Naturalness Primer

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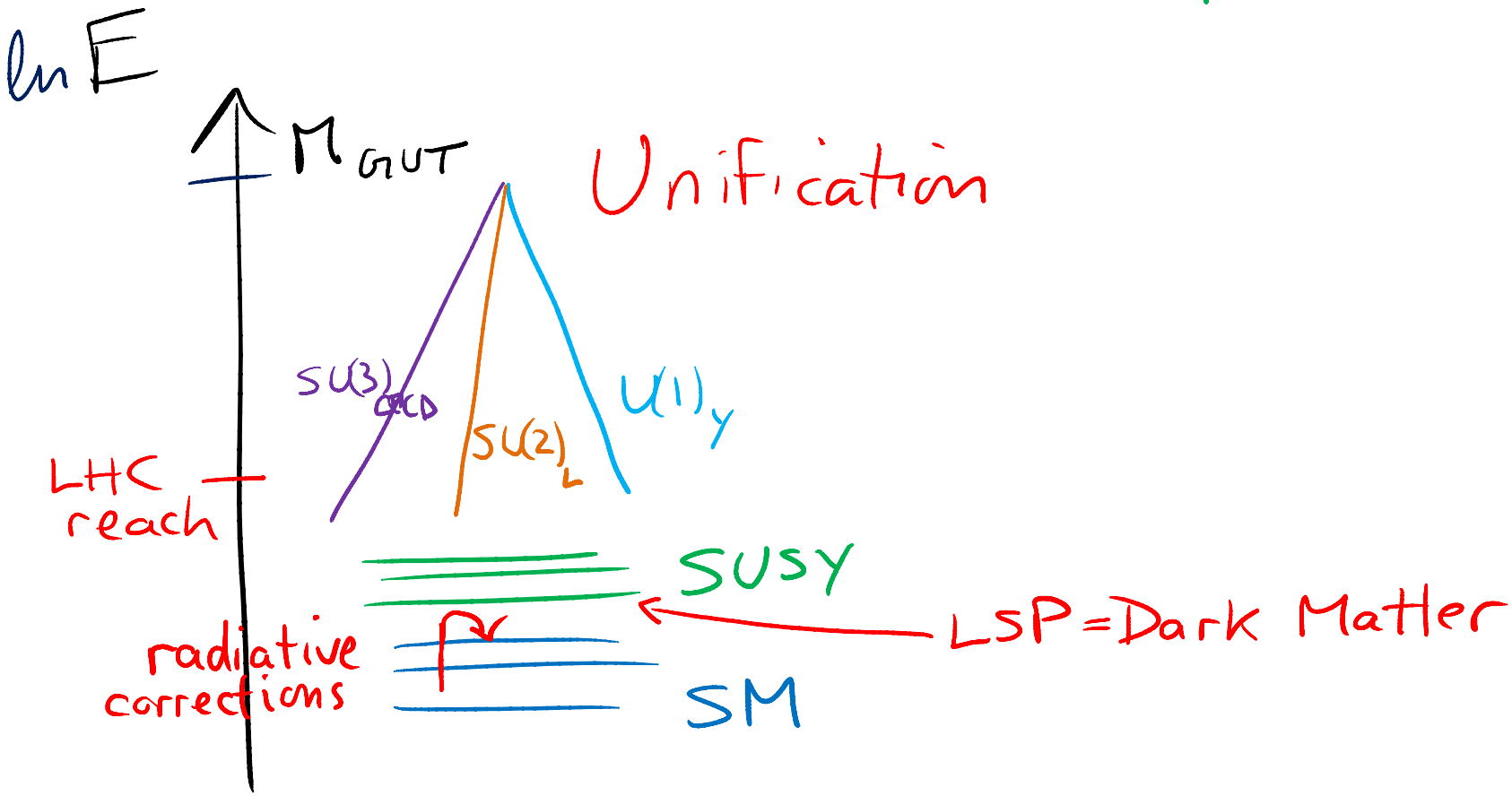
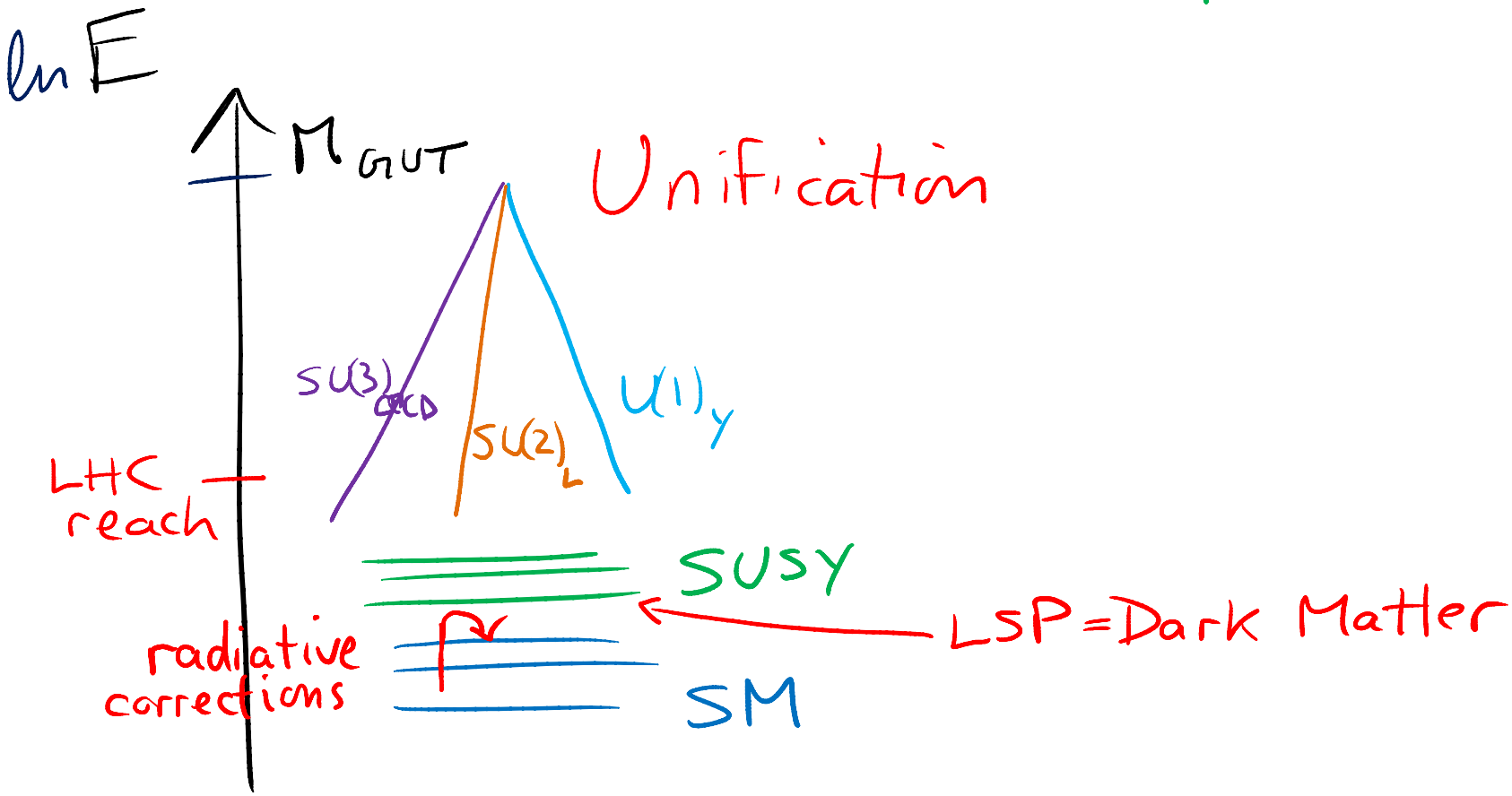
The Way it was supposed to be



$\not{E}$, jets, ℓ ...

