FLAVOR BEYOND THE STANDARD MODEL

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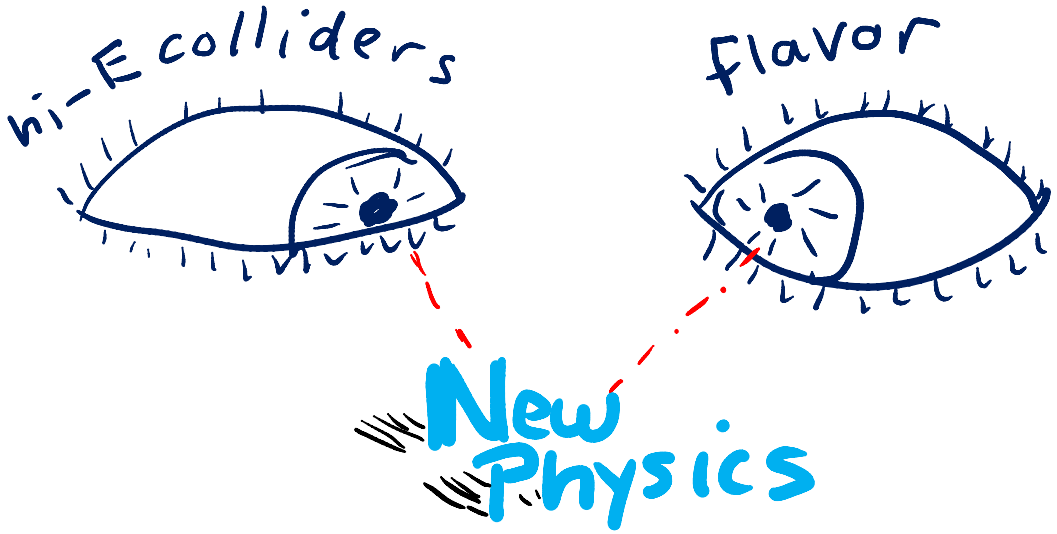
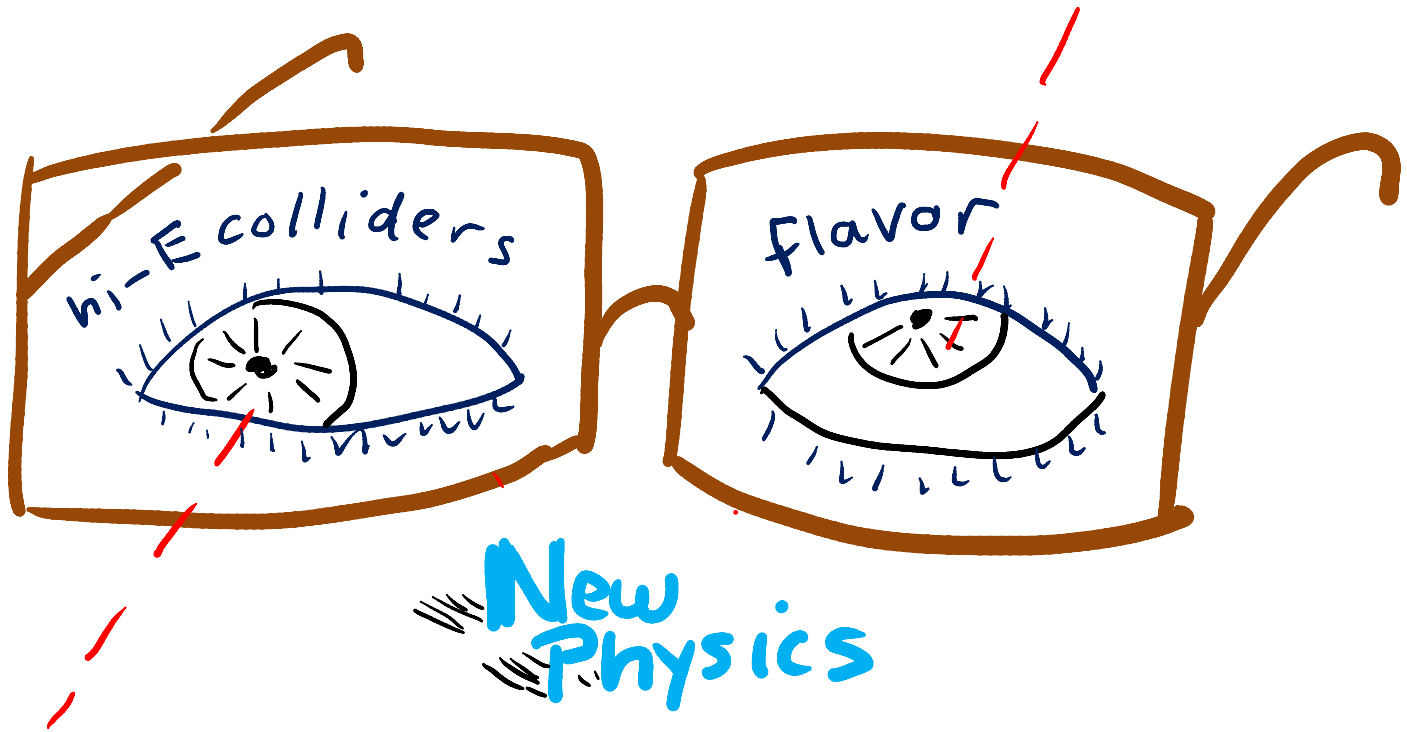


Flavor expt. is tool for discovery & understanding of New Physics.



Where should we look?

How hard should we try?

How should we coordinate?

Origins of flavor structure lie Beyond Standard Model

$$g_{strong}, g_{weak}, g_Y(m_Z) \sim O(1)$$

suggests

$$Y^u_{ij} \sim O(1)_{ij}$$

$$Y^d_{ij} \sim O(1)_{ij}$$

random matrices

Origins of flavor structure lie Beyond Standard Model

$$g_{strong}, g_{weak}, g_Y(m_Z) \sim O(1)$$

DATA suggests something like

$$Y^u_{ij} \sim O(1)_{ij}\, \varepsilon_i^{q_L} \varepsilon_j^{u_R}$$

$$Y^d_{ij} \sim O(1)_{ij}\, \varepsilon_i^{q_L} \varepsilon_j^{d_R}$$

hierarchical

$0 \leq \varepsilon_i \leq 1$

Chiral Hierarchy

terminology from Giudice, Gripaios, Sundrum '11

$$y_{top} = 1 \Rightarrow \epsilon_3^{u_R} \sim \epsilon_3^{q_L} \sim O(1)$$

$$V_{CKM} = \begin{pmatrix} \sim 1 & O(\epsilon_1^q/\epsilon_2^q) & O(\epsilon_1^q/\epsilon_3^q) \\ O(\epsilon_1^q/\epsilon_2^q) & \sim 1 & O(\epsilon_2^q/\epsilon_3^q) \\ O(\epsilon_1^q/\epsilon_3^q) & O(\epsilon_2^q/\epsilon_3^q) & \sim 1 \end{pmatrix}$$

