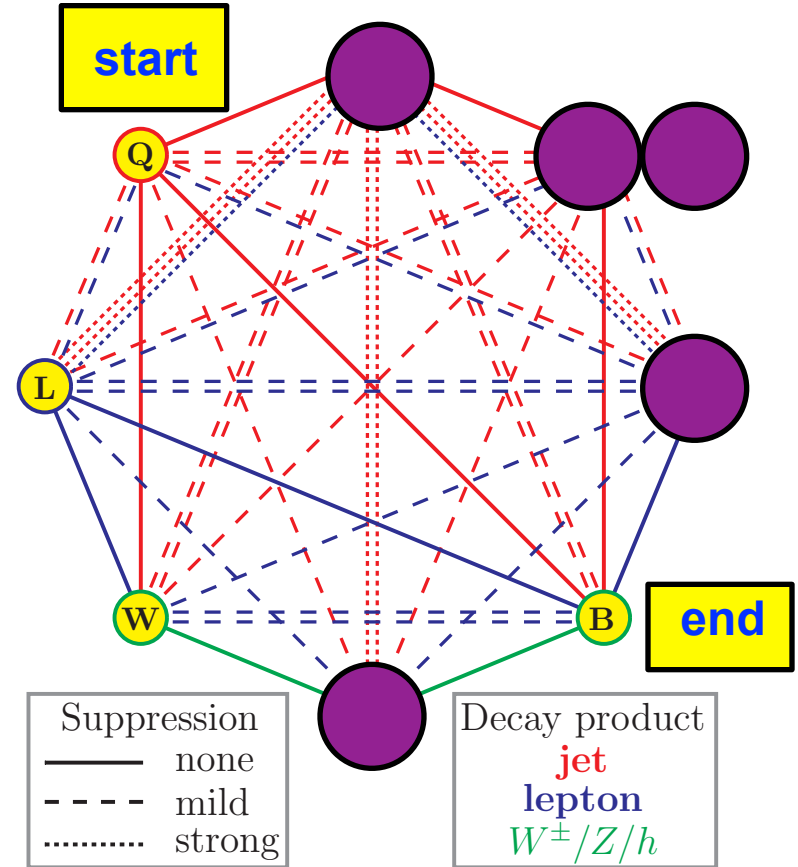


# LCP decays: yet another example

\_\_\_\_\_ Q W L B



- Two paths:
  - QWLB: gives 1 jet plus 2L
  - QB: gives only 1 jet
- Which path to choose?
  - both
  - the one with more leptons
    - “maximally leptonic signature”



# Counting signatures

- Counting all possible dominant LCP decays

TABLE II: Number of hierarchies for the various dominant decay modes of the LCP  $\mathcal{C}$ .

$n_\ell$	$n_\nu = 0$		$n_\nu = 1$		$n_\nu = 2$	
	$n_j = 1$	$n_j = 2$	$n_j = 1$	$n_j = 2$	$n_j = 1$	$n_j = 2$
0	79296	26880	12768	3360	1344	672
1	30240	10080	1824	480	192	96
2	19770	6030	1500	180	0	0
3	4656	1296	312	72	6	6
4	1656	396	66	6	0	0

x 2

8 lepton events!

- Only the maximally leptonic dominant LCP decays

TABLE III: Number of hierarchies for the *maximally leptonic* decay modes of the LCP  $\mathcal{C}$ .

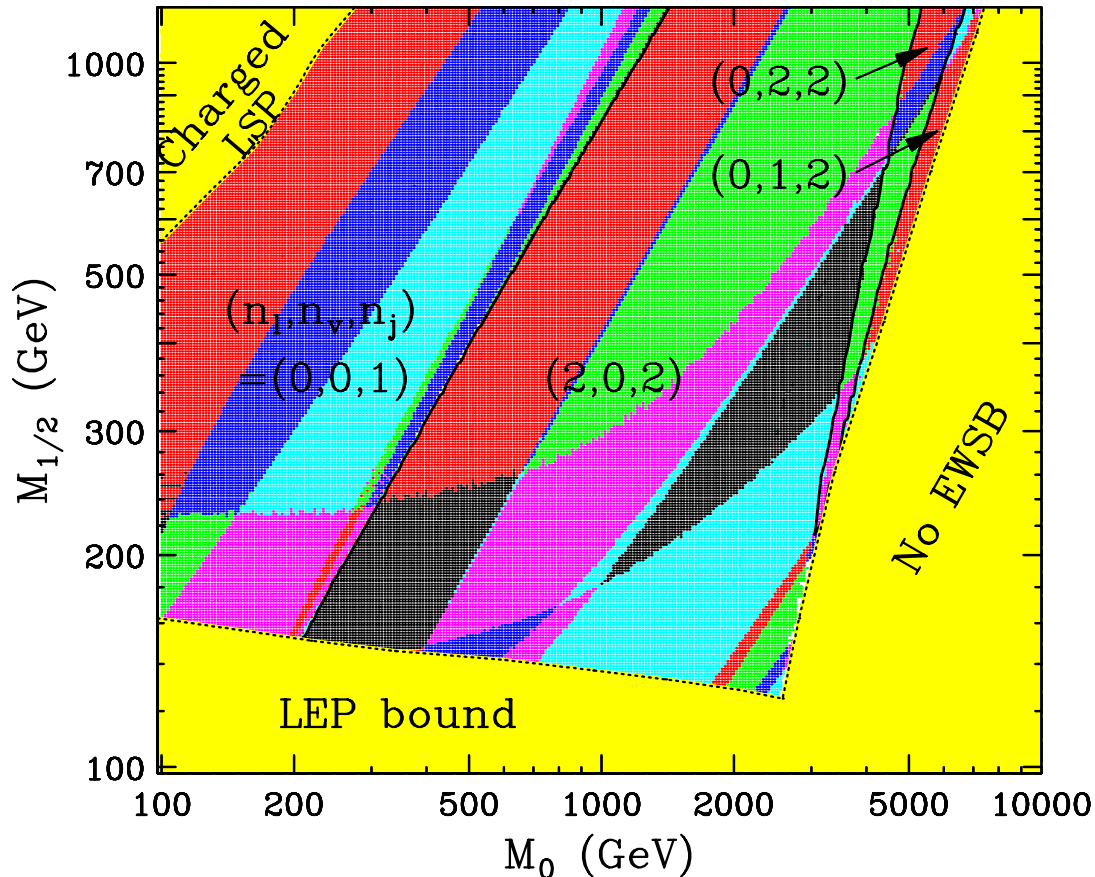
$n_\ell$	$n_\nu = 0$		$n_\nu = 1$		$n_\nu = 2$	
	$n_j = 1$	$n_j = 2$	$n_j = 1$	$n_j = 2$	$n_j = 1$	$n_j = 2$
0	61488	21168	8310	2550	780	420
1	24150	8310	1278	378	132	72
2	17190	5550	1230	150	0	0
3	4362	1242	312	72	6	6
4	1656	396	66	6	0	0

