

BUMPS ON THE ROAD TO NEW PHYSICS

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DICTIONARY

Bump (n.)

1) "Bump on the road..."
(surmountable)
obstacle in achieving
goals



AIN'T SEEN NOTHING ^{→ BSM}
YET

How do we gamble experimentally?

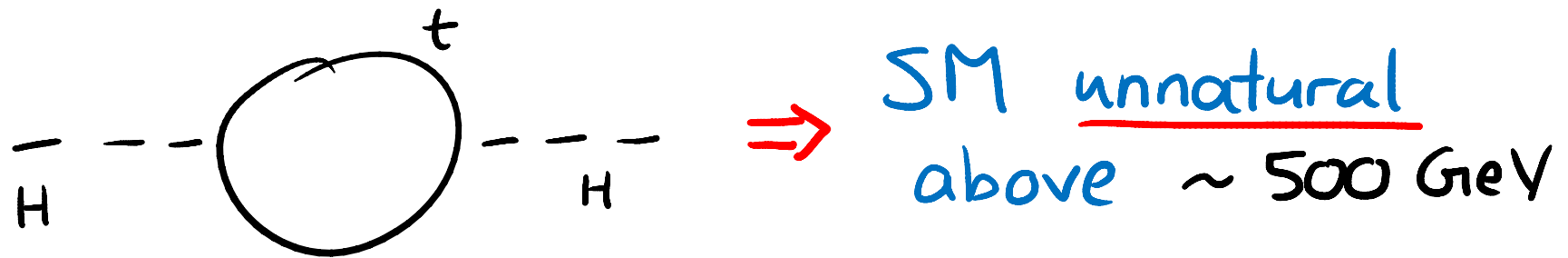
How do we gamble theoretically?

How hard should we try in any
direction?

When should we give up on a
scenario?

Does Particle Physics have "no-lose" program?

BEEN THAT WAY
FOR A MIGHTY LONG TIME



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

... LEP, LEP 2, 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

NEW PHYSICS CAN EASILY BE
AWAITING DISCOVERY, NEVERTHELESS

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.

A POOR ANALOGY?

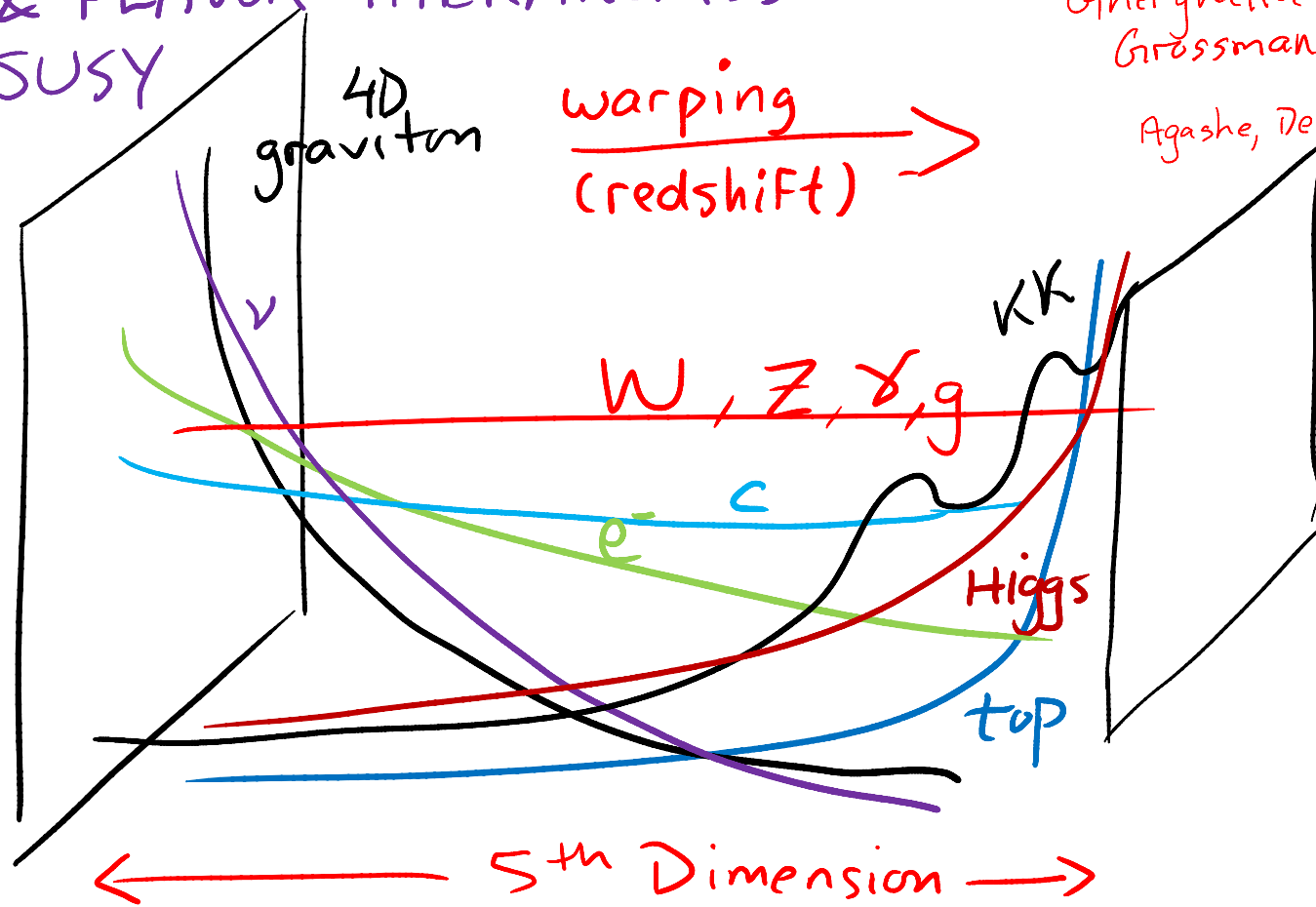
Solution to Hierarchy Problem
requires rich new spectrum

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

OR IS NOTHING
OUT THERE?

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 '08
Contino, Nomura, Pomarol '03

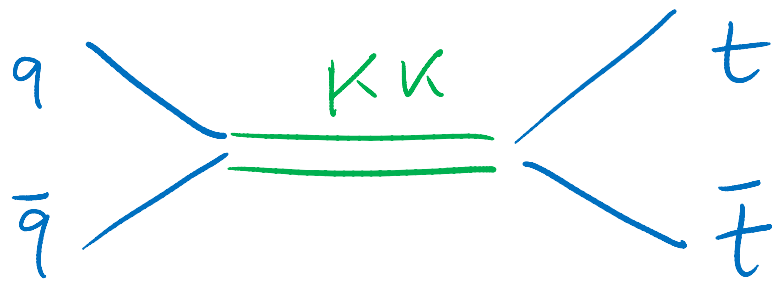
Agashe, Contino, Pomarol '05

⋮

Without any "tricks"/flavor-tuning,
flavor/CP tests $\Rightarrow M_{KK} \sim 20-30 \text{ TeV}$

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

MOTIVATES ONGOING KK GLUON SEARCHES



"bump"

Agashe, Belyaev,
Krapovnickas,
Perez, Virzi '06
Lillie, Randall, Wang '07
⋮

maybe simple "tricks" allow $m_{KK} \sim \text{few TeV}$

UV COMPLETION OF 5D non-renormalizable
EFT ADS/CFT DUAL to COMPOSITE HIGGS
with PARTIAL COMPOSITENESS

Georgi, Kaplan '84

Kaplan '91

MAYBE UV COMPLETIONS DON'T EXIST?!

FIRST STRING FORAYS

Strassler '03

(w/o SUSY help)

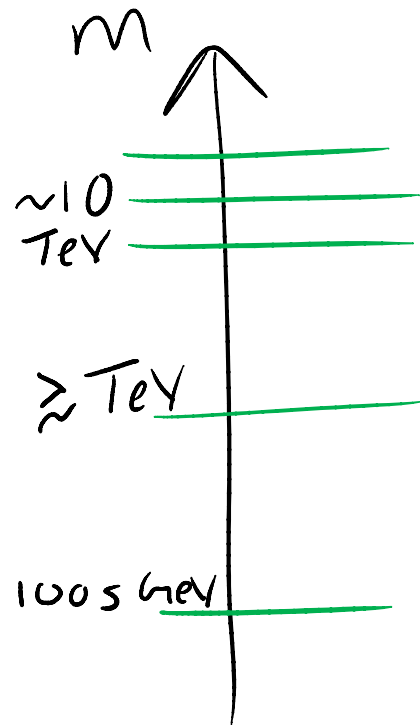
Kachru, Simic, Trivedi '09

CAN NATURE $\sim E_{\text{LHC}}$

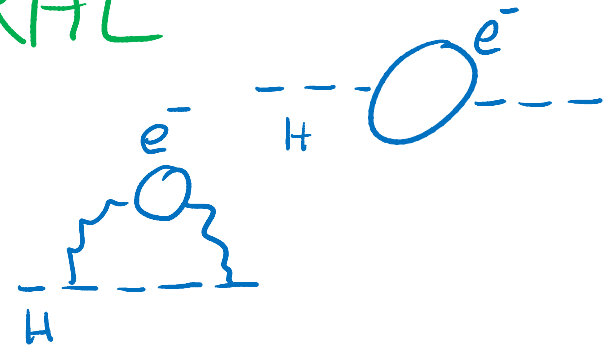
PLAUSIBLY BE

SPARSE ?

