Initial Systematic Investigations of the Weakly Coupled Free Fermionic Heterotic String Landscape Statistics

Timothy Renner,Jared Greenwald, Douglas Moore, Yanbin Deng and Gerald Cleaver

Baylor University

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Outline

- Introduction
- NAHE-Based Statistics
- NAHE Variation-Based Statistics
- Conclusions and Future Work

Weakly Coupled Free Fermionic Heterotic Strings

- Independent left and right moving modes,
  - left moving modes being supersymmetric (D=10),
  - right moving modes bosonic (D=26).
- Each of the bosonic modes of both left and right part is exchanged for two fermionic modes.
- Boundary conditions on the fermionic modes give rise to physical states.
- The boundary conditions are encoded using L (layer) basis vectors.
- Each basis vector is associated with an order, N, specifying the number of allowed boundary conditions.

WCFFHS Construction Process

- Starting with a basis vector set and GSO (Gliozzi, Scherk, Olive) matrix
  - Both the basis vector set and the GSO matrix must be modularly invariant to be quantum mechanically consistent
- Build sectors as linear combinations of basis vectors;
- Build particle states from sectors;
- Keep only massless states (at string scale);
- Apply GSO projection to filter out the unphysical states;
- Identify gauge group;
- Identify matter representations;

Systematic Survey

- Systematic searches examine all possible basis vectors and k_{ij} matrices.
- The searches are parameterized by the number of basis vectors used in constructing the models.

There are several challenges to performing systematic searches

- The parameter space is very large.
- Mass-producing models makes cross-checking difficult.

The Original NAHE Results

QTY	$SU(4)$	$SU(4)$	$SU(4)$	$SO(10)$	E_8
2	$\overline{4}$	1	1	16	1
2	1	$\overline{4}$	1	16	1
2	1	1	$\overline{4}$	16	1
2	1	1	4	16	1
1	1	1	6	10	1
2	1	4	1	16	1
1	1	6	1	10	1
1	1	6	6	1	1
2	4	1	1	16	1
1	6	1	1	10	1
1	6	1	6	1	1
1	6	6	1	1	1

NAHE: Nanopoulos, Antoniadis, Hagelin, Ellis.

5 basis vectors used therein.

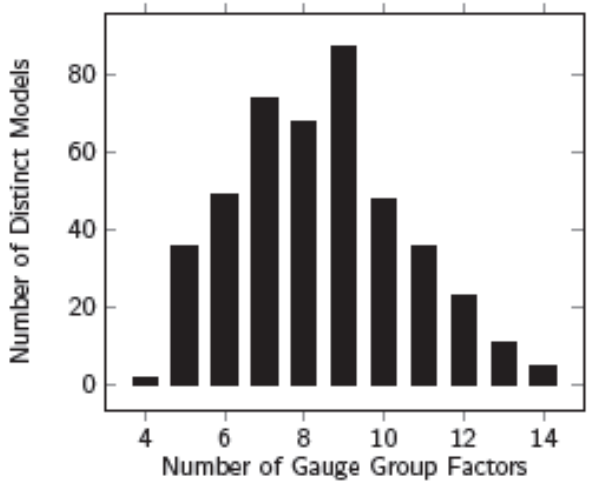
It has N=1 Spacetime SUSY.

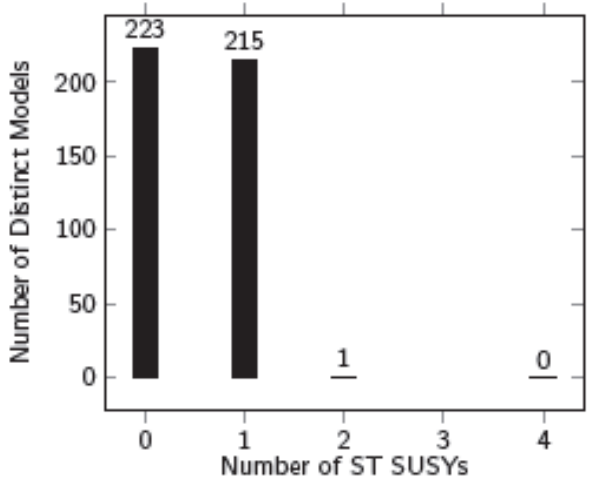
Potentially good.