x 2

19  
8 lepton events!

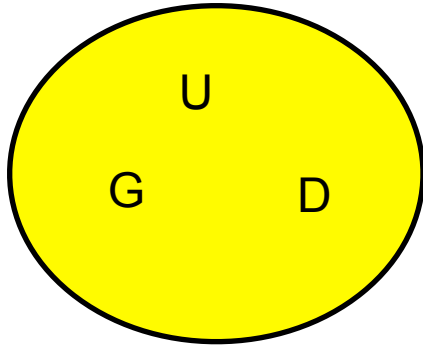
# MSUGRA result

- Only 47 out of the 161,280 possible hierarchies
- Only 4 out of the 26 possible decay channels.

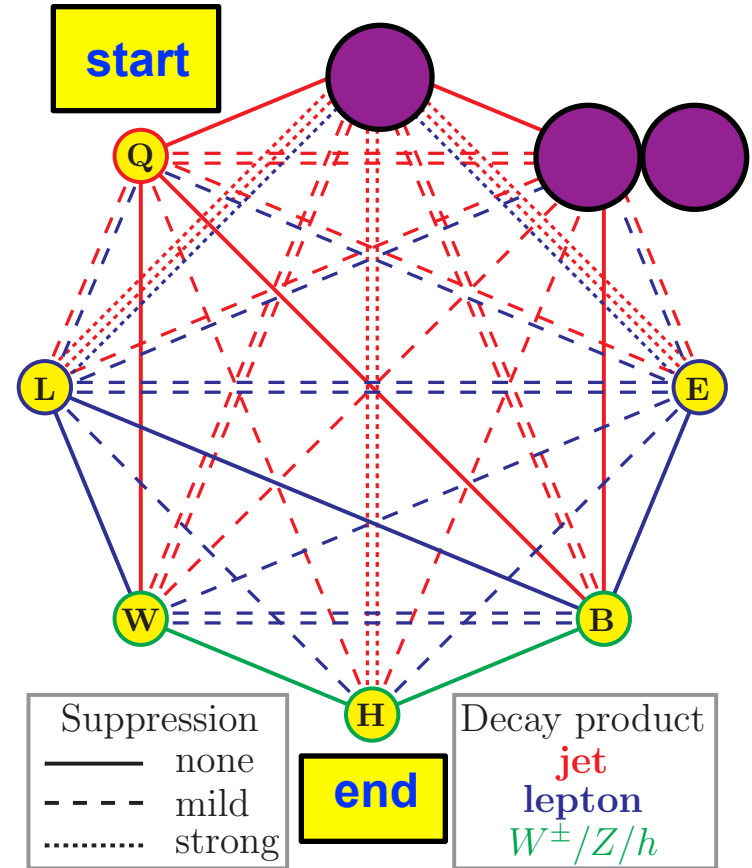


# An example with 4 leptons

\_\_\_\_\_ Q W L B E H

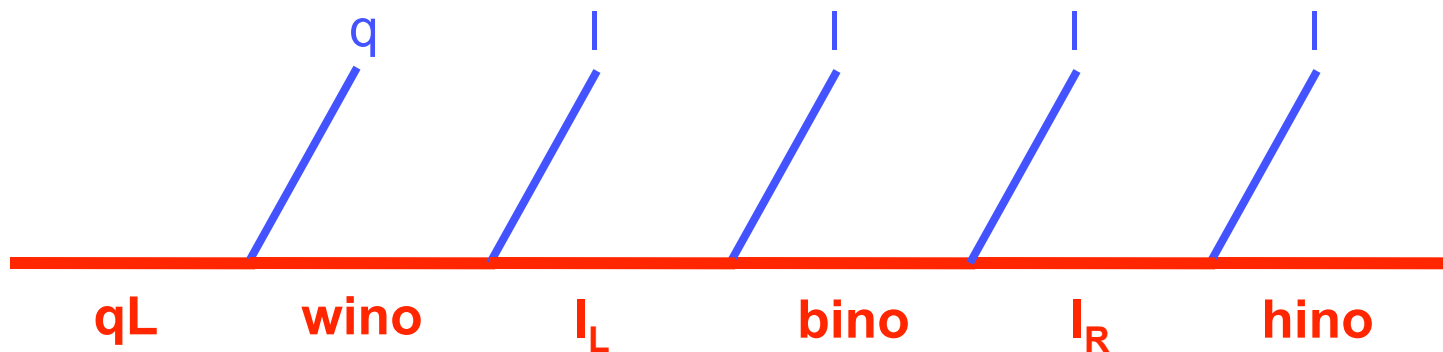
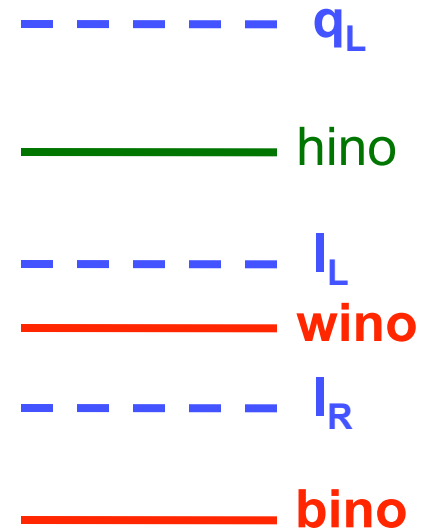


