From Feynman Diagrams to Graphs

(towards a complete classification of SUSY signatures)

Konstantin Matchev

UF UNIVERSITY of FLORIDA
The Foundation for The Gator Nation

In collaboration with:
P. Konar, M. Park, G. Sarangi,
Phys. Rev. Lett. 105 (2010) 221801;
13xx.yyyy

Loopfest 2013, Tallahassee
May 14, 2013


Loopfest XII
Radiative Corrections for the LHC and Future Colliders
May 13 – 15, 2013
The Florida State University
Organizers:
Sally Dawson
Lance Dixon
Frank Petriello
Seth Quackenbush
Laura Reina
Doreen Wackeroth
FLORIDA STATE UNIVERSITY
1851
PHYSICS
FLORIDA STATE UNIVERSITY
http://indico.cern.ch/event/loopfest12
Sponsored by the Physics Department, the College of Arts and Sciences, and the Office of Research of the Florida State University.


Loopfest XII
Radiative Corrections for the LHC and Future Colliders
May 13 – 15, 2013
The Florida State University
Organizers:
Sally Dawson
Lance Dixon
Frank Petriello
Seth Quackenbush
Laura Reina
Doreen Wackeroth
FLORIDA STATE UNIVERSITY
1851
PHYSICS
FLORIDA STATE UNIVERSITY
http://indico.cern.ch/event/loopfest12
Sponsored by the Physics Department, the College of Arts and Sciences, and the Office of Research of the Florida State University.

Outline

- Feynman diagrams versus graphs
  - using graphs in phenomenology/model building
- Supersymmetry (SUSY) in general (no prejudice!).
  - theoretical motivations
    - light Higgs boson
    - 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, e.g. UED Cheng,KM,Schmaltz 2002
- This talk: a fresh new look at SUSY phenomenology

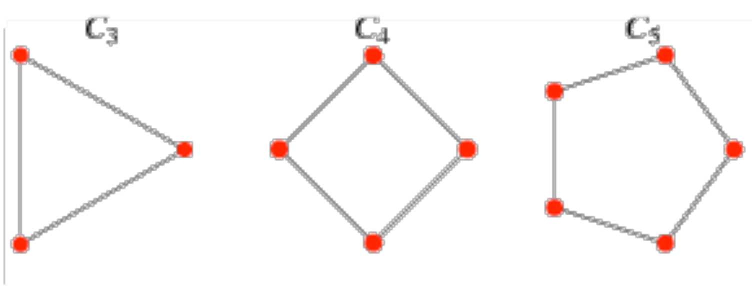
	Theory constructs		Number of parameters	Number of relevant event topologies under study
simplification by assumption ↑	Theory of Everything, e.g. string theory		one?	NA
	SUSY breaking “model”		a few	all
	General MSSM		way too many	all
simplification by relevance ↓	pMSSM	JoAnne’s talk	nineteen	all
	a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

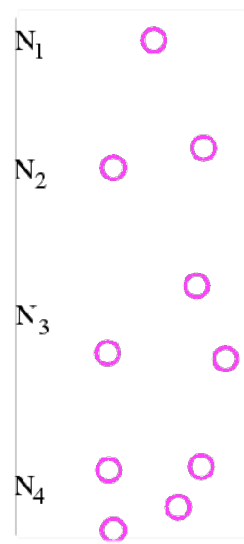
Some math

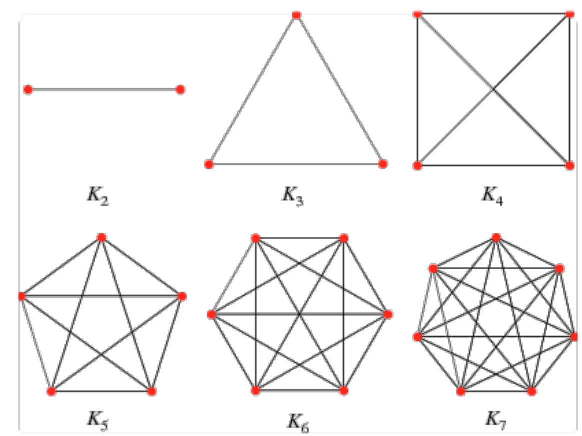
- Set
  - A collection of distinct objects, none of which is the set itself
  - Russell's paradox
    - Ordinary sets, e.g. A={1,2,3}
    - Extraordinary sets, e.g. A={1,2,3,A}
    - Every set is either ordinary or extraordinary
    - Consider S={all ordinary sets}. Is S ordinary or extraordinary?
      - if S is ordinary, then S={...,S} => S is extraordinary.
      - if S is extraordinary, then S={...,S} => S is ordinary.
- Graph: an object consisting of
  - a vertex set $\{v_i\}$ (any finite non-empty set)
  - an edge set $\{e_i\}$ (two-element subsets of the vertex set)
    - the edge set may be empty

Some common graphs

- The "cyclic graph on v vertices" C_v
  - v=e, each vertex has degree 2
- The "null graph on v vertices" N_v
  - e=0
- The "complete graph on v vertices" K_v
  - e=n(n-1)/2



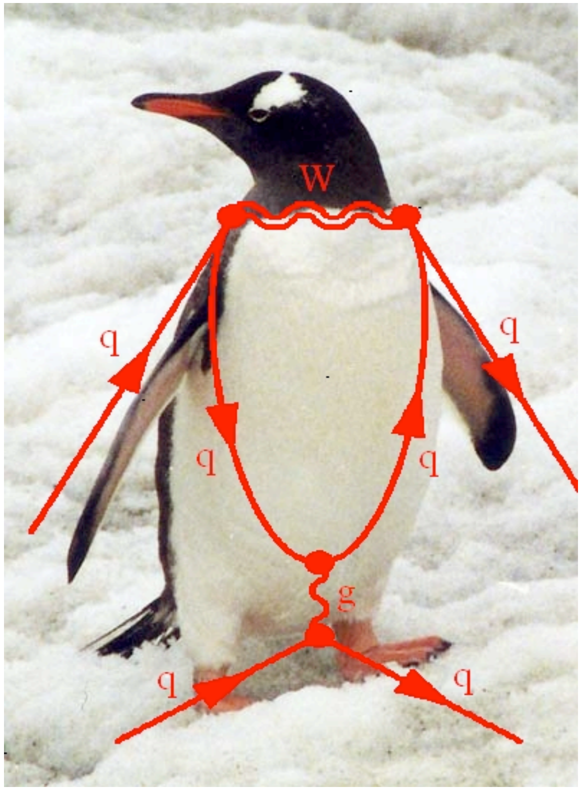




Feynman diagrams are not graphs

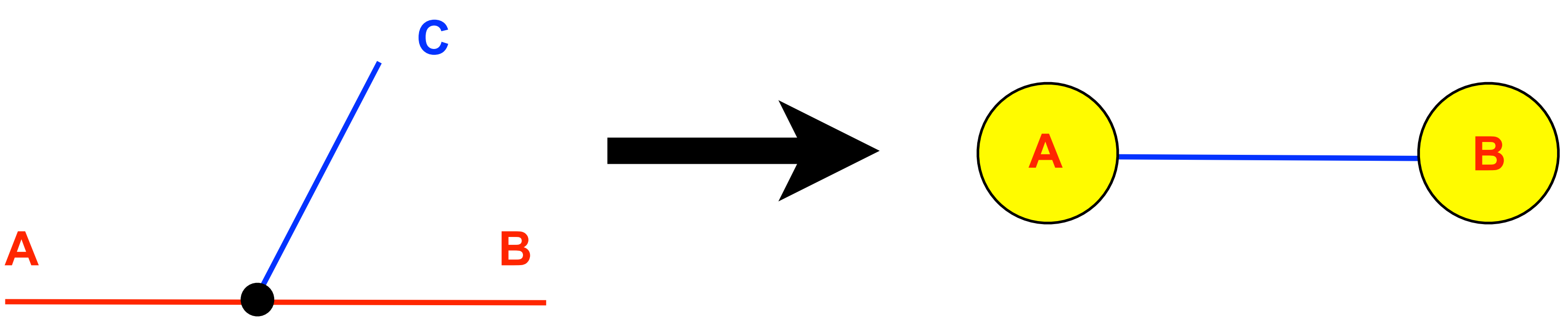
- An edge must have a vertex at each end
  - by definition
- Graphs are not allowed to have “loops”
  - vertices joined to themselves (the elements of the vertex set are distinct)
- Graphs may have “cycles”
- If the edges are directed, we get a directed graph (digraph)

vertices=interactions
edges=propagators

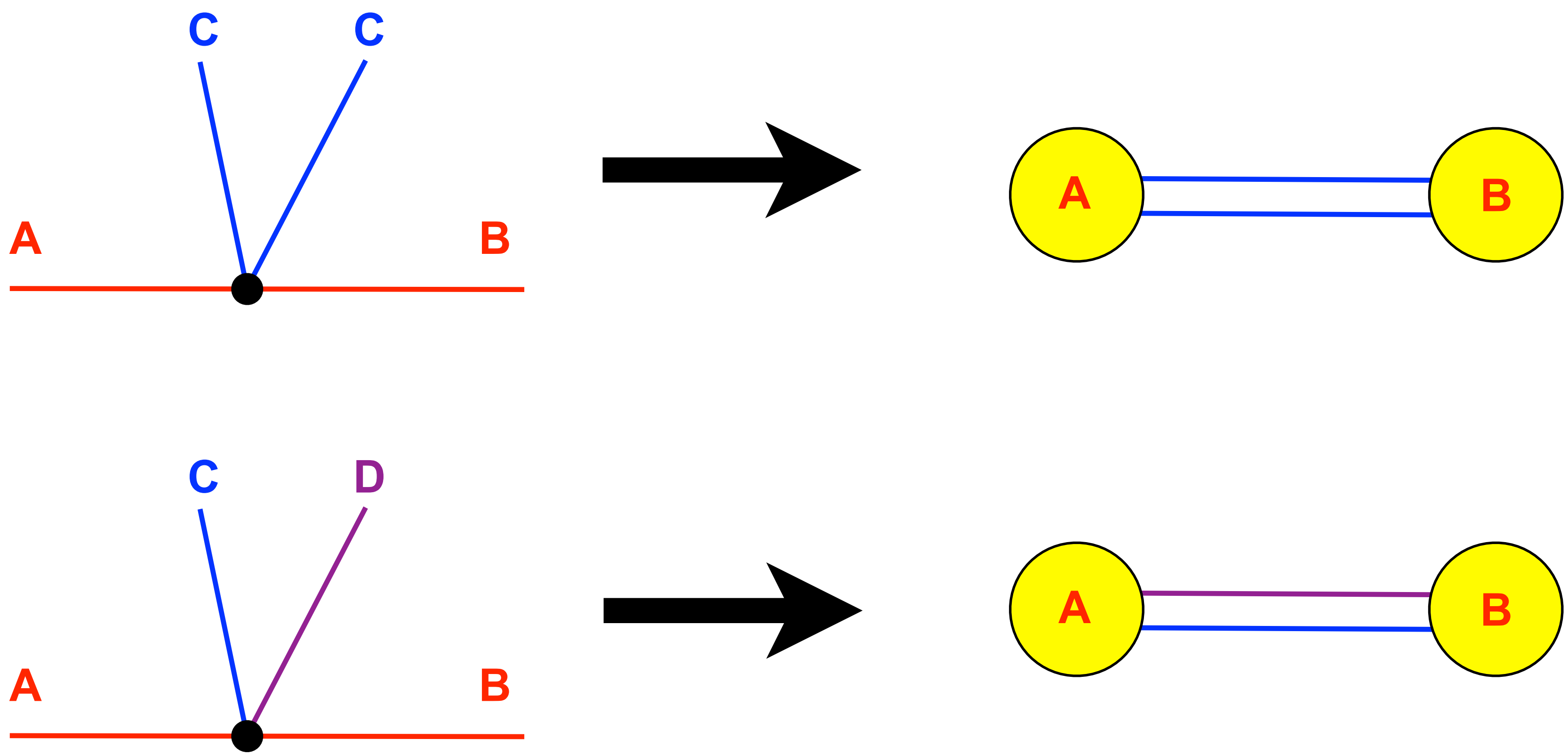


Graphs in SUSY phenomenology

- In Feynman diagrams we identify
  - vertices = interactions
  - edges = propagators (particles)
- Let us instead consider graphs where
  - vertices = particles
  - edges = interactions



More examples



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

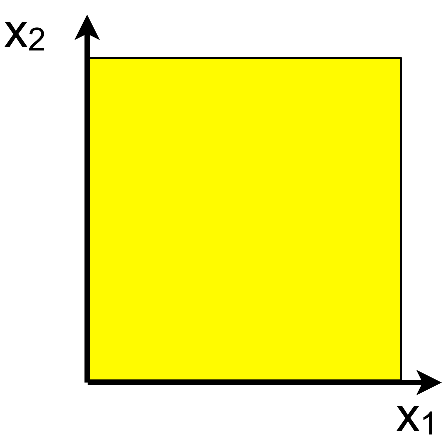
Mass parameter space factorization

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**

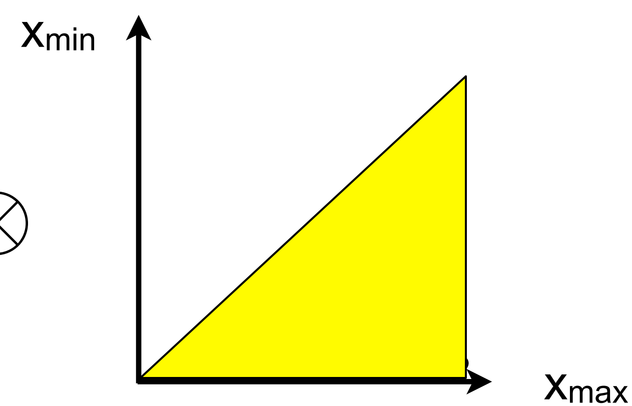
Let us study this part!

