THE STATE OF SUPERSYMMETRY

(Non)-Standard Model Higgs Boson
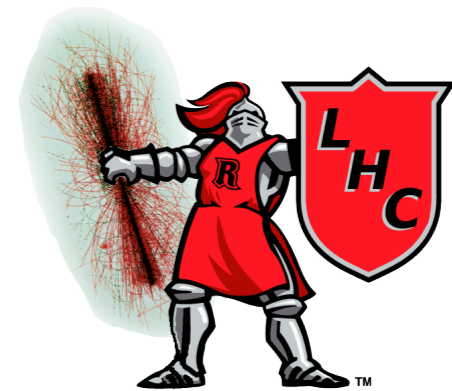
NATHANIEL CRAIG
RUTGERS UNIVERSITY

LHCP   2014

HIERARCHY PROBLEM

- IN THE B.H. ("BEFORE HIGGS") ERA, COULD TAKE FOR GRANTED THAT HIERARCHY PROBLEM MOTIVATES BSM @ WEAK SCALE.

- NOT TRUE NOW; HIGGS + EXCLUSIONS CALL NATURALNESS INTO QUESTION.

- CONFUSION IS GOOD, SIGN OF PROGRESS!

- ...BUT WE SHOULD STILL SUBJECT ALL PROPOSED ALTERNATIVES TO SCRUTINY.

HIERARCHY PROBLEM

"THE SM IS ALL THAT THERE IS"

- STATEMENT IS (A BIT) VACUOUS. CAN'T PREDICT THE HIGGS MASS IN "JUST THE SM". ALSO, THIS ASKS A LOT FROM GRAVITY.

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EVEN SIDESTEPPING THIS,

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- NEEDS UV COMPLETION @ LOW SCALE.

- UV COMPLETING THIS AT THE WEAK SCALE IS HARD! (PRECISION ELECTROWEAK, FLAVOR)

HIERARCHY PROBLEM

"IS DIM REG THE PREFERRED SCHEME?"

[BARDEEN, FERMILAB-CONF-95-391-T]

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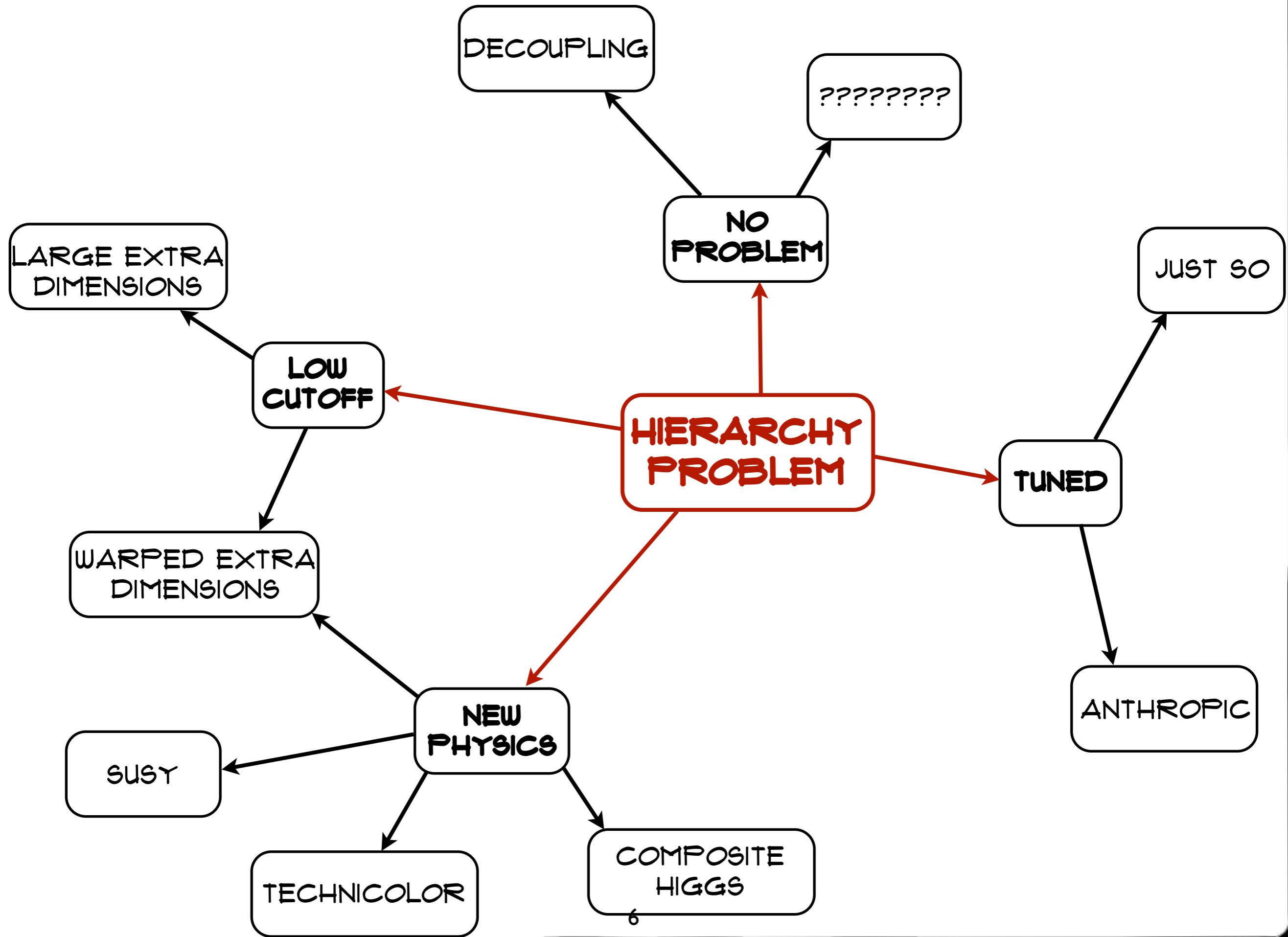
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- DEFLECT COUPLINGS $\Rightarrow$ INTRODUCE SCALE $\Rightarrow$ HIERARCHY PROB! (EVEN IF SCALE SQUISHY).

HIERARCHY PROBLEM

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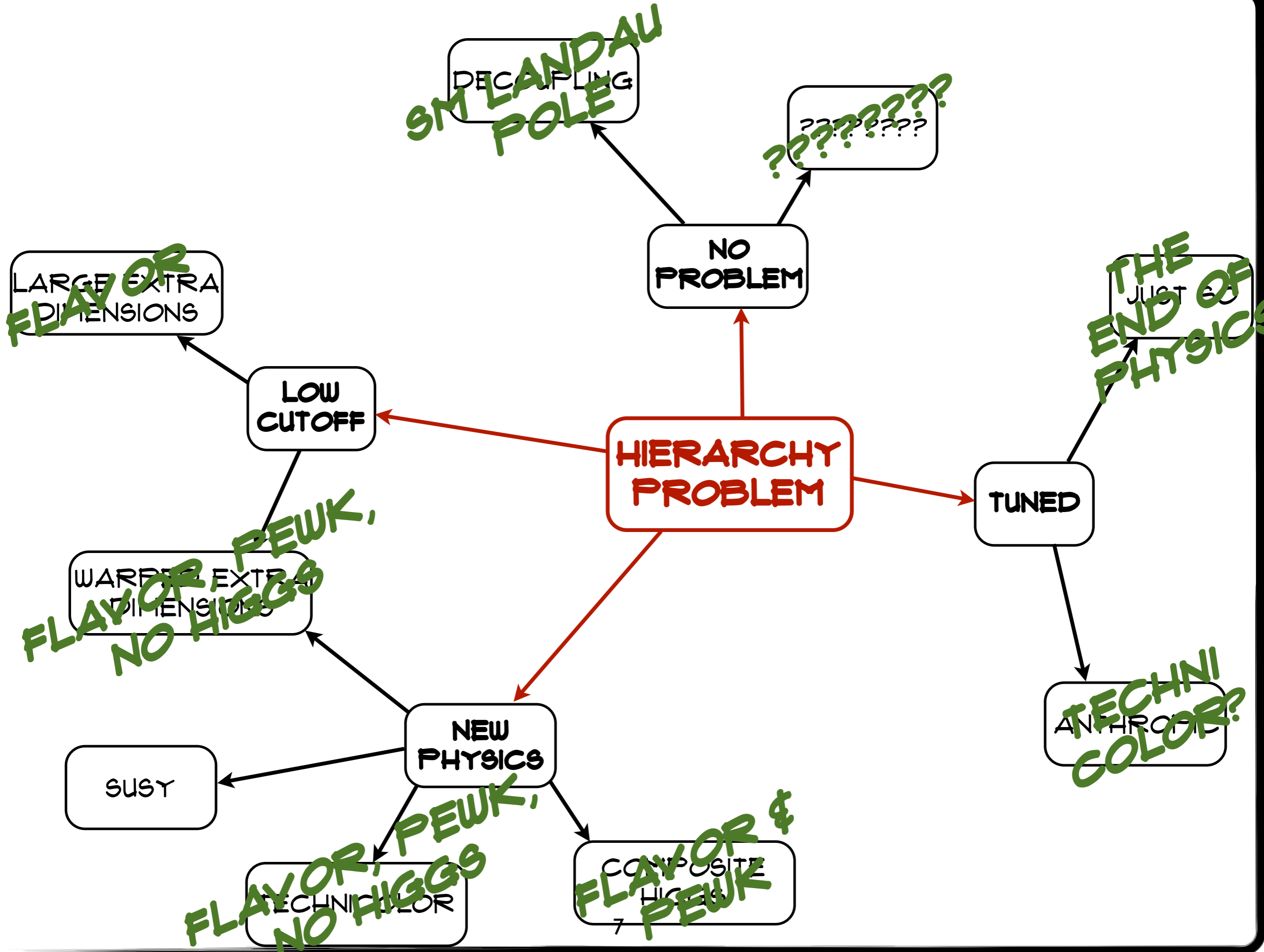
- $\Rightarrow$ NEW PHYSICS AT LOW SCALES. [MARQUES TAVARES, SCHMALTZ, SKIBA 1308.0025]

4

SUBJECT TO SCRUTINY, PROPOSALS FOR "ALTERNATE PATH" (SO FAR) TURN OUT TO REQUIRE BSM PHYSICS.

THERE IS A HIERARCHY PROBLEM; WASN'T JUST SOME COLLECTIVE PSYCHOSIS! IF SOLVED, THERE SHOULD BE SIGNS NEAR WEAK SCALE.

MOTIVATION FOR WEAK-SCALE BSM IS AS STRONG AS EVER.

HIERARCHY PROBLEM

- NO PROBLEM
  - DECOUPLING POLE → *SM LANDAU POLE*
  - ??????? → *???????*
- LOW CUTOFF → *FLAVOR*
  - LARGE EXTRA DIMENSIONS
  - WARPED EXTRA DIMENSIONS → *FLAVOR, PEWK, NO HIGGS*
- NEW PHYSICS
  - SUSY
  - TECHNICOLOR → *FLAVOR, PEWK, NO HIGGS*
  - COMPOSITE HIGGS → *FLAVOR & PEWK*
- TUNED
  - JUST SO → *THE END OF PHYSICS*
  - ANTHROPIC → *TECHNICOLOR?*

WHY SUSY?

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- COMPLETELY SOLVES HIERARCHY PROBLEM.

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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!

SUSY

N=1

MSSM

NMSSM

pMSSM

CMSSM
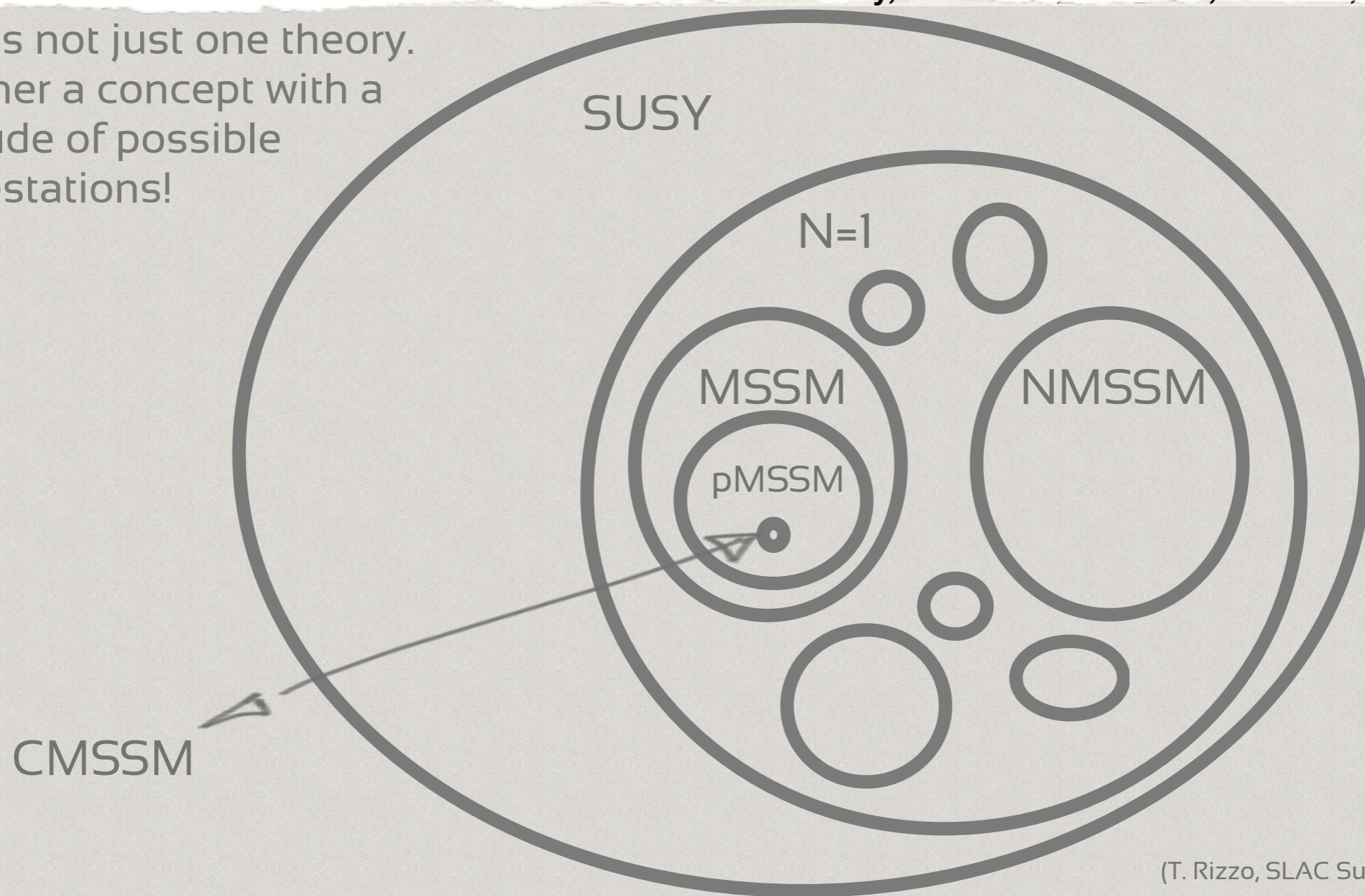
(T. Rizzo, SLAC Summer Institute, 2012)