- Maximally leptonic path:
  - QWLBEH: gives 1 jet plus 4L
- Events with 8 leptons!
- Signature jargon:
  - 3 leptons: gold plated
  - 4 leptons: platinum plated
  - 8 leptons: ???



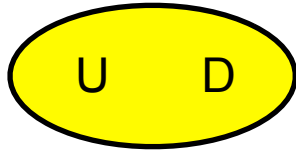
# How can such a spectrum arise?

- Start with MSUGRA
  - typical hierarchy: QHLWEB
- Go to the stau LSP corner
  - typical hierarchy: QHWLBE
- Consider nuSUGRA
  - higgsino mass can be anything, thus:
    - QWLBEH



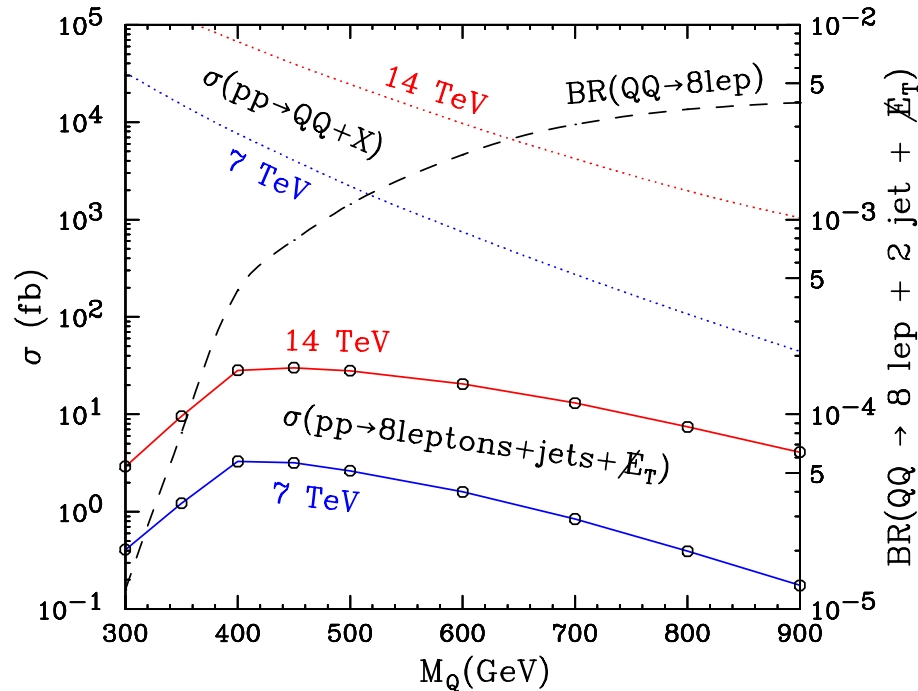
**All 4 leptons come from the same side!**

# Study this 8-lepton hierarchy



                G     Q     W     L     B     E     H  

- The study points are chosen to maximize the rate
  - maximize the mass splittings for a given  $M_Q$