Konar,KM,Park,Sarangi 2010

- Example: n=2



$=$ (x_1,x_2) or (x_2,x_1) $\otimes$

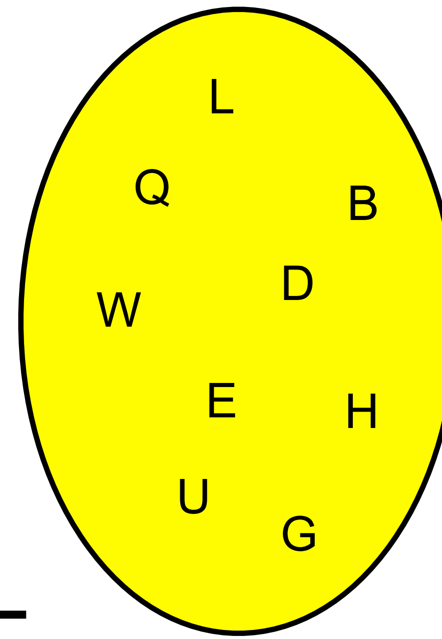


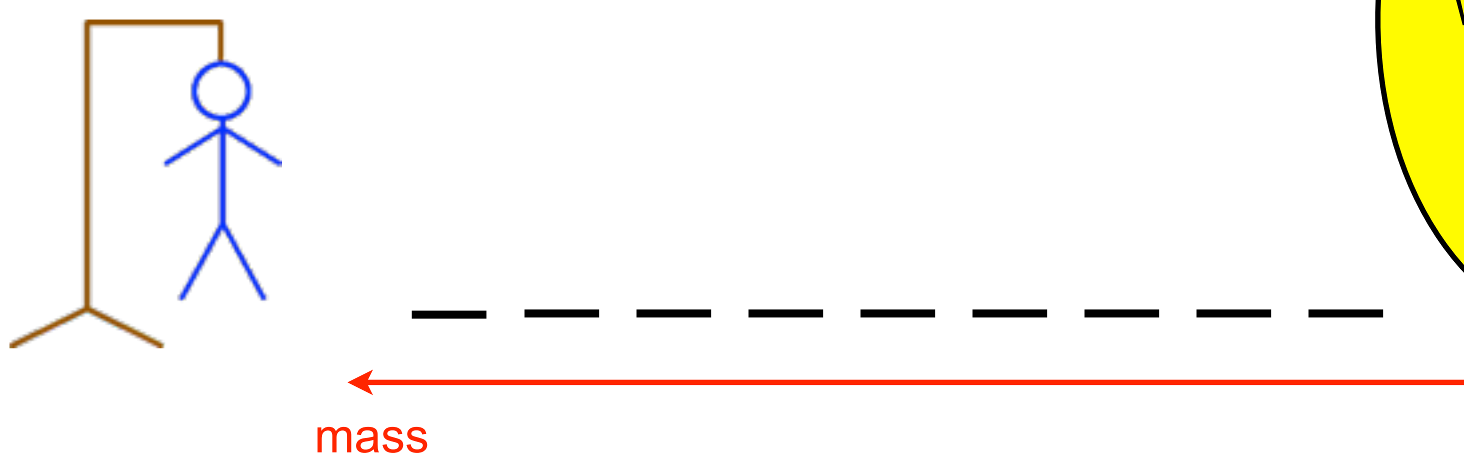
The SUSY parameter space

- 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.

$\tilde{u}_L,\, \tilde{d}_L$	$\tilde{u}_R$	$\tilde{d}_R$	$\tilde{e}_L,\, \tilde{\nu}_L$	$\tilde{e}_R$	$\tilde{h}^{\pm},\, \tilde{h}^0_u,\, \tilde{h}^0_d$	$\tilde{b}^0$	$\tilde{w}^{\pm}, \tilde{w}^0$	$\tilde{g}$
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

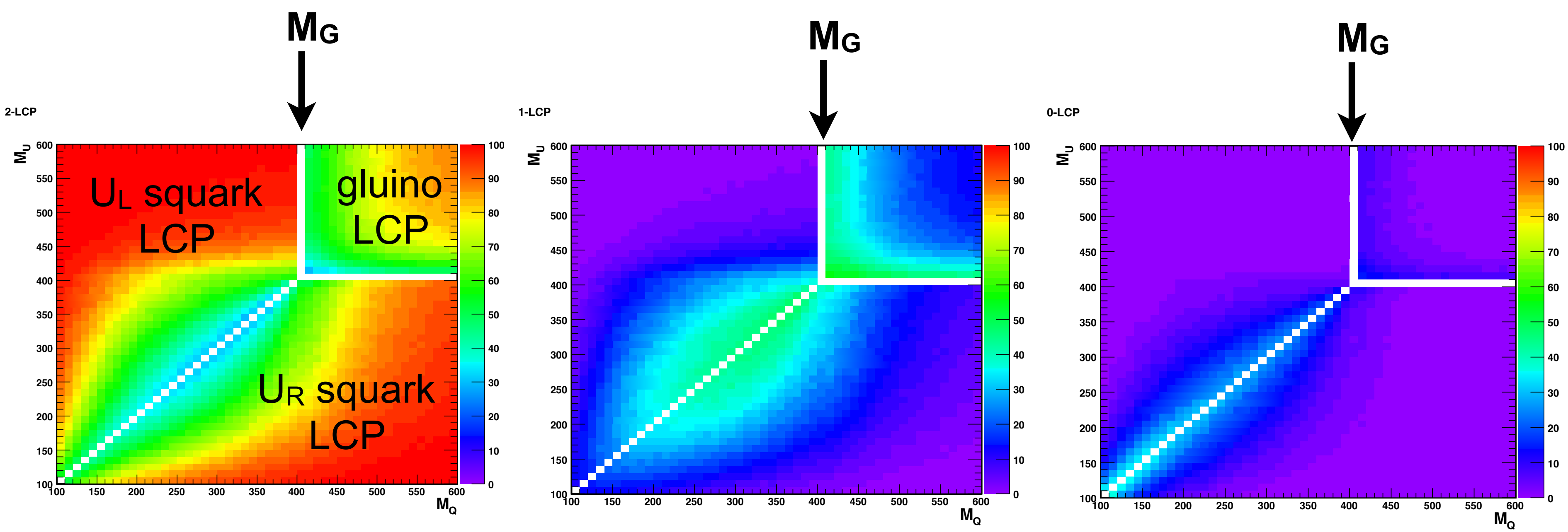
- There are 9!=362,880 possible permutations
- First: who is the LSP (lightest superpartner)
  - CHAMP (8!=40,320) if LSP=E
  - R-hadron (4x8!=161,280) if LSP=G, Q, U or D
  - Missing energy (4x8!=161,280) if LSP=L, H, W or B
- Second: who is the LCP (lightest colored particle)
  - most abundantly produced at hadron colliders
- Third factor: what is the dominant decay of the LCP
  - count suppressions by multi-body phase space
  - count suppressions from "ino" mixing angles

$$x \ldots x \, \mathcal{C} \, y \ldots y \, \mathcal{L}$$

Strong production cross-section

Konar,KM,Park,Sarangi 2011

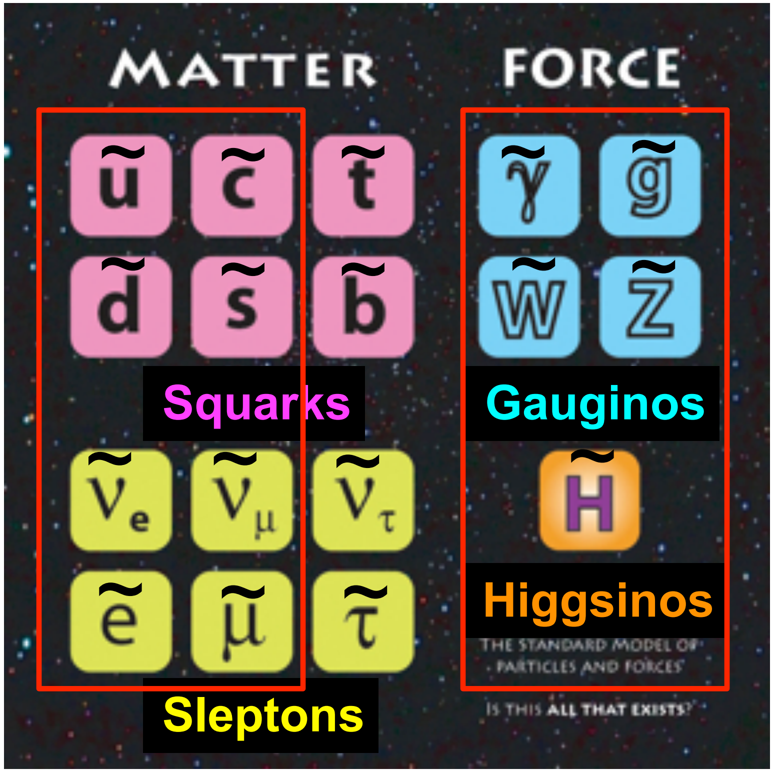
- Does the LCP cross-section really dominate?
  - compare the inclusive production of gluinos and squarks