The Way it was supposed to be



$\not{E}$, jets, ℓ ... unseen

$m_h = 125$ GeV seen, but hard to accomodate

Eg. MSSM ⇒ multi-TeV squarks

Non-SUSY Option

Strong Dynamics $\xrightarrow{\text{tough to compute}}$ (Technicolor or) Composite Higgs, t + excitations

what you see in $\mathcal{L}$ $\neq$ what you get in lab

Non-SUSY Option

Strong Dynamics → (Technicolor or) Composite Higgs, t + excitations

what you see in $\mathcal{L}$ ≠ what you get in lab

robust possibility

Warped Extra Dimensions → Kaluza-Klein excitations

easier to compute

weak coupling

Non-SUSY Option

Strong Dynamics → (Technicolor or) Composite Higgs, t + excitations

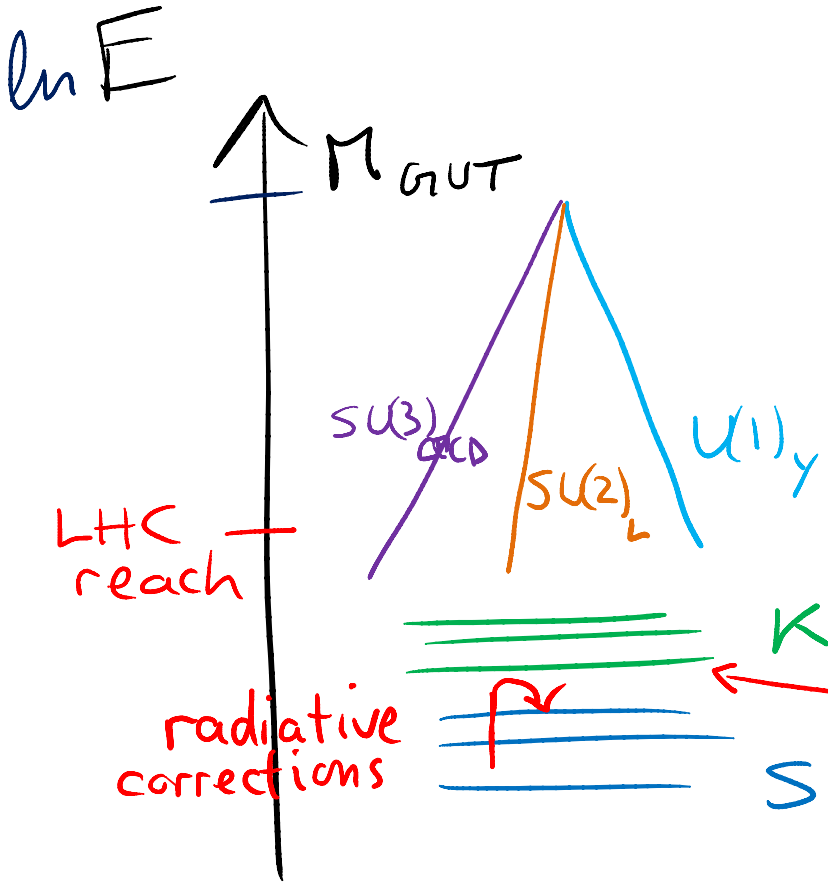
what you see in $\mathcal{L}$ ≠ what you get in lab

AdS/CFT equivalent

Warped Extra Dimensions → Kaluza-Klein excitations

weak coupling

The Way Non-SUSY was supposed to be



Precision unification via top-Higgs compositeness

Agashe, Contino, Sundrum '05

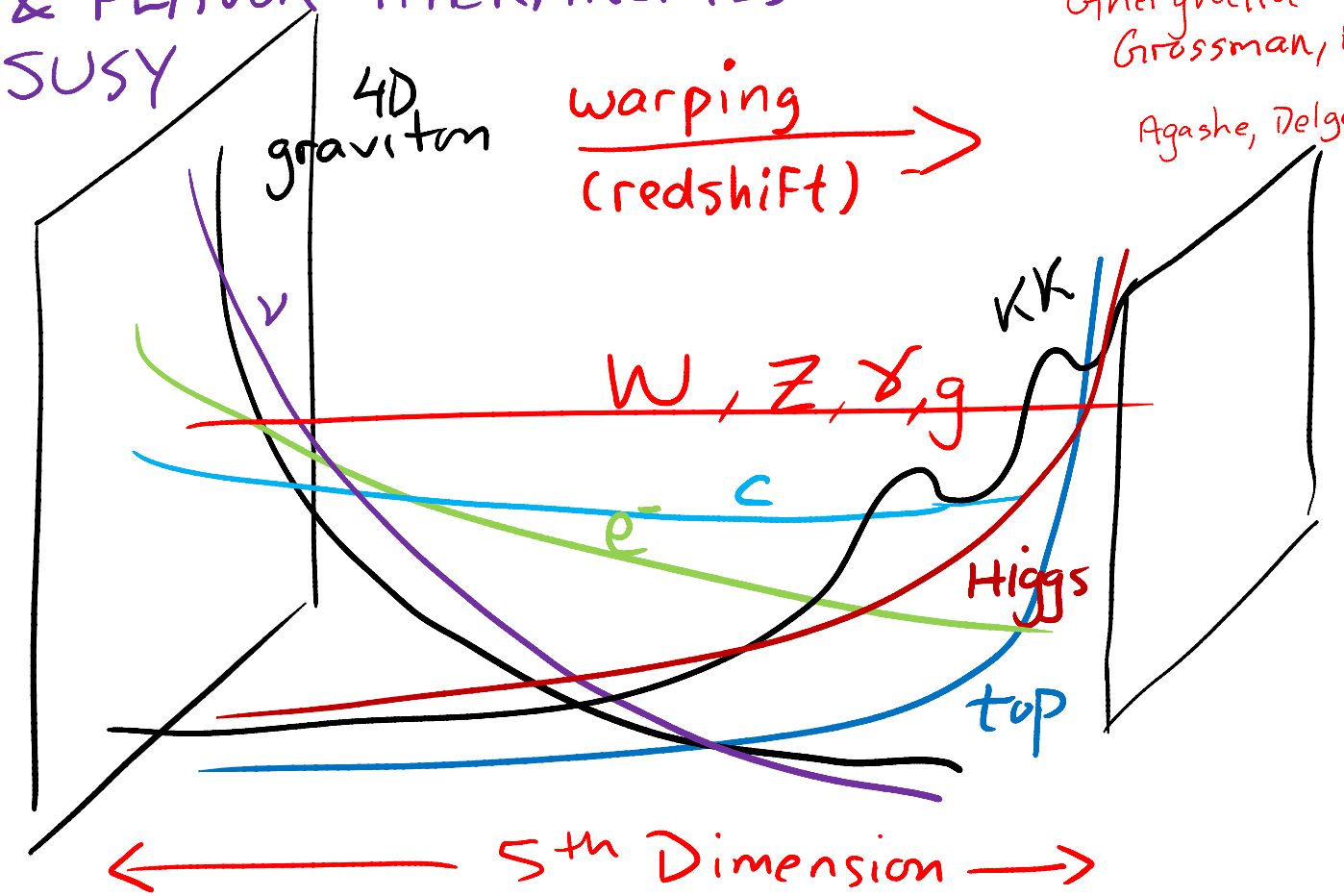
stable Dark Matter easy to implement

TeV $t\bar{t}$, EW boson, ...
resonances

4D COSMOS FROM 5D CHAOS

ELEGANT THEORY OF
EW & FLAVOR HIERARCHIES
w/o SUSY

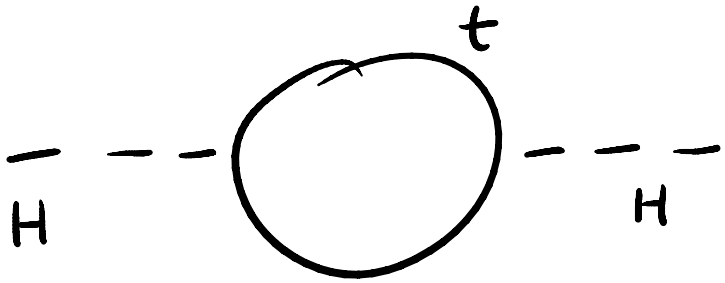
Randall, Sundrum '99
Goldberger, Wise '99
Gherghetta Pomarol '00
Grossman, Neubert '00
⋮
Agashe, Delgado, May, Sundrum '03
Contino, Nomura, Pomarol '03
Agashe, Contino, Pomarol '05
⋮



Without any "tricks"/flavor-tuning,
flavor/CP tests ⇒ $m_{KK} \sim 20$ TeV

Agashe, Perez, Soni '04 . . . .
. . . Csaki, Falkowski, Weiler '08 . . .
. . . Keren-Zur, Lodone, Nardecchia, Papadopulu, Rattazzi, Vecchi '12

More generally,



$\Rightarrow$ SM unnatural above ~ 500 GeV

Little Hierarchy Problem: No new physics seen at earlier colliders, on-shell or virtually up to ~ 10 TeV

... LEP, LEP2, Tevatron

Flavor Hierarchy Problem: No new physics seen in low-energy flavor + CP, virtually sensitive to $\sim 100{,}000$ TeV

NO ELEGANT, NATURAL MODELS ARE KNOWN

fully

GOALS

How do we gamble experimentally?

How do we gamble theoretically?

How hard should we try in any direction?

When should we give up on a scenario?

Does Particle Physics have "no-lose" program?

NEW PHYSICS CAN EASILY BE AWAITING DISCOVERY

Eg. SM Higgs boson

EW particle, diverse couplings

Yet, cut & count searches not definitive

Bump structure crucial in some channels

Theory plays central role in motivating, in understanding "safety" from flavor tests, & correlating different channels, tentative signals in separate channels looking more compelling taken together.

A POOR ANALOGY?

