# BEYOND THE STANDARD MODEL @ THE TEV SCALE

NATHANIEL CRAIG
UC SANTA BARBARA

2017 ICTP SUMMER SCHOOL ON PARTICLE PHYSICS

# NOT YOUR ADVISOR'S "BEYOND THE STANDARD MODEL"


BSM IS AS OLD AS THE STANDARD MODEL, GIVING RISE TO DOMINANT PARADIGMS (THE MSSM, WIMPS, ETC.) THAT FILL LECTURES SUCH AS THESE. *BUT WE ARE IN AN ERA RICH WITH DATA THAT IS CHALLENGING THESE PARADIGMS, SO LET'S KEEP AN EYE ON PROMISING ALTERNATIVES.*

# OUTLINE

## PROLOGUE: EFFECTIVE FIELD THEORY

## PART 1: HIERARCHY PROBLEMS

- NATURALNESS
- SCALAR MASSES
- VERSIONS OF THE HIERARCHY PROBLEM

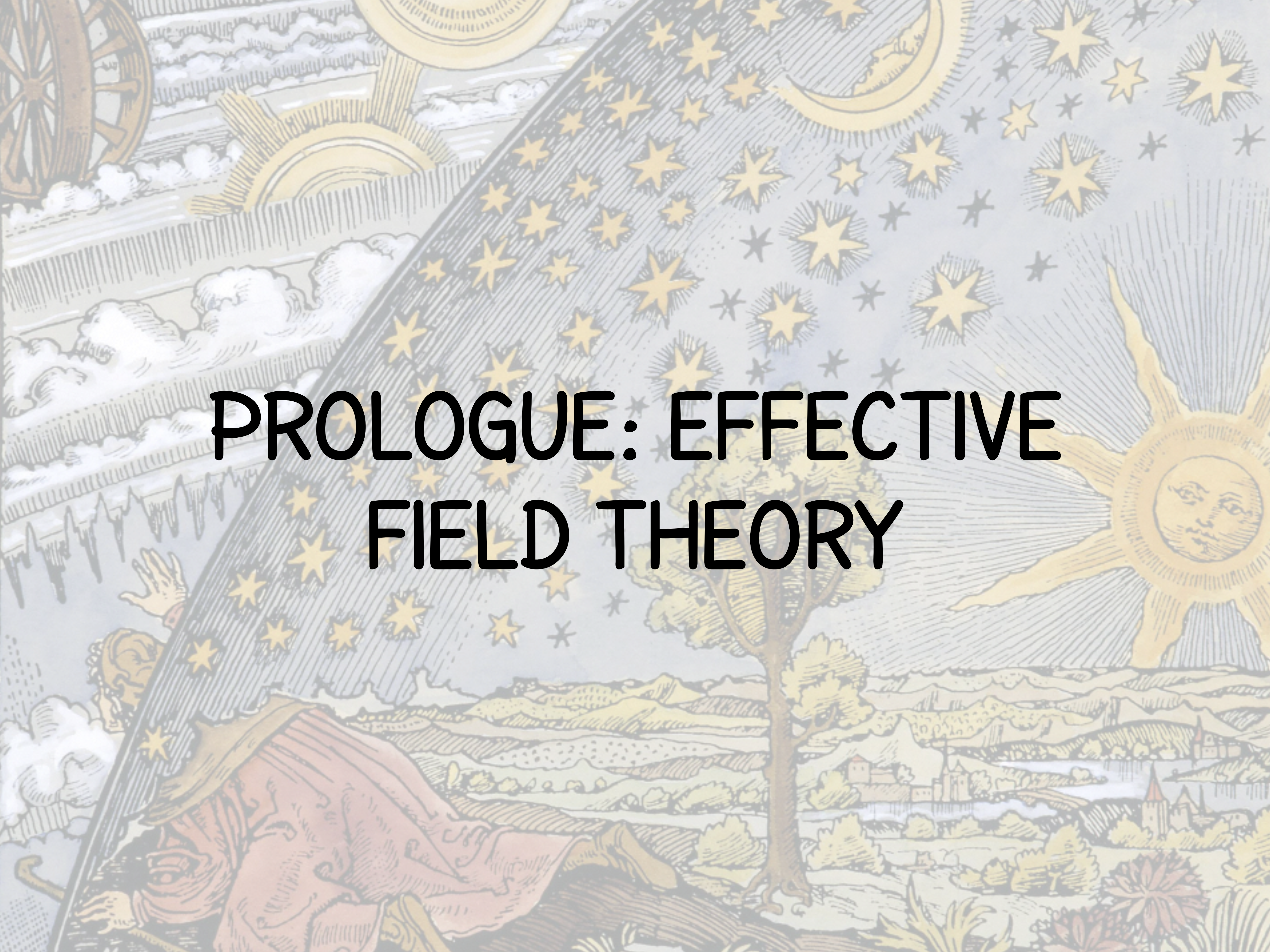
## PART 2: HIERARCHY SOLUTIONS

- MULTIPLE VACUA
- LOW CUTOFFS
- SYMMETRIES

## PART 3: EVERYTHING* ELSE

- STRONG CP PROBLEM
- UNIFICATION
- BARYOGENESIS

## EPILOGUE: LOOKING TO THE FUTURE

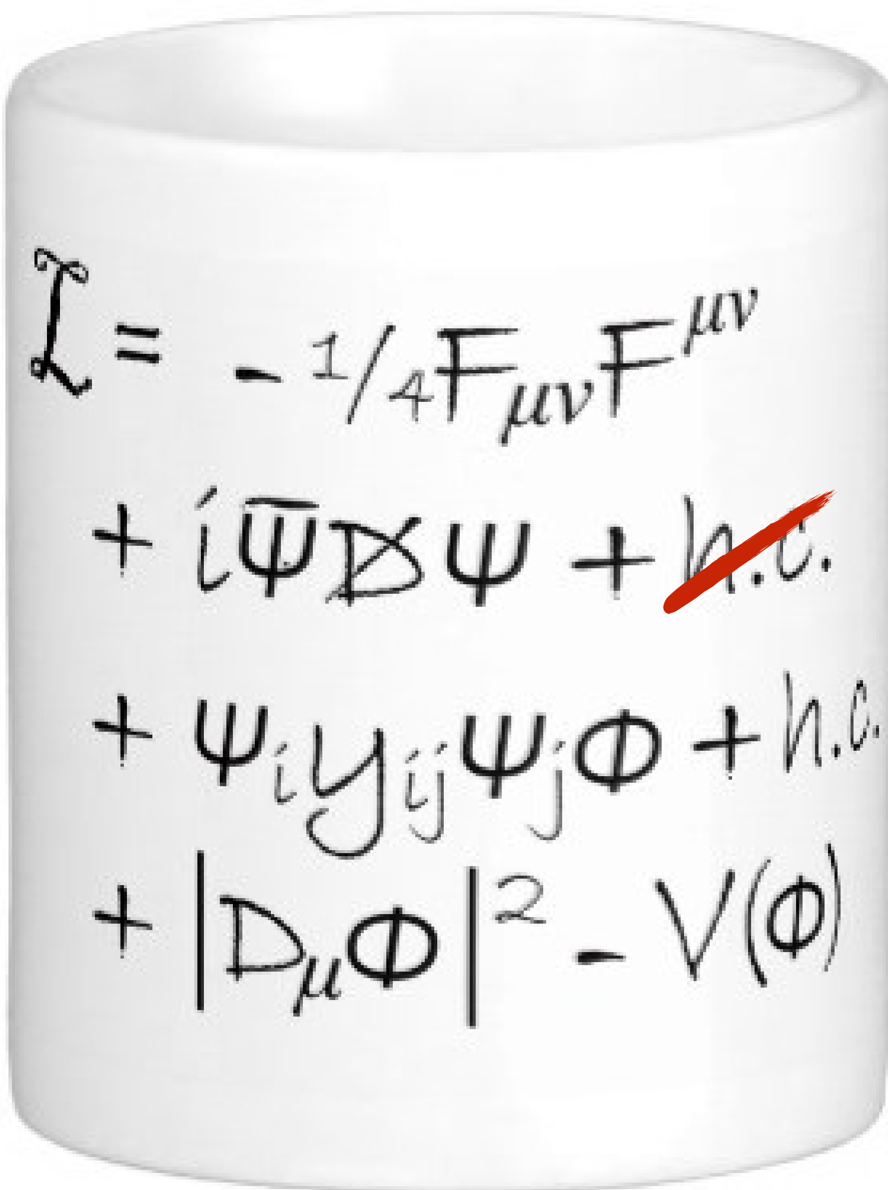


# PROLOGUE: EFFECTIVE FIELD THEORY

SEE LECTURES BY Y. NIR

# BEYOND?

BY ***STANDARD MODEL***, LET US TAKE THIS TO MEAN




(1) THE OBSERVED MATTER (THREE GENERATIONS OF QUARKS & LEPTONS), HIGGS DOUBLET, AND GAUGE FIELDS.

(2) ALL RENORMALIZABLE (MARGINAL OR RELEVANT) INTERACTIONS ALLOWED BY THE FIELD CONTENT & GAUGE SYMMETRIES ("TOTALITARIAN PRINCIPLE")

**BSM** ENTAILS ANYTHING BEYOND THIS (NEW FIELDS ***OR*** IRRELEVANT OPERATORS)

# IRRELEVANT?

CONSIDER SCALAR FIELD THEORY IN 4 DIMENSIONS W/ SOME POLYNOMIAL POTENTIAL:

$$S[\phi] = \int d^4x \left[\frac{1}{2}\partial^\mu\phi\partial_\mu\phi - \frac{1}{2}m^2\phi^2 - \frac{1}{4!}\lambda\phi^4 - \frac{1}{6!}\tau\phi^6\right]$$

IN ANY D, MASS DIMENSIONS OF LENGTH & ACTION FIXED, $[x] = -1, [S] = 0$

SO: $[d^4x] = -4$ $[\phi] = 1$ $[m^2] = 2$ $[\lambda] = 0$ $[\tau] = -2$

STUDY THEORY AT LONG DISTANCES IN SCALING LIMIT $x^\mu = s x'^\mu$, $s \to \infty$, $x'^\mu$ fixed

*KEEP CANONICAL KINETIC TERM, SO WORK W/* $\phi(x) = s^{(2-d)/2}\phi'(x')$

$$S'[\phi'] = \int d^4x' \left[\frac{1}{2}\partial^\mu\phi'\partial_\mu\phi' - \frac{1}{2}m^2 s^2\phi'^2 - \frac{1}{4!}\lambda s^0\phi'^4 - \frac{1}{6!}\tau s^{-2}\phi'^6\right]$$

GROWS AT LONG DISTANCE (**RELEVANT**)

CONSTANT (**MARGINAL**)

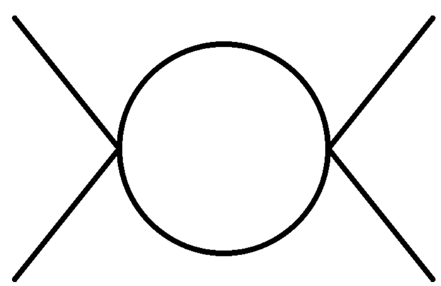
SHRINKS (**IRRELEVANT**)

# RENORMALIZABLE?

THEORIES WITH ONLY MARGINAL & RELEVANT OPERATORS ARE *RENORMALIZABLE.*
HISTORICALLY IMPOSE RENORMALIZABILITY IN ORDER TO PRESERVE *PREDICTIVITY.*

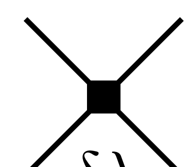
LOOPS INTRODUCE DIVERGENCES, REMOVED W/ COUNTERTERMS. FIX COUNTERTERMS WITH DATA.
*RENORMALIZABILITY = FINITE # OF COUNTERTERMS = PREDICTIVE*
(I.E. USE SOME DATA TO FIX COUNTERTERMS, MAKE PREDICTIONS FOR OTHER MEASUREMENTS)

IN OUR EXAMPLE, ONLY DIVERGENCE FROM MARGINAL/RELEVANT OPERATORS IS



$$\sim \lambda^2 \int \frac{d^4k}{k^4} \sim \lambda^2 \log \Lambda$$

$\Rightarrow$NEED COUNTERTERM

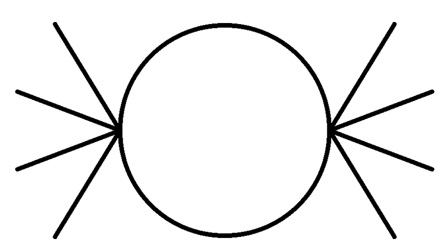


$\delta\lambda$

RENORMALIZES THE MARGINAL OPERATOR

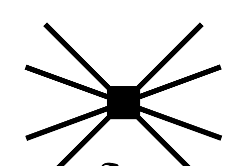
$$\lambda\phi^4$$

BUT IRRELEVANT OPERATOR $\phi^6$ GENERATES



$$\sim \tau^2 \int \frac{d^4k}{k^4} \sim \tau^2 \log \Lambda$$

$\Rightarrow$NEED COUNTERTERM



$\delta\rho$

RENORMALIZES *NEW* IRRELEVANT OPERATOR

$$\rho\phi^8$$

ADDING $\phi^8$ OPERATOR THEN GENERATES $\phi^{10}$ OPERATOR, AND SO ON *AD INFINITUM.*

NEED INFINITE # OF MEASUREMENTS TO FIX ALL COEFFICIENTS.

# ALL IS NOT LOST

*CAN WE LIVE WITH A NONRENORMALIZABLE THEORY?*

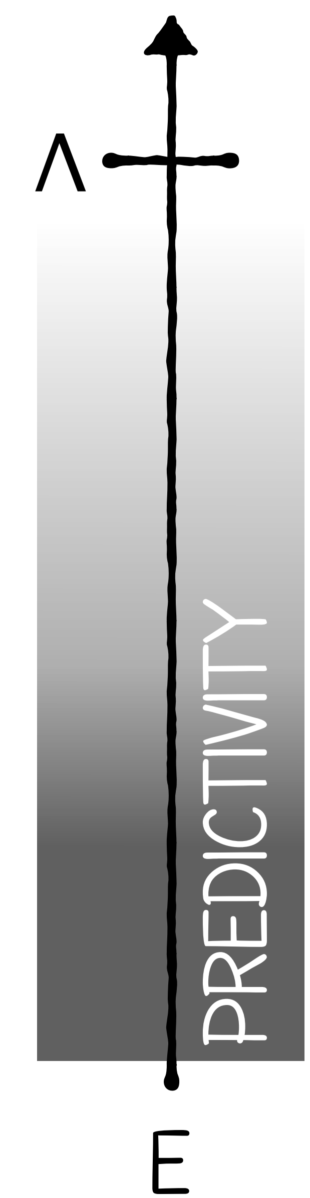
$$[d^4x] = -4 \quad [\phi] = 1 \quad [m^2] = 2 \quad [\lambda] = 0 \quad [\tau] = -2$$

$\tau$ HAS MAS DIMENSION -2. AT SOME SCALE $\Lambda$, $\tau \sim 1/\Lambda^2$.

AT ENERGIES $E \ll \Lambda$, EFFECTS OF $\phi^6$ ON MARGINAL/RELEVANT PHYSICS ARE $O(E^2/\Lambda^2)$
$\phi^8$ EFFECTS ARE $O(E^4/\Lambda^4)$, AND SO ON.

IF WE ONLY STUDY PHYSICS AT $E \ll \Lambda$, CAN INCLUDE *SOME* IRRELEVANT OPERATORS & NEGLECT $\phi^N$ OPERATORS AS LONG AS WE ONLY WORK TO $O(E^N/\Lambda^N)$ PRECISION.
*FINITE # OF IRRELEVANT OPERATORS = $O(E^N/\Lambda^N)$ PREDICTIVE*

GOOD FOR $E \ll \Lambda$. AS WE APPROACH $\Lambda$ ALL OPERATORS EQUALLY IMPORTANT, NEED UV COMPLETION



# EFFECTIVE FIELD THEORY

DESCRIBING A PHYSICAL SYSTEM REQUIRES SPECIFYING:

- **IMPORTANT DEGREES OF FREEDOM:** *IN QFT, WHAT FIELDS?*
- **IMPORTANT SYMMETRIES:** *IN QFT, WHAT INTERACTIONS?*

THIS + RENORMALIZABILITY GIVES US THE STANDARD MODEL.
BUT WE CAN RELAX RENORMALIZABILITY IF IN ADDITION WE SPECIFY

- **EXPANSION PARAMETERS:** *IN QFT, WHAT POWER COUNTING?*

THIS LAST INGREDIENT GIVES US **EFFECTIVE FIELD THEORY.**
POWER COUNTING IS USUALLY IN *DISTANCES/ENERGIES.*

# EFFECTIVE FIELD THEORY

TWO KINDS:

## TOP-DOWN EFT

HIGH ENERGY THEORY IS UNDERSTOOD, BUT USEFUL TO HAVE SIMPLER THEORY AT LOW ENERGIES.

$$\mathcal{L}_{High} \to \sum_n \mathcal{L}_{low}^{(n)}$$

| |
|---|
| Theory 1 |
| $\downarrow$ |
| Theory 2 |

INTEGRATE OUT & MATCH (MATRIX ELEMENTS) AT INTERMEDIATE SCALE

E.G. THEORY OF WEAK INTERACTIONS (FERMI EFFECTIVE THEORY). WAAAAY EASIER TO COMPUTE QCD CORRECTIONS.

## BOTTOM-UP EFT

UNDERLYING THEORY IS UNKNOWN OR MATCHING IS TOO DIFFICULT TO CARRY OUT

$$\sum_n \mathcal{L}_{low}^{(n)}$$

| |
|---|
| ??? |
| $\downarrow$ |
| Theory 2 |

WRITE DOWN ALL INTERACTIONS CONSISTENT W/ SYMMETRIES. COUPLINGS NOT PREDICTED, BUT FIT TO DATA.

E.G. CHIRAL LAGRANGIAN, QUANTUM EINSTEIN GRAVITY, OR **STANDARD MODEL**

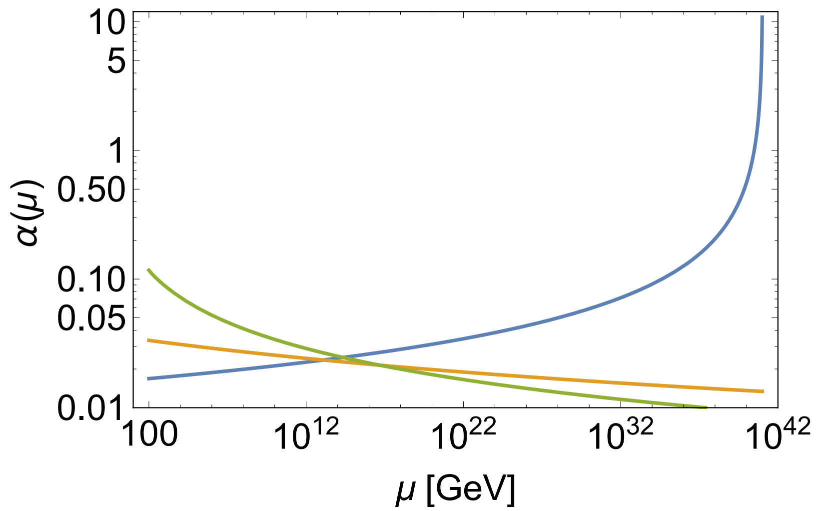
# THE STANDARD MODEL AS EFT

*IF WE LIMIT SM TO ONLY RENORMALIZABLE OPS, WHY WORRY ABOUT ALL THIS?*

THE STANDARD MODEL IS NOT UV COMPLETE.

(1) "QUANTUM" GRAVITY CONSISTENT BUT NON-RENORMALIZABLE, DEMANDS UV COMPLETION AT THE PLANCK SCALE; PRESUMABLY ALSO INVOLVES SM*.

(2) WE HAVE INCONTROVERTIBLE EVIDENCE FOR ADDITIONAL FIELDS AND/OR OPERATORS BEYOND SM.




***WHAT IF GRAVITY DECOUPLES FROM SM IN THE UV?**

RUNNING SM GAUGE COUPLINGS INTO FAR UV EVENTUALLY GIVES LANDAU POLE IN $U(1)_Y$. WOULD CAUSE FERMIONS TO CONDENSE IN UV. SO UV COMPLETION OF SM IS UNAVOIDABLE!

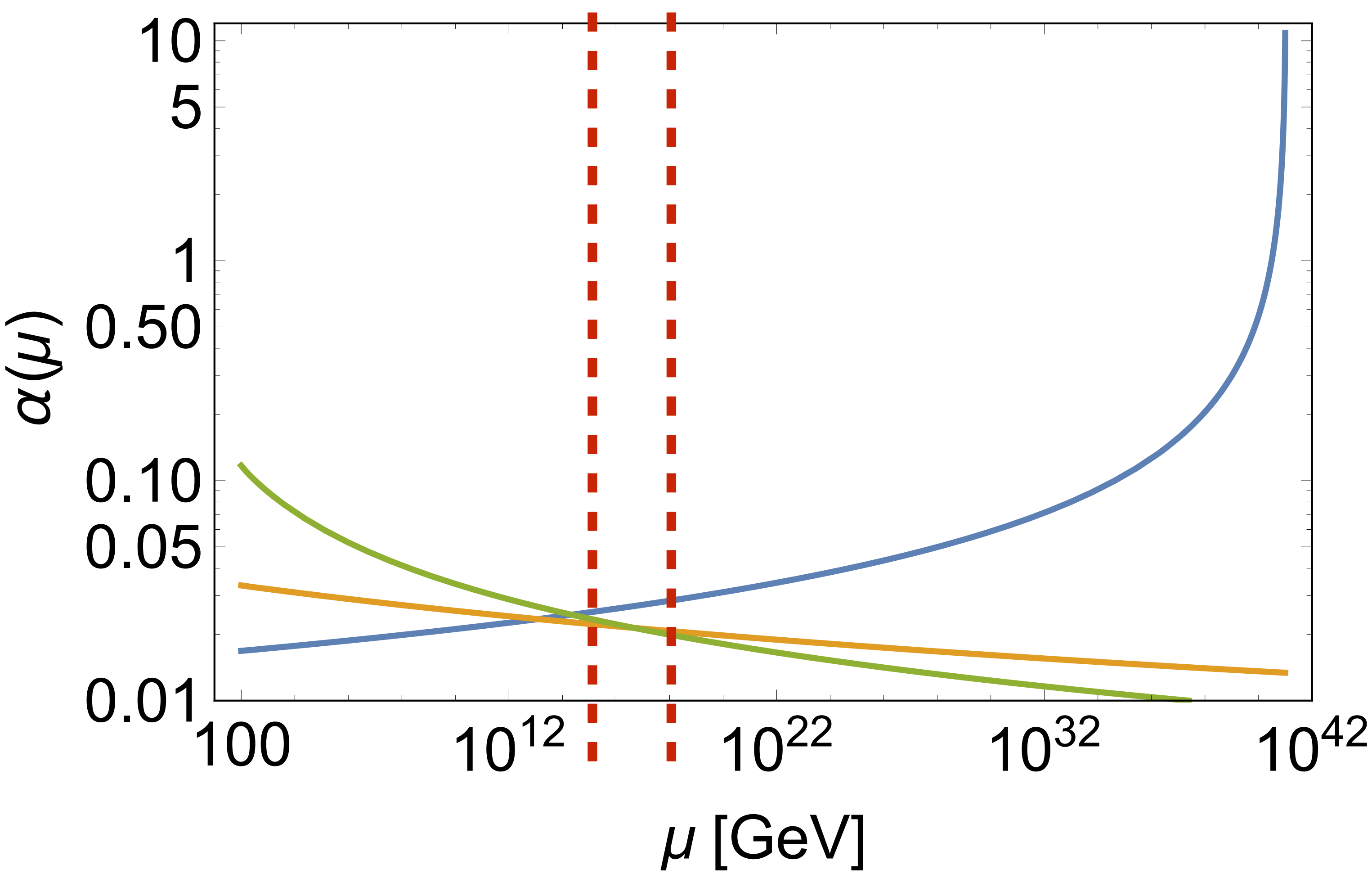
*NOTE: NOT ALL EVIDENCE FOR BSM COMES FROM HIGH ENERGIES; THE MOST COMPELLING IS FROM SCALES AT OR BELOW THE WEAK SCALE.*

# THE STANDARD MODEL AS EFT

## WHAT'S THE MATTER WITH HYPERCHARGE?

$$\frac{\partial \alpha_i}{\partial \ln \mu} = \beta_i = b_i \frac{\alpha_i^2}{2\pi} + \dots \Rightarrow \frac{1}{\alpha_i(\mu)} - \frac{1}{\alpha_i(m_Z)} = -\frac{b_i}{2\pi} \ln\left(\frac{\mu}{m_Z}\right) + \dots \qquad \alpha_i \equiv \frac{g_i^2}{4\pi}$$

$$b_1 = 41/10 \qquad b_2 = -19/6 \qquad b_3 = -7$$




SIGN OF U(1) BETA FUNCTION FIXED; ADDITIONAL CHARGED STATES ONLY INCREASE COEFFICIENT. ALL NON-TRIVIAL U(1)'S RUN TO LANDAU POLES IN THE UV.