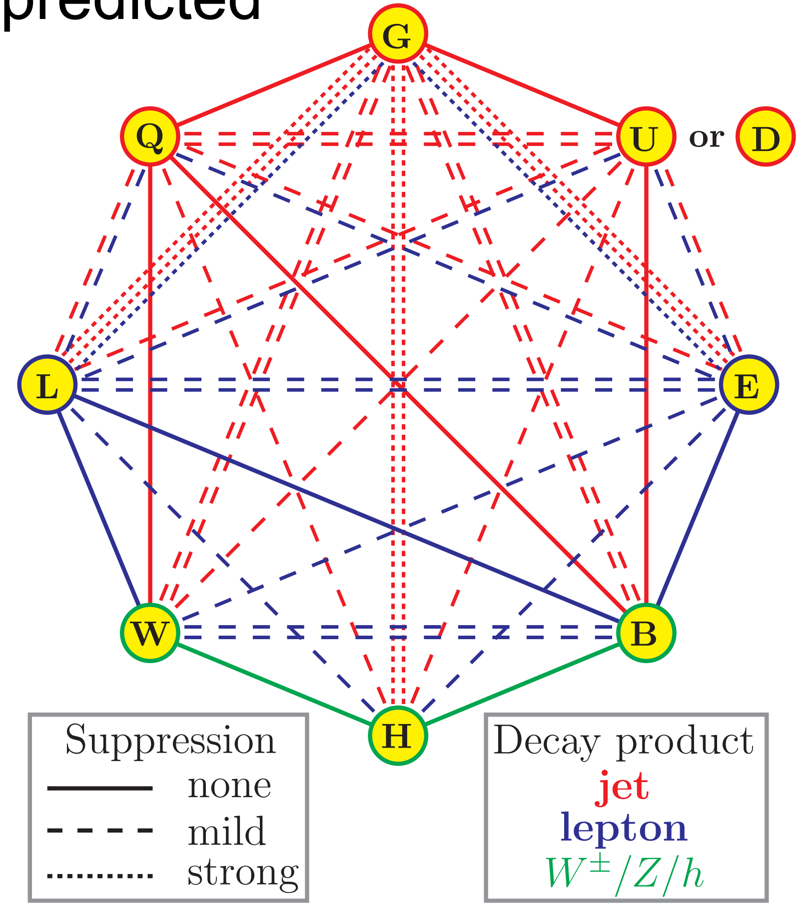


2 LCP + X   1 LCP + X   0 LCP + X

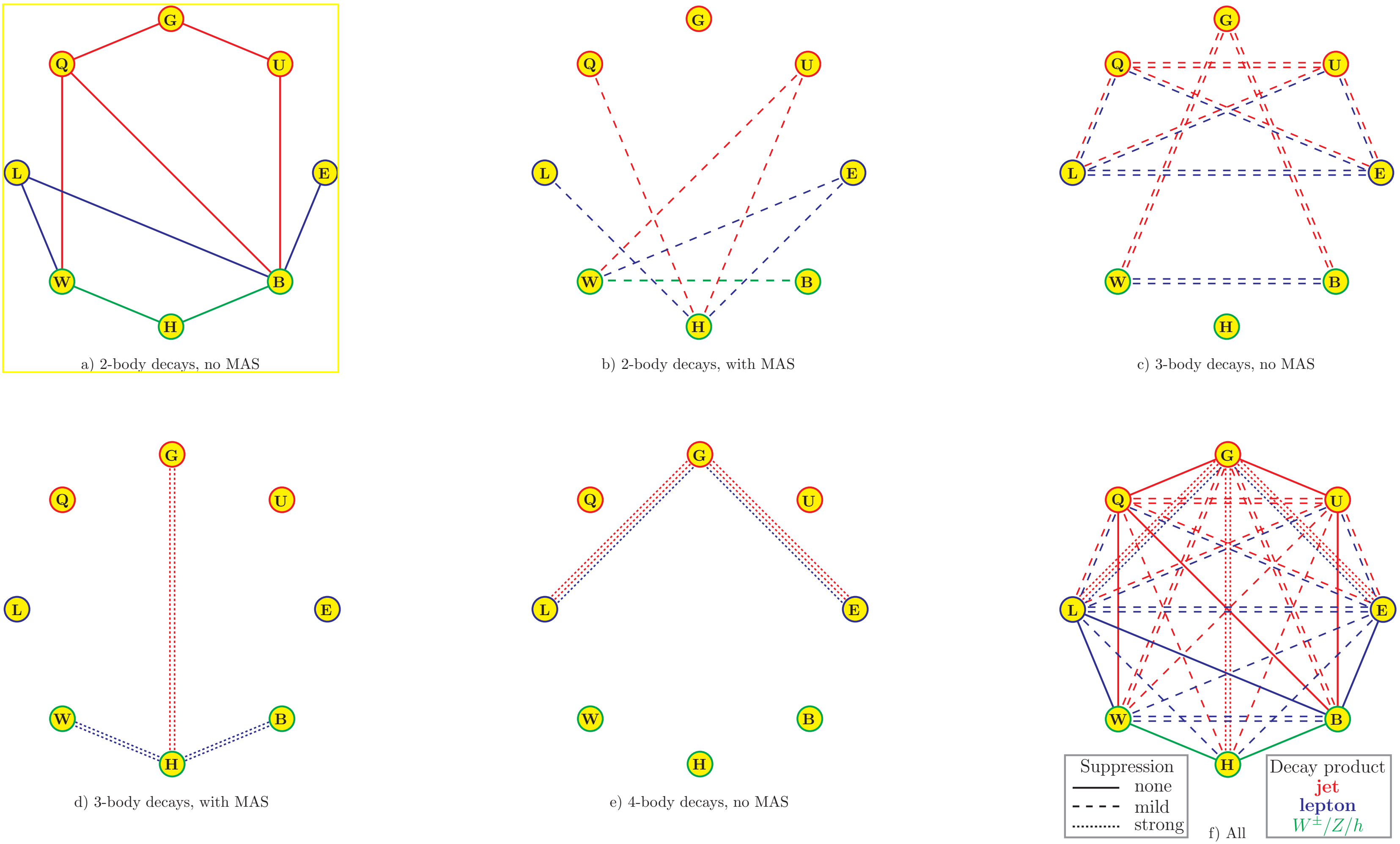
SUSY decay modes

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

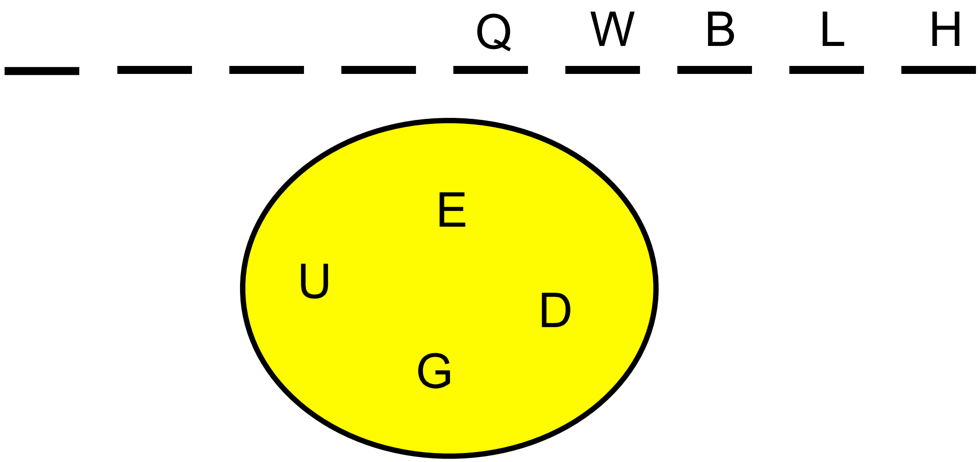


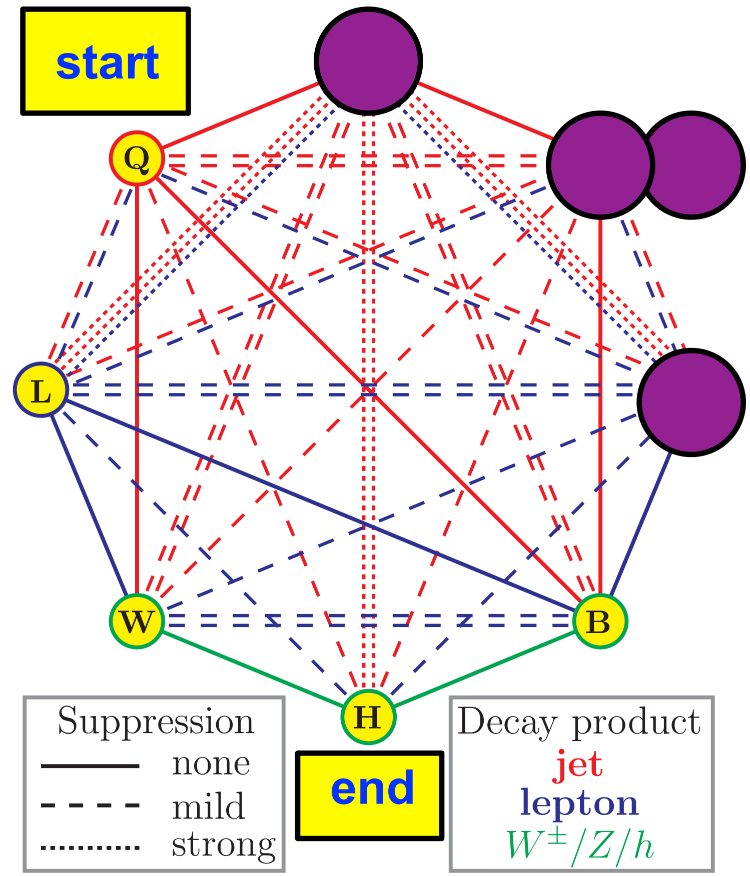


Counting suppression factors



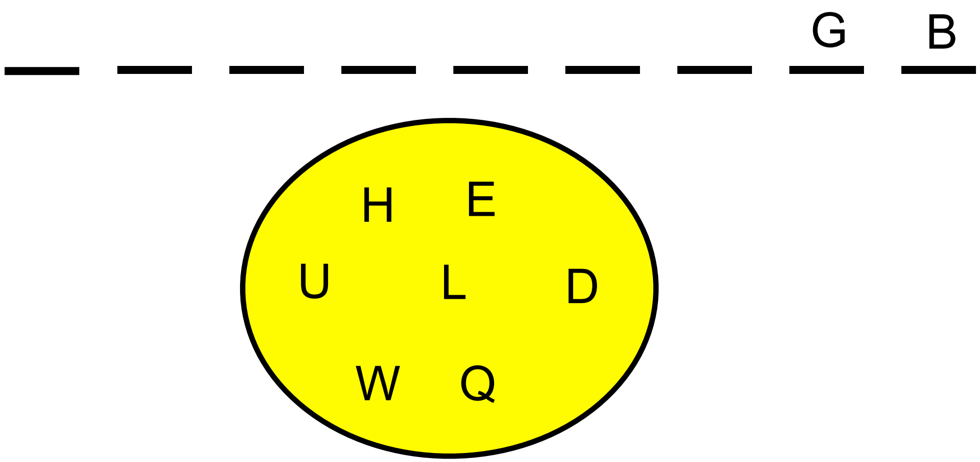
LCP decays: an example



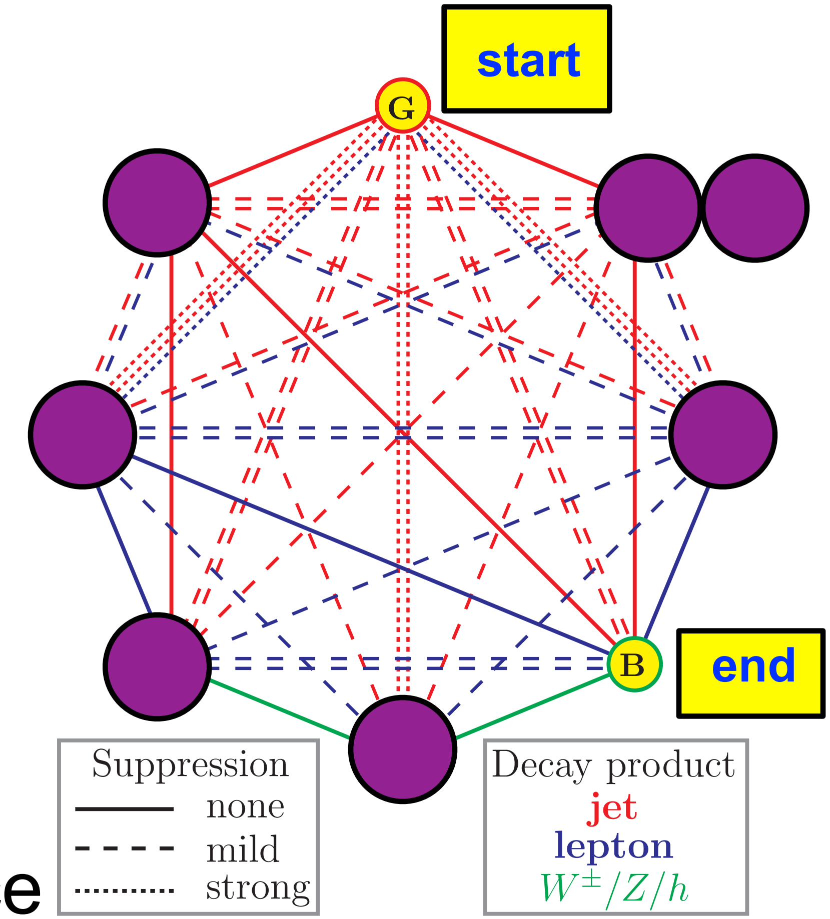


- A variation of the traveling salesman problem
- Several possible paths:
  - QBH, QWH: give jet plus V
  - QBLH, QWLH, give jet plus 2L
- Count all such “dominant” signatures for each permutation

LCP decays: another example



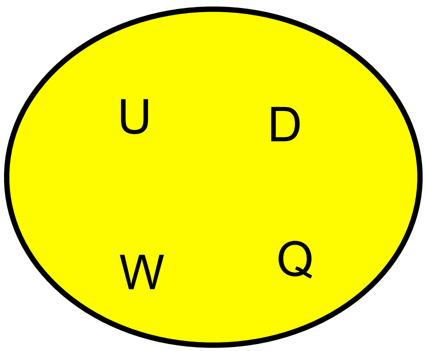
- This example is trivial
- Single unique path:
  - GB: gives 2 jets
- SMS “T1” in CMS parlance