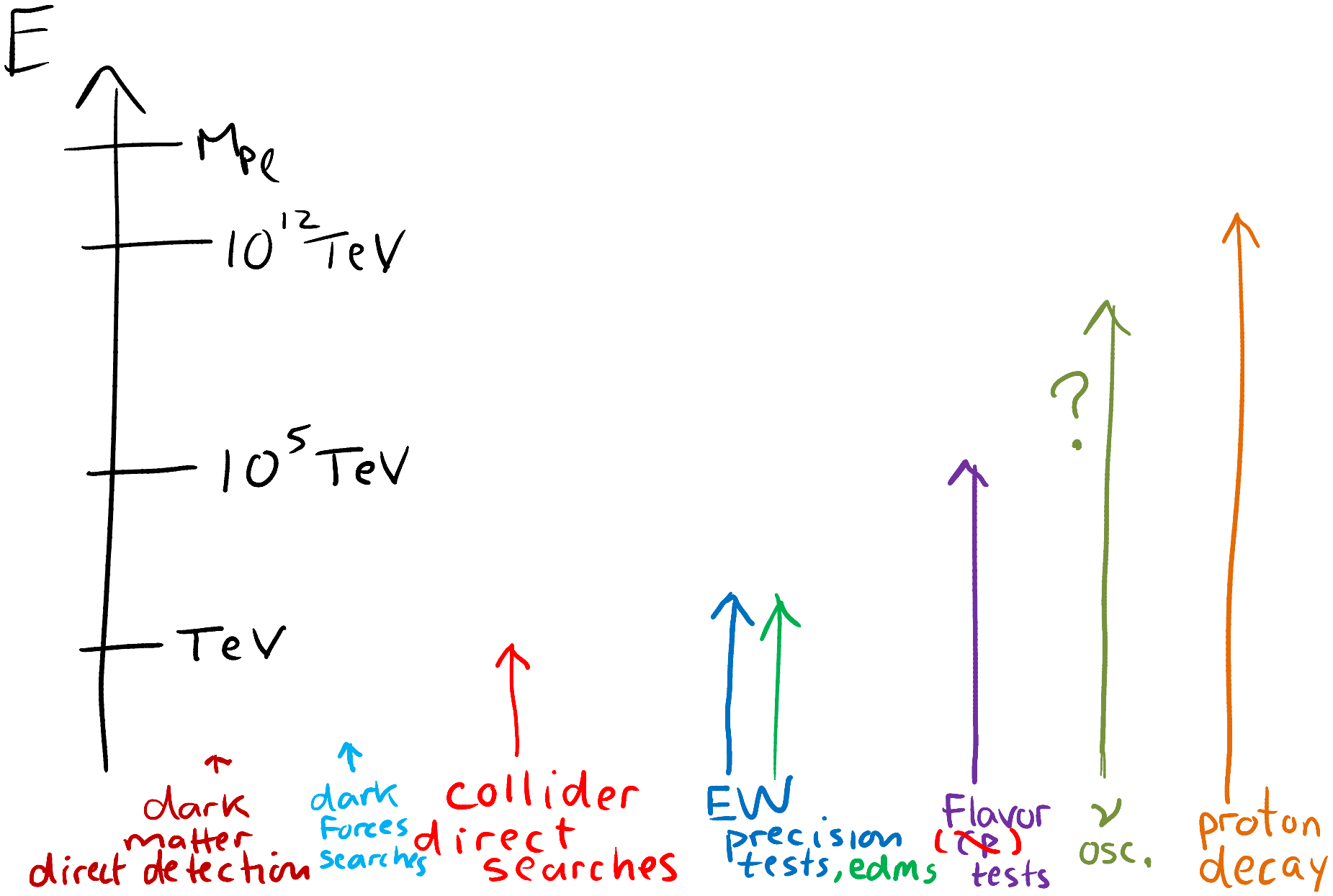
$\Rightarrow$ V_{us}, V_{ub}, V_{cb} measurements

$$\epsilon_1^q \sim \theta_{Cabibbo}, \quad \epsilon_2^q \sim \theta_{Cabibbo}^2$$

$$m_u, m_d, m_c, m_s, m_b \Rightarrow \epsilon_3^d \sim \frac{m_b}{m_t}, \quad \epsilon_2^d \sim \frac{m_s}{m_t V_{cb}}, \quad \epsilon_1^d \sim \frac{m_d}{m_t V_{us} V_{cb}}$$

$$\epsilon_2^u \sim \frac{m_c}{m_t V_{cb}}, \quad \epsilon_1^u \sim \frac{m_u}{m_t V_{us} V_{cb}}$$

NOTHING YET ?


E
M_{Pl}
10^{12} TeV
10^{5} TeV
TeV
dark matter direct detection
dark Forces searches
collider direct searches
EW precision tests, edms
Flavor (CP) tests
?
ν osc.
proton decay

KEEP HOPE ALIVE!

New Physics can hide well:

Examples:

1) Dark Matter exists & could be WIMP

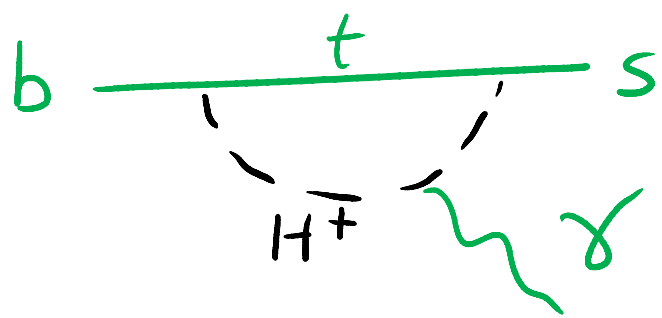
2) $m_\nu \neq 0$ with rich lepton flavor physics

3) Even rich pheno of SM Higgs boson hides quite well from generic new physics collider search strategies. It required all-out coordinated effort for discovery.

4) Two-Higgs-Doublet SM also hides very well from collider searches.

H_{up}, H_{down} structure generalizes GIM & hides well from flavor tests too.

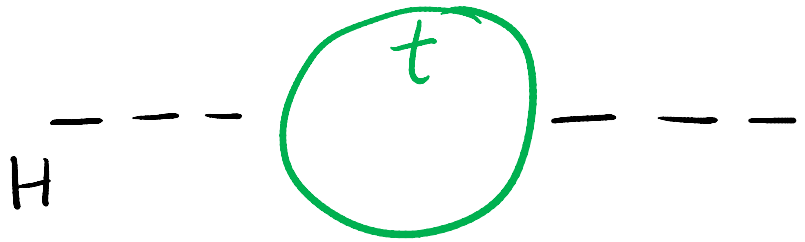
But not arbitrarily well...



New physics can enhance SM flavor violation, even without new sources of flavor violation

