BEYOND THE STANDARD MODEL @ THE TEV SCALE

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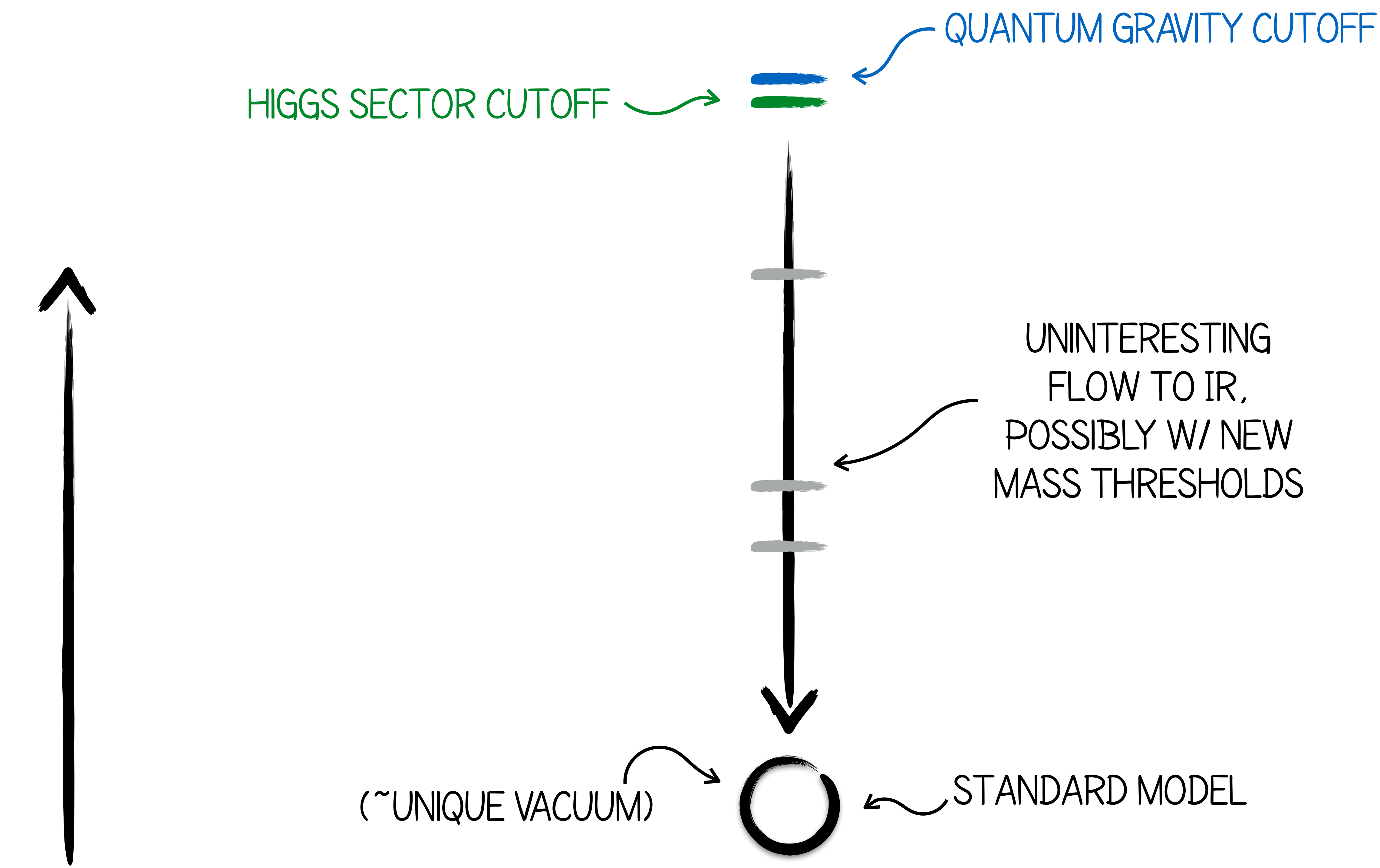
2017 ICTP SUMMER SCHOOL ON PARTICLE PHYSICS