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

AN ANALOGY

AN ANALOGY

- PROBLEM: WEAK INTERACTIONS

AN ANALOGY

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- FRAMEWORK: GAUGE THEORY

AN ANALOGY

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- SIMPLE INSTANTIATION: O(3) SCHWINGER MODEL (1957)

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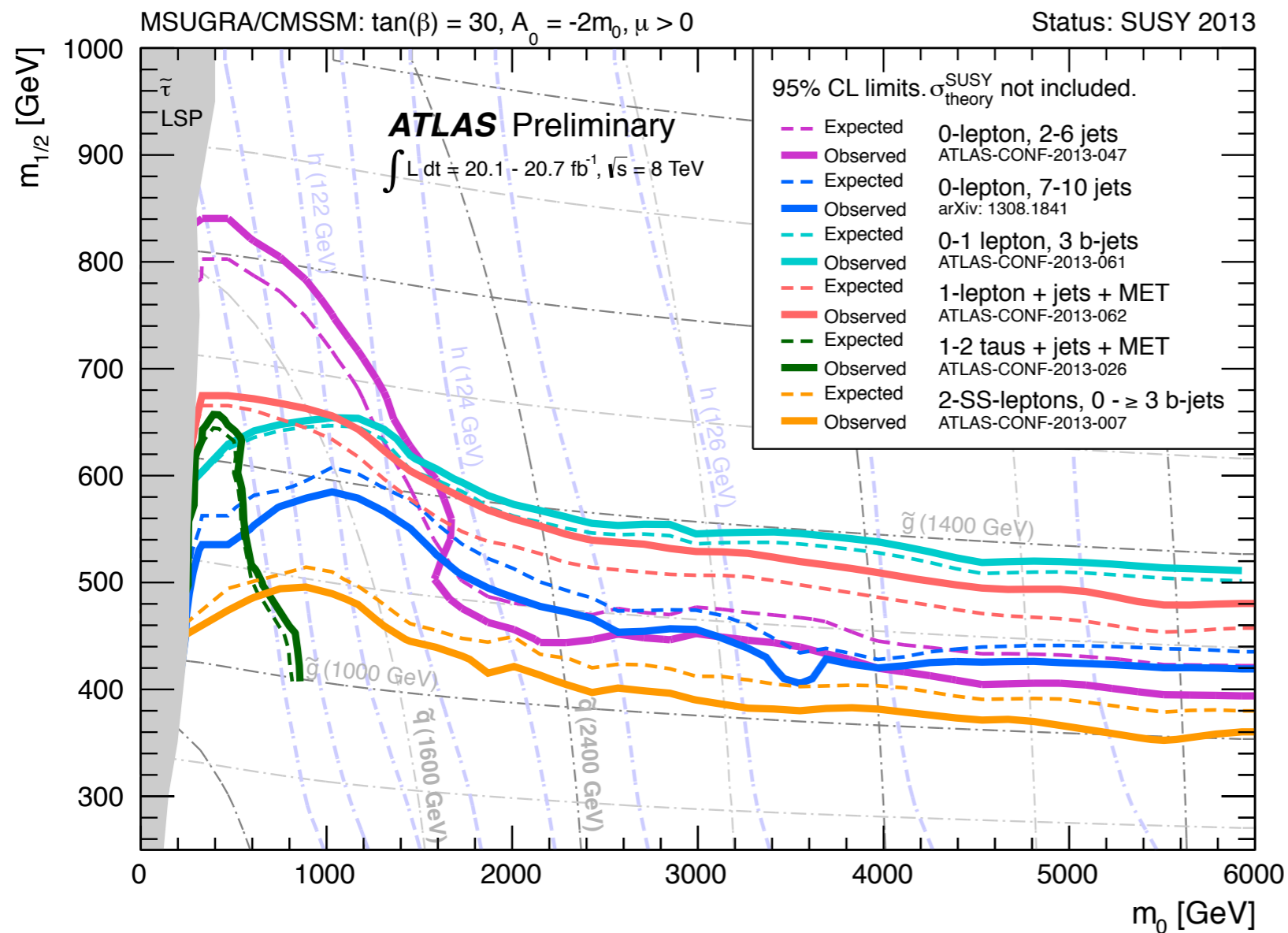
- PROBLEMS: NO Z, NOT V-A.

AN ANALOGY

- PROBLEM: WEAK INTERACTIONS

- FRAMEWORK: GAUGE THEORY

- SIMPLE INSTANTIATION: O(3) SCHWINGER MODEL (1957)

- PROBLEMS: NO Z, NOT V-A.

- UGLIER INSTANTIATION: SU(2)xU(1) GLASHOW MODEL (1961)

AN ANALOGY

- PROBLEM: WEAK INTERACTIONS

- FRAMEWORK: GAUGE THEORY

- SIMPLE INSTANTIATION: O(3) SCHWINGER MODEL (1957)

- PROBLEMS: NO Z, NOT V-A.

- UGLIER INSTANTIATION: SU(2)xU(1) GLASHOW MODEL (1961)

- *FRAMEWORK CORRECT, SPECIFIC REALIZATION IN NATURE NON-MINIMAL.*

SIGNPOSTS

- LHC DATA CUTTING OFF CERTAIN POSSIBILITIES, POINTING OUT OTHERS.

- THEORY GOAL: USE THESE SIGNPOSTS TO FIND NEW MODELS WHERE DESIDERATA ARE GENERIC.
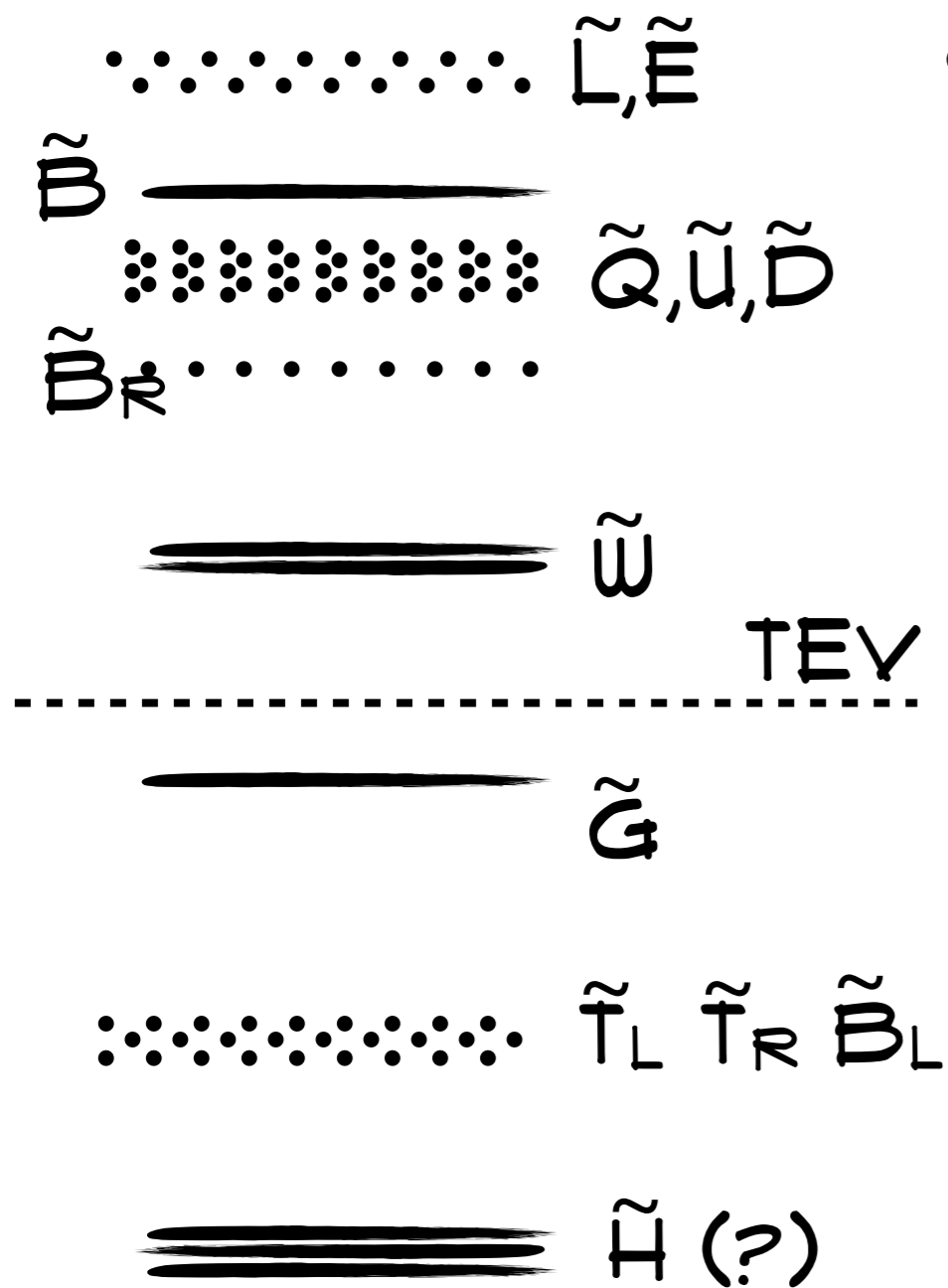
- NEW MODELS CAN DRIVE NEW SEARCH OPPORTUNITIES @ LHC.

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

MSUGRA/CMSSM: $\tan(\beta) = 30$, $A_0 = -2m_0$, $\mu > 0$ Status: SUSY 2013

95% CL limits. σ_{theory}^{SUSY} not included.

ATLAS Preliminary
$\int L\, dt = 20.1 - 20.7\, fb^{-1}$, $\sqrt{s} = 8$ TeV

- Expected / Observed — 0-lepton, 2-6 jets — ATLAS-CONF-2013-047
- Expected / Observed — 0-lepton, 7-10 jets — arXiv: 1308.1841
- Expected / Observed — 0-1 lepton, 3 b-jets — ATLAS-CONF-2013-061
- Expected / Observed — 1-lepton + jets + MET — ATLAS-CONF-2013-062
- Expected / Observed — 1-2 taus + jets + MET — ATLAS-CONF-2013-026
- Expected / Observed — 2-SS-leptons, 0 - ≥ 3 b-jets — ATLAS-CONF-2013-007

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

$\tilde{L}, \tilde{E}$

$\tilde{B}$

$\tilde{Q}, \tilde{u}, \tilde{D}$

$\tilde{B}_R$

$\tilde{W}$

TEV

$\tilde{G}$

$\tilde{T}_L \; \tilde{T}_R \; \tilde{B}_L$

$\tilde{H}$ (?)

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

O(1) COUPLINGS ARE Y_T, G_3

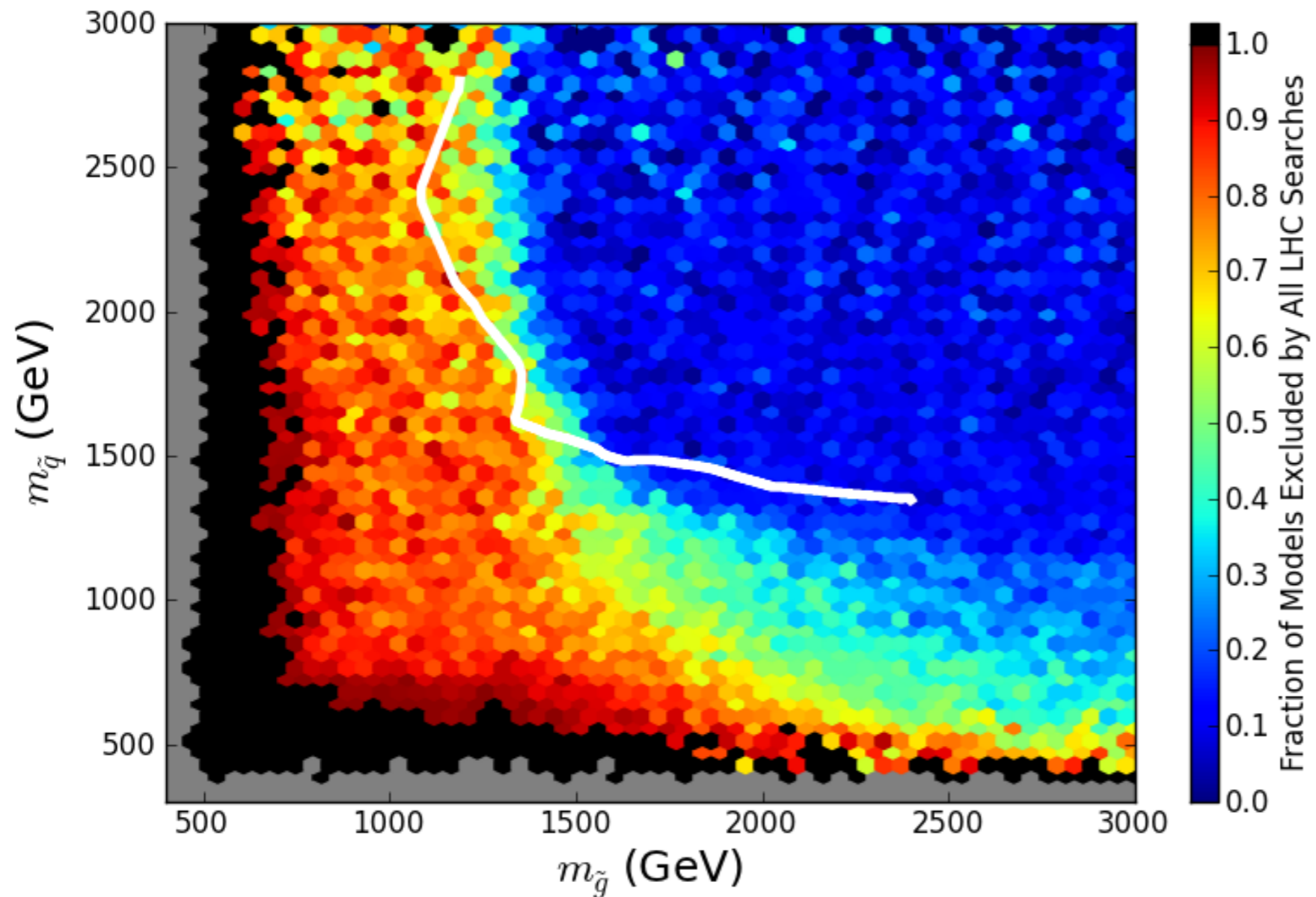NATURALNESS OF THE WEAK SCALE ONLY DEMANDS LIGHT TOP PARTNERS; GLUINO ENTERS AT TWO LOOPS, RELEVANT IF MAJORANA.

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

REMAINING STATES NATURALLY ABOVE TEV.

IN GENERAL, THE MSSM LOOKS FINE.