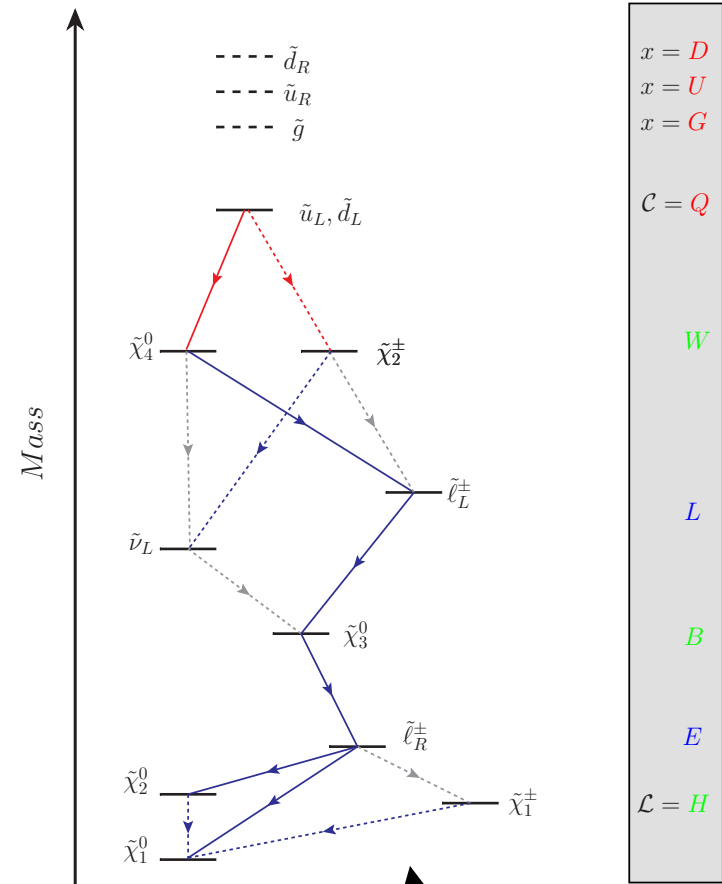
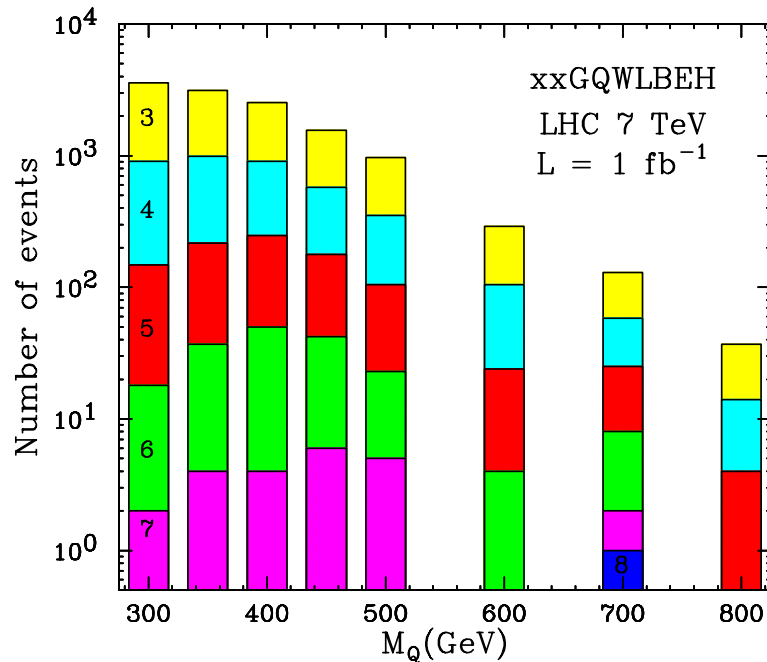
NLCP LCP

LSP

$M_G$	$M_Q$	$M_W$	$M_L$	$M_B$	$M_E$	$M_H$
400	300	220	190	130	130	130
450	350	280	190	120	120	120
500	400	280	190	120	120	120
550	450	310	200	120	120	120
600	500	350	210	130	120	120
700	600	420	230	150	130	120
800	700	480	250	160	130	120
900	800	500	250	170	130	120
1000	900	510	250	170	130	120

# Multi-lepton yields

- Simulation: PYTHIA+PGS
  - count leptons with default cuts.
  - often leptons are missed because of the acceptance
- Easy discovery

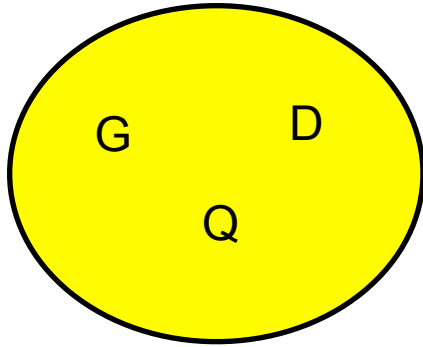


a simplified model?

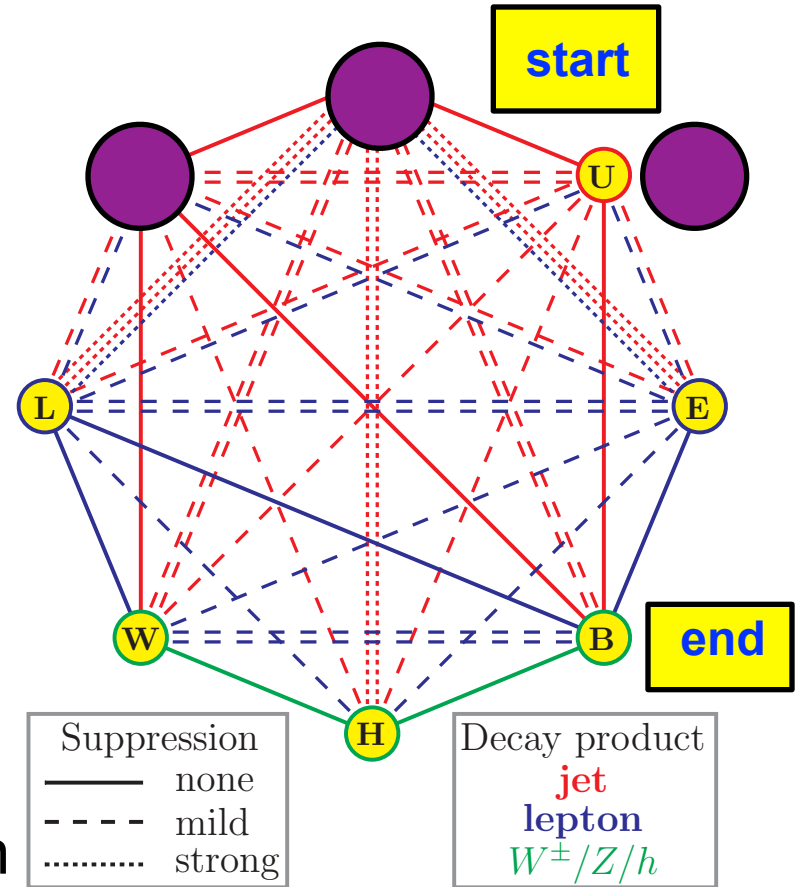


# Another example with 4 leptons

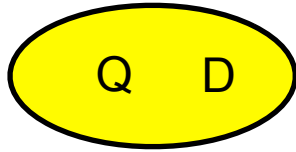
\_\_\_\_\_ U B E W L H \_\_\_\_\_



- Maximally leptonic path:
  - UBEWLH: gives 1 jet plus 4L
  - Bottleneck at the EW transition
    - E to W, E to L and E to H are all equally suppressed