SPARSE BUT NATURAL

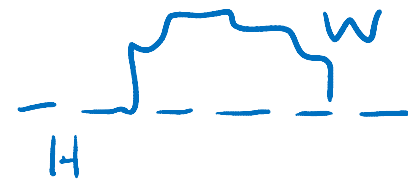


Big hierarchy cuts off
problem solution



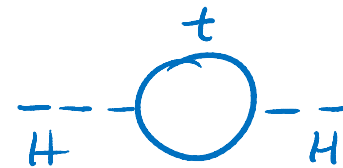
$\sim \text{TeV}$

W partner symmetry
cancels

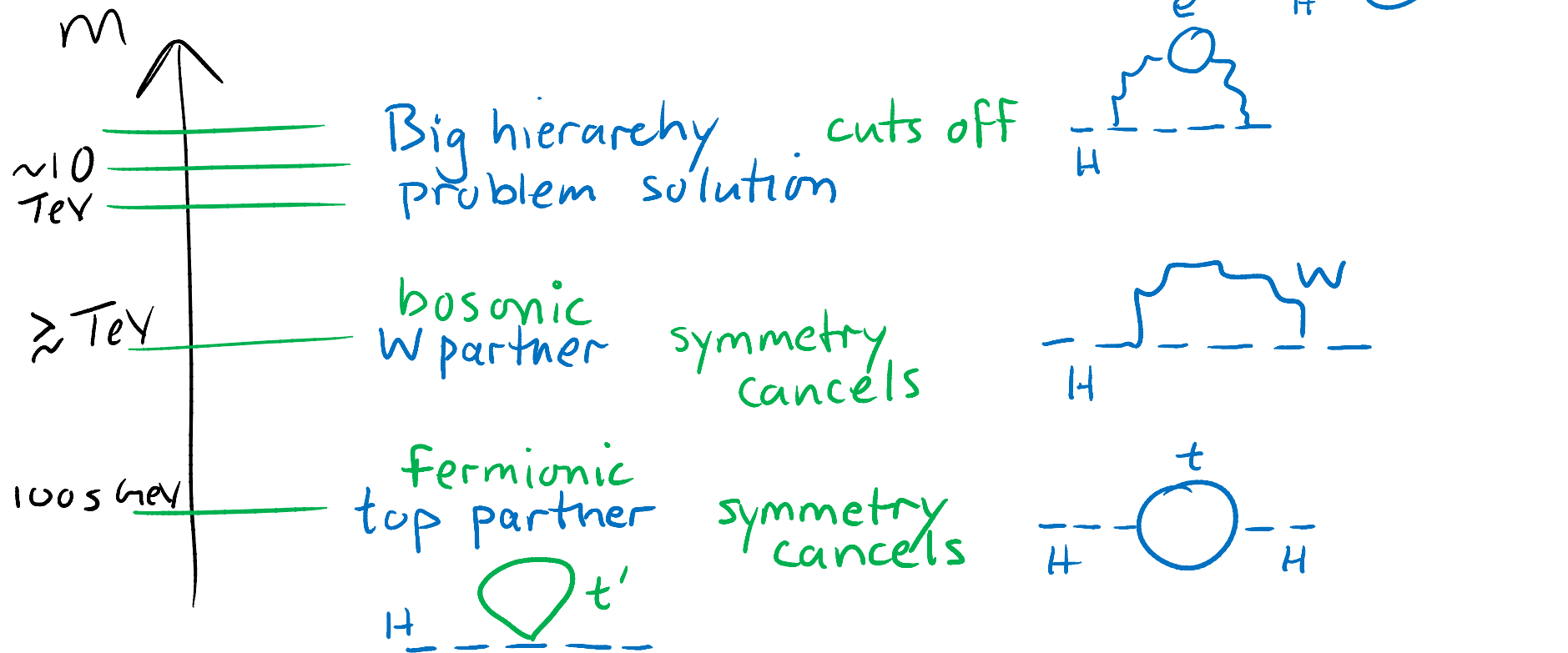


100 GeV

top partner symmetry
cancels

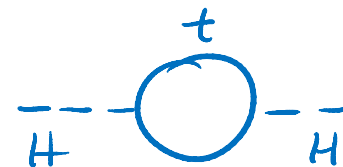
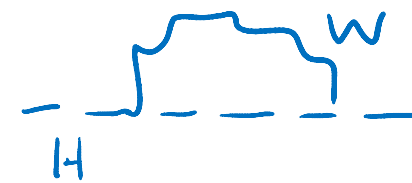
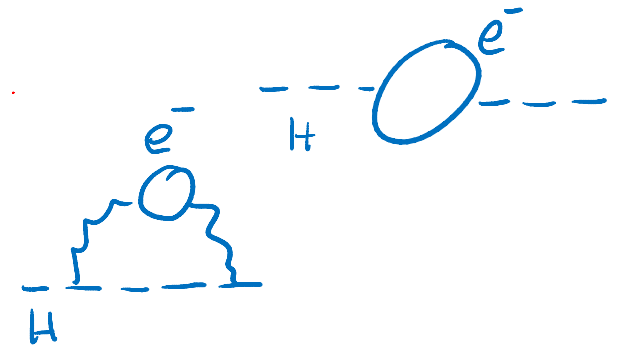
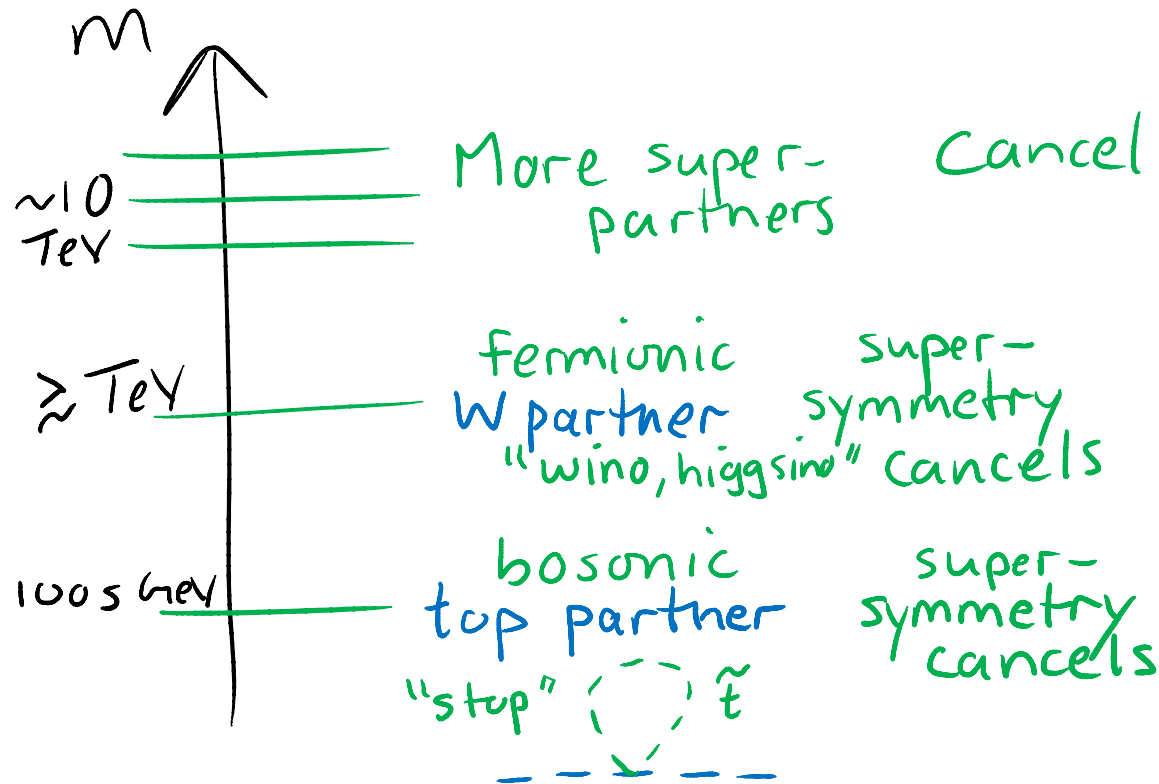


SPARSE BUT NATURAL



Eg. Little Higgs Arkani-Hamed, Cohen, Georgi '01 . . .
 LHCpheno Han, Logan, McElrath, Wang '03; Perelstein, Peskin, Pierce '04
 . . . Berger, Hubisz, Perelstein '12
 Twin Higgs Chacko, Goh, Harnik '05

"NATURAL SUSY"