[CAHILL-ROWLEY, HEWETT, ISMAIL, RIZZO, 1307.8444]

PMSSM: 120 MSSM PARAMS DISTILLED TO 19-20 PARAMS

LOTS OF ROOM FOR NATURAL WEAK SCALE.
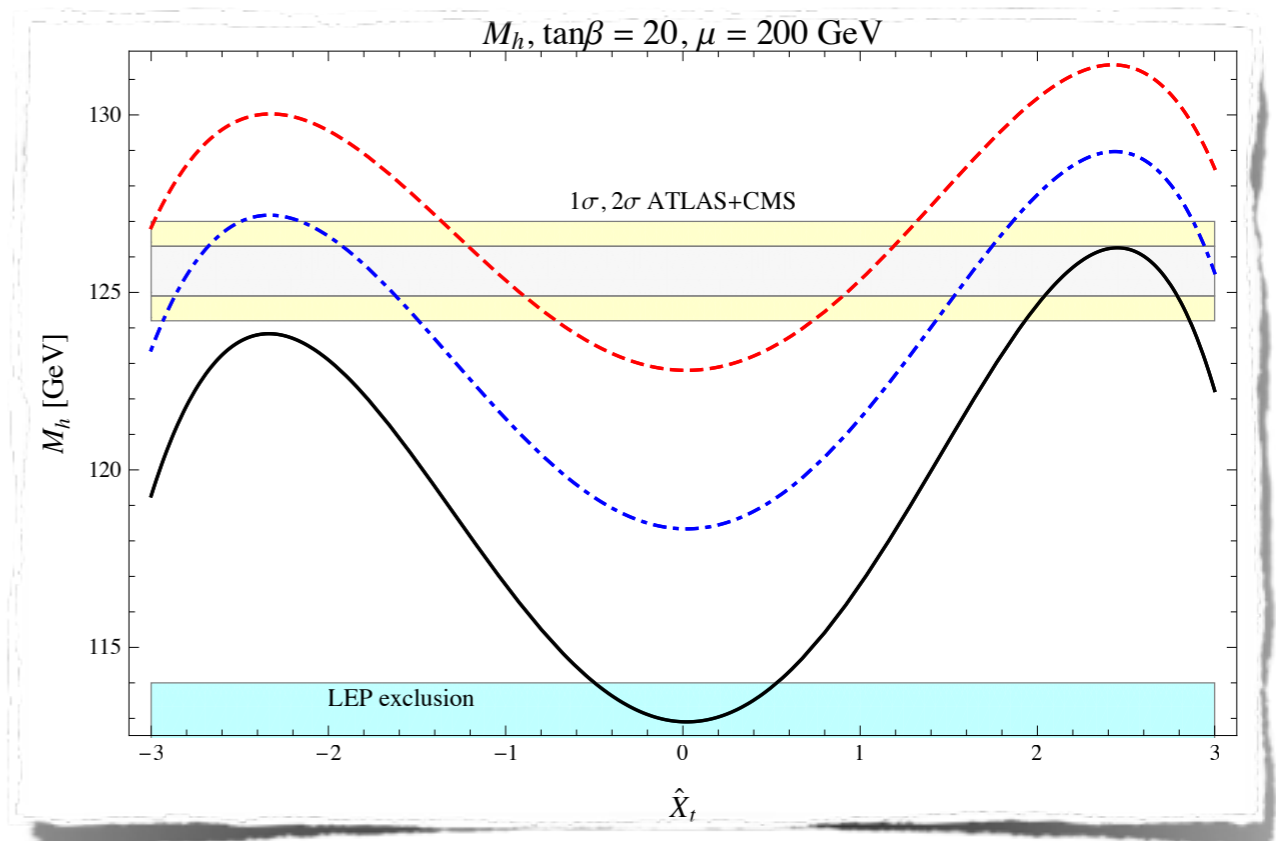
HOW TO POPULATE?
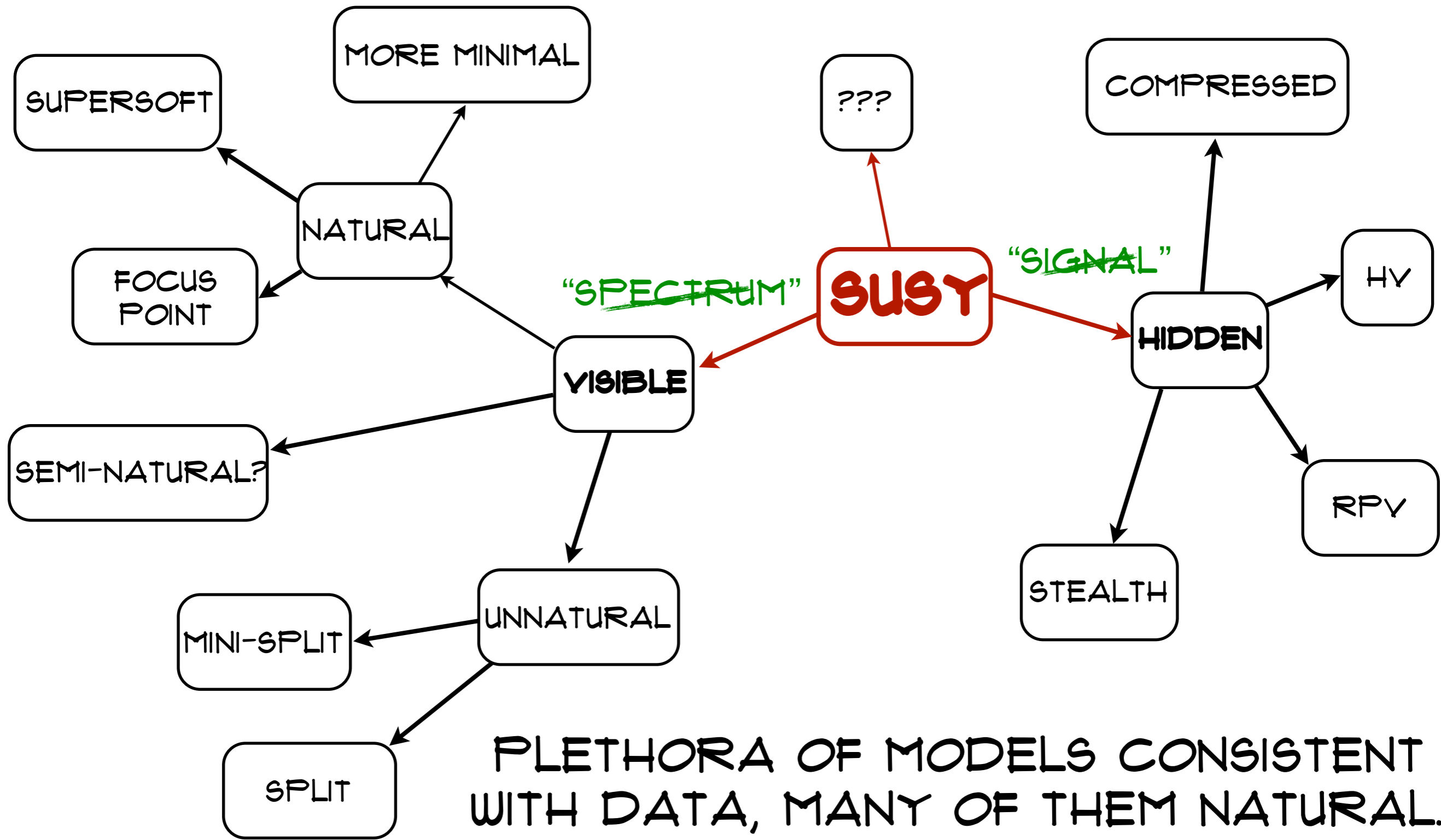
PLETHORA OF MODELS CONSISTENT WITH DATA, MANY OF THEM NATURAL. WHERE DOES THE DATA POINT US?

HIGGS MASS

M_h, $Q_{RG} = M_S$, $X_t/M_S = 0$, $\tan\beta = 20$, $\mu = 200$ GeV

MSSM HIGGS MASS:
TREE-LEVEL TERM
BOUNDED BY M_Z, PLUS
LOG AND THRESHOLD.

M_h, $\tan\beta = 20$, $\mu = 200$ GeV
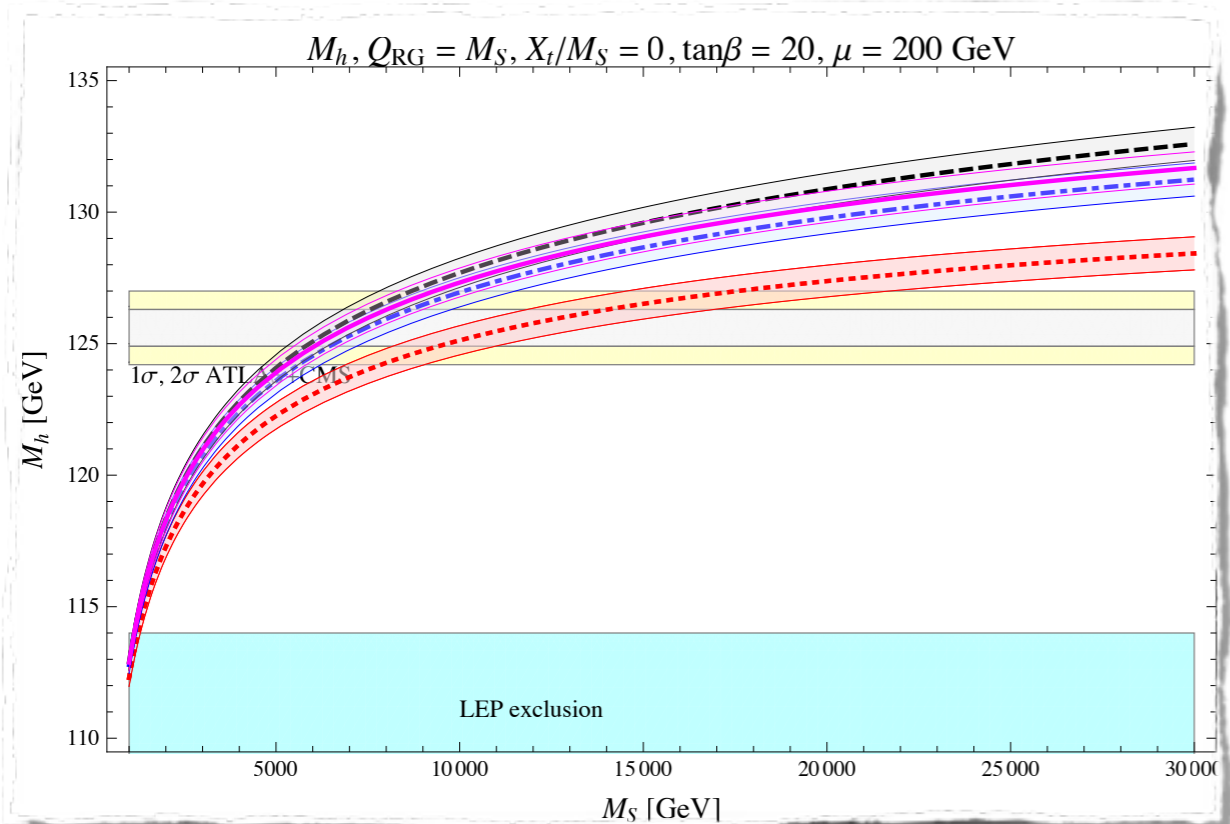
MSSM REQUIRES HEAVY
STOPS OR LARGE
THRESHOLDS; %-LEVEL
NATURAL AT BEST.

A SIGN HIGGS SECTOR IS NOT MSSM-LIKE?

[DRAPER, LEE, WAGNER 1312.5743]

F-TERM QUARTIC?

SUSY GIVES US TWO WAYS TO MAKE NEW QUARTICS: VIA NEW YUKAWA COUPLINGS OR GAUGE COUPLINGS

[GHERGHETTA, VON HARLING, MEDINA, SCHMIDT 1212.5243]
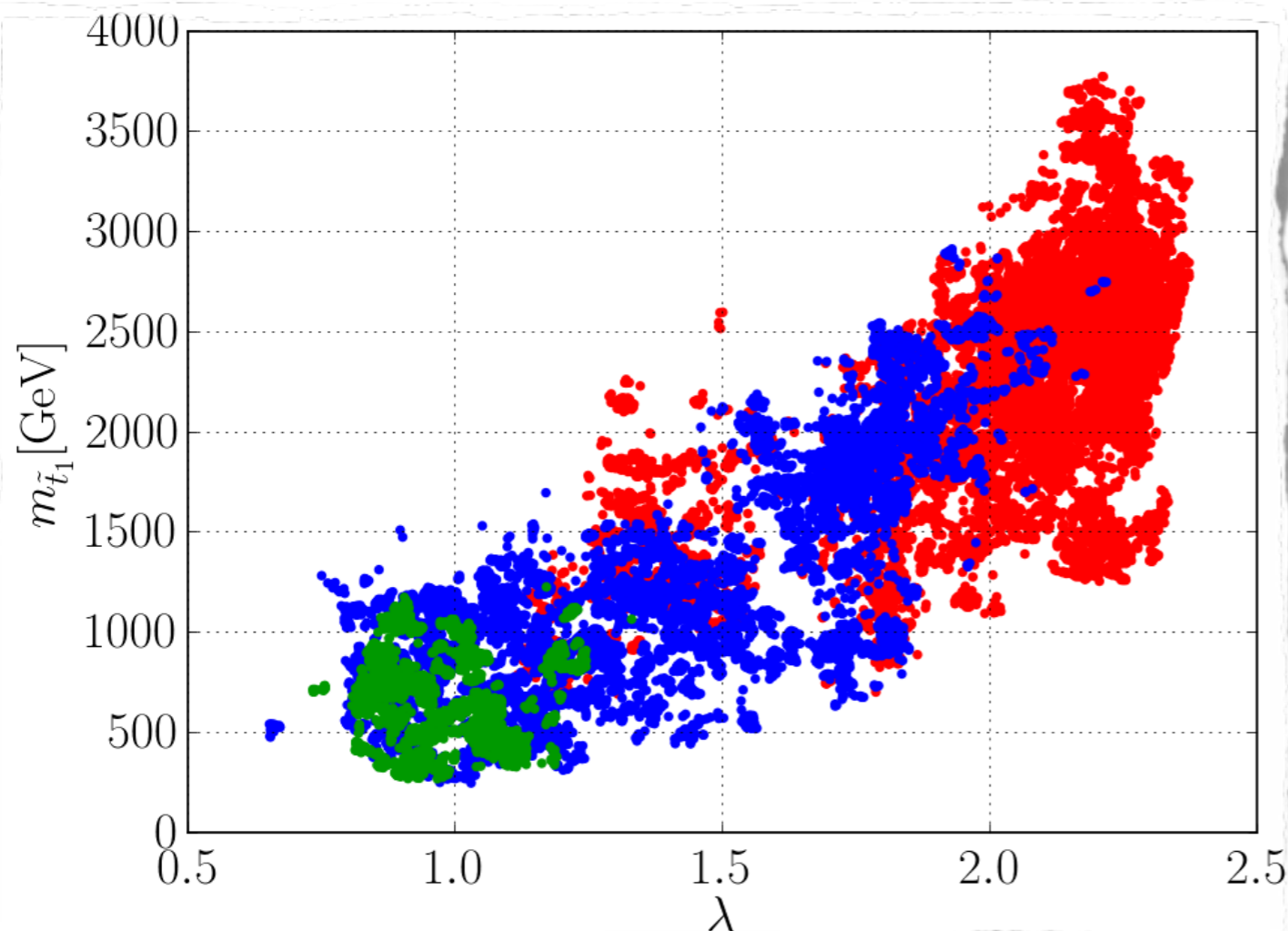
NMSSM THE CANONICAL EXAMPLE; SINGLET PROVIDES QUARTIC.

TOTAL TUNING (MASS, VEV) BETTER THAN ~5%

LANDAU POLE IN NEW COUPLING → HIGGS SECTOR COMPOSITE IN FAR UV?

D-TERM QUARTIC?

QUARTICS THROUGH GAUGE COUPLINGS
→ GAUGE EXTENSION OF THE MSSM.