HIERARCHY PROBLEM

$m_Z^2 / M_{Pl}^2 \ll 1$ but SM radiative corrections $\sim O(1)$

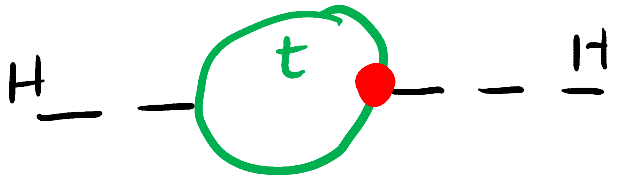


2 BROAD MECHANISMS known:

Algebraic

SUSY cancelations

Dynamical

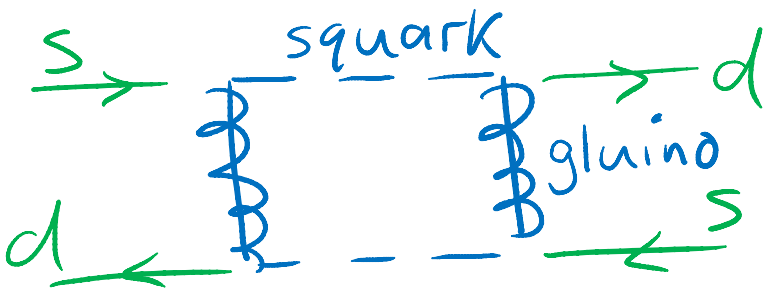


Form-factor suppression of Higgs COMPOSITENESS

$\Rightarrow$ VERY RICH SPECTRUM

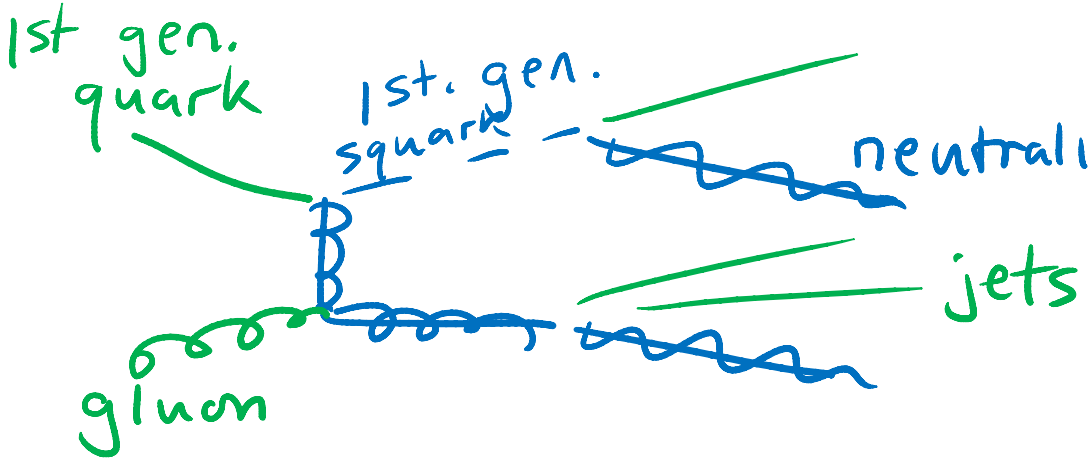
- No perfect BSM model is known, but $\exists$ beautiful mechanisms
- Extending GIM mechanism protection against mediating excessive FCNCs is central model-building concern.
- Discoveries may well require both "eyes", direct searches + flavor expt.

SUSY (+ R-parity)



What flavor expt. tests best

avoided if squark mass matrix $\propto$ I
"flavor universal"



What LHC tests best

$\lesssim 1.5$ TeV

There is now a tension between LHC & flavor universality & naturalness

"Natural" SUSY

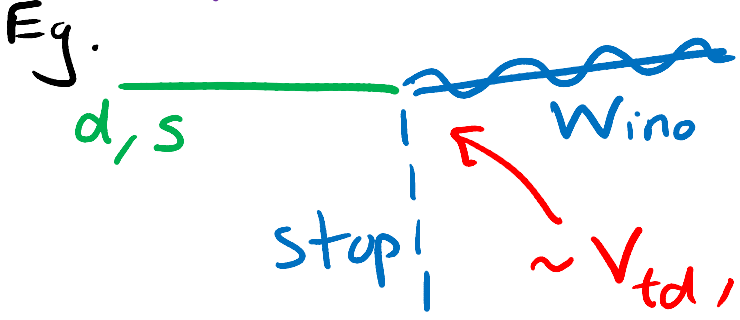
Naturalness $\Rightarrow$ stops $\lesssim$ TeV (roughly)

but other squarks may be much heavier

Perhaps just 1-2 gen. universality

This minimal sub-TeV physics hides much better at LHC (but not for long).

Distinctive flavor violation because stops/sbottom are in gauge basis.



Provides automatically interesting-but-not-dead targets for Flavor & edms.

Brust, Katz, Lawrence Sundrum '11 + Refs. therein

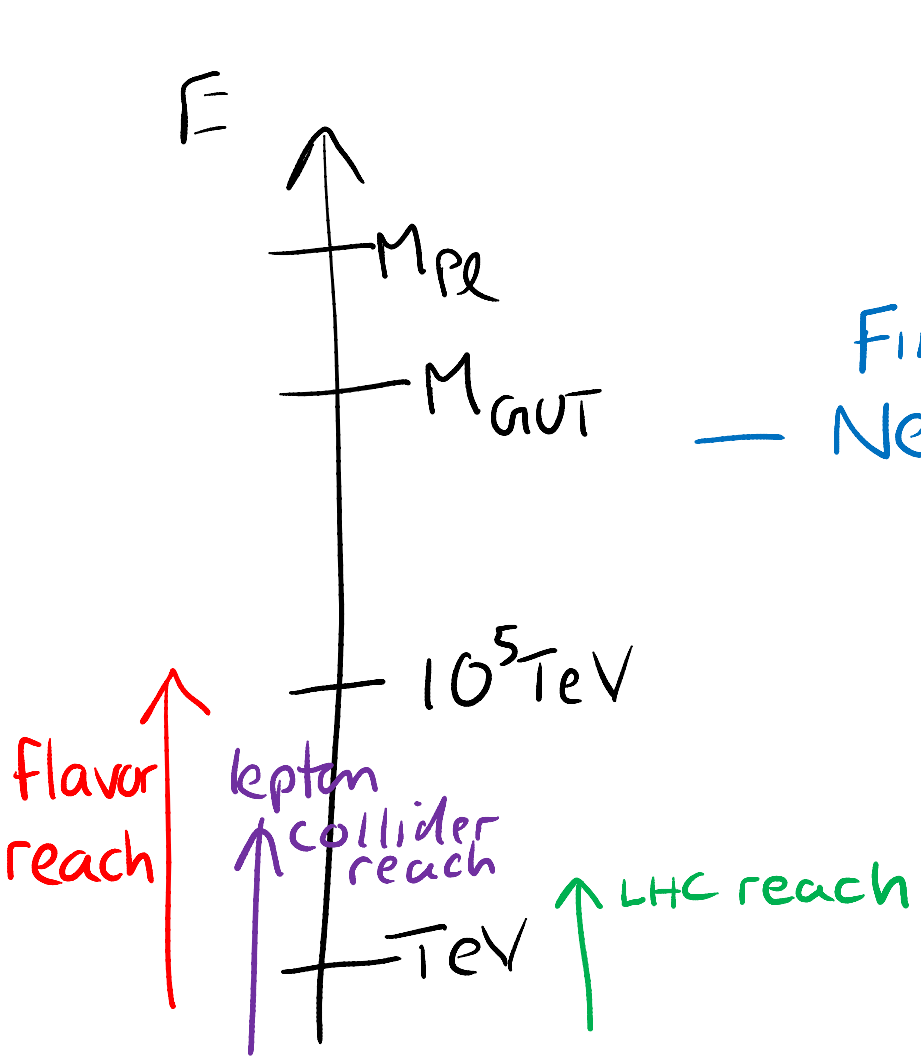
Failure IS an option

Naturalness & Hierarchy Problem are simple betting tools For New Physics.

But there may be complications: anthropic principle, multiple string vacua, multiverse, ... Eg. Douglas, Kachru '07

The jury is out...