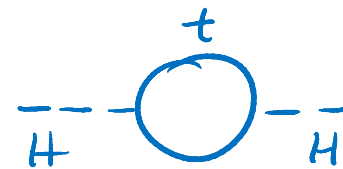
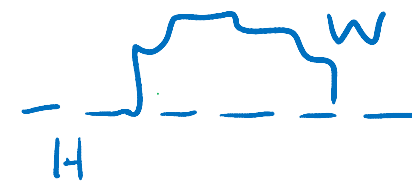
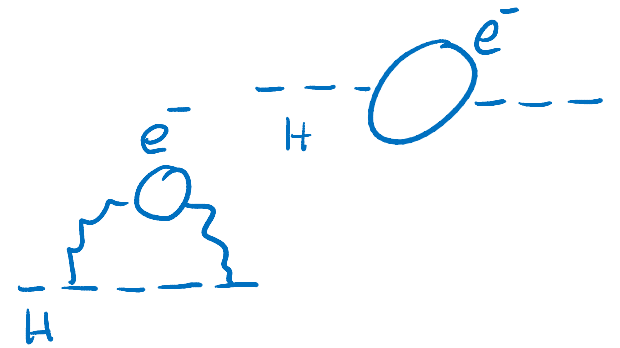
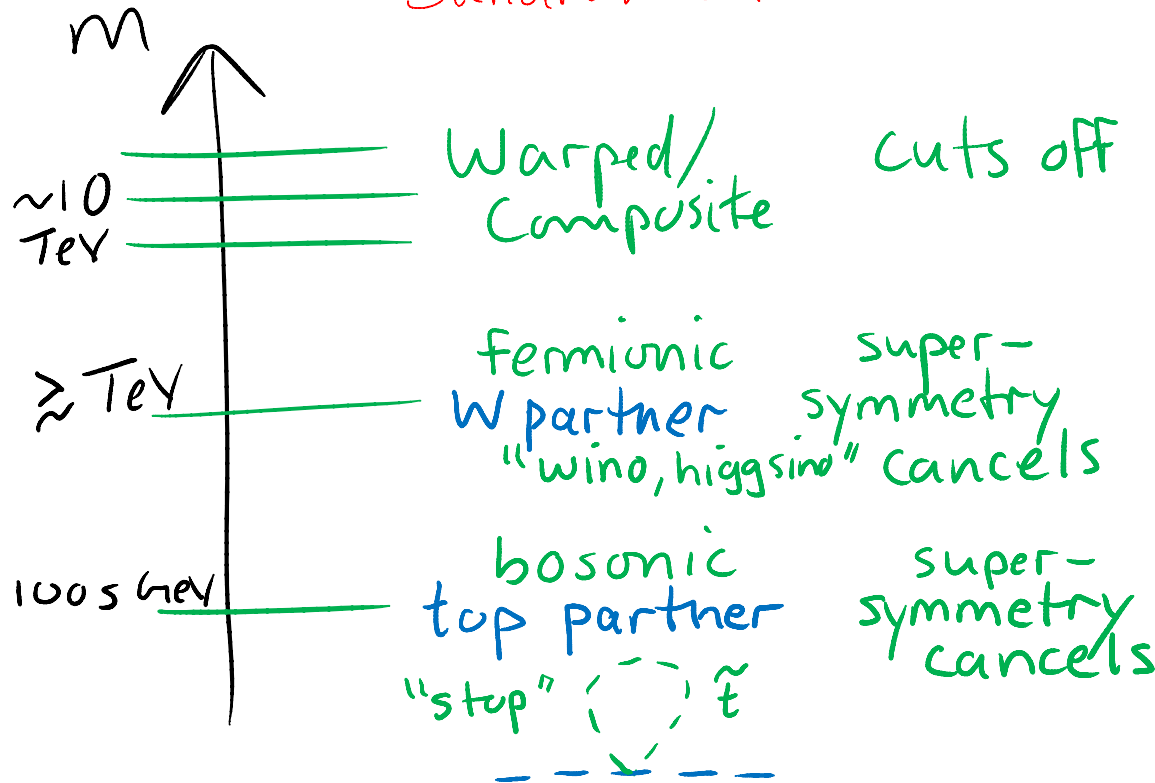


Dimopoulos, Giudice '95; Cohen, Kaplan, Nelson '96 ...
 ... Barbieri, Bertuzzo, Fara, Lodone, Pappadopulo '10 ...

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

RE-EMERGENT SUSY

Sundrum '09



baryon violating

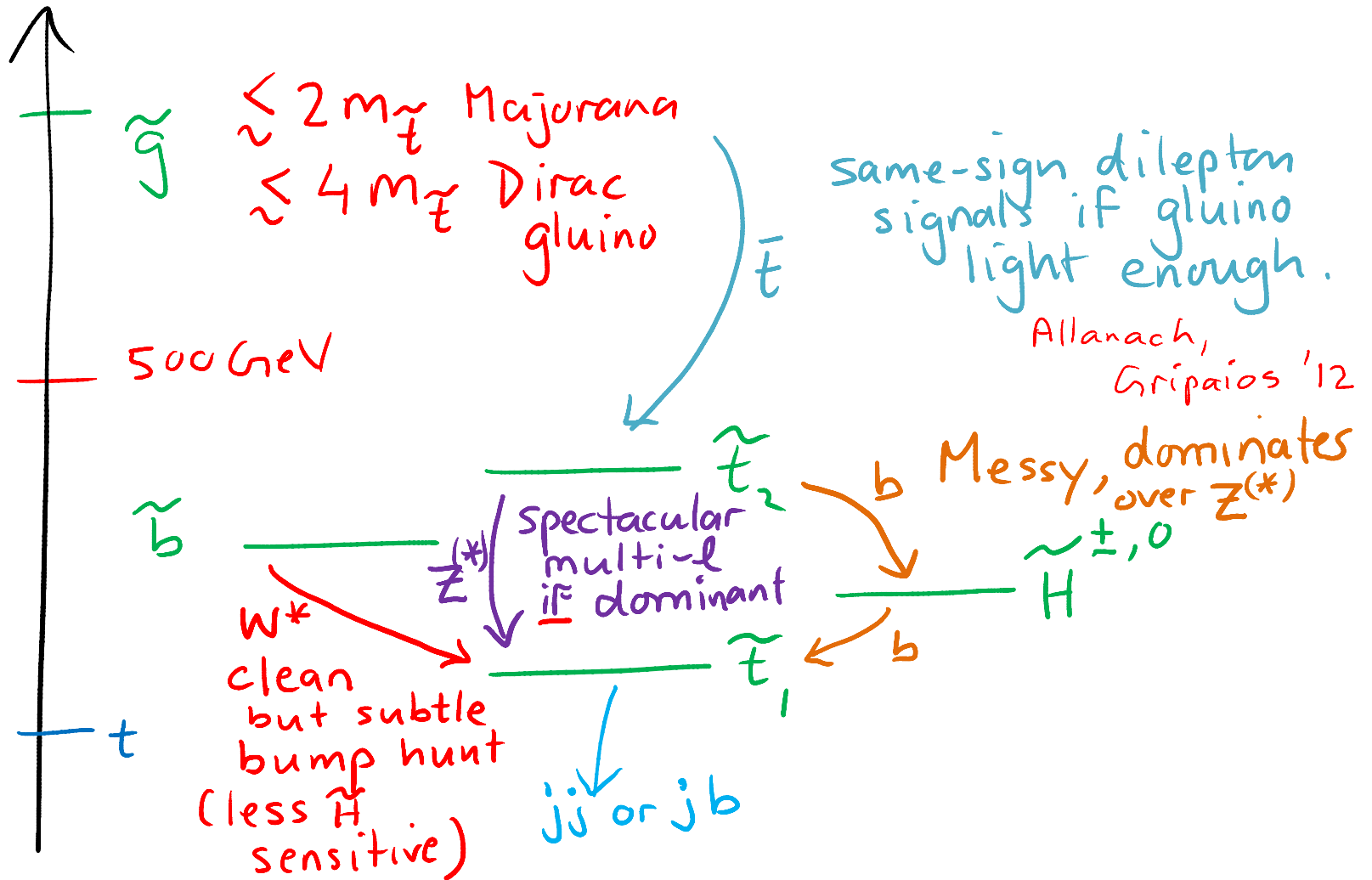
Accidental $U(1)_{\text{baryon}}$: $\mathcal{L}(M_{\text{Pl}}) = \bar{q}(i\not{D} - m)q - \frac{1}{4}G_{\mu\nu}^2 + \frac{g^6}{M_{\text{Pl}}^5} + \dots$
 can easily generalize to warped case

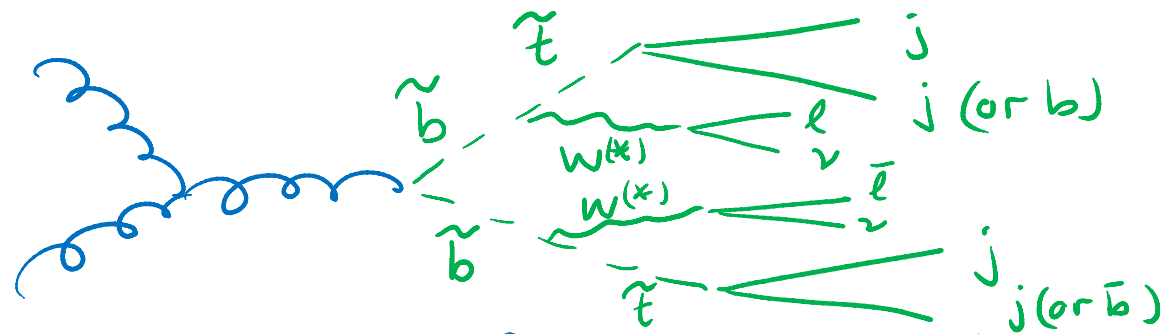
Accidental SUSY: Kaplan '84; Luty, Rattazzi '99; Luty '02;
 Groh, Luty, Ng '03; Gherghetta, Pomarol '03; Strassler '03

R-parity not relevant for proton stability $\Rightarrow$ ~~R-parity~~
 Brust, Katz, Lawrence, Sundrum '11

(Effective) NATURAL SUSY & ~~B~~ RPV

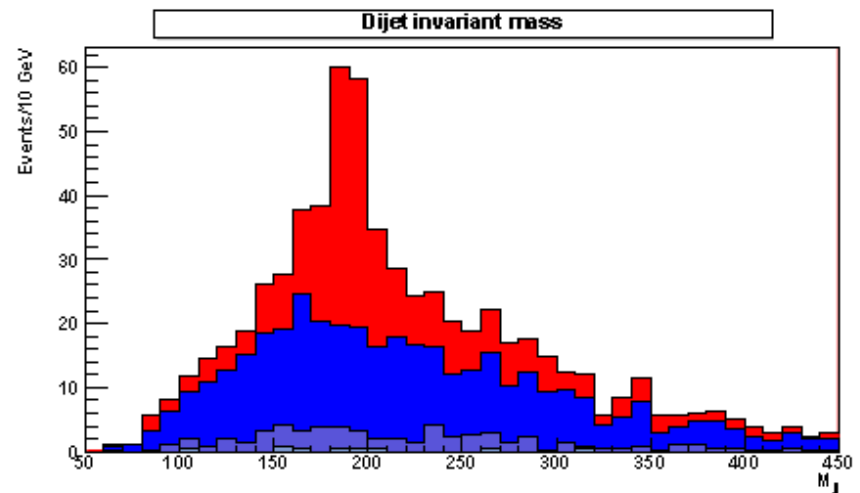
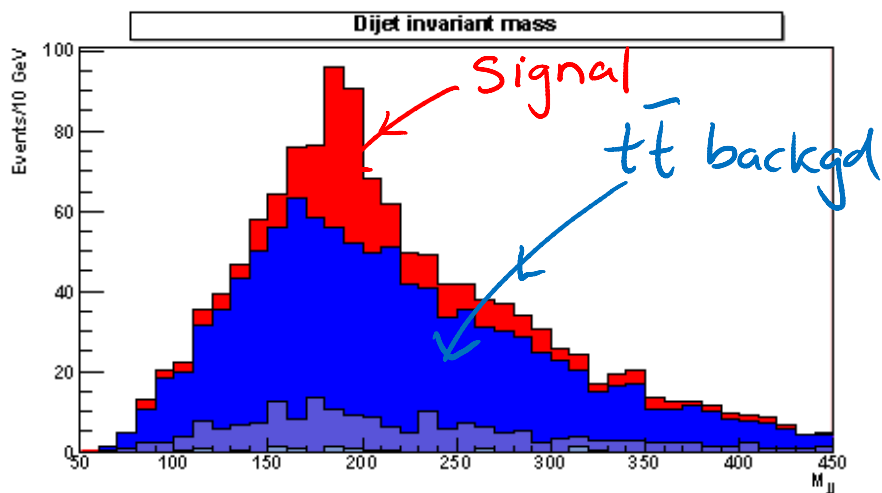
Kilić, Thomas '11 (CDF Wjj anomaly) m
 Brust, Katz, Sundrum '12 (L-conserving)