USUAL ASSUMPTION: RUNNING CUT OFF BY UNIFICATION AROUND $10^{15}$ GEV OR QUANTUM GRAVITY AROUND $10^{18}$ GEV

WITHOUT SUCH A CUTOFF, LANDAU POLE INEVITABLE.

# THE SMEFT

TREAT SM AS "BOTTOM-UP EFT", WRITE DOWN ALL OPERATORS CONSISTENT WITH SYMMETRIES TO GIVEN ORDER IN POWER COUNTING

**DIM-5**: 1 OPERATOR*

$$\frac{1}{\Lambda}(HL)^2$$

**DIM-6**: 59+4 OPERATORS*

SCHEMATICALLY

GAUGE BOSON OPERATORS

$$\frac{1}{\Lambda^2}|H|^2 V_{\mu\nu}V^{\mu\nu} \qquad \frac{1}{\Lambda^2}(D^\mu V_{\mu\nu})^2$$

FOUR-FERMI OPERATORS

$$\frac{1}{\Lambda^2}(\bar{\psi}\gamma^\mu\psi)(\bar{\psi}\gamma^\mu\psi)$$

HIGGS OPERATORS

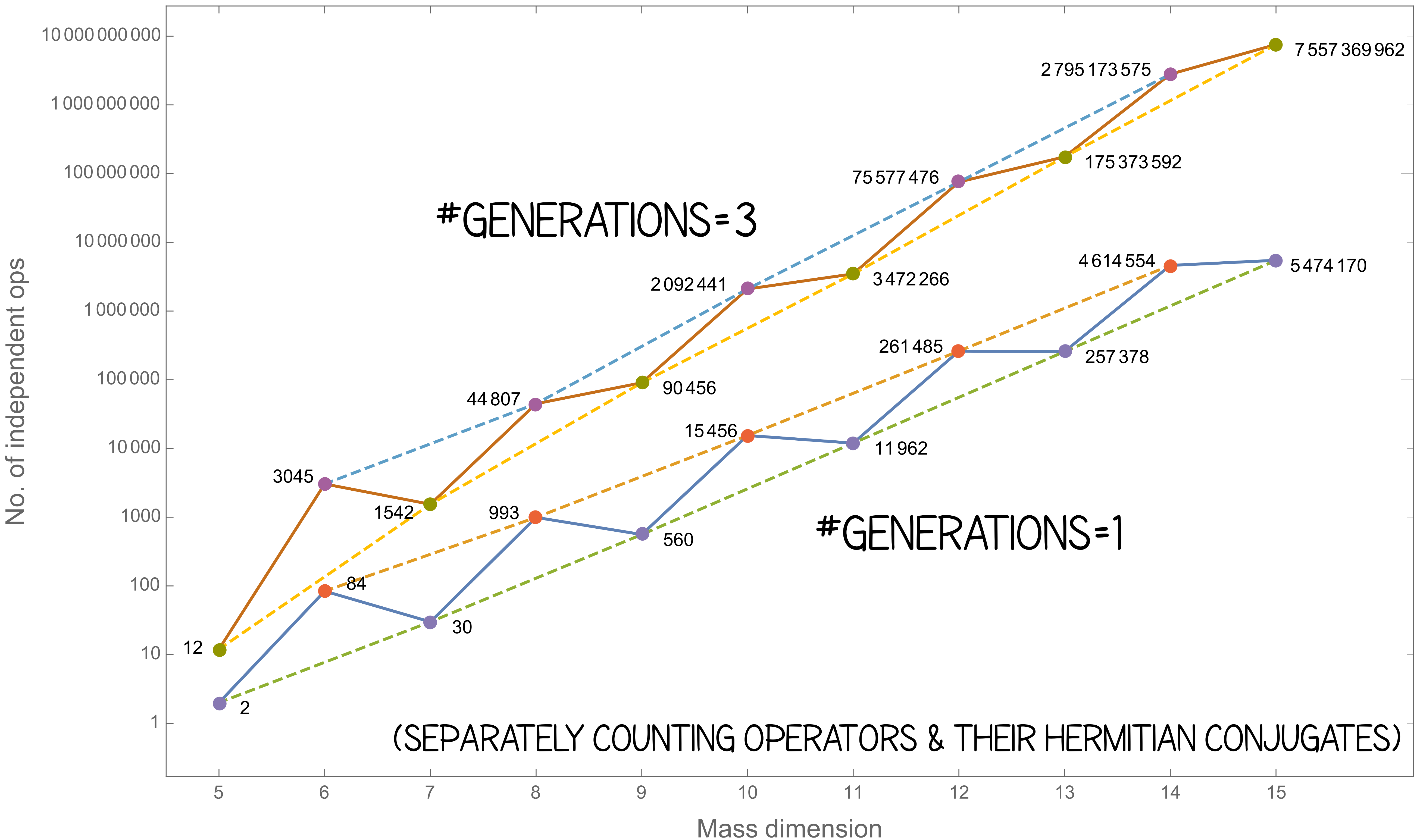
$$\frac{1}{\Lambda^2}(\partial^\mu|H|^2)^2 \qquad \frac{1}{\Lambda^2}|H^\dagger D_\mu H|^2 \qquad \frac{1}{\Lambda^2}|H|^2|D_\mu H|^2 \qquad \frac{1}{\Lambda^2}|H|^6$$

*THE GAME: FIX/CONSTRAIN COEFFICIENTS WITH DATA!*

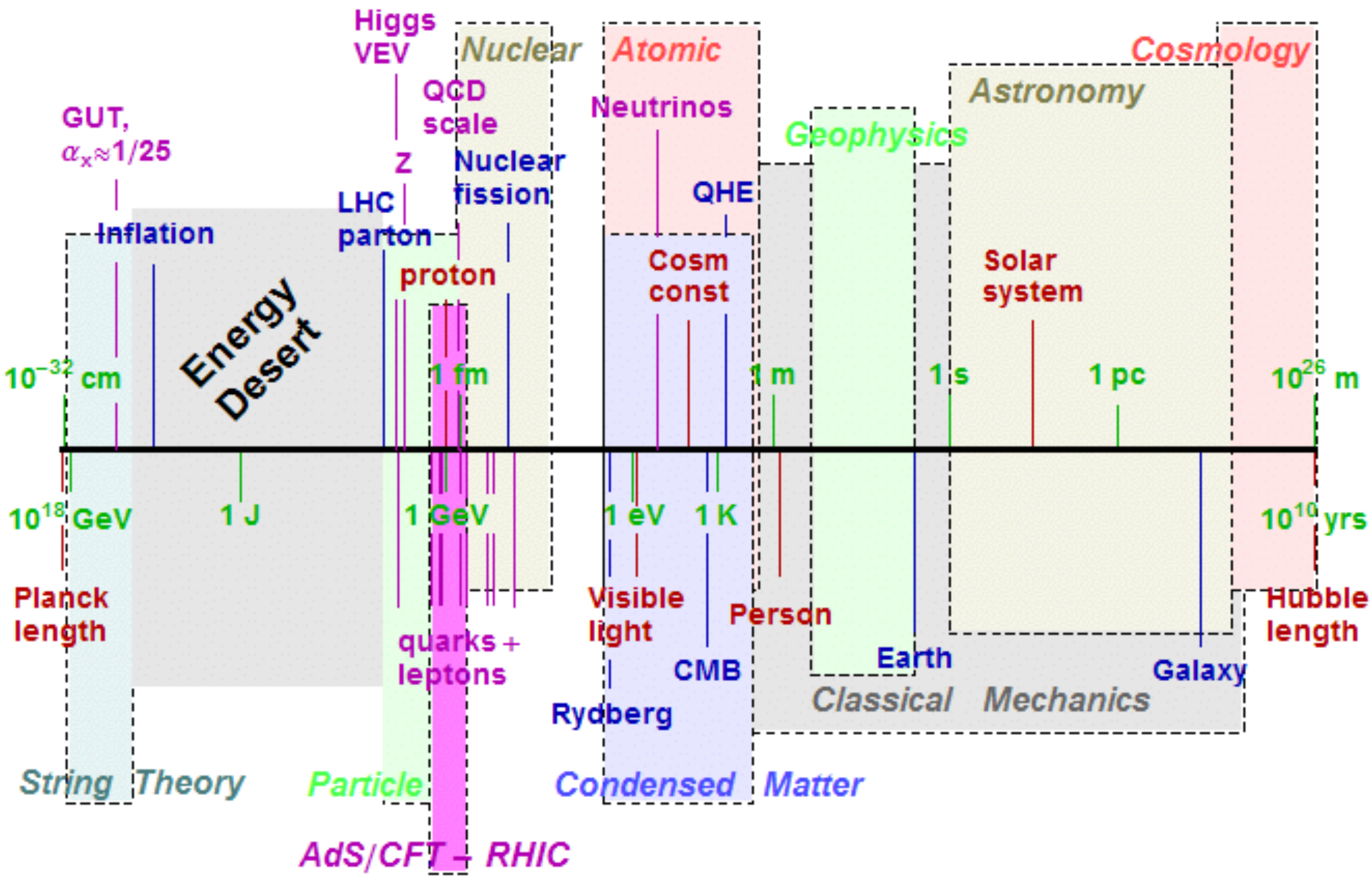
*NEGLECTING FLAVOR, I.E. 1 GENERATION AT A TIME.

# THE SMEFT

HENNING, LU, MELIA, MURAYAMA '15



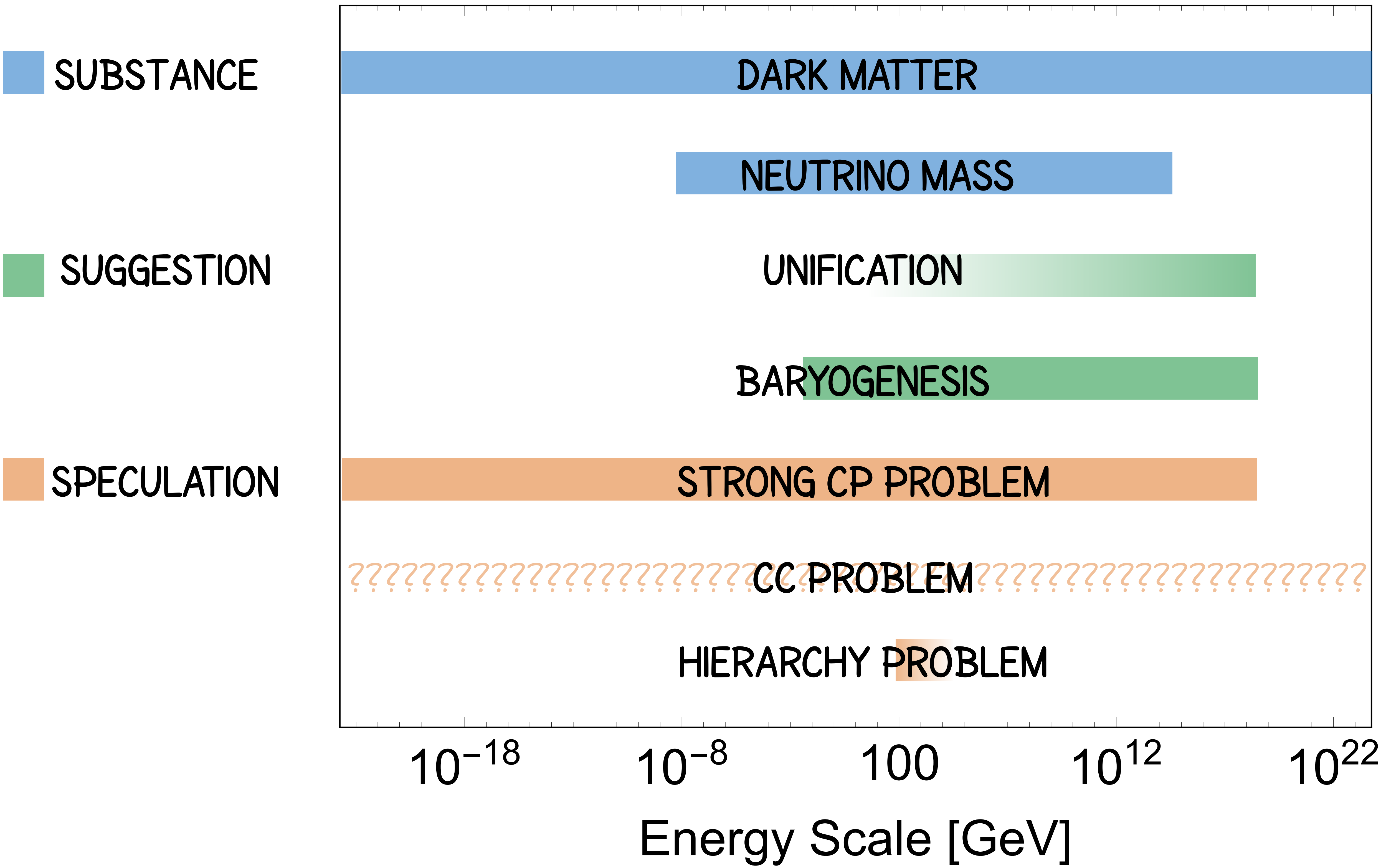
# THE DATA



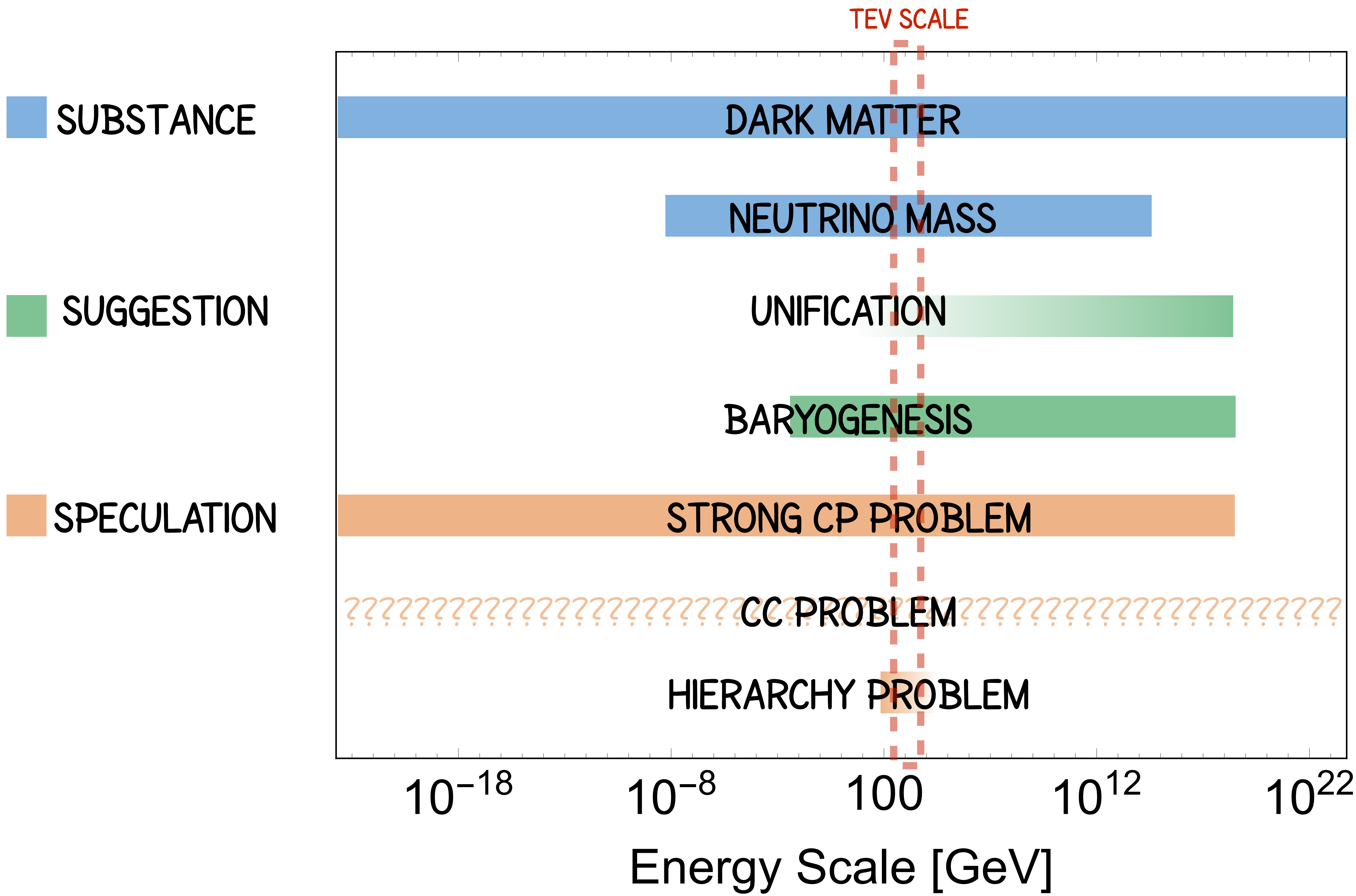

SO FAR, ONLY ONE NONZERO COEFFICIENT. MAJORITY OF BOUNDS ON SMEFT AT OR NEAR TEV SCALE; EXCEPTIONS ARISE IN SOME HIGH-PRECISION SETTINGS (E.G., FLAVOR, EDM)

# BEYOND THE STANDARD MODEL

*LOOK FOR SPECIFIC GUIDANCE IN THE SHORTCOMINGS OF THE STANDARD MODEL*



# BEYOND THE STANDARD MODEL



# PART 1: THE HIERARCHY PROBLEM

# NATURALNESS CRITERIA

"**DIRAC NATURAL**:" IN THEORY WITH FUNDAMENTAL SCALE $\Lambda$,
NATURAL SIZE OF OPERATOR COEFFICIENTS IS

$$c_O = \mathcal{O}(1) \times \Lambda^{4-\Delta_O}$$

*BORNE OUT COUNTLESS TIMES IN NATURE & SIMULATION.*

"**TECHNICALLY NATURAL** ('T HOOFT):" COEFFICIENTS CAN BE MUCH SMALLER IF THERE IS AN ENHANCED SYMMETRY WHEN THE COEFFICIENT IS ZERO.

$$c_O = \mathcal{S} \times \mathcal{O}(1) \times \Lambda^{4-\Delta_O}$$

WHERE $\mathcal{S}$ IS A PARAMETER THAT VIOLATES SYMMETRY.

*PHILOSOPHICAL UNDERPINNING: QUANTUM CORRECTIONS RESPECT SYMMETRY; IF SYMMETRY IS BROKEN, QUANTUM CORRECTIONS PROPORTIONAL TO SYMMETRY BREAKING.*

# NATURALNESS IN NATURE

**DIRAC'S QUESTION: WHY IS $m_p \ll M_{PL}$?**

18 ORDERS OF MAGNITUDE!

ANSWER: QCD SCALE IS DYNAMICALLY GENERATED BY LOGARITHMIC EVOLUTION OF QCD COUPLING: "DIMENSIONAL TRANSMUTATION"

$$\frac{\partial \alpha_i}{\partial \ln \mu} = \beta_i = b_i \frac{\alpha_i^2}{2\pi} + \ldots \quad \Rightarrow \frac{1}{\alpha_3(M_{Pl})} - \frac{1}{\alpha_3(\mu)} = -\frac{b_3}{2\pi} \ln\left(\frac{M_{Pl}}{\mu}\right) + \ldots \quad (\mu < M_{Pl})$$

$b_3$=-7, SO THERE EXISTS A SCALE WHERE $\alpha_3 \to \infty$: CONFINEMENT

$$\frac{1}{\alpha_3(\Lambda_{QCD})} = 0 \to \Lambda_{QCD} = M_{Pl} e^{\frac{2\pi}{b_3} \frac{1}{\alpha_s(M_{Pl})}}$$

PROTON ACQUIRES MOST OF ITS MASS FROM CONFINEMENT, $m_p \sim \Lambda_{QCD}$

*THE DIMENSIONLESS COUPLING IS O(1), TOTALLY NATURAL*

# NATURALNESS IN NATURE

SEE LECTURES BY Y. NIR

**FLAVOR HIERARCHIES:** LARGE RANGE OF YUKAWAS,

$$y_e/y_t \sim 10^{-5} \qquad y_\nu/y_t \sim 10^{-11}$$

ANSWER: NOT DIRAC NATURAL, BUT TECHNICALLY NATURAL!

IN LIMIT Y→0, ENHANCED SYMMETRY OF SM: $U(3)^5$ FLAVOR SYMMETRY

$$SU(3)_Q \times SU(3)_U \times SU(3)_D \times SU(3)_L \times SU(3)_E$$
$$\times U(1)_B \times U(1)_L \times U(1)_Y \times U(1)_{PQ} \times U(1)_E$$

YUKAWAS ARE SPURIONS FOR BREAKING THIS SYMMETRY:

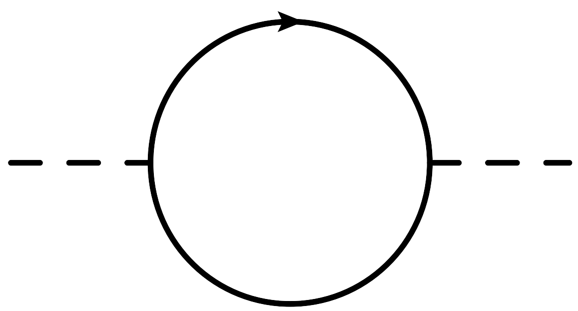
$$Y^u \sim (3,\bar{3},1)_{SU(3)^3_q} \qquad Y^d \sim (3,1,\bar{3})_{SU(3)^3_q} \qquad Y^e \sim (3,\bar{3})_{SU(3)^2_\ell}$$

RADIATIVE CORRECTIONS TO YUKAWAS PROPORTIONAL TO YUKAWAS,
HIERARCHIES ARE RADIATIVELY STABLE

*WOULD STILL LIKE AN EXPLANATION FOR YUKAWA HIERARCHIES (E.G. FROGGATT-NIELSEN)*

$\Delta_O = 2$
$\text{natural} \sim \mathcal{O}(1)\Lambda^2$

# HIERARCHY PROBLEM



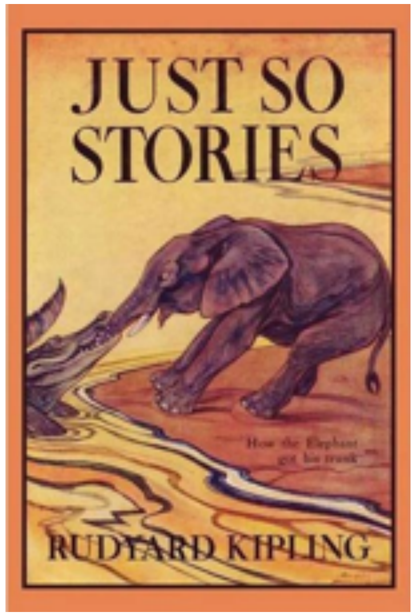
*OFTEN HEARD:*
"HIGGS MASS IS QUADRATICALLY DIVERGENT, STANDARD MODEL LOOPS UP TO CUTOFF $\Lambda$ GIVE CONTRIBUTION:"

$$\delta m_H^2(\mu) = \frac{\Lambda^2}{16\pi^2}\left[6\lambda(\mu) + \frac{9}{4}g_2^2(\mu) + \frac{3}{4}g_Y^2(\mu) - 6\lambda_t^2(\mu)\right]$$

BUT THEN YOU REMEMBER: DIVERGENCES ARE NOT PHYSICAL, WE INTRODUCE COUNTERTERMS TO ABSORB THEM AND USE DATA TO FIX THE COUPLINGS!

WHY NOT CANCEL DIVERGENCE WITH COUNTERTERM? OR BETTER YET, USE A REGULARIZATION & RENORMALIZATION SCHEME WITHOUT DIVERGENCES, E.G. DIMENSIONAL REGULARIZATION WITH MINIMAL SUBTRACTION?