$\sqrt{s} = 7$ TeV

PEW

0.5 TeV

m_X (TeV)

Higgs Mass

1 TeV

LHC

2 TeV

1.6 1.8 2.0 2.2 2.4 2.6 2.8 3.0

10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2}
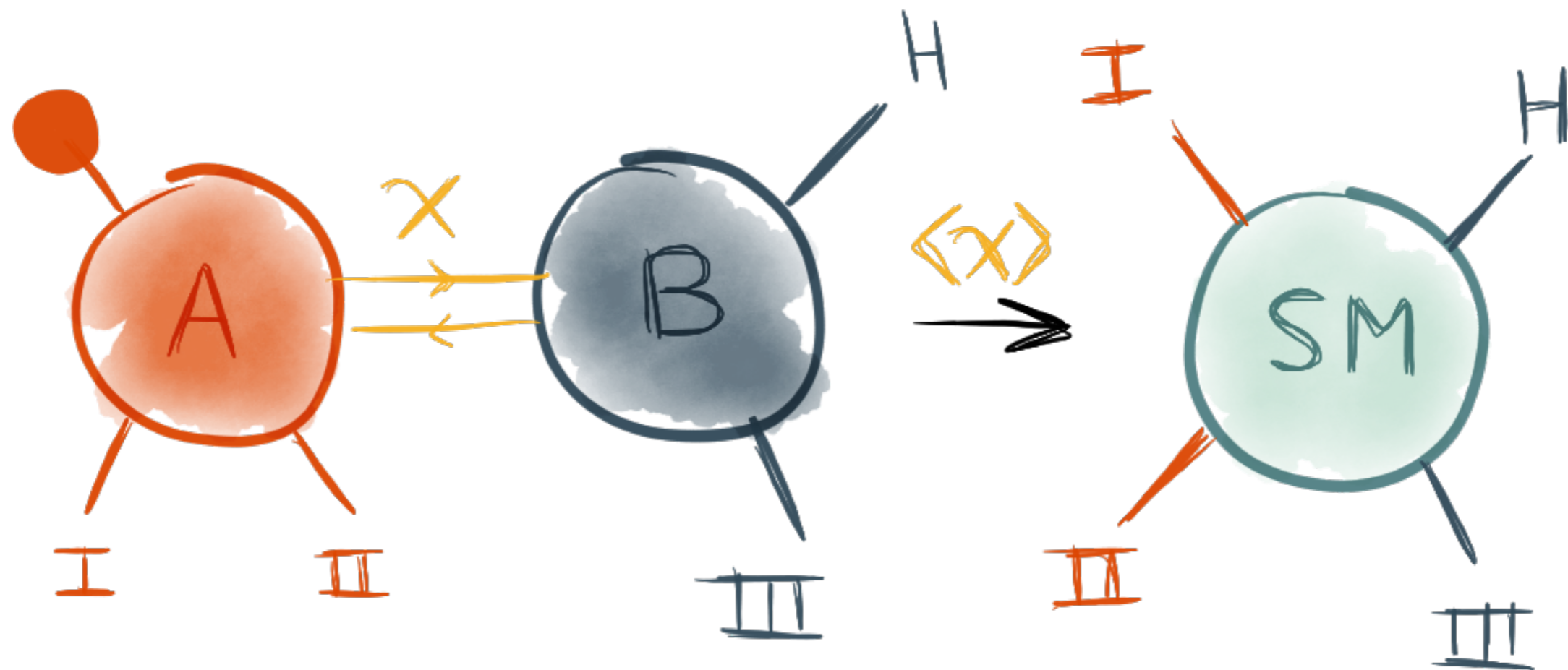
σBR (pb)
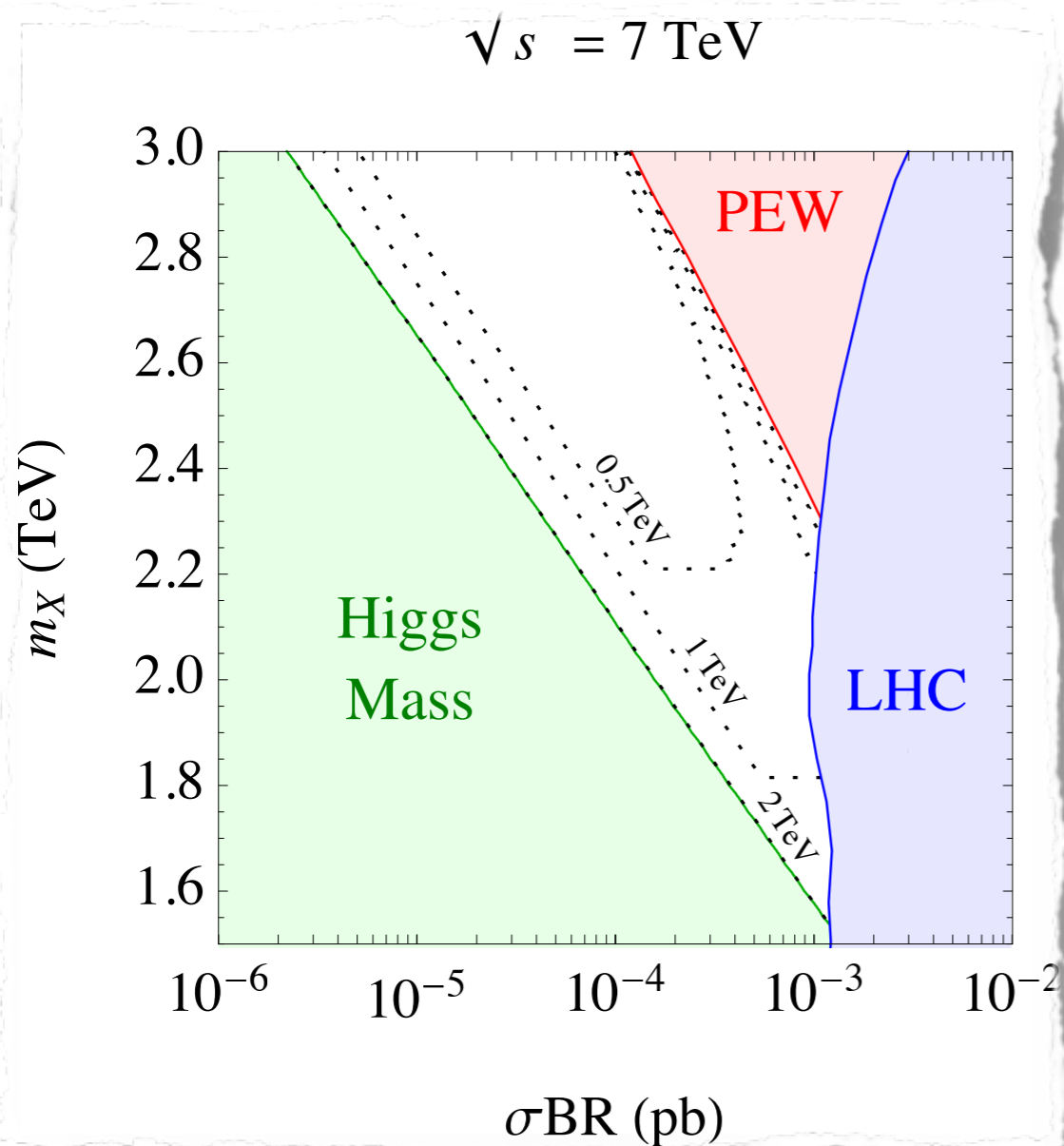
NEED AT LEAST NEW SU(2) OR U(1) ACTING ON HIGGS

NEW GAUGE BOSONS & FERMIONS IN 1-10 TEV RANGE; NEW OPPORTUNITIES

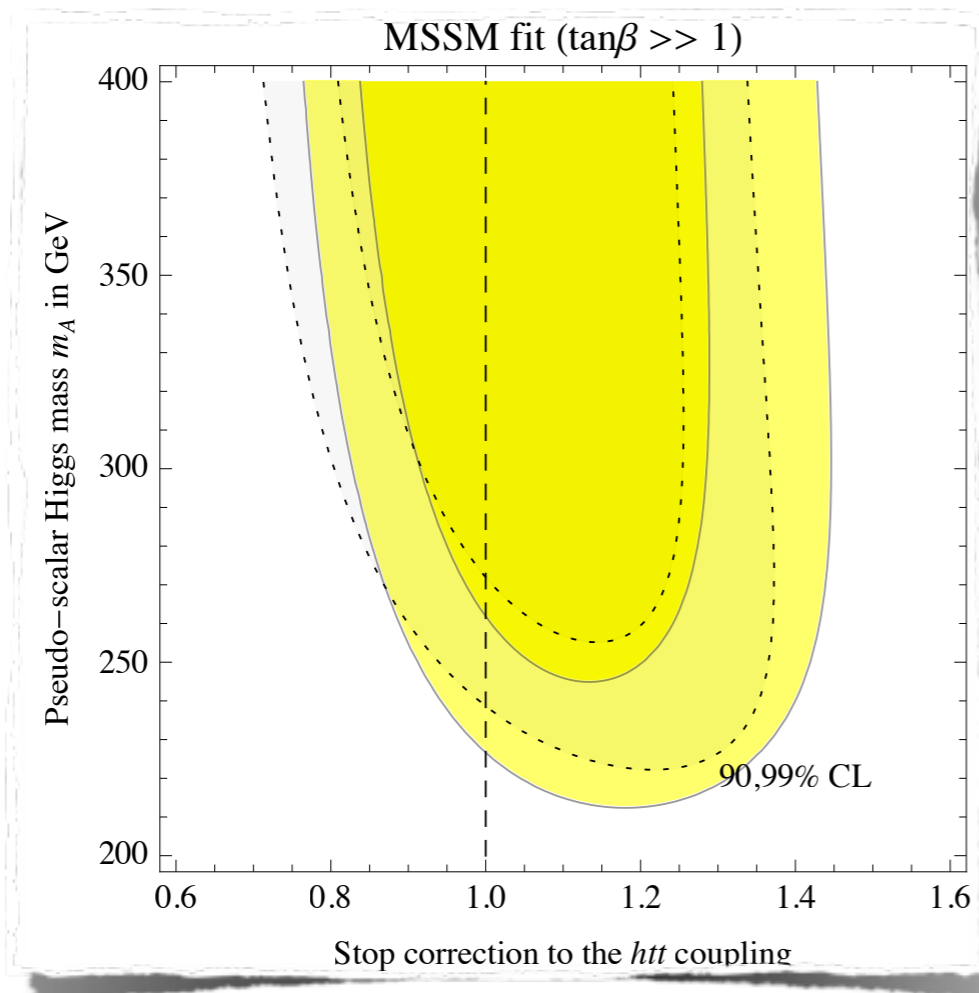COUPLINGS & MASS SCALES BOUNDED BY EXPLAINING HIGGS MASS.

[CHEUNG, ROBERTS 1207.0123]   18

SYNTHESIS

- NATURAL SUSY SPECTRUM.
- APPROXIMATE THEORY OF FLAVOR.
- HIGGS MASS FROM D-TERMS.
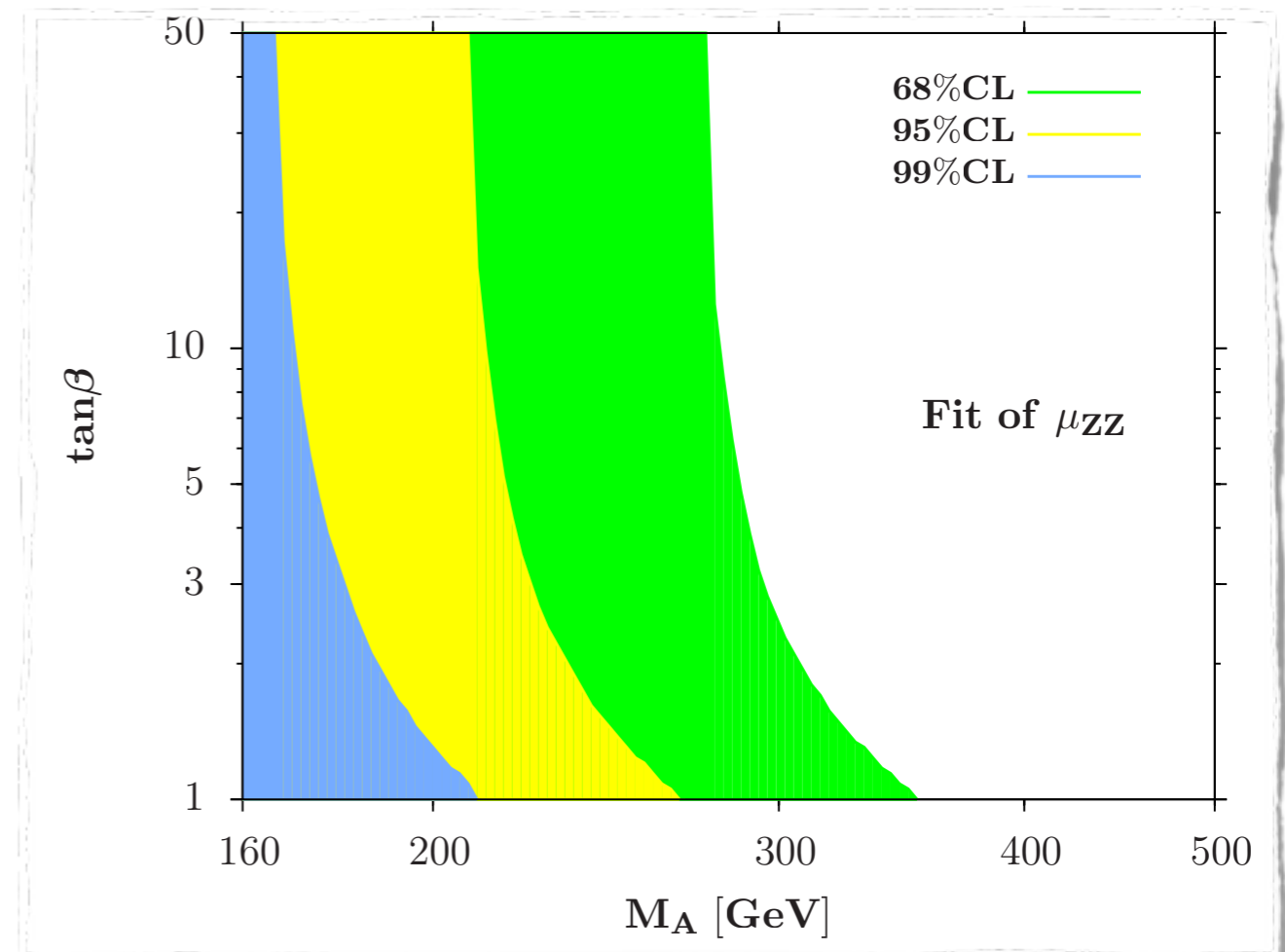- LOW RADIATIVE CUTOFF.