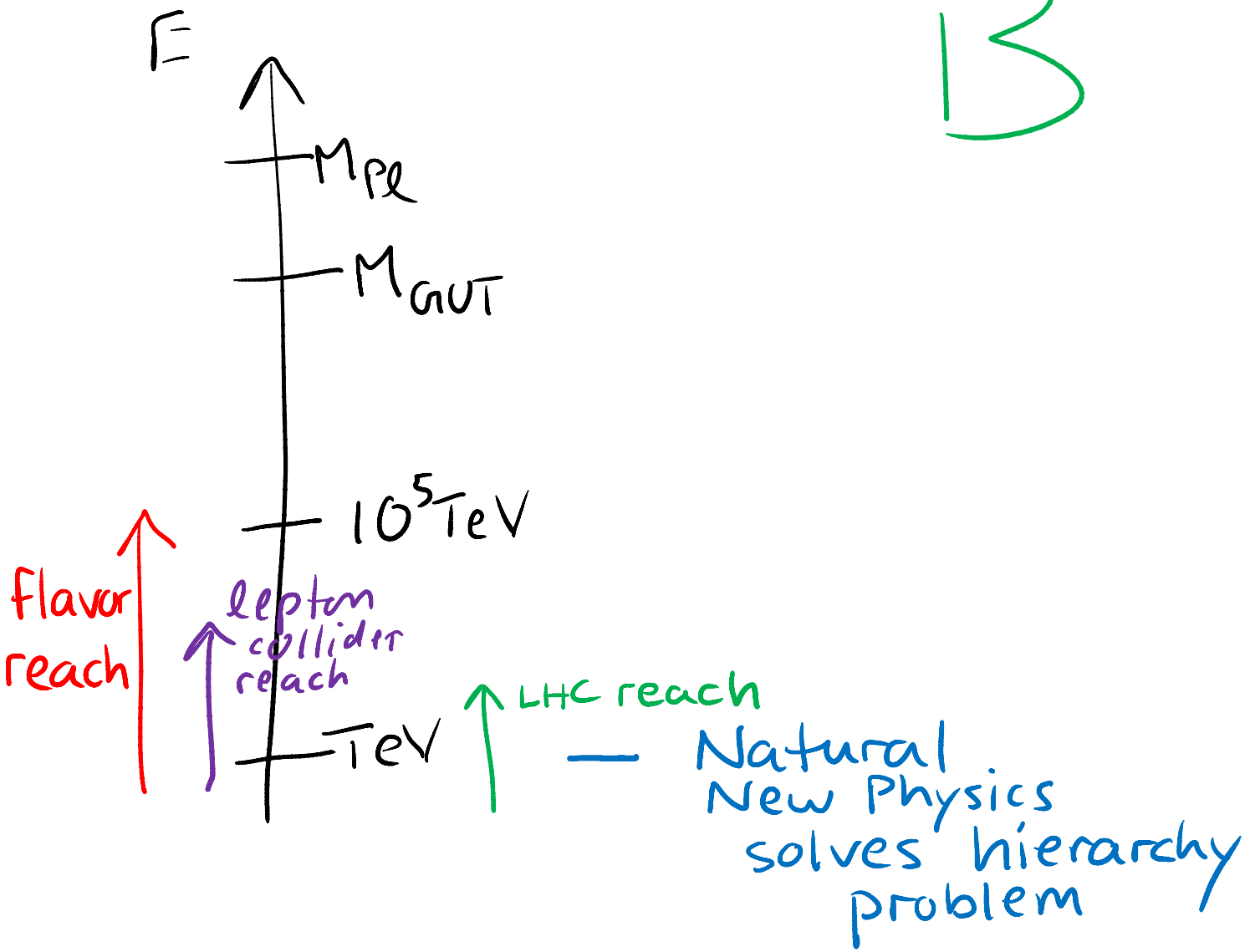
NATURE'S OPTIONS



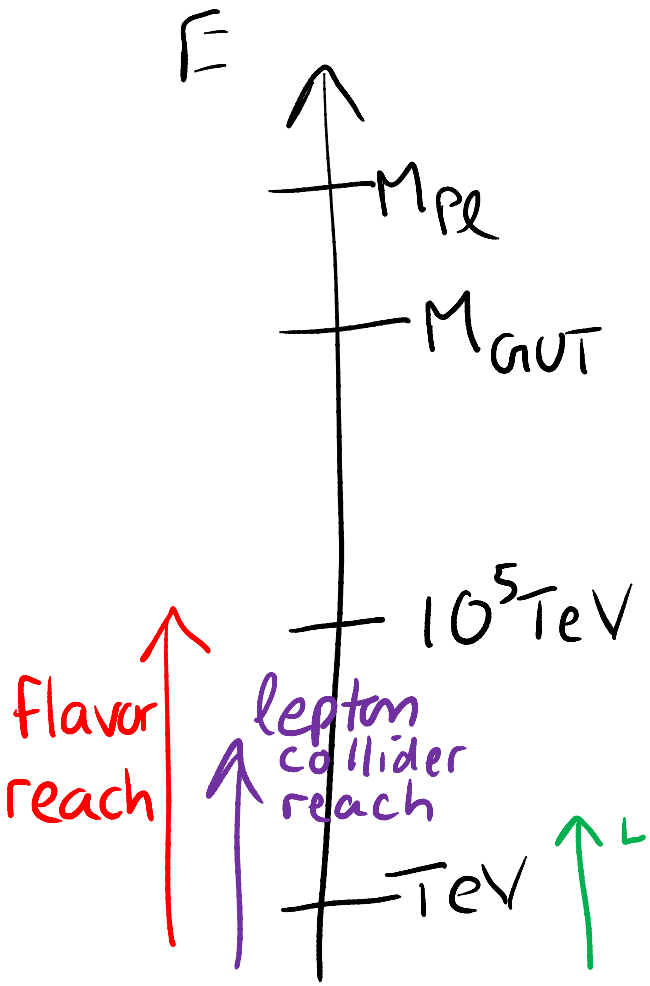
Fine-tuned
— New Physics

NATURE'S OPTIONS

B



NATURE'S OPTIONS



C

& my best guess

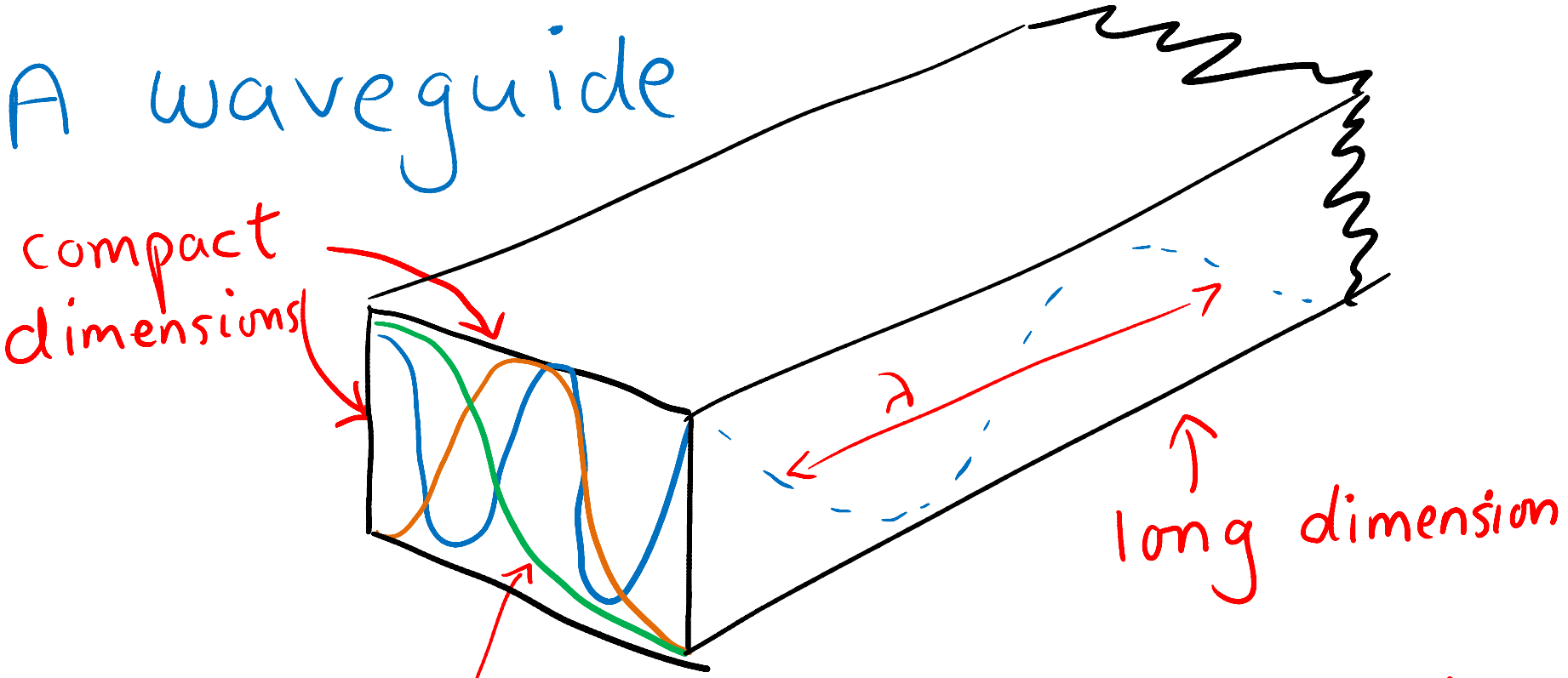
"Meso-tuned" — New Physics

imperfectly solves hierarchy problem

Flavor expts. might be only game in town

FLAVOR STRUCTURE ORIGINATES IN...