Extened NAHE Results, Order 2, Layer 1

- There were 439 distinct models out of 1,945,088 total models.
- In addition, 9.5% of the models without rank-cuts and 13% of the models with rank-cuts were removed as duplicates.

GUT Group	% of Models
E_6	0.2278%
$SO(10)$	36.45%
$SU(5) \otimes U(1)$	0%
PS	55.35%
LR	0%
MSSM	0%

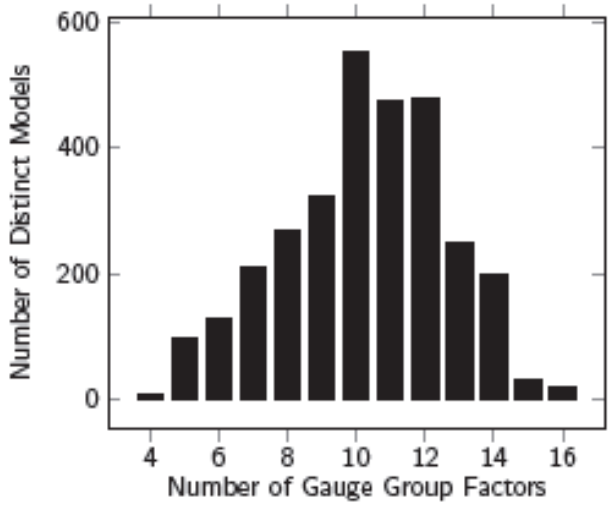


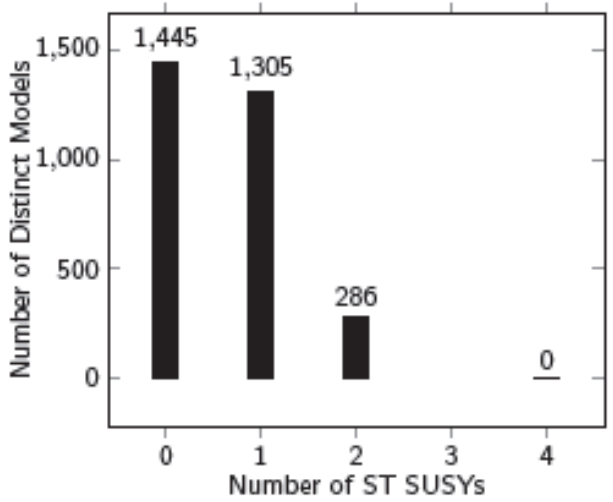


Extened NAHE Results, Order 3, Layer 1

- There were 3,036 distinct models out of 373,152.
- Based on the estimates from the O2L1 models without rank-cuts, the systematic uncertainty for these models is 10%.

GUT Group	% of Models
E_6	6.36%
$SO(10)$	21.71%
$SU(5) \otimes U(1)$	17.89%
PS	54.28%
LR	20.69%
MSSM	25.53%





Summary of NAHE-based GUT Searches

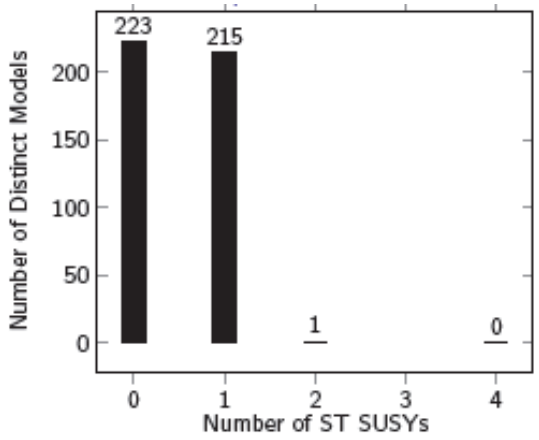
GUT	Chiral Generations?	3 Generations?
O2L1 $SO(10)$	Yes	No
O2L1 Pati-Salam	No	No
O3L1 E_6	Yes	No
O3L1 $SO(10)$	Yes	No
O3L1 $SU(5) \otimes U(1)$	Yes	Yes
O3L1 Pati-Salam	Yes	No
O3L1 L-R Symmetric	Yes	Yes
O3L1 MSSM	Yes	Yes