without b-veto, for $\tilde{t}_1 \rightarrow b+j$

with b-veto, for $\tilde{t}_1 \rightarrow jj$

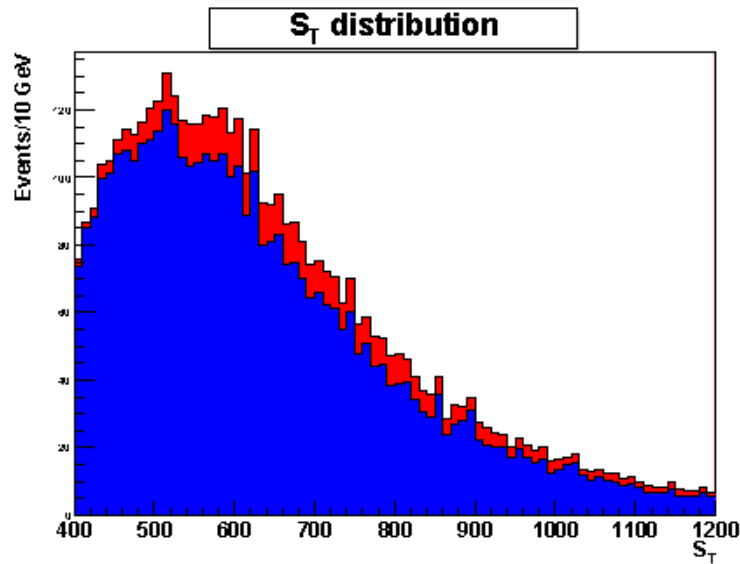


Pairing up leading jets: $|M_{jj}^{(1)} - M_{jj}^{(2)}| \leq 10 \text{ GeV}$

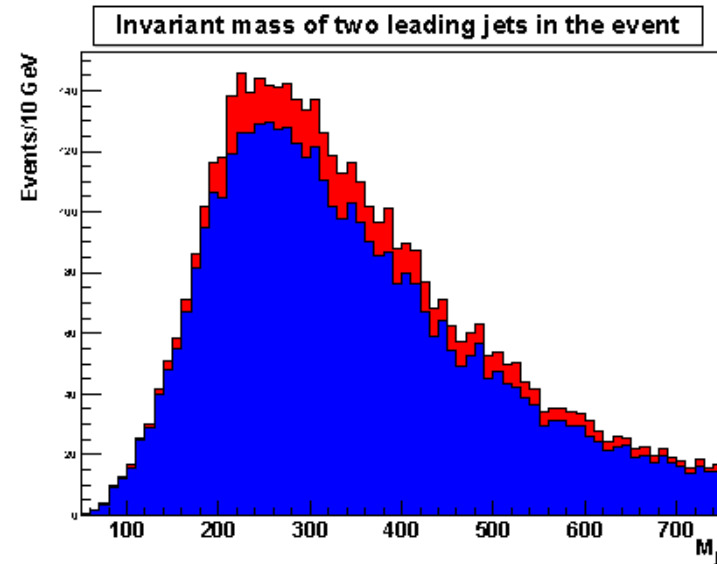
Require hard event with "soft" leptons, $\cancel{E}_T$

Brust, Katz, Sundrum '12

without b-veto



with b-veto



Analogous cut & count strategy (no bump hunt)

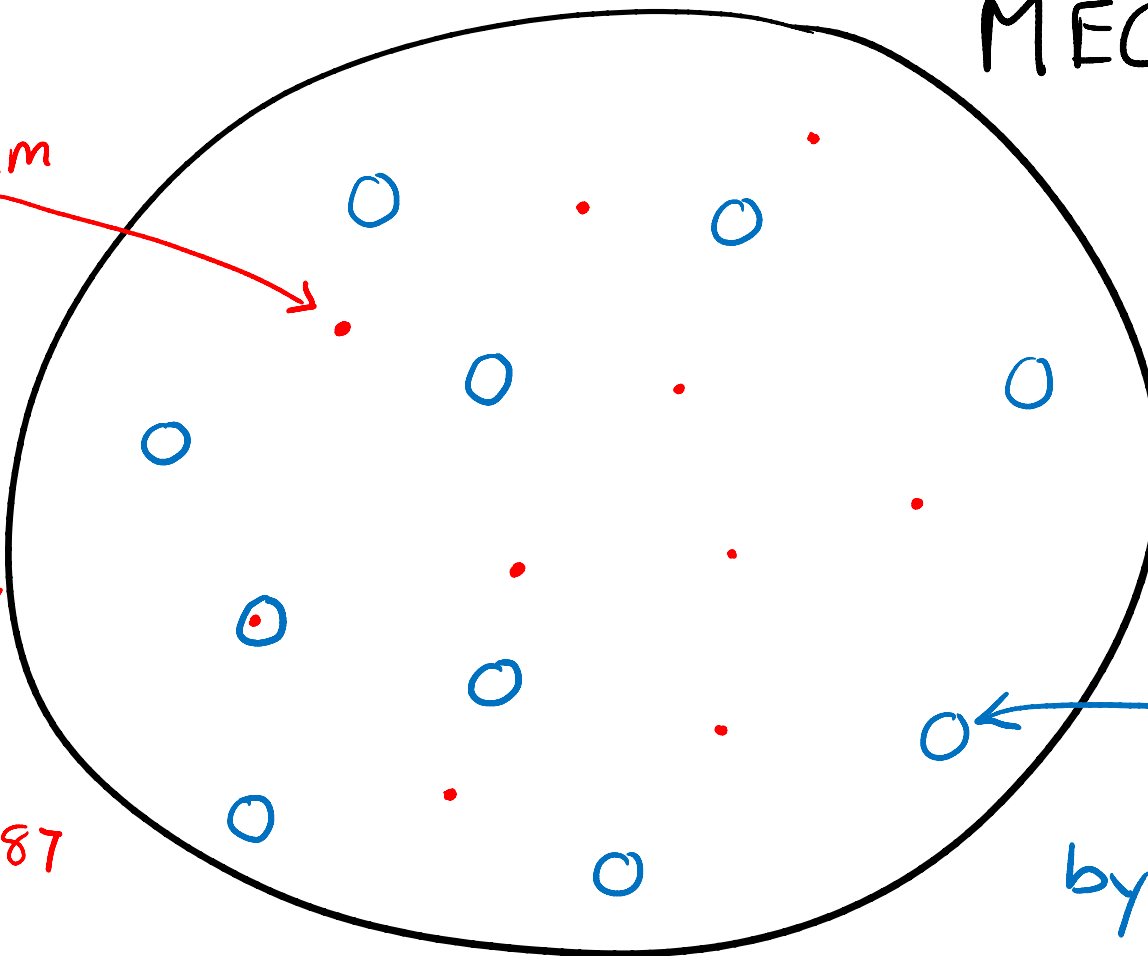
MESO-TUNING

ANTHROPIC PRINCIPLE

— making the Universe safe for humans
& dangerous for physicists

MEGaverse

Vacuum
energy
small
enough
to allow
galaxy
formation,
by fine-
tuning
Weinberg '87