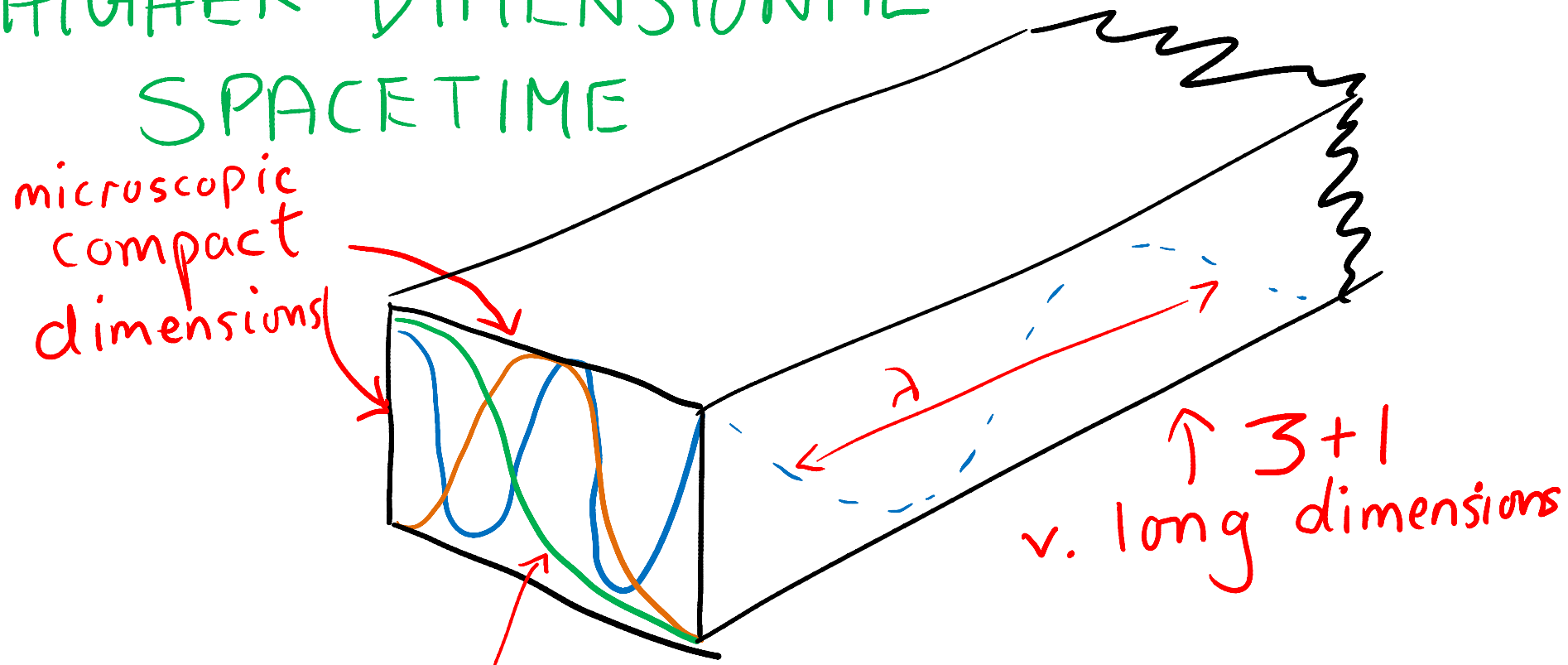
A waveguide



different modes have different fixed profiles in compact dimensions, but arbitrary λ

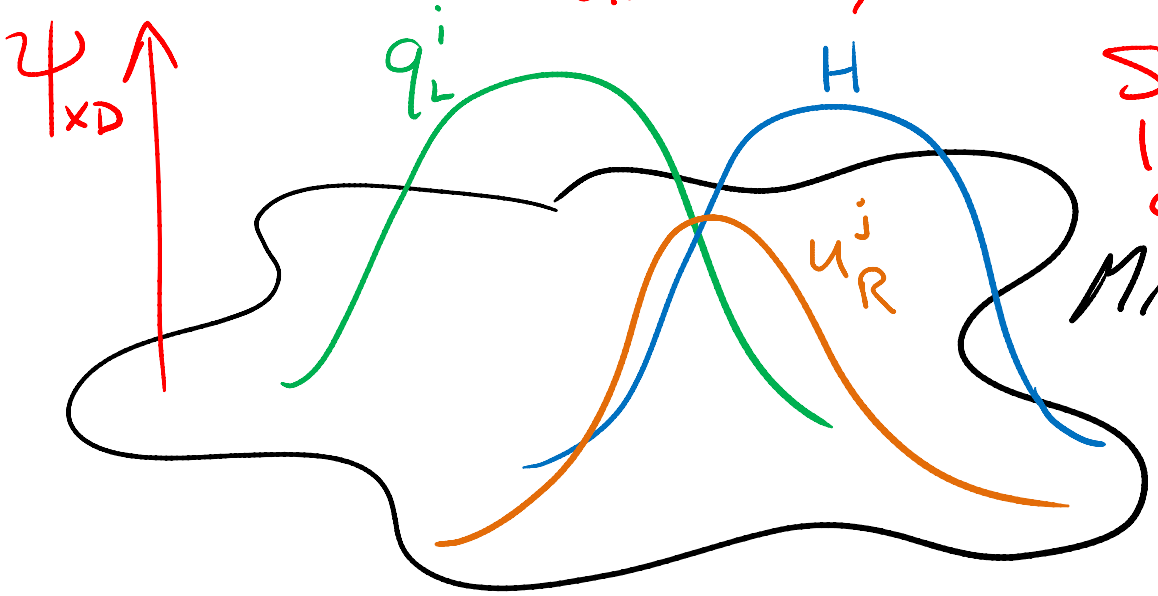
FLAVOR STRUCTURE ORIGINATES IN...

HIGHER DIMENSIONAL SPACETIME



EXTRA DIMENSIONS (XD)

string theory; Arkani-Hamed, Schmaltz '99; Grossman, Neubert '00; Gherghetta, Pomarol '00...