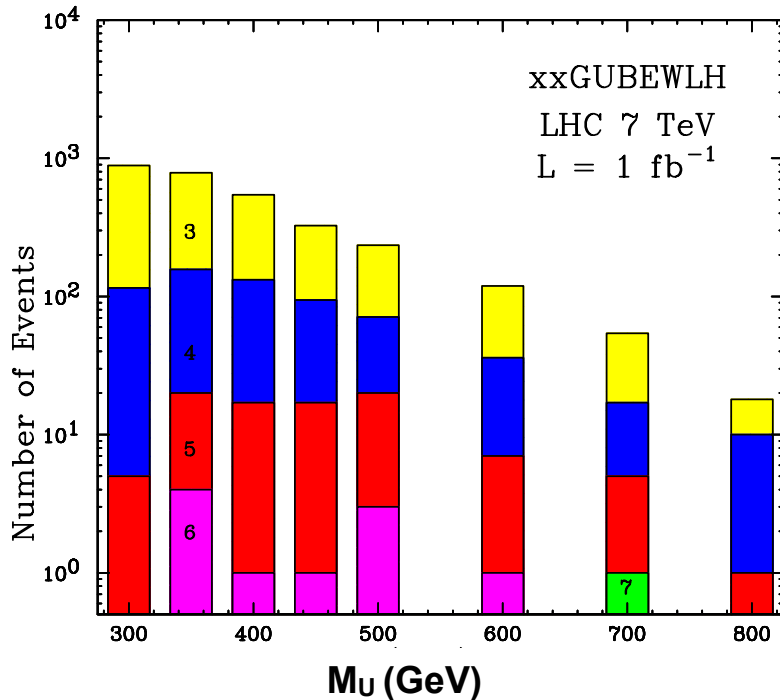


# Multi-lepton yields



                G     U     B     E     W     L     H  

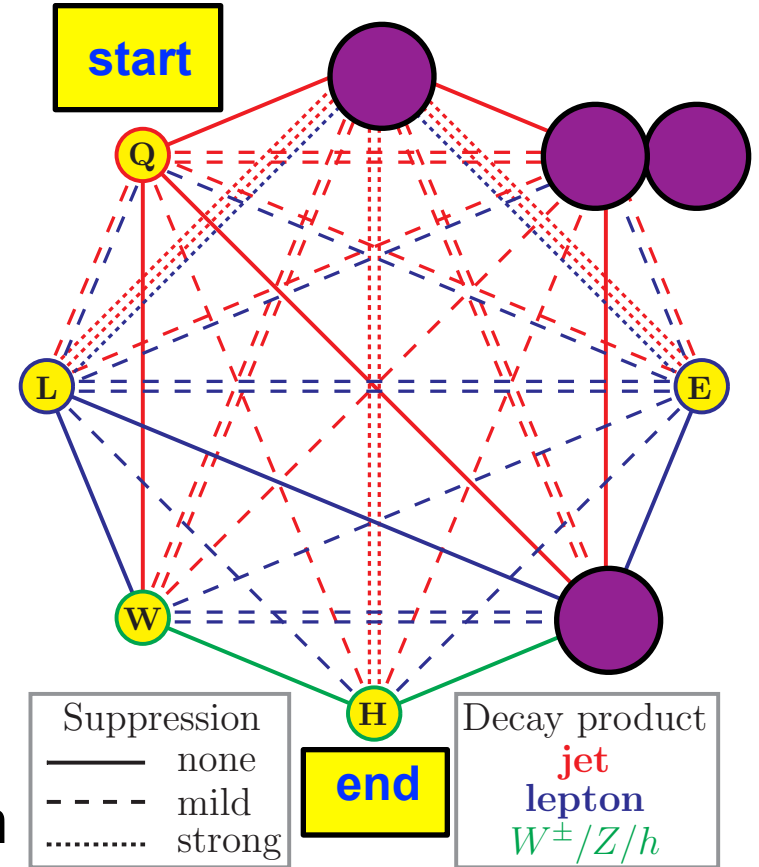
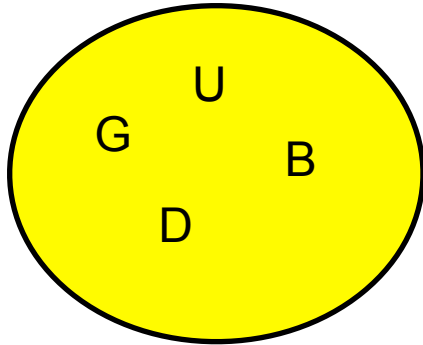
- The study points are chosen to maximize the rate
  - maximize the mass splittings for a given  $M_U$



	NLCP	LCP	LSP				
	$M_G$	$M_U$	$M_B$	$M_E$	$M_W$	$M_L$	$M_H$
	400	300	260	240	160	160	160
	450	350	280	240	160	160	160
	500	400	320	260	160	160	160
	550	450	320	260	160	160	160
	600	500	380	280	160	160	160
	700	600	500	320	160	160	160
	800	700	560	340	160	160	160
	900	800	620	360	160	160	160
	1000	900	640	360	160	160	160