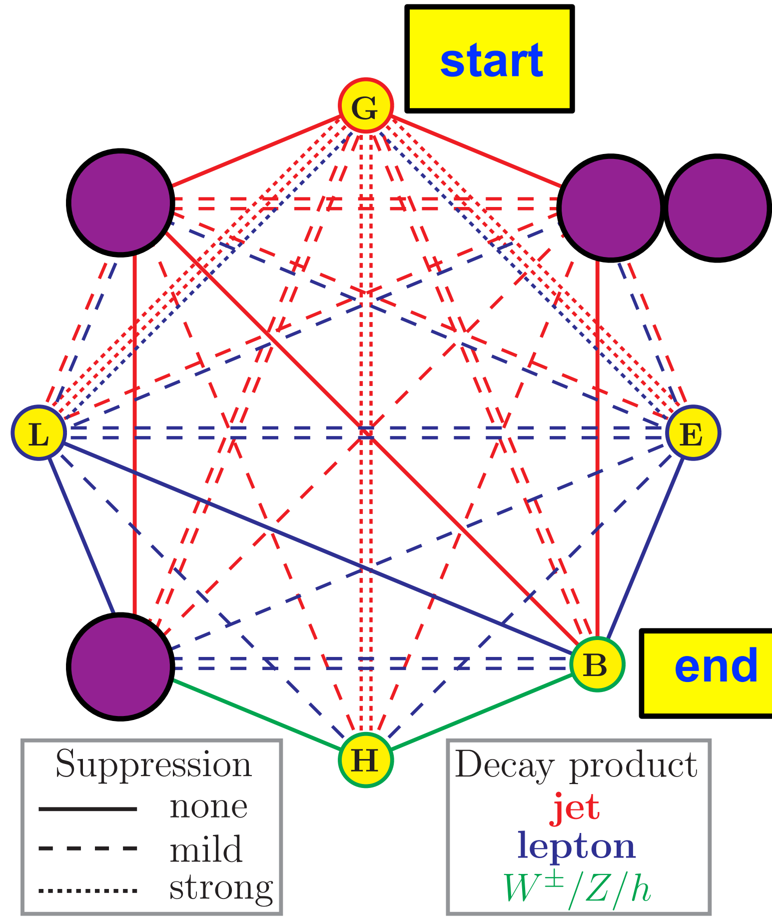


“T1” SMS

LCP decays: yet another example

___ ___ ___ ___ G H L E B



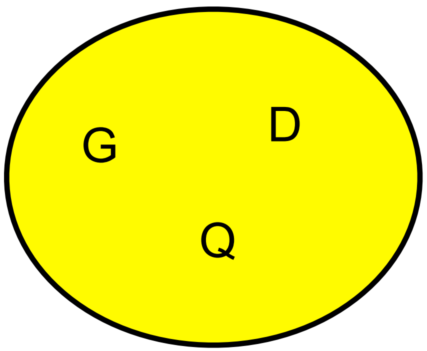


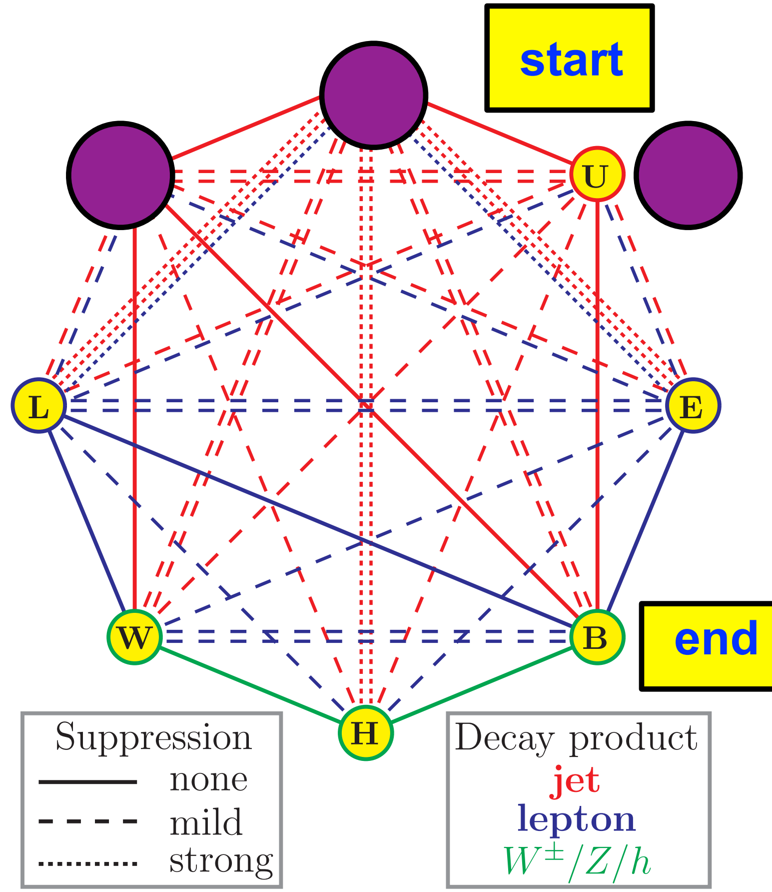
- This example is also trivial
- Single unique path:
  - GB: gives 2 jets
  - G to L is a 4 body decay
  - G to E is a 4 body decay
  - G to H is a 3 body decay with mixing angle suppression

"T1" SMS

LCP decays: yet another example

_ _ _ U H L W E B



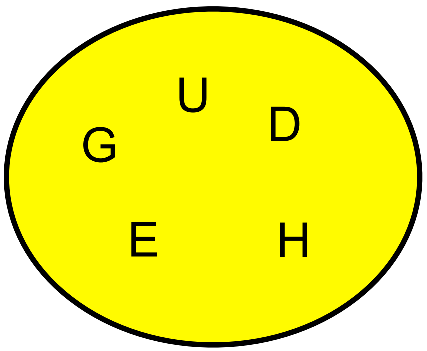


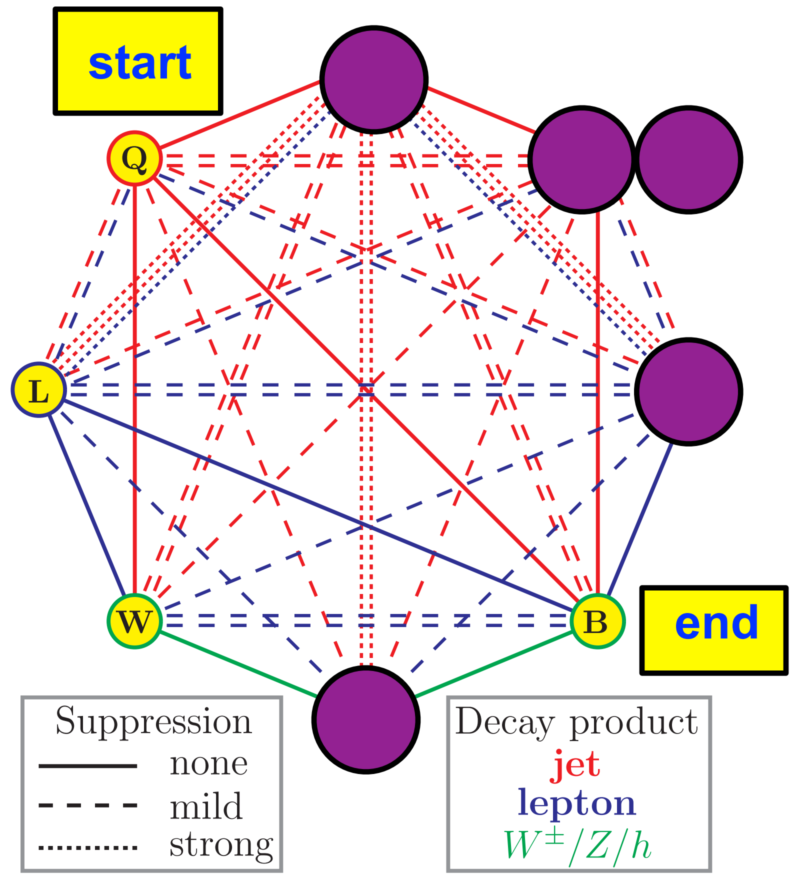
- MSUGRA-like example
- Single unique path:
  - UB: gives 1 jet
  - U to L is a 3 body decay
  - U to E is a 3 body decay
  - U to W suppressed by mixing
  - U to H suppressed by mixing

"T2" SMS

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 $\mathcal{C}$.

	$n_v = 0$		$n_v = 1$		$n_v = 2$	
n_ℓ	$n_j = 1$	$n_j = 2$	$n_j = 1$	$n_j = 2$	$n_j = 1$	$n_j = 2$
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 $\mathcal{C}$.

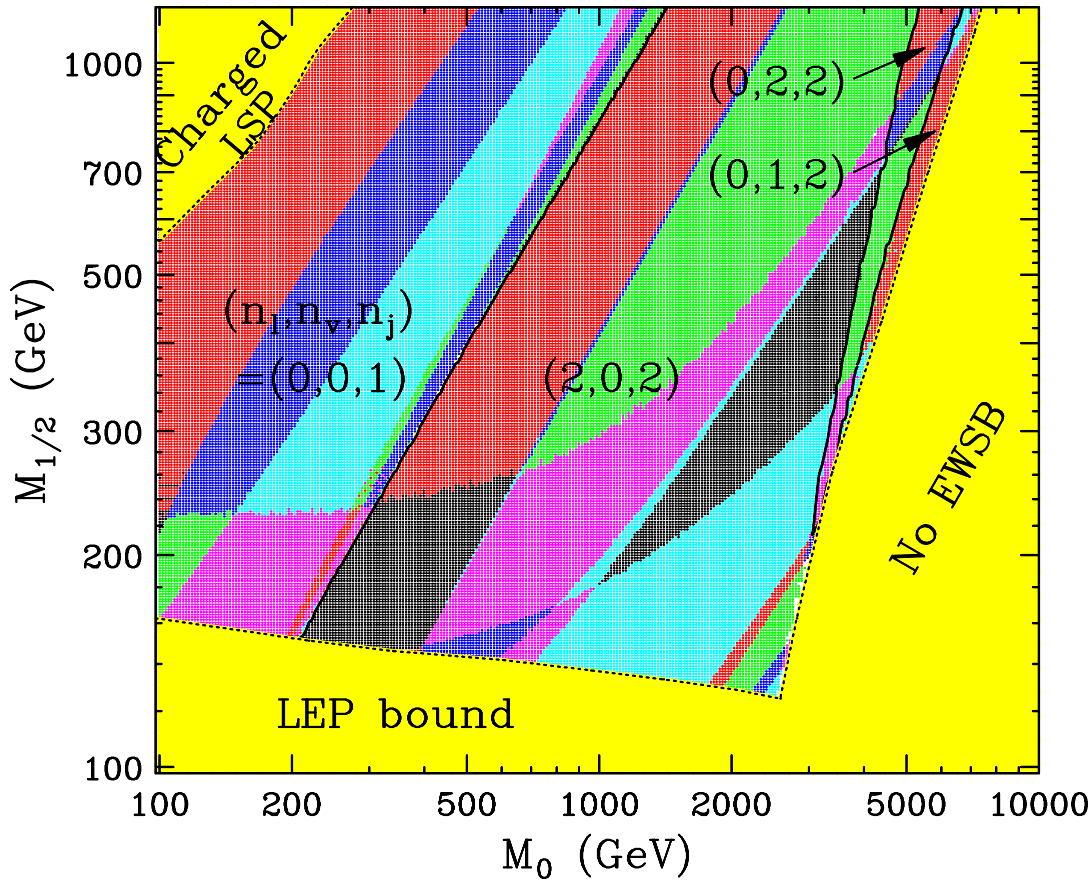
	$n_v = 0$		$n_v = 1$		$n_v = 2$	
n_ℓ	$n_j = 1$	$n_j = 2$	$n_j = 1$	$n_j = 2$	$n_j = 1$	$n_j = 2$
0	61488	21168	8310	2550	780	420
1	24150	8310	1278	378	132	72
2	17190	5550	1230	150	0	0
3	4362	1242	312	72	6	6
4	1656	396	66	6	0	0

x 2

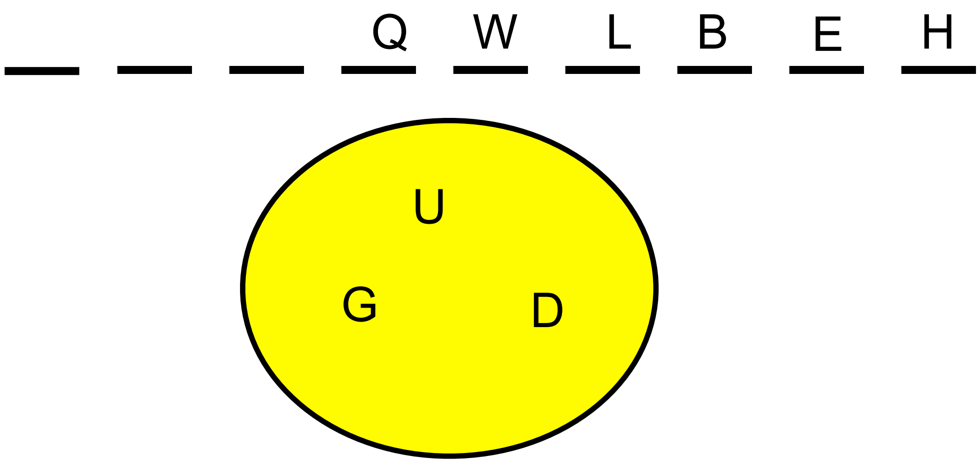
8 lepton events!