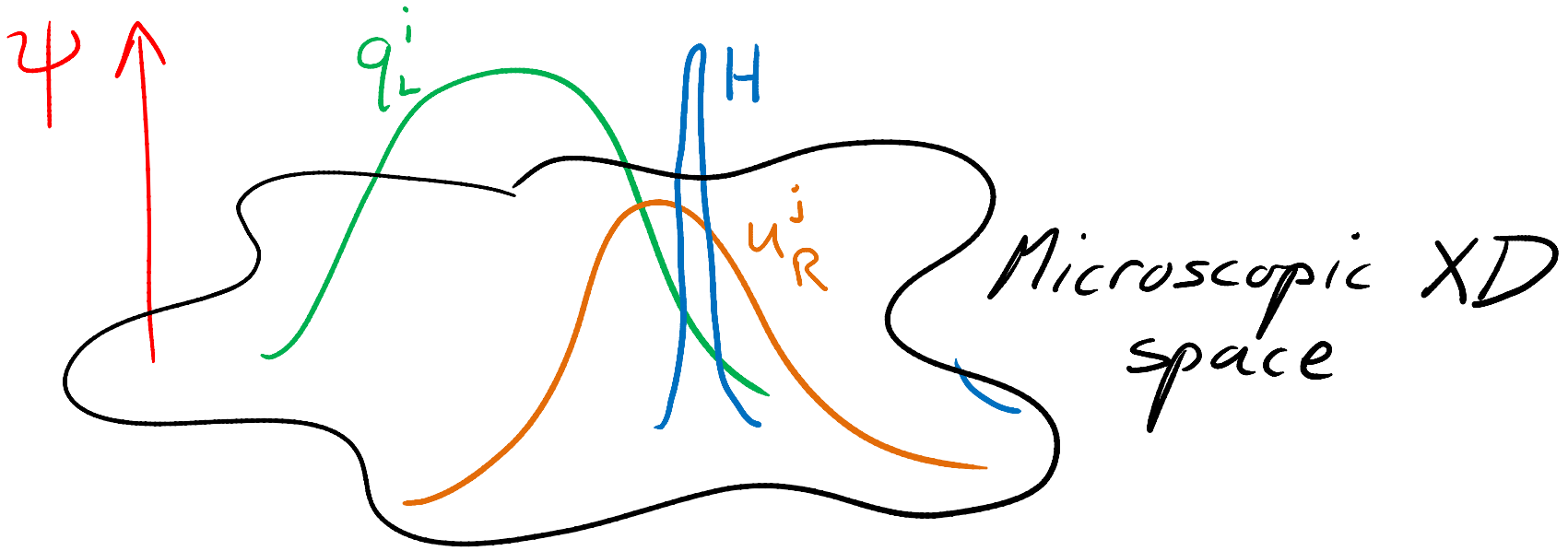


SM fields localized differently in Microscopic XD space

XD wavefunction overlaps

$$Y_{ij} = O(1)_{ij} \int d^{XD} \psi_i \psi_j \psi_H$$

EXTRA DIMENSIONS (XD)



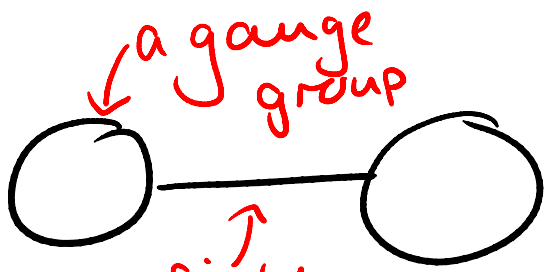
$$Y_{ij} = O(1)_{ij} \int d^{XD} \psi_i \psi_j \psi_H$$

$$\sim O(1)_{ij}\, \varepsilon_i \varepsilon_j \text{ if } \psi_H \text{ most sharply peaked}$$

$\Rightarrow$ CHIRAL HIERARCHY

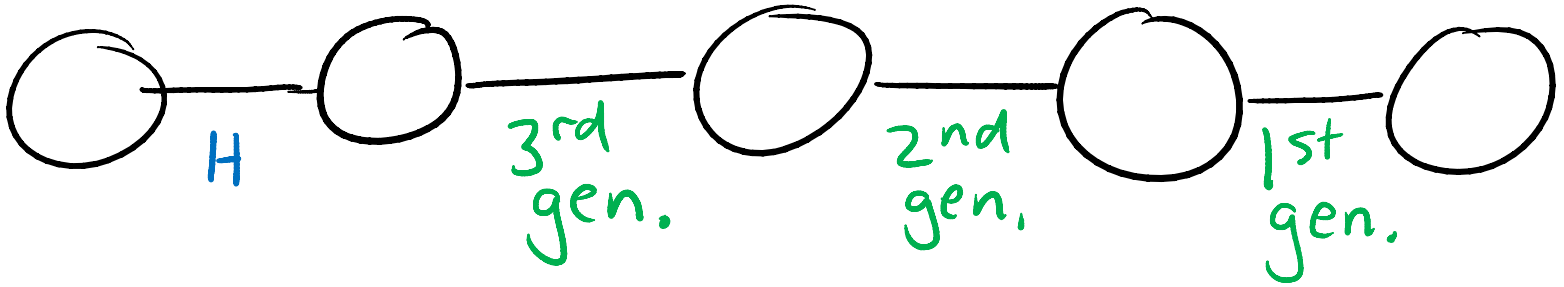
~ SUBSUMES OTHER IDEAS

SM fields differentiated by richer UV gauge structure



~ SUBSUMES OTHER, MORE ALGEBRAIC, IDEAS

SM fields differentiated by richer UV gauge structure



~ "Lattice XD" ("Theory Space")

Arkani-Hamed, Cohen, Georgi '01
Hill, Pokorski, Wang '01

Frogatt-Nielsen flavor mechanism resembles XD: $\varepsilon_i \equiv \left(\langle \phi_{FN} \rangle / M\right)^{Q_i}$

COMPOSITE HIGGS

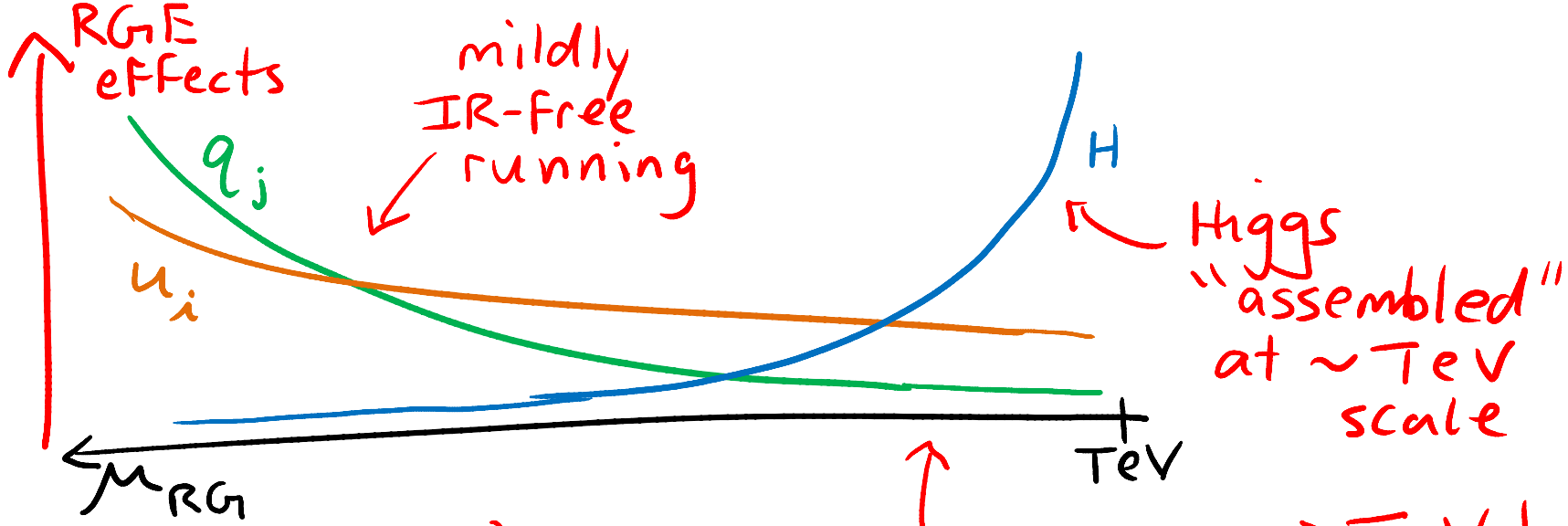
Georgi, Kaplan '84

H = "hadron" of TeV-scale new strong dynamics

Partial Compositeness

Kaplan '91

$q_i \mathcal{O}_i$ SM fermions mix with different fermionic operators of strong sector



origins of flavor structure $\gtrsim$ TeV !