# A less trivial example with 4 leptons

\_\_\_\_\_ Q W L E H



- Maximally leptonic path:
  - QWLEH: gives 1 jet plus 4L
  - Bottleneck at the LE transition
    - L to E and L to H equally suppressed
- The three body decay  $L \rightarrow E + 2 \text{ leptons}$  is not in PYTHIA

# Summary

- “What is the signature?” is a qualitative question
  - can be answered by studying all possible hierarchical orderings of the masses of the new particles
  - in a pMSSM without the third generation:  $4 \times 8! = 161,280$  MET hierarchies

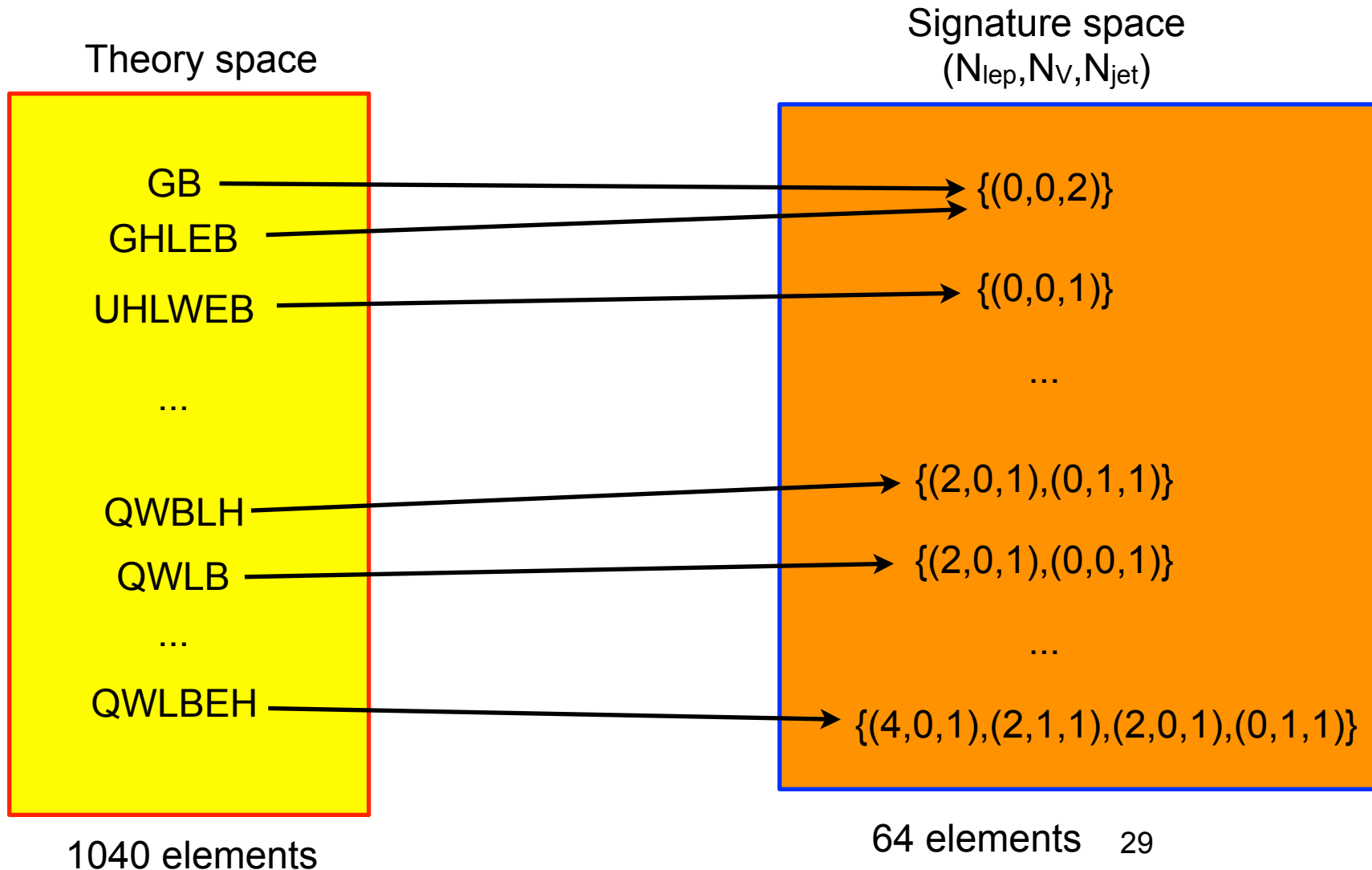
$$x \dots x C y \dots y \mathcal{L}$$

- Restricting to the subchain from the LCP to LSP
  - 1,040 distinct model hierarchies