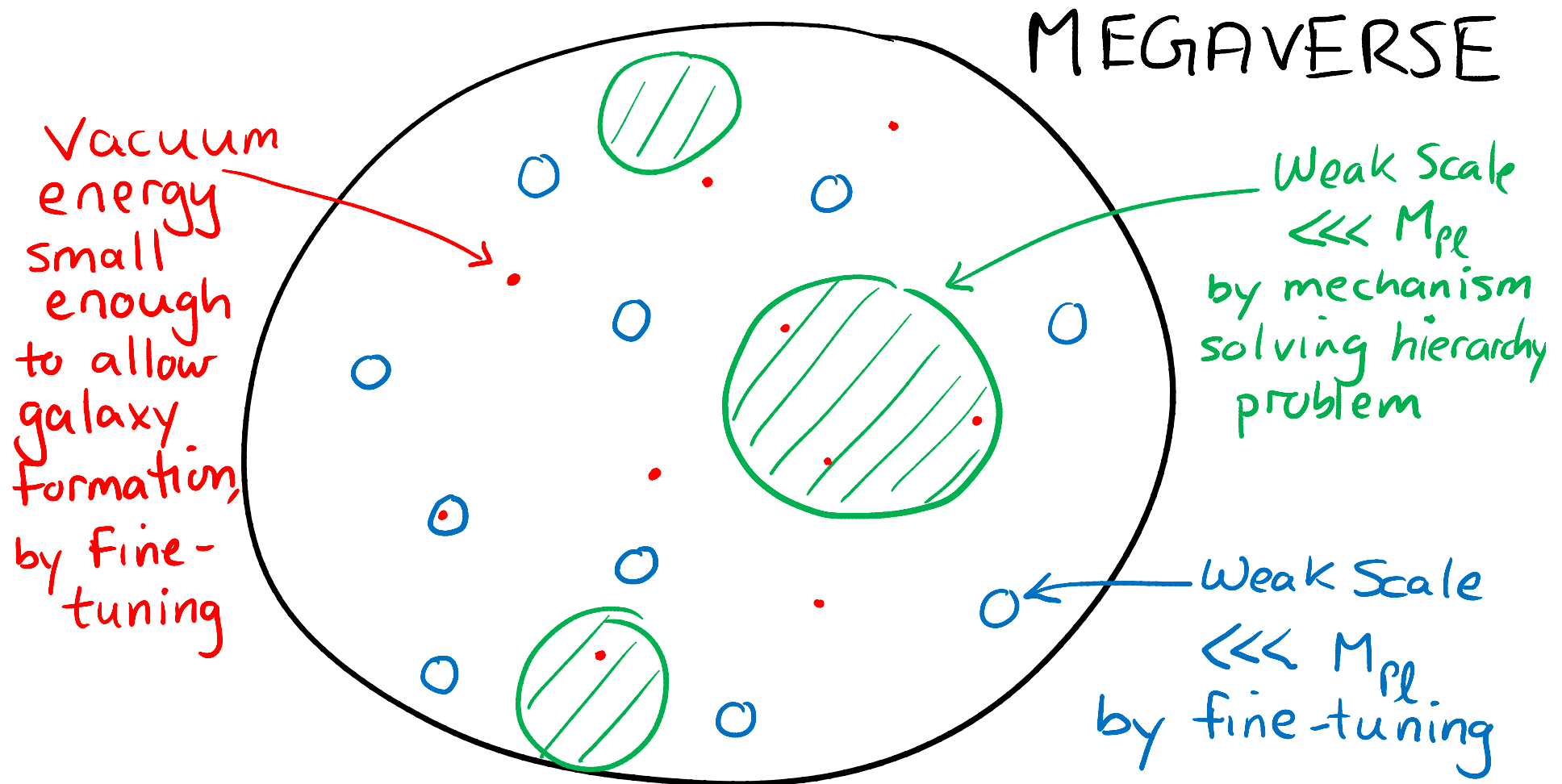


Bousso, Polchinski '00
Kachru, Kallosh, Linde,
Trivedi '03
Douglas, Denef '03
Arkani-Hamed, Dimopoulos
'04
Giudice, Romanino '04
Wells '04

Weak Scale
 $\ll M_{\text{Pl}}$
by fine-tuning

A MECHANISM BEATS FINE-TUNING

UNLESS THERE IS NO MECHANISM



WHY SUSY MIGHT FAIL

Eg.

Suppose quantum gravity $\Rightarrow$ Super gravity

Suppose almost all EFTs have

$$\langle W \rangle \lesssim M_{Pl} \Rightarrow - \frac{|\langle W \rangle|^2}{M_{Pl}^2} \text{ vacuum energy}$$

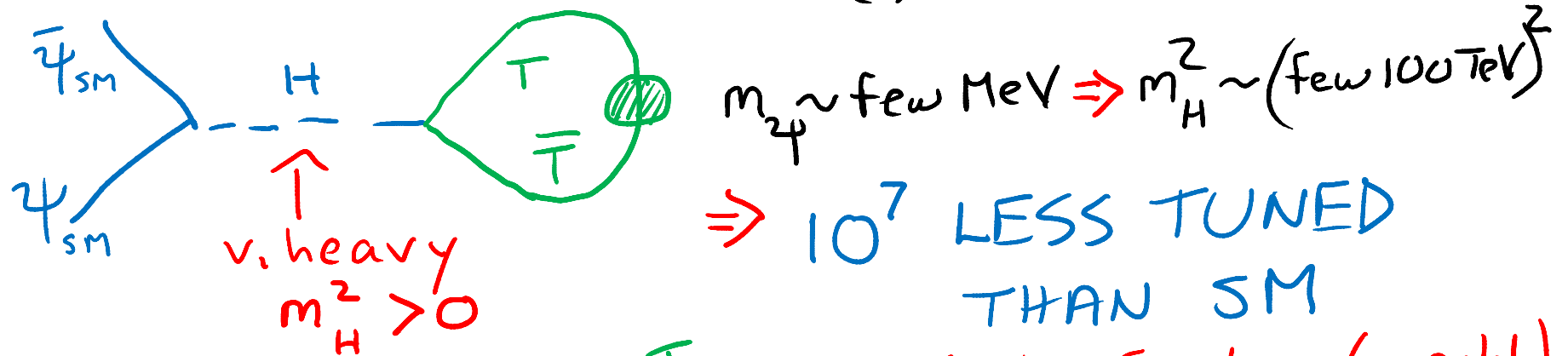
unless canceled by +ve vacuum energy
from ~~SUSY~~

in which case $m_{SSM}^2 \lesssim M_{Pl}^2 \sim \frac{V_{\cancel{SUSY}}}{M_{Pl}^2} \sim \frac{|\langle W \rangle|^2}{M_{Pl}^4}$

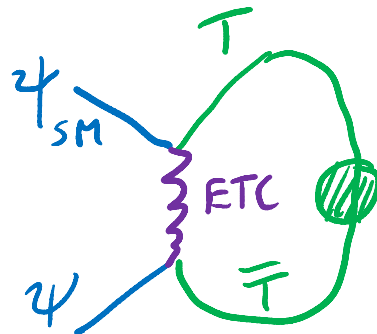
BEFORE ACCEPTING "ANTHROPOLOGICALLY"
FINE-TUNED SM, HAVE TO CONSIDER
THE ALTERNATIVES

Eg. "Weakless Universe" Harnik, Kribs, Perez '06

Eg. $\mathcal{L} =$ 1-generation "SM" + minimal TC
+ $\alpha(1) \bar{T} T H$

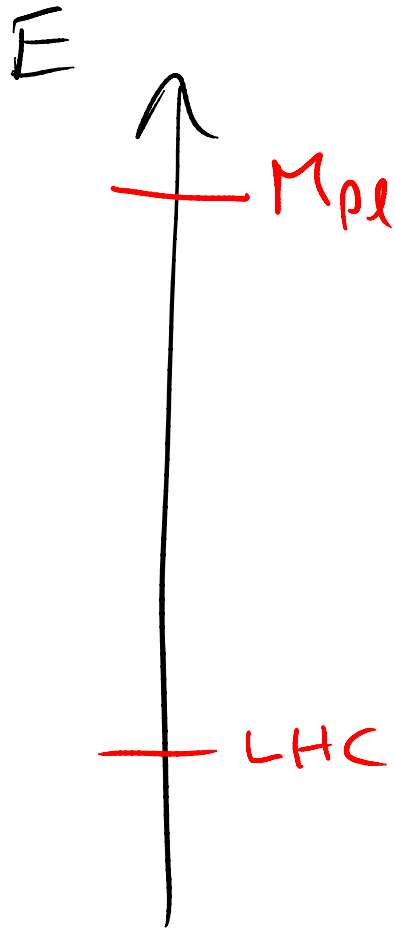


Eg. 1-generation "ETC" model



Kaplan, Sundrum (unpubl.)
 ONLY v. MILDLY TUNED

INSIGHTFUL BUT INCONCLUSIVE, SO 3 OPTIONS...



hierarchy
problem "unsolved"

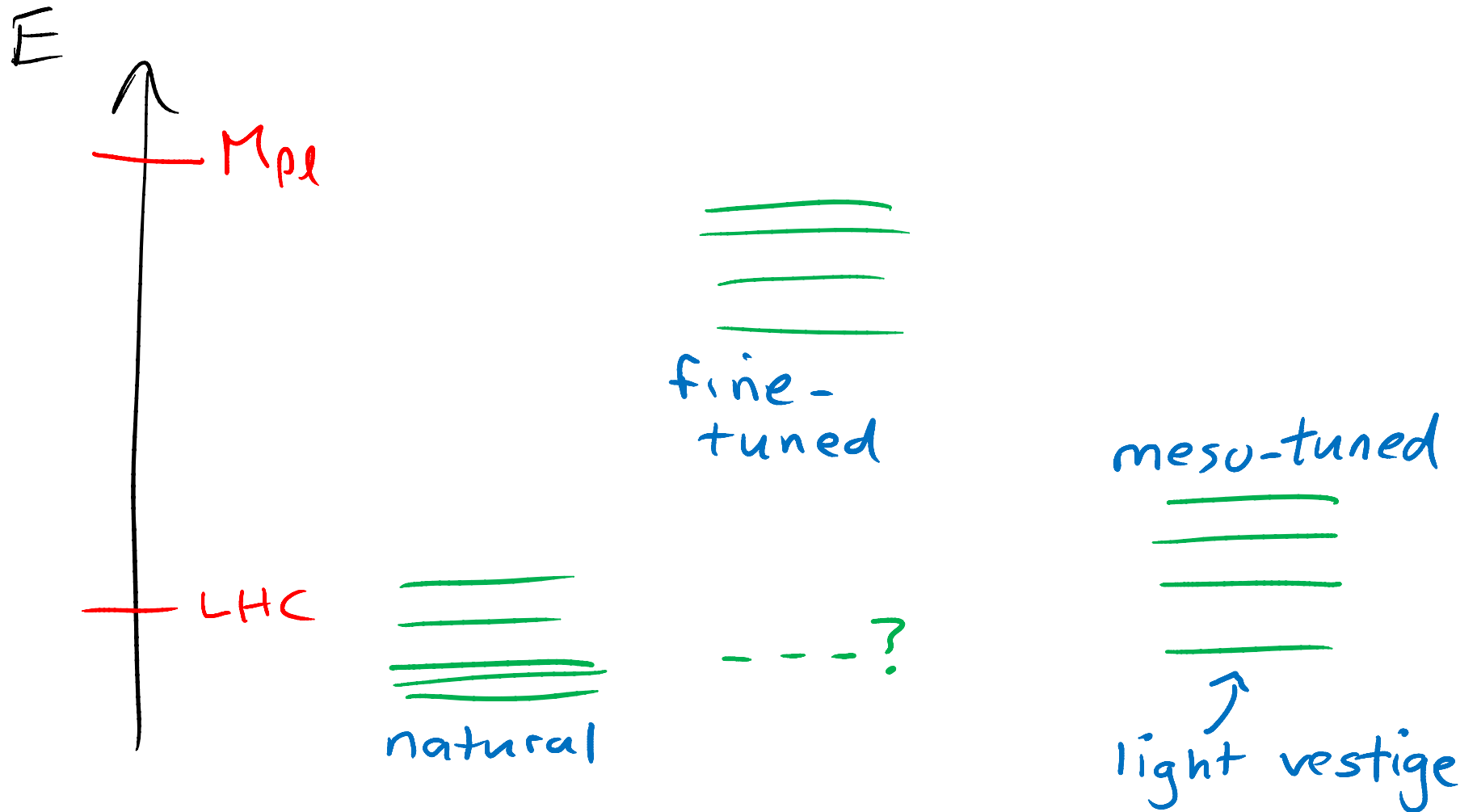
weak scale
tuned "anthropically"