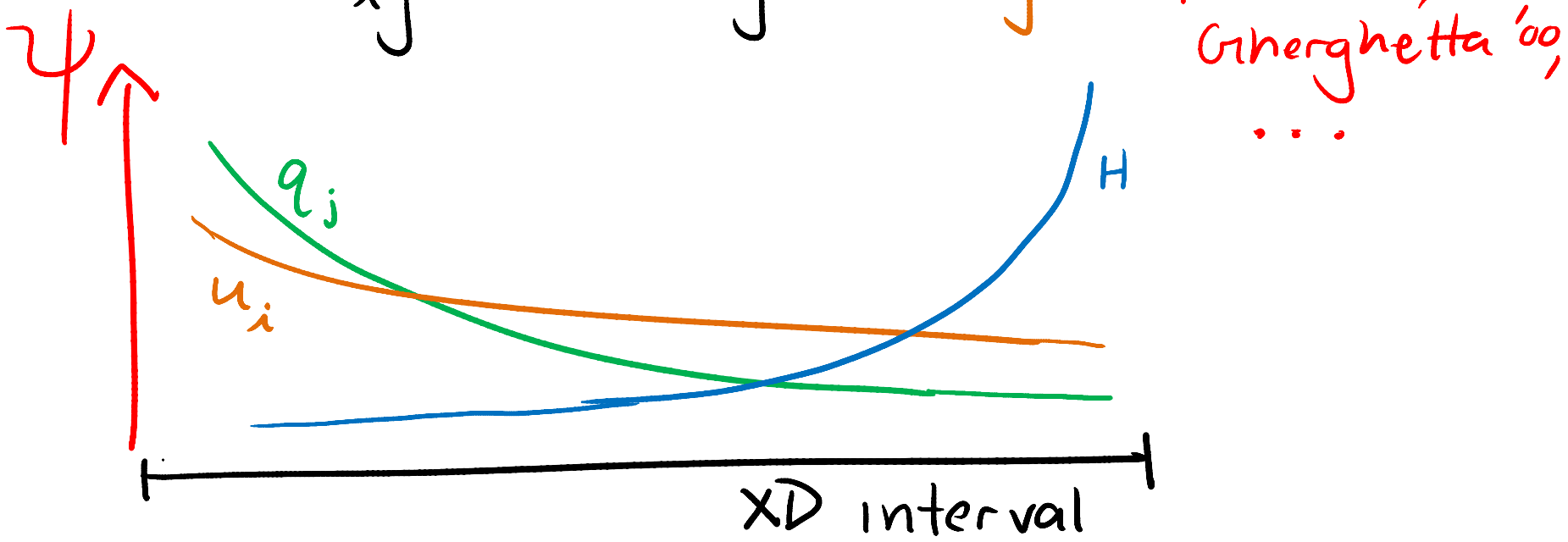
RS1 / Warped XD

AdS/CFT duality

Partial Compositeness
= Warped XD overlap
$\Longrightarrow$ Chiral Hierarchy

$$Y_{ij} = O(1)_{ij}\, \varepsilon_i\, \varepsilon_j$$

Pomarol, Gherghetta '00, ...



RS1/Warped XD.

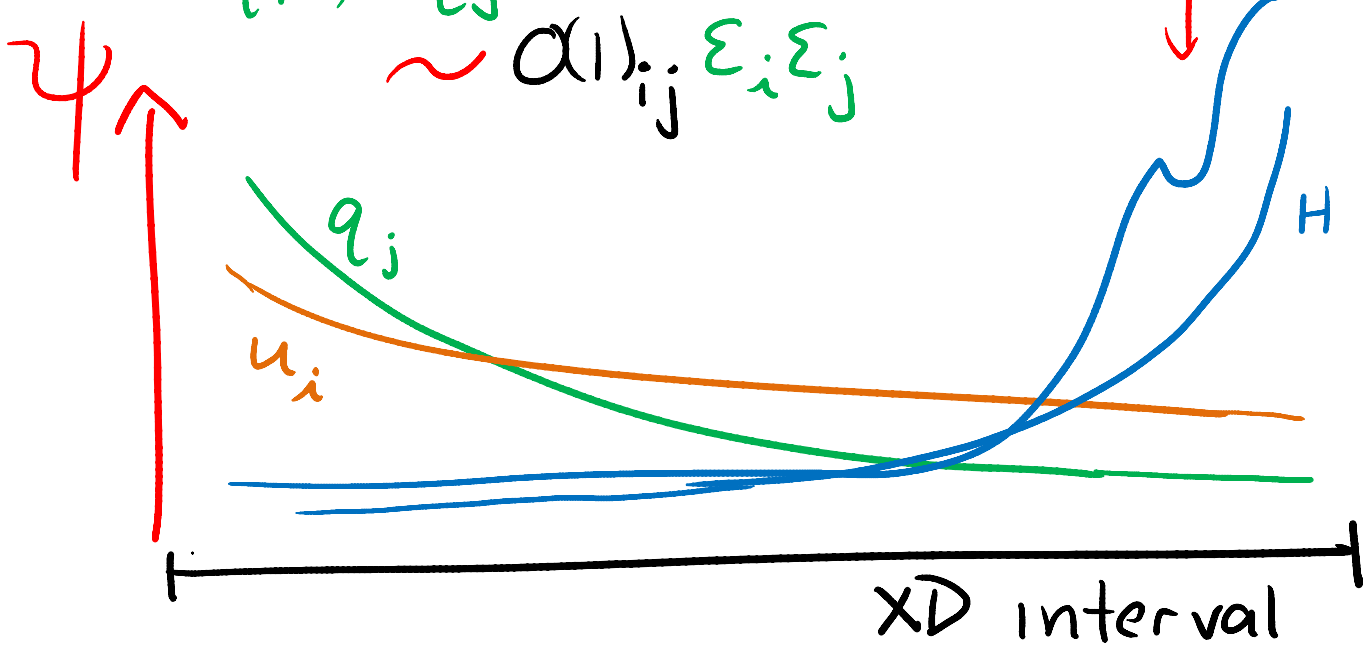
AdS/CFT duality

New physics excitations couple hierarchically too

Eg. $\bar{q}_i \gamma_\mu q_j V^\mu$ ← spin-1 excitation

$\sim a(1)_{ij} \varepsilon_i \varepsilon_j$

Kaluza-Klein excitation (excited composite)