19   [CRAIG, GREEN, KATZ 1103.3708]

HIGGS COUPLINGS

HIGGS COUPLING MEASUREMENTS SM-LIKE BUT MSSM DECOUPLES RAPIDLY; CONSISTENT WITH EXTENDED HIGGS SECTOR @~FEW HUNDRED GEV.
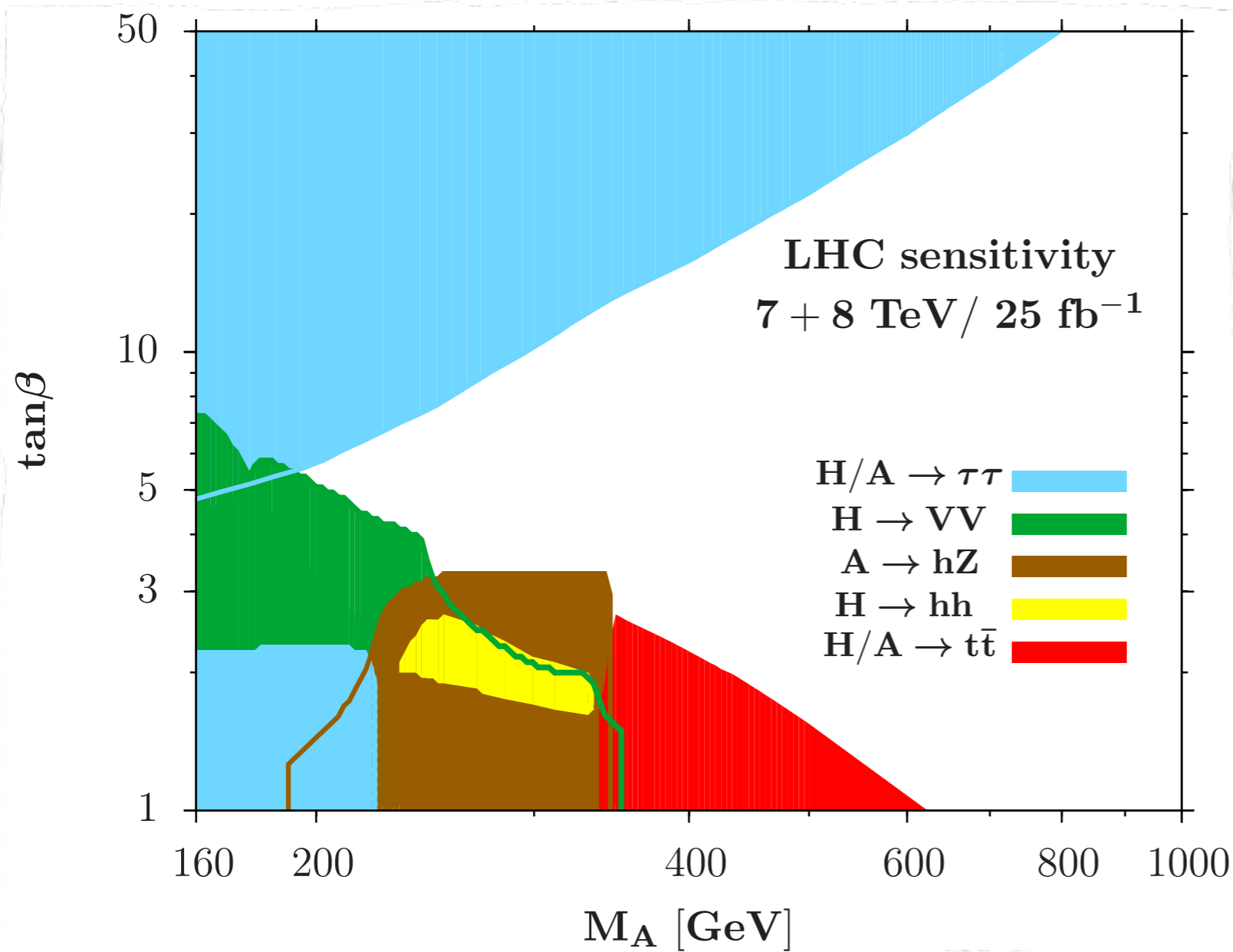
[GIARDINO, KANNIKE, MASINA, RAIDAL, STRUMIA, 1303.3570]

MSSM fit ($\tan\beta \gg 1$)

Pseudo-scalar Higgs mass m_A in GeV

90,99% CL

Stop correction to the htt coupling

68%CL
95%CL
99%CL

$\tan\beta$

Fit of μ_{ZZ}

M_A [GeV]

[DJOUADI & QUEVILLON, 1304.1787]

MORE HIGGSES?

[DJOUADI & QUEVILLON, 1304.1787]

LHC sensitivity
$7 + 8$ TeV/ 25 fb^{-1}

$H/A \to \tau\tau$
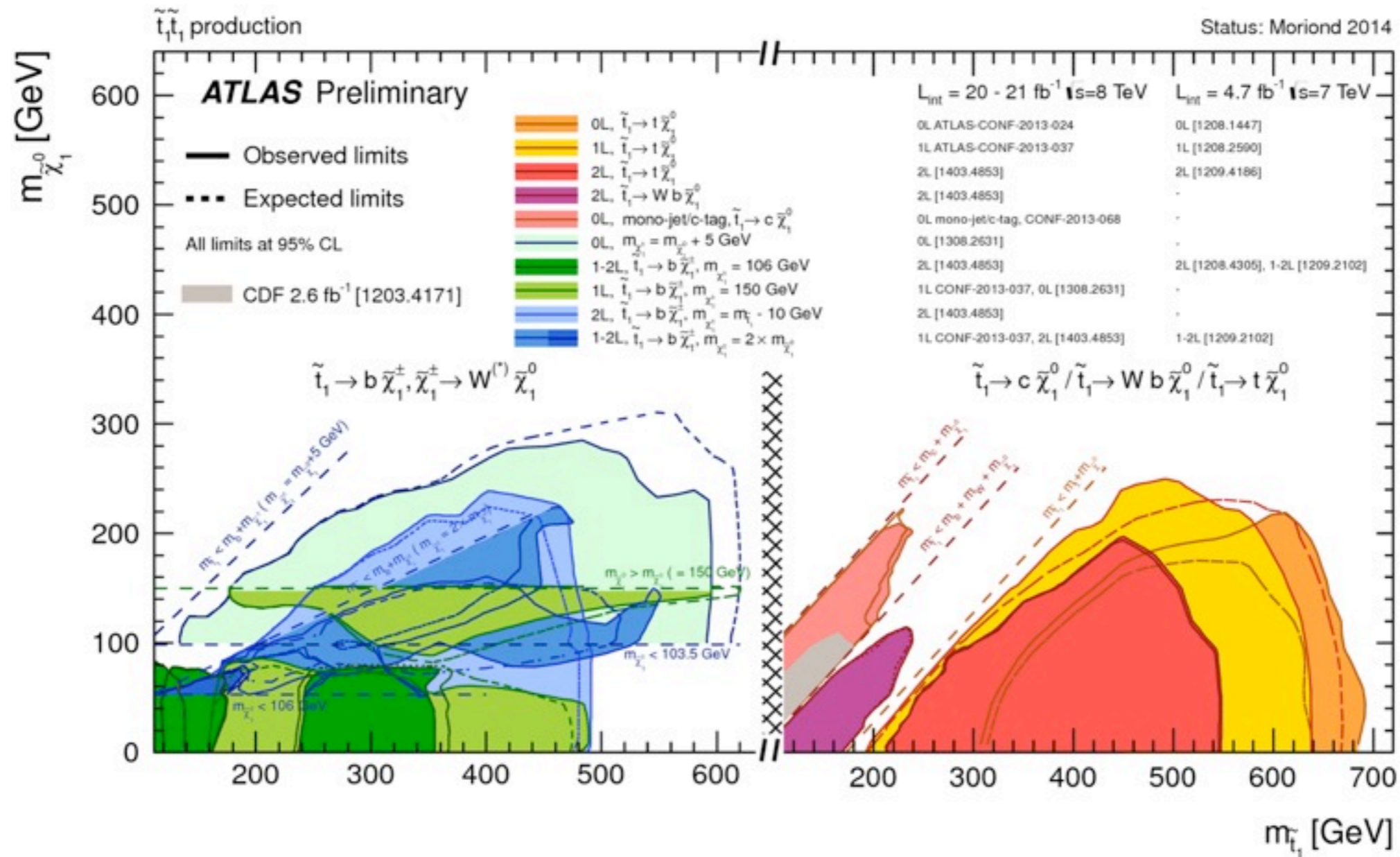$H \to VV$
$A \to hZ$
$H \to hh$
$H/A \to t\bar{t}$

INDIRECT LIMIT ONLY @ 200-300 GEV; COULD HAVE BSM HIGGS STATES RIGHT ABOVE US.
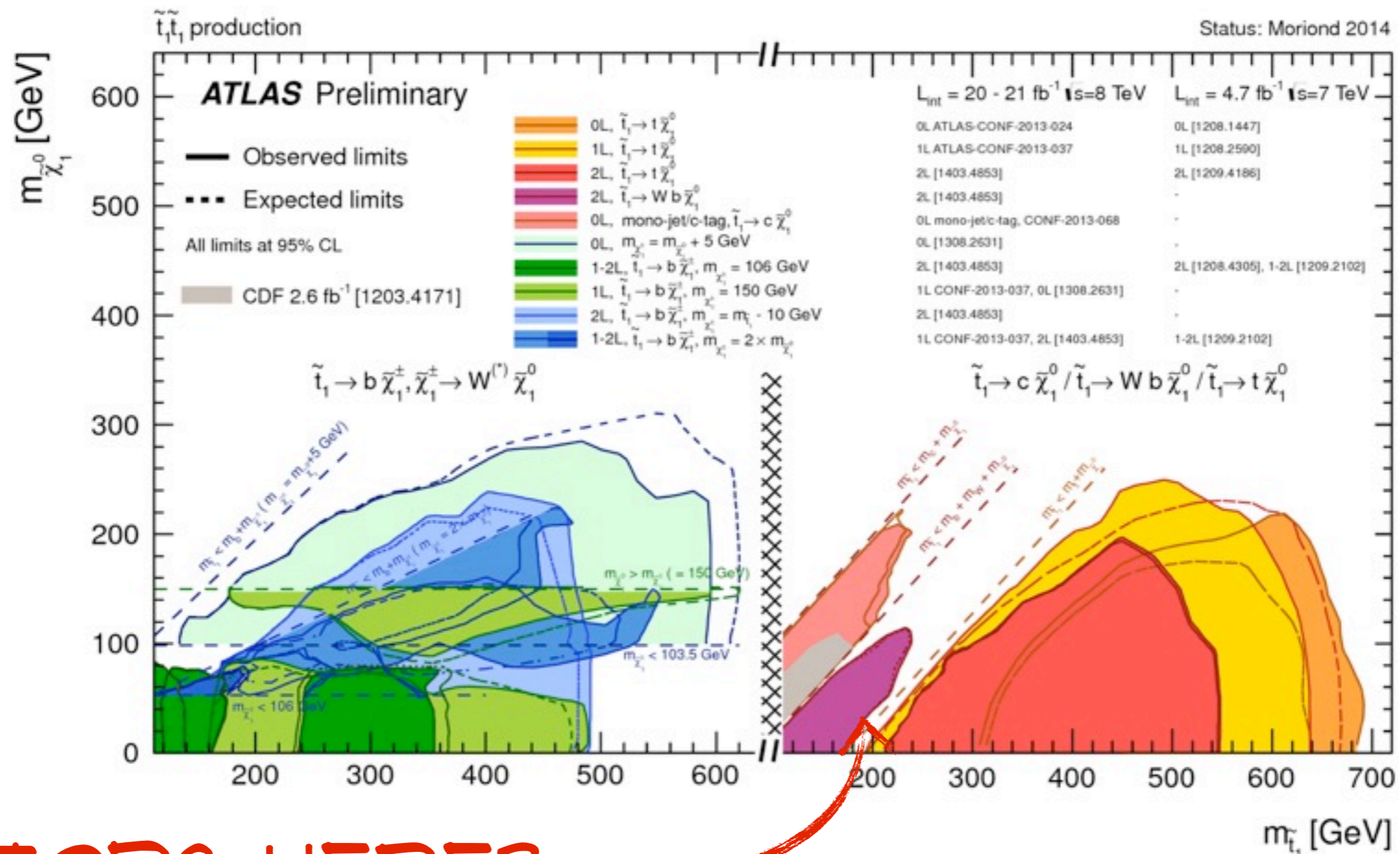
IF WE HAVE NEW QUARTIC, VIABLE @ SMALL TANβ

NON-CANONICAL SUSY HIGGS SIGNS: A→Zh, H→hh
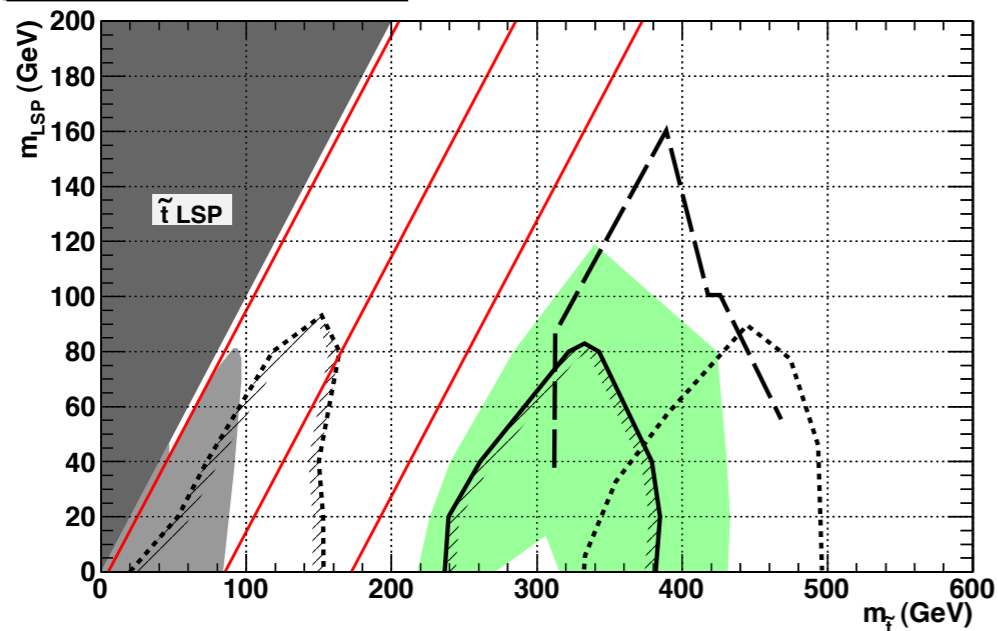
EVEN RICHER IN NMSSM, ETC.