$$C y \dots y \mathcal{L}$$

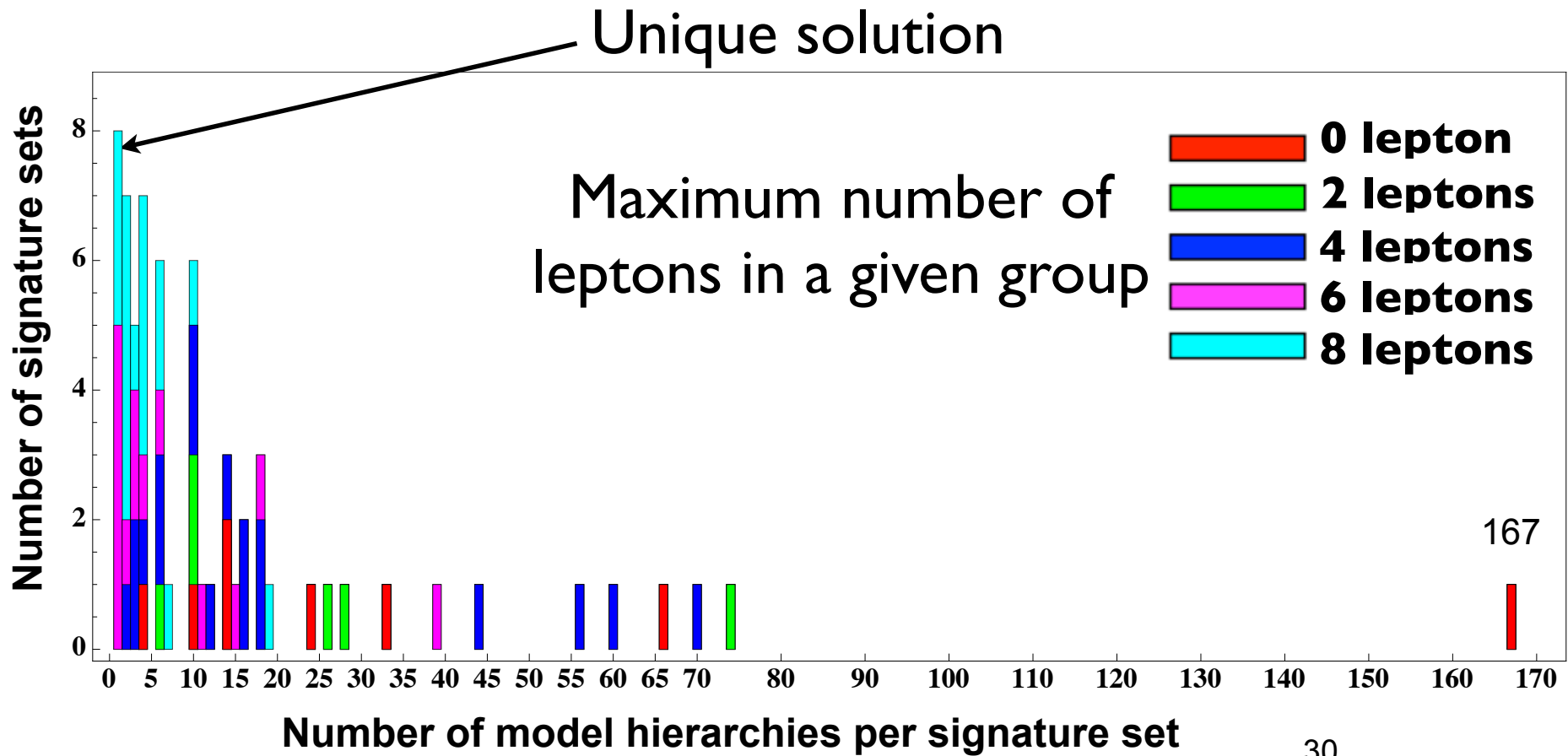
- Each model hierarchy comes with a set of signatures
  - the “maximally leptonic” + possibly others
  - there are 64 distinct sets of **dominant** signatures

# The map from theory space to (MET) signature space



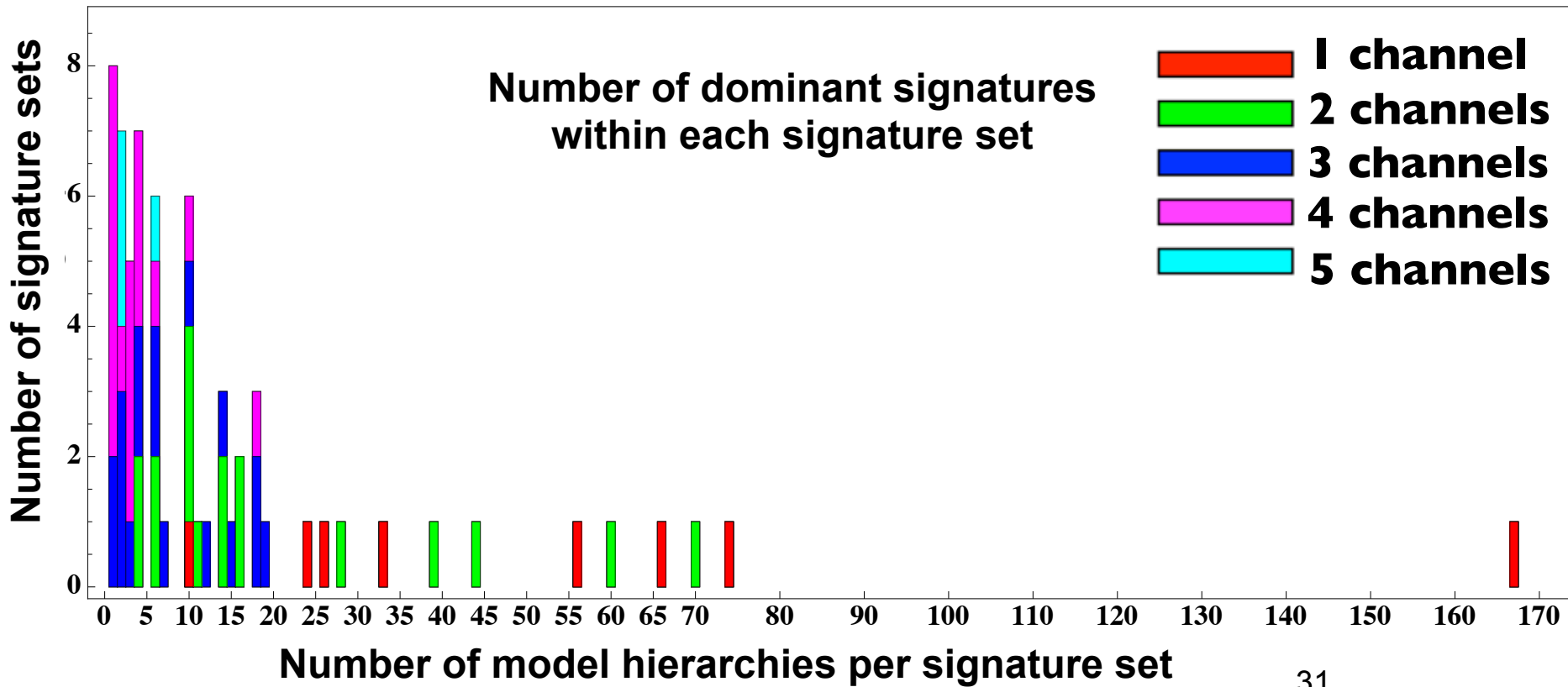
# Is the map invertible?