See eg. Csaki, Falkowski, Weiler '08 & refs. therin & citations thereof

LOW-ENERGY IMPACT

New Physics ANARCHY

suppressed, but plausible in some ~~susy~~ scenarios

$$\mathcal{L}_{\text{effective}} = \mathcal{L}_{SM} + \mathcal{L}_{\text{non-ren.}}\left(q^L_i, u^R_j, d^R_j, \text{bosons}^{SM}\right)$$

operators suppressed by new scale M with $\mathcal{O}(1)$ flavor-dependent coefficients

Eg. $\dfrac{\mathcal{O}(1)_{ijkl}}{M^2}\bar{q}_i\gamma_\mu q_j\,\bar{d}_k\gamma^\mu d_l$

Partial Compositeness

See recent Keren-Zur, Lodone, Nardecchia, Pappadopulo, Rattazzi, Vecchi '12 +Refs.

$$\mathcal{L}_{\text{eff.}} = \mathcal{L}_{SM} + \mathcal{L}_{\text{non-ren}}\left(\varepsilon^q_i q_i, \varepsilon^u_j u^R_j, \varepsilon^d_k d^R_k\right)$$

Eg. $\mathcal{O}(1)_{ijkl}\,\varepsilon_i\varepsilon_j\varepsilon_k\varepsilon_l\,\bar{q}_i\gamma_\mu q_j\,\bar{d}_k\gamma^\mu d_l/M^2$

Minimal Flavor Violation (MFV)

Ansatz

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \mathcal{L}_{non\text{-}ren}\left(q_i, u_j, d_k, Y^{u/d}_{ln}\right)$$

Flavor-violating only via SM Yukawa matrices

Eg. $\frac{Y^d_{il} Y^{*d}_{jk}}{M^2} \bar{q}_i \gamma^\mu q_j \bar{d}_k \gamma^\mu d_l$

With current UV theory, I find MFV poor bet.

Nevertheless Partial Compositeness "$\sim \alpha(1)\sqrt{\text{MFV}}$"

or slightly more generally "NMFV"

Agashe, Papucci, Perez, Pirjol '06

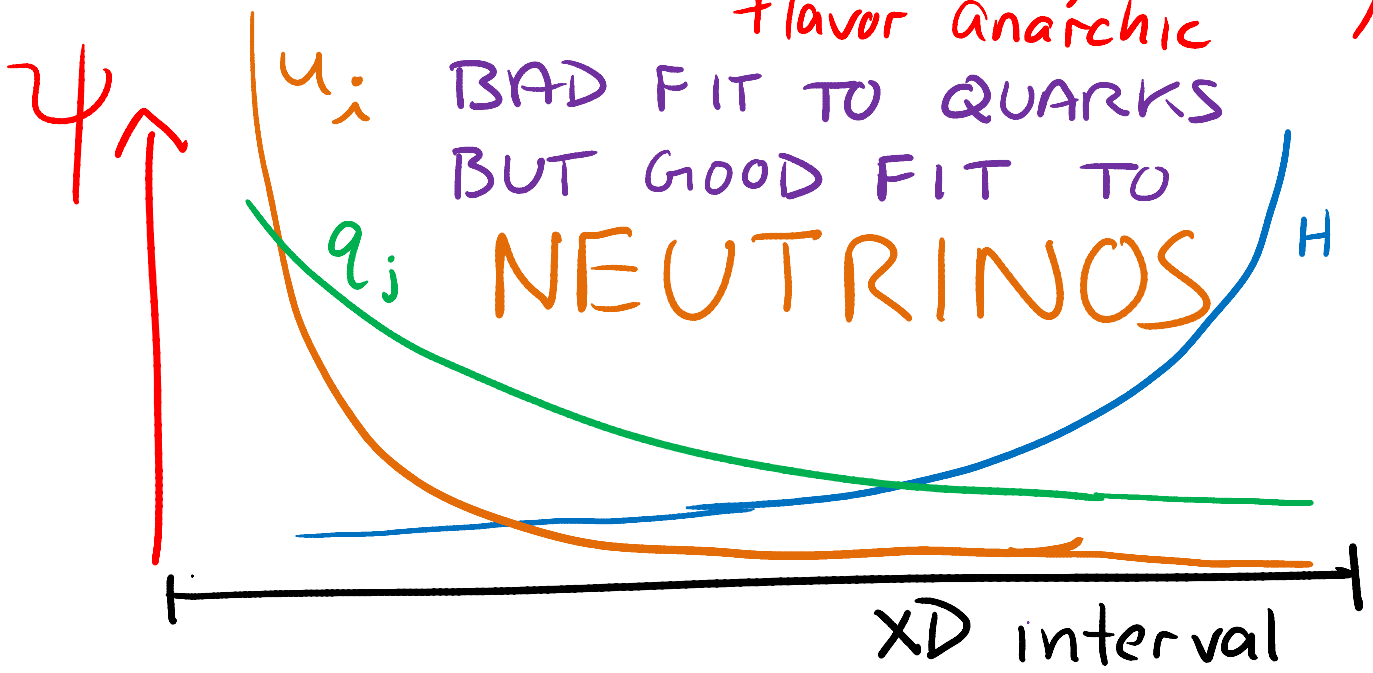
Extremely Light Fermions

can have (one chirality) even more localized than H:

$$\int dx_D \, \psi_i \psi_j \psi_H \sim \mathcal{O}(1)_{ij} \, \psi_H^{(\text{far left})}$$

flavor anarchic

but v. small



Agashe, Okui, Sundrum '08

EXTRA DIMENSIONS (XD)

More generally than partial compositeness

New Particles can couple with v. different hierarchies from H if localized in XD differently:

$$\sim \int dx_D \, \psi_i^{SM} \psi_j^{SM} \psi_{new}$$

Case study: DIQUARKS

Scalar diquarks, eg. $\phi\, d^R_i d^R_j$,

color triplets

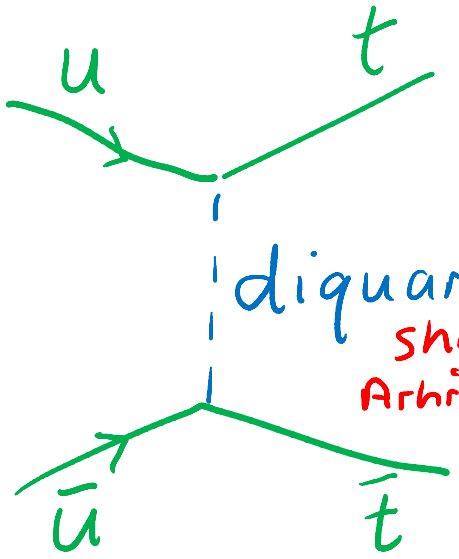
are unusually (accidentally) CP & flavor-safe, permitting unusual (non-H-like) flavor hierarchies. They can mediate ~~flavor~~, visible in future.

Giudice, Gripaios, Sundrum '11 + Refs.

They are prototype of squarks in R-parity-violating SUSY.

Flavor & collider searches can combine to understand tentative anomalies

Egs. Tevatron



Shu, Tait, Wang '10
Arhrib, Benbrik, Chen '10

Kilic, Thomas '11

$\Rightarrow W(jj)_{\text{resonance}}$

$\Rightarrow A_{FB}^{top}$

Flavor implications crucial to vet, & guess where to look next Giudice, Gripaios, Sundrum '11

CONCLUSIONS

- NEW flavor physics may be around corner.
- Testable flavor structures compared: anarchy, partial comp., (N)MFV, Natural SUSY, diquarks, lepton flavor.
- 3rd gen. ~~Flavor~~ + edms are "preferred" bet, but mildly. Any channel may prove to be decisive, BSM theory v. open.
- Coordinated rapid response to vet tentative anomalies, & suggest where to look next. ?