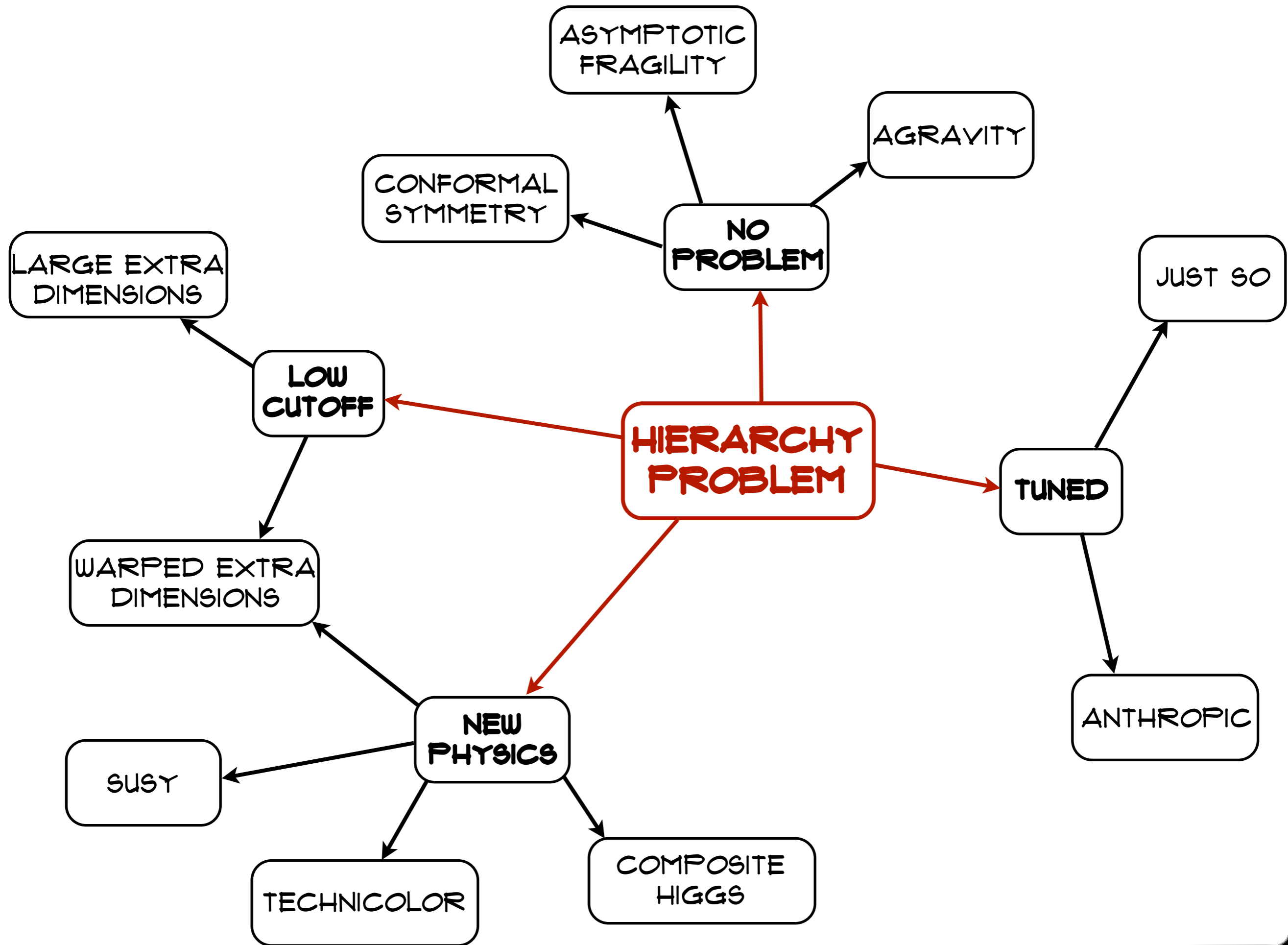


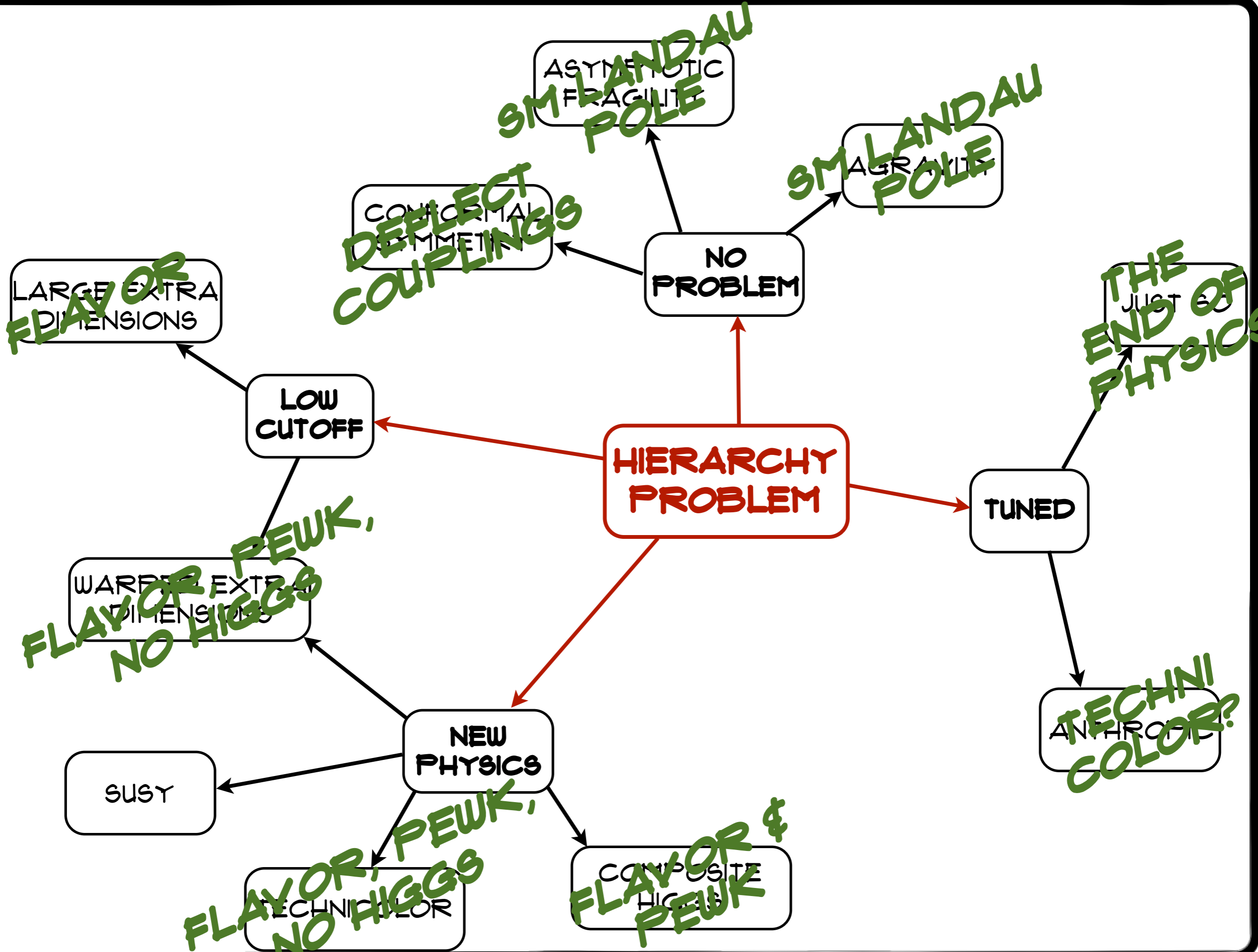
# SUPERSYMMETRIC OPTIMISM

## AT LHC-13/14

NATHANIEL CRAIG  
UCSB







WHY SUSY?

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- COMPLETELY SOLVES HIERARCHY PROBLEM.

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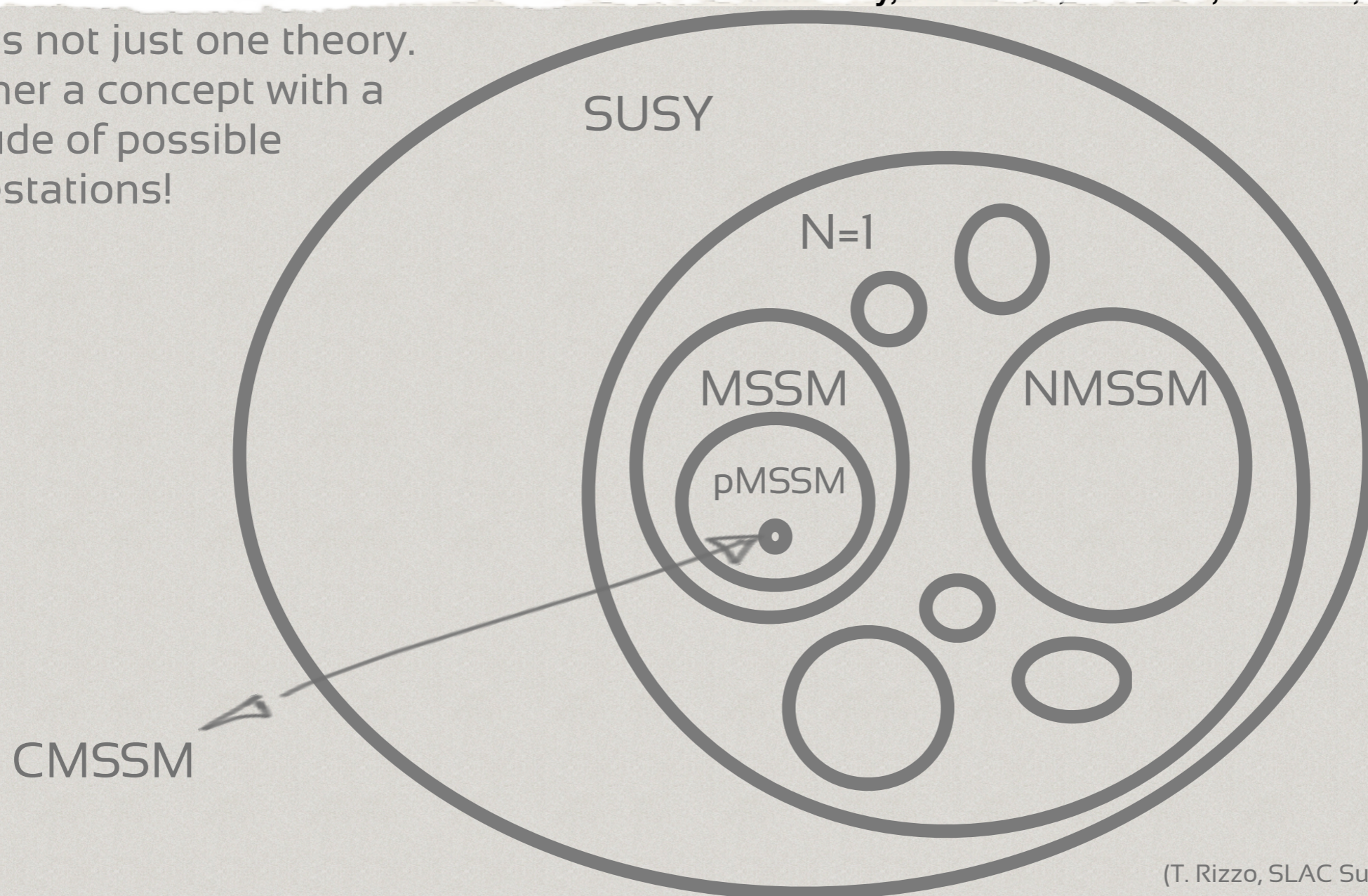
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- ...BELOW 135 GEV (IN THE MSSM).
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VS

- MOST SIMPLISTIC VERSIONS UNDER STRESS.

# FRAMEWORK VS. MODEL

SUSY is not just one theory.  
It's rather a concept with a  
multitude of possible  
manifestations!



(T. Rizzo, SLAC Summer Institute, 2012)

[BORROWED FROM RIZZO SLAC S.I. 2012 VIA LYKKEN LHCP 2013]

AN ANALOGY

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- PROBLEM: WEAK INTERACTIONS

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- SIMPLE INSTANTIATION:  $O(3)$   
SCHWINGER MODEL (1957)
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- UGLIER INSTANTIATION:  $SU(2) \times U(1)$   
GLASHOW MODEL (1961)
- FRAMEWORK CORRECT, SPECIFIC  
REALIZATION IN NATURE NON-MINIMAL.

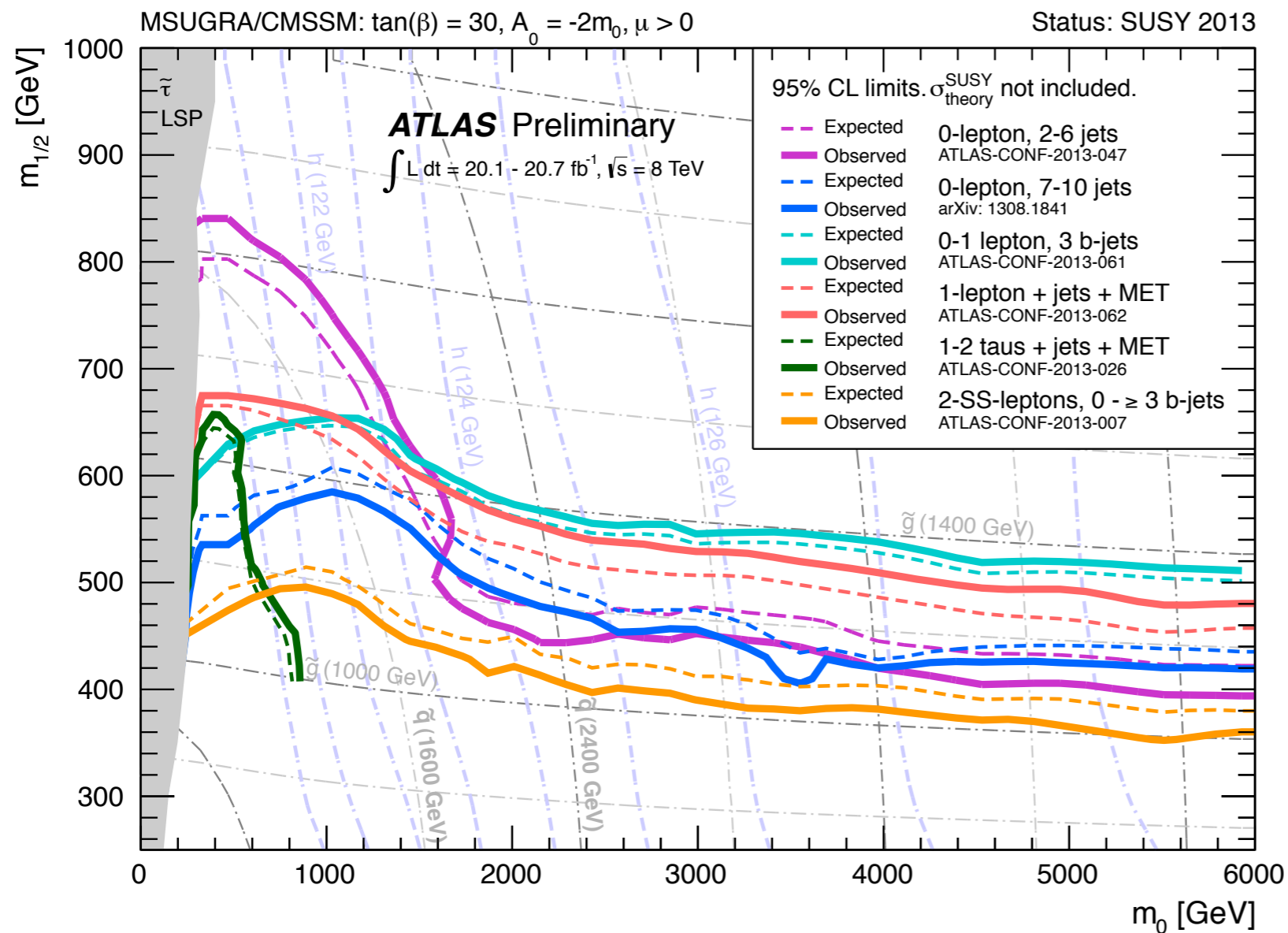
OR IF YOU DON'T BUY THAT,  
BE PRAGMATIC: SUSY IS A  
PHENOMENAL SIGNAL  
GENERATOR. WIDE RANGE  
OF TOPOLOGIES;  
DISAPPEARING TRACKS;  
R-HADRONS; HSCPS;  
DISPLACED PHOTONS; ETC.