MSUGRA result

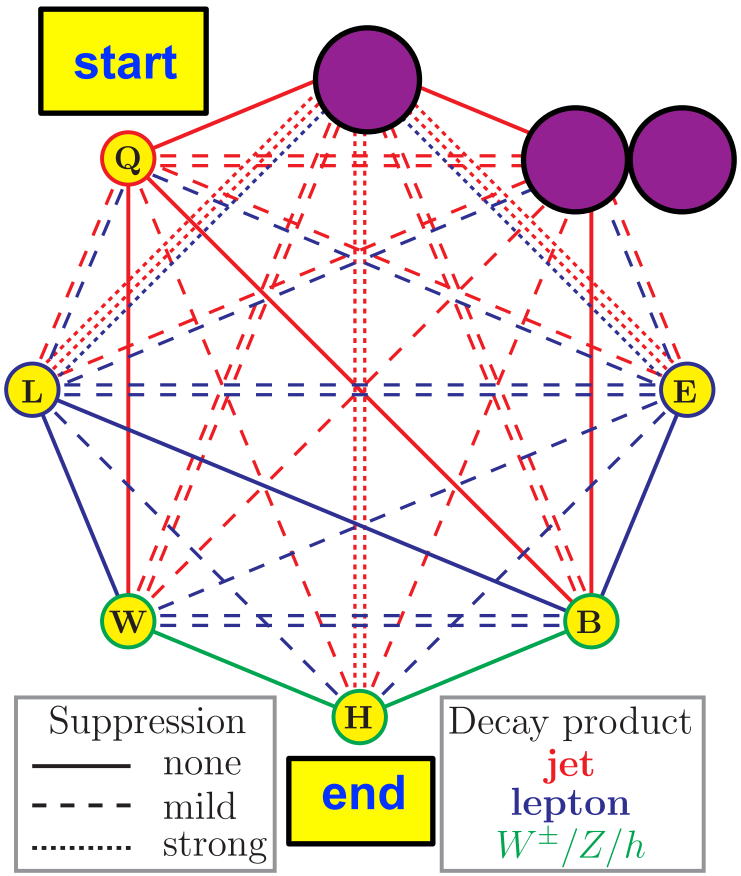
- Only 47 out of the 161,280 possible hierarchies
- Only 4 out of the 26 possible decay channels.



An example with 4 leptons



- 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: ???



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: 4x8!=161,280 MET hierarchies

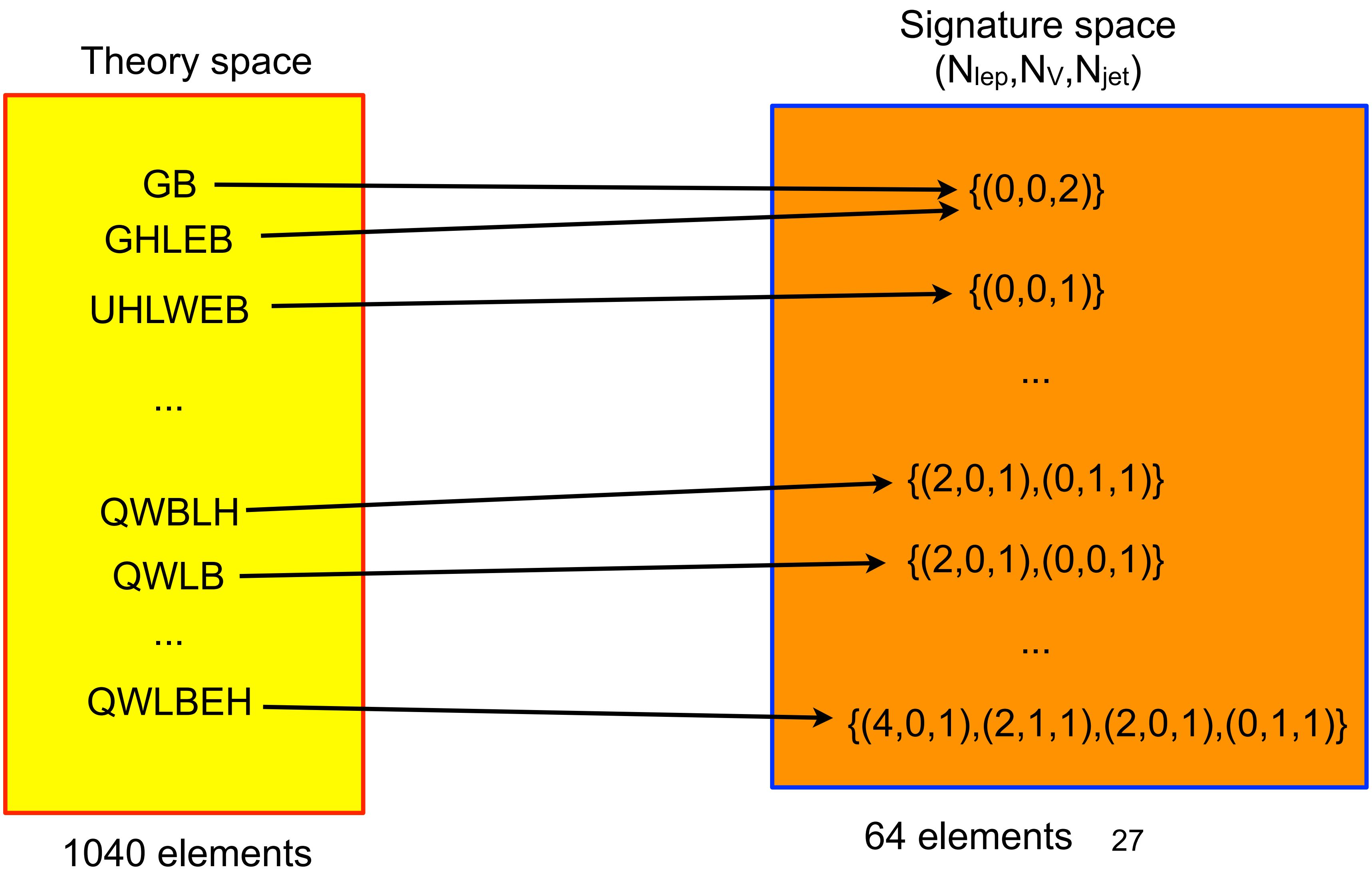
$$x \dots x \, \mathcal{C} \, y \dots y \, \mathcal{L}$$

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

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

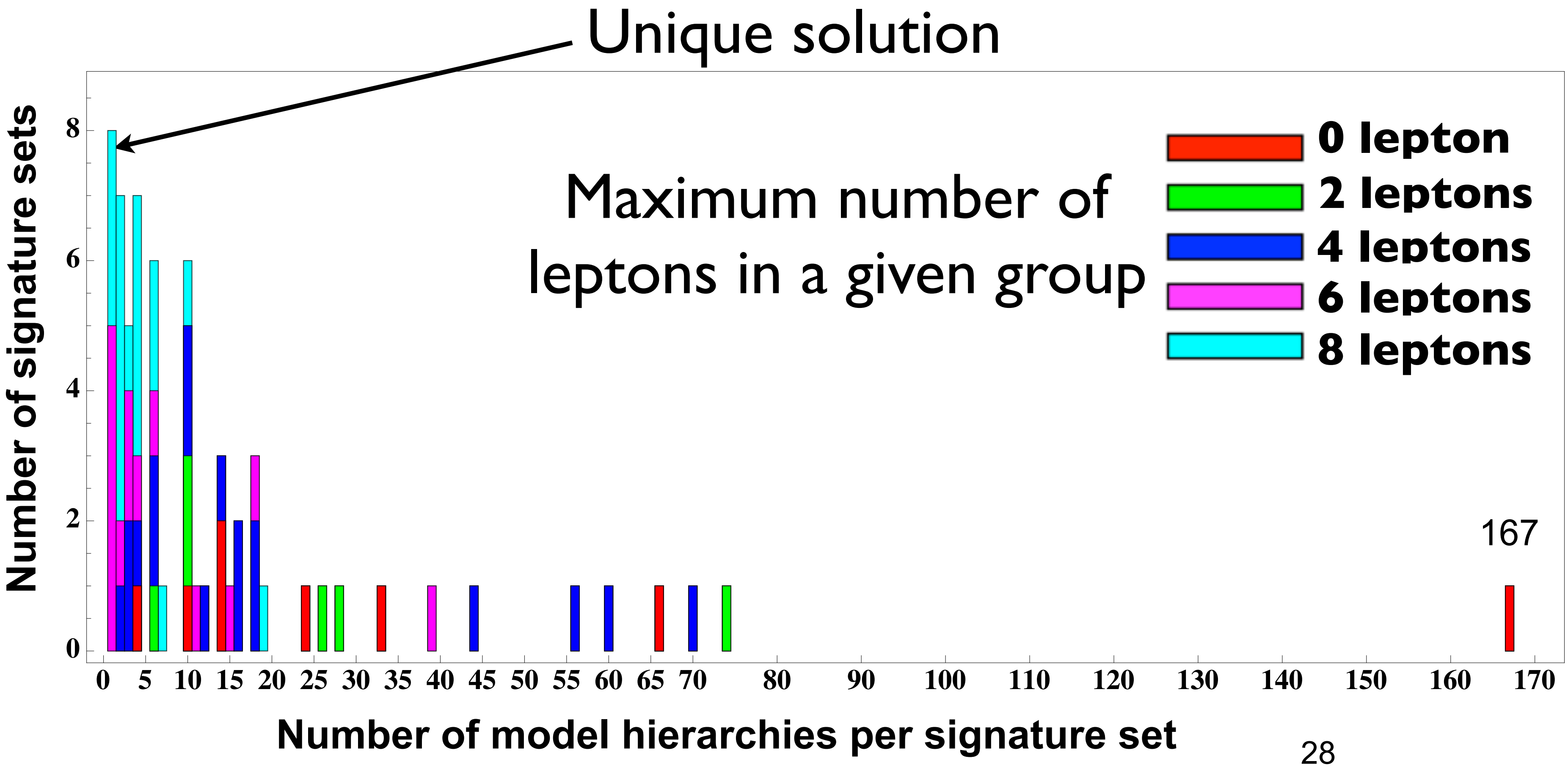
- Each model hierarchy comes with a set of signatures
  - the "maximally leptonic" + possibly others
  - there are 64 distinct sets of **dominant** signatures

The map from theory space to (MET) signature space



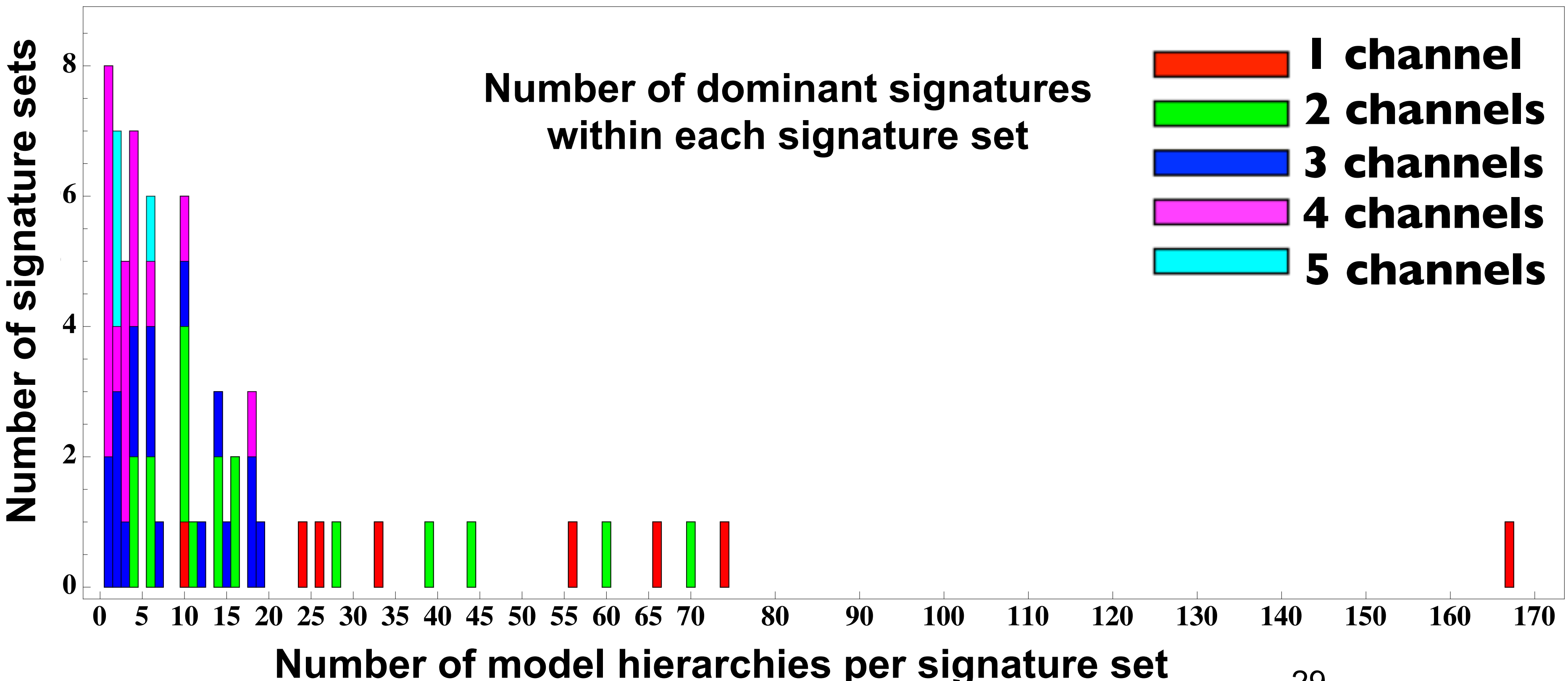
Is the map invertible?

- Sometimes, but not always...