One Example: A Three-Generation Flipped-SU(5) Model

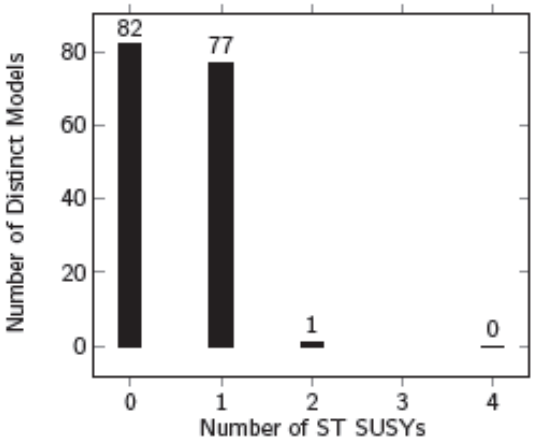
QTY	$SU(3)$	$SU(3)$	$SU(4)$	$SU(5)$	$SU(7)$
2	1	$\overline{3}$	1	5	1
1	1	1	4	5	1
2	1	1	1	$\overline{5}$	1
3	1	1	1	5	1
1	1	1	$\overline{4}$	5	1
2	1	3	1	$\overline{5}$	1
1	$\overline{3}$	1	1	$\overline{10}$	1
2	$\overline{3}$	1	1	$\overline{5}$	1

- This model also has five $U(1)$ gauge groups, and N=1 ST SUSY.
- There are 14 extra 5's and 8 extra $\overline{5}$'s.

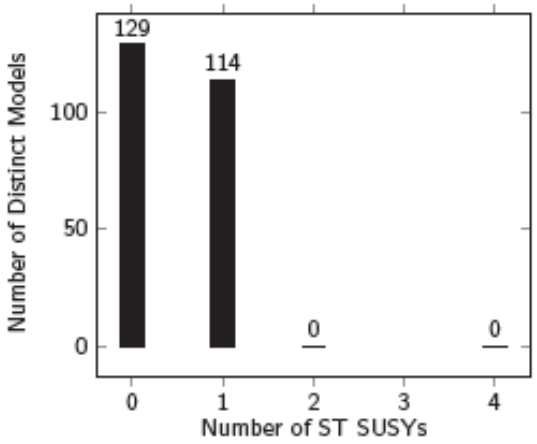
Spacetime SUSY Distributions, O2L1



(a) Full data set.

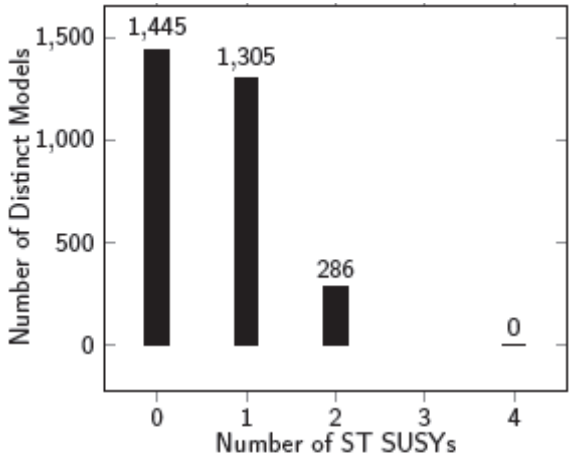


(b) $SO(10)$ models.

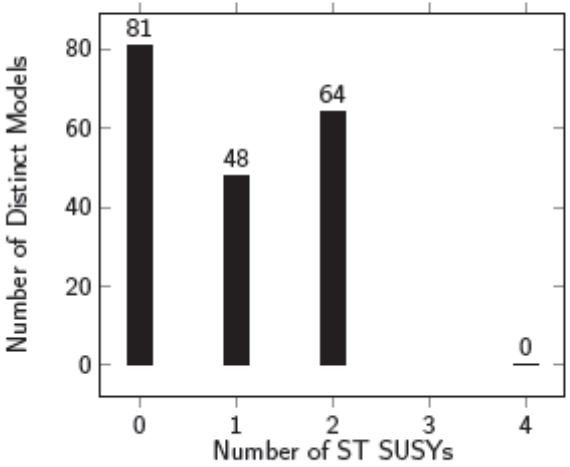


(c) Pati-Salam models.