Solution to Hierarchy Problem requires rich new spectrum

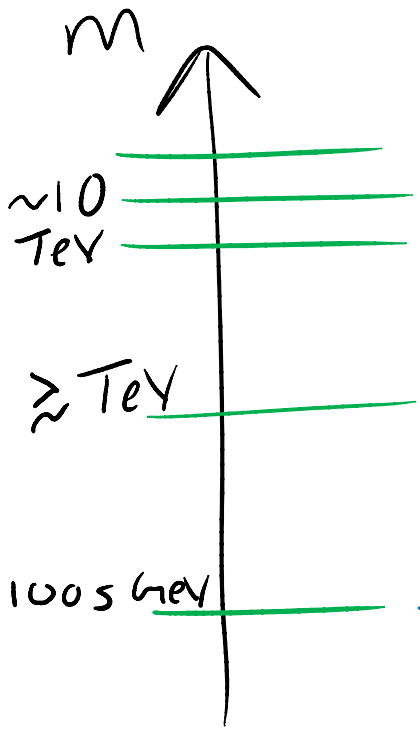
It is much harder for all this to have evaded direct searches & EW + Flavor precision tests.

CAN NATURE $\sim E_{LHC}$

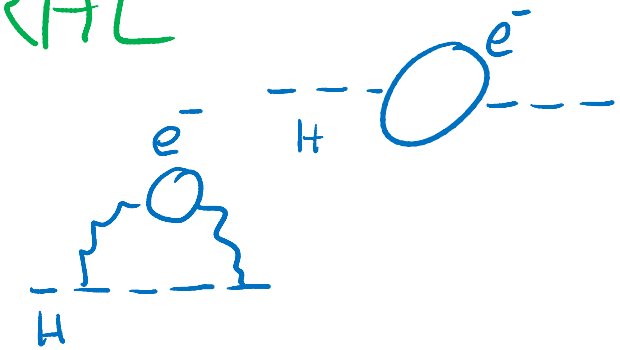
PLAUSIBLY BE

SPARSE ?

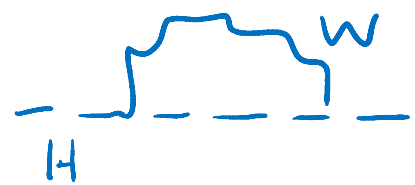
SPARSE BUT NATURAL



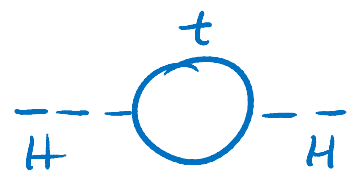
Big hierarchy problem solution cuts off



W partner symmetry cancels



top partner symmetry cancels



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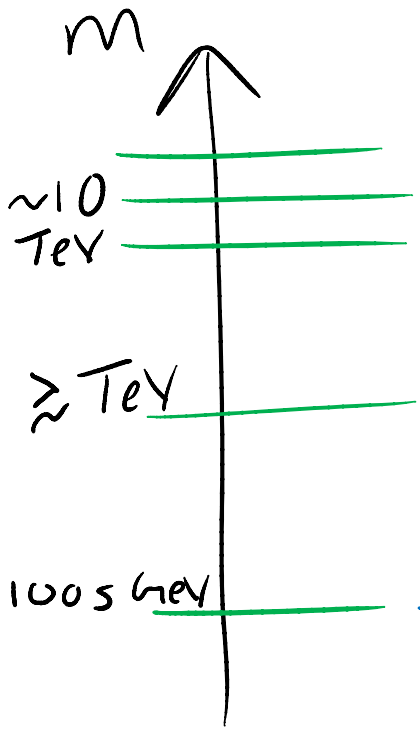

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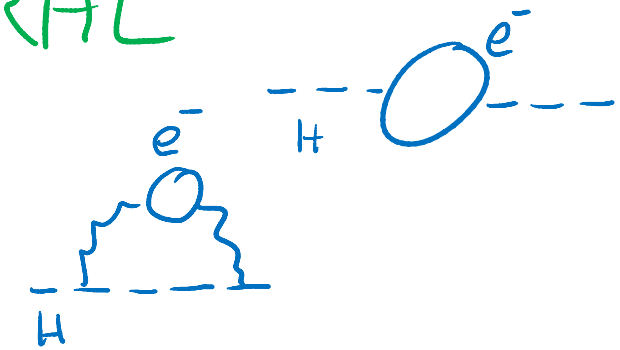
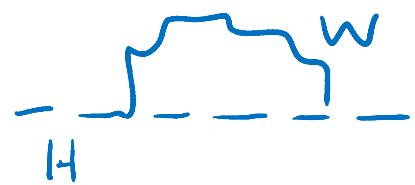
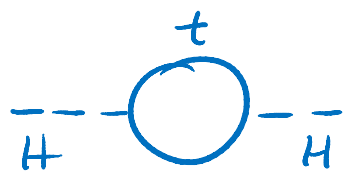


bosonic W partner symmetry cancels



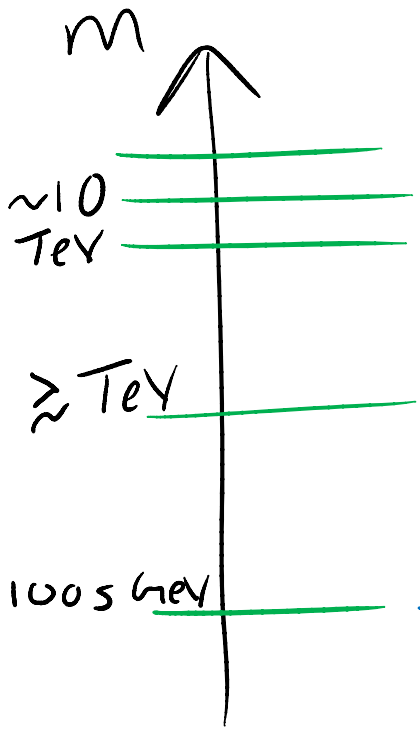
fermionic top partner symmetry cancels



Eg. Little Higgs Arkani-Hamed, Cohen, Georgi '01 . . .
LHC pheno Han, Logan, McElrath, Wang '03; Perelstein, Peskin, Pierce '04
. . . Berger, Hubicz, Perelstein '12

Twin Higgs Chacko, Goh, Harnik '05

SPARSE BUT NATURAL



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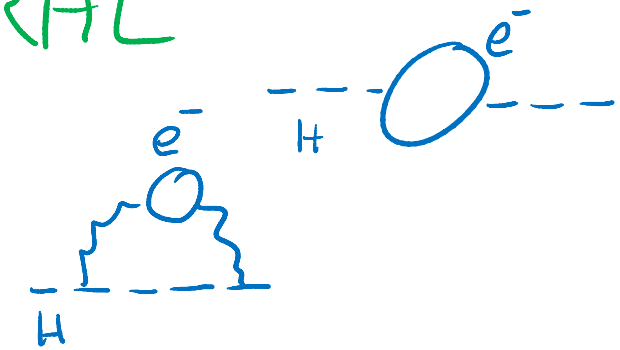

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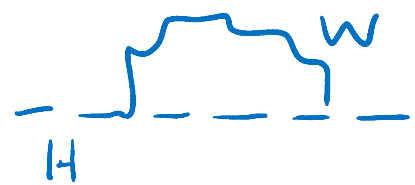

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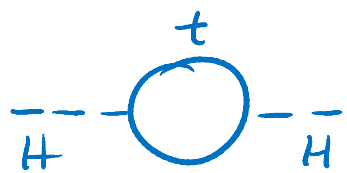
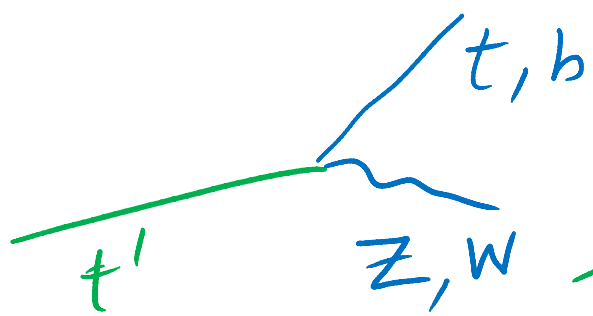
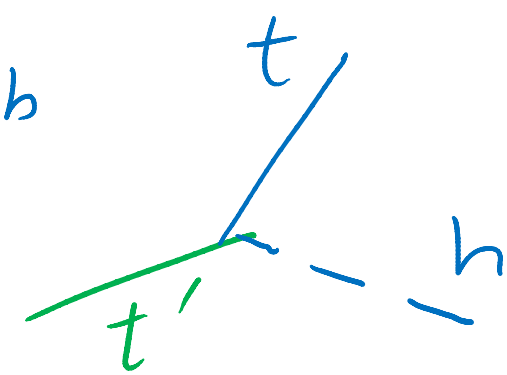
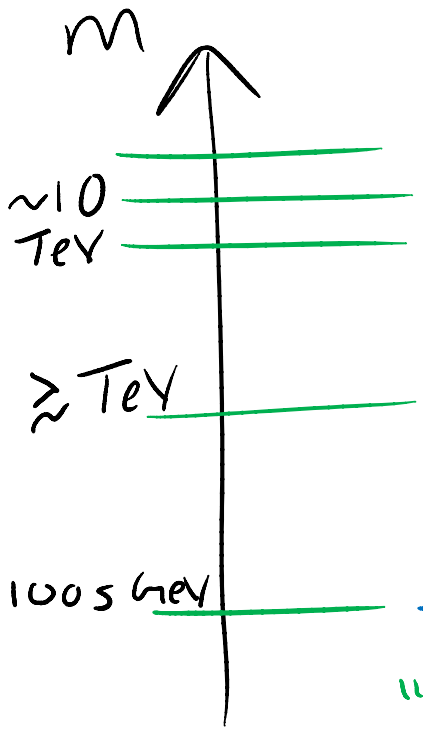