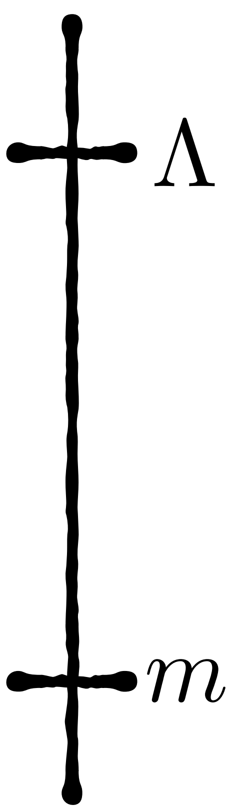
*NOT THE ACTUAL PROBLEM. "QUADRATIC DIVERGENCE" IS AN INDICATION OF THE PROBLEM, BUT NOT THE PROBLEM ITSELF...*




# SCALARS ARE SPECIAL

*MASS NEITHER NATURAL NOR TECHNICALLY NATURAL IN SM,*

*HIERARCHY PROBLEM IS NOT A "JUST-SO STORY"*




| FIELD | SYMMETRY AS $m \to 0$ | IMPLICATION |
|---|---|---|
| SPIN-1/2 $m\Psi\bar{\Psi}$ | $\Psi \to e^{i\alpha\gamma_5}\Psi$ (CHIRAL SYMMETRY) | $\delta m \propto m$ NATURAL! |
| SPIN-1 $m^2 A_\mu A^\mu$ | $A_\mu \to A_\mu + \partial_\mu \alpha$ (GAUGE INVARIANCE) | $\delta m \propto m$ NATURAL! |
| SPIN-0 $m^2 \lvert H \rvert^2$ | NONE | $\delta m \propto \Lambda$ UNNATURAL! |

# TWO DEGREES OF DANGER

$$\delta m_H^2(\mu) = \frac{\Lambda^2}{16\pi^2}\left[6\lambda(\mu) + \frac{9}{4}g_2^2(\mu) + \frac{3}{4}g_Y^2(\mu) - 6\lambda_t^2(\mu)\right]$$

1. **THE STRONG FORM OF THE HIERARCHY PROBLEM**: FUNDAMENTAL THEORY IS *FINITE*. DIVERGENCES IN AN EFFECTIVE THEORY ARE PHYSICAL (E.G. CUTOFF = LATTICE SPACING), COUNTERTERMS JUST IMPLEMENT TUNING. "QUADRATIC DIVERGENCE" IN SMEFT IS A DIRECT MEASURE OF FINE TUNING.

2. **THE WEAK FORM OF THE HIERARCHY PROBLEM:** LET US ONLY SPEAK OF OBSERVABLE QUANTITIES LIKE POLE MASSES. DIVERGENCES ARE UNPHYSICAL. THE "QUADRATIC DIVERGENCE" IN THE SMEFT IS A STAND-IN FOR FINITE THRESHOLD CORRECTIONS FROM *POSSIBLE* NEW PHYSICS.

STRONG FORM HOLDS TRUE IN ALL KNOWN EXTENSIONS OF THE STANDARD MODEL THAT ARE FINITE (E.G. SUPERSYMMETRY, STRING THEORY), I.E., WHEREVER THE HIGGS MASS CAN BE *PREDICTED*.

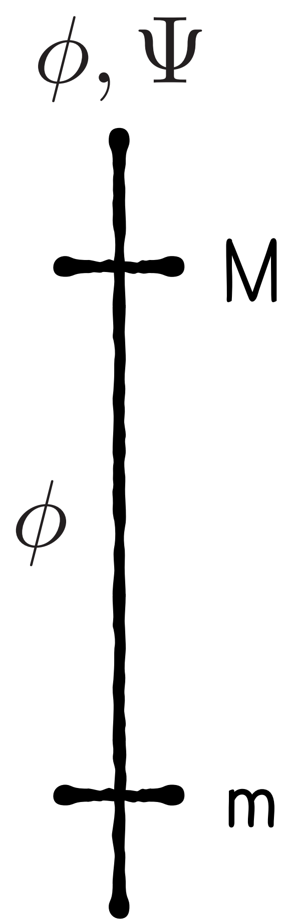
*BUT EVEN THE WEAK FORM POSES AN IMMENSE DANGER.*

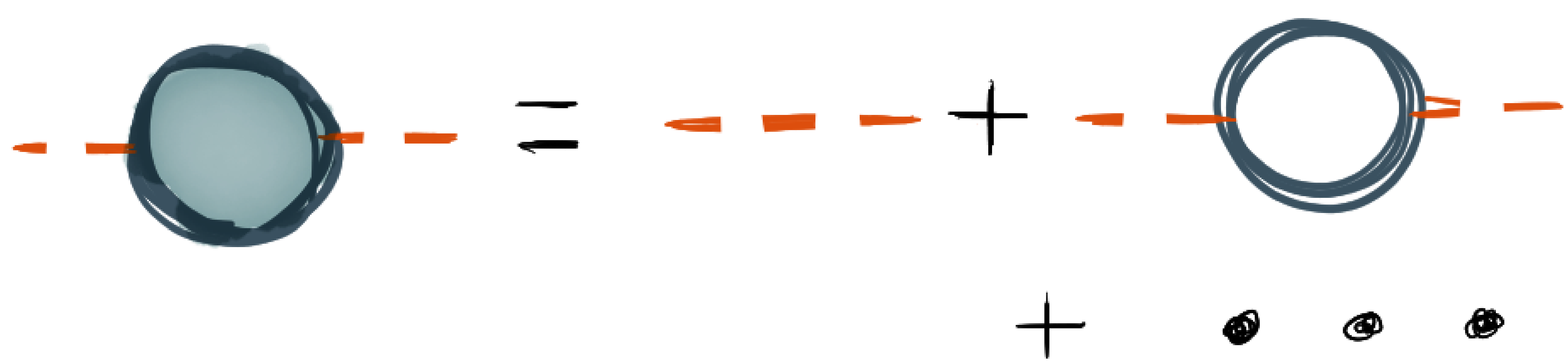
# (WEAK) HIERARCHY PROBLEM

CONSIDER A TOY MODEL WITH A SCALAR AND DIRAC FERMION:

$$\mathcal{L} = \frac{1}{2}(\partial_\mu \phi)^2 - \frac{1}{2} m^2 \phi^2 - \frac{\lambda}{4!}\phi^4 + \overline{\Psi} i \not{\partial} \Psi - M \overline{\Psi}\Psi + y\phi\overline{\Psi}\Psi$$

IMAGINE WE ARRANGE FOR THE SCALAR TO BE MUCH LIGHTER, $m \ll M$.
WE CAN STUDY THE EFFECTIVE THEORY AT ENERGIES $E \ll M$.



ENTAILS INTEGRATING OUT THE FERMIONS AT THE SCALE M AND MATCHING BETWEEN THE EFFECTIVE THEORY AND THE FULL THEORY.

# (WEAK) HIERARCHY PROBLEM

COMPUTE SCALAR MASS IN THE EFFECTIVE THEORY WITH A HARD MOMENTUM CUTOFF $\Lambda$:

$$m_{eff}^2 = m^2 + \frac{y^2}{16\pi^2}\left[c_1\Lambda^2 + c_2 m^2 \ln\frac{\Lambda}{\mu} + c_3 M^2 + \mathcal{O}(M^4/\Lambda^2)\right]$$

OR COMPUTED USING DIMENSIONAL REGULARIZATION IN 4-$\epsilon$ DIMENSIONS WITH MINIMAL SUBTRACTION:

$$m_{eff}^2 = m^2 + \frac{y^2}{16\pi^2}\left[\frac{c_2}{\epsilon}m^2 + c_3 M^2 + \mathcal{O}(\epsilon)\right]$$

IN BOTH CASES, CAN WRITE THE ANSWER IN TERMS OF THE RENORMALIZED MASS $m^2(\mu=M)$:

$$m_{eff}^2(\mu = M) = m^2(\mu = M) + \frac{c_3 y^2}{16\pi^2}M^2$$

FINITE THRESHOLD CORRECTION

NO DEPENDENCE ON CUTOFF, BUT DEPENDENCE ON M.

# (WEAK) HIERARCHY PROBLEM

$$m^2_{eff}(\mu = M) = m^2(\mu = M) + \frac{c_3 y^2}{16\pi^2} M^2$$

SCALAR WANTS TO BE WITHIN A LOOP FACTOR OF THE DIRAC FERMION. TO KEEP SCALAR LIGHTER, NEED TO TUNE RENORMALIZED PARAMETERS OF THE FULL THEORY SO THERE IS A CANCELLATION ON THE RHS.

THIS REQUIRES A TUNING OF ORDER $\frac{y^2}{16\pi^2}\frac{M^2}{m^2}$

SEE FINE-TUNING IN TERMS OF RENORMALIZED PARAMETERS, INDEPENDENT OF REGULATOR; APPARENT EVEN IN DIM. REG. WHERE THERE ARE NO QUADRATIC DIVERGENCES.

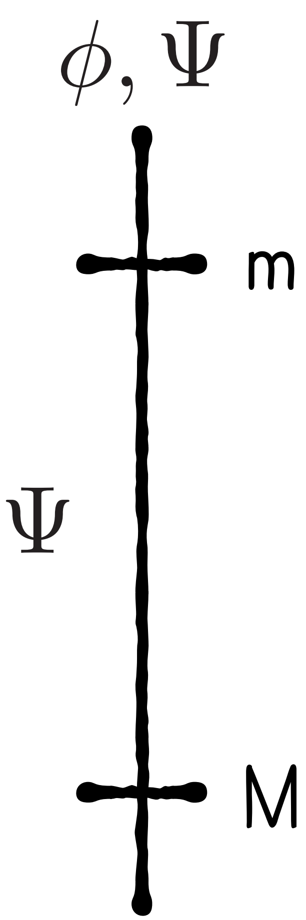
THE INTUITION ABOUT QUADRATIC DIVERGENCES IS CORRECT IF WE ASSOCIATE $\Lambda \sim M$, *I.E., CUTOFF ~ THRESHOLD.*

$$\delta m^2_H \propto \frac{y^2}{16\pi^2}\Lambda^2$$

# (NO FERMIONIC PROBLEM)

IMAGINE WE RAN THE LOGIC IN THE OTHER DIRECTION:
MAKE THE SCALAR HEAVY, STUDY THE LIGHT FERMION

$$\mathcal{L} = \frac{1}{2}(\partial_\mu \phi)^2 - \frac{1}{2}m^2\phi^2 - \frac{\lambda}{4!}\phi^4 + \overline{\Psi} i \not{\partial} \Psi - M\overline{\Psi}\Psi + y\phi\overline{\Psi}\Psi$$




E.G. DIMENSIONAL REGULARIZATION IN 4-$\epsilon$ DIMENSIONS WITH MINIMAL SUBTRACTION:

$$M_{eff} = M + \frac{y^2}{16\pi^2}\left[\frac{c_2}{\epsilon}M + c_3 M + \mathcal{O}(\epsilon, M/m)\right]$$

CORRECTIONS PROPORTIONAL TO FERMION MASS, VANISH
IN THE LIMIT M → 0. DUE TO THE CHIRAL SYMMETRY

$$\Psi \rightarrow e^{i\alpha\gamma_5}\Psi$$

NO LARGE THRESHOLD CORRECTIONS MATCHING TO UV THEORY W/ SCALAR

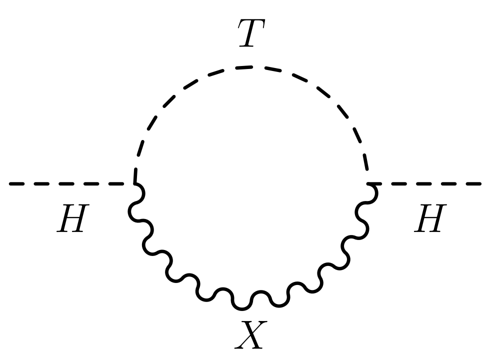
*NOTE: WORKS ONLY IF M IS THE ONLY SOURCE OF CHIRAL SYMMETRY BREAKING.*

# BSM CREATES A PROBLEM

*MOTIVATED BSM THEORY INTRODUCES THESE CORRECTIONS TO THE HIGGS.*

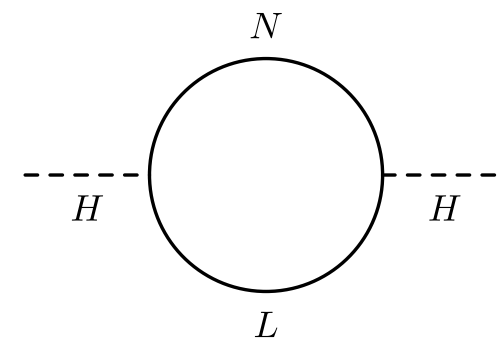
## UNIFICATION

FINITE CORRECTIONS FROM LOOPS OF HEAVY GAUGE BOSONS/HIGGS TRIPLETS.




$$\delta m_H^2 \sim \frac{\alpha_{GUT}}{4\pi} M_{GUT}^2$$

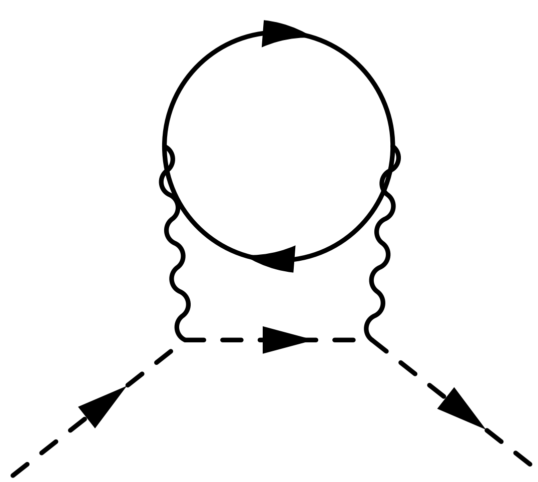
## NEUTRINOS




FINITE CORRECTIONS FROM LEPTON + RHN

$$\delta m_H^2 = -\frac{1}{4\pi^2} \sum_{ij} |y_{ij}|^2 M_j^2$$

## DARK MATTER



FINITE CORRECTIONS AT TWO LOOPS FROM WIMP DARK MATTER (I.E. LIVES IN SU(2) MULTIPLET)

$$\delta m_H^2 \sim \left(\frac{\alpha}{4\pi}\right)^2 \times g\left(\frac{m_W^2}{m_\Psi^2}\right) \times m_\Psi^2$$

| Quantum numbers $SU(2)_L$ | $U(1)_Y$ | Spin | DM could decay into | DM mass in TeV | $m_{DM^\pm} - m_{DM}$ in MeV | Finite naturalness bound in TeV | $\sigma_{SI}$ in $10^{-46}$ cm$^2$ |
|---|---|---|---|---|---|---|---|
| 2 | 1/2 | 0 | $EL$ | 0.54 | 350 | $0.4 \times \sqrt{\Delta}$ | $(0.4 \pm 0.6)\,10^{-3}$ |
| 2 | 1/2 | 1/2 | $EH$ | 1.1 | 341 | $1.9 \times \sqrt{\Delta}$ | $(0.3 \pm 0.6)\,10^{-3}$ |
| 3 | 0 | 0 | $HH^*$ | $2.0 \to 2.5$ | 166 | $0.22 \times \sqrt{\Delta}$ | $0.12 \pm 0.03$ |
| 3 | 0 | 1/2 | $LH$ | $2.4 \to 2.7$ | 166 | $1.0 \times \sqrt{\Delta}$ | $0.12 \pm 0.03$ |
| 3 | 1 | 0 | $HH, LL$ | $1.6 \to ?$ | 540 | $0.22 \times \sqrt{\Delta}$ | $0.001 \pm 0.001$ |
| 3 | 1 | 1/2 | $LH$ | $1.9 \to ?$ | 526 | $1.0 \times \sqrt{\Delta}$ | $0.001 \pm 0.001$ |
| 4 | 1/2 | 0 | $HHH^*$ | $2.4 \to ?$ | 353 | $0.14 \times \sqrt{\Delta}$ | $0.27 \pm 0.08$ |
| 4 | 1/2 | 1/2 | $(LHH^*)$ | $2.4 \to ?$ | 347 | $0.6 \times \sqrt{\Delta}$ | $0.27 \pm 0.08$ |
| 4 | 3/2 | 0 | $HHH$ | $2.9 \to ?$ | 729 | $0.14 \times \sqrt{\Delta}$ | $0.15 \pm 0.07$ |
| 4 | 3/2 | 1/2 | $(LHH)$ | $2.6 \to ?$ | 712 | $0.6 \times \sqrt{\Delta}$ | $0.15 \pm 0.07$ |
| 5 | 0 | 0 | $(HHH^*H^*)$ | $5.0 \to 9.4$ | 166 | $0.10 \times \sqrt{\Delta}$ | $1.0 \pm 0.2$ |
| 5 | 0 | 1/2 | stable | $4.4 \to 10$ | 166 | $0.4 \times \sqrt{\Delta}$ | $1.0 \pm 0.2$ |
| 7 | 0 | 0 | stable | $8 \to 25$ | 166 | $0.06 \times \sqrt{\Delta}$ | $4 \pm 1$ |

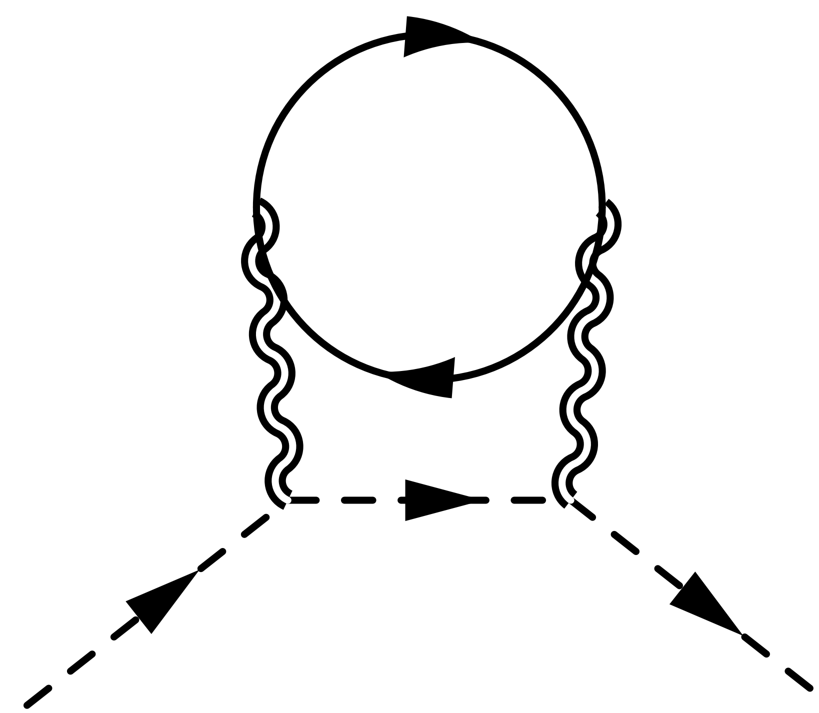
# GRAVITY IS WORSE

DON'T KNOW THE THEORY OF QUANTUM GRAVITY, BUT REASONABLE TO SUPPOSE IT CONTAINS NEW STATES WHOSE MASSES ARE OF ORDER $M_{PL}$

CONSIDER E.G. A HEAVY FERMION THAT ONLY COUPLES TO THE HIGGS THROUGH LOOPS OF GRAVITONS.

(CAN COMPUTE THIS USING QUANTUM GRAVITY EFT)

$$\delta m_H^2 \sim \frac{m_H^2}{(16\pi^2)^2} \frac{m_\Psi^4}{M_{Pl}^4}$$

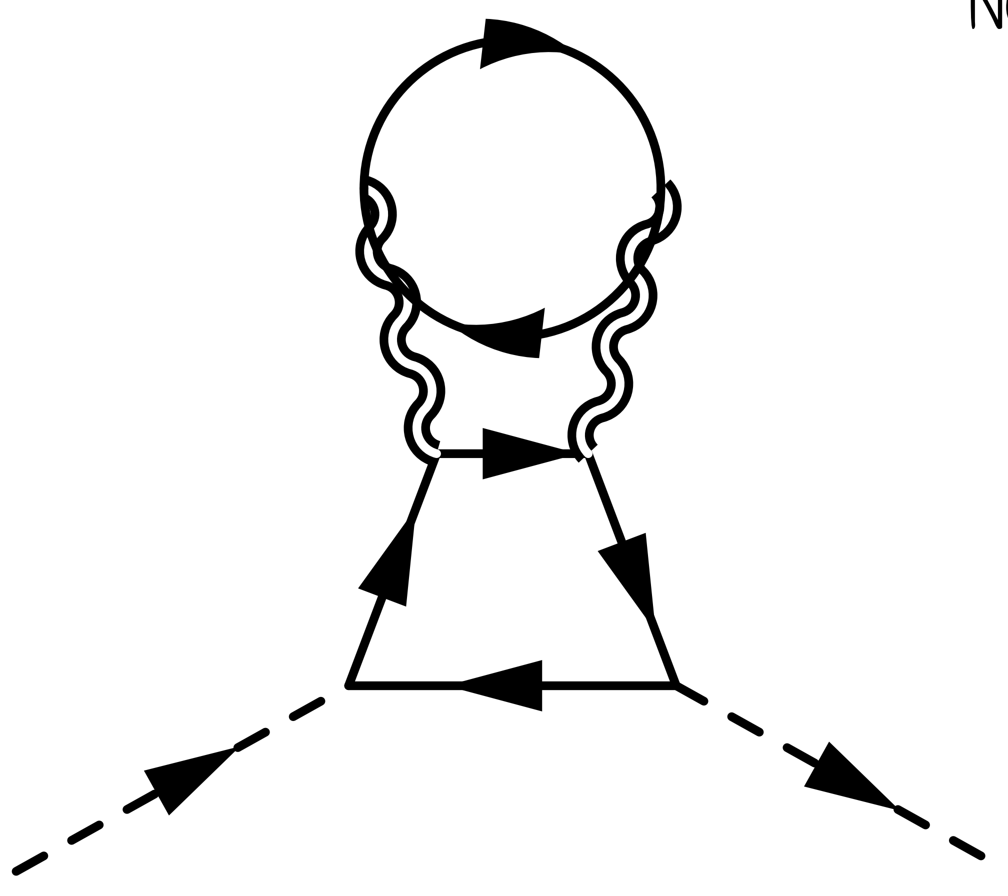


HEY WAIT, THAT'S NOT SO BAD!

(SMALL BECAUSE THE GRAVITON COUPLING TO A MASSLESS, ON-SHELL PARTICLE AT ZERO MOMENTUM VANISHES, SO RESULT IS PROPORTIONAL TO $M_H$)

# GRAVITY IS WORSE

LET'S GO TO THREE LOOPS, SO THE GRAVITON COUPLES VIA A LOOP OF TOP QUARKS. TOP QUARKS ARE OFF SHELL, SO COUPLING NOT SUPPRESSED



NOW WE FIND A CORRECTION PROPORTIONAL TO MASS OF THE HEAVY FERMION,

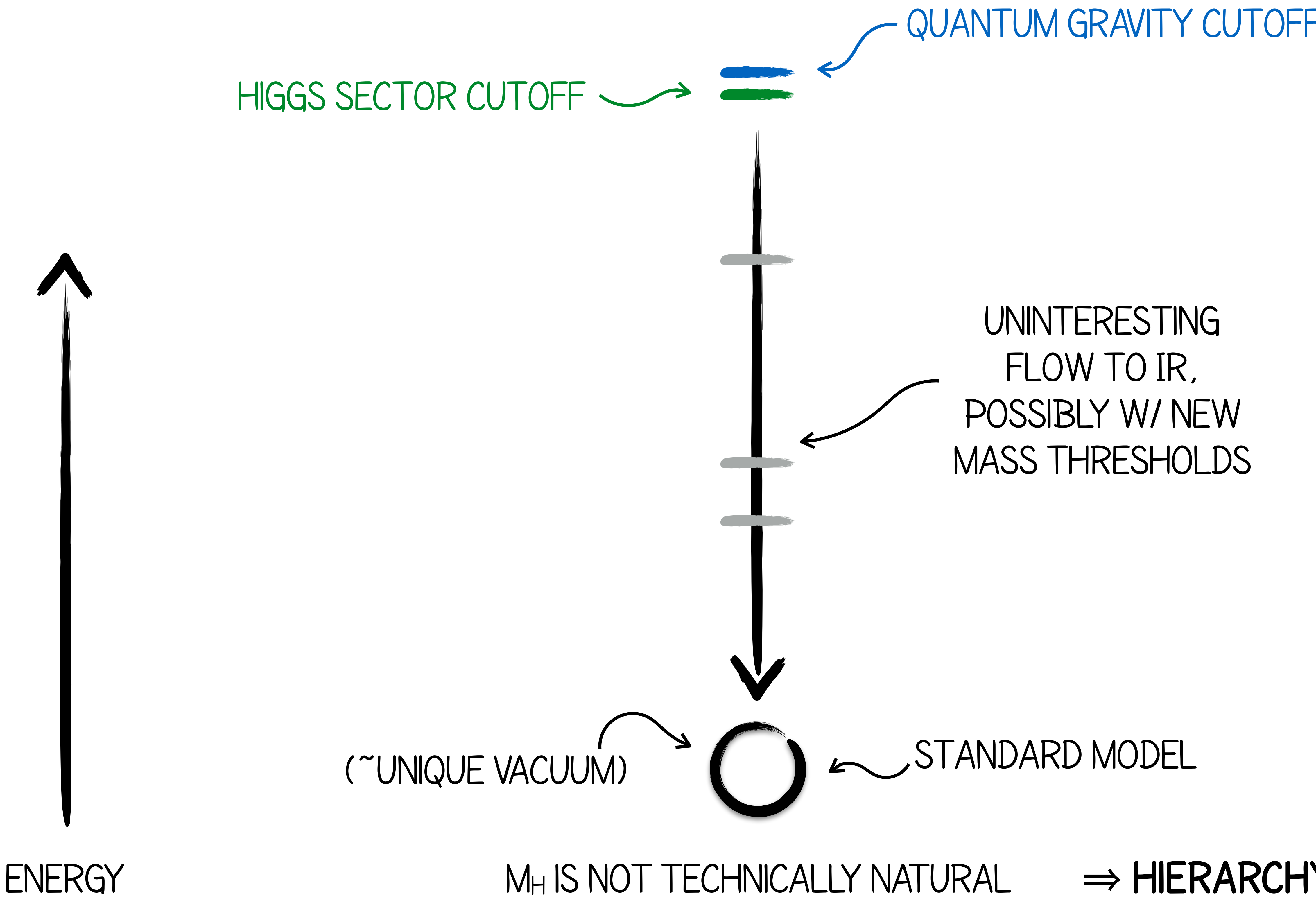
$$\delta m_H^2 \sim \frac{6y_t^2}{(16\pi^2)^3}\frac{m_\Psi^6}{M_{Pl}^4}$$

SUMMING OVER ALL SM PARTICLES IN THE LOOP, THIS LOOKS LIKE OUR NAIVE ONE-LOOP QUADRATIC DIVERGENCE CALCULATION WITH

$$\Lambda \sim M_{Pl}/16\pi^2$$

SO EVEN HEAVY STUFF WITH PURELY GRAVITATIONAL COUPLINGS TO SM GIVES LARGE FINITE CORRECTIONS.