hierarchy
problem
solved

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

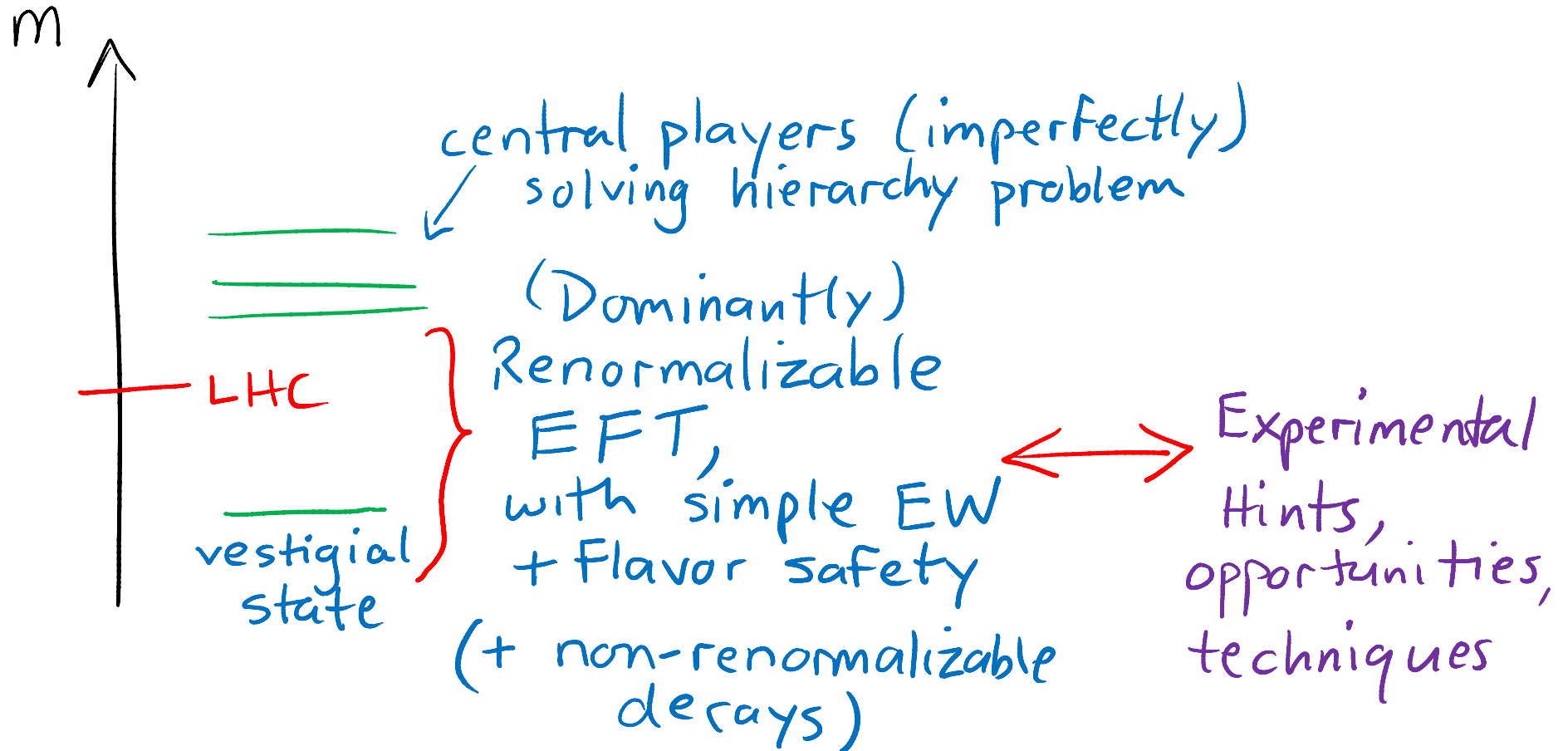
MESO-TUNING

MESO-TUNING LIES AT INTERSECTION OF PLAUSIBILITY & OPPORTUNITY



SPECTRA HAVE SOME SPREAD

IF LHC SEEKS "LIGHT VESTIGES"
RATHER THAN "CENTRAL ORGANS" SOLVING
HIERARCHY PROBLEM, WHAT ARE
CANDIDATES ??



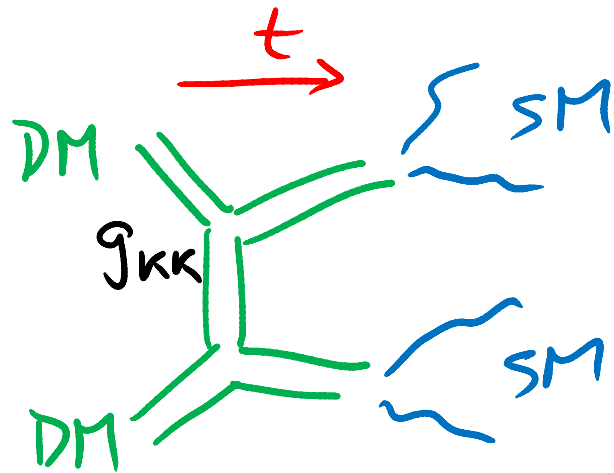
WHY MIGHT WARPED/COMPOSITE PHYSICS BE MESO-TUNED?

Tension with some other anthropic imperative

Eg. Imagine KK/Composite stable particle

= Dark Matter,

stabilized by accidental symmetry



IF anthropics prefer
WIMP miracle $\Rightarrow$

$$\frac{g_{KK}^4}{m_{KK}^2} \sim \frac{g_{weak}^4}{TeV^2} \sim \sigma_{WIMP}$$

$$g_{KK} \sim g_{SM} \sqrt{\log \frac{M_{UV}}{v_{weak}}}$$

$$\Rightarrow m_{KK} \sim O(10 TeV)$$

WARPED/COMPOSITE UNIFICATION

Agashe, Contino, Sundrum '05

Unified 5D Bulk gauge symmetry
+ Flavor-dependent fermion profiles

(composite t_R, H , unified global
symmetry of composite dynamics)

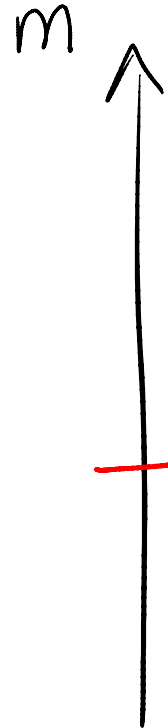
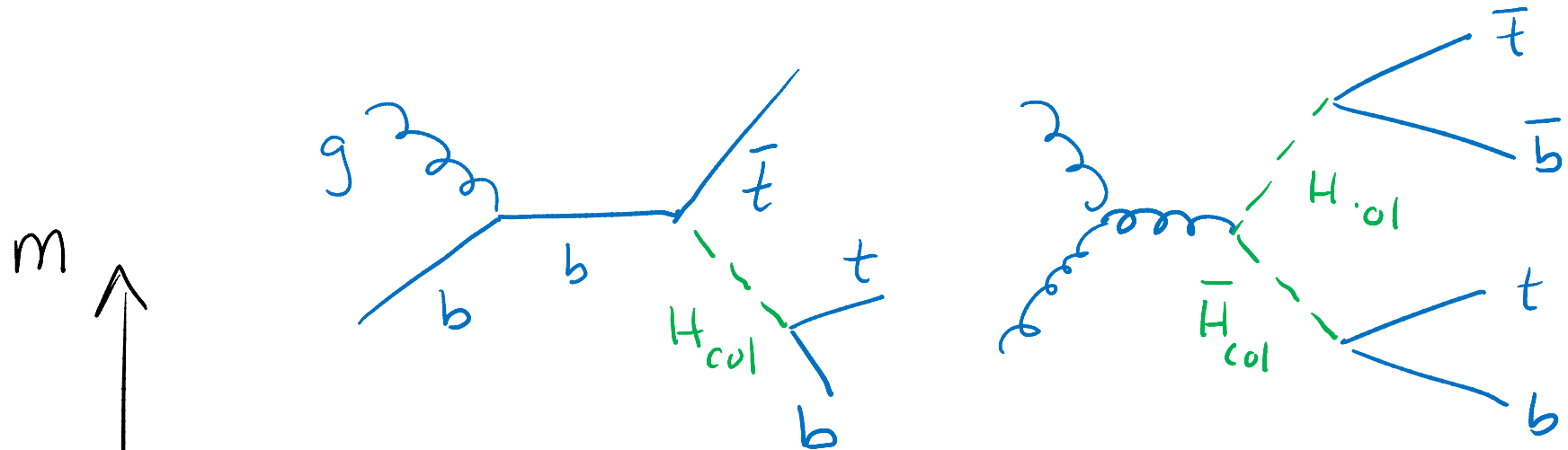
$\Rightarrow$ Quite robust & precise gauge
coupling unification!