Vector-like t'



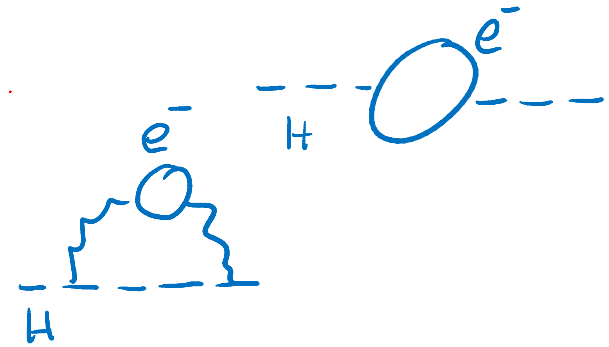


"NATURAL SUSY"



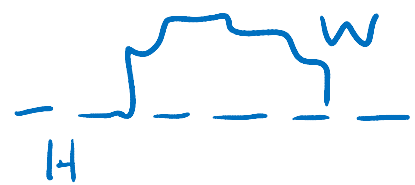
More super-partners

Cancel



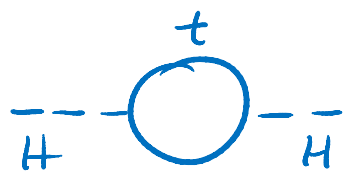
fermionic W partner "wino, higgsino"

super-symmetry cancels



bosonic top partner "stop" $\tilde{t}$

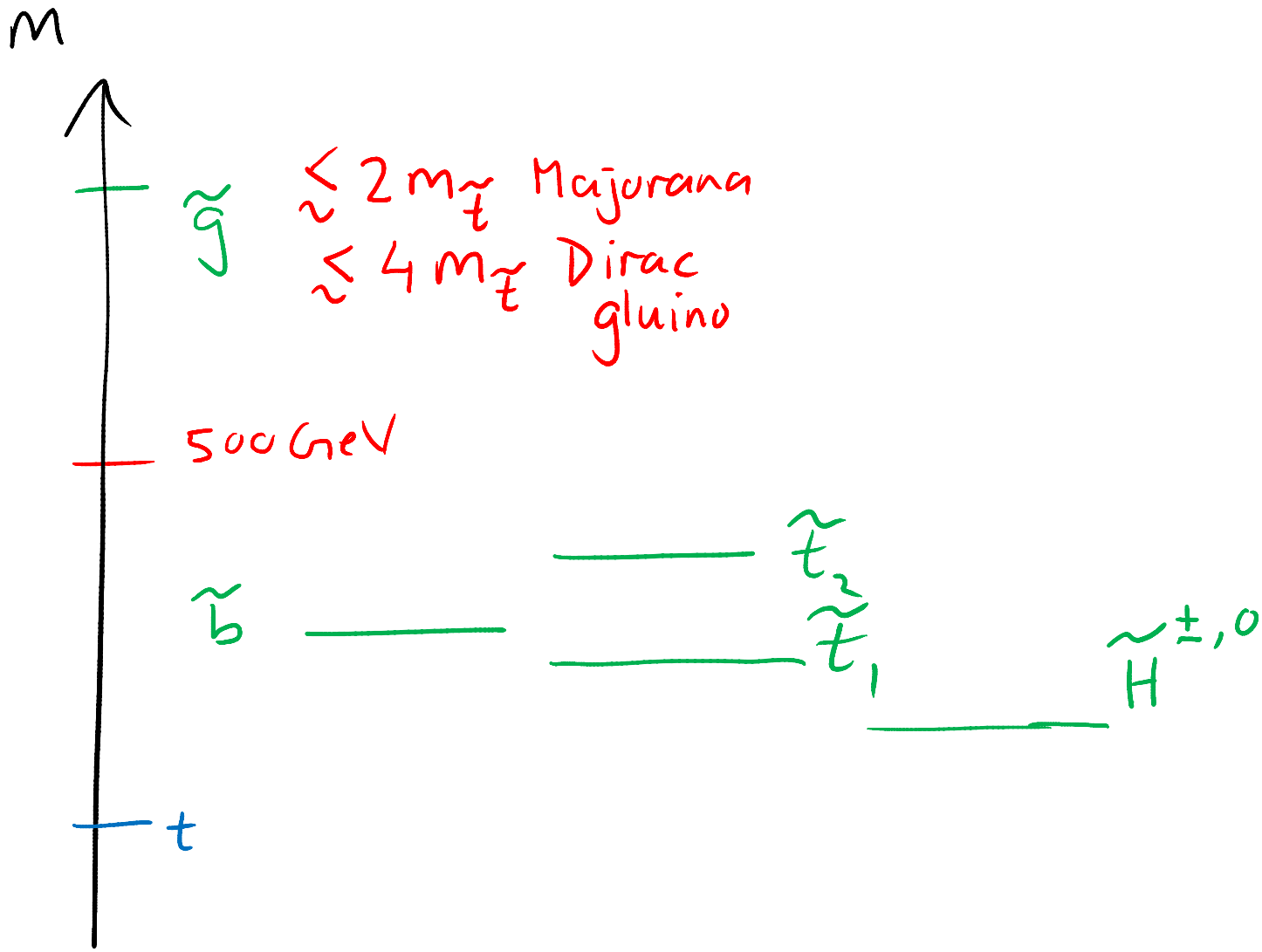
super-symmetry cancels



Dimopoulos, Giudice '95; Cohen, Kaplan, Nelson '96 ...
... Barbieri, Bertuzzo, Farina, Lodone, Pappadopulo '10 ...

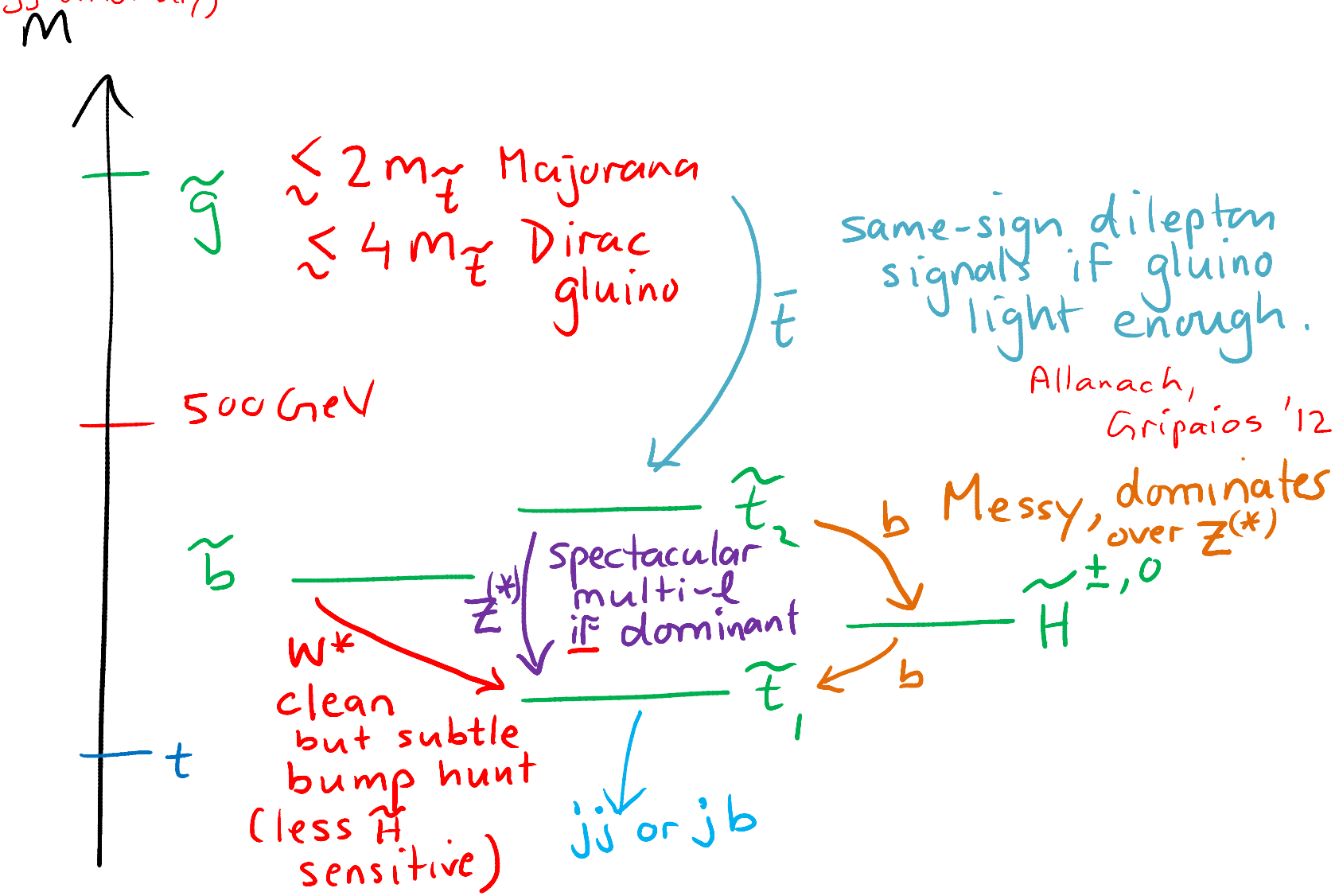
Post-LHC-start pheno: Katz, Meade, Reece '11; Papucci, Ruderman, Weiler '11;
Essig, Izaguirre, Kaplan, Wacker '11; Brust, Katz, Lawrence, Sundrum '11
.....