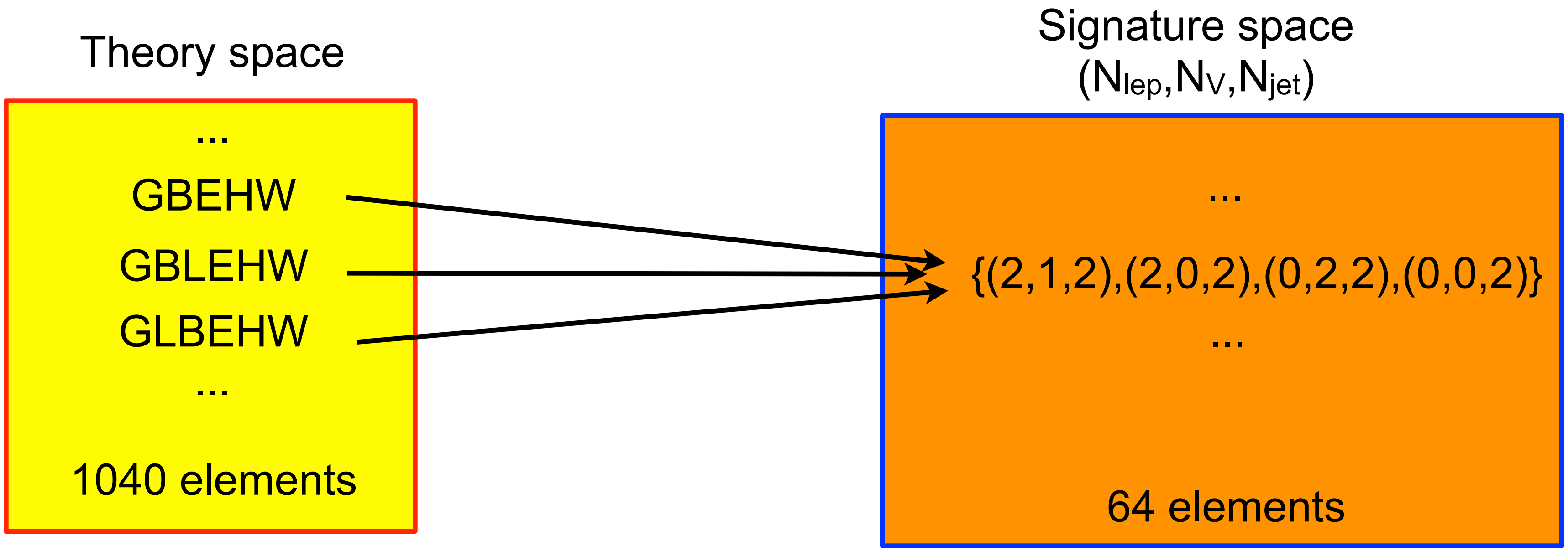


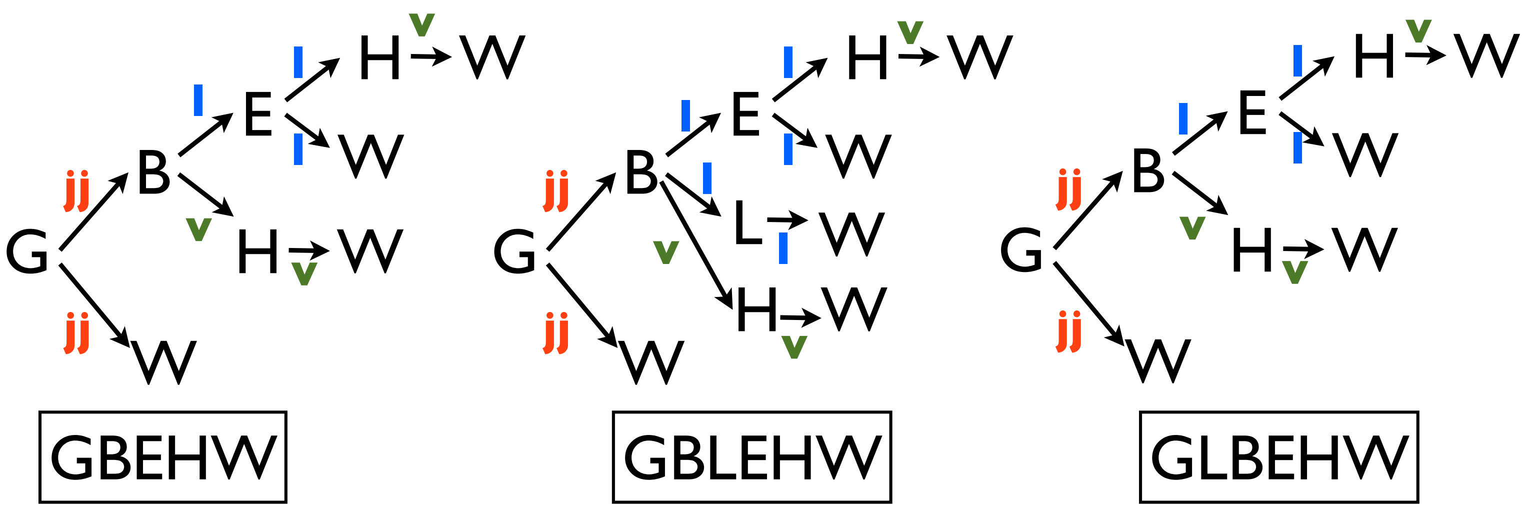
Inverse map again

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



An example of ambiguity





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
- The analysis is a proof of principle - extend to
  - RPV, third generation Dreiner,Staub,Vicente,Porod 2012
  - NMSSM Dreiner,Staub,Vicente 2012
  - distinguish between
    - leptons and neutrinos
    - W, Z and H bosons
    - jets, b-jets and top quarks

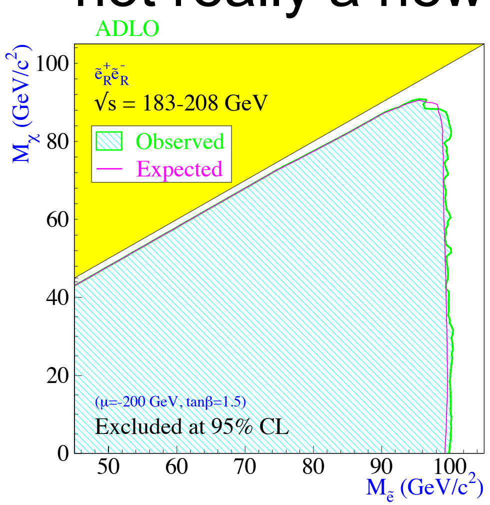
in preparation

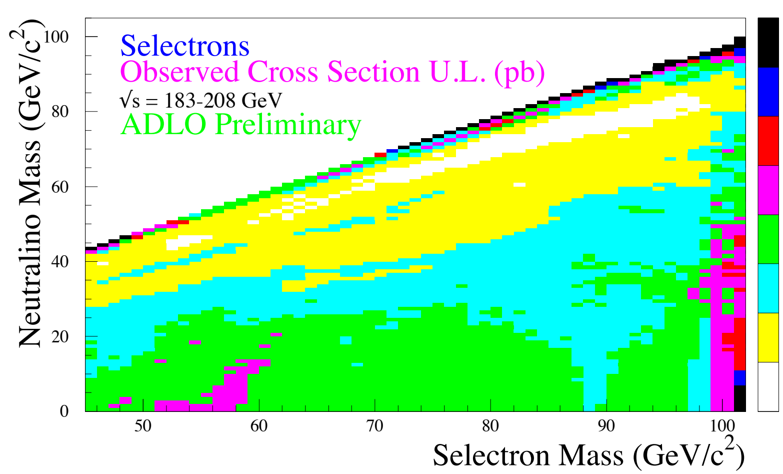
BACKUPS

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



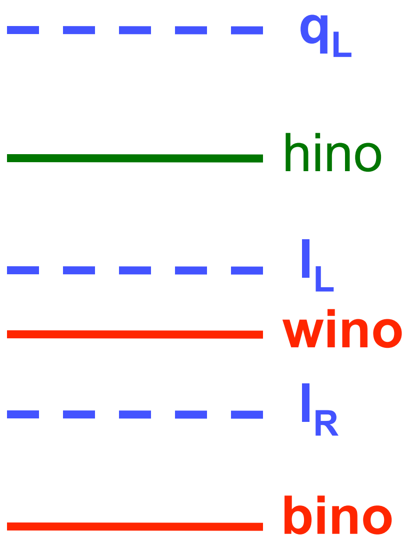


SUSY under the lamppost

- 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

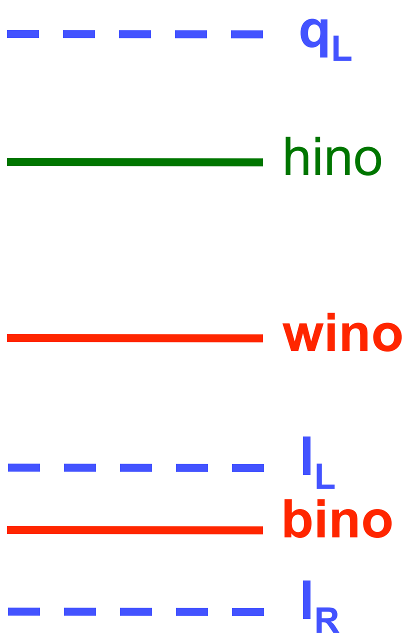
How can such a spectrum arise?

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



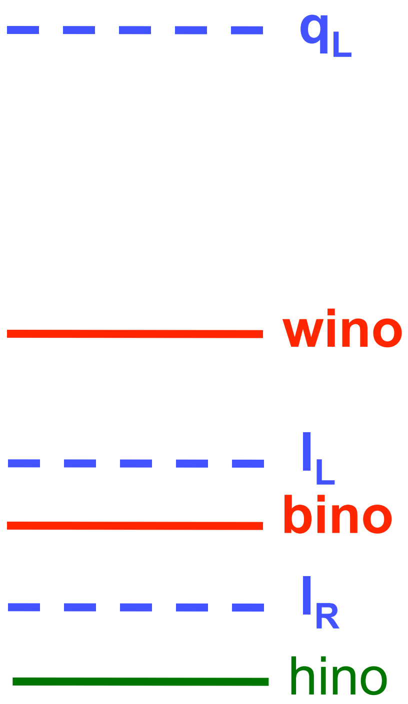
How can such a spectrum arise?

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



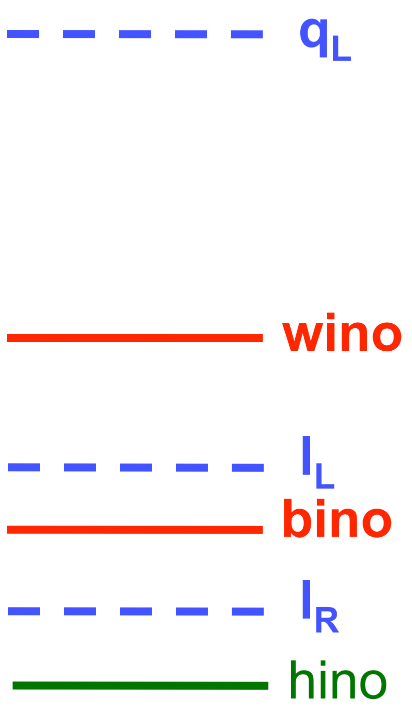
How can such a spectrum arise?

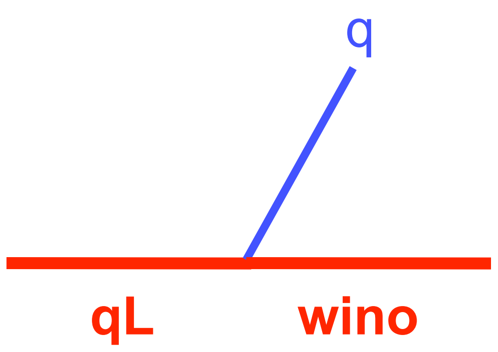
- Start with MSUGRA
  - typical hierarchy: QHLWEB
- Go to the stau LSP corner
  - typical hierarchy: QHWLBE
- Consider nuSUGRA
  - higgsino mass can be anything, thus:
    - QWLBEH



How can such a spectrum arise?

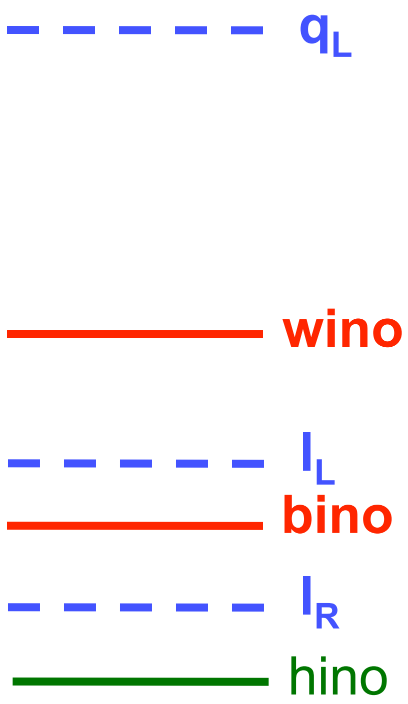
- Start with MSUGRA
  - typical hierarchy: QHLWEB
- Go to the stau LSP corner
  - typical hierarchy: QHWLBE
- Consider nuSUGRA
  - higgsino mass can be anything, thus:
    - QWLBEH

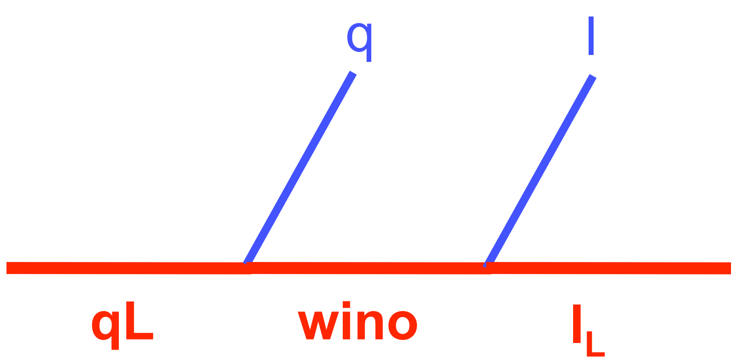




How can such a spectrum arise?