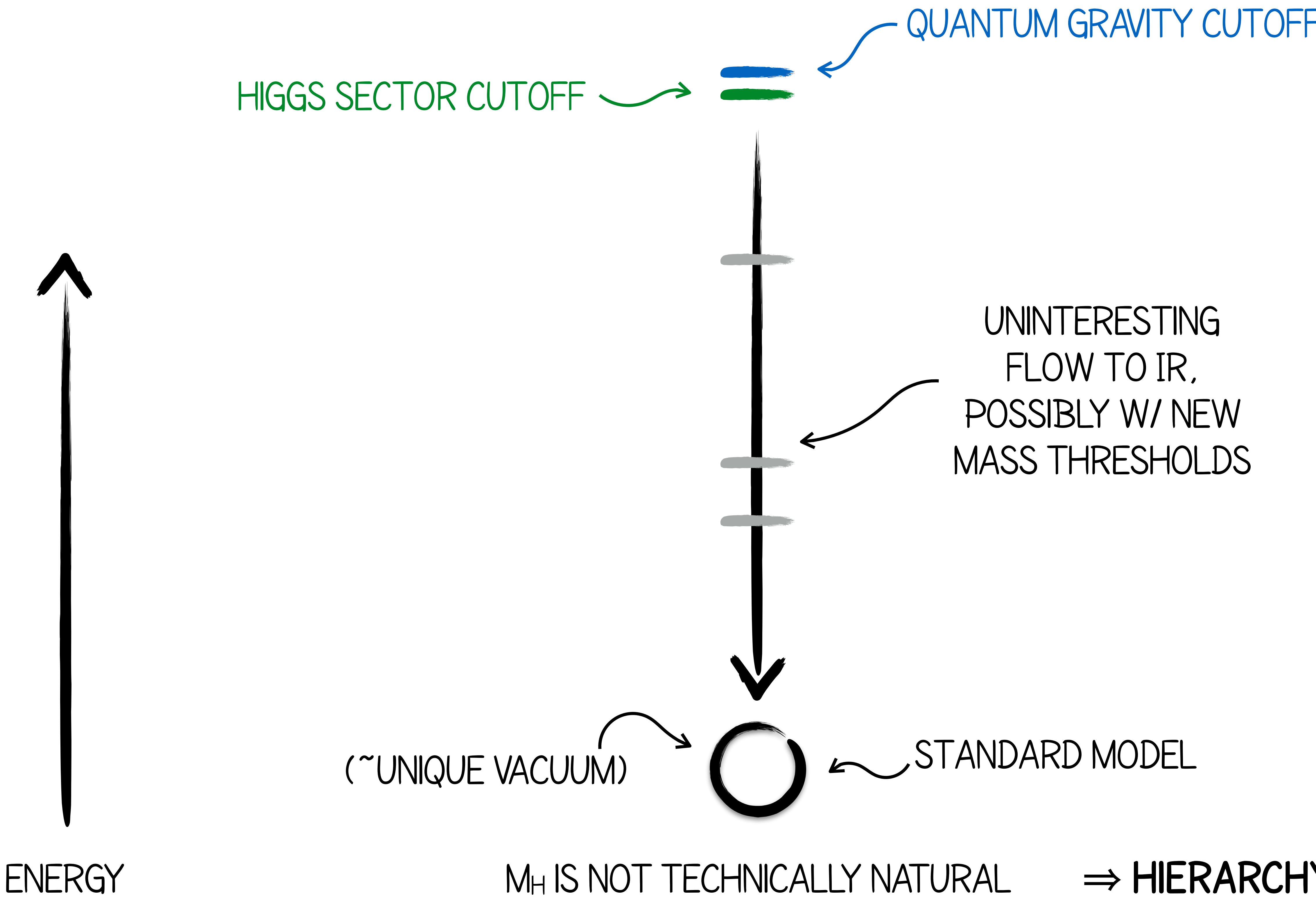
# THE HIERARCHY PROBLEM




$M_H$ IS NOT TECHNICALLY NATURAL ⇒ **HIERARCHY PROBLEM**

# PART 2: HIERARCHY SOLUTIONS

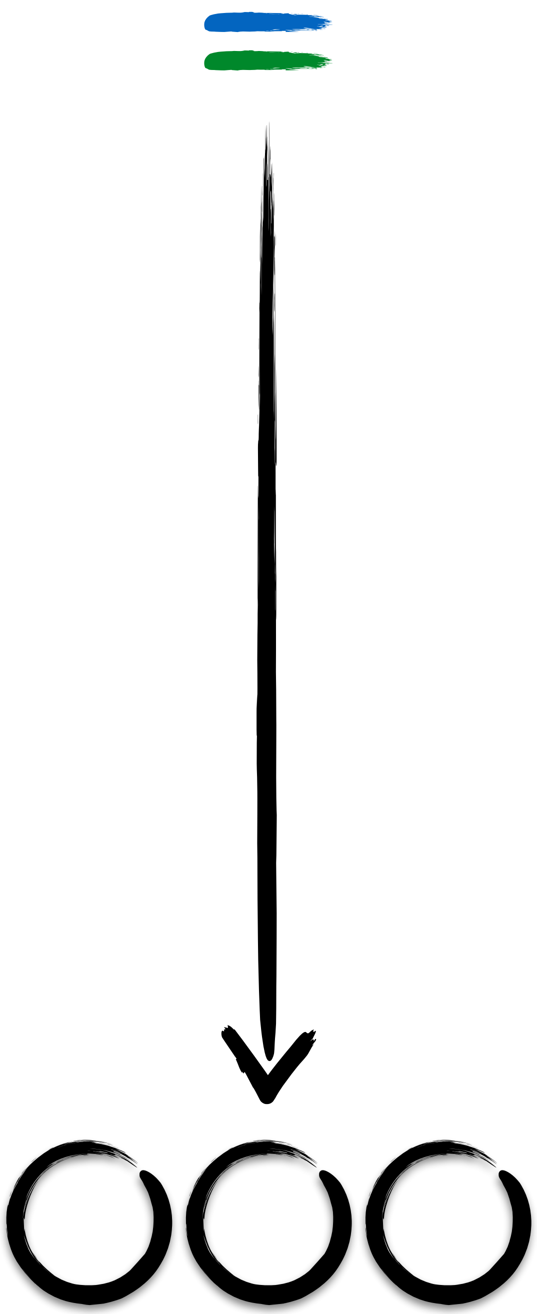
# THE HIERARCHY PROBLEM




$M_H$ IS NOT TECHNICALLY NATURAL ⇒ **HIERARCHY PROBLEM**

# SELECTING A VACUUM

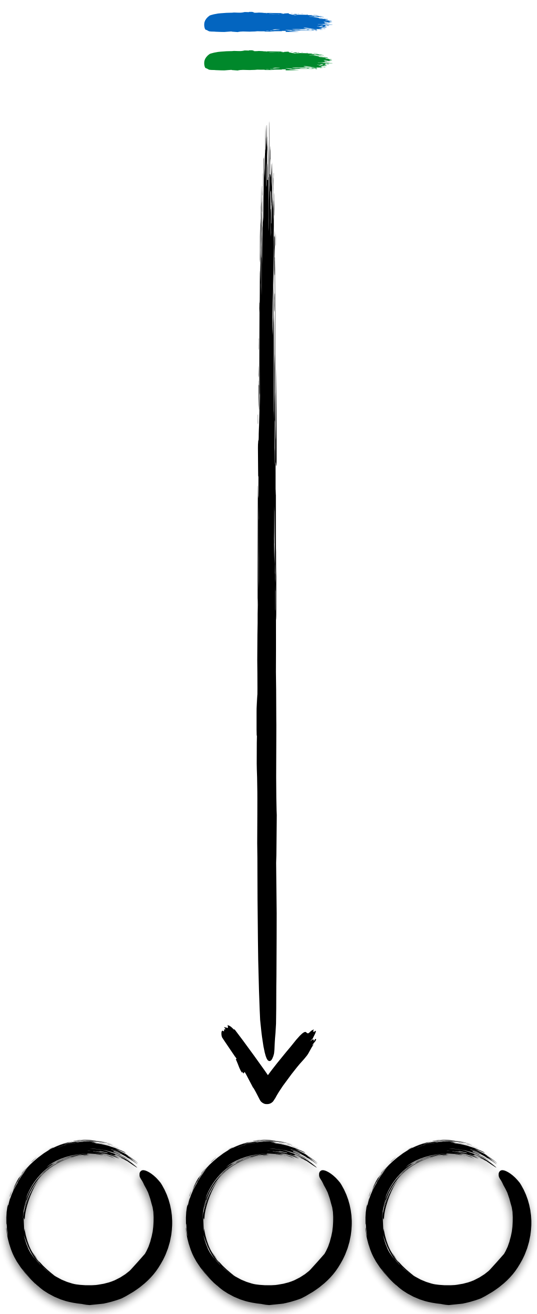
VACUUM IS ONE OF MANY; END UP IN OBSERVED VACUUM THROUGH SOME CONSTRAINT.



1. ANTHROPICS

- **LIGHTNESS OF THE HIGGS RESULTS FROM FINELY TUNED CANCELLATION.**
- EXPLICABLE W/ ANTHROPIC REASONING: THERE IS A LANDSCAPE OF VACUA ACROSS WHICH THE HIGGS MASS VARIES, BUT ONLY LOW/ TUNED HIGGS MASSES ARE COMPATIBLE WITH OBSERVERS.
- PLAUSIBILITY DEPENDS STRONGLY ON WHAT QUANTITIES YOU ASSUME ARE ALLOWED TO VARY OVER THE LANDSCAPE!
- EVEN IF THERE IS A MULTIVERSE & ANTHROPIC PRESSURE, WHY SHOULD THE UNIVERSE BOTHER WITH AN ELEMENTARY SCALAR? TECHNICOLOR WOULD HAVE WORKED JUST FINE.

# (ANTHROPIC ASIDE)



- FOR EXAMPLE, YOU CAN IMAGINE AN ANTHROPIC PRESSURE IN A MULTIVERSE WHERE THE HIGGS MASS/VEV VARIES BUT DIMENSIONLESS COUPLINGS (YUKAWAS) ARE HELD FIXED.
- WHEN $V \ll V_{SM}$, PROTONS DECAY INTO NEUTRONS SINCE

$$m_n - m_p = (3v/v_{SM} - 1.7)\ \mathrm{MeV}$$

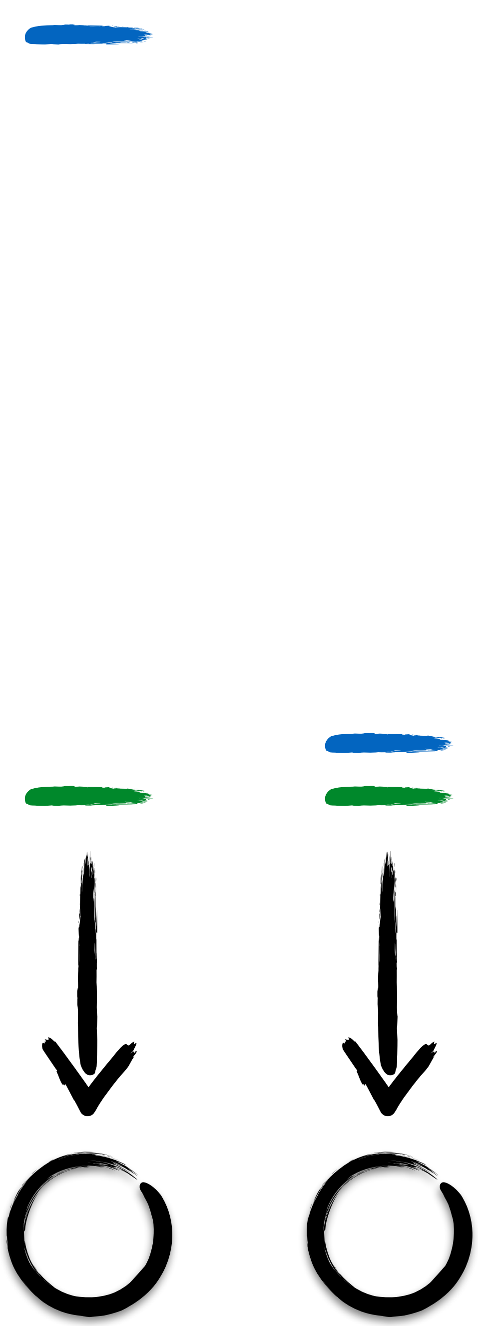
- WHEN $V \gg V_{SM}$, THE NEUTRON IS NO LONGER STABLE WITHIN NUCLEI BECAUSE THE NEUTRON-PROTON MASS SPLITTING EXCEEDS THE NUCLEAR BINDING ENERGY:

$$m_n - m_p > B_d$$

- PROVIDES AN ANTHROPIC PRESSURE FOR $V \sim V_{SM}$, UNDER THE ASSUMPTION THAT ONLY THE VEV VARIES.
- BUT NOT AN EXPLANATION IF YUKAWAS CAN VARY, OR IF THERE CAN BE EXTRA GAUGE GROUPS.

# LOWERING THE CUTOFF

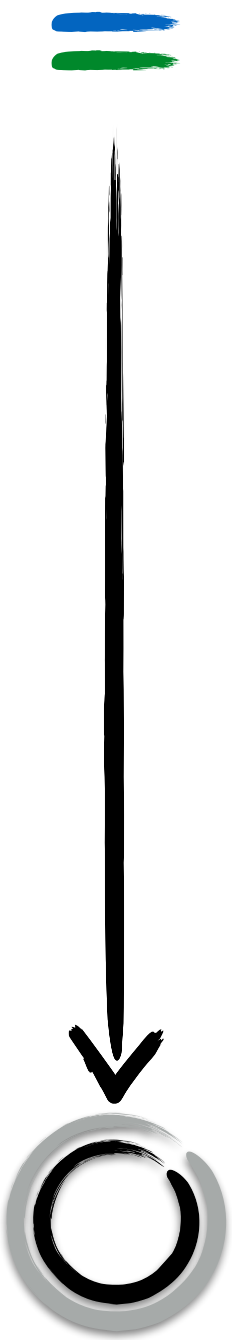
...IN DIVERSE DIMENSIONS



1. RANDALL-SUNDRUM / TECHNICOLOR
2. LARGE EXTRA DIMENSIONS / $10^{32}$ X SM
3. LITTLE STRING THEORY

- **THE 4D UV CUTOFF (HIGGS ALONE, OR WHOLE SM) IS EXTREMELY LOW, AROUND 1 TEV**
- FLAVOR PHYSICS HAPPENS HERE (HIGGS OR WHOLE SM CUTOFF), ALSO QUANTUM GRAVITY & ALL OTHER UV PHYSICS (SM CUTOFF)
- PROBLEM: SEEN A HIGGS + MASS GAP (LIMITS IN THE FEW TEV RANGE FROM DIRECT SEARCHES, MUCH HIGHER FOR FLAVOR/PRECISION ELECTROWEAK). NO INDICATION THE SM OR EVEN JUST HIGGS HAS CUTOFF AT THE TEV SCALE.

# ADDING A SYMMETRY



EXTEND THE SM WITH A SYMMETRY THAT MAKES HIGGS MASS TECHNICALLY NATURAL

1. SUPERSYMMETRY
2. GLOBAL SYMMETRY

- **THE 4D UV CUTOFF (HIGGS ALONE, OR WHOLE SM) CAN BE HIGH, BUT SYMMETRY MUST BE VALID DOWN TO LOW SCALES**
- SYMMETRY MUST BE BROKEN IN A WAY THAT DOESN'T REINTRODUCE UV SENSITIVITY; PREDICTS NEW PARTICLES
- WEAKLY COUPLED REALIZATIONS ALLOW A FINITE MASS GAP BETWEEN HIGGS AND NEW STATES.

# WHAT'S THE SCALE?

IF HIERARCHY PROBLEM IS SOLVED, WHERE DOES A NEW SYMMETRY OR CUTOFF ENTER?

QUANTIFY SENSITIVITY OF HIGGS MASS TO NEW PHYSICS VIA RATIO

$$\Delta \equiv \frac{2\delta m_H^2}{m_h^2}$$

A *GUIDEPOST* TO WHERE NEW PHYSICS SHOULD ENTER; IN THE SM WITH A UNIFORM CUTOFF $\Lambda$, SM LOOPS UP TO $\Lambda$ GIVE

$$\delta m_H^2(\mu) = \frac{\Lambda^2}{16\pi^2}\left[6\lambda(\mu) + \frac{9}{4}g_2^2(\mu) + \frac{3}{4}g_Y^2(\mu) - 6\lambda_t^2(\mu)\right]$$

EXPECT NEW PHYSICS TO ENTER AND ALTER SM AT SOME SCALE*

$\Delta \lesssim 1$ (NO TUNING) REQUIRES $\Lambda \lesssim 500$ GEV;

$\Delta \lesssim 10$ (10%-LEVEL TUNING) REQUIRES $\Lambda \lesssim 1.6$ TEV;

$\Delta \lesssim 100$ (1%-LEVEL TUNING) REQUIRES $\Lambda \lesssim 5$ TEV.

*BEST-CASE SCENARIO, NO LARGE LOGS

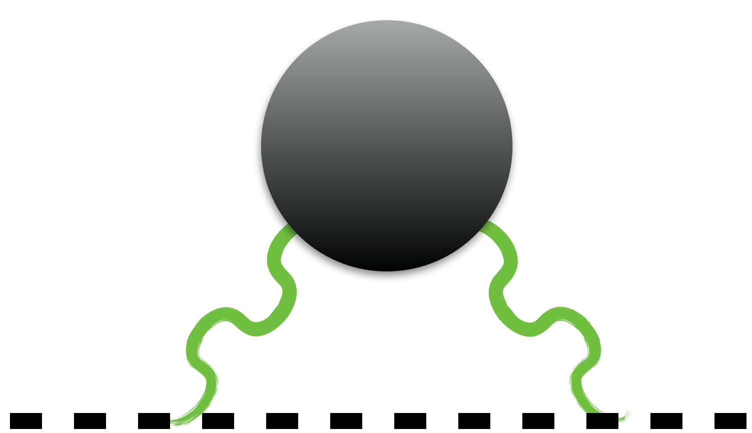
# THE NATURALNESS STRATEGY

THIS IS A *STRATEGY* FOR NEW PHYSICS NEAR $M_H$, NOT A *NO-LOSE THEOREM*, BECAUSE THE THEORY DOES NOT BREAK DOWN IF IT IS UNNATURAL.

BUT NATURALNESS HAS OFTEN BEEN A VERY *SUCCESSFUL* STRATEGY. WE HAVE OTHER SCALARS IN NATURE, THANKS TO QCD.

*E.G. CHARGED PIONS*

PIONS ARE GOLDSTONES, BUT ELECTROMAGNETISM EXPLICITLY BREAKS GLOBAL SYMMETRY.



ELECTROMAGNETIC CONTRIBUTION TO THE CHARGED PION MASS SENSITIVE TO THE CUTOFF OF THE PION EFT.

$$m_{\pi^\pm}^2 - m_{\pi^0}^2 = \frac{3\alpha}{4\pi}\Lambda^2$$

$$m_{\pi^\pm}^2 - m_{\pi^0}^2 = (35.5\,\mathrm{MeV})^2 \Rightarrow \Lambda < 850\,\mathrm{MeV}$$

RHO MESON (NEW PHYSICS!) ENTERS AT 770 MEV: $\Delta \sim 1$

# POSSIBLE SYMMETRIES

WHAT SYMMETRIES MIGHT WE EMPLOY?