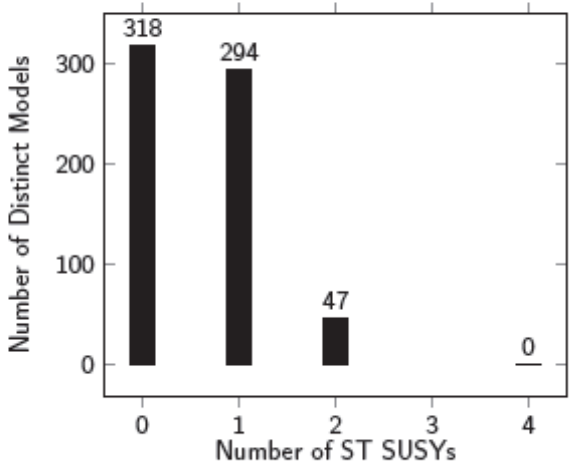
Spacetime SUSY Distributions, O3L1



(d) Full data set.



(e) E_6 models.



(f) $SO(10)$ models.

Original NAHE Variation Results

QTY	$SO(22)$	E_6
30	22	1
15	1	27
90	1	1
15	1	$\overline{27}$

- The NAHE variation also has five $U(1)$'s and $N = 1$ ST SUSY.
- It also allows for models with "mirroring."

Original NAHE Variation Results

2 of the 5 orignial NAHE basis vectors are

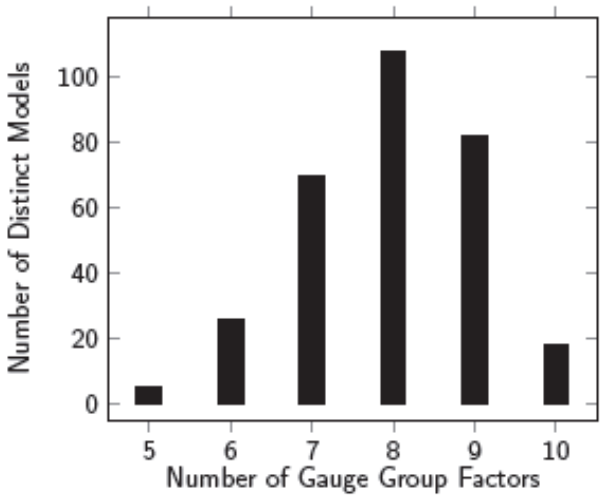
QTY	$SO(22)$	E_6
30	22	1
15	1	27
90	1	1
15	1	$\overline{27}$

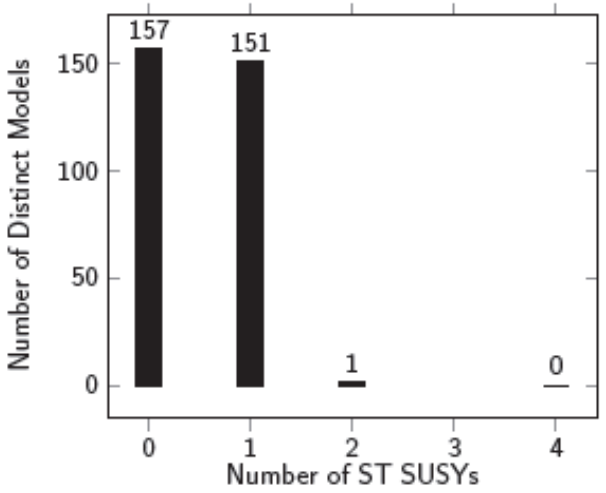
- The NAHE variation also has five $U(1)$'s and $N = 1$ ST SUSY.
- It also allows for models with "mirroring."