STOP SEARCHES

STOP SEARCHES

22

STOP SEARCHES

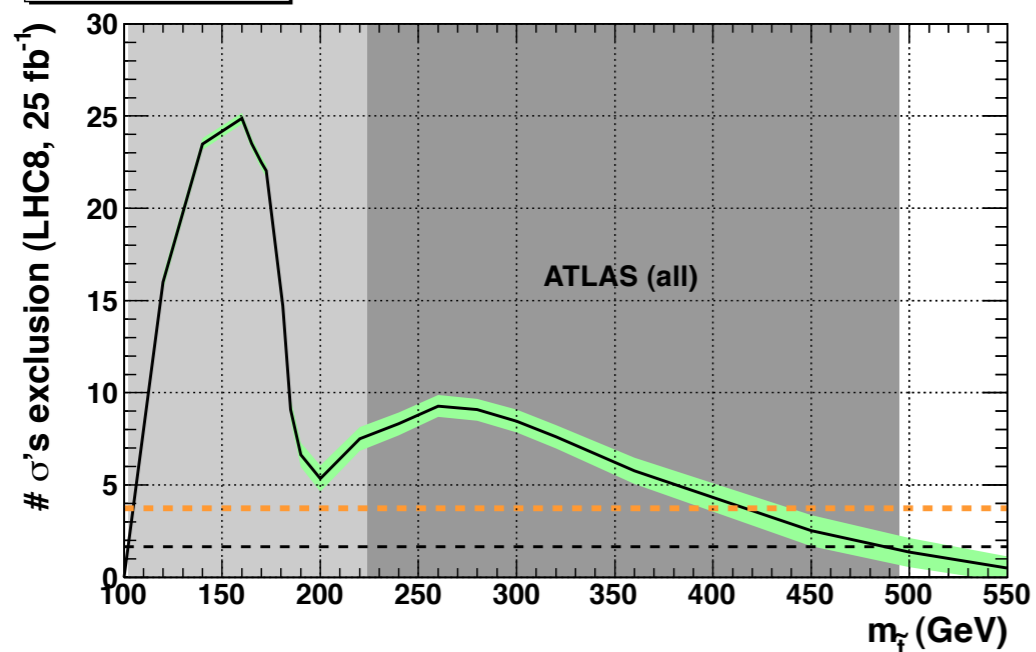$\tilde{t}_R \to t\tilde{h}^0 / \tilde{t}_L \to t\tilde{B}$ (2012)

EXISTENCE OF HOLE DEPENDS ON LSP.

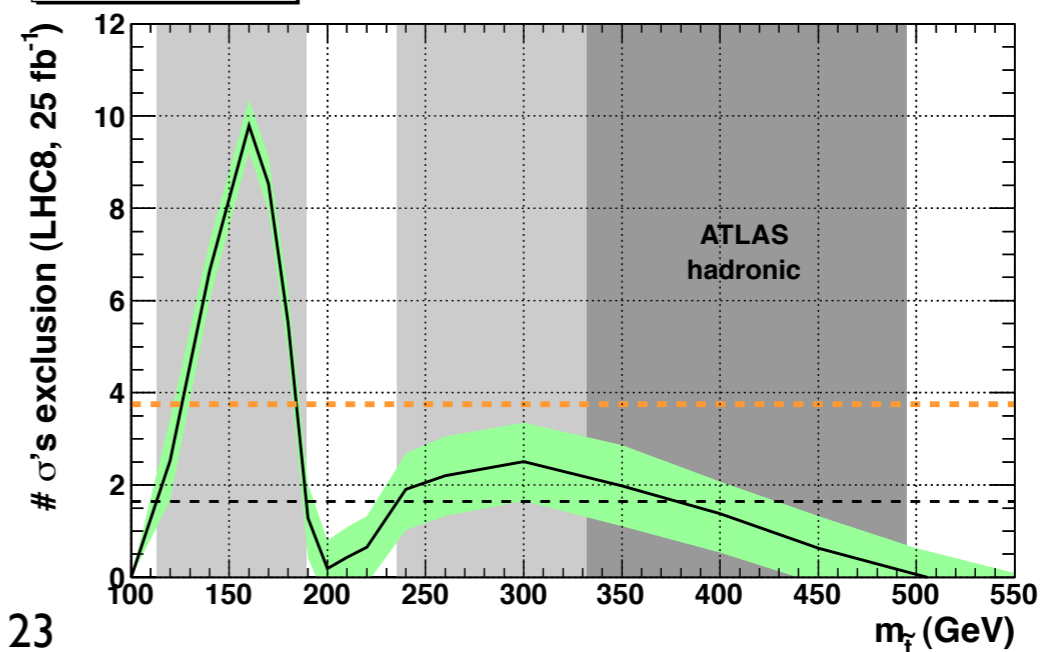### DILEPTONIC M_{T2} PROPOSAL

[KILIC & TWEEDIE, 1211.6106]

$\tilde{t}_R \to t\tilde{G}$ (2012)

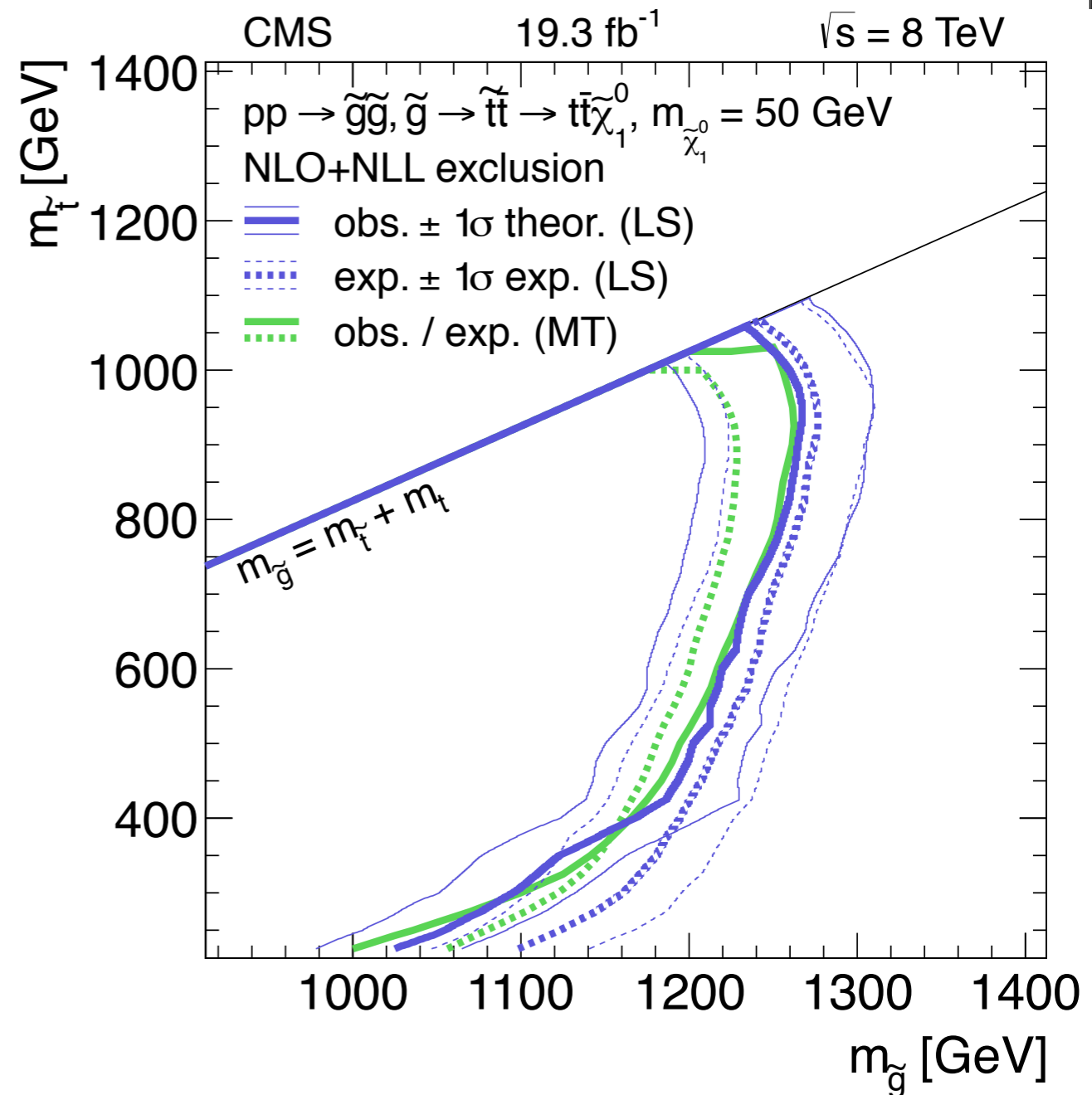

$\tilde{t}_L \to t\tilde{G}$ (2012)

STOP SEARCHES ⟩

GLUINOS MATTER.

LOOPS PULL STOPS
WITHIN FACTOR OF ~2 (5)
OF MAJORANA (DIRAC)
GLUINOS.

VERY LIGHT STOPS
SUGGEST EXTENDED
GAUGINO SECTOR.

CMS   19.3 fb^{-1} $\sqrt{s}$ = 8 TeV

$pp \rightarrow \tilde{g}\tilde{g}, \tilde{g} \rightarrow \tilde{t}\bar{t} \rightarrow t\bar{t}\tilde{\chi}_1^0$, $m_{\tilde{\chi}_1^0}$ = 50 GeV

NLO+NLL exclusion

— obs. ± 1σ theor. (LS)

···· exp. ± 1σ exp. (LS)

— obs. / exp. (MT)

$m_{\tilde{g}} = m_{\tilde{t}} + m_t$

$m_{\tilde{t}}$ [GeV]

$m_{\tilde{g}}$ [GeV]

STOP SEARCHES ⟩

...AND *BOTH STOPS* MATTER.

CMS Preliminary $\sqrt{s}$ = 8 TeV, $\int \mathscr{L}\,dt$ = 19.5 fb^{-1}

Observed UL,

Expected UL:

$\tilde{t}_2 \to tZ\tilde{\chi}_1^0$ =0%

$\tilde{t}_2 \to tZ\tilde{\chi}_1^0$ =50%

$\tilde{t}_2 \to tZ\tilde{\chi}_1^0$ =100%

$m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0}$ =175 GeV

$m_{\tilde{t}_2} < m_{\tilde{t}_1}$

$\tilde{t}_2 \to tH\tilde{\chi}_1^0$ not allowed

$m_{\tilde{t}_2} > m_{\tilde{t}_1} + m_H$
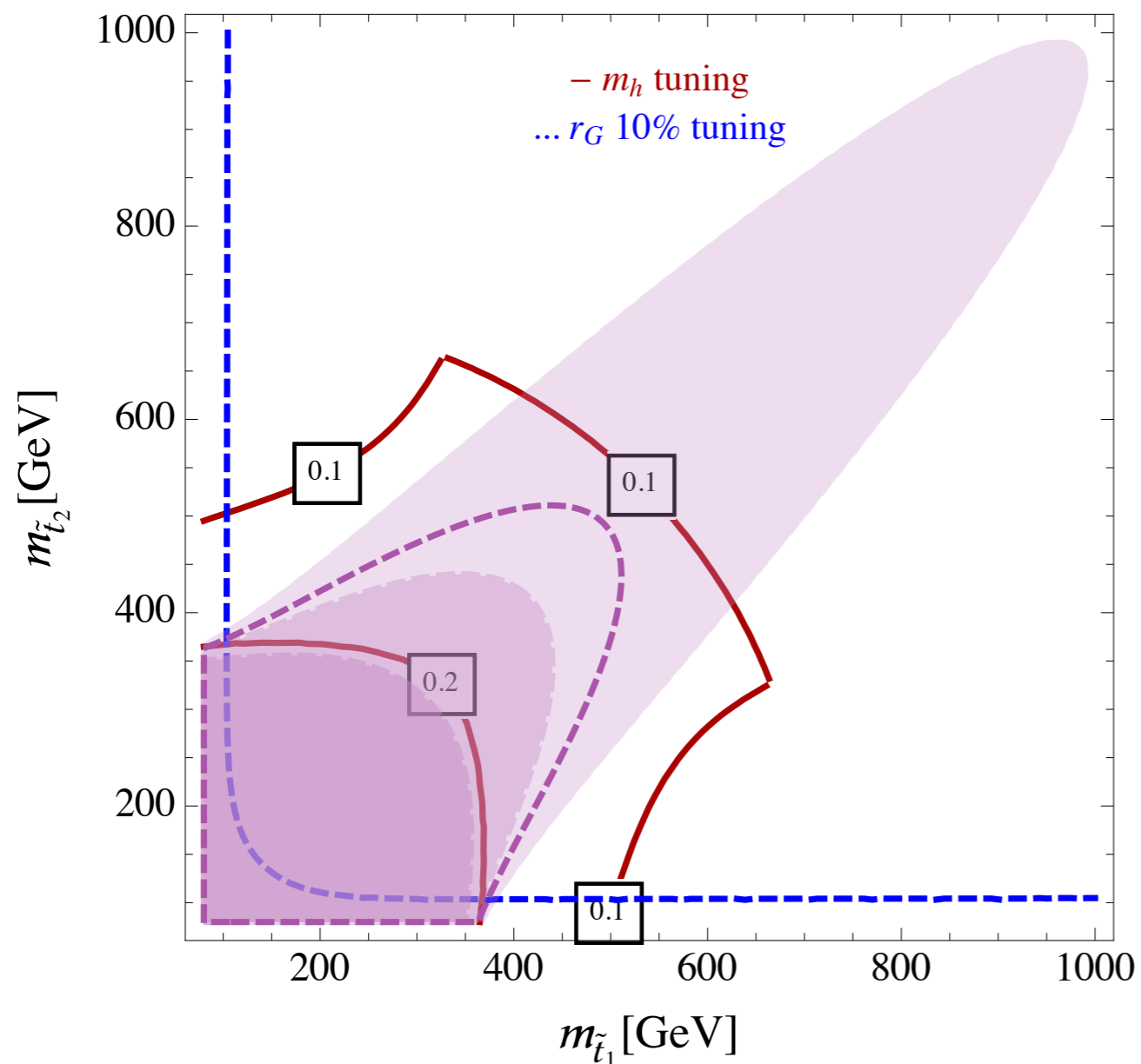
$m_{\tilde{t}_1}$ [GeV]

$m_{\tilde{t}_2}$ [GeV]
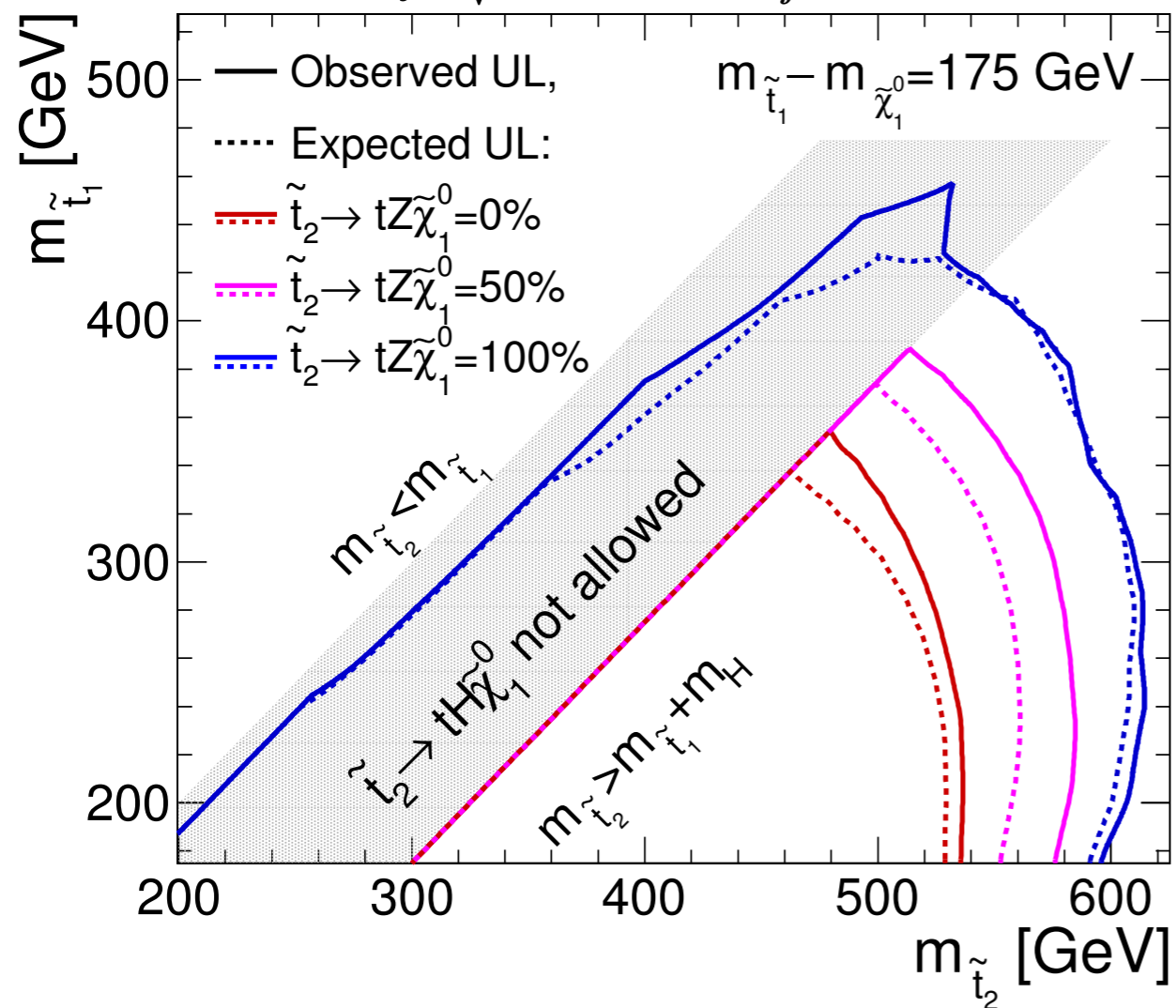
$$\Delta^{-1} \propto -\frac{3y_t^2}{8\pi^2}\left(m_{\tilde{t}_1}^2 + m_{\tilde{t}_2}^2 - 2m_t^2 + A_t^2\right)\log\left(\frac{\Lambda}{m_{\tilde{t}}}\right)$$