**The Coleman-Mandula theorem (1967):** *in a theory with non-trivial interactions (scattering) in more than 1+1 dimensions, the only possible conserved quantities that transform as tensors under the Lorentz group are the energy-momentum vector* $P_\mu$*, the generators of Lorentz transformations* $M_{\mu\nu}$*, and possible scalar symmetry charges* $Z_i$ *corresponding to internal symmetries, which commute with both* $P_\mu$ *and* $M_{\mu\nu}$*.*

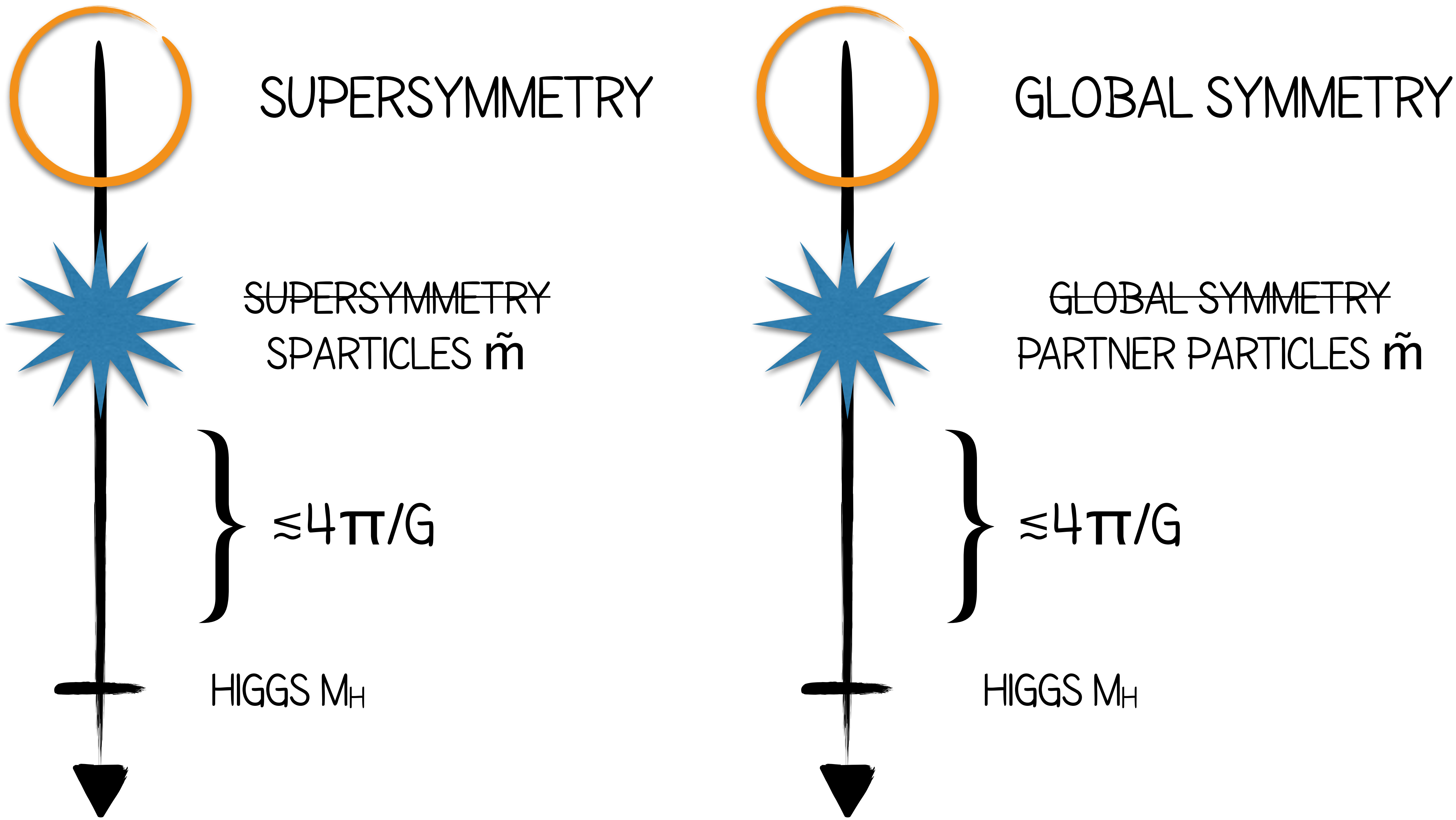
*EXTENSION TO SPINOR SYMMETRY CHARGES BY HAAG, LOPUSZANSKI, SOHNIUS*

SO THE OPTIONS ARE: **GLOBAL SYMMETRY** OR **SUPERSYMMETRY**

(CAN FANCY THE THEORY UP IN EXTRA DIMENSIONS, ETC., BUT 4D EFFECTIVE THEORY STILL USES ONE OF THESE SYMMETRIES)

# POSSIBLE SYMMETRIES

*EXTEND THE SM WITH A SYMMETRY ACTING ON THE HIGGS*



# NEW PARTICLES

CONTINUOUS SYMMETRIES COMMUTING W/ SM →
PARTNER STATES W/ SM QUANTUM NUMBERS

- SUPERSYMMETRY

$$\phi \to \phi + \epsilon\psi$$
$$\psi \to \psi + c^\mu \partial_\mu \phi$$

OPPOSITE-STATISTICS PARTNER FOR EVERY SM PARTICLE

- GLOBAL SYMMETRY

$$\Phi \to (1 + i\alpha T)\Phi$$

SAME-STATISTICS PARTNER FOR EVERY SM PARTICLE

CONTRIBUTE TO THE HIGGS MASS: $m_h^2 \sim \frac{3y_t^2}{4\pi^2}\tilde{m}^2 \log(\Lambda^2/\tilde{m}^2)$

# SUPERSYMMETRY

EXTENDED SPACETIME SYMMETRY

EXTEND POINCARE SYMMETRY W/ SPINORIAL CHARGES $Q_\alpha, \tilde{Q}_{\dot{\alpha}}$

(MINIMAL N=1 SUPERSYMMETRY IN D=4)

SUPER-EXTENSION OF POINCARE ALGEBRA:

$$[P_\mu, Q_\alpha] = [P_\mu, \tilde{Q}^{\dot{\alpha}}] = 0$$

$$[M^{\mu\nu}, Q_\alpha] = i(\sigma^{\mu\nu})_\alpha^\beta Q_\beta$$

$$[M^{\mu\nu}, Q^{\dot{\alpha}}] = i(\bar{\sigma}^{\mu\nu})^{\dot{\alpha}}_{\dot{\beta}} \tilde{Q}^{\dot{\beta}}$$

ALONG WITH $\{Q_\alpha, \tilde{Q}_{\dot{\beta}}\} = 2P_\mu(\sigma^\mu)_{\alpha\dot{\beta}}$ AND $\{Q_\alpha, Q_\beta\} = 0$

# SUPERFIELDS

ORGANIZE FIELDS INTO IRREPS OF SUPER-POINCARE SYMMETRY

SUPERFIELDS CONTAIN BOTH BOSONS AND FERMIONS

$$Q|\mathrm{Boson}\rangle = |\mathrm{Fermion}\rangle \qquad Q|\mathrm{Fermion}\rangle = |\mathrm{Boson}\rangle$$

$\mathrm{tr}[(-1)^{N_f}] = 0 \to n_F = n_B$ ⇒ SAME # OF BOSONIC & FERMIONIC D.O.F.

$[P^2, Q_\alpha] = [P^2, \tilde{Q}_{\dot\alpha}] = 0$ ⇒ COMPONENTS HAVE SAME MASS

AT MOST ONE U(1) GLOBAL SYMMETRY DOES NOT COMMUTE W/ SUPERCHARGES

$$[R, Q_\alpha] = -Q_\alpha \qquad [R, Q^\dagger_{\dot\alpha}] = Q^\dagger_{\dot\alpha}$$

⇒ COMPONENTS HAVE SAME QUANTUM #'S APART FROM $U(1)_R$

TRANSFORMATIONS ACTING ON FIELDS

$$\delta\phi = \epsilon^\alpha \psi_\alpha$$

$$\phi \to \phi + \delta\phi \qquad \psi \to \psi + \delta\psi \qquad \delta\psi_\alpha = -i(\sigma^\nu \epsilon^\dagger)_\alpha \partial_\nu \phi$$

# THE MSSM

## ONE SUPERMULTIPLET FOR EACH SM FIELD + SECOND HIGGS DOUBLET

| Names | | spin 0 | spin 1/2 | $SU(3)_C,\ SU(2)_L,\ U(1)_Y$ |
|---|---|---|---|---|
| squarks, quarks (×3 families) | $Q$ | $(\widetilde{u}_L\ \ \widetilde{d}_L)$ | $(u_L\ \ d_L)$ | $(\ \mathbf{3},\ \mathbf{2}\ ,\ \frac{1}{6})$ |
| | $\overline{u}$ | $\widetilde{u}^*_R$ | $u^\dagger_R$ | $(\ \overline{\mathbf{3}},\ \mathbf{1},\ -\frac{2}{3})$ |
| | $\overline{d}$ | $\widetilde{d}^*_R$ | $d^\dagger_R$ | $(\ \overline{\mathbf{3}},\ \mathbf{1},\ \frac{1}{3})$ |
| sleptons, leptons (×3 families) | $L$ | $(\widetilde{\nu}\ \ \widetilde{e}_L)$ | $(\nu\ \ e_L)$ | $(\ \mathbf{1},\ \mathbf{2}\ ,\ -\frac{1}{2})$ |
| | $\overline{e}$ | $\widetilde{e}^*_R$ | $e^\dagger_R$ | $(\ \mathbf{1},\ \mathbf{1},\ 1)$ |
| Higgs, higgsinos | $H_u$ | $(H_u^+\ \ H_u^0)$ | $(\widetilde{H}_u^+\ \ \widetilde{H}_u^0)$ | $(\ \mathbf{1},\ \mathbf{2}\ ,\ +\frac{1}{2})$ |
| | $H_d$ | $(H_d^0\ \ H_d^-)$ | $(\widetilde{H}_d^0\ \ \widetilde{H}_d^-)$ | $(\ \mathbf{1},\ \mathbf{2}\ ,\ -\frac{1}{2})$ |

| Names | spin 1/2 | spin 1 | $SU(3)_C,\ SU(2)_L,\ U(1)_Y$ |
|---|---|---|---|
| gluino, gluon | $\widetilde{g}$ | $g$ | $(\ \mathbf{8},\ \mathbf{1}\ ,\ 0)$ |
| winos, W bosons | $\widetilde{W}^\pm\ \ \widetilde{W}^0$ | $W^\pm\ \ W^0$ | $(\ \mathbf{1},\ \mathbf{3}\ ,\ 0)$ |
| bino, B boson | $\widetilde{B}^0$ | $B^0$ | $(\ \mathbf{1},\ \mathbf{1}\ ,\ 0)$ |

# SOFTLY BROKEN SUPERSYMMETRY

SUPERSYMMETRY MUST BE BROKEN; BREAKING WITH RELEVANT OPERATORS GUARANTEES IT REMAINS A GOOD SYMMETRY IN THE UV

$$
\begin{aligned}
\mathcal{L}_{\rm soft}^{\rm MSSM} = & -\frac{1}{2}\left(M_3 \widetilde{g}\widetilde{g} + M_2 \widetilde{W}\widetilde{W} + M_1 \widetilde{B}\widetilde{B} + \text{h.c.}\right) \\
& - \left(\widetilde{\overline{u}}\, \mathbf{a_u}\, \widetilde{Q} H_u - \widetilde{\overline{d}}\, \mathbf{a_d}\, \widetilde{Q} H_d - \widetilde{\overline{e}}\, \mathbf{a_e}\, \widetilde{L} H_d + \text{c.c.}\right) \\
& - \widetilde{Q}^\dagger\, \mathbf{m^2_Q}\, \widetilde{Q} - \widetilde{L}^\dagger\, \mathbf{m^2_L}\, \widetilde{L} - \widetilde{\overline{u}}\, \mathbf{m^2_{\overline{u}}}\, \widetilde{\overline{u}}^\dagger - \widetilde{\overline{d}}\, \mathbf{m^2_{\overline{d}}}\, \widetilde{\overline{d}}^\dagger - \widetilde{\overline{e}}\, \mathbf{m^2_{\overline{e}}}\, \widetilde{\overline{e}}^\dagger \\
& - m^2_{H_u} H_u^* H_u - m^2_{H_d} H_d^* H_d - (b H_u H_d + \text{c.c.})
\end{aligned}
$$

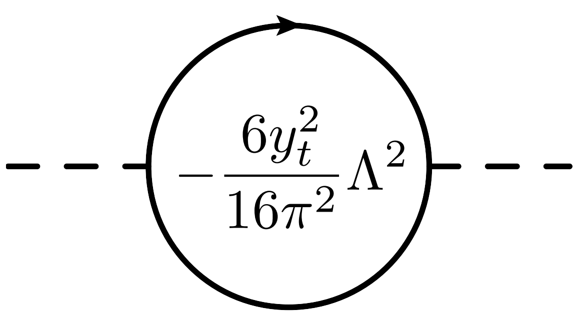
INCREASES MASSES OF NEW SUPERPARTNERS RELATIVE TO SM COUNTERPARTS

# SUSY & THE HIERARCHY PROBLEM

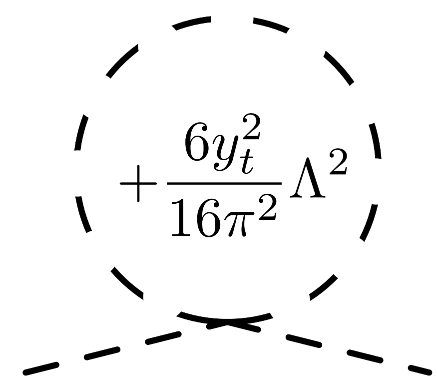
SUPERSYMMETRY RELATES SCALARS TO FERMIONS, SO CHIRAL SYMMETRY MAKES HIGGS MASS TECHNICALLY NATURAL.

NEW INTERACTIONS RELATED BY SUPERSYMMETRY TO SM INTERACTIONS. E.G. IN TOP-STOP SECTOR,

$$\mathcal{L} \supset y_t H Q_3 t_R^\dagger + |y_t|^2 |H \cdot \tilde{Q}_3|^2 + |y_t|^2 |H|^2 |\tilde{t}_R|^2$$



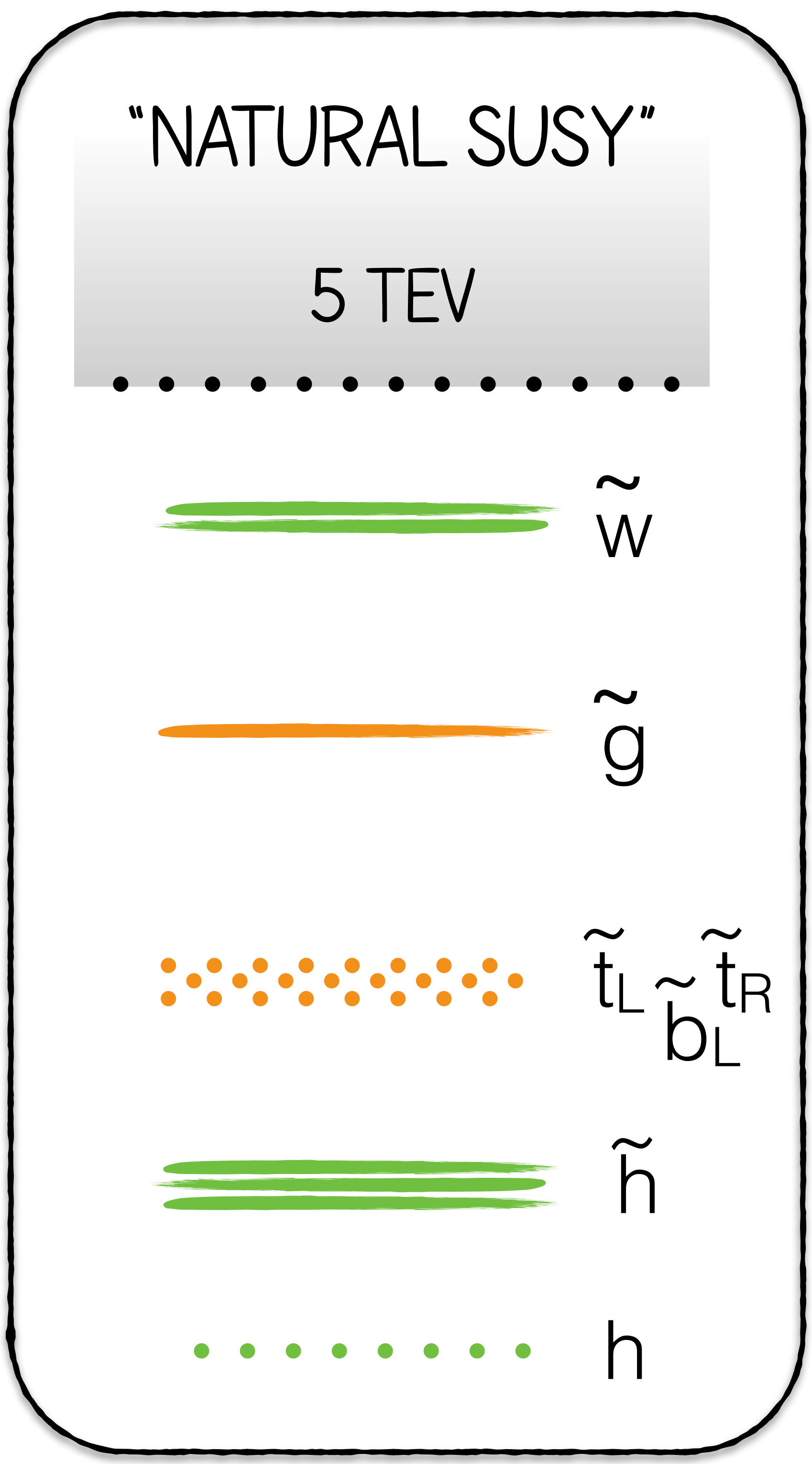

ELIMINATION OF UV SENSITIVITY APPARENT IN "QUADRATIC DIVERGENCE", WHICH CANCELS BETWEEN TOP & STOP LOOPS




LEAVES ONLY FINITE THRESHOLD CORRECTION $m_H^2 \sim -\frac{6y_t^2}{16\pi^2}\tilde{m}_t^2$

*SUPERSYMMETRY PROTECTS AGAINST ARBITRARY PHYSICS AT HIGH SCALES, BUT SUPERPARTNERS MUST ENTER NEAR WEAK SCALE.*

# SUSY EXPECTATIONS




BEST CASE SCENARIO GIVEN NULL RESULTS: SUPERPARTNER MASS HIERARCHY INVERSELY PROPORTIONAL TO CONTRIBUTION TO HIGGS MASS

$$\delta m_h^2 \propto \mu^2 \qquad \text{("HIGGSINOS")}$$

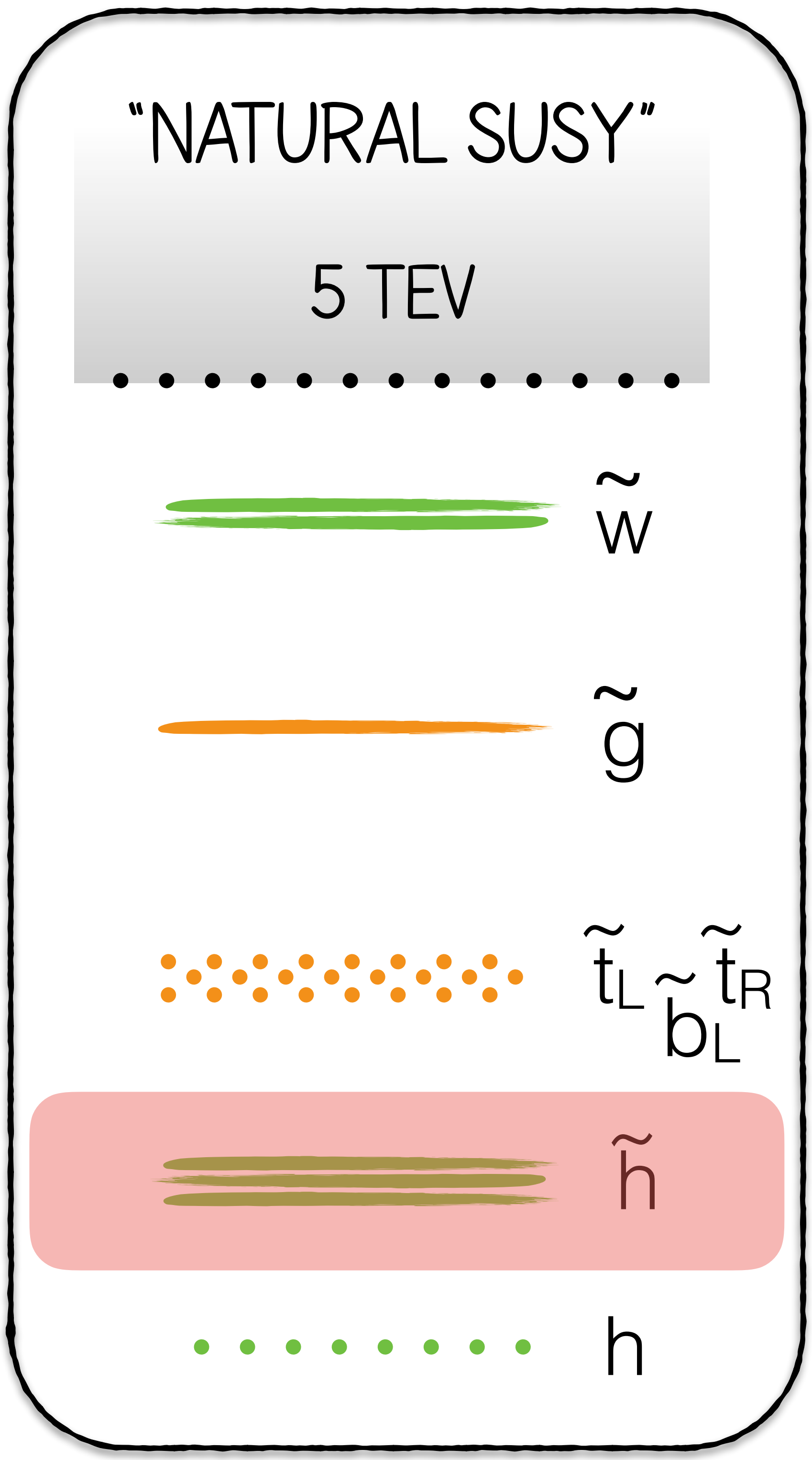
$$m_h^2 \sim \frac{3y_t^2}{4\pi^2} \tilde{m}^2 \log(\Lambda^2/\tilde{m}^2) \qquad \text{(STOPS)}$$

ETC...

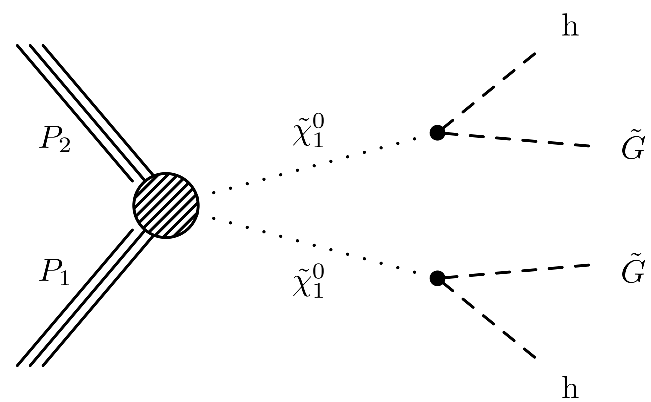
QCD PRODUCTION OF STOPS, GLUINOS LEADS TO STRONGEST CONSTRAINTS

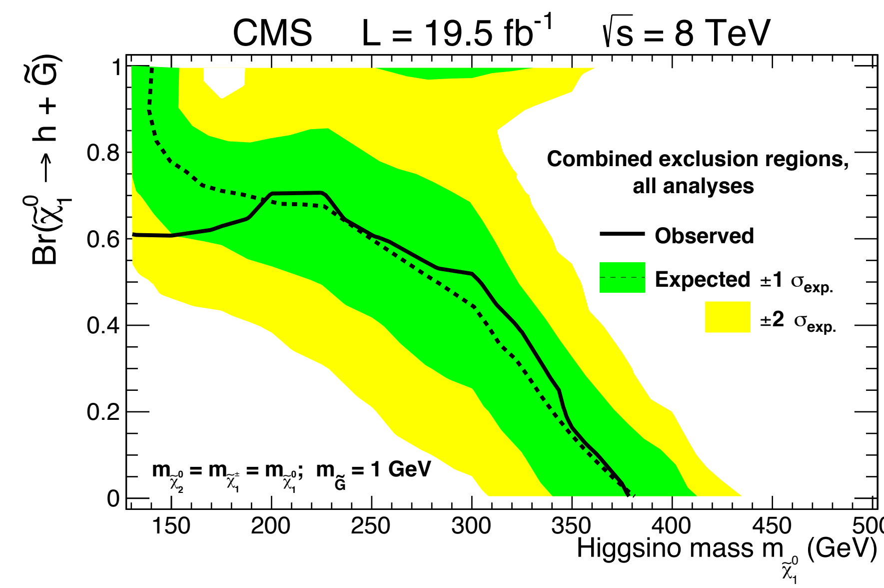
[DIMOPOULOS, GIUDICE '95; COHEN, KAPLAN, NELSON '96; PAPUCCI, RUDERMAN, WEILER '11; BRUST, KATZ, LAWRENCE, SUNDRUM '11]

# HIGGSINO SIGNALS



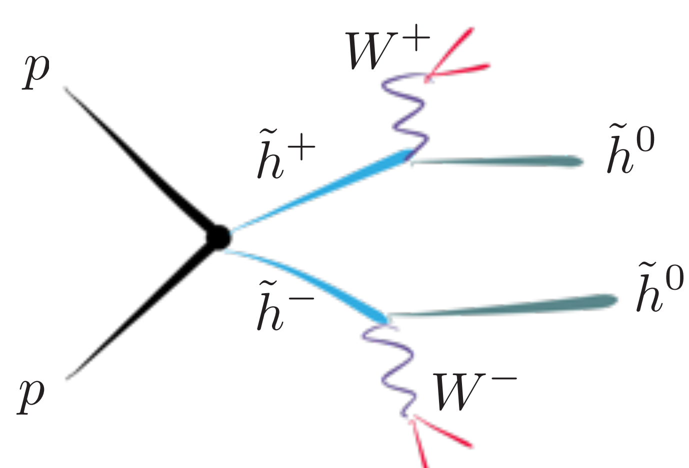

LOTS OF SEARCHES...