# SIGNPOSTS



- LHC DATA CUTTING OFF CERTAIN POSSIBILITIES, POINTING OUT OTHERS.
- THEORY GOAL: USE THESE SIGNPOSTS TO FIND NEW MODELS WHERE DESIDERATA ARE GENERIC.
- NEW MODELS CAN DRIVE NEW SEARCH OPPORTUNITIES @ LHC.

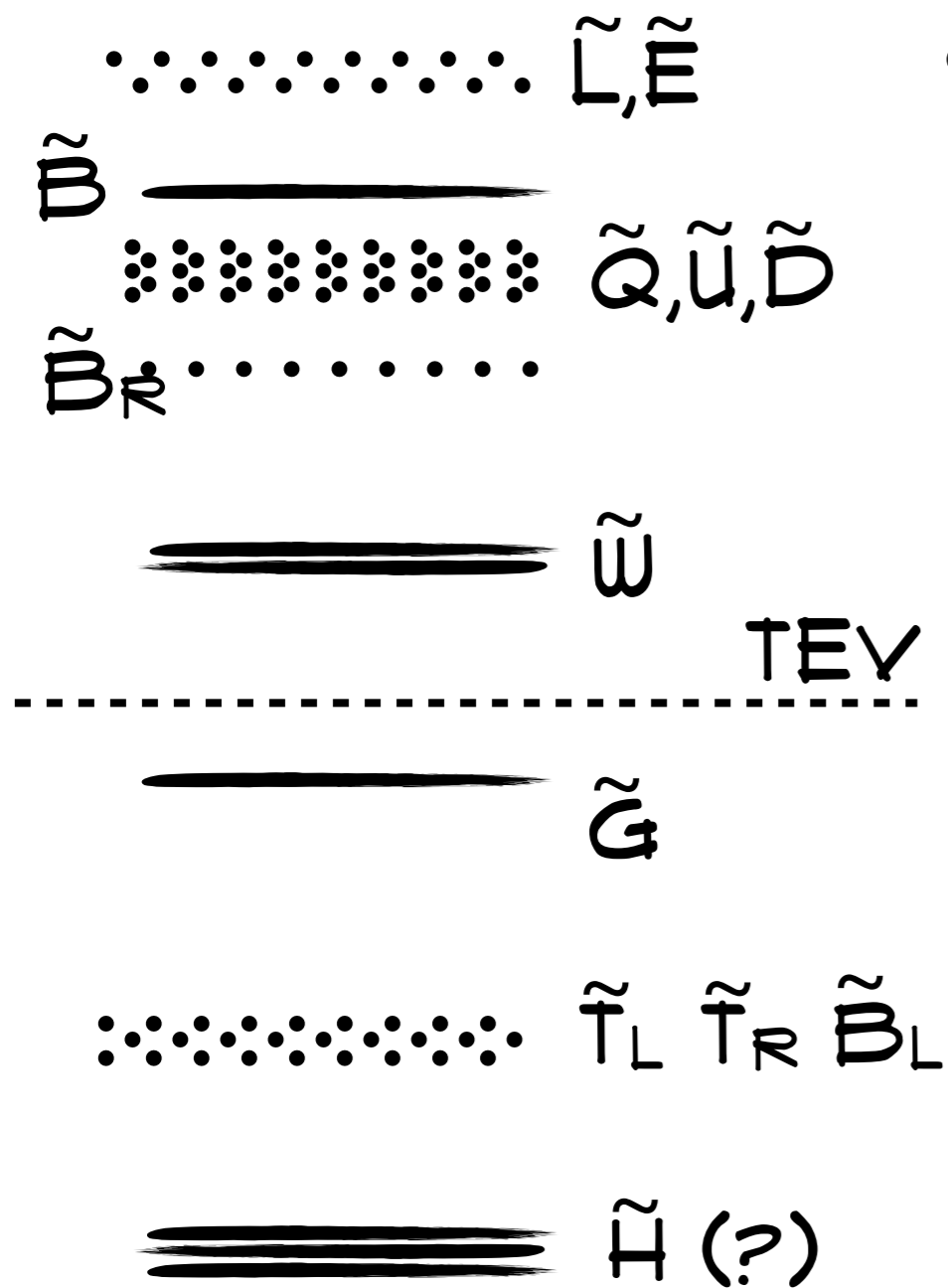
# THE "O(3)" VERSION OF SUSY LOOKS BAD



CMSSM: 120 MSSM  
 PARAMETERS  
 DISTILLED TO 4  
 PARAM + SIGN

CONSISTENCY  
 WITH HIGGS  
 MASS, LIMITS  
 PUSHES TUNING  
 OF WEAK SCALE  
 BELOW 0.1%

# BUT NATURALNESS DEMANDS LESS



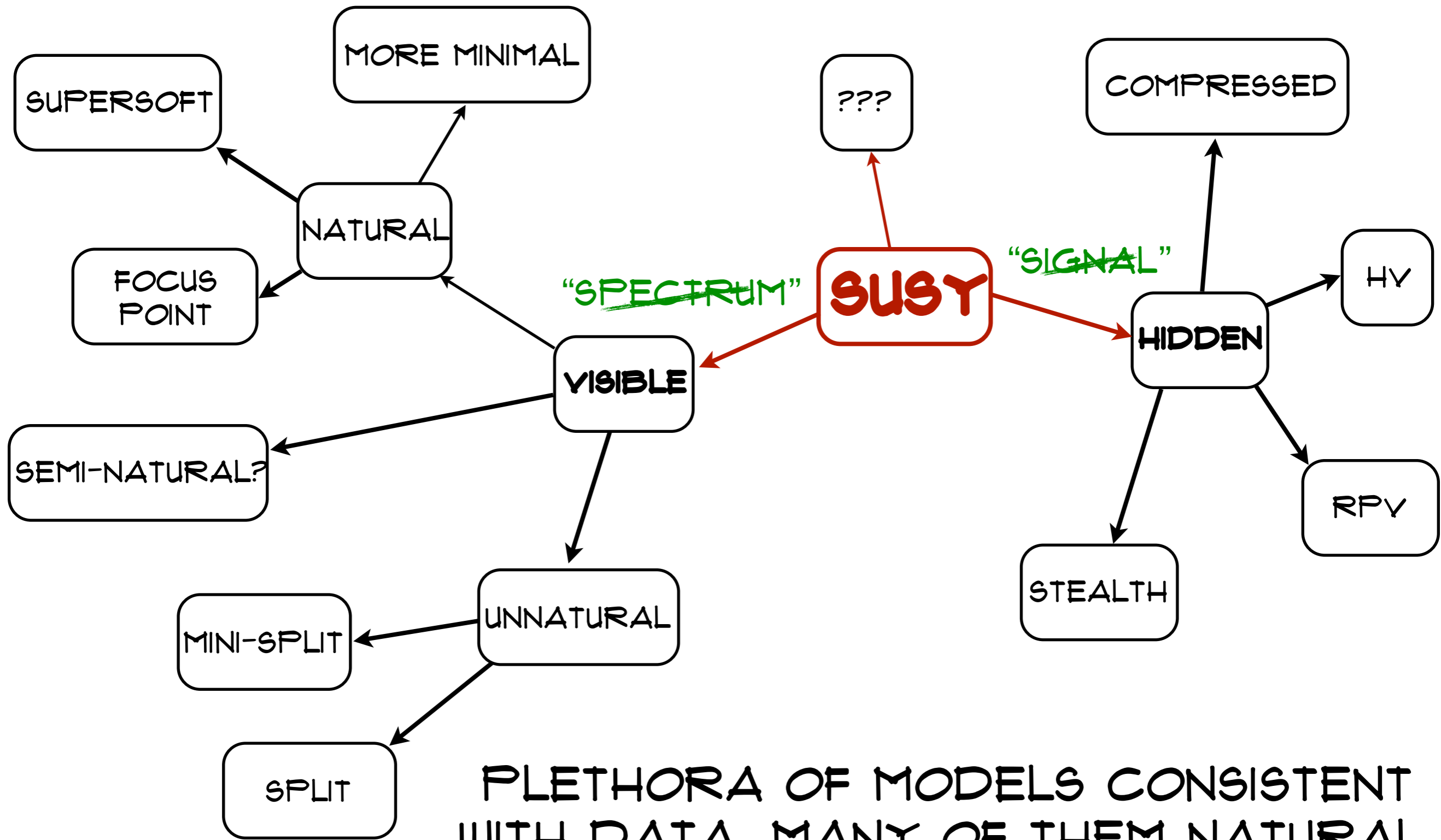
$O(1)$  COUPLINGS ARE  $Y_T, G_3$

NATURALNESS OF THE WEAK SCALE ONLY DEMANDS LIGHT TOP PARTNERS; GLUINO ENTERS AT TWO LOOPS, RELEVANT IF MAJORANA.

HIGGSINOS RELEVANT AT TREE LEVEL, BUT EVEN THIS IS NOT UNAVOIDABLE.

REMAINING STATES NATURALLY ABOVE TEV.

[DIMOPOULOS & GIUDICE '95, COHEN, KAPLAN, NELSON '96]

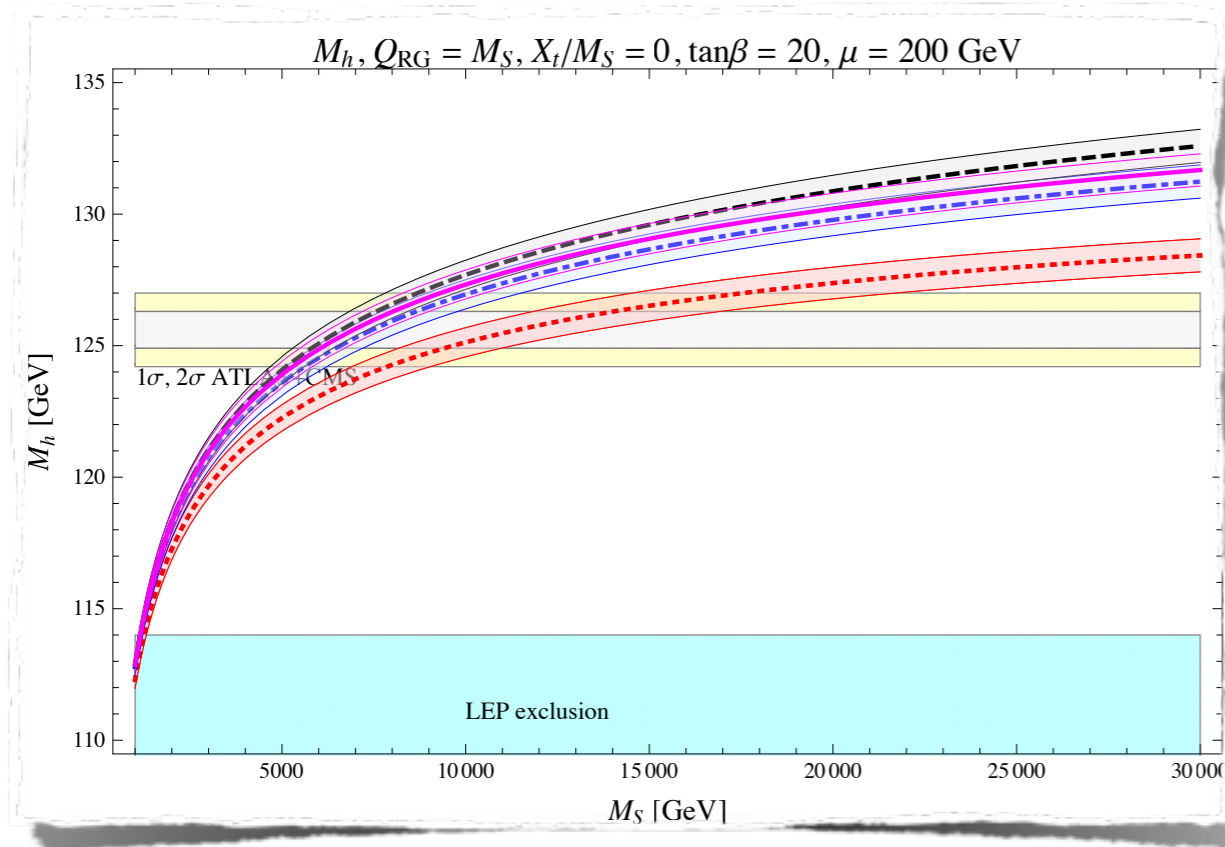


PLETHORA OF MODELS CONSISTENT WITH DATA, MANY OF THEM NATURAL. WHERE DOES THE DATA POINT US?