Order 2, Layer 1 Extensions

- There were 309 unique models out of 1,315,328 total consistent models.
- 2% of the models without rank-cuts were duplicates, while none of the models with rank-cuts were duplicates.

GUT Group	% of Models
E_6	32.69%
$SO(10)$	40.45%
$SU(5) \otimes U(1)$	0%
PS	0%
LR	0%
MSSM	0%

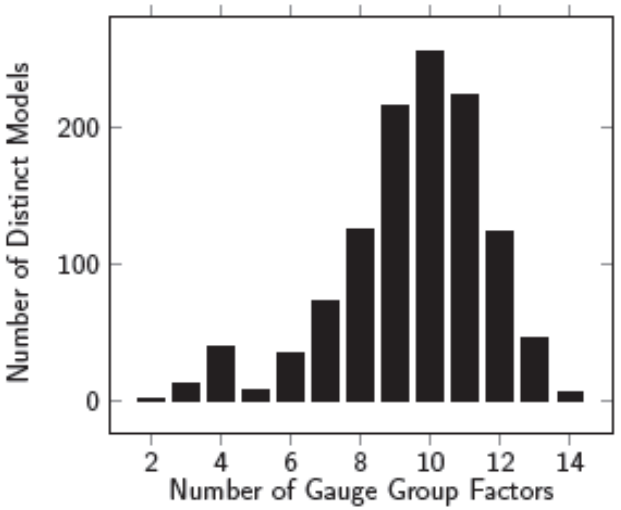


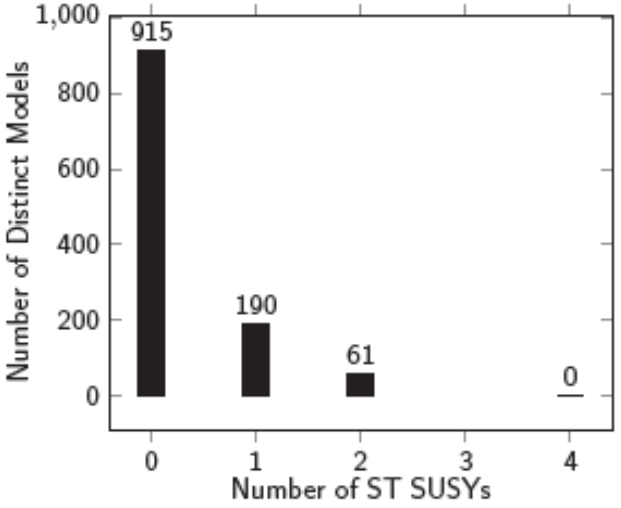


Order 3, Layer 1 Extensions

- There were 1,166 distinct models out of 442,272.
- The estimated systematic uncertainty for models in this data set is 2%.

GUT Group	% of Models
E_6	5.832%
$SO(10)$	23.24%
$SU(5) \otimes U(1)$	14.15%
PS	10.72%
LR	5.232%
MSSM	5.403%





NAHE Variation-based GUT Searches

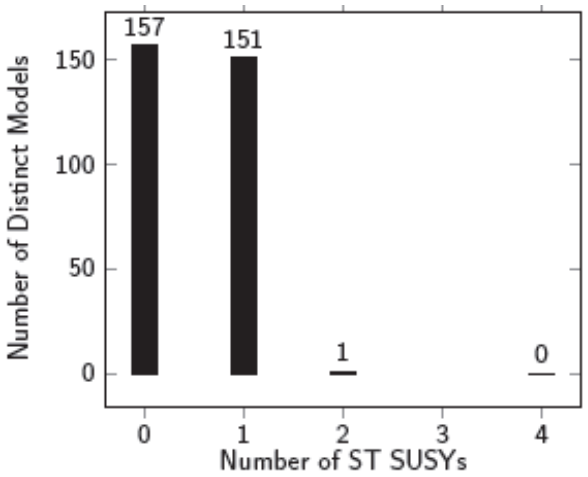
GUT	Chiral Generations?	3 Generations?
O2L1 E_6	Yes	No
O2L1 $SO(10)$	Yes	No
O3L1 E_6	No	No
O3L1 $SO(10)$	No	No
O3L1 $SU(5) \otimes U(1)$	No	No
O3L1 Pati-Salam	No	No
O3L1 L-R Symmetric	No	No
O3L1 MSSM	No	No