- Sometimes, but not always...



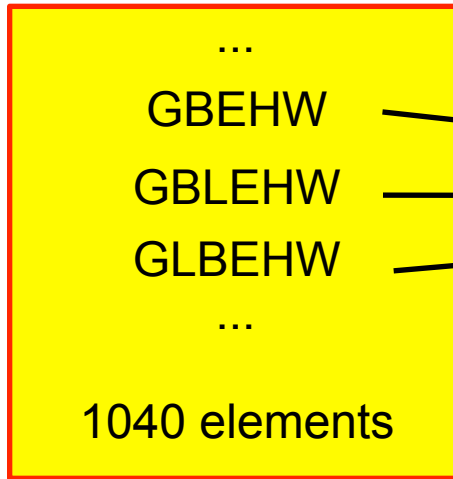
# Inverse map again

- Categorization by signature multiplicity
  - hard to discriminate models with fewer signatures



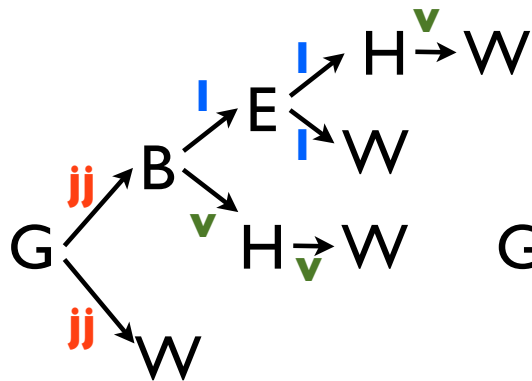
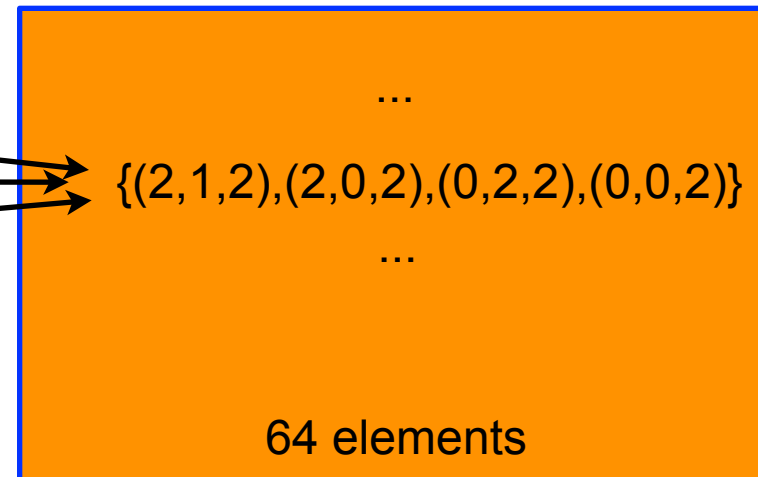
# An example of ambiguity

Theory space

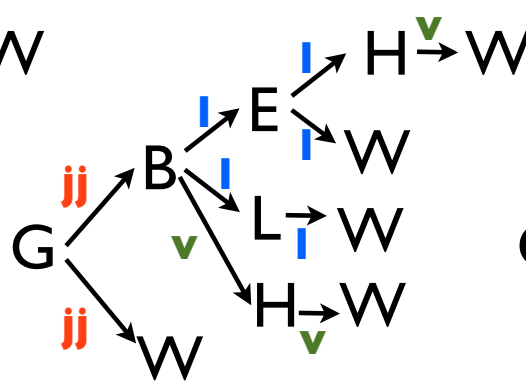


Signature space

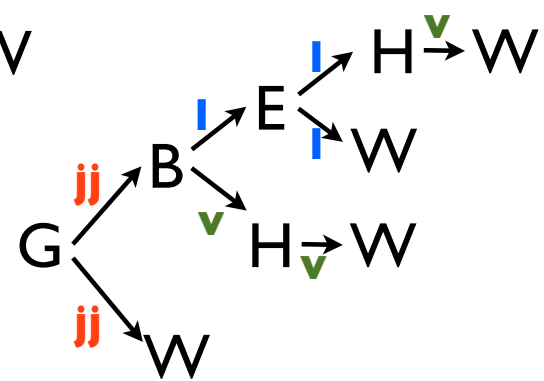
$(N_{lep}, N_V, N_{jet})$



GBEHW



GBLEHW



GLBEHW



# Conclusions

- By studying the hierarchical ordering of the superpartners, one can already learn a lot about the qualitative aspects of their collider signatures
- Finite number of permutations => one can exhaustively study **all** model hierarchies
  - build the inverse map from signature space to theory space
- Many details about the quantitative aspects were swept under the rug
- The analysis is a proof of principle - can be extended to include
  - third generation scalar superpartners
  - top quarks, b-jets, tau-jets among the signature objects