(Effective) NATURAL SUSY



(Effective) NATURAL SUSY & $\not{B}$ RPV

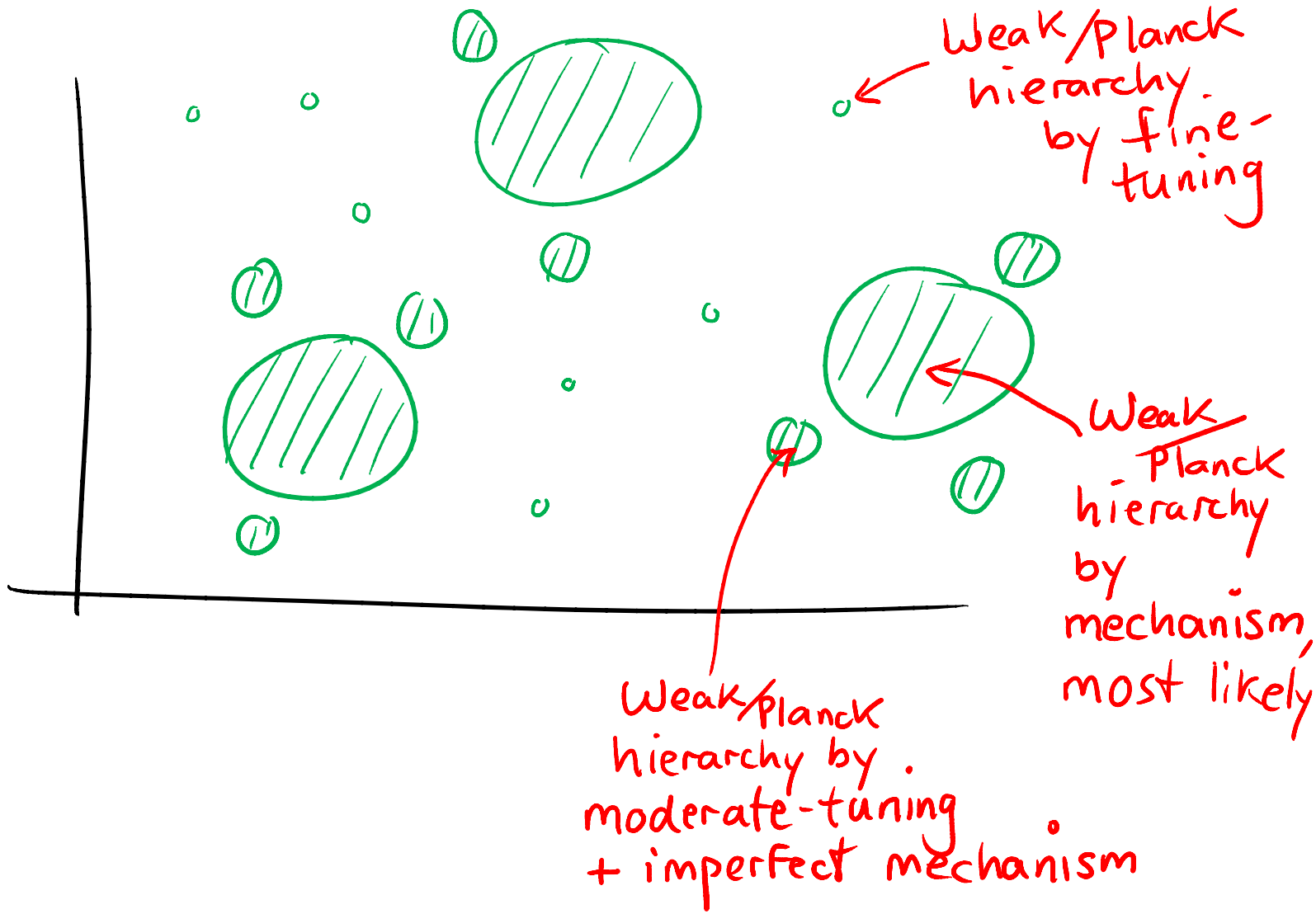
Kilic, Thomas '11 : Brust, Katz, Sundrum '12 (L-conserving)
(CDF Wjj anomaly)



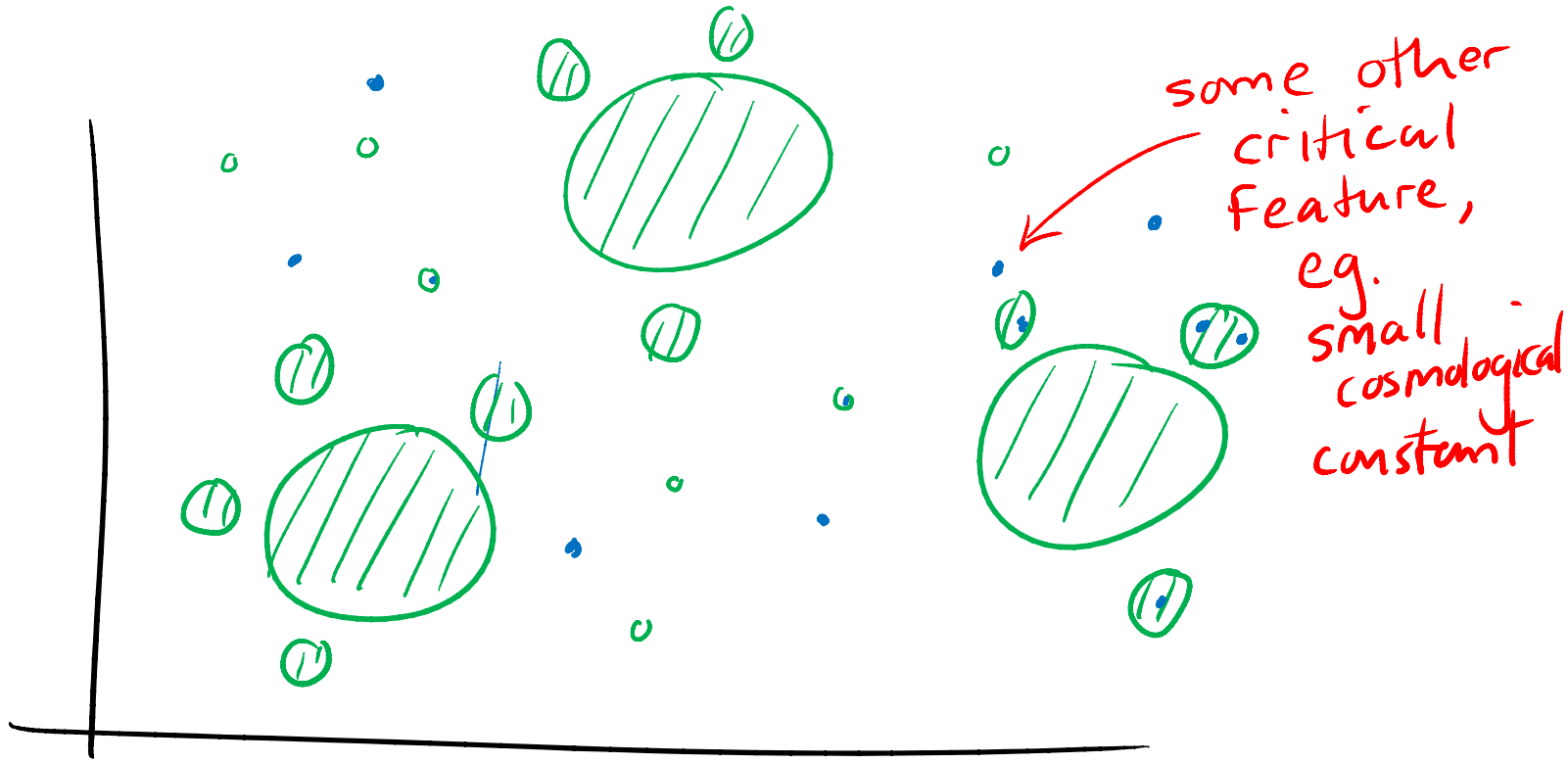
MESO-TUNING

THEORY SPACE
= MULTIVERSE

[SPACE OF CLIMATES
= MANY PLANETS]