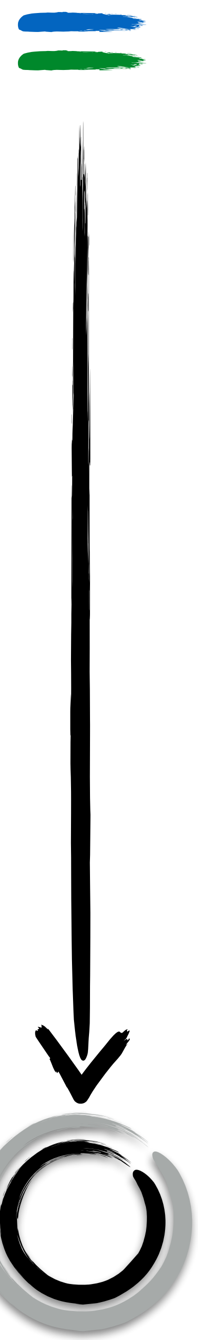
THE HIERARCHY PROBLEM



M_H IS NOT TECHNICALLY NATURAL $\Rightarrow$ **HIERARCHY PROBLEM**

ADDING A SYMMETRY

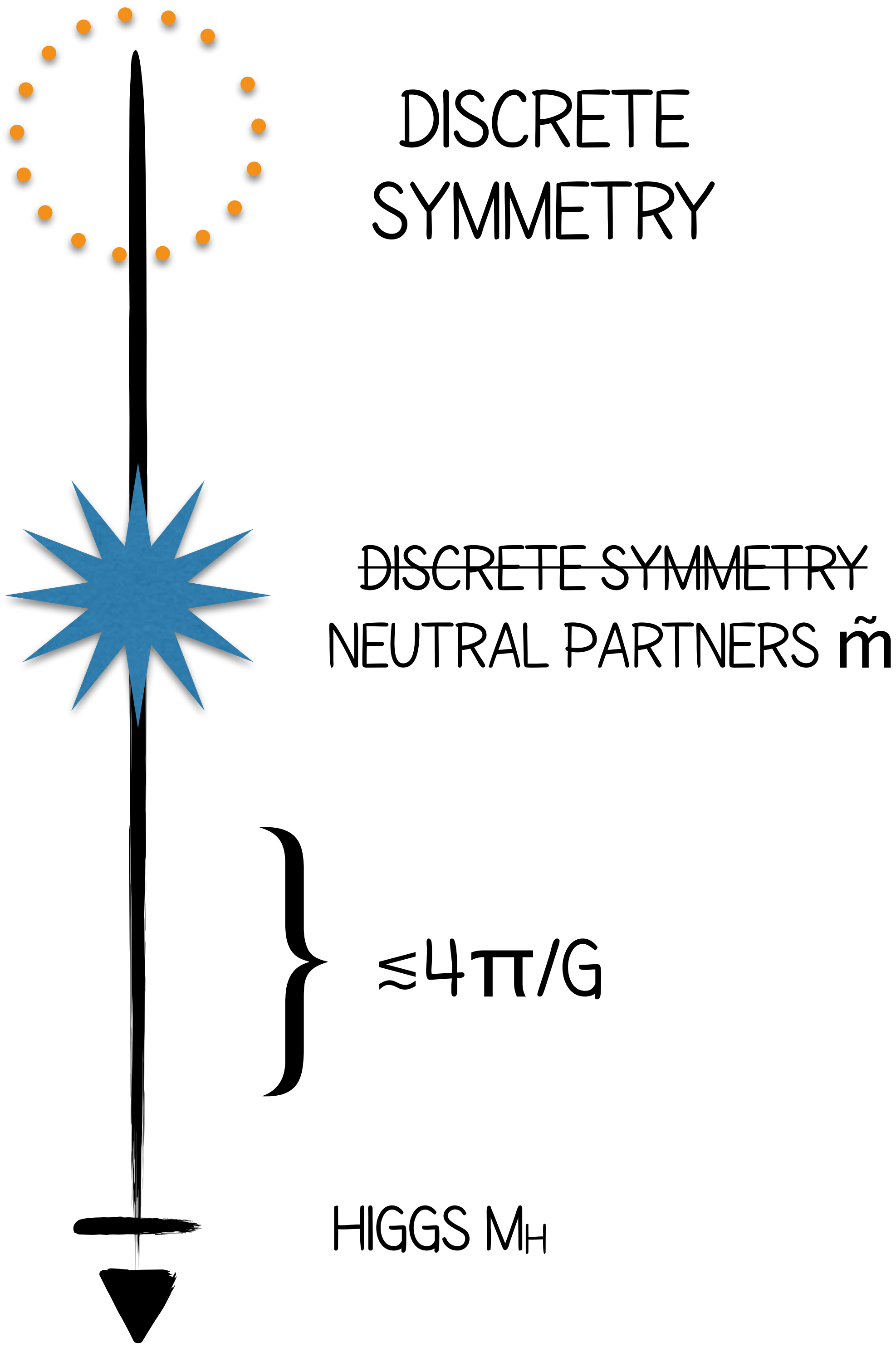
...AND BREAKING IT SOFTLY



WE ASSUMED THE SYMMETRY PROTECTING THE WEAK SCALE WAS CONTINUOUS. ARE THEIR OTHER OPTIONS?

$\Rightarrow$ "NEUTRAL NATURALNESS"

DISCRETE SYMMETRIES



SYMMETRY-BASED APPROACHES TO HIERARCHY PROBLEM EMPLOY *CONTINUOUS SYMMETRIES.*

LEADS TO PARTNER STATES W/ SM QUANTUM NUMBERS.

DISCRETE SYMMETRIES CAN ALSO SERVE TO PROTECT THE HIGGS.

LEADS TO PARTNER STATES W/ NON-SM QUANTUM NUMBERS.

"NEUTRAL NATURALNESS"

[CHACKO, GOH, HARNIK '05]

THE TWIN HIGGS

CONSIDER A SCALAR H TRANSFORMING AS A FUNDAMENTAL UNDER A GLOBAL SU(4) SYMMETRY:

$$V(H) = -m^2|H|^2 + \lambda|H|^4$$

POTENTIAL LEADS TO SPONTANEOUS SYMMETRY BREAKING,

$$|\langle H\rangle|^2 = \frac{m^2}{2\lambda} \equiv f^2$$

$SU(4) \to SU(3)$ YIELDS SEVEN GOLDSTONE BOSONS.

THE TWIN HIGGS

NOW GAUGE $SU(2)_A \times SU(2)_B \subset SU(4)$, W/ $H = \begin{pmatrix} H_A \\ H_B \end{pmatrix}$

US

TWINS

THEN 6 GOLDSTONES ARE EATEN, LEAVING ONE BEHIND.

EXPLICITLY BREAKS THE SU(4); EXPECT RADIATIVE CORRECTIONS.