LESSONS FROM  
RUN 1

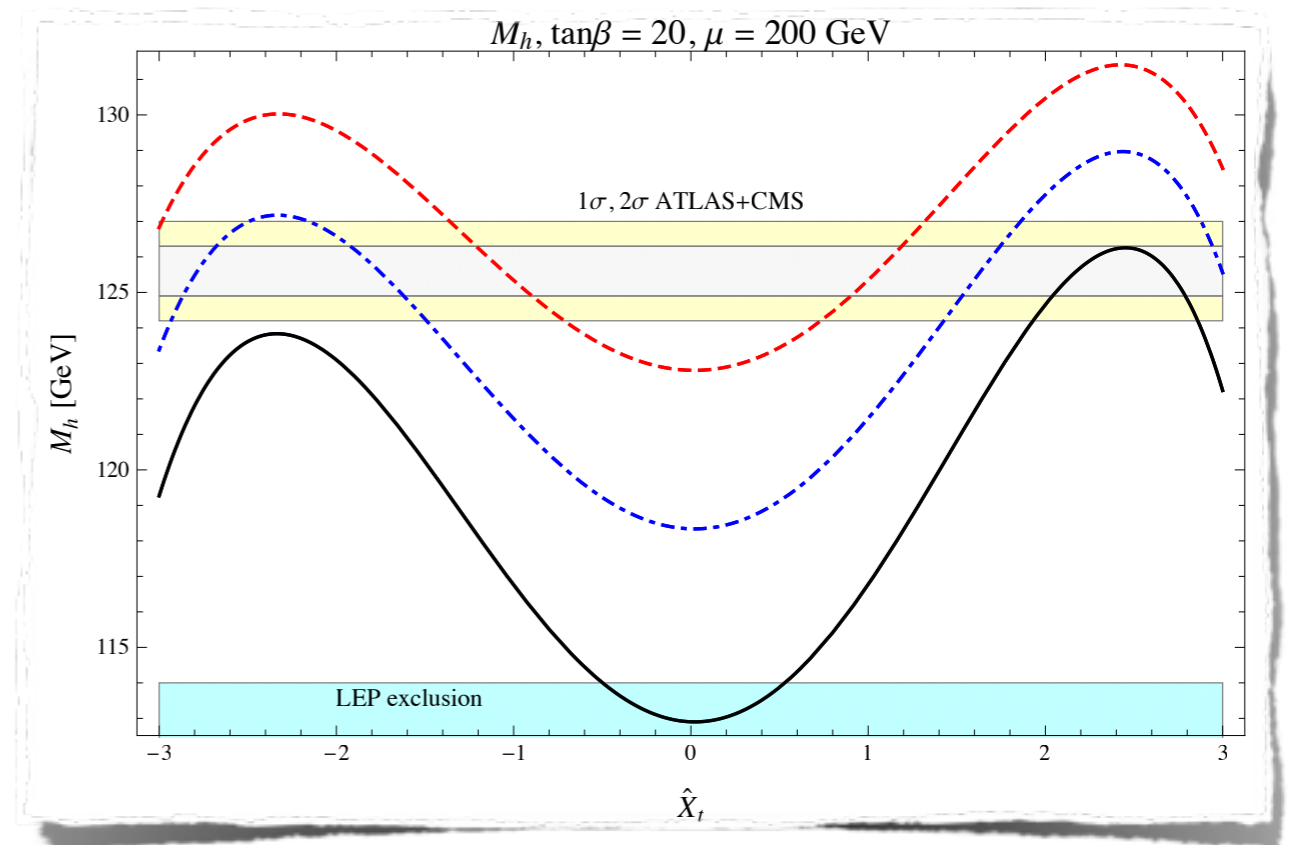


# HIGGS MASS

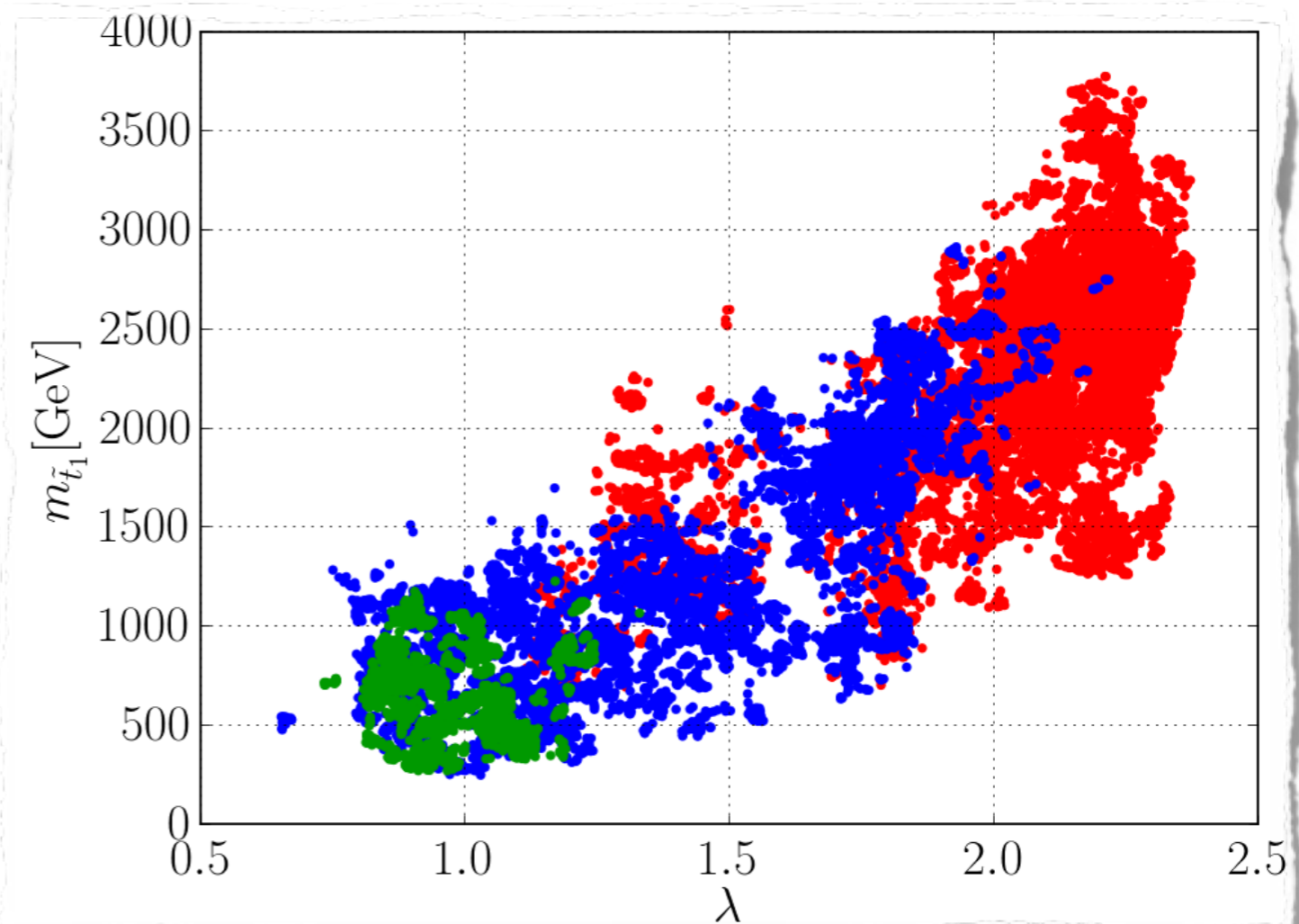
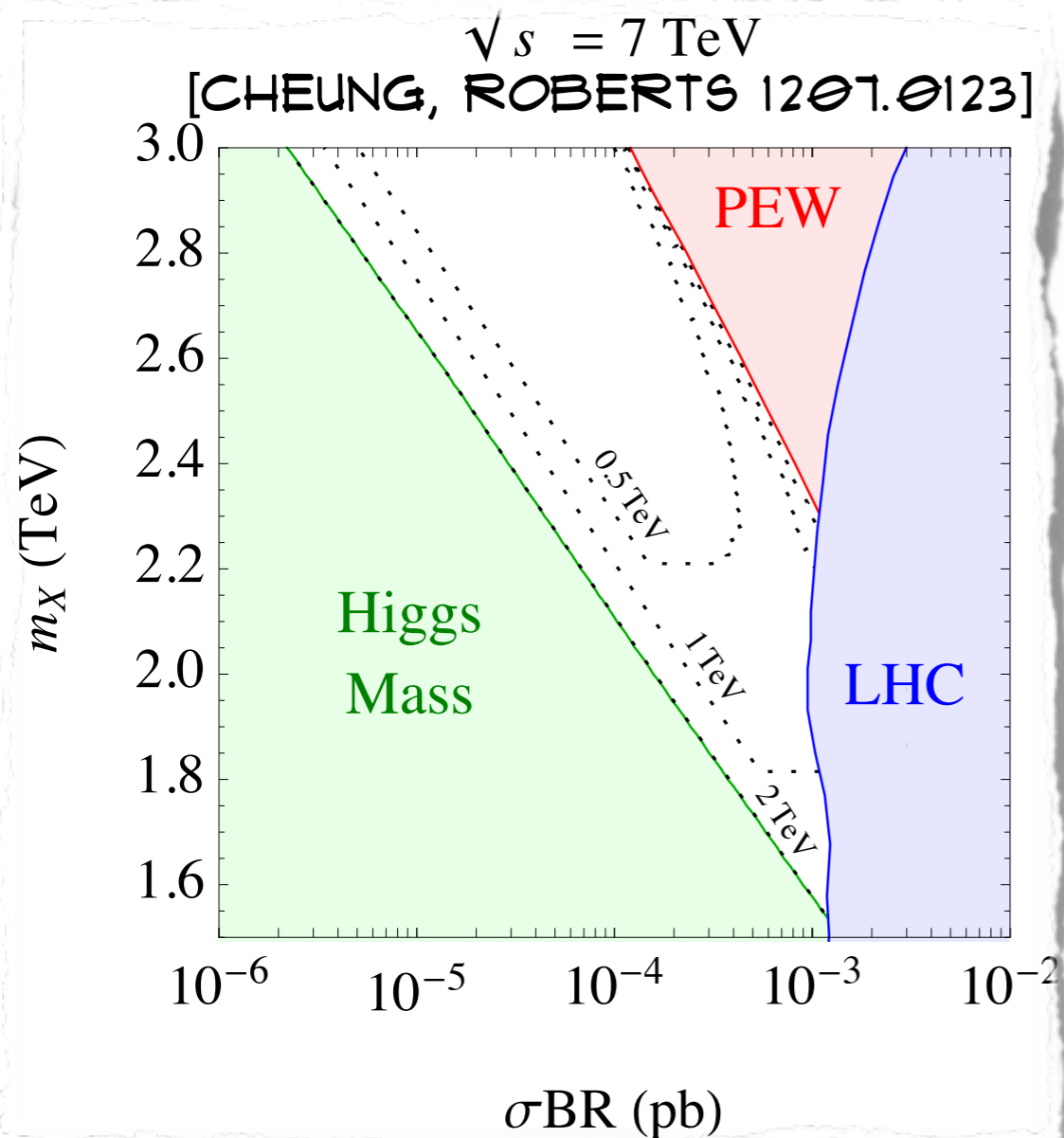


MSSM WITH  
MIXING DEMANDS  
STOPS ABOVE 1  
TEV ( $\sim 1\%$  TUNED)

MSSM W/OUT MIXING  
DEMANDS STOPS ABOVE  
5 TEV ( $\sim 0.05\%$  TUNED);



OR PERHAPS  
NEW QUARTIC  
FROM F-TERM...



[GHERGHETTA, VON HARLING,  
MEDINA, SCHMIDT 1212.5243]

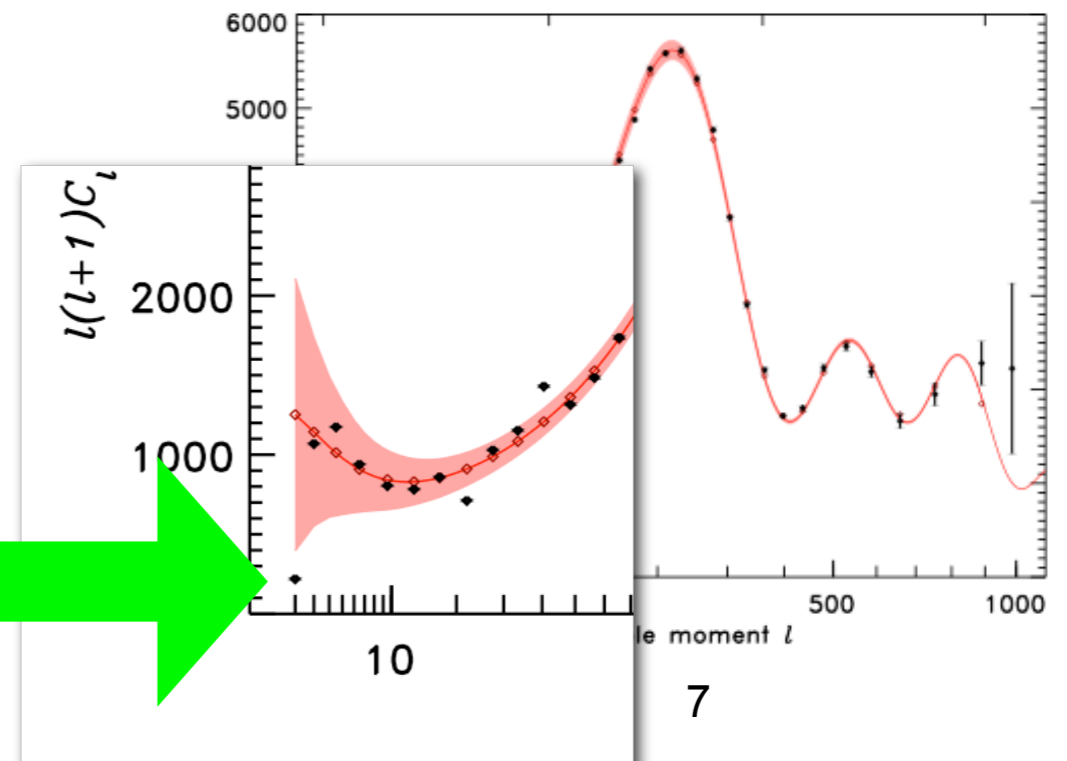
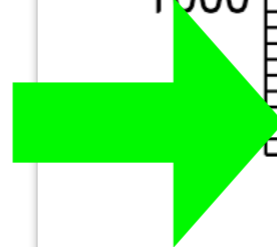
...OR D-TERM...  
EITHER WAY,  
TUNING  $\sim 1-5\%$   
PROBLEM?