Orbifold GUTs : Kawamura '00; Hall, Nomura

Warped Pomarol '00; Randall, Schwartz '01;
Goldberger, Nomura, Smith '03;
Agashe, Delgado, Sundrum '04

$\Rightarrow$ COLORED HIGGS H_{col}

UNIFICATION - PARTNER OF EW HIGGS



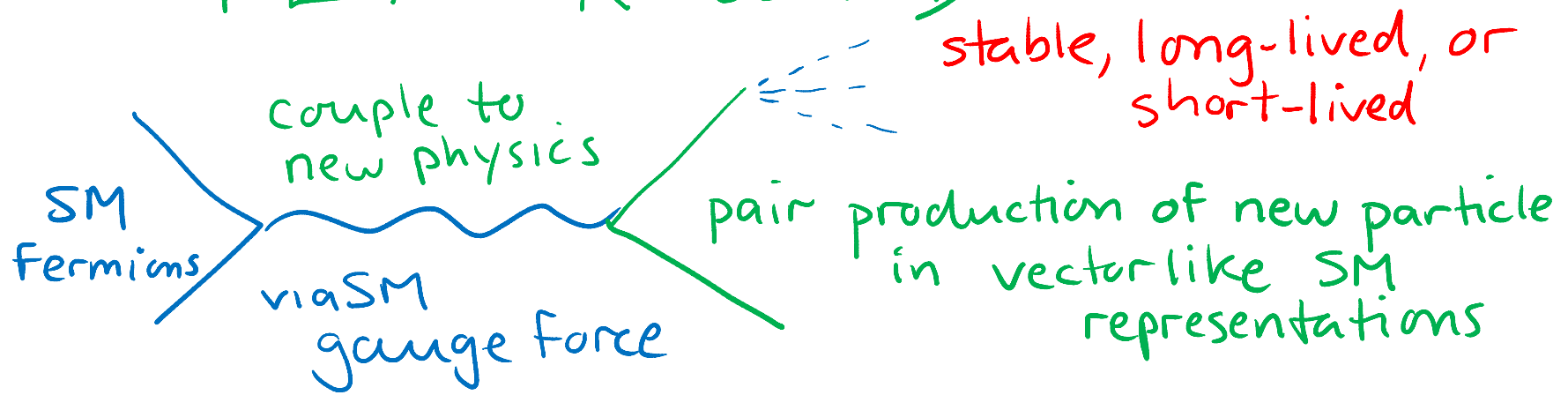
LHC

vestigial state

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \lambda H_{col} t b + \dots$$

Contino, Son, Sundrum (unfinished)

FLAVOR BLIND VESTIGES



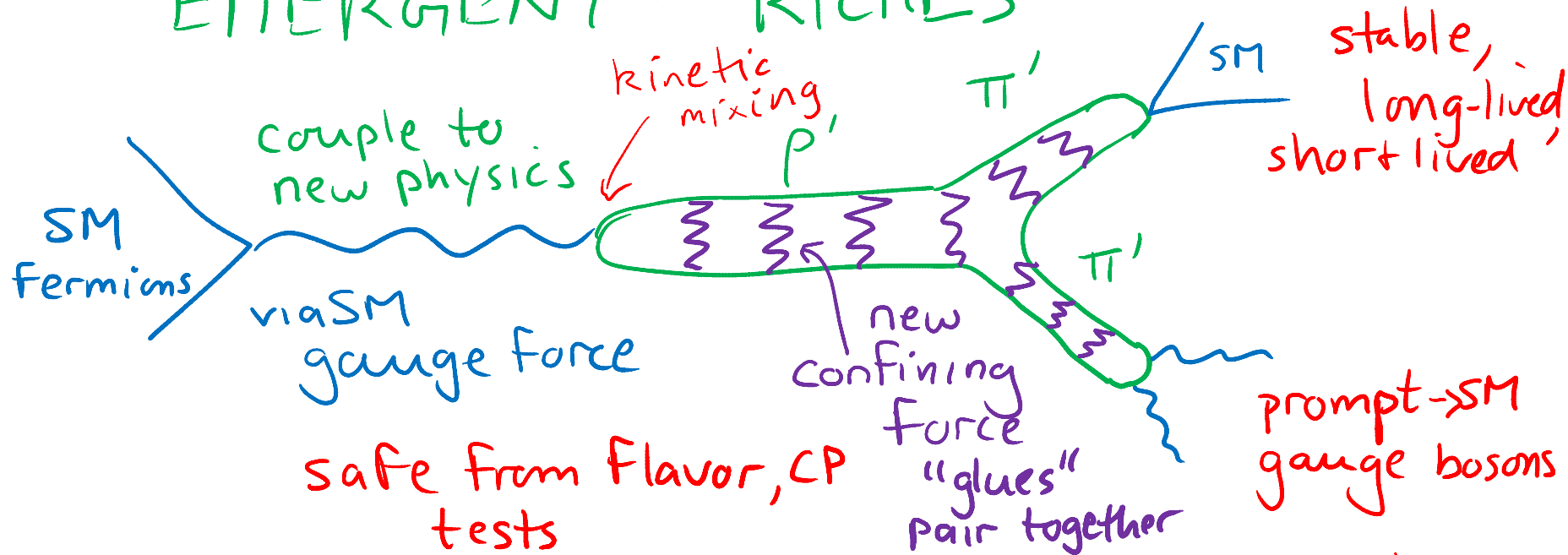
safe from Flavor, CP tests

$\tilde{E}$, CHAMPS, "R-HADRONS", DISPLACED VERTICES
are generic vestigial options

Classic Eg. SPLIT SUSY

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

"EMERGENT" RICHES



VECTORLIKE CONFINEMENT

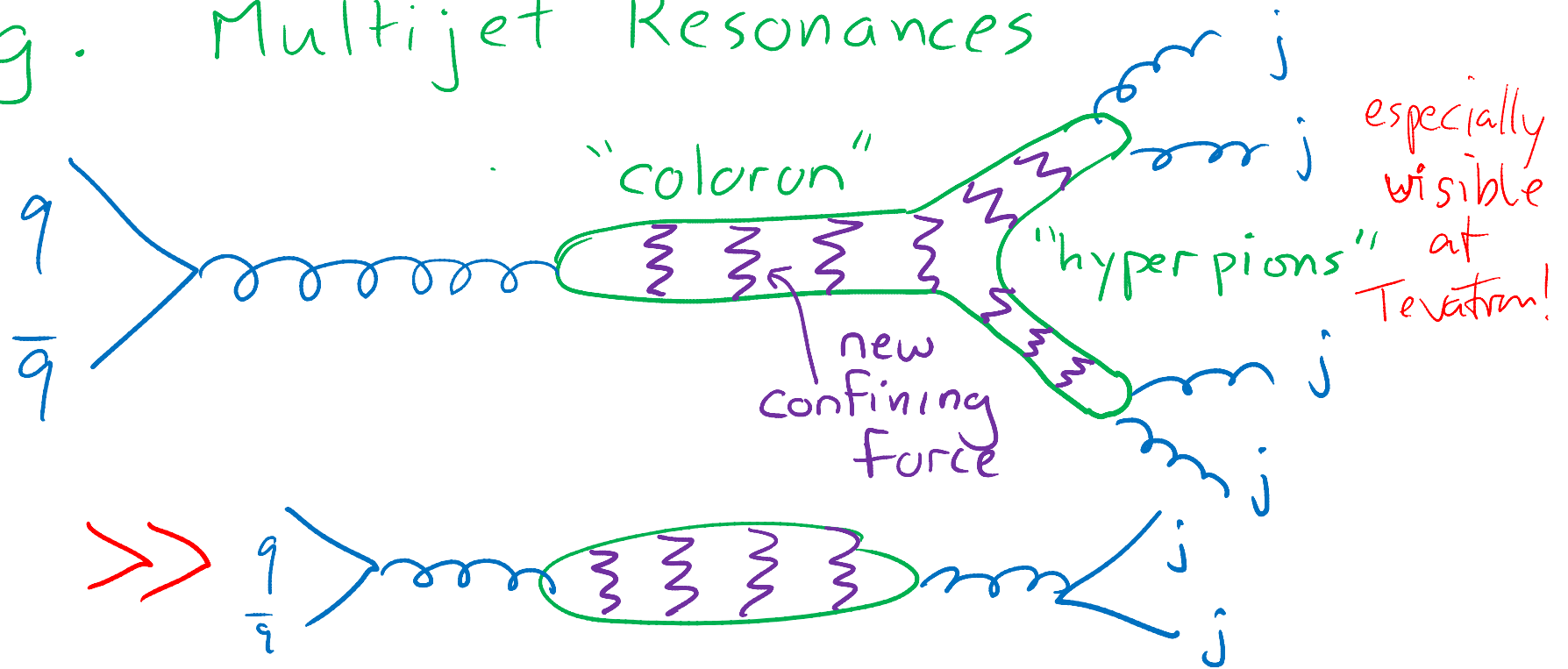
$$\mathcal{L} = \mathcal{L}_{SM} + \bar{\psi}(i\not{D} - m)\psi - \frac{1}{4}H_{\mu\nu}^2 + \text{non-ren.}$$

$\not{E}$, CHAMPS, "R-HADRONS", DISPLA~~E~~ VERTICES
generic vestigial options

similarities with Hidden Valley: Strassler, Zurek '07
Quirks: Kang, Luty '08

~ EXCITEMENT OF TECHNICOLOR WITHOUT THE DANGER (OR AMBITION)