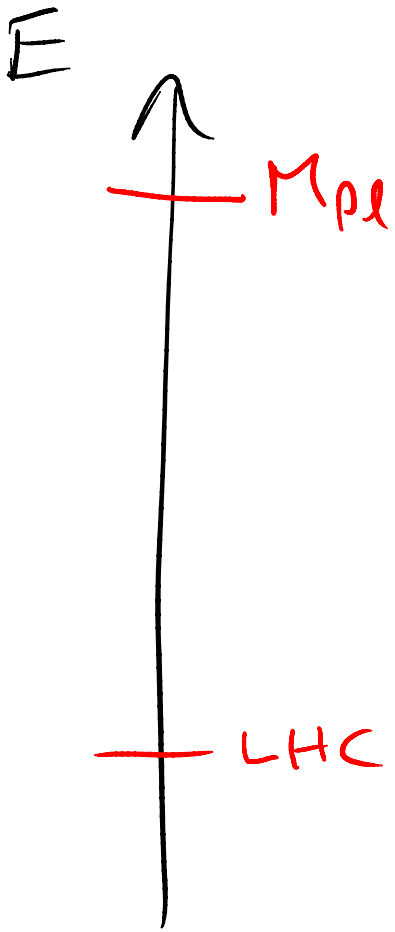


THEORY SPACE = MULTIVERSE



Meso-tuning or fine-tuning can result if some other critical feature is anti-correlated with weak/Planck hierarchy mechanism

INSIGHTFUL BUT INCONCLUSIVE, SO 3 OPTIONS...



hierarchy problem "unsolved"

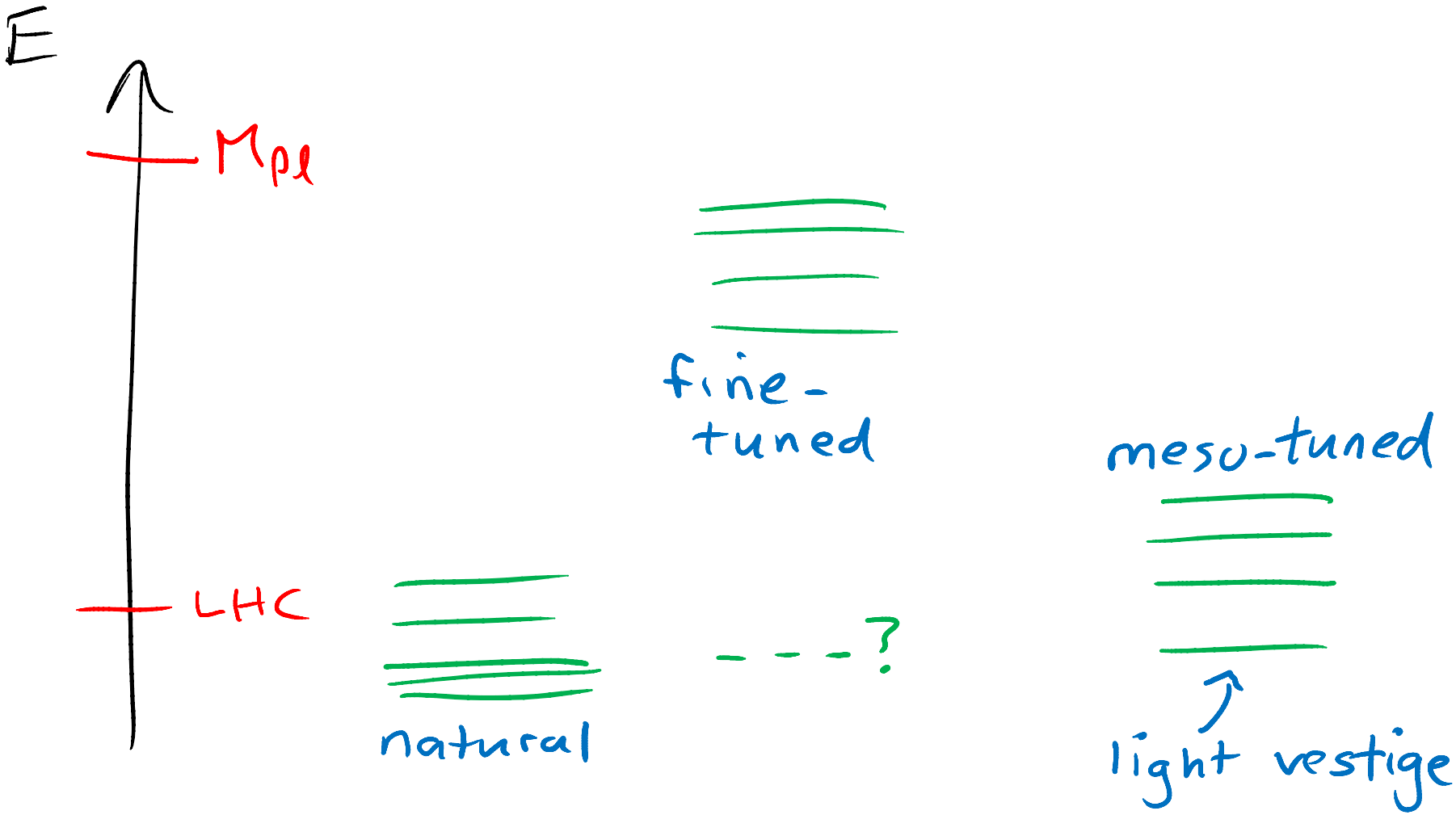
weak scale tuned "anthropically"

hierarchy problem solved

hierarchy problem "almost solved", tension between hierarchy mechanism & anthropic imperatives