# OTHER %-LEVEL COINCIDENCES

LOW CMB  
QUADRUPOLE



1%  
tuning

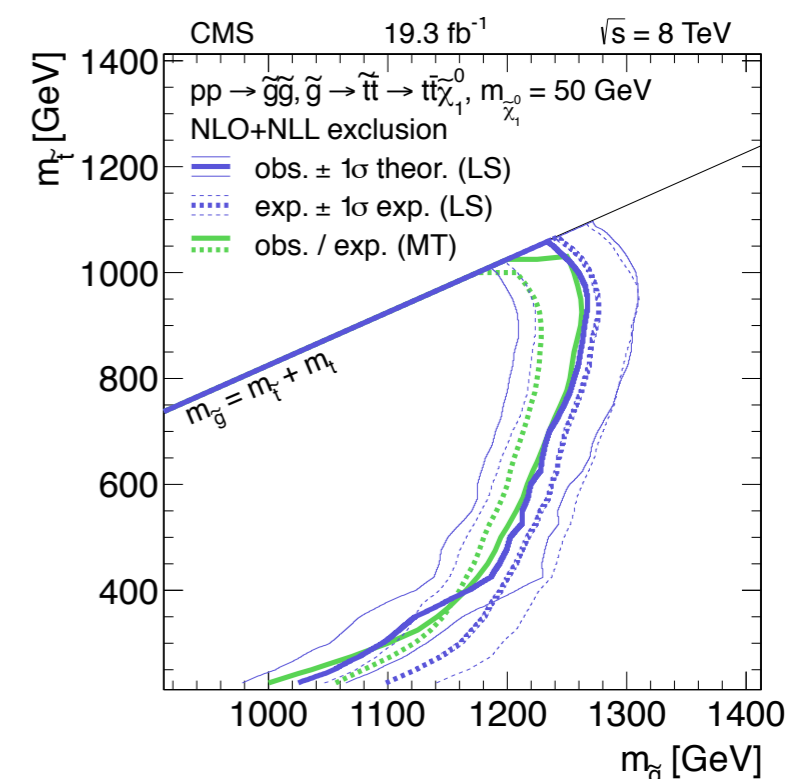
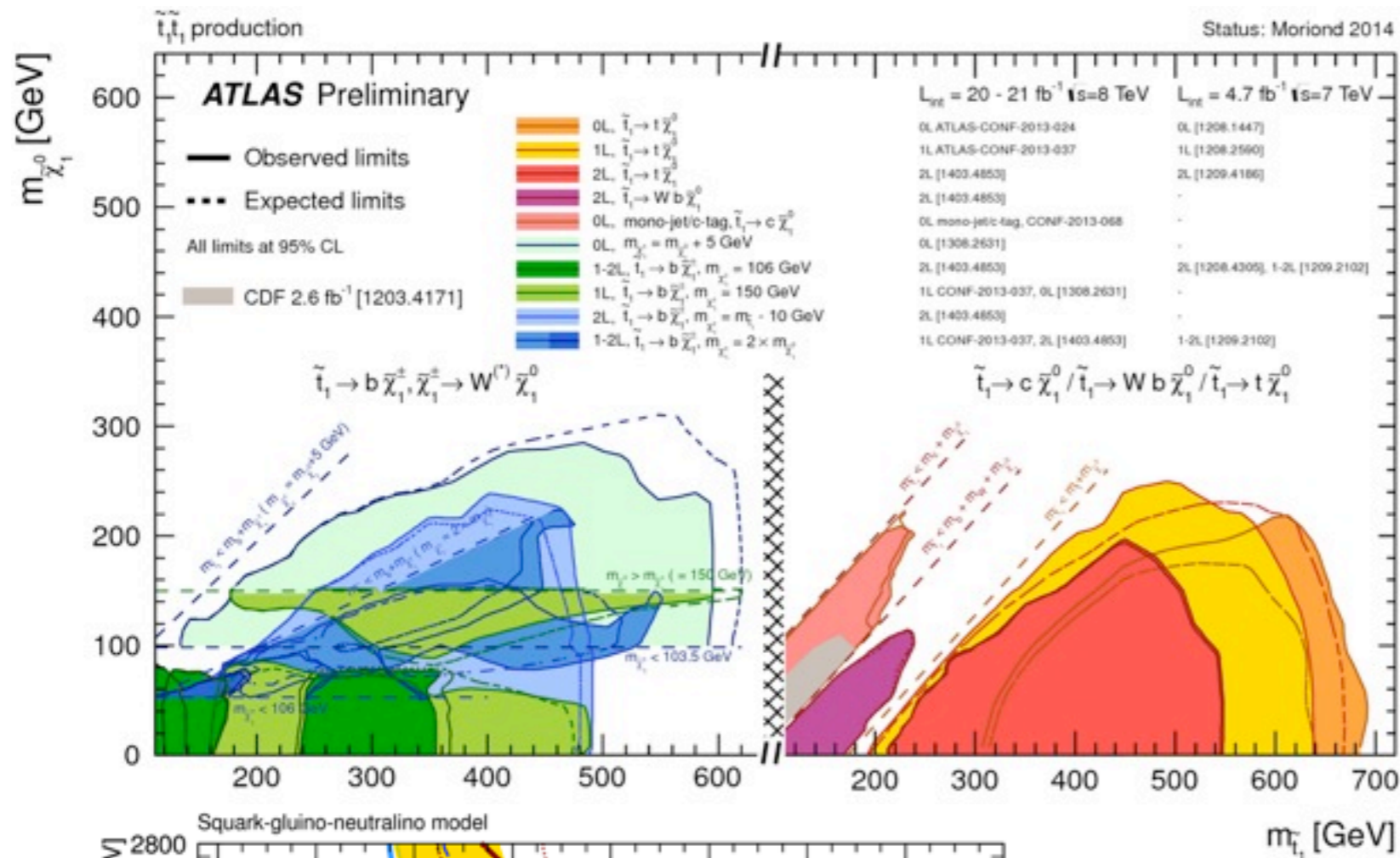


MOON & SUN  
 $\sim 0.5^\circ$  OF ARC

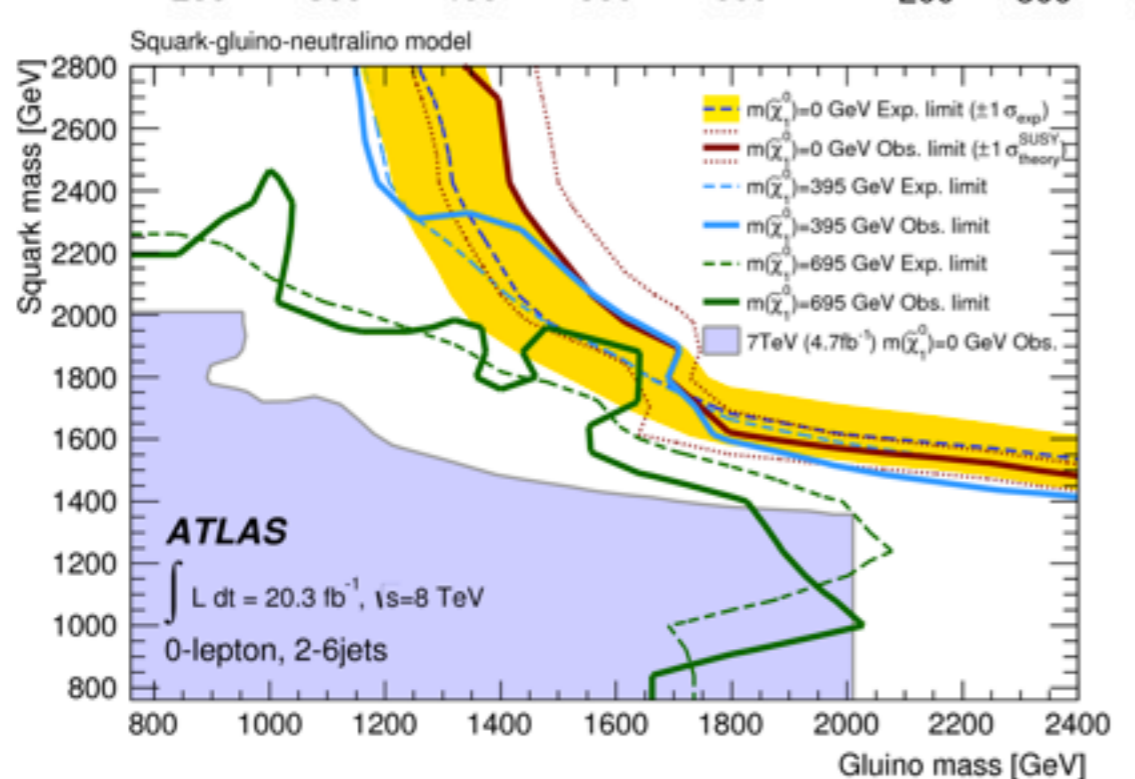
NEUTRONS FAIL TO BIND BY  $60$  KEV

.....

# DIRECT SEARCHES



STOPS ARE ABOVE 100 GEV OR COMPRESSED

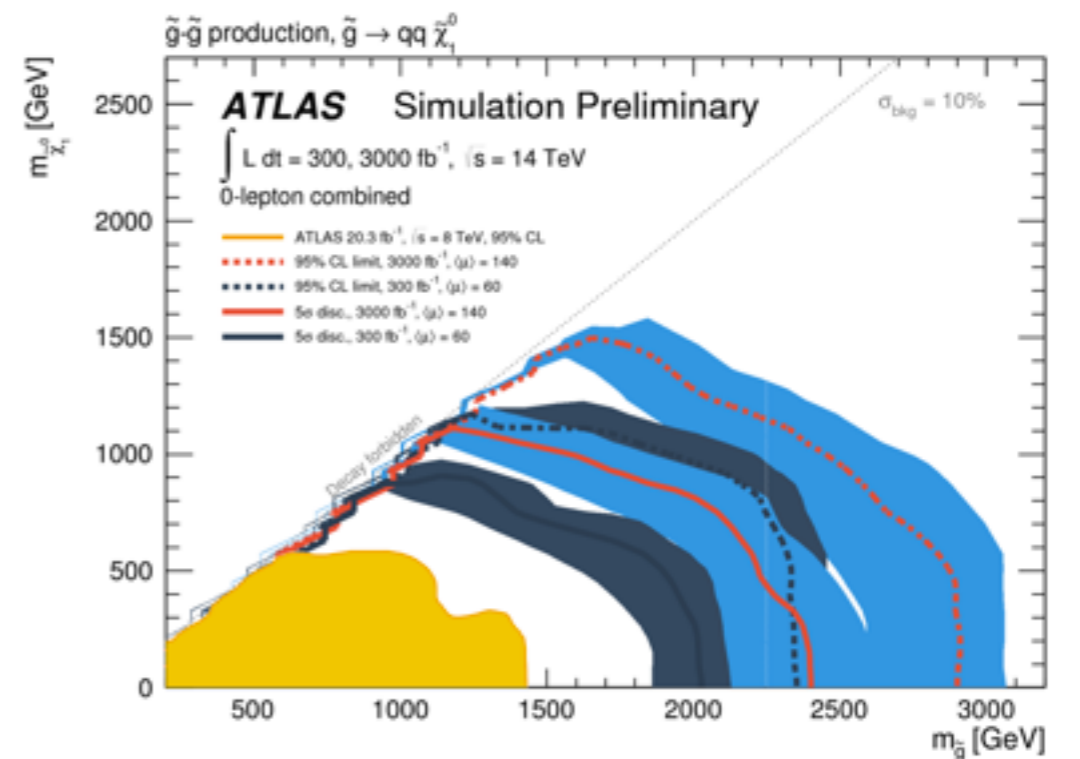
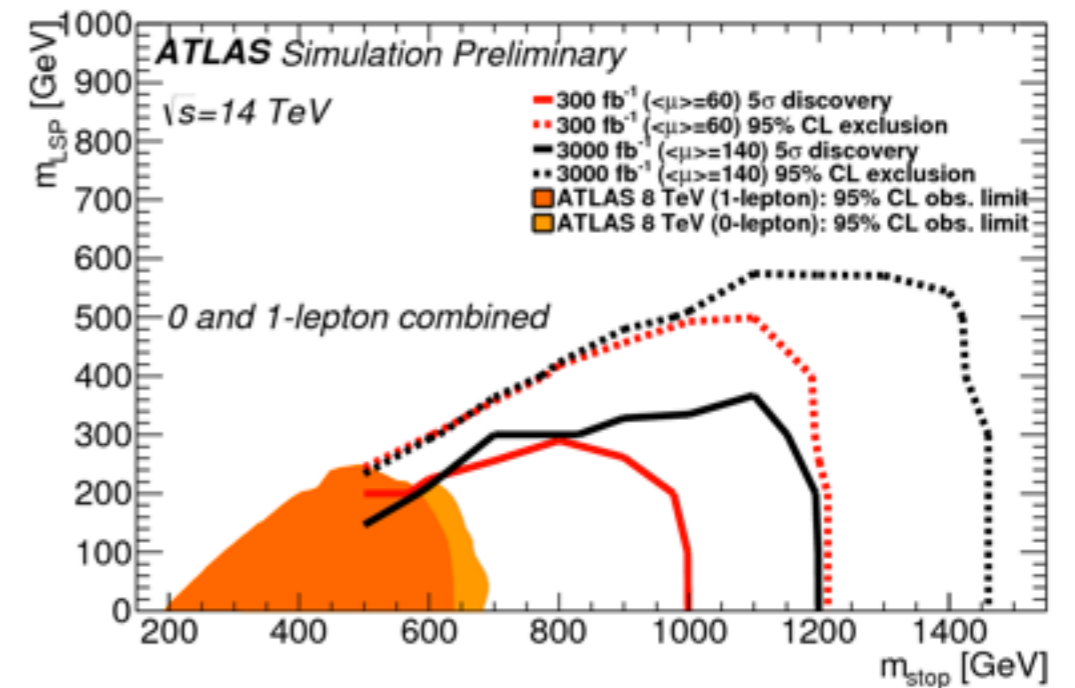


IF STOPS LIGHT, GLUINOS, 1/2-GEN SQUARKS MUST BE HEAVY; NEED RADIATIVE STABILITY.

# MOVING FORWARD

- NATURALNESS @ PERCENT LEVEL, BEST IF STOPS ARE LIGHT & GLUINOS, 1/2 GEN DECOUPLED.
- GIVEN HIGGS MASS, STOP BOUNDS UNSURPRISING; MAYBE %-LEVEL ACCIDENTS OKAY.
- 13-14 TEV RUN IS THE TIME TO LOOK FOR STOPS.

*THEORY CHALLENGE: LOOK FOR CLASSES OF MODELS WHERE FEATURES ARE GENERIC.*

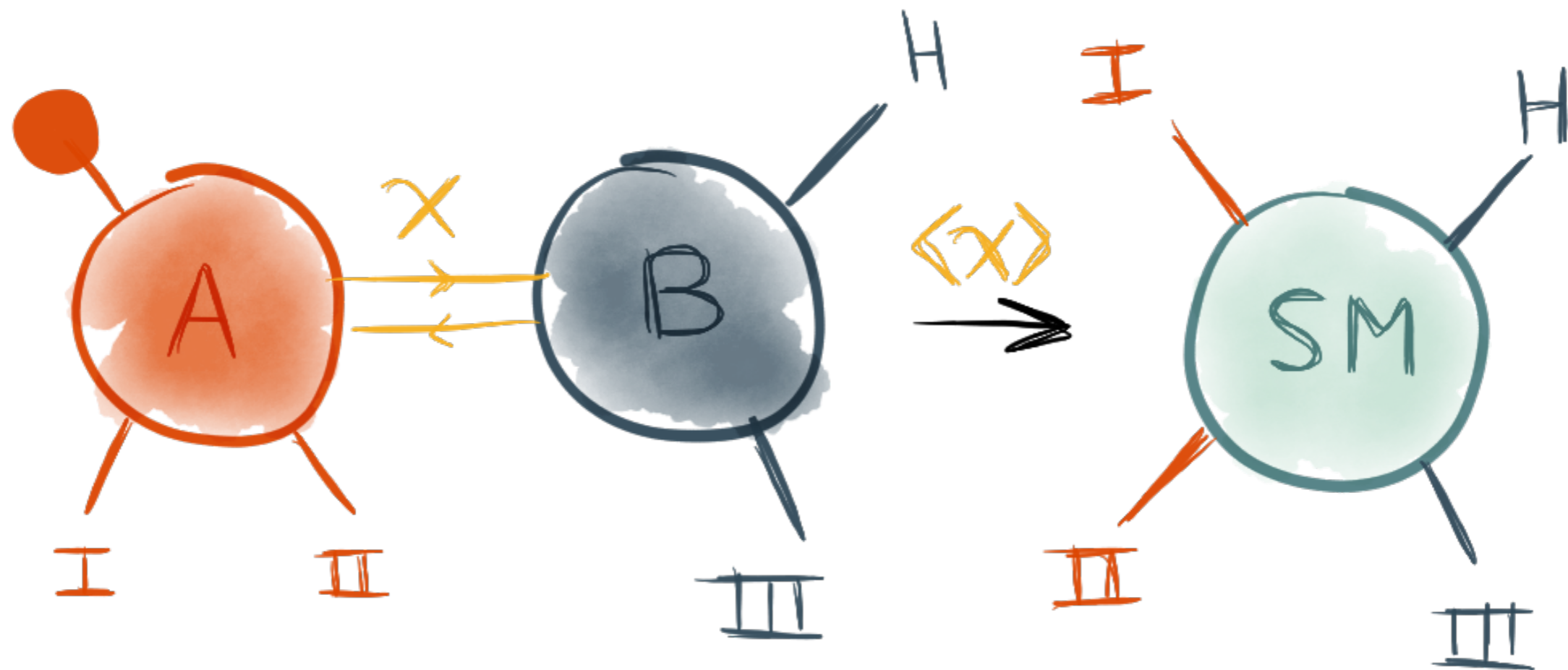


# THEORY DESIDERATA FOR LHC13-14



POPULATE THE  
FRAMEWORK.