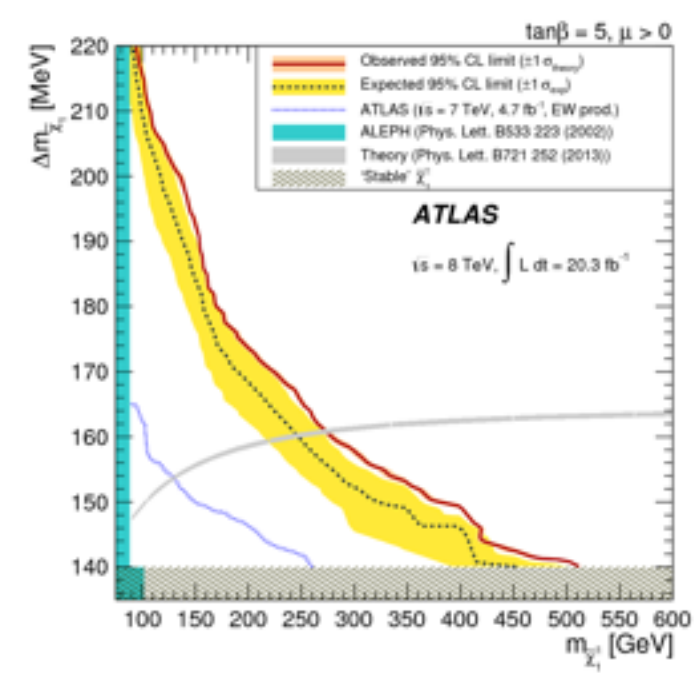


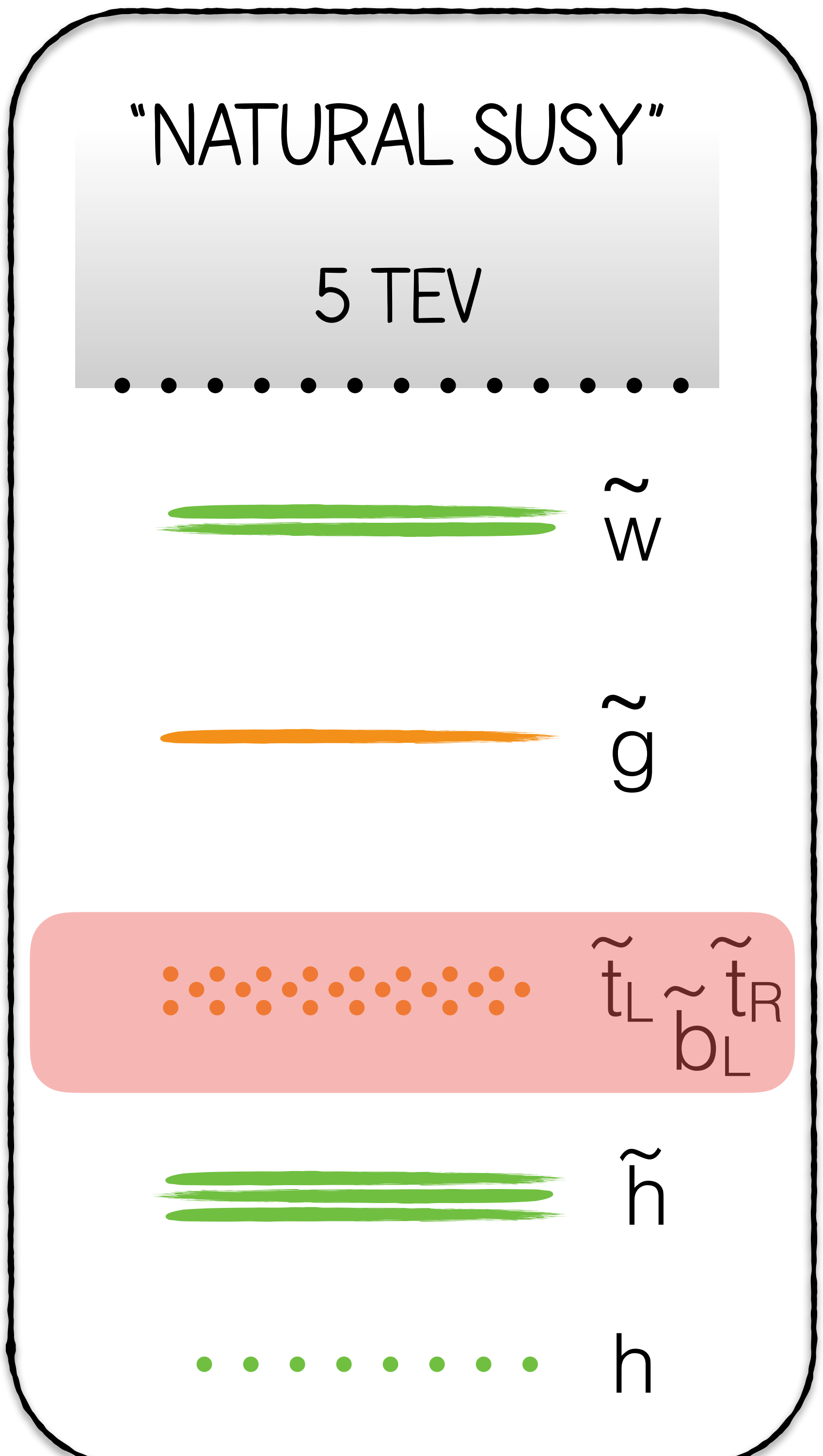

...BUT NO IRREDUCIBLE LIMITS

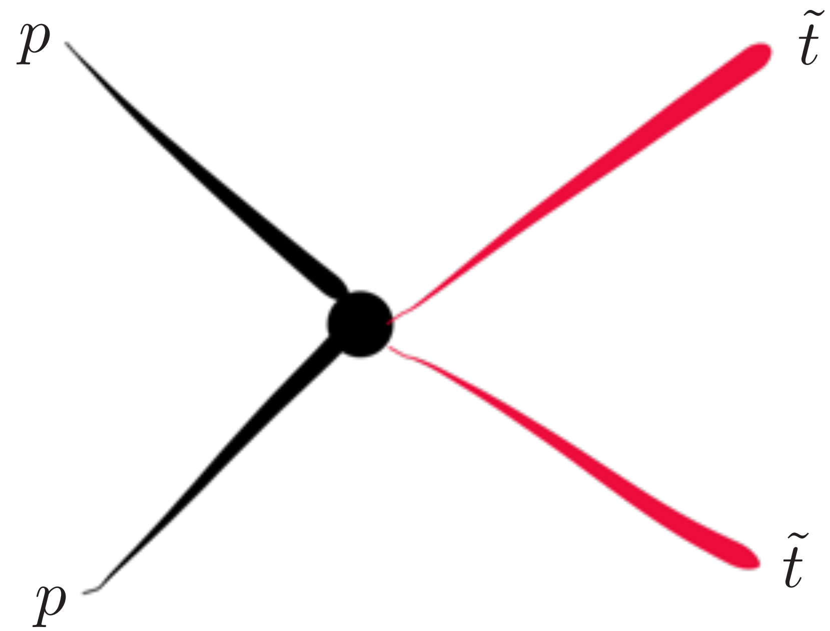
CHARGINO-NEUTRALINO SPLITTING IN PURE HIGGSINO MULTIPLET: 355 MEV
[THOMAS, WELLS '98]