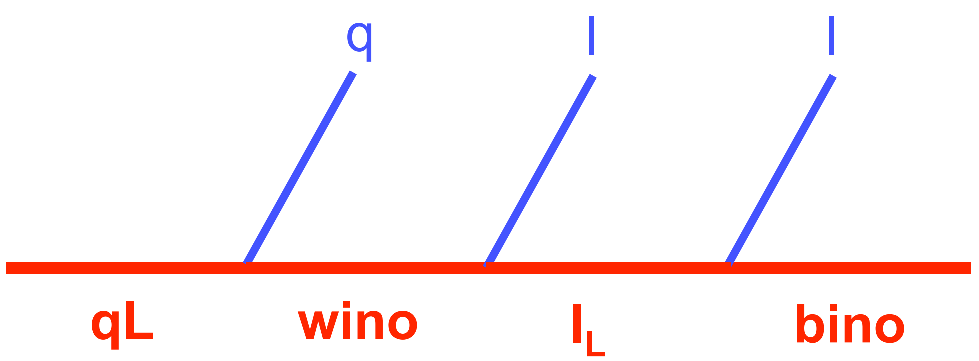
- Start with MSUGRA
  - typical hierarchy: QHLWEB
- Go to the stau LSP corner
  - typical hierarchy: QHWLBE
- Consider nuSUGRA
  - higgsino mass can be anything, thus:
    - QWLBEH

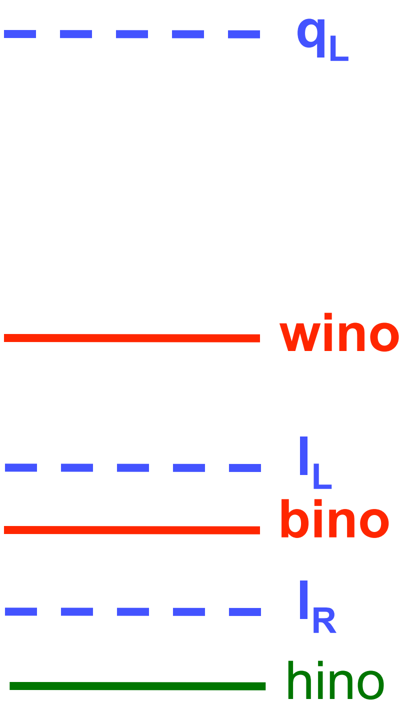




How can such a spectrum arise?

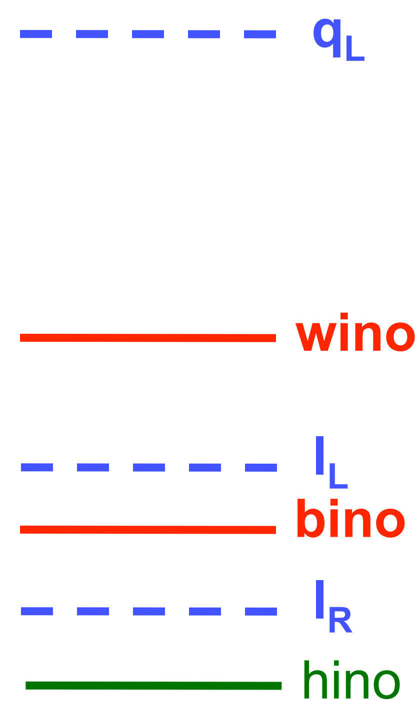
- Start with MSUGRA
  - typical hierarchy: QHLWEB
- Go to the stau LSP corner
  - typical hierarchy: QHWLBE
- Consider nuSUGRA
  - higgsino mass can be anything, thus:
    - QWLBEH

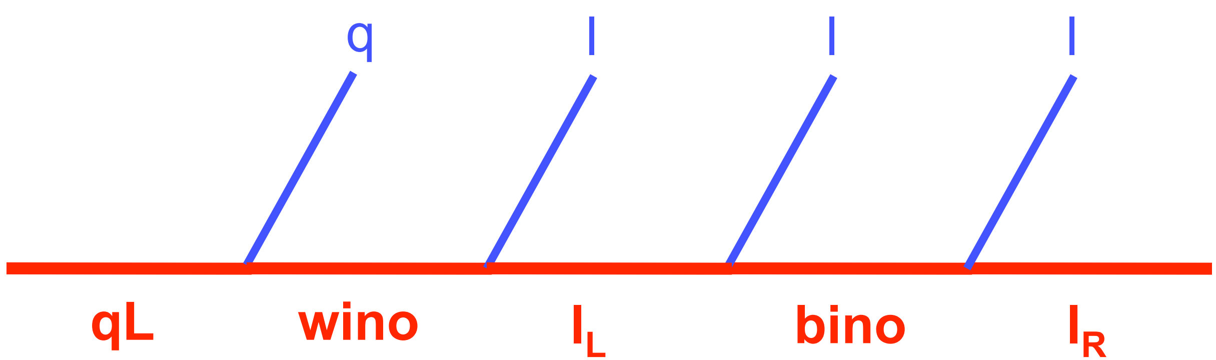




How can such a spectrum arise?

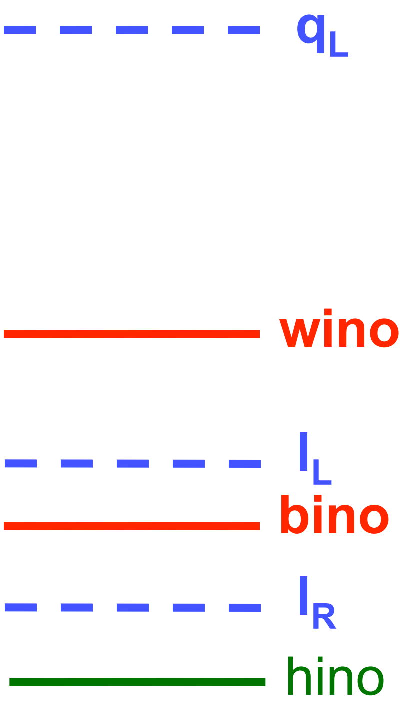
- Start with MSUGRA
  - typical hierarchy: QHLWEB
- Go to the stau LSP corner
  - typical hierarchy: QHWLBE
- Consider nuSUGRA
  - higgsino mass can be anything, thus:
    - QWLBEH

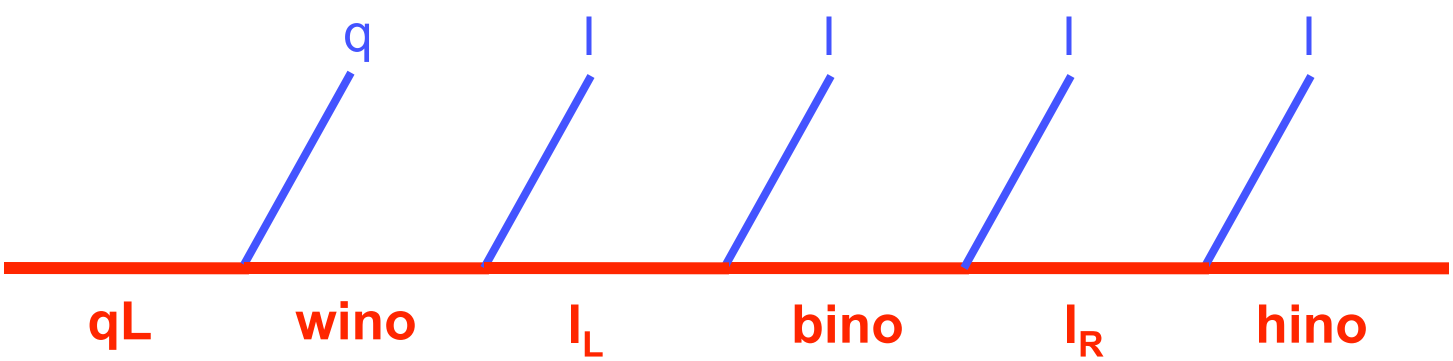




How can such a spectrum arise?

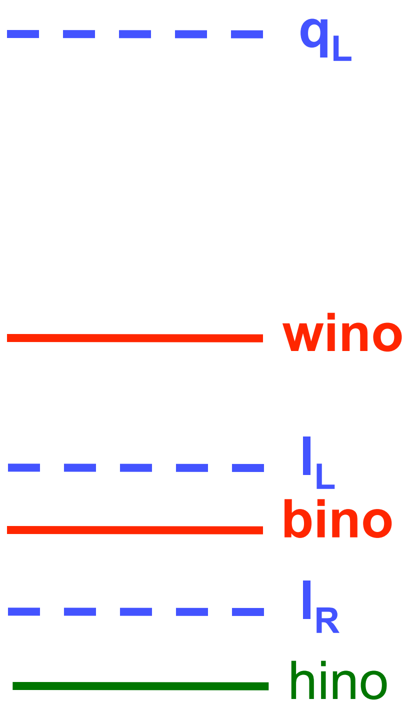
- Start with MSUGRA
  - typical hierarchy: QHLWEB
- Go to the stau LSP corner
  - typical hierarchy: QHWLBE
- Consider nuSUGRA
  - higgsino mass can be anything, thus:
    - QWLBEH

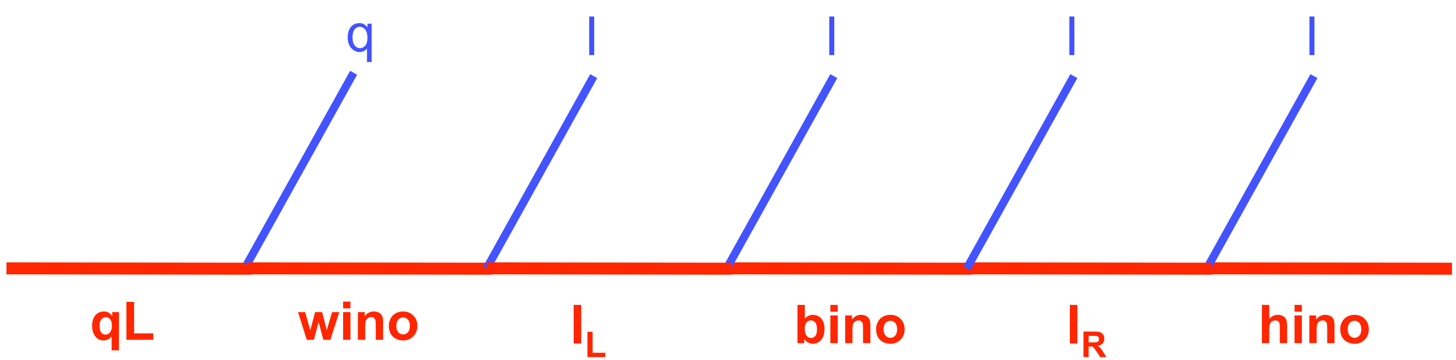




How can such a spectrum arise?

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



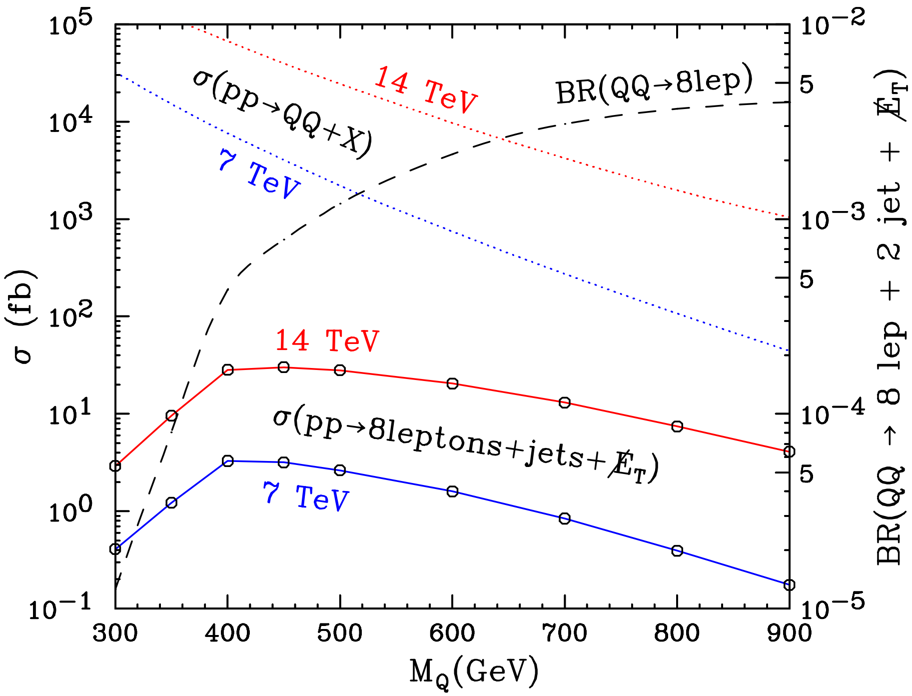


All 4 leptons come from the same side!