# DECONSTRUCTION



- NATURAL SUSY SPECTRUM.
- APPROXIMATE THEORY OF FLAVOR.

- HIGGS MASS FROM D-TERMS.
- LOW RADIATIVE CUTOFF.



# SUSY FROM THE 5TH DIMENSION

- REDUCE SUSY WITH B.C.'S IN 5TH DIM.
- NO LARGE LOGS.
- (OFTEN) DIRAC GAUGINOS.
- ZERO MODES NOT SUPERSYMMETRIC (HIGGSINO LIFTED).

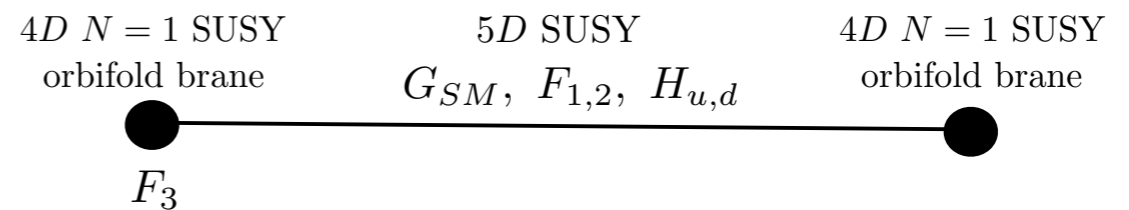


Fig. 1a

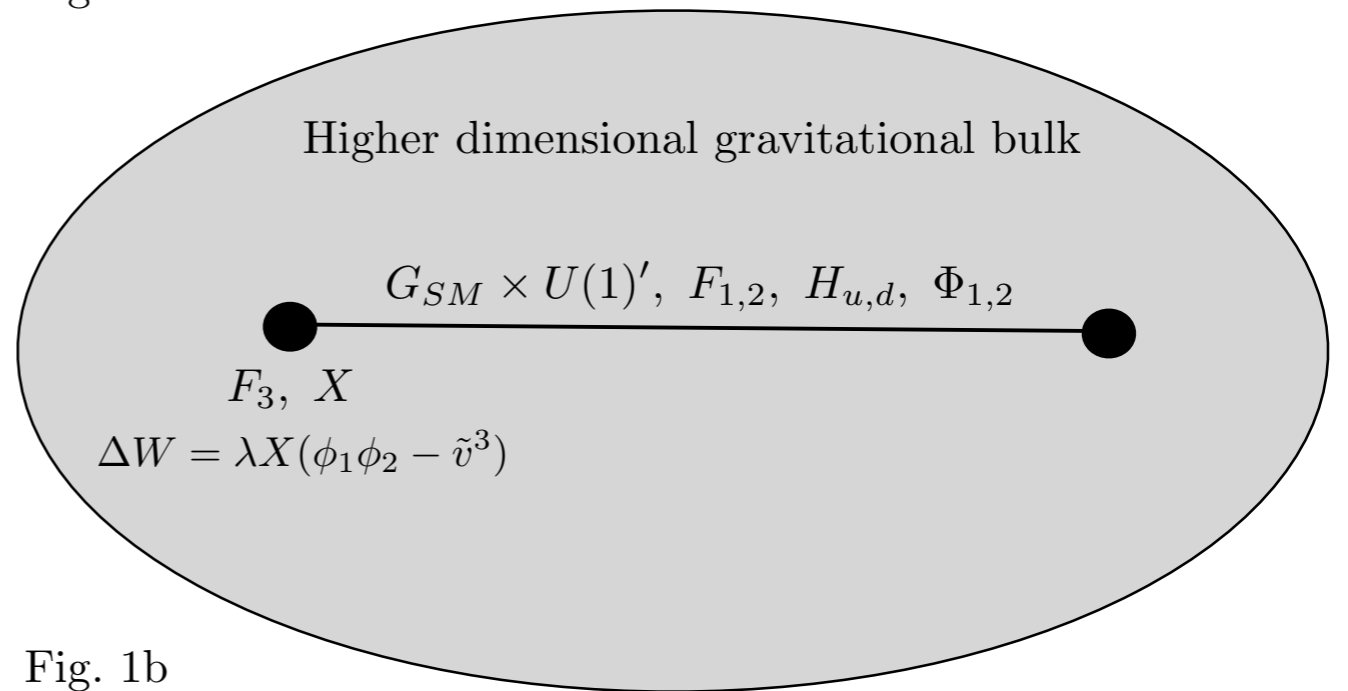
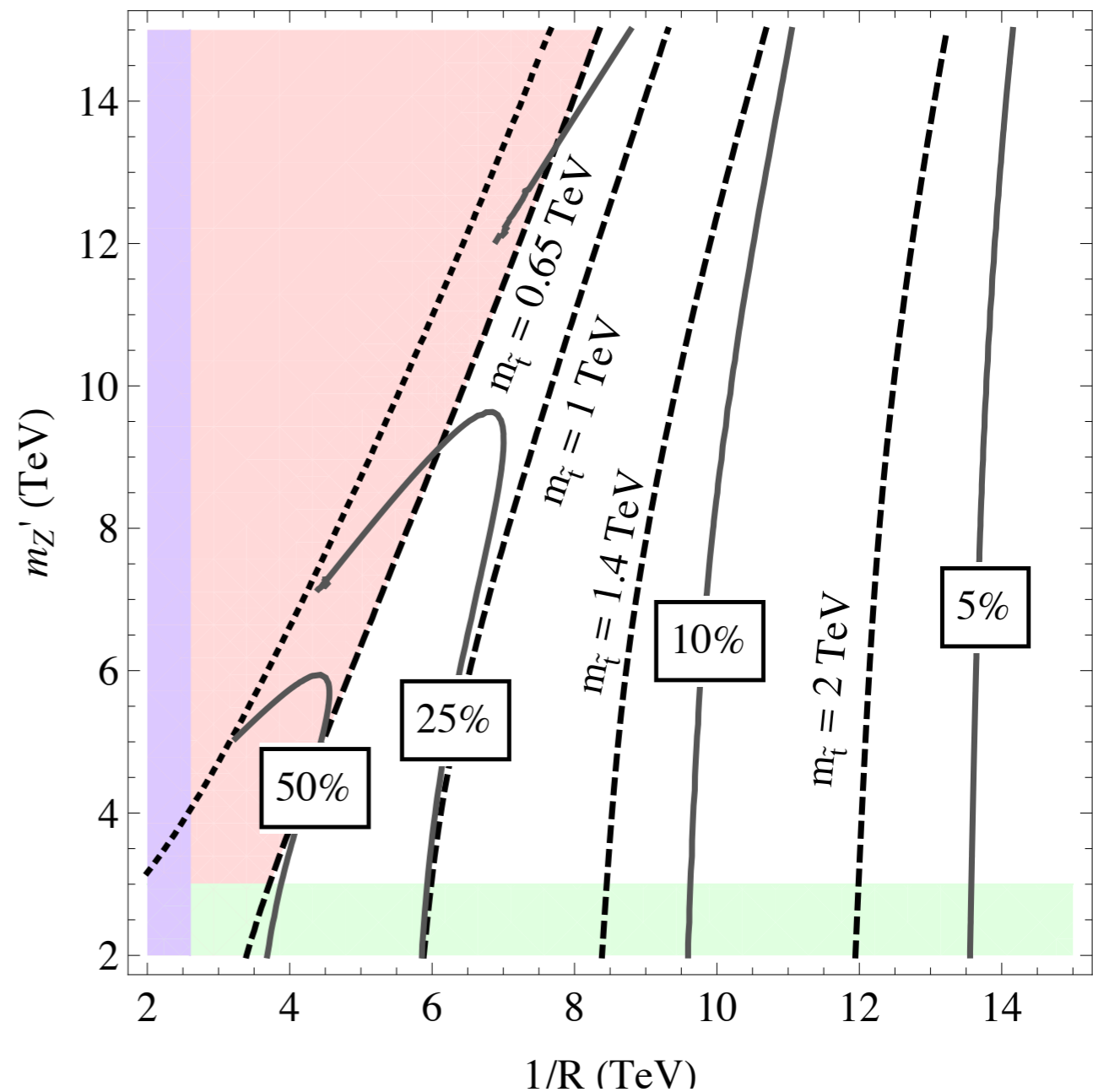
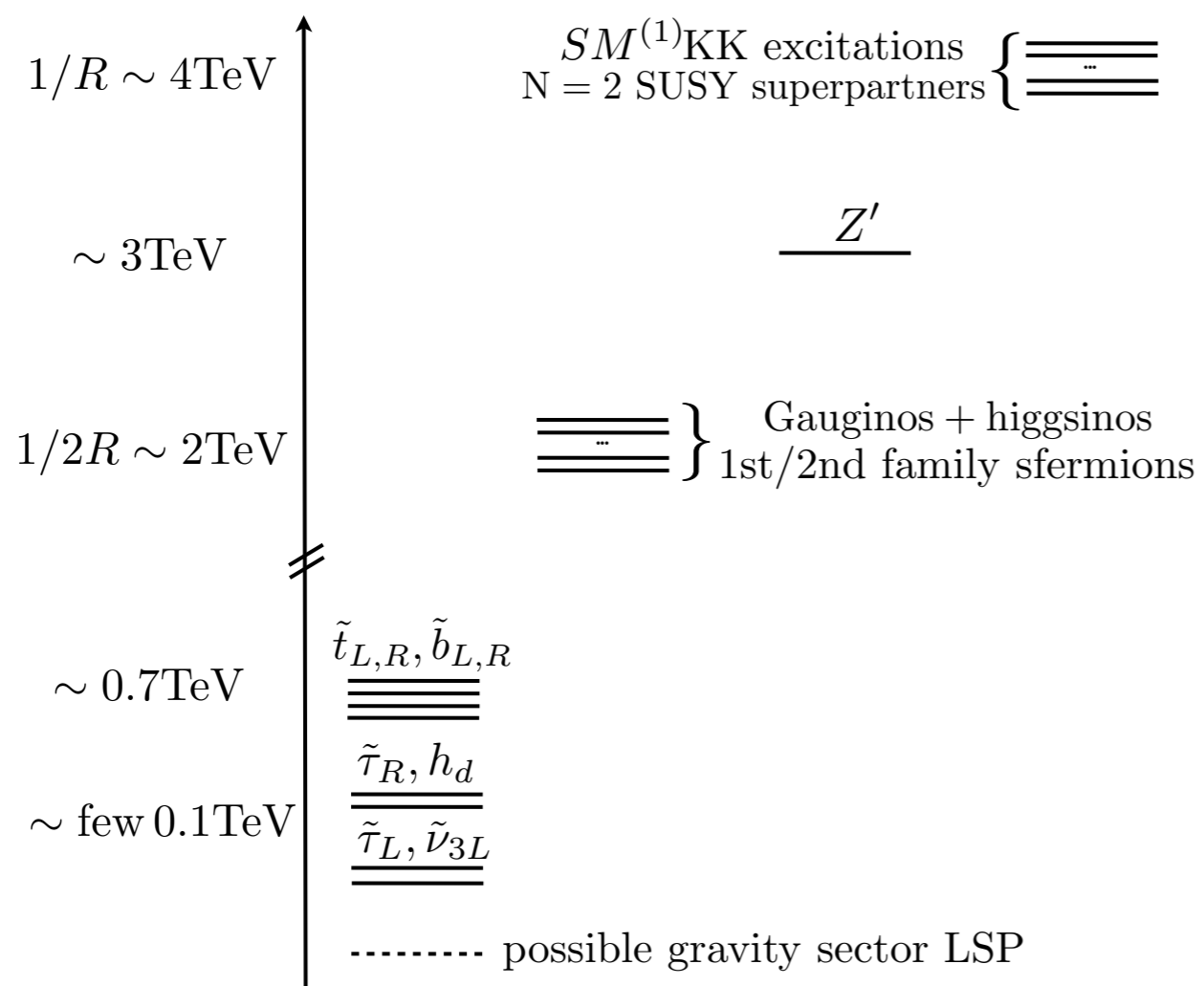


Fig. 1b

[QUIROS, POMAROL '98  
AND MANY OTHERS]

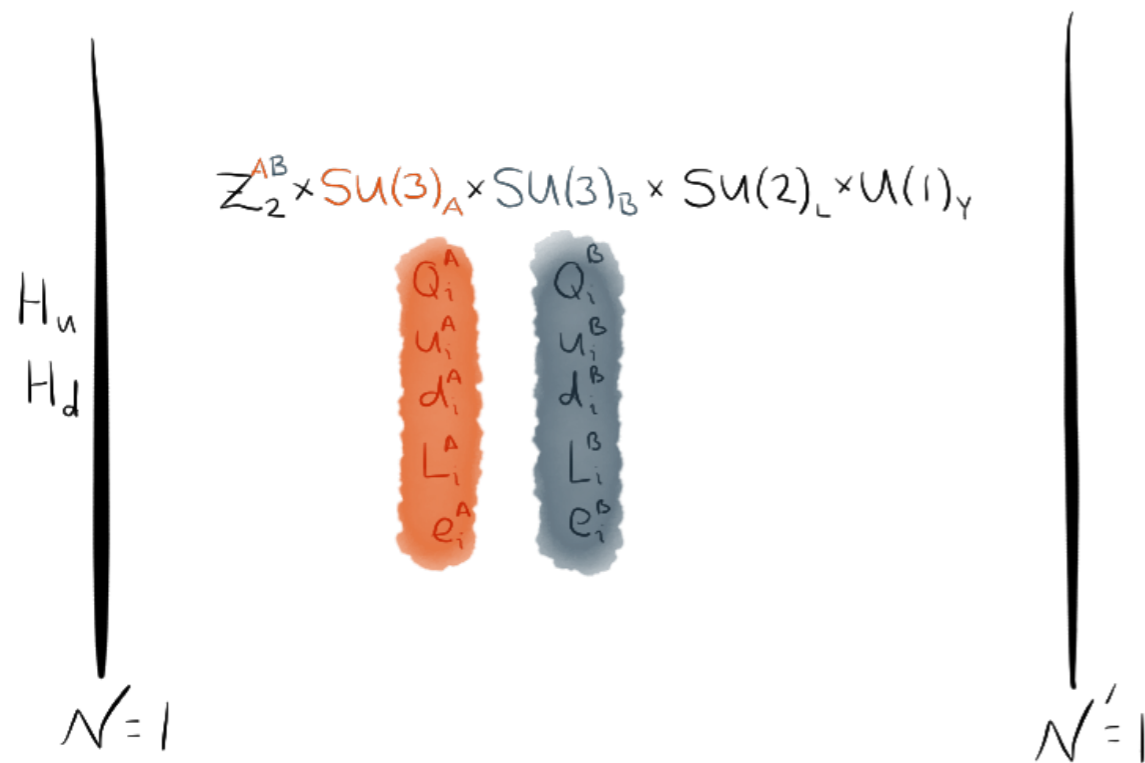
[DIMOPOULOS, HOWE, MARCH-  
RUSSELL 1404.7554]