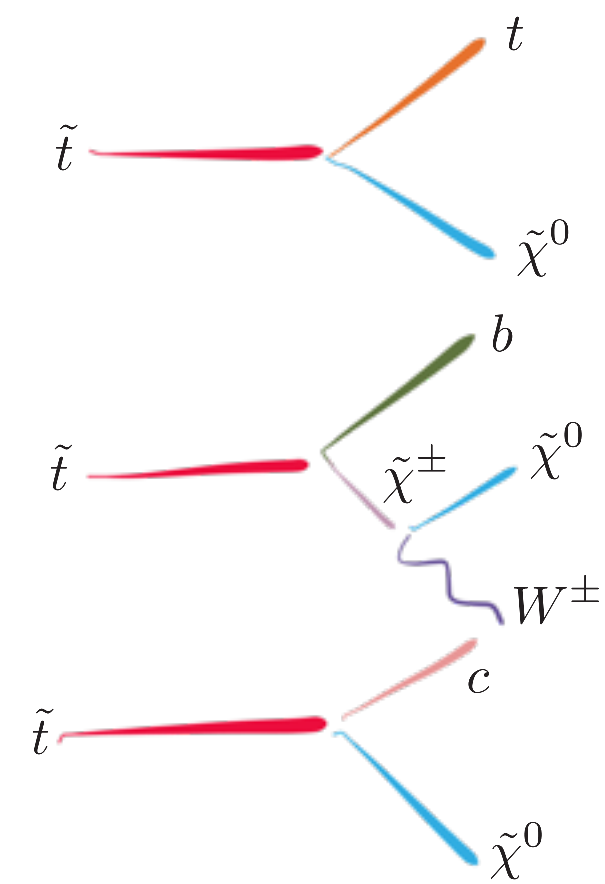


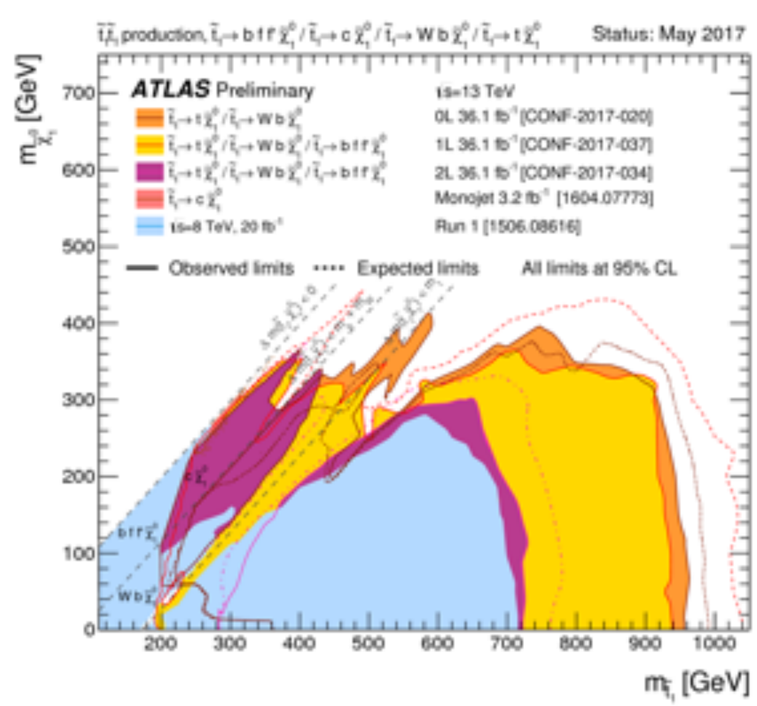



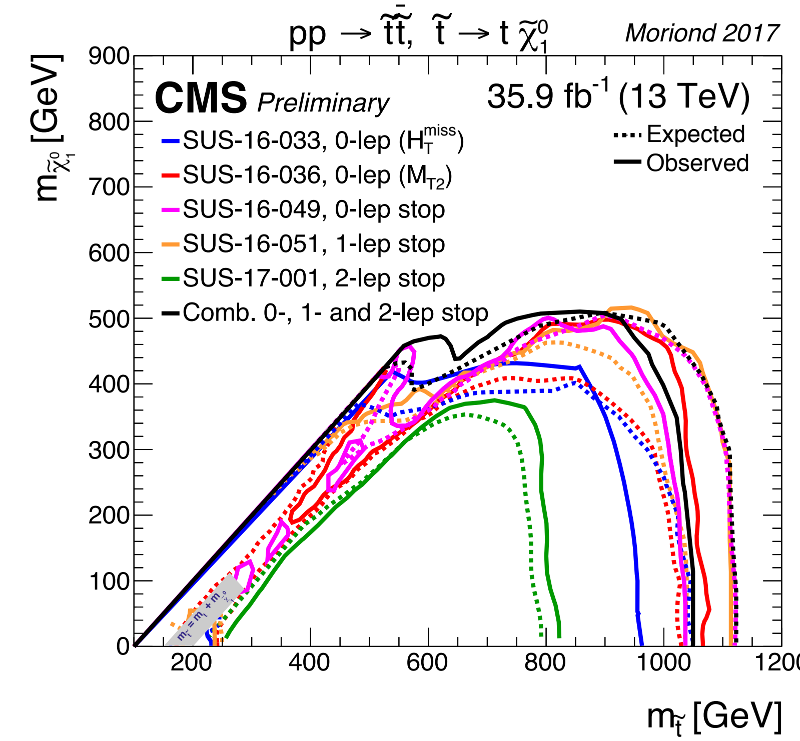
# STOP SIGNALS



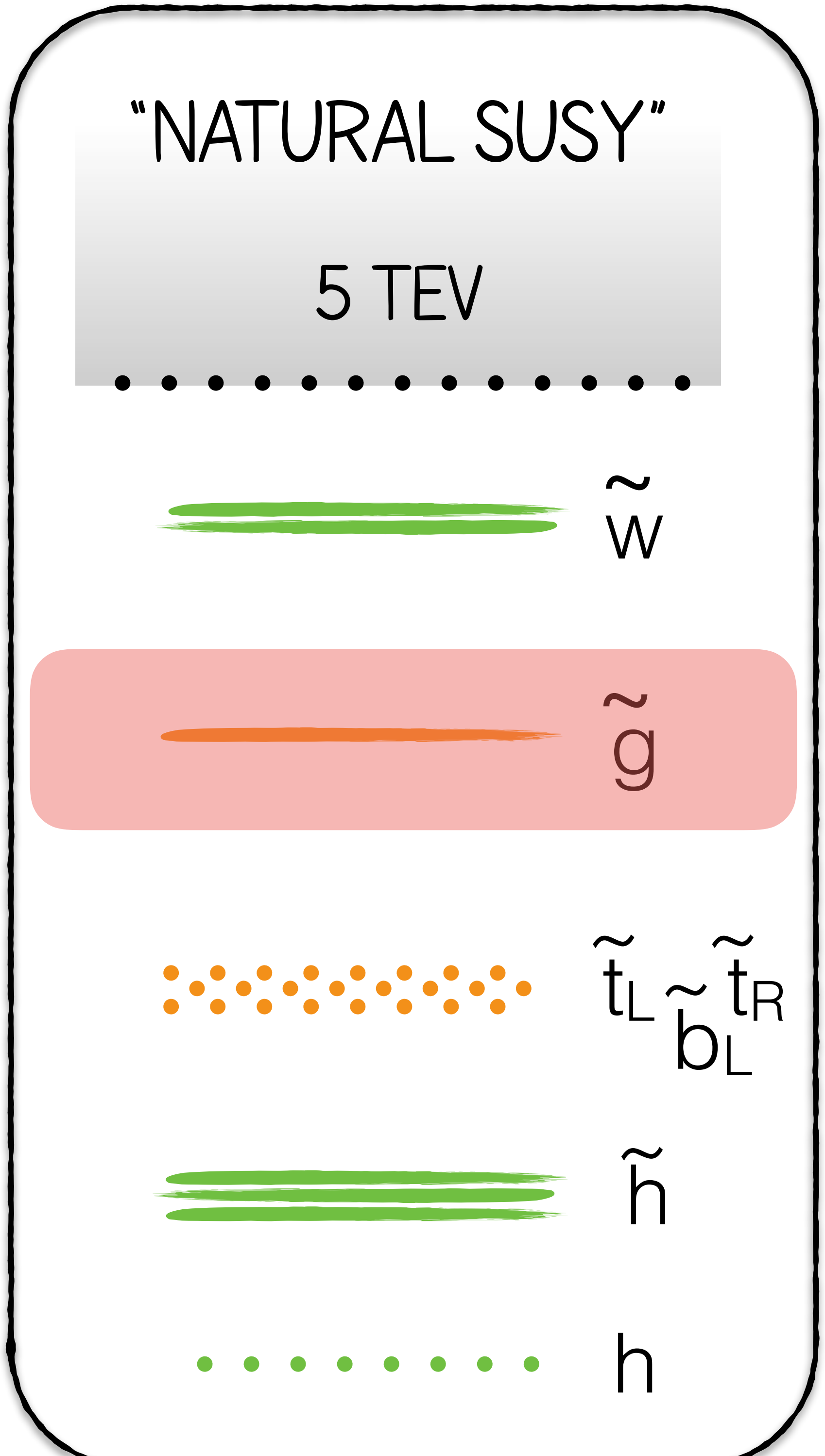



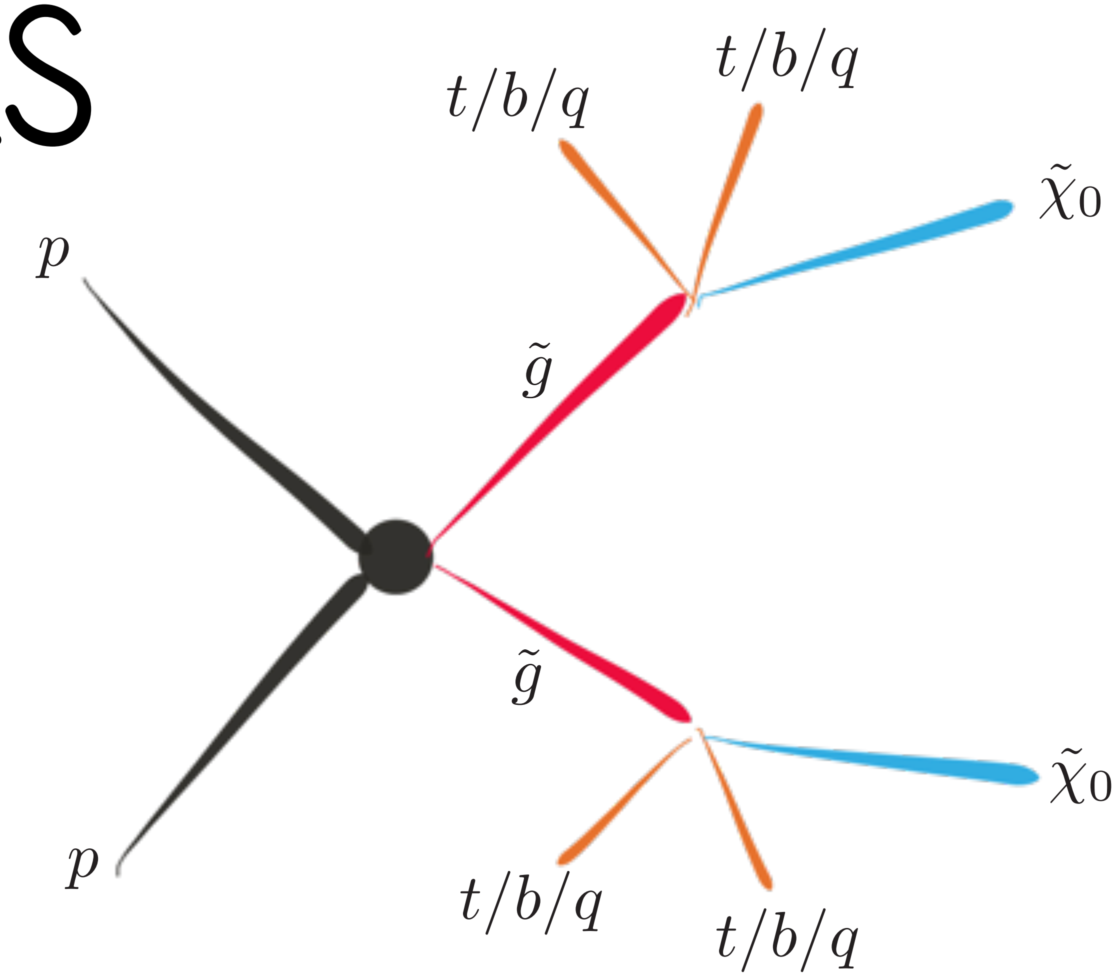



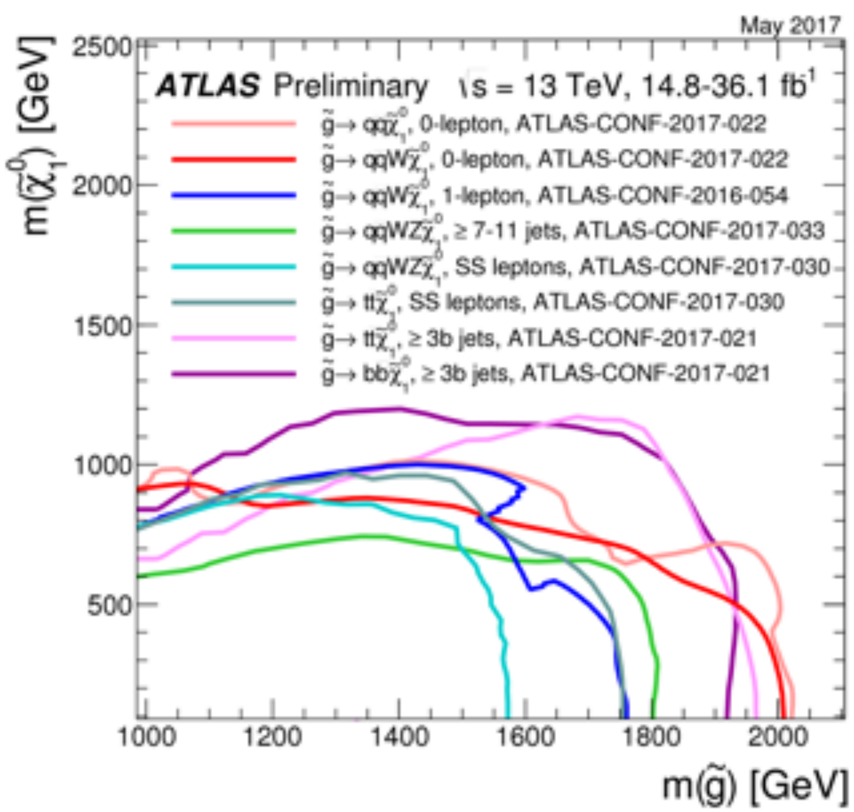



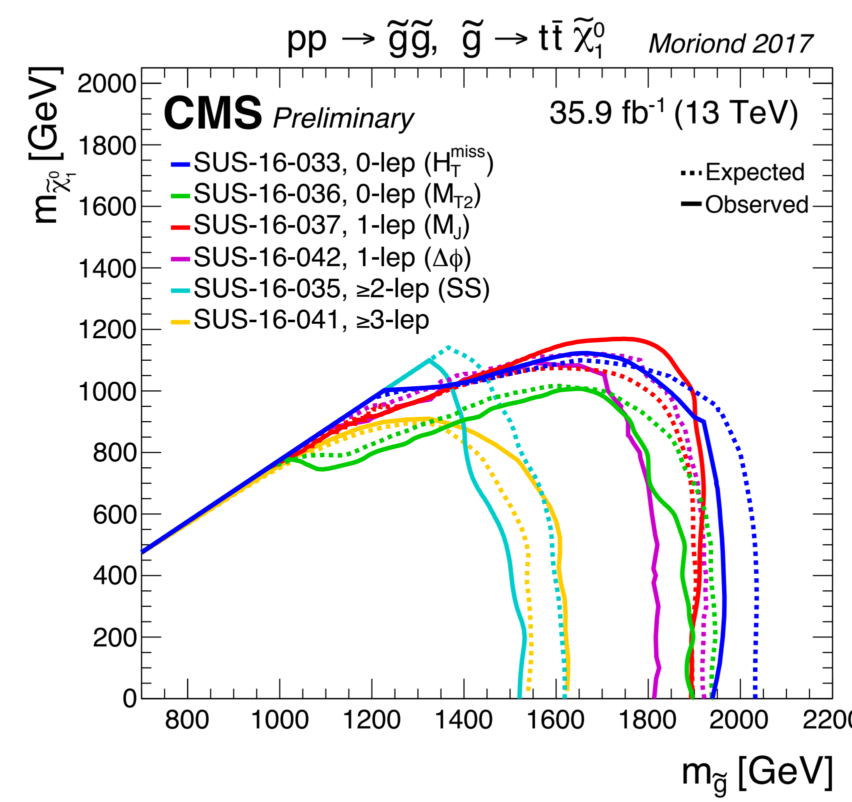



# GLUINO SIGNALS



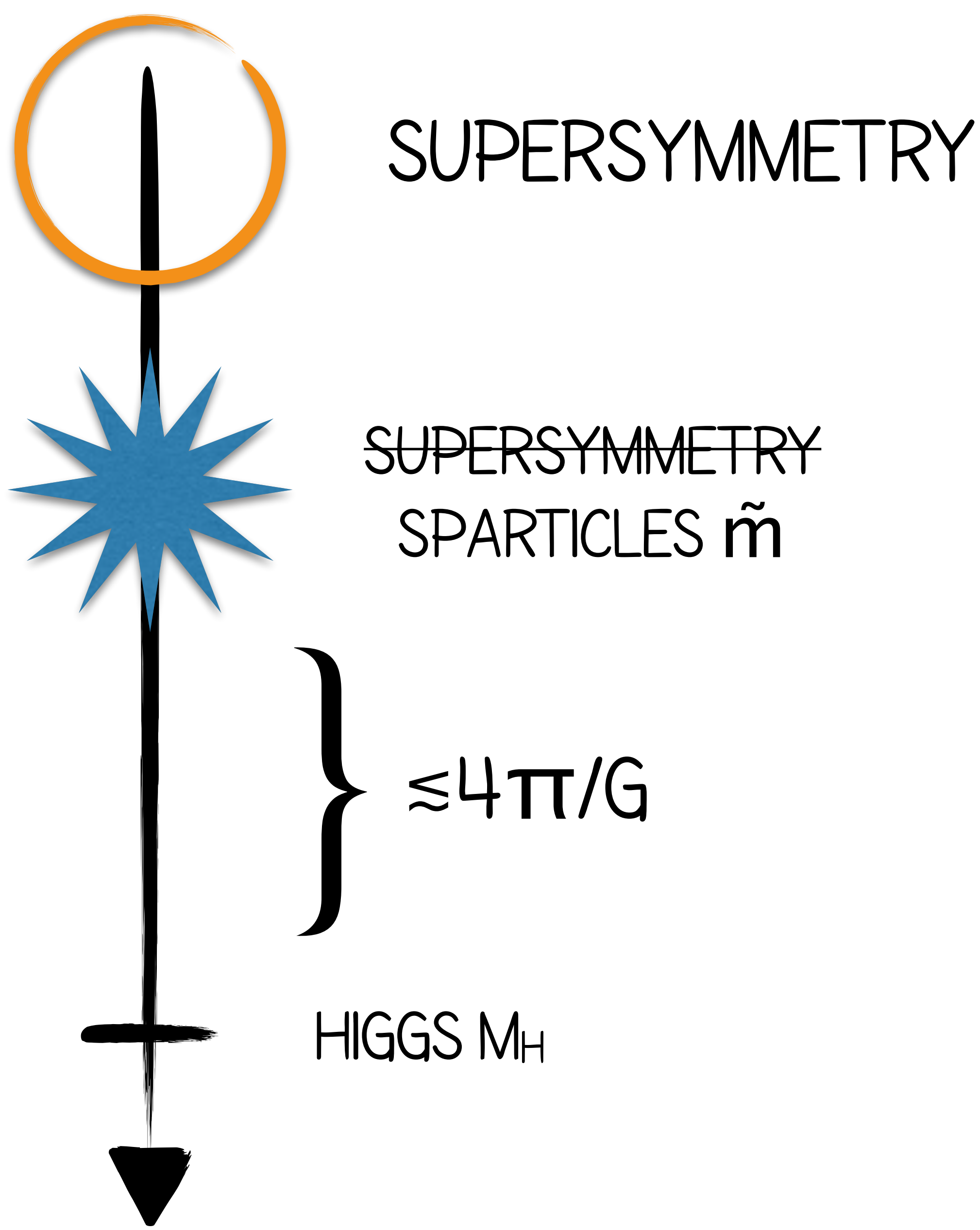



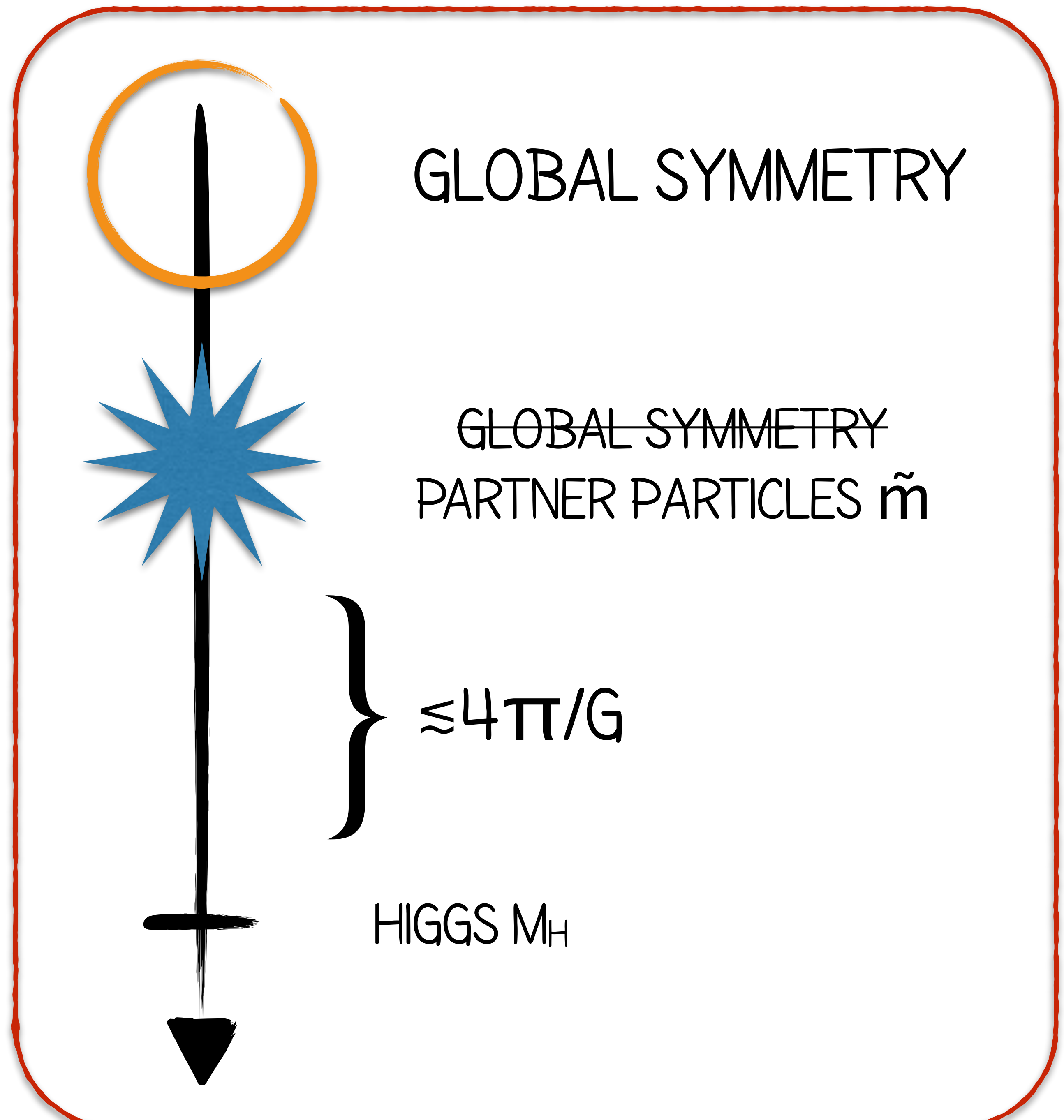



# POSSIBLE SYMMETRIES

*EXTEND THE SM WITH A SYMMETRY ACTING ON THE HIGGS*



# GLOBAL SYMMETRY: AN EXAMPLE

CONSIDER AN SU(N) GLOBAL SYMMETRY, SPONTANEOUSLY BROKEN BY VEV OF A FUNDAMENTAL SCALAR $\phi$

$$SU(N) \to SU(N-1)$$

GOLDSTONE COUNTING: $$[N^2-1]-[(N-1)^2-1] = 2N-1$$

ORGANIZE INTO N-1 COMPLEX SCALARS + ONE REAL

EXPAND $\phi$ IN TERMS OF GOLDSTONES $\pi$:

$$\phi = \exp\left[\frac{i}{f}\left(\begin{array}{ccc|c} & & & \pi_1 \\ & & & \vdots \\ & & & \pi_{N-1} \\ \hline \pi_1^* & \cdots & \pi_{N-1}^* & \pi_0/\sqrt{2} \end{array}\right)\right]\begin{pmatrix} 0 \\ \vdots \\ 0 \\ f \end{pmatrix} \equiv e^{i\pi/f}\phi_0$$

LOW-ENERGY THEORY OF $\pi$ INDEPENDENT OF DETAILS OF SYMMETRY BREAKING

# GLOBAL SYMMETRY: AN EXAMPLE

UNBROKEN SU(N-1) GENERATORS:

$$U_{N-1} = \begin{pmatrix} \hat{U}_{N-1} & 0 \\ 0 & 1 \end{pmatrix}$$

$\phi$ TRANSFORMS AS A FUNDAMENTAL, SO

$$\phi \to U_{N-1}\phi = (U_{N-1} e^{i\pi/f} U_{N-1}^\dagger) U_{N-1}\phi_0 = e^{\frac{i}{f}(U_{N-1}\pi U_{N-1}^\dagger)}\phi_0$$

THE $\pi$ TRANSFORM AS

$$\left(\begin{array}{c|c} & \vec{\pi} \\ \hline \vec{\pi}^\dagger & \pi_0/\sqrt{2} \end{array}\right) \to U_{N-1} \left(\begin{array}{c|c} & \vec{\pi} \\ \hline \vec{\pi}^\dagger & \pi_0/\sqrt{2} \end{array}\right) U_{N-1}^\dagger = \left(\begin{array}{c|c} & \hat{U}_{N-1}\vec{\pi} \\ \hline \vec{\pi}^\dagger \hat{U}_{N-1}^\dagger & \pi_0/\sqrt{2} \end{array}\right)$$

I.E., THE $\vec{\pi}$ TRANSFORM AS FUNDAMENTALS UNDER UNBROKEN SU(N-1)

TRANSFORMATION UNDER BROKEN GENERATORS MORE COMPLICATED, BUT AT LINEAR ORDER TRANSFORM BY A SHIFT:

$$\vec{\pi} \to \vec{\pi} - \vec{\alpha} + \ldots$$

THE USUAL SHIFT SYMMETRY OF GOLDSTONES. A SYMMETRY TO PROTECT SCALARS...

# GLOBAL SYMMETRY: AN EXAMPLE

LET'S NOW CONSTRUCT A TOY MODEL FOR THE HIGGS

CONSIDER SU(3)→SU(2)

CONVENIENT TO PARAMETERIZE GOLDSTONES AS

$$\pi = \left(\begin{array}{cc|c} -\eta/2 & 0 & H_1 \\ 0 & -\eta/2 & H_2 \\ \hline H_1^* & H_2^* & \eta \end{array}\right)$$

SUGGESTIVE: H TRANSFORMS AS A COMPLEX DOUBLET OF UNBROKEN SU(2) & ENJOYS A SHIFT SYMMETRY

LOW-ENERGY THEORY FOR H INHERITS NON-RENORMALIZABLE INTERACTIONS

$$f^2|\partial_\mu \phi|^2 = |\partial_\mu H|^2 + \frac{H^\dagger H |\partial_\mu H|^2}{f^2} + \dots$$

LOOPS IN THIS EFT ARE OF ORDER $\frac{1}{f^2}\frac{\Lambda^2}{16\pi^2}$

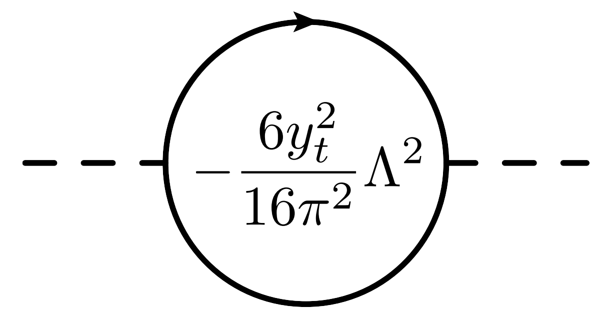
SO CONSISTENT POWER COUNTING IMPLIES $\Lambda \lesssim 4\pi f$

# GLOBAL SYMMETRY: AN EXAMPLE

OF COURSE, HIGGS MUST COUPLE TO SM FIELDS; COUPLINGS BREAK SU(3) AND HENCE VIOLATE SHIFT SYMMETRY

$$\mathcal{L} \supset -\lambda_t t_R^\dagger \tilde{H} Q_3$$ WHERE $\tilde{H} = (i\sigma_2 H)^\dagger$ AND $Q_3 = (t_L, b_L)$

GIVES THE USUAL QUADRATIC DIVERGENCE, NOT PROTECTED BY SHIFT SYMMETRY




MIGHT AS WELL HAVE NEVER INTRODUCED GLOBAL SYMMETRY...

SOLUTION: EXTEND TOP MULTIPLET TO SU(3):

$$Q_3 \to \hat{Q}_3$$
$$t_R \to \hat{t}_R + \hat{T}_R$$

$$\hat{Q}_3 = (\sigma_2 Q_3, T_L)$$

+ ADD SU(3) SYMMETRIC TOP YUKAWA,

$$\mathcal{L} \supset -(\lambda_1 \hat{t}_R^\dagger + \lambda_2 \hat{T}_R^\dagger)\phi^\dagger \hat{Q}_3 + \text{h.c.}$$

# GLOBAL SYMMETRY: AN EXAMPLE

BELOW SCALE OF SPONTANEOUS SU(3) BREAKING, INTERACTIONS ARE

$$\mathcal{L} = -f(\lambda_1 \hat{t}_R^\dagger + \lambda_2 \hat{T}_R^\dagger) T_L - \lambda_1 \hat{t}_R^\dagger \tilde{H} Q_3 + \frac{\lambda_1}{2f}(H^\dagger H)\hat{t}_R^\dagger T_L + \text{h.c.} + \ldots$$

MASS EIGENSTATES $T_L, t_L$ $\quad t_R = \frac{\lambda_2 \hat{t}_R - \lambda_1 \hat{T}_R}{\sqrt{\lambda_1^2 + \lambda_2^2}} \quad T_R = \frac{\lambda_1 \hat{t}_R + \lambda_2 \hat{T}_R}{\sqrt{\lambda_1^2 + \lambda_2^2}}$

IN TERMS OF THE MASS EIGENSTATES, INTERACTIONS ARE

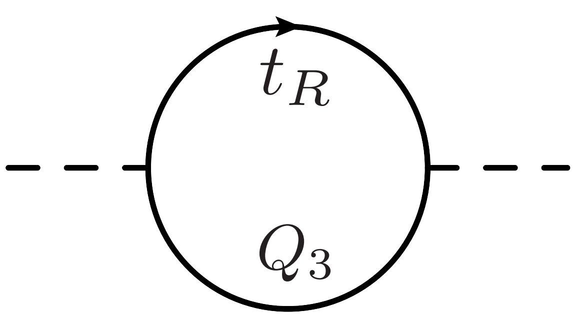
$$\mathcal{L} = -\lambda_t t_R^\dagger \tilde{H} Q_3 - \lambda_T T_R^\dagger \tilde{H} Q_3 + \frac{\lambda_1^2}{m_T}(H^\dagger H) T_R^\dagger T_L + \text{h.c.} + \ldots$$

WHERE $m_T = \sqrt{\lambda_1^2 + \lambda_2^2} f \quad \lambda_t = \frac{\lambda_1 \lambda_2}{\sqrt{\lambda_1^2 + \lambda_2^2}} \quad \lambda_T = \frac{\lambda_1^2}{\sqrt{\lambda_1^2 + \lambda_2^2}}$

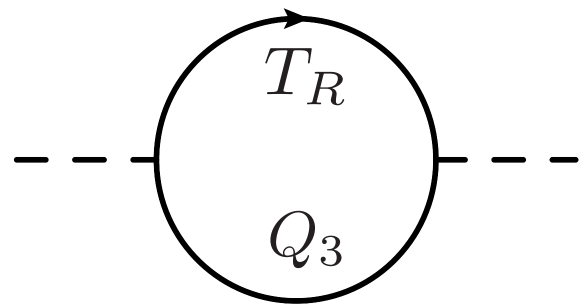
# GLOBAL SYMMETRY & THE HIERARCHY PROBLEM

TOP YUKAWA NOW ARISES FROM SU(3) SYMMETRIC INTERACTION, SO SHIFT SYMMETRY IS PRESERVED

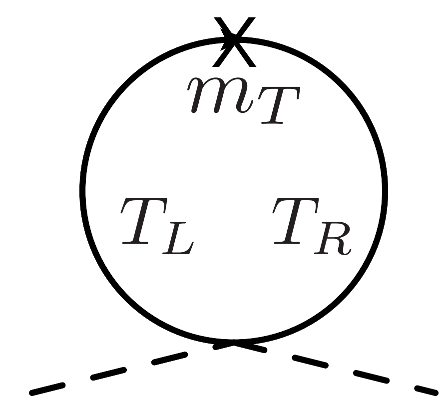
IN TERMS OF THE LOW-ENERGY THEORY, STUDY QUADRATIC DIVERGENCE:




$$-\frac{6\lambda_t^2}{16\pi^2}\Lambda^2$$




$$-\frac{6\lambda_T^2}{16\pi^2}\Lambda^2$$



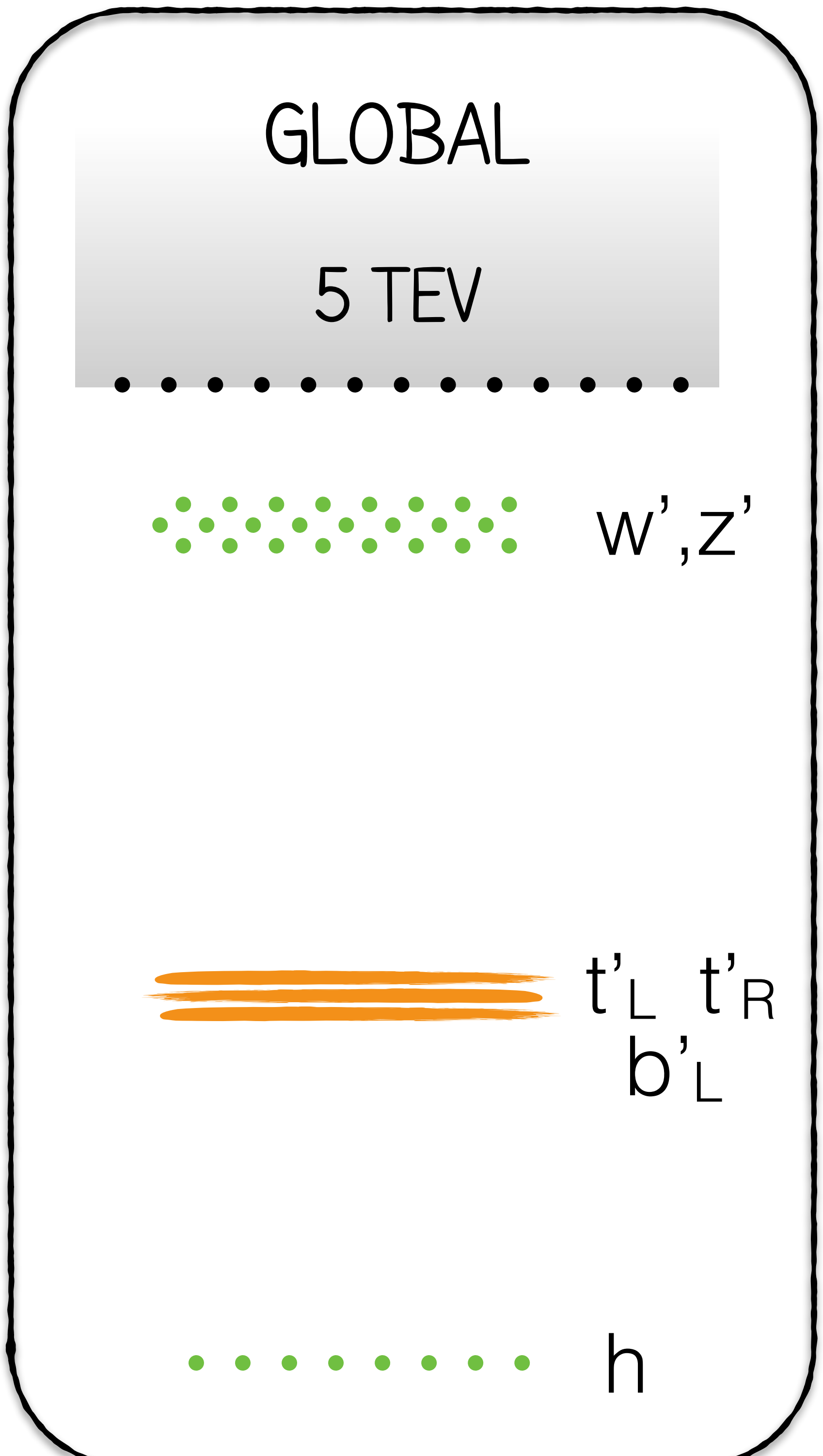

$$+\frac{6(\lambda_t^2+\lambda_T^2)}{16\pi^2}\Lambda^2$$

COUPLINGS EXACTLY SO THAT TOP PARTNER CANCELS RADIATIVE CONTRIBUTIONS FROM HIGHER SCALES. LOOKS MAGICAL, BUT GUARANTEED BY SYMMETRY STRUCTURE

REMAINING CONTRIBUTION IS FINITE THRESHOLD CORRECTION DUE TO SPLITTING IN MULTIPLET

$$m_H^2 \sim -\frac{6y_t^2}{16\pi^2} m_T^2 \log(\Lambda^2/m_T^2)$$

# GLOBAL EXPECTATIONS




STORY BASICALLY THE SAME AS SUSY, BUT NOW W/ LIGHT FERMIONIC TOP PARTNERS & HIGGS TUNING

$$m_H^2 \sim -\frac{6y_t^2}{16\pi^2} m_T^2 \log(\Lambda^2/m_T^2)$$ (TOP PARTNERS)

RADIATIVE HIGGS POTENTIAL FROM PARTNERS

$$V(h) \sim \frac{N_c}{16\pi^2} m_\psi^4 \epsilon^2 \left[ c_1 \frac{h^2}{f^2} + c_2 \frac{h^4}{f^4} \right]$$

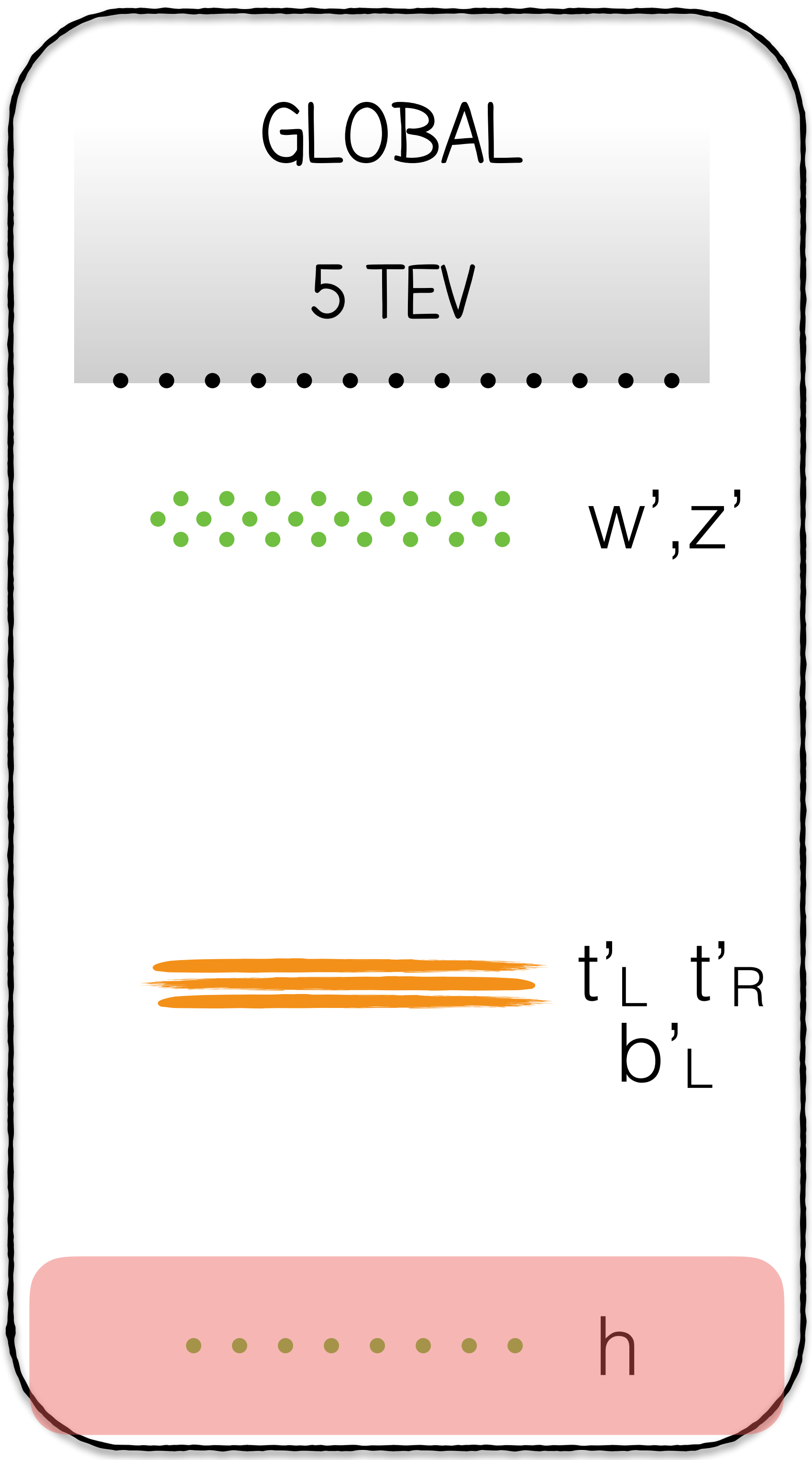
QUARTIC & $M^2$ AT SAME LOOP ORDER, EXPECT **V~F**

*I.E., NO SEPARATION BETWEEN WEAK SCALE & GLOBAL BREAKING*

MAKING **V < F** REQUIRES TREE-LEVEL TUNING OF TERMS IN THE POTENTIAL $\Delta \sim f^2/v^2$

LIMITS NOW FROM QCD-CHARGED STATES & HIGGS MIXING.