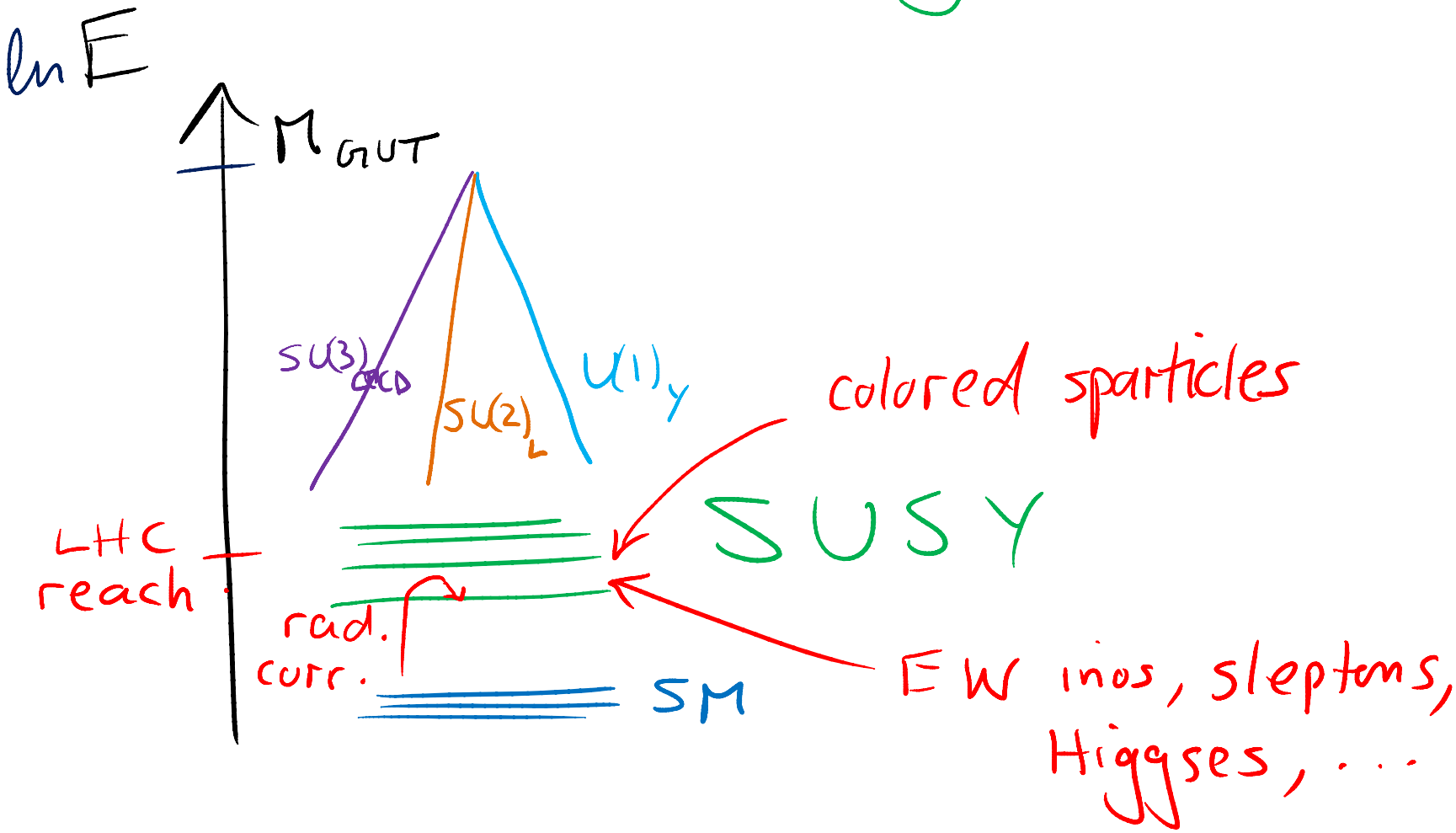
MESO-TUNING

MESO-TUNING LIES AT INTERSECTION OF PLAUSIBILITY & OPPORTUNITY

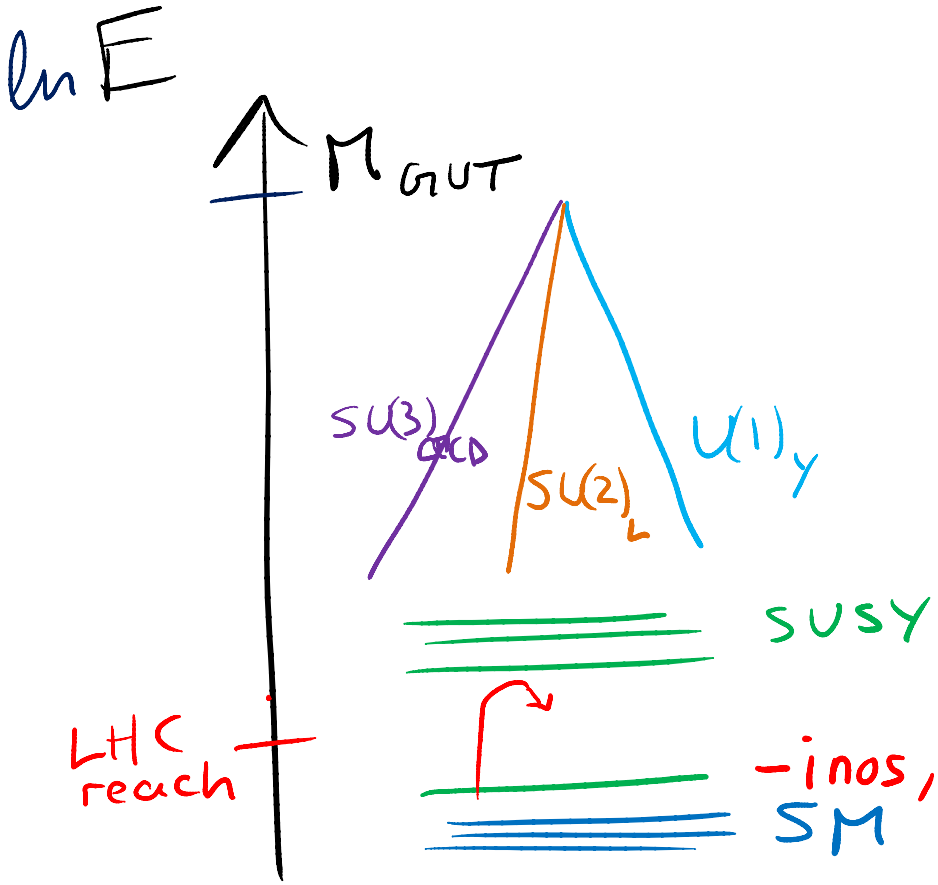


SPECTRA HAVE SOME SPREAD

The Way it might be



The Way it might be

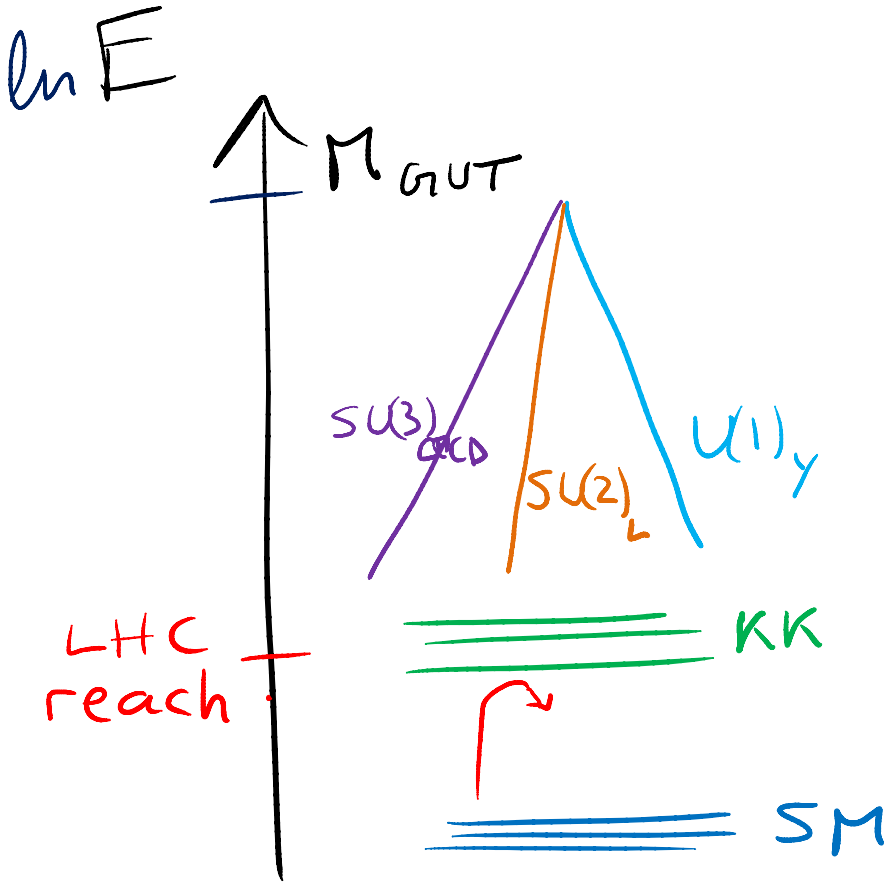


as in

Split SUSY

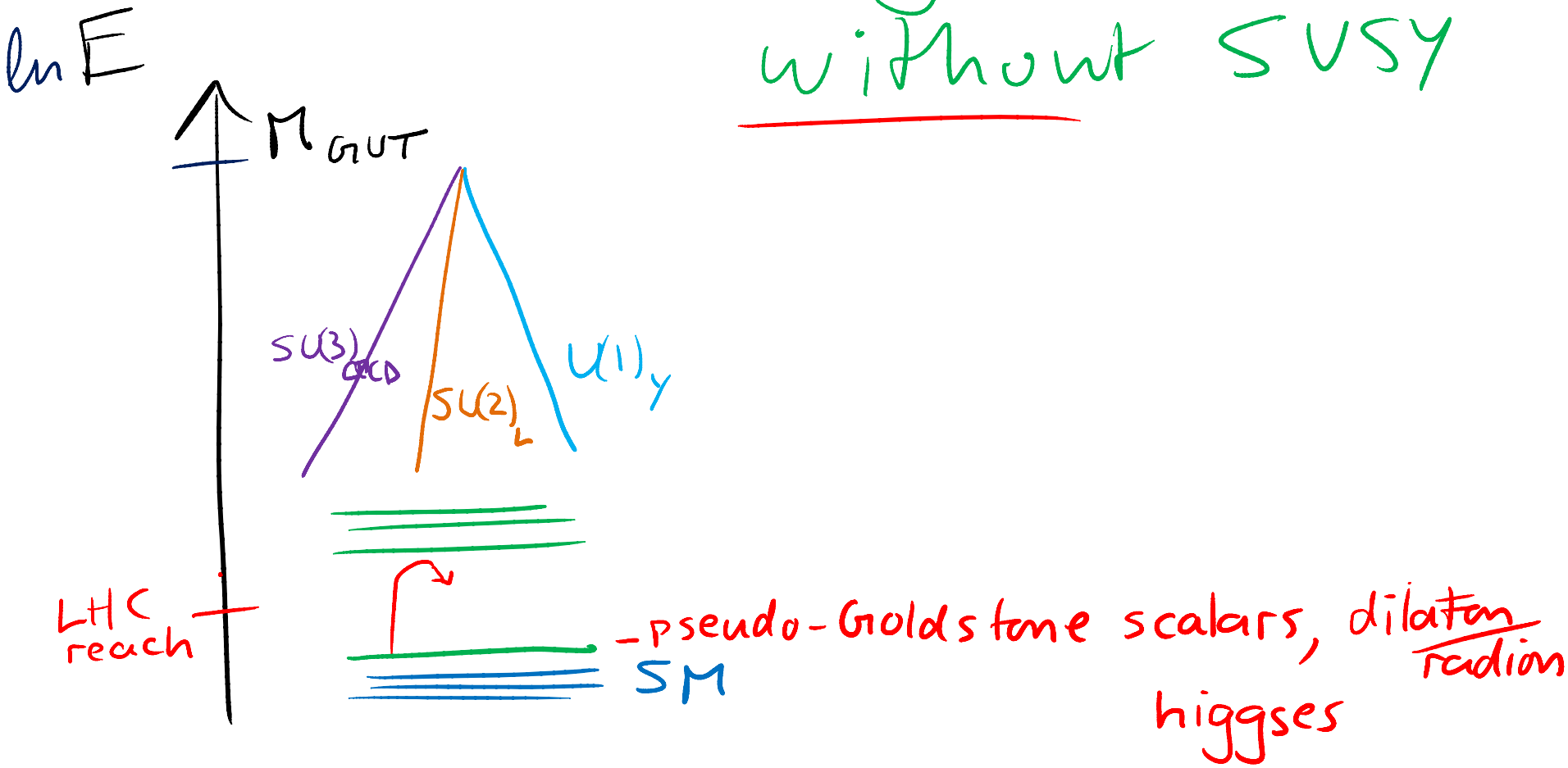
Arkani Hamed, Dimopoulos '04
Giudice, Romanino '04
Wells '04