# MAXIMALLY NATURAL SUPERSYMMETRY?



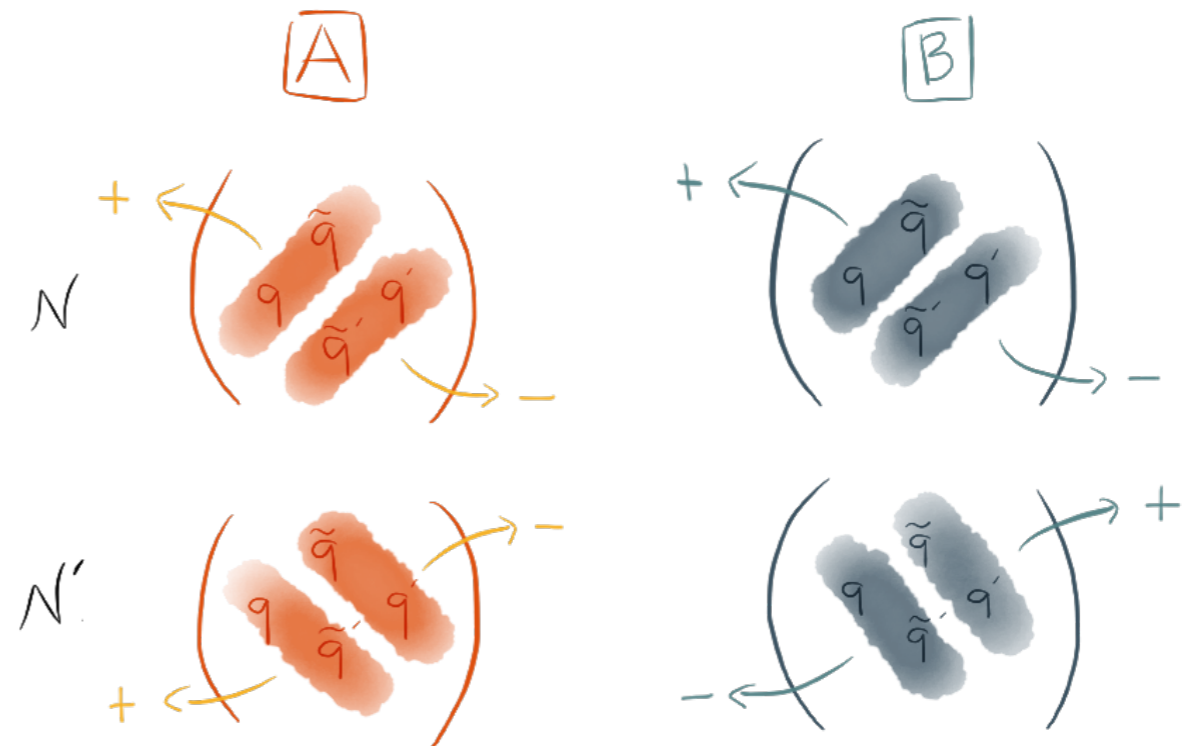
[DIMOPOULOS, HOWE, MARCH-RUSSELL 1404.7554]

# COLORLESS SUSY?



USE BOUNDARY CONDITIONS IN AN EXTRA DIMENSION TO REDUCE BOTH SUPERSYMMETRY AND GAUGE/GLOBAL SYMMETRIES.

CAN LEAD TO LIGHT SUPERPARTNERS WITH DIFFERENT GAUGE QUANTUM NUMBERS FROM SM COUNTERPARTS



[BURDMAN, CHACKO, GOH, HARNIK HEP-PH/0609152]

# COLORLESS STOPS

COUPLINGS RELATED BY SUSY

$$\mathcal{L} \supset \lambda_t H_u q_3^A u_3^A + \lambda_t^2 |H_u \cdot \tilde{q}_3^B|^2 + \lambda_t^2 |H_u|^2 |\tilde{u}_3^B|^2$$

NORMAL TOP QUARKS

...PLUS TOWERS  
OF KK STATES

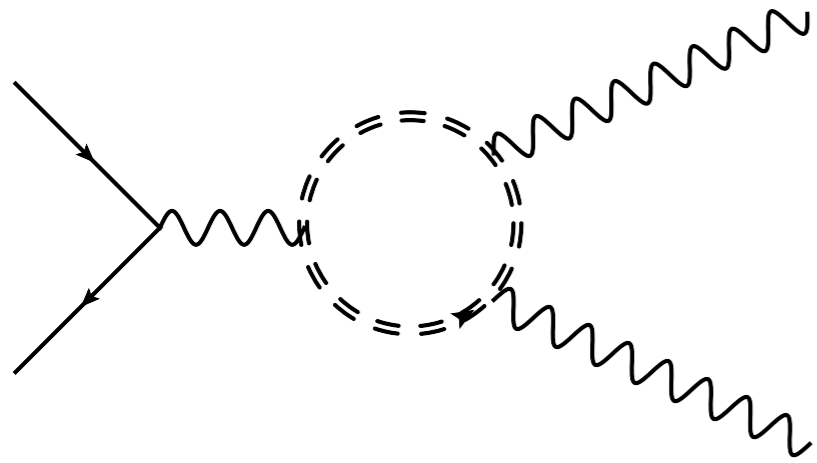
CHARGED UNDER A  
HIDDEN SU(3); ONLY  
CARRY ELECTROWEAK  
SM QUANTUM #'S.

PROBABLY NOT THE THEORY OF NATURE,  
BUT A PROOF OF PRINCIPLE FOR THE  
WIDE SCOPE OF SUSY PHENOMENA.

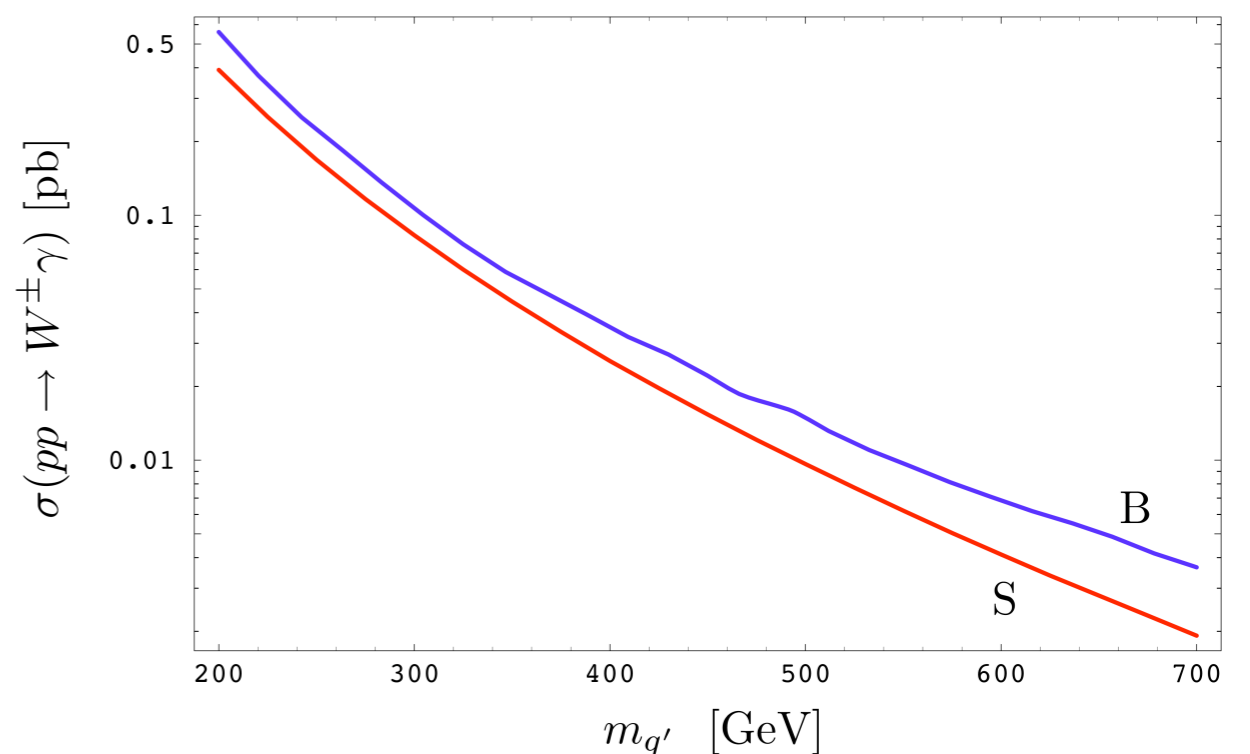
# COLORLESS SIGNALS

FOLDED SQUIRKS CARRY ELECTROWEAK QUANTUM NUMBERS. PRODUCED VIA A Z, THEY TYPICALLY ANNIHILATE INTO HIDDEN GLUEBALLS.

PRODUCED VIA A W, THEY ANNIHILATE BACK INTO THE SM TO SHED THEIR CHARGE.



DETAILED PHYSICS IS COMPLICATED, BUT A DOMINANT CHANNEL IS OFTEN  $W+\gamma/H$ ; S/B IS REASONABLE FOR  $W\gamma/WH$  IN A FIXED INVARIANT MASS WINDOW AROUND TWICE THE SQUIRK MASS.



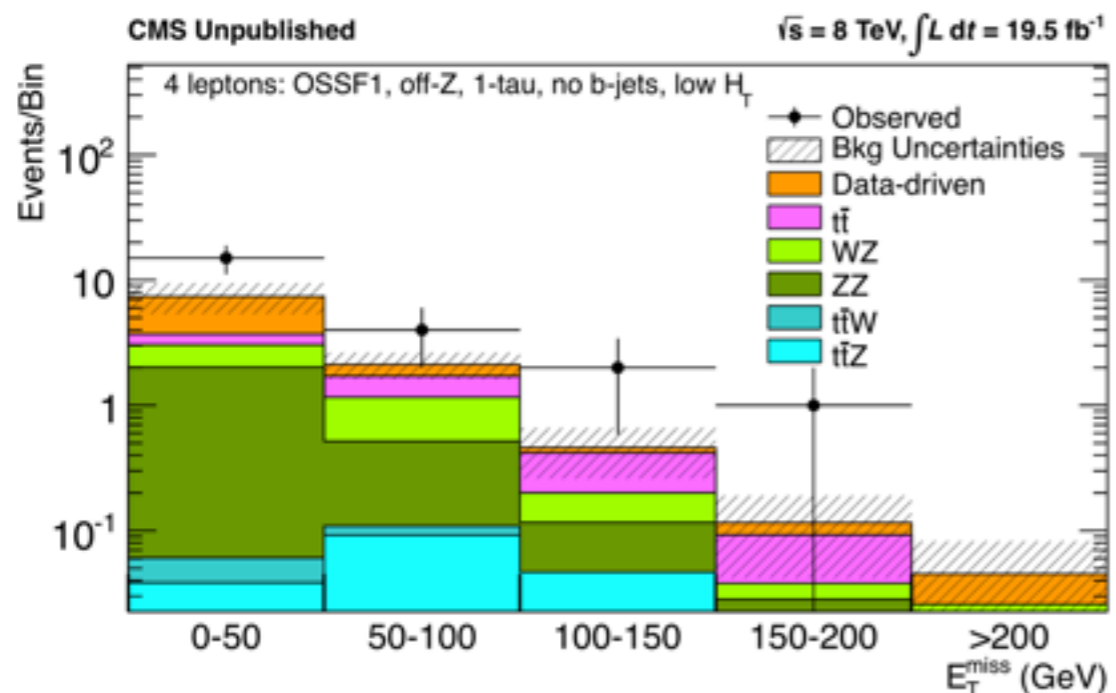
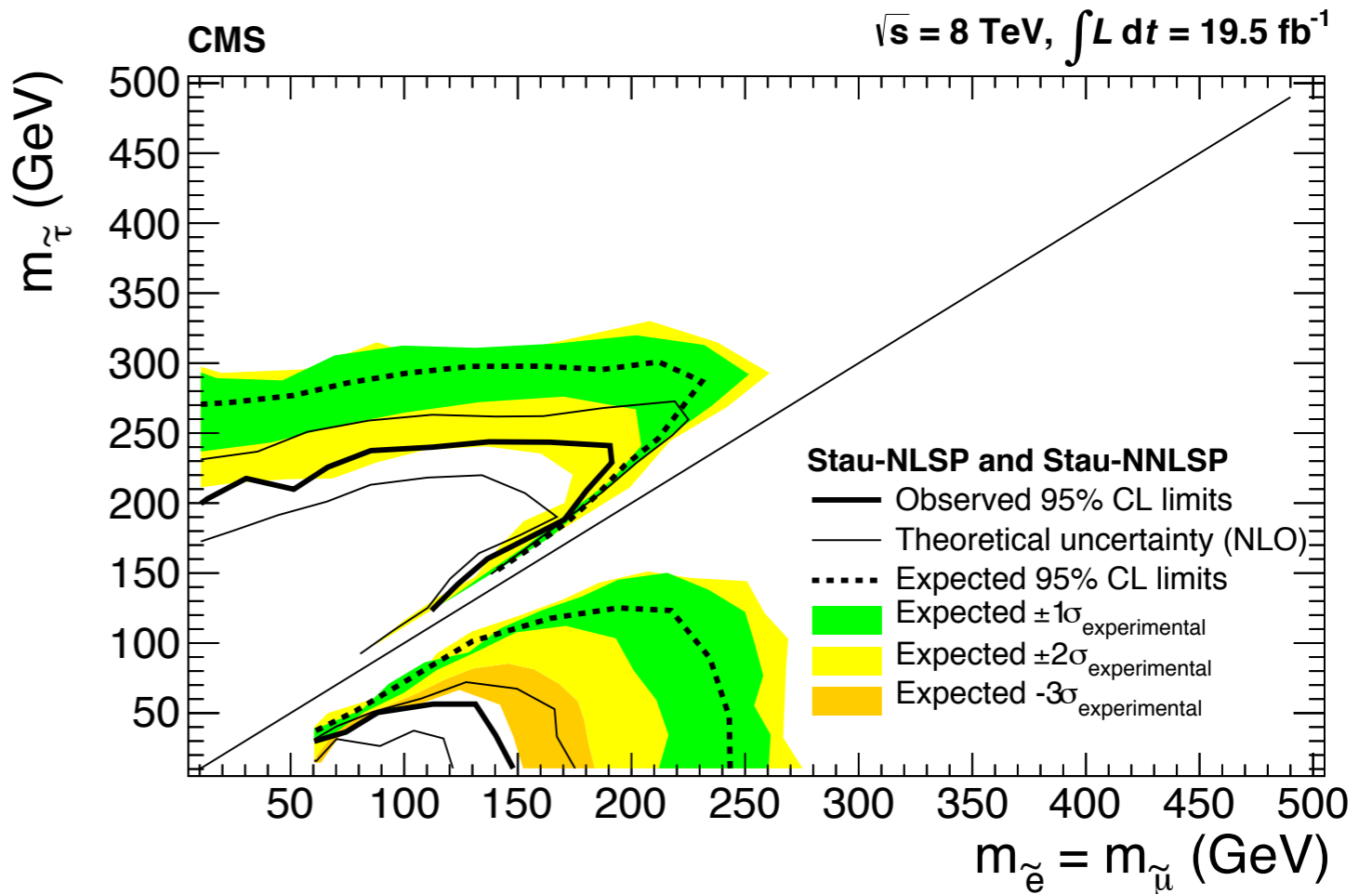
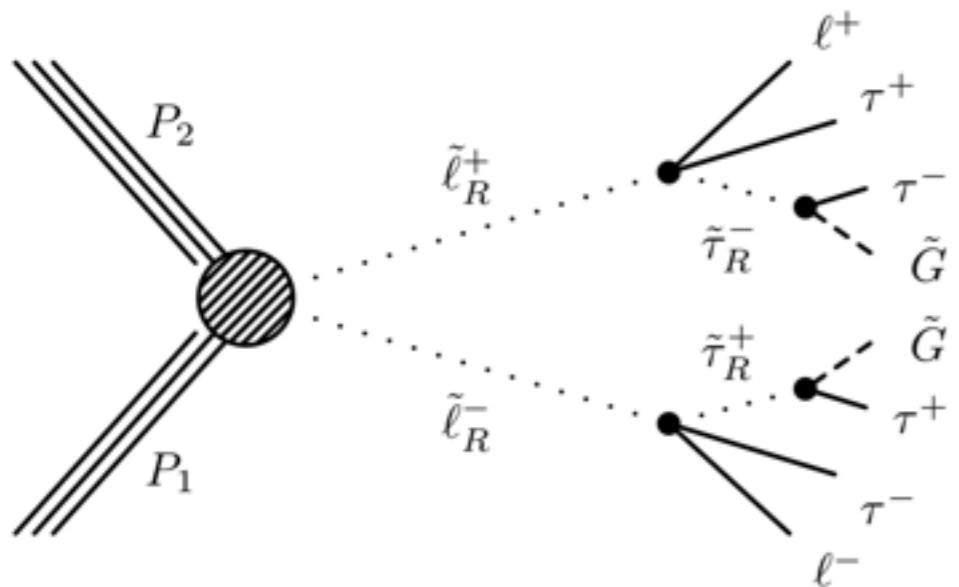
THESE ARE JUST A FEW  
EXAMPLES ILLUSTRATING HOW  
DATA POINTS US TOWARDS  
NEW DIRECTIONS IN THE SUSY  
FRAMEWORK. IN TURN, THESE  
MODELS PROVIDE NEW  
OPPORTUNITIES FOR LHC  
SEARCHES.