# HIGGS SIGNALS

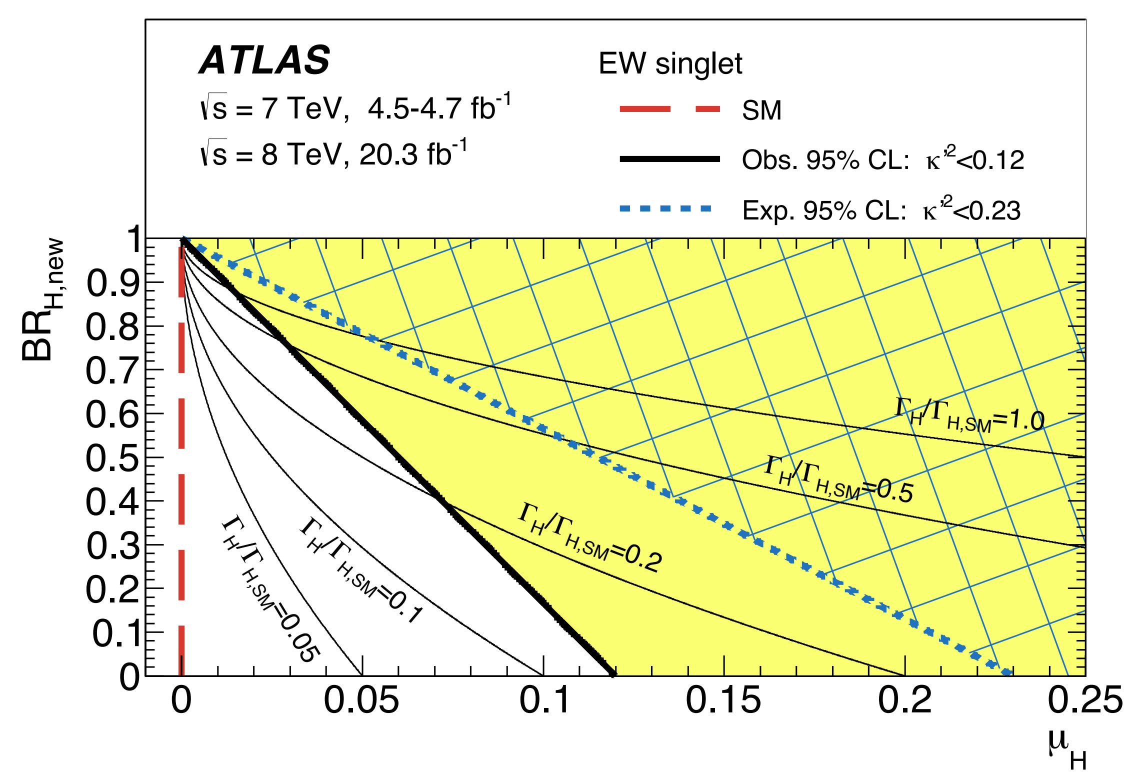



$$|\partial_\mu H|^2 + \frac{H^\dagger H}{f^2}|\partial_\mu H|^2 \to \left(1+\frac{v^2}{f^2}\right)\frac{1}{2}(\partial_\mu h)^2$$

CANONICALLY NORMALIZE $\quad h \to (1 - v^2/2f^2)h$

SHIFTS HIGGS COUPLINGS UNIFORMLY, E.G.

$$\frac{m_Z^2}{v} h Z_\mu Z^\mu \to \frac{m_Z^2}{v}(1 - v^2/2f^2) h Z_\mu Z^\mu$$



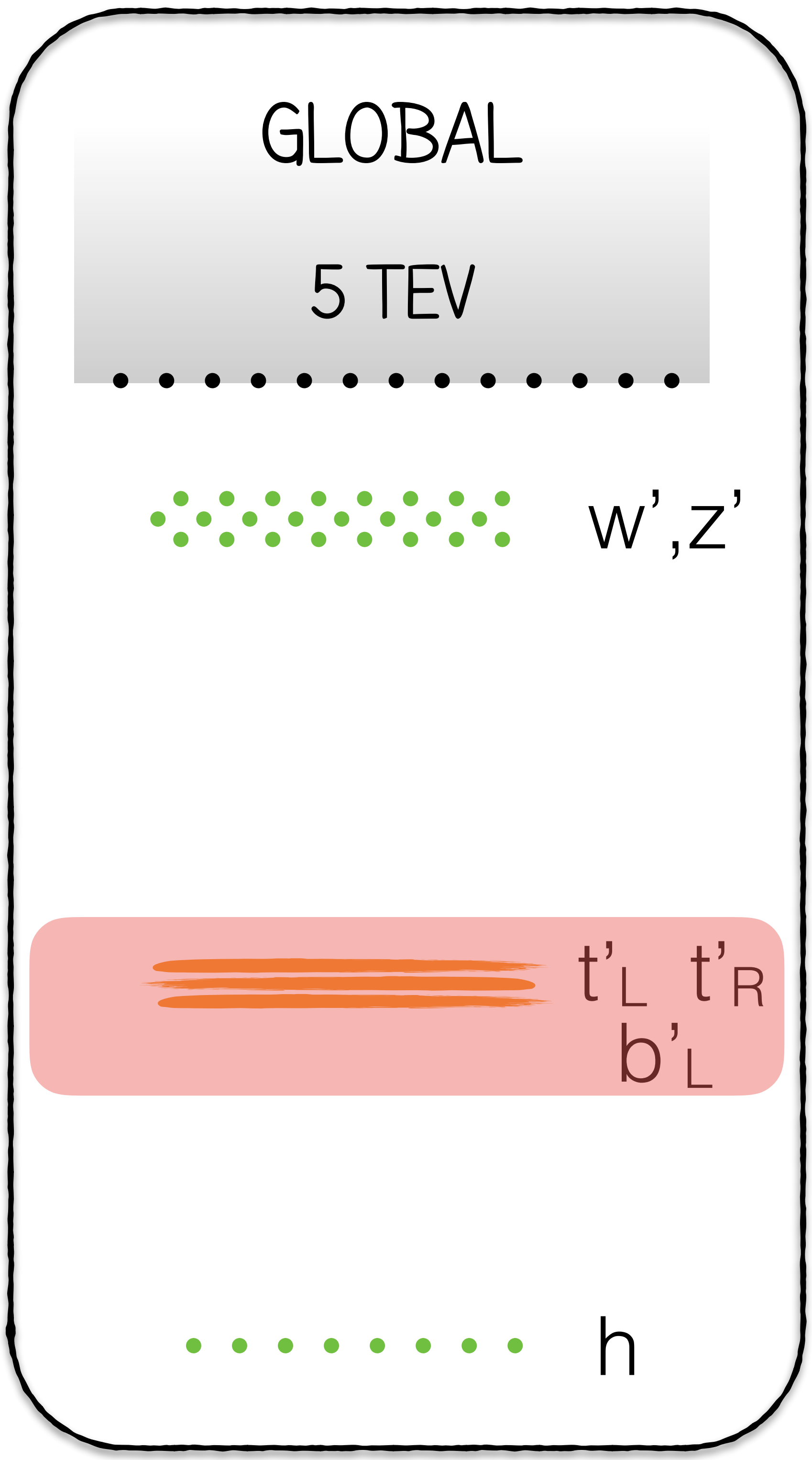

LIMIT

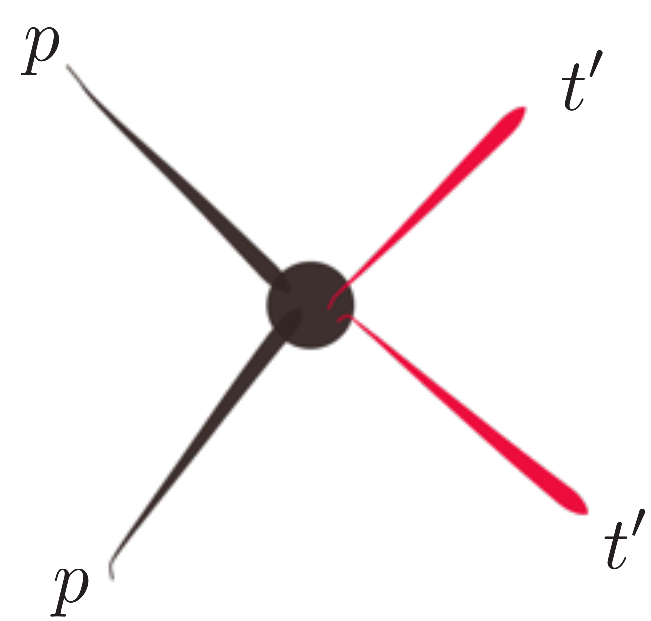
$v^2/f^2 < 0.1$

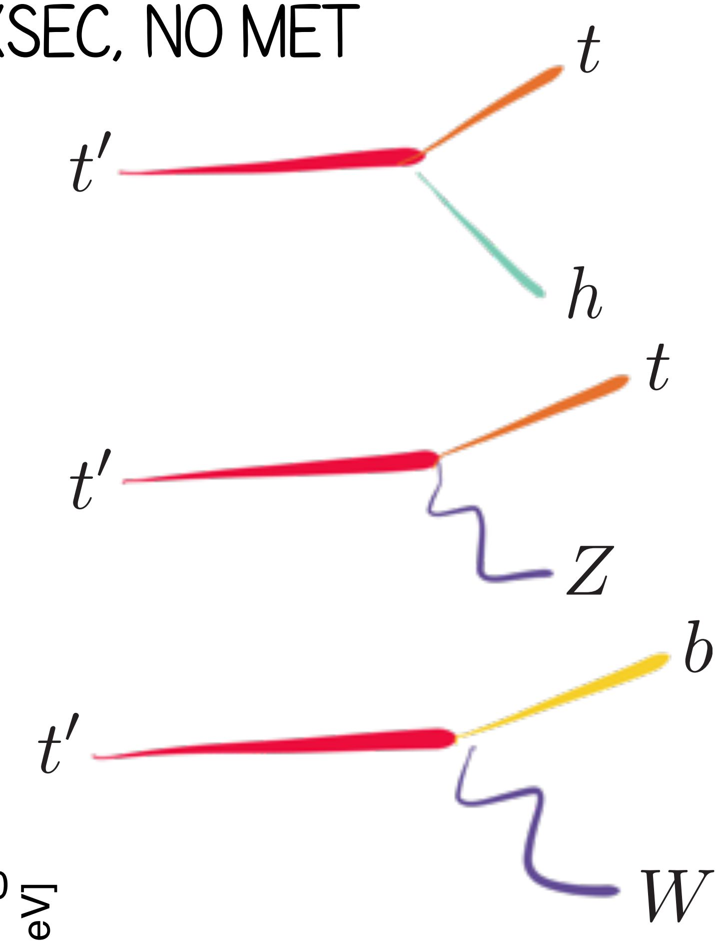
*UNLIKELY TO IMPROVE MUCH IN FUTURE OF LHC*

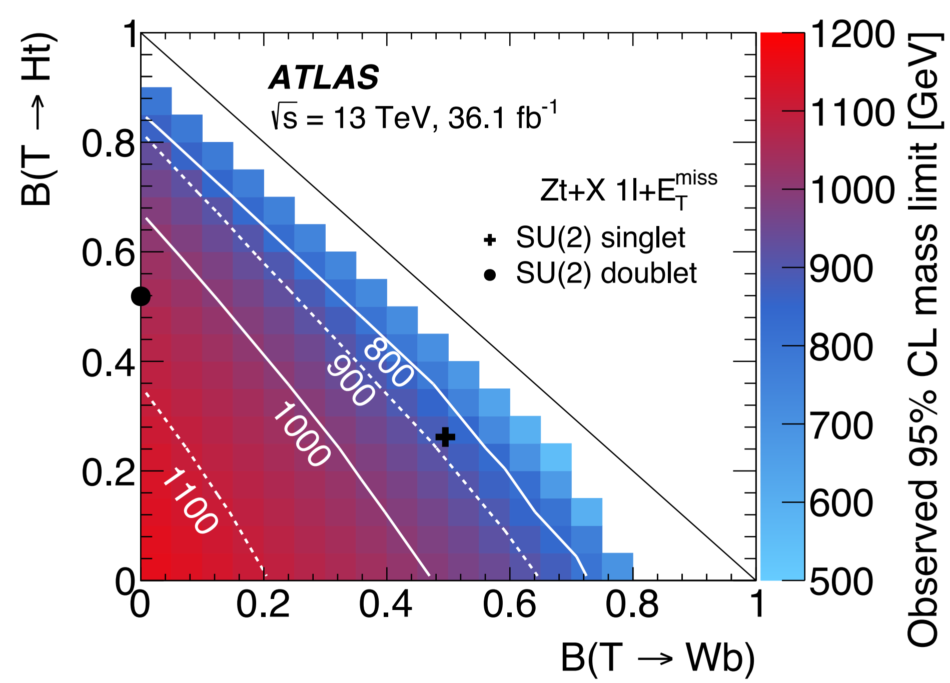
# TOP PARTNER SIGNALS

3RD-GENERATION VECTOR-LIKE QUARKS.
EASIER THAN SUSY: LARGER XSEC, NO MET



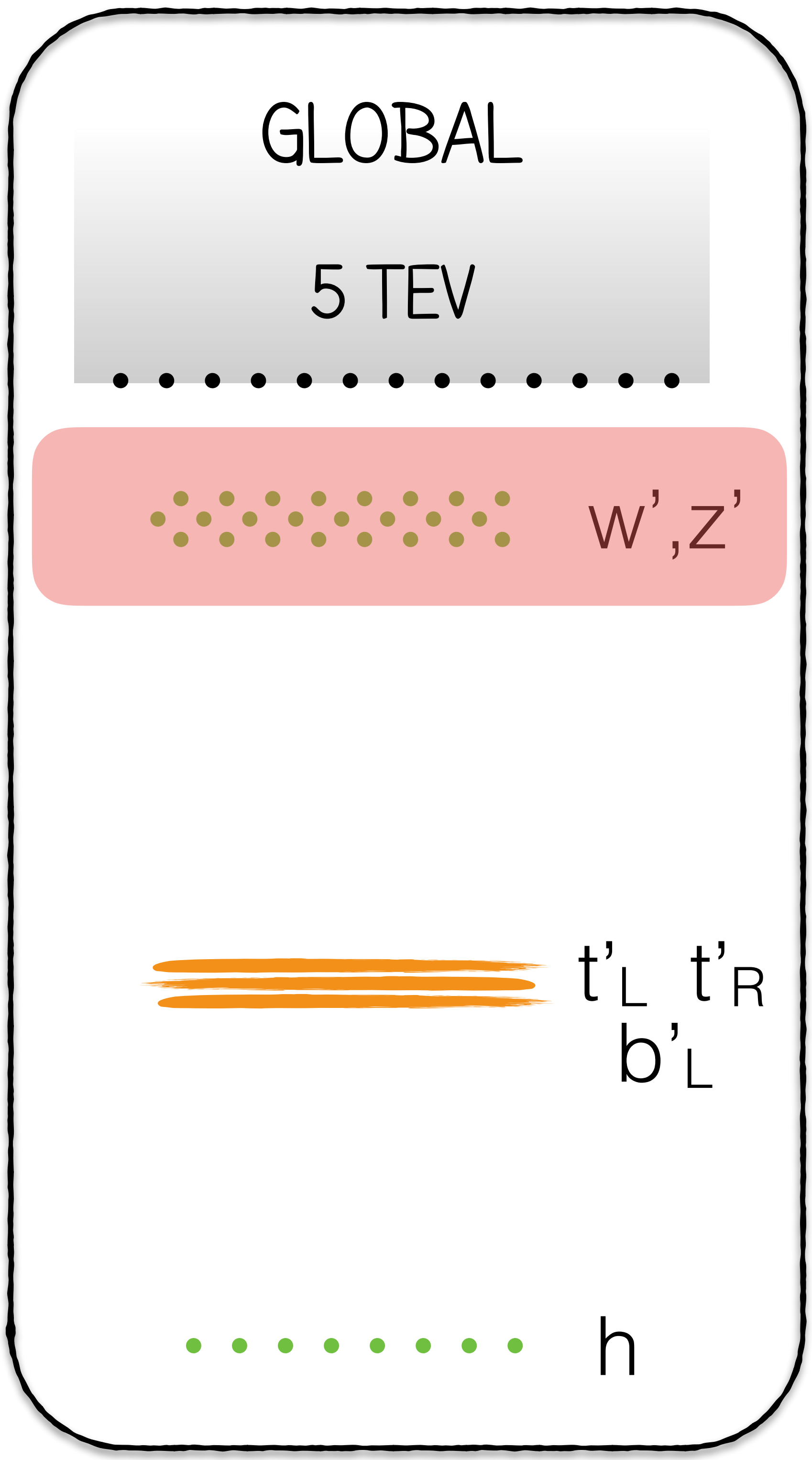



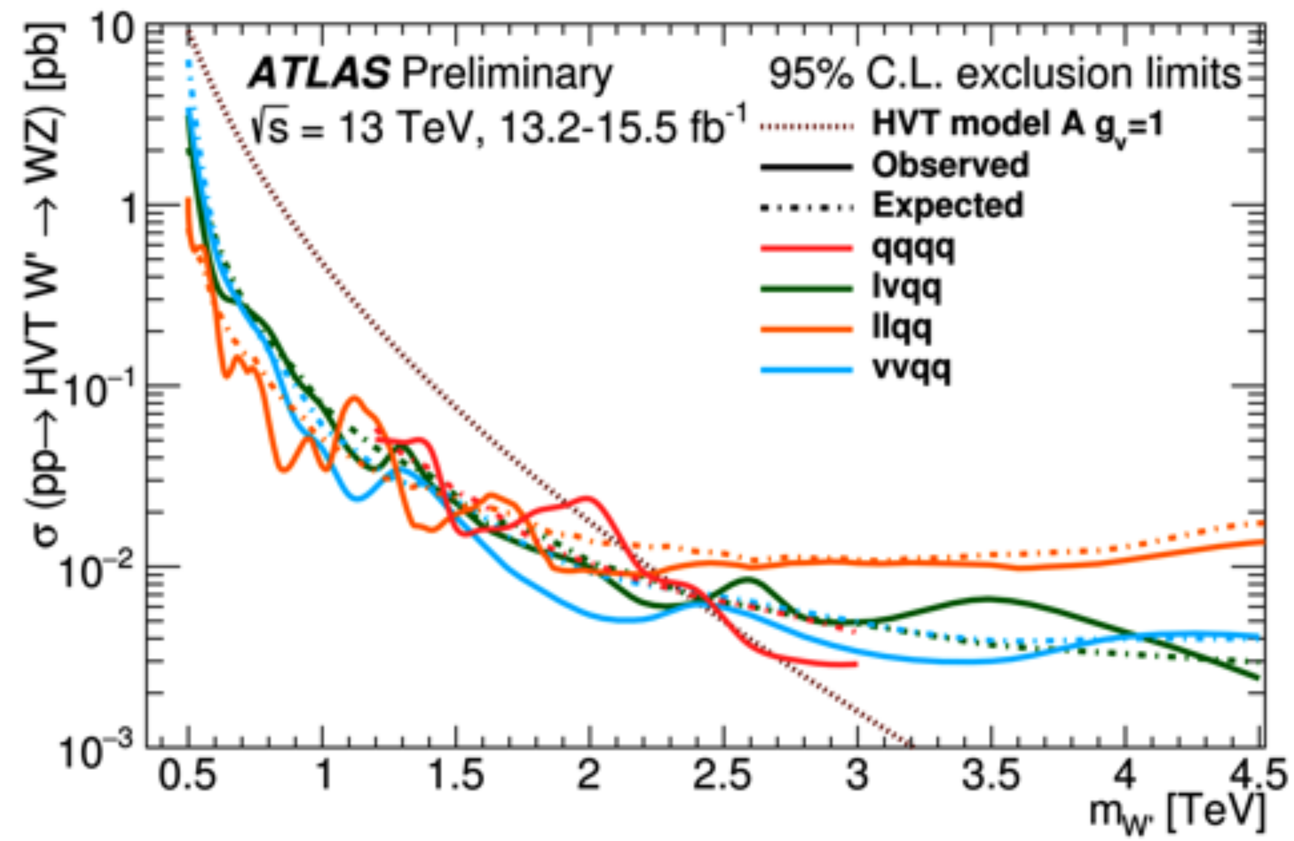




VARIOUS FINAL STATES

# RESONANCE SIGNALS



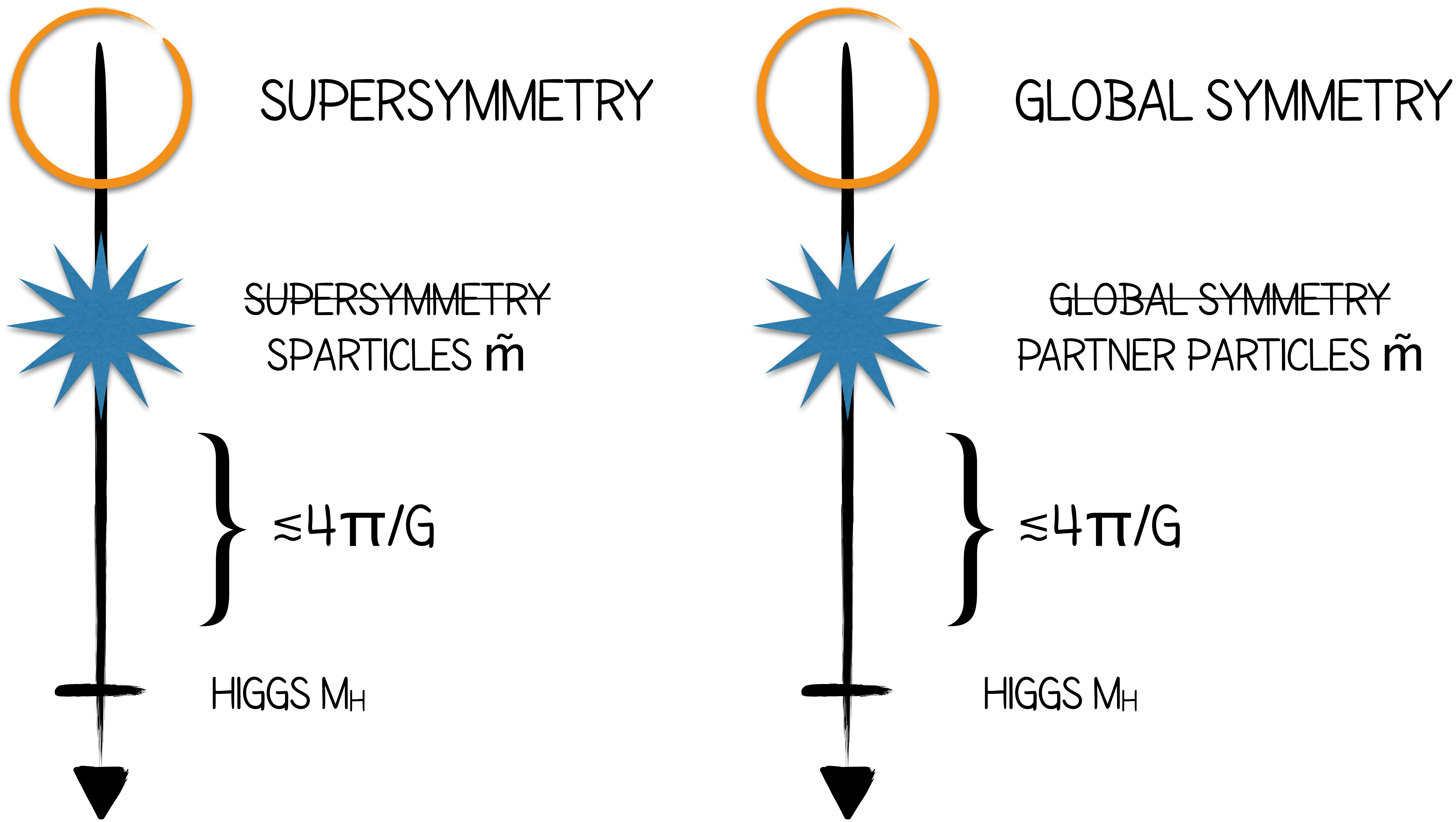

WIDE VARIETY OF POSSIBLE RESONANCES & SIGNALS




COMPARABLE TO PRECISION ELECTROWEAK LIMITS

$$S = 4\pi(1.36)\left(\frac{v}{m_\rho}\right)^2 \to m_\rho \gtrsim 3\ \text{TeV}$$

# SYMMETRY SUMMARY




SYMMETRY SOLUTIONS TO THE HIERARCHY PROBLEM PREDICT A SYSTEMATIC SET OF SIGNALS. NO EVIDENCE SO FAR. COULD STILL BE AROUND THE CORNER, BUT WORTH ASKING...

# IS THIS ALL THERE IS?