P_2

P_1

$\tilde{t}_2$

$\tilde{t}_1$

$\tilde{t}_2^*$

$\tilde{t}_1^*$

Z

t

$\tilde{\chi}_1^0$

$\tilde{\chi}_1^0$

$\bar{t}$

H
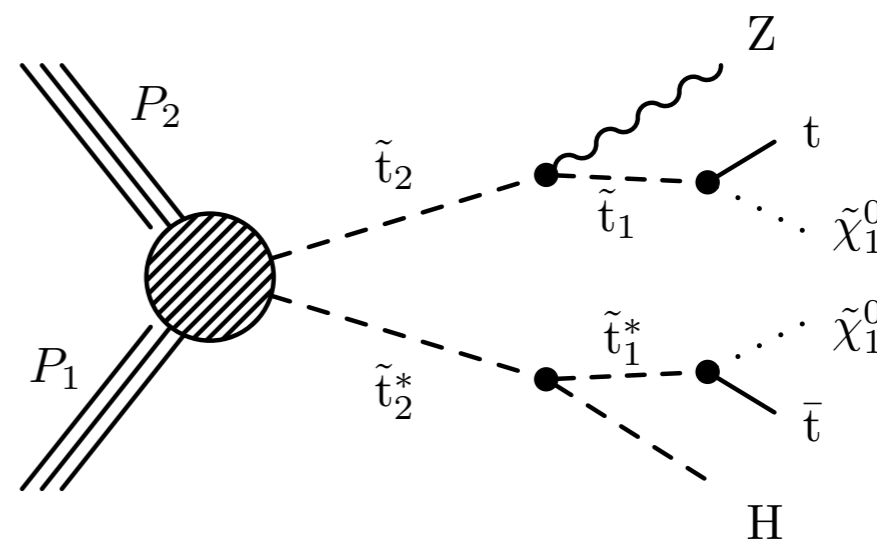
GIVEN LIGHT FIRST STOP, SECOND STOP ABOVE 500-600 GEV.

[CMS-SUS-13-024

25

STOP SEARCHES

[FAN, REECE 1401.7671]

$- m_h$ tuning

$\cdots r_G$ 10% tuning

0.1

0.1

0.2

0.1

$m_{\tilde{t}_2}$ [GeV]

$m_{\tilde{t}_1}$ [GeV]
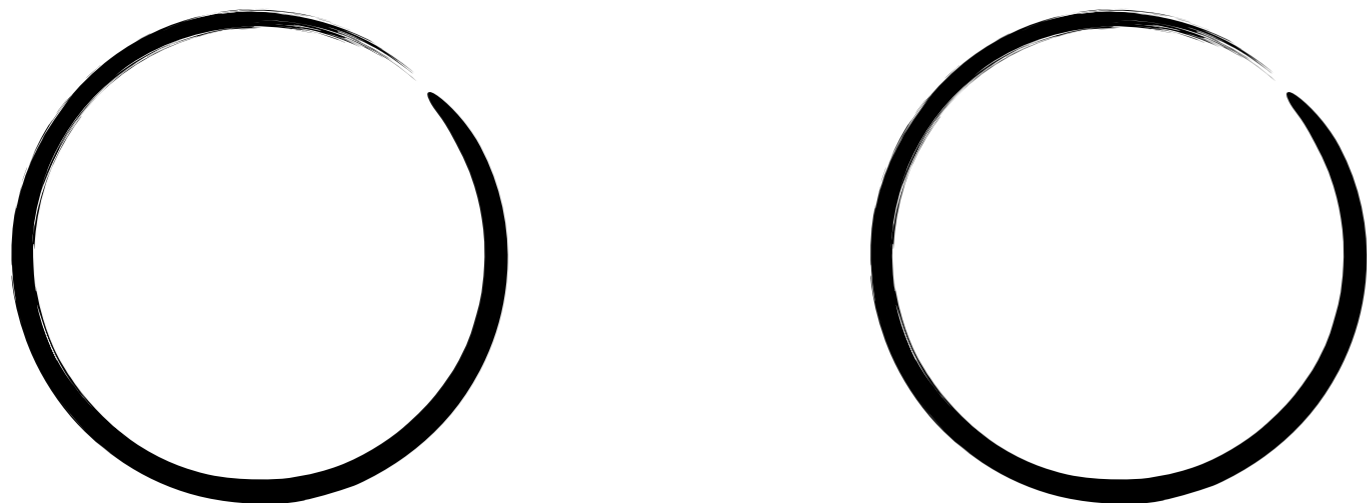
HIGGS COUPLING MEASUREMENTS.

3 PARAMS, 2 MASSES, BUT MASS SPECTRUM & MIXING MUST BE CONSISTENT.

IF STOP 1 IS ~175 GEV, STOP 2 MUST BE >400 GEV, COMPARABLE TO DIRECT LIMITS.

CAN WE BELIEVE IN NATURAL LIGHT STOPS?

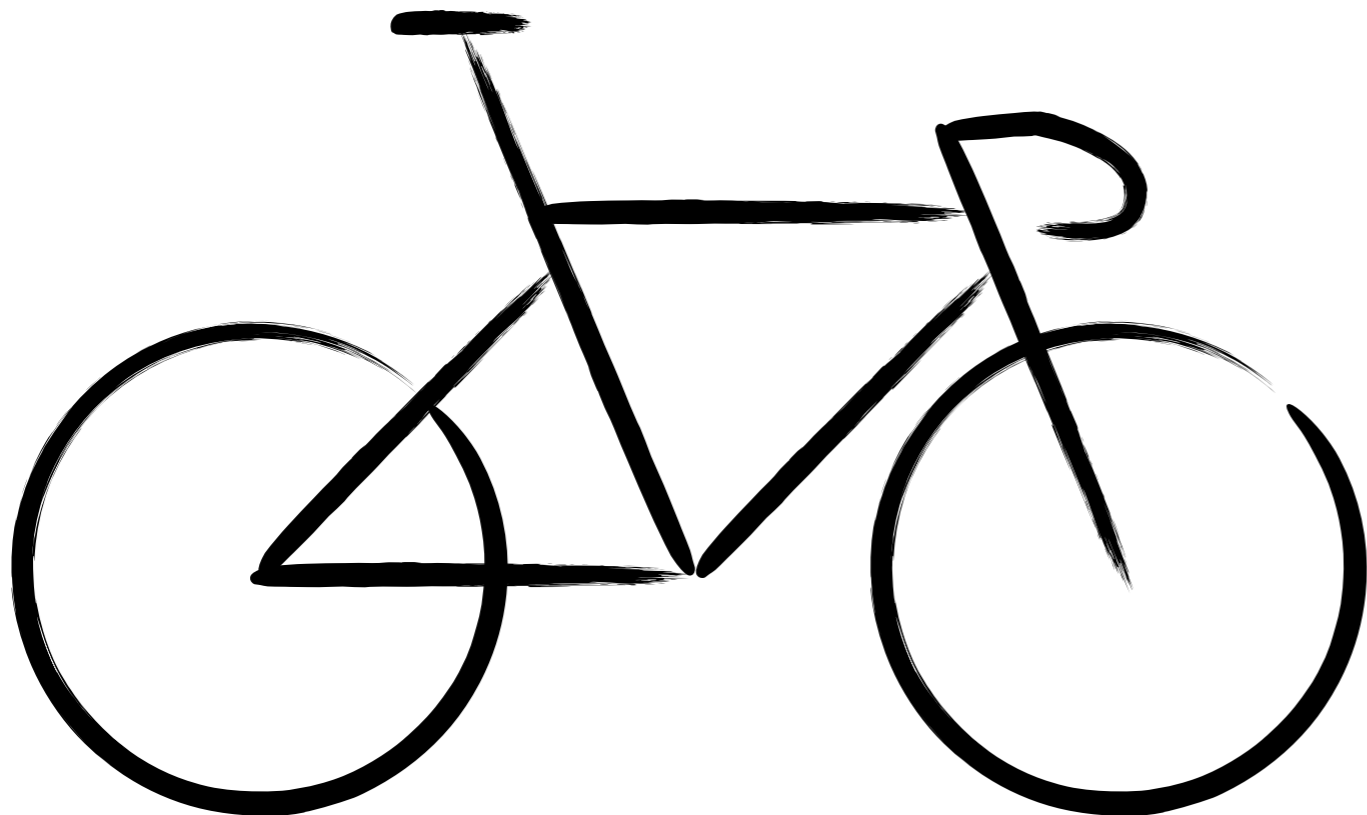- DIRAC GLUINO
- SPLIT SOFT TERMS
- HIGGSINO LSP?

SEVERAL EPICYCLES?

CAN WE BELIEVE IN NATURAL LIGHT STOPS?

- DIRAC GLUINO
- SPLIT SOFT TERMS
- HIGGSINO LSP?

- SUPERSYMMETRIC EXTRA DIMENSION, SUSY BROKEN AT BOUNDARIES.

SEVERAL EPICYCLES?

OR JUST A BICYCLE?

GENERAL LESSONS

- HIGGS MASS IMPLIES MULTI-TEV SCALARS OR DEPARTURE FROM MSSM HIGGS SECTOR.

- HIGGS COUPLINGS STILL ALLOW EXTENDED HIGGS SECTOR JUST ABOVE WEAK SCALE.

- NATURALNESS OKAY; LOOKS BEST IF STOPS ARE LIGHT BUT GLUINOS CAN BE DECOUPLED.

LOOK FOR CLASSES OF MODELS WHERE FEATURES ARE GENERIC.

EACH PROVIDES OPPORTUNITIES FOR NEW/REFINED SEARCHES.

SUSY FROM THE 5TH DIMENSION

- REDUCE SUSY WITH B.C.'S IN 5TH DIM.

- NO LARGE LOGS.

- (OFTEN) DIRAC GAUGINOS.
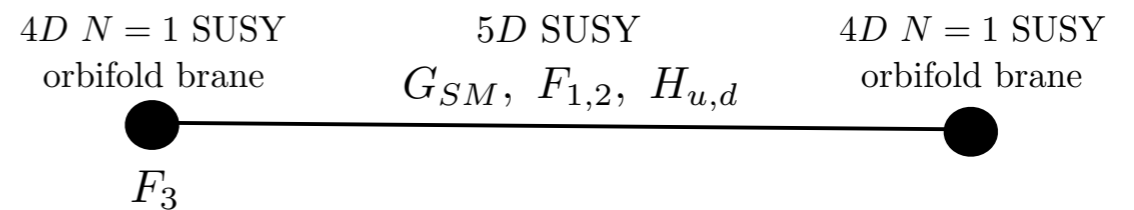
- ZERO MODES NOT SUPERSYMMETRIC.

$4D$ $N = 1$ SUSY orbifold brane $\quad$ $5D$ SUSY $\quad$ $4D$ $N = 1$ SUSY orbifold brane