*THERE ARE MANY SUCH MODELS, AND  
NOW IS THE TIME TO EXPLORE THEM.*

# EXPERIMENTAL DESIDERATA FOR LHC13-14



# 1. DISCOVER, DON'T EXCLUDE

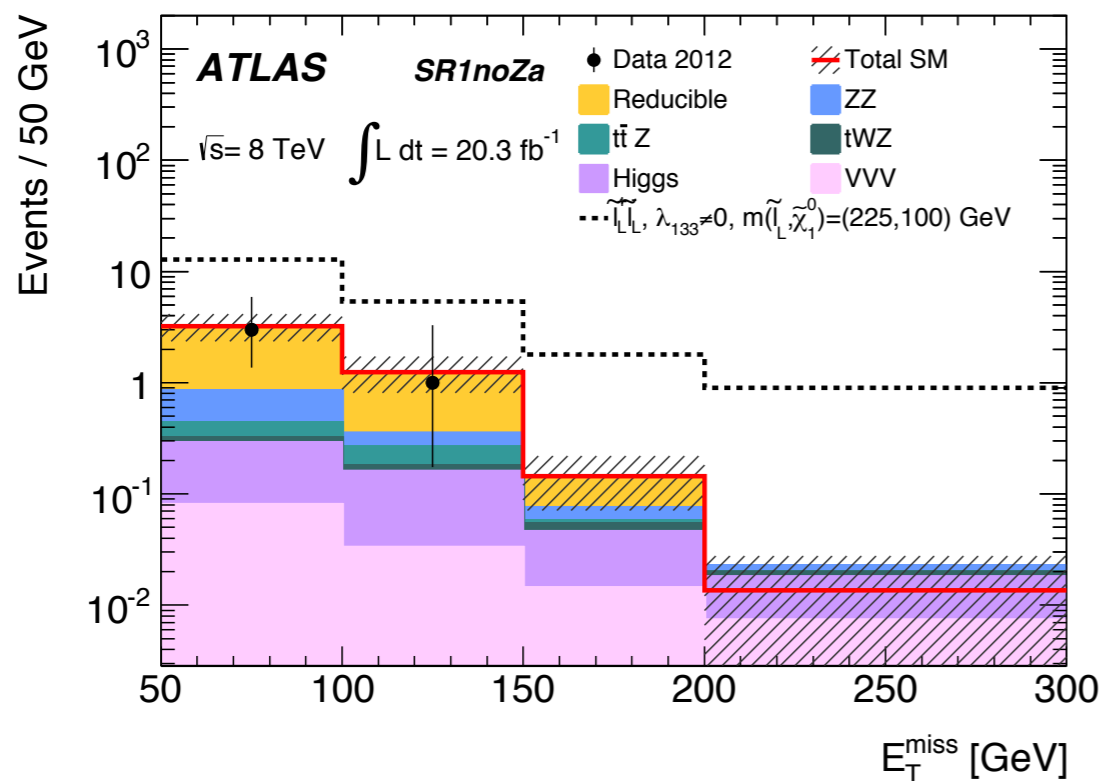
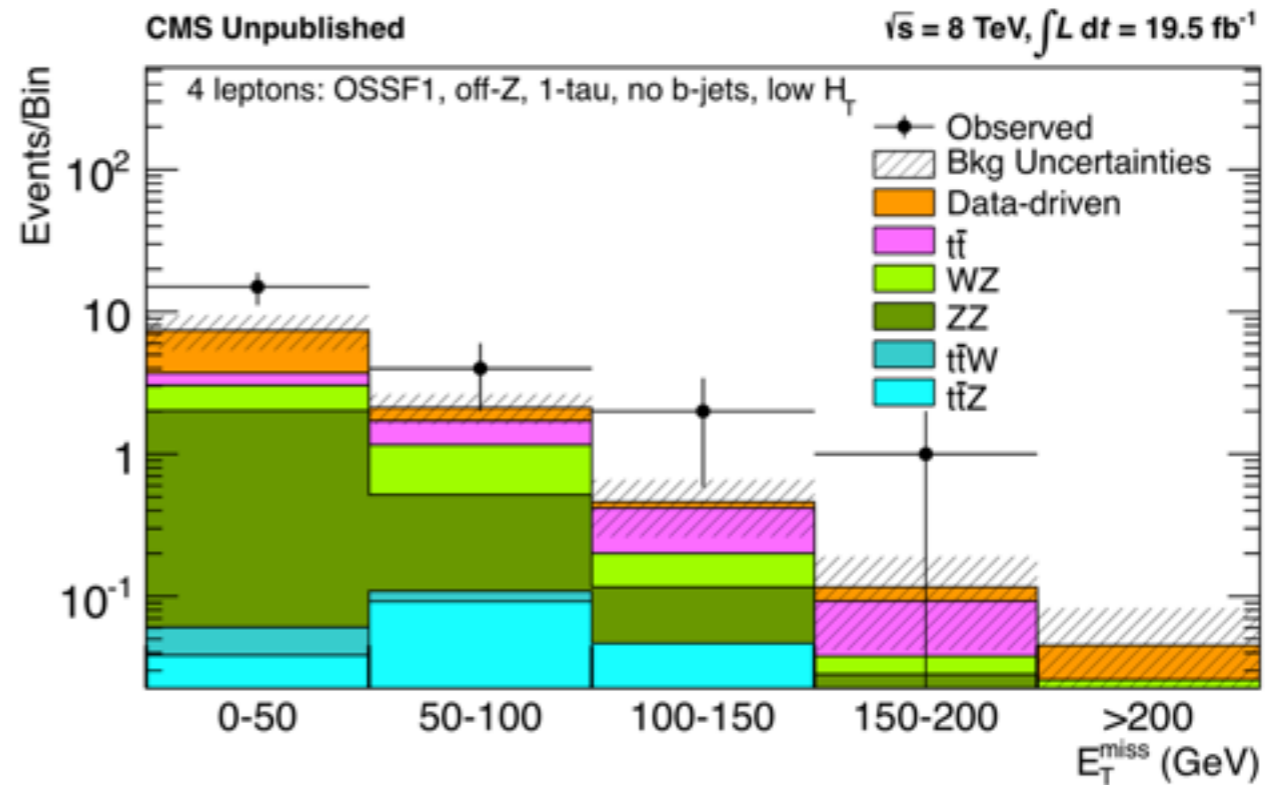


CMS MULTI-LEPTONS:  
 CONSISTENT W/ FLUCTUATION  
 (156 EXCLUSIVE CATEGORIES),  
 BUT AMONG BIGGEST  
 FLUCTUATIONS IN RUN 1.  
 PLAUSIBLE INTERPRETATION  
 IN TERMS OF STAU NLSP

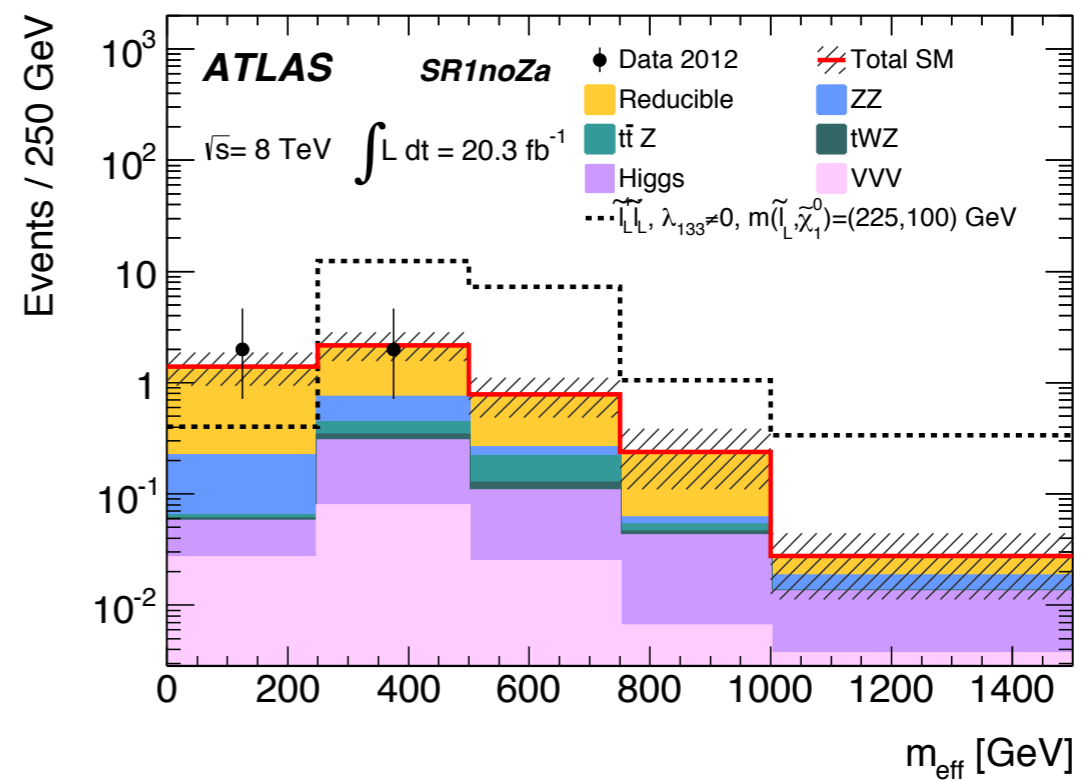


# 1. DISCOVER, DON'T EXCLUDE

EFFECTIVELY IN  
 SIDEBAND OF ATLAS  
 4-LEPTON SEARCH  
 (THOUGH THERE'S NO  
 EXCESS THERE).