The Way it might be without SUSY

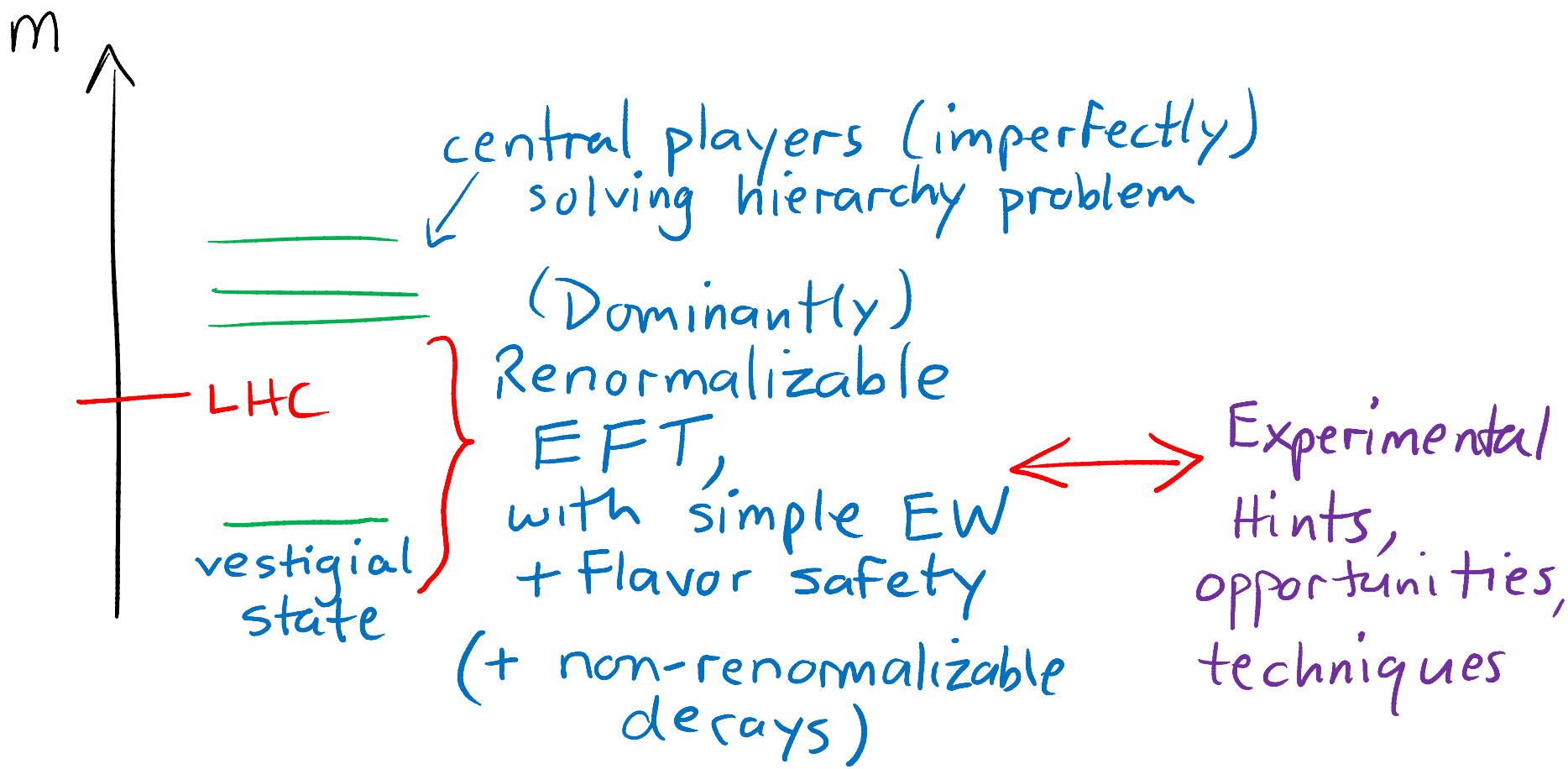


boosted $t\bar{t}$, ...
resonance

The Way it might be without SUSY



IF LHC SEEKS "LIGHT VESTIGES" RATHER THAN "CENTRAL ORGANS" SOLVING HIERARCHY PROBLEM, GENERALLY CLASSIFY CANDIDATES



⇒ Vector-like fermions

resonances, CHAMPS, "R-hadrons", $\not{E}$, displaced vertices

Hidden Valleys hi-multiplicity, lo-mass,

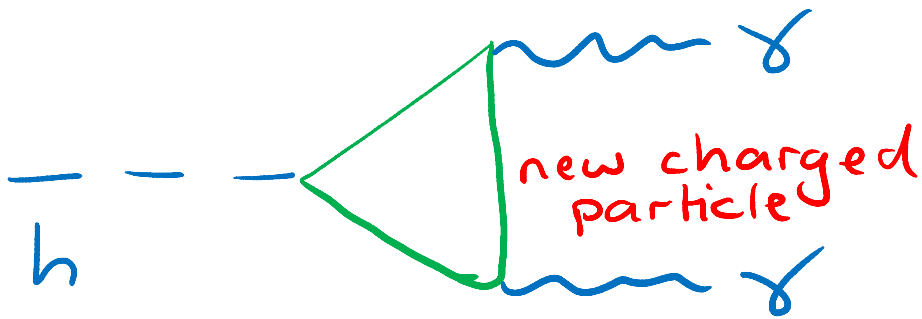
Quirks weird for triggering

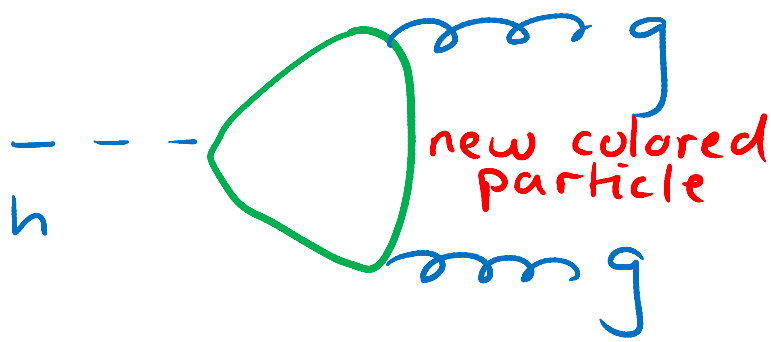
Vector-like Confinement multi-jet multi-bosons, resonances, + ↑

Diquarks flavorful pheno, but flavor-safe.

Precision Higgs measurements complementary to direct searches for light vestiges

Eg.





might hide well inside backgrounds in direct searches

CONCLUSIONS

Nature plausibly SPARSE and/or MESO-TUNED

Main players of hierarchy problem

- may be out of reach. Flavor/CP
  $\Rightarrow$ best vestigial gambles
- may be <u>only</u> particles within reach. There must be <u>concerted</u> effort to cover all places t-partner could hide.

DISCOVERY or EXCLUSION = VICTORY

Hunting may require back & forth with theory rather than set-piece models or cut & count.