An Example: A Model with Mirrored Matter Content

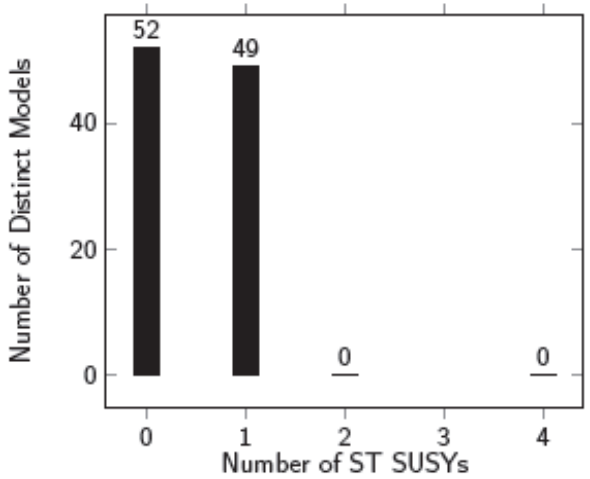
QTY	$SO(14)$	E_6	E_6
12	14	1	1
6	1	27	1
6	1	1	27
6	1	1	$\overline{27}$
6	1	$\overline{27}$	1

- This model has three $U(1)$ gauge groups and N=2 ST SUSY.
- There were no models which had completely mirrored matter representations.

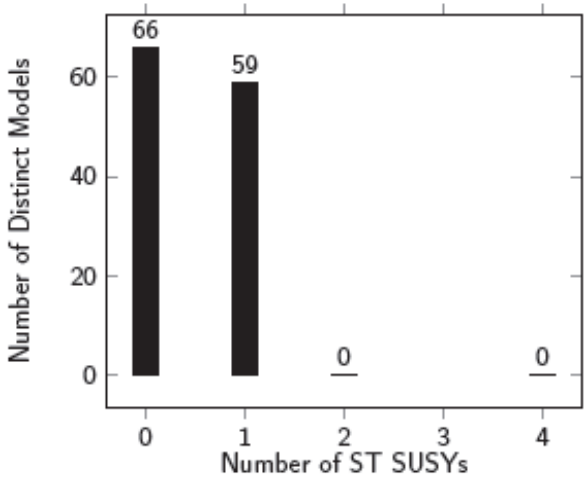
Spacetime SUSY Distributions, O2L1



(g) Full data set.

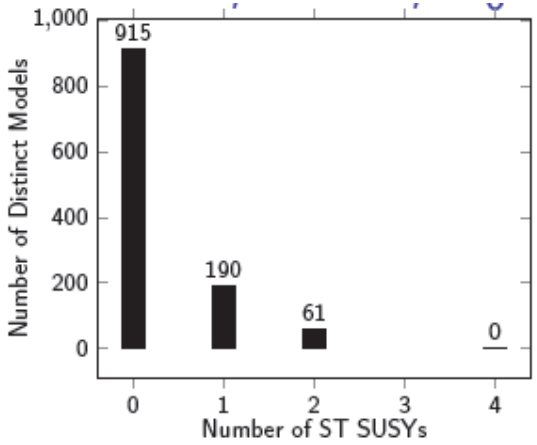


(h) E_6 models.

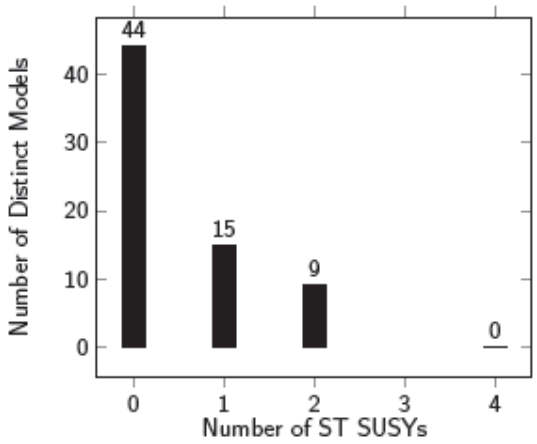


(i) $SO(10)$ models.