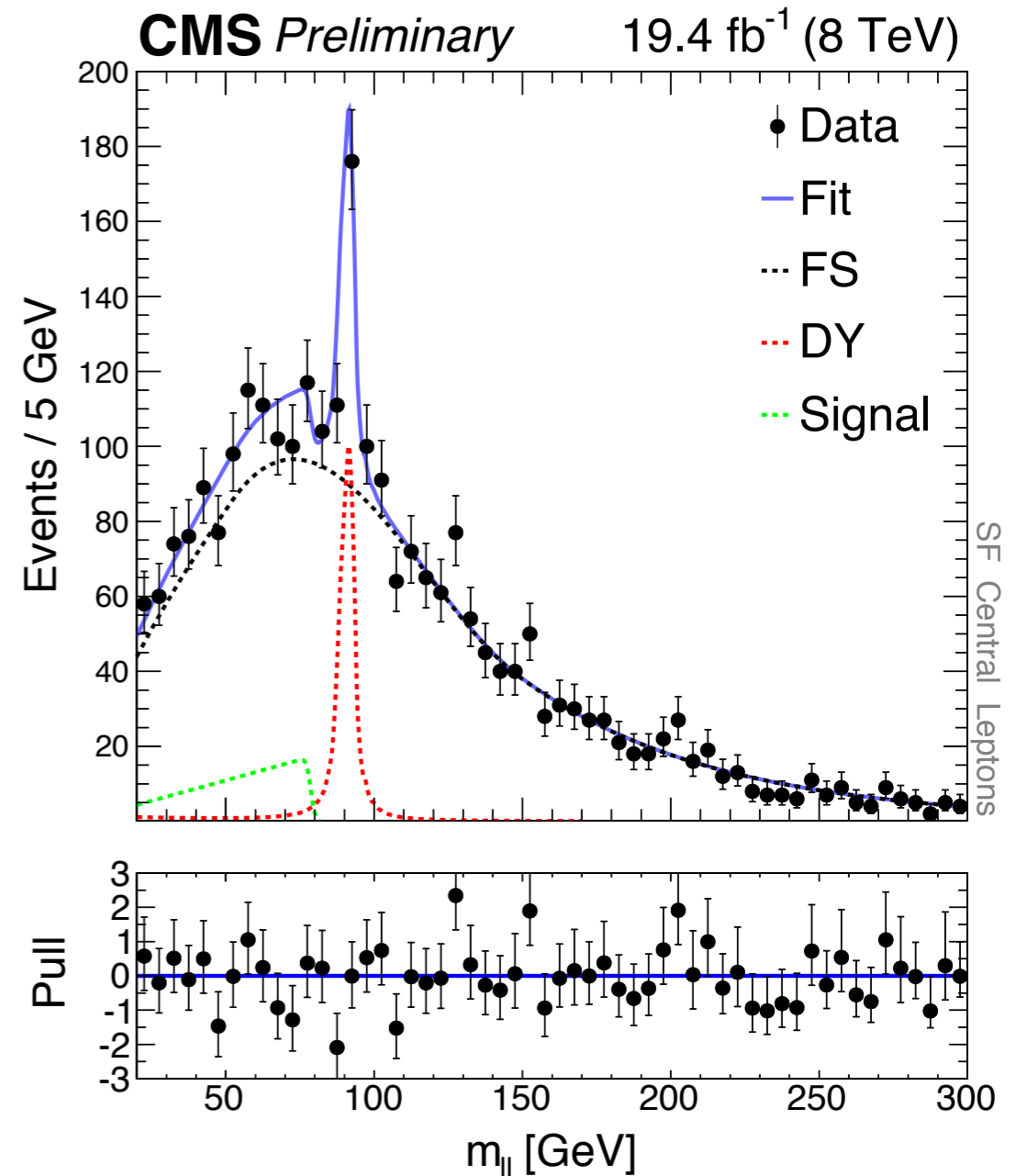
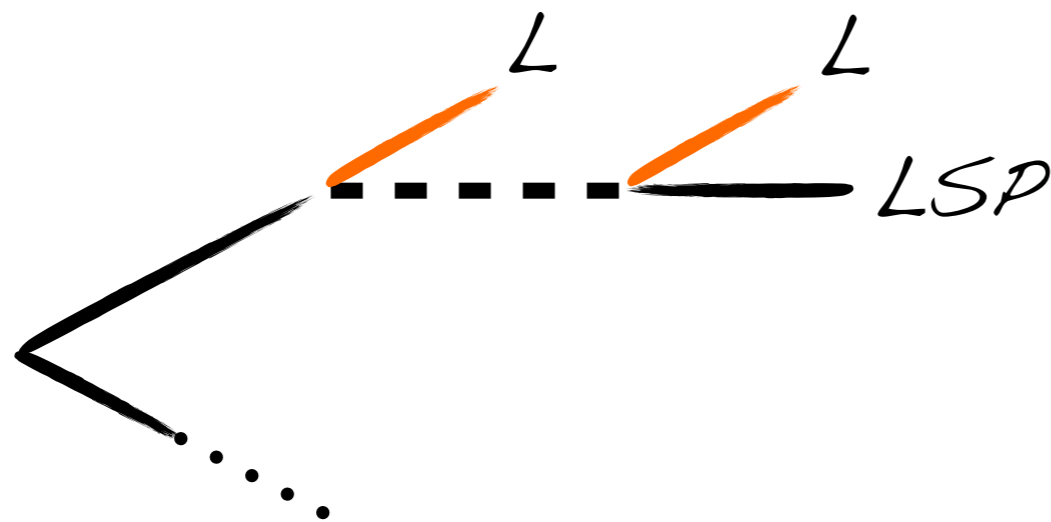
(c) SR1noZa



(d) SR1noZa

# 2. LOOK FOR TRIANGLES

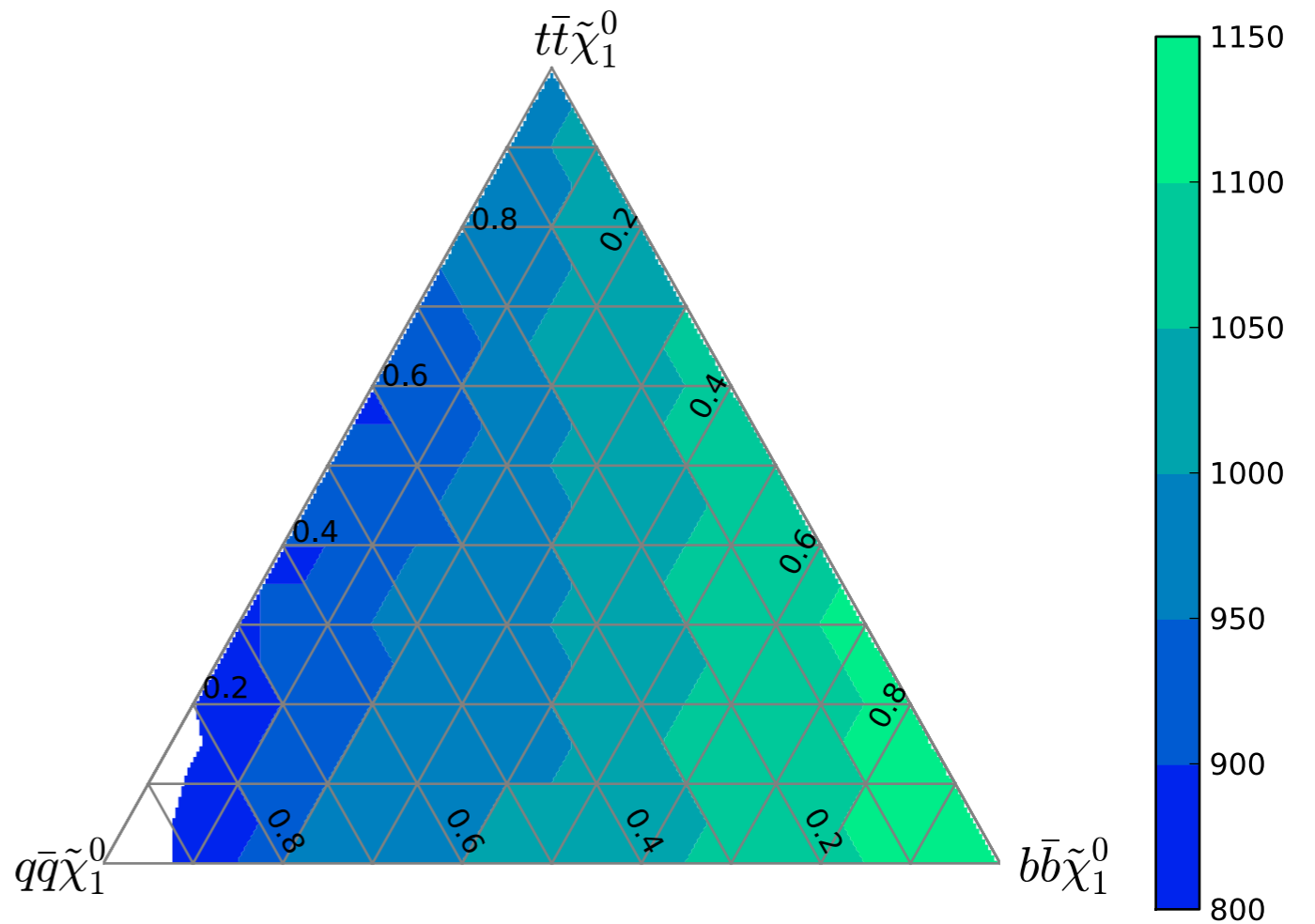
PhysicsResultsSUS12019 (25 Aug 2014, KeithUlmer)



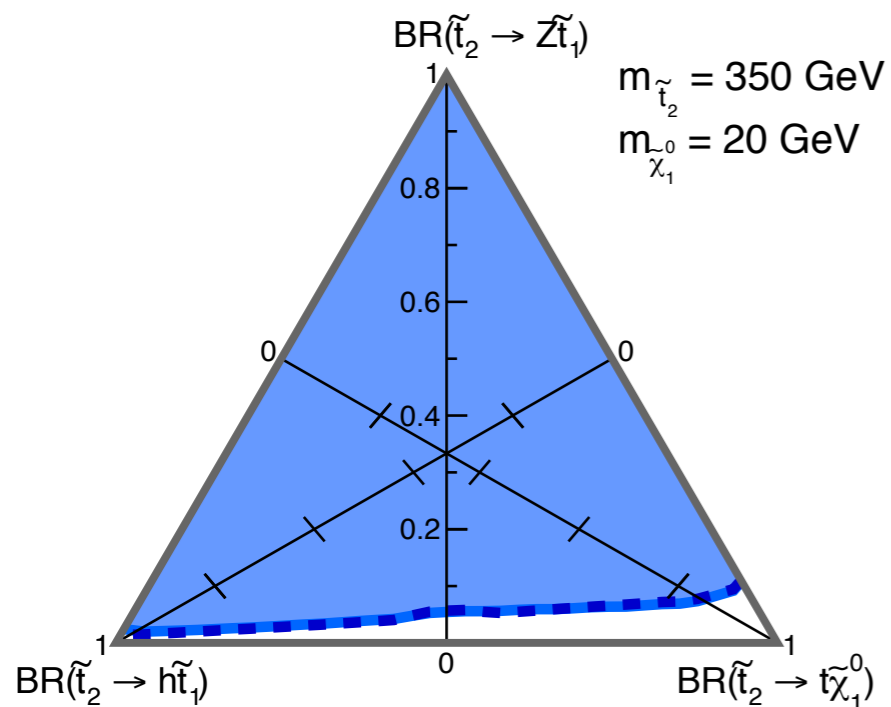
- EDGE IN DILEPTON INVARIANT MASS FROM 2-BODY OR 3-BODY DECAY (ON-SHELL OR OFF-SHELL SLEPTON)
- ATLAS EQUIVALENT SEARCH JUST GETTING STARTED.
- THIS ISN'T NEW PHYSICS, BUT ARE WE MISSING ANY KINEMATIC FEATURES IN SIMPLIFIED MODELS?

# 3. MAKE TRIANGLES

A SHORTCOMING OF SUSY SIMPLIFIED MODELS TO DATE IS FAILURE TO ACCOMMODATE MIXED DECAY MODES.



[ANANDAKRISHNA, HILL; 1403.4294]



**ATLAS**  $L_{\text{int}} = 20.3 \text{ fb}^{-1}$   $\sqrt{s} = 8 \text{ TeV}$

$\tilde{\chi}_2\text{-}\tilde{t}_2$  production,  $\tilde{t}_2 \rightarrow Z\tilde{t}_1, h\tilde{t}_1, t\tilde{\chi}_1^0$ ;  $\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$

$m_{\tilde{t}_1} = m_{\tilde{\chi}_1^0} + 180 \text{ GeV}$

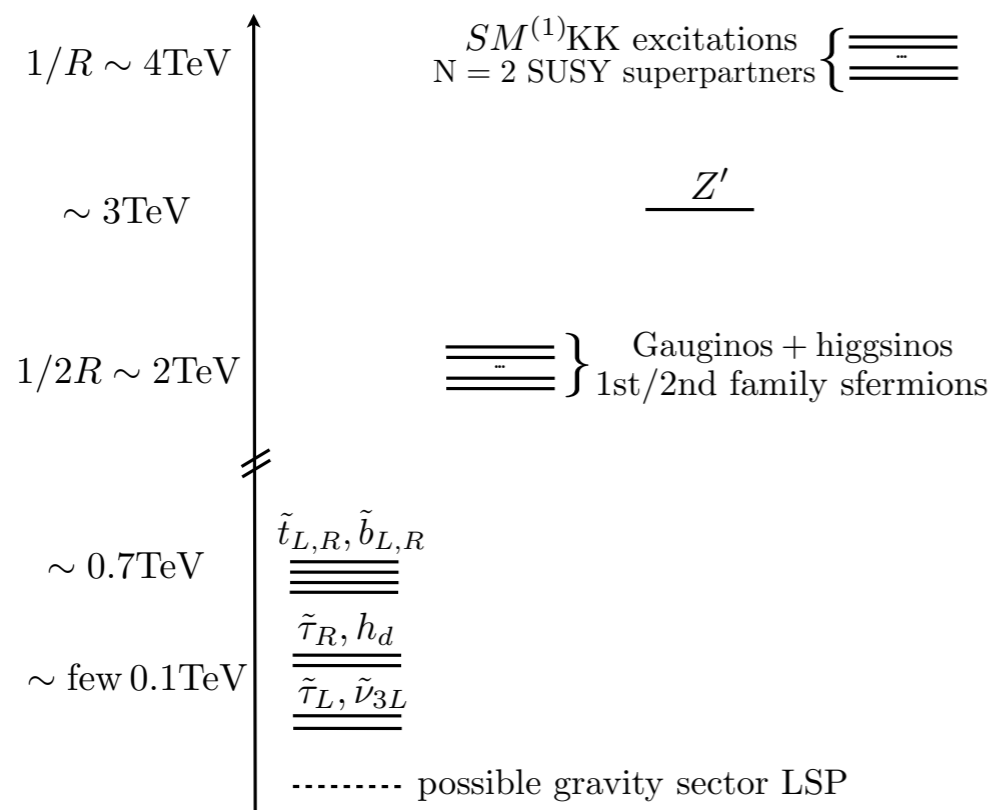
Observed  
Expected

ALREADY SUCCESSFUL IN EXOTICS GROUP. MAY PROVIDE A CONCRETE SENSE OF WHERE THE HOLES ARE.

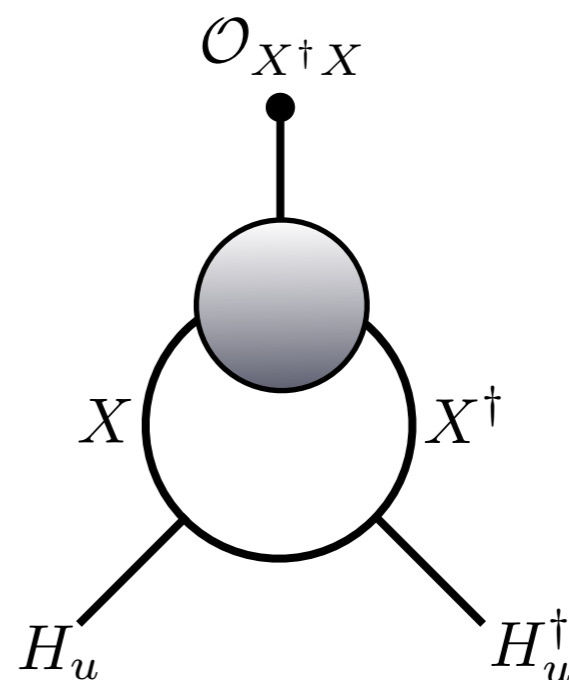
# 4. LOOK EVERYWHERE

- "NATURALNESS DEMANDS THE HIGGSINO MUST BE LIGHTER THAN 200 GEV"

-LOTS OF THEORISTS



$$X^\dagger(z)X(0) \sim \mathcal{C}|z|^{\Delta_{X^\dagger X} - 2\Delta_X} \mathcal{O}_{X^\dagger X}(0) + \dots$$



COUNTEREXAMPLE: SUSY  
EXTRA DIMENSIONS

COUNTEREXAMPLE: HIDDEN  
SECTOR DYNAMICS

# CONCLUSIONS

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*SO LETS GO OUT AND FIND THEM!*