Study this 8-lepton hierarchy

U D ___ ___ 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

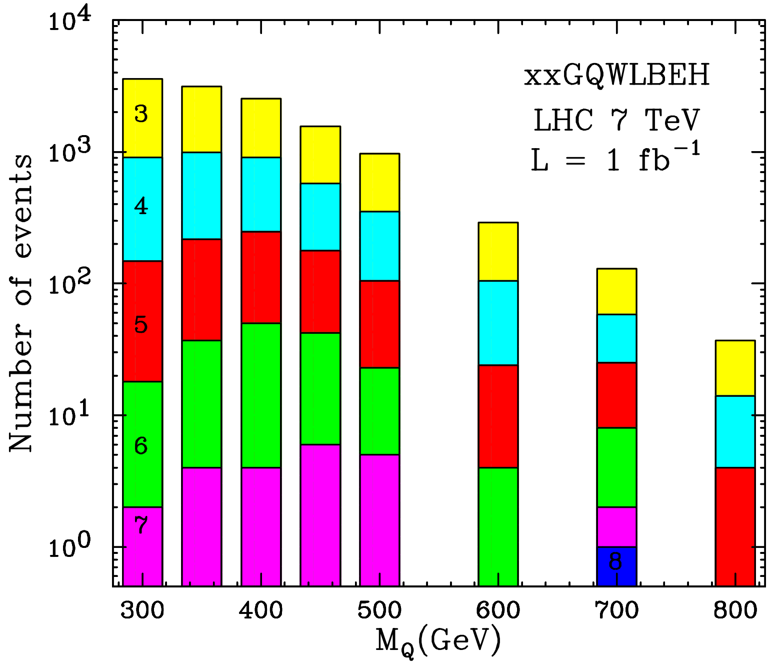


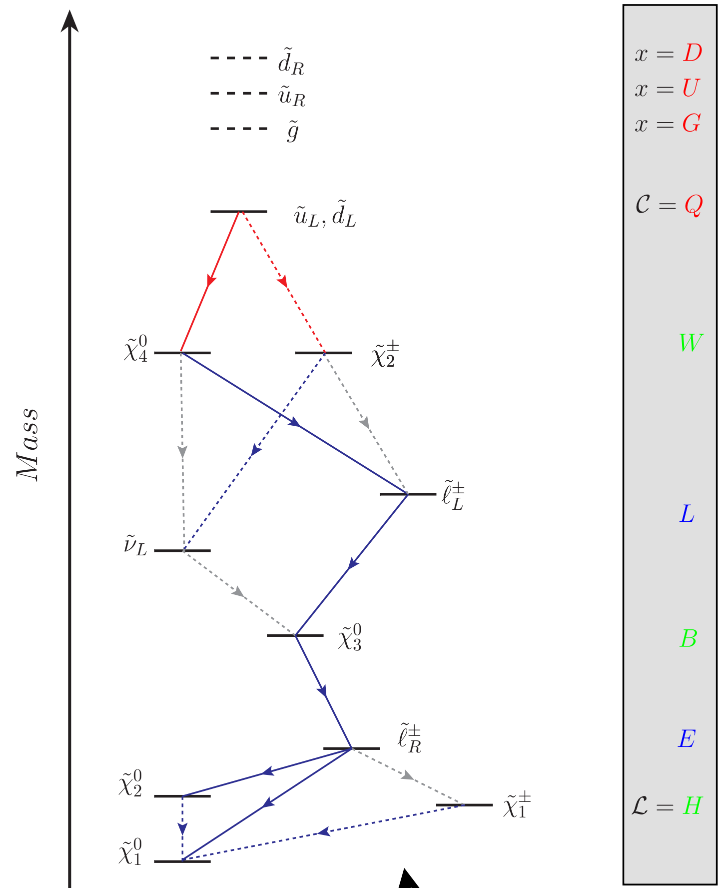
NLCP LCP LSP

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

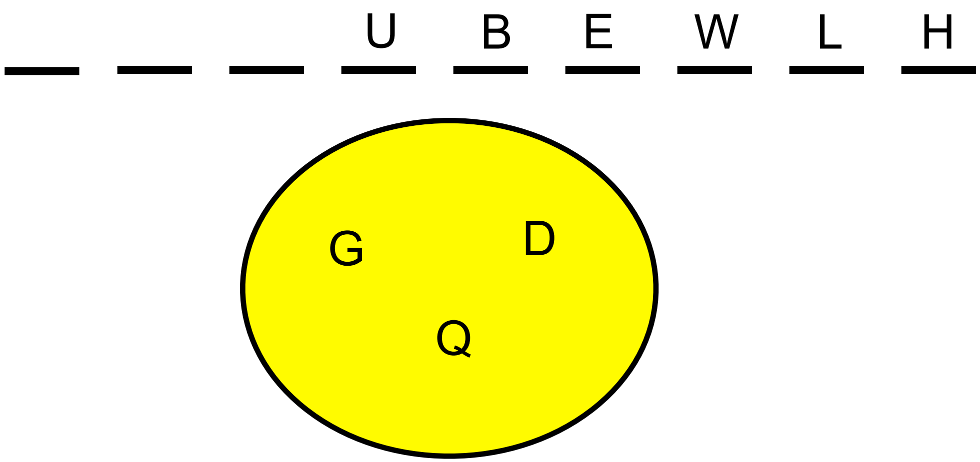
- Simulation: PYTHIA+PGS
  - count leptons with default cuts.
  - often leptons are missed because of the acceptance
- Easy discovery

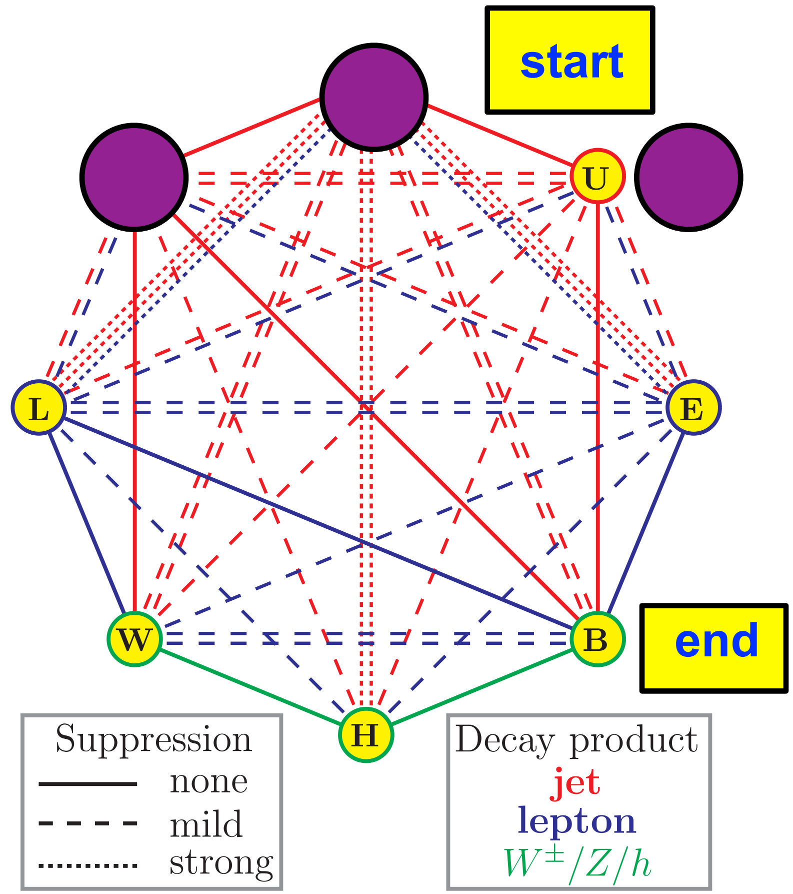




a simplified model?

Another example with 4 leptons



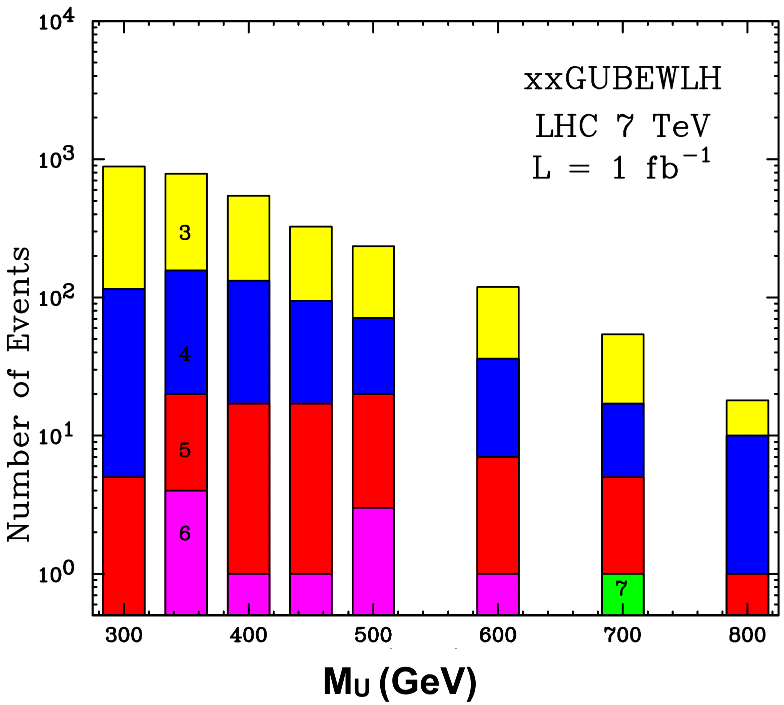


- Maximally leptonic path:
  - UBEWLH: gives 1 jet plus 4L
  - Bottleneck at the EW transition
    - E to W, E to L and E to H are all equally suppressed

Multi-lepton yields

Q D __ __ 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

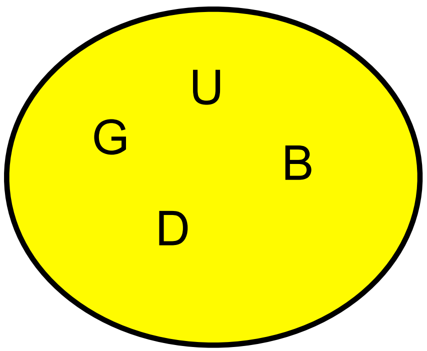


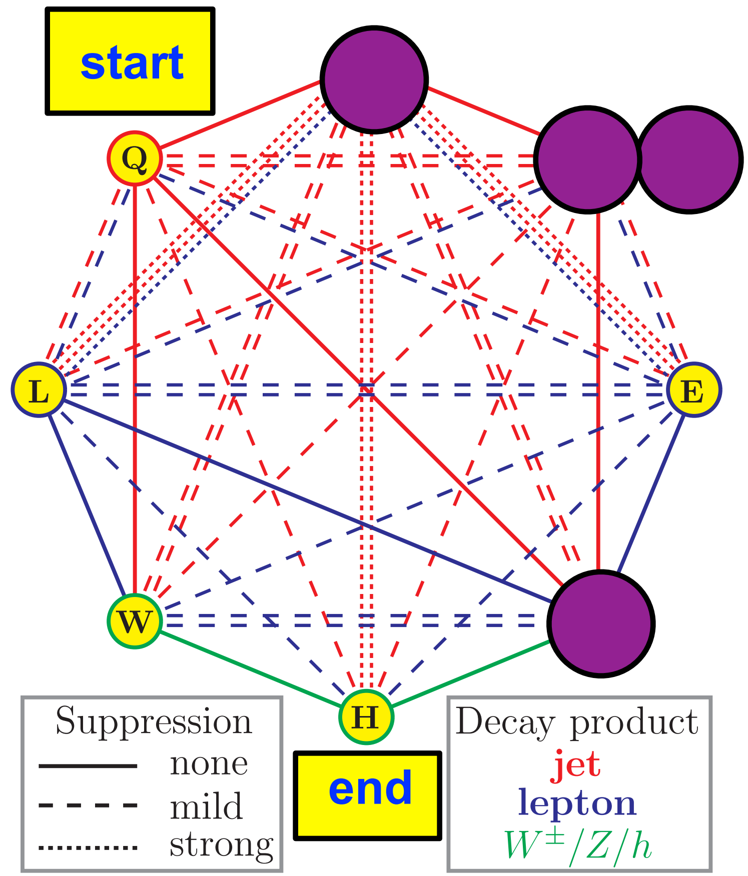
NLCP LCP LSP

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 -> E + 2 leptons is not in PYTHIA