Eg. Multijet Resonances



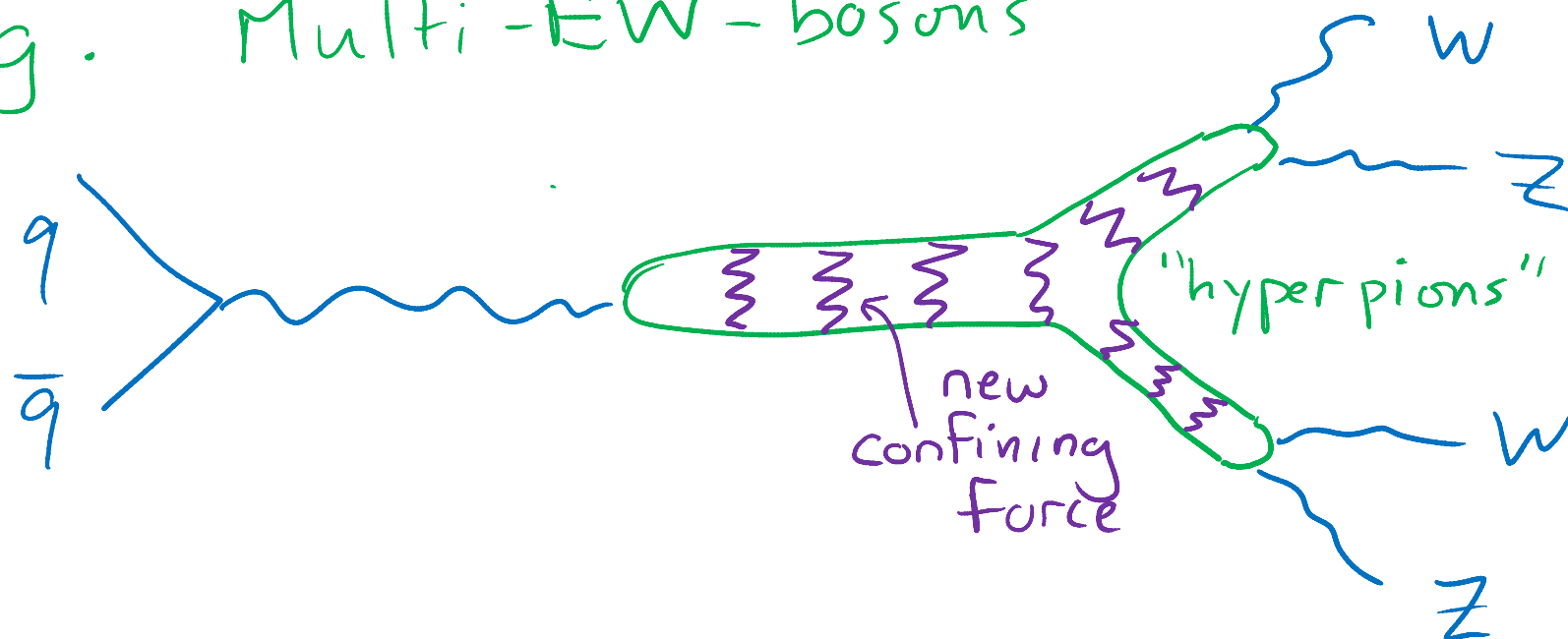
dijet bump suppressed

Kilić, Okui, Sundrum '08

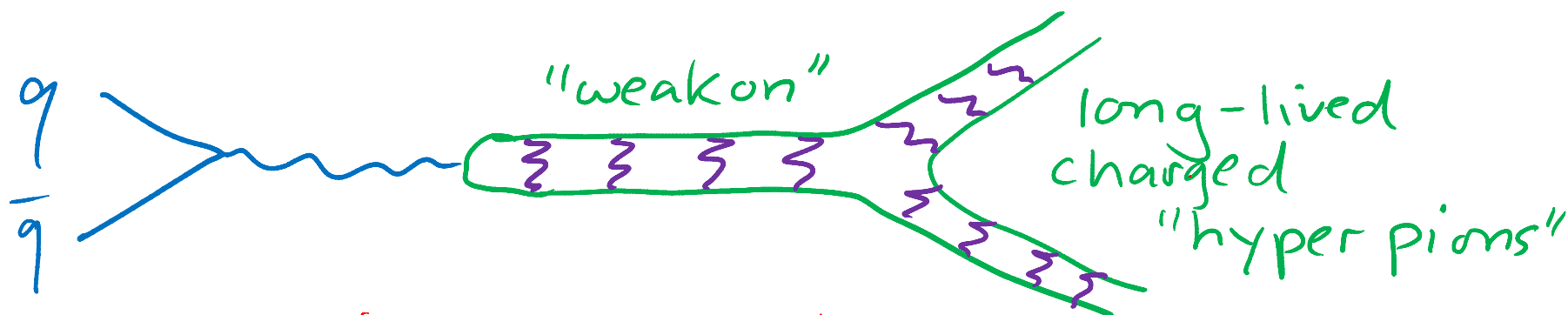
Kilić, Schumann, Son, '09

similarities with "colorons" of
Dobrescu, Kong, Mahbubani '07

Eg. Multi-EW-bosons



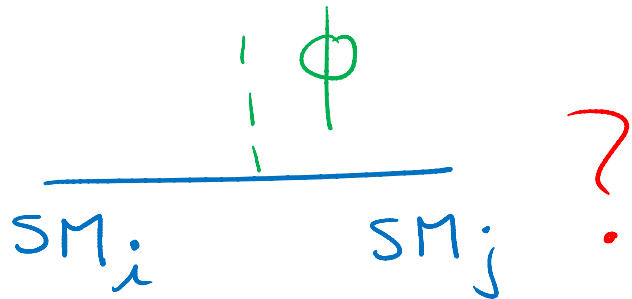
Di-CHAMP resonance



Kilić, Okui, Sundrum '10
Kilić, Okui '10

FLAVORFUL VESTIGES - DIQUARKS

Giudice, Gripaio, Sundrum '11



$$\bar{q}_{Li} q_{Rj} \phi \quad \text{"Higgslike"}$$

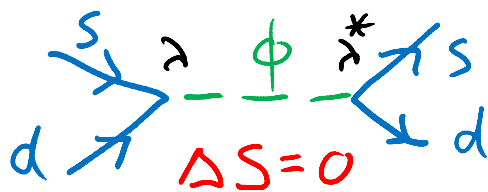
$$\bar{q}_i l_j \phi \quad \text{leptoquark} \quad \text{Gripaio '10}$$

$$q_i q_j \phi \quad \text{diquark}$$

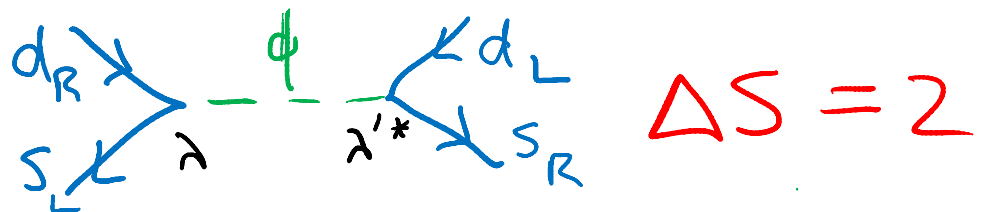
Diquarks remarkably flavor+CP safe

Simple 2-generation example, $\phi = 3_{QCD}$

$$\lambda_{ij} d_{iR}^a d_{jR}^b \phi^c \epsilon_{abc}^{color} \equiv \lambda s d \phi$$



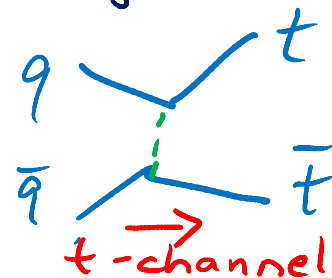
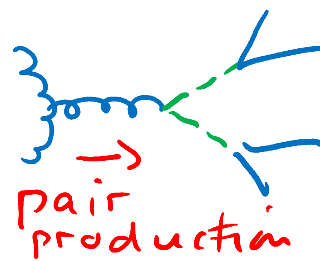
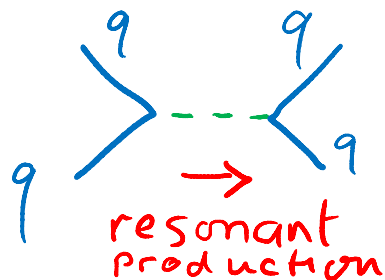
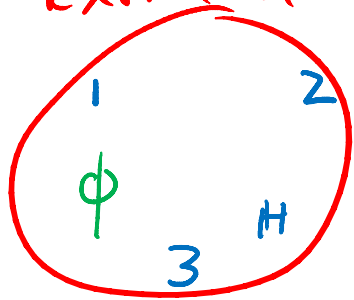
c/w $\phi = \text{Higgs}$ $\lambda \bar{s}_L d_R \phi + \lambda' \bar{d}_L s_R \phi$



EXTENSIONS OF HIERARCHICAL FLAVOR STRUCTURE

from standard elegant flavor paradigms
 ~ Froggatt-Nielsen, extra-dimensional flavor
 wavefunctions,
 partial compositeness

Regular hierarchy dominantly $\phi q_{3\text{-gen}} q_{2\text{-gen}}$
 Inverted hierarchy dominantly $\phi q_1 q_2$
 Perverted hierarchy dominantly $\phi q_1 q_3$
 Extra dimensions Egs. Colored Higgs ϕtb
 $stop_R \phi d_R; d_R; j$



CONCLUSIONS

Nature plausibly SPARSE and/or
MESO-TUNED

Main players of hierarchy problem

— may be out of reach. Flavor/CP
⇒ best vestigial gambles

— may be only particles within
reach. There must be concerted
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.

Likely, mechanisms matter more than detailed UV models

String theory can explore plausibility of mechanisms in string landscape/multi-verse, especially strong dynamics via AdS/CFT

Flavor tests & LHC hugely complementary

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BUMPS ARE COOL!