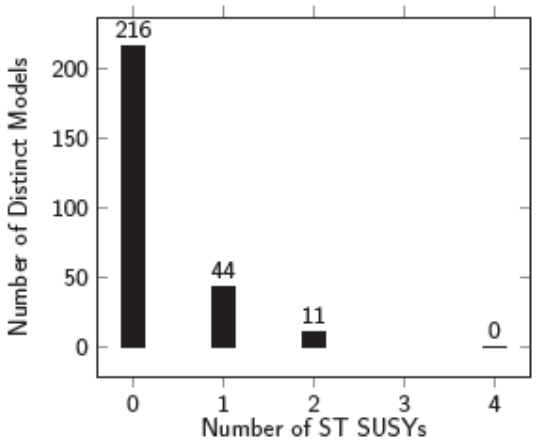
Spacetime SUSY Distributions, O3L1



(j) Full data set.

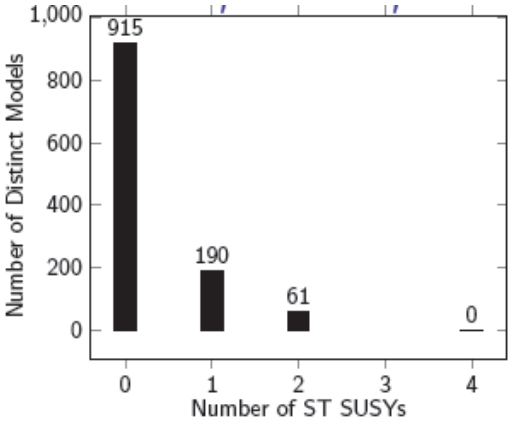


(k) E_6 models.

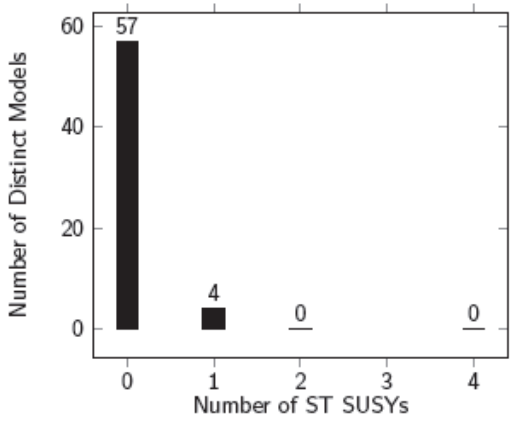


(l) $SO(10)$ models.

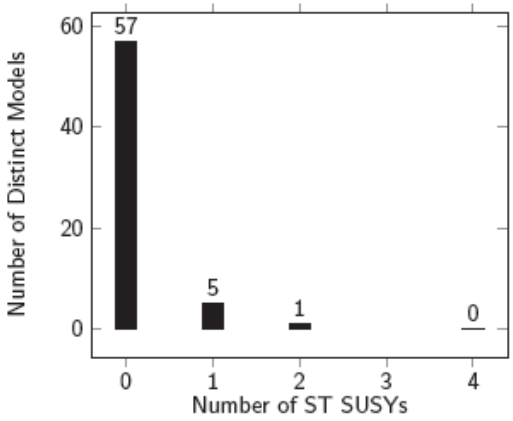
Spacetime SUSY Distributions, O3L1



(m) Full data set.



(n) Left-Right Symmetric models.



(o) MSSM models.

Conclusions

- Some theoretical work is still needed to proceed with large-scale searches.
- Even with a limited sample set, interesting classes of models not previously examined have been found.

Future Works

- Higher layer and higher order studies of NAHE & NAHE variation extension might put us closer to more phenomenologically realistic models.
- Perform flat direction analysis on quasi-realistic models.

Acknowledgements

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- This talk is based on Timothy Renner's doctoral dissertation.
- For more details, refer to papers: arXiv: 1111.1917, arXiv:1111.1263.