G_{SM}, $F_{1,2}$, $H_{u,d}$

F_3

Fig. 1a

Higher dimensional gravitational bulk

$G_{SM} \times U(1)'$, $F_{1,2}$, $H_{u,d}$, $\Phi_{1,2}$

F_3, X

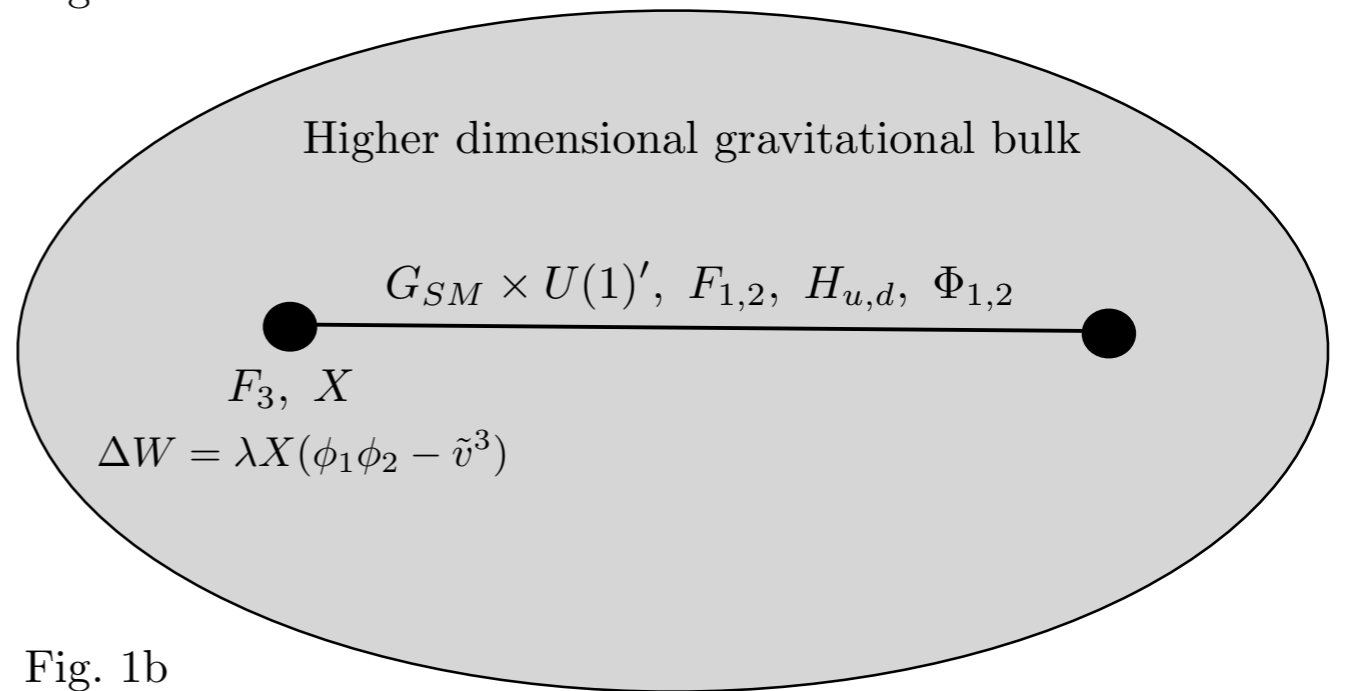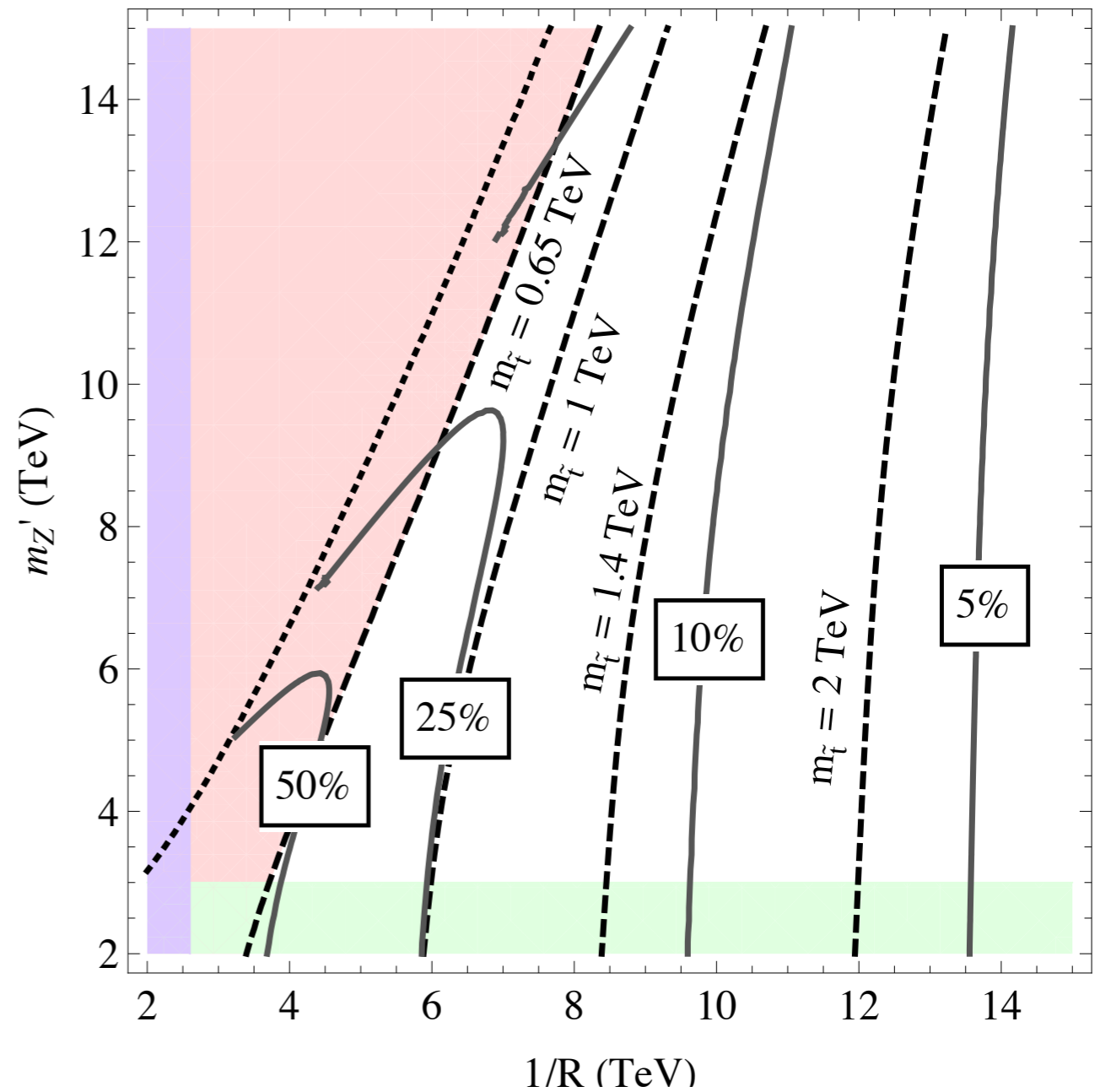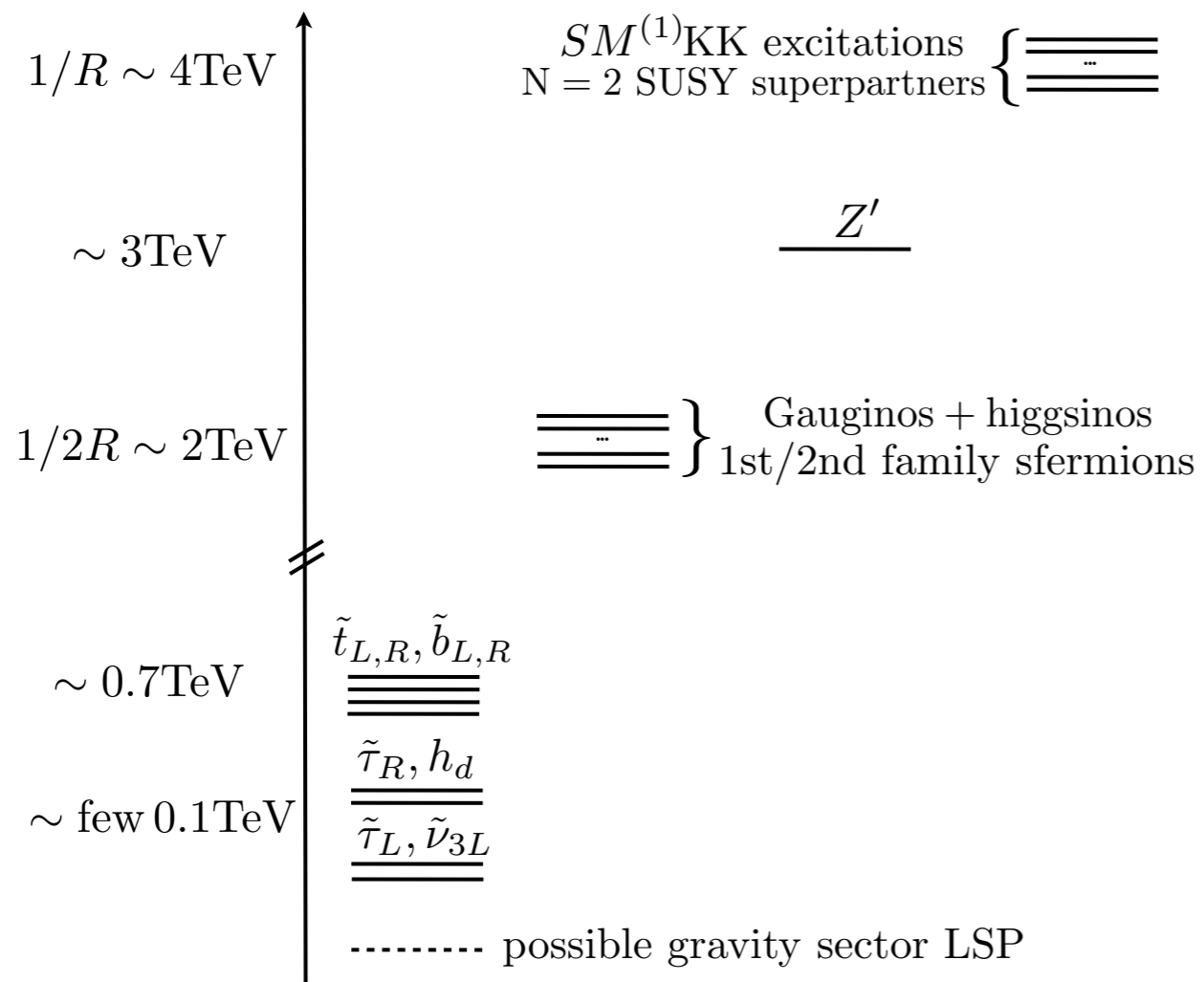$\Delta W = \lambda X (\phi_1 \phi_2 - \tilde{v}^3)$

Fig. 1b

[QUIROS, POMAROL '98 AND MANY OTHERS]

[DIMOPOULOS, HOWE, MARCH-RUSSELL 1404.7554]

MAXIMALLY NATURAL SUPERSYMMETRY?

$1/R \sim 4\text{TeV}$

$SM^{(1)}\text{KK excitations}$
$N = 2$ SUSY superpartners

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$SM^{(1)}\text{KK excitations}$
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$\sim 3\text{TeV}$

Z'

$1/2R \sim 2\text{TeV}$

Gauginos + higgsinos
1st/2nd family sfermions

$\sim 0.7\text{TeV}$ $\tilde{t}_{L,R}, \tilde{b}_{L,R}$

$\sim$ few 0.1TeV $\tilde{\tau}_R, h_d$
$\tilde{\tau}_L, \tilde{\nu}_{3L}$

- - - - - possible gravity sector LSP

[DIMOPOULOS, HOWE, MARCH-RUSSELL 1404.7554]

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COLORLESS SUSY?

$$Z_2^{AB} \times SU(3)_A \times SU(3)_B \times SU(2)_L \times U(1)_Y$$
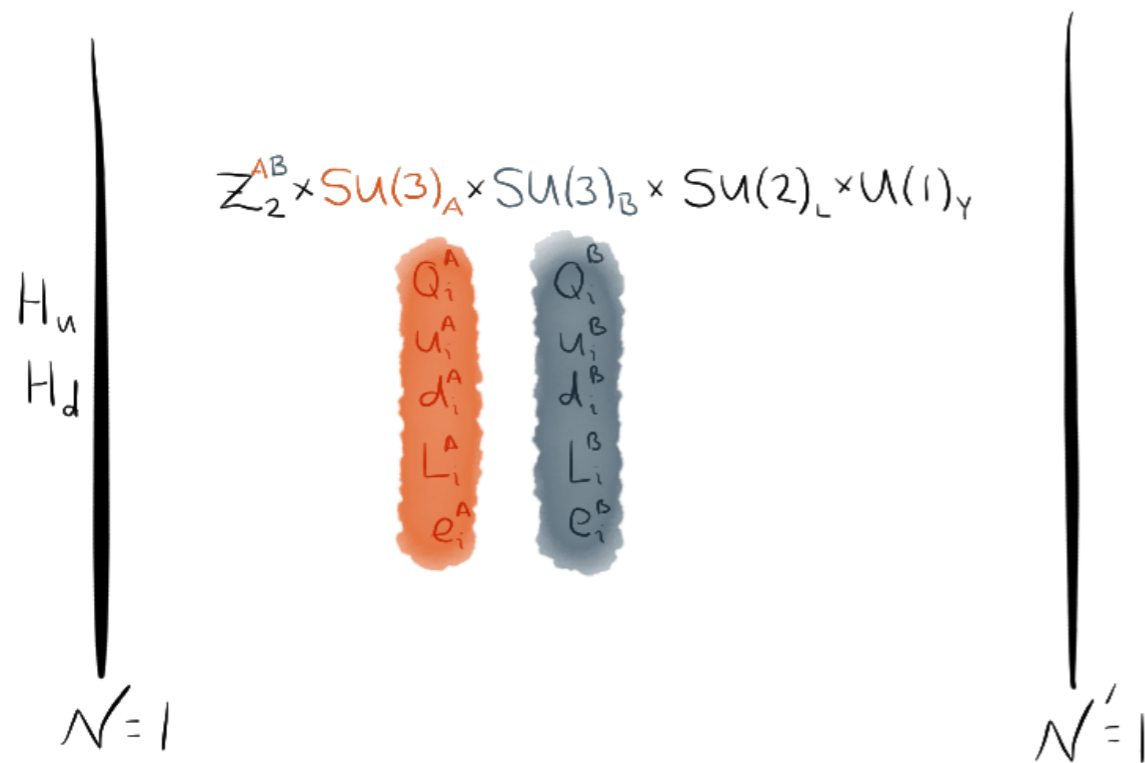
USE BOUNDARY CONDITIONS IN AN EXTRA DIMENSION TO REDUCE BOTH SUPERSYMMETRY AND GAUGE/GLOBAL SYMMETRIES.

CAN LEAD TO LIGHT SUPERPARTNERS WITH DIFFERENT GAUGE QUANTUM NUMBERS FROM SM COUNTERPARTS
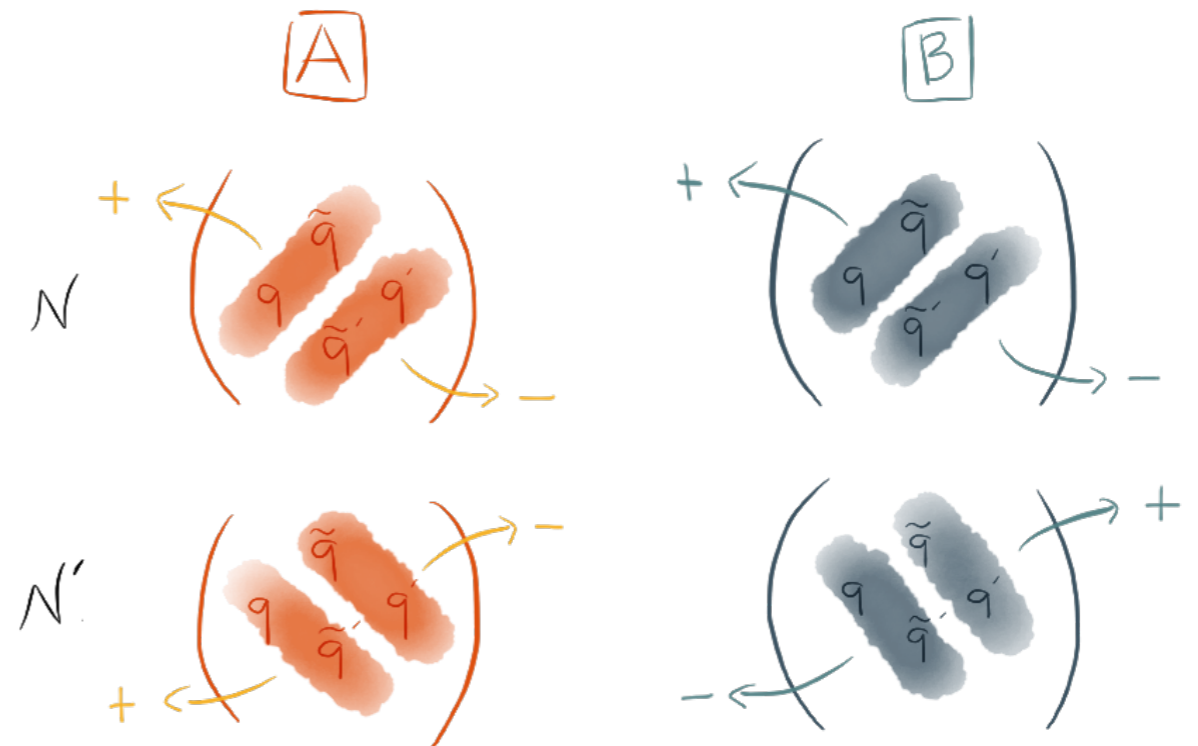
[BURDMAN, CHACKO, GOH, HARNIK HEP-PH/0609152]

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.

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.

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SO LETS GO OUT AND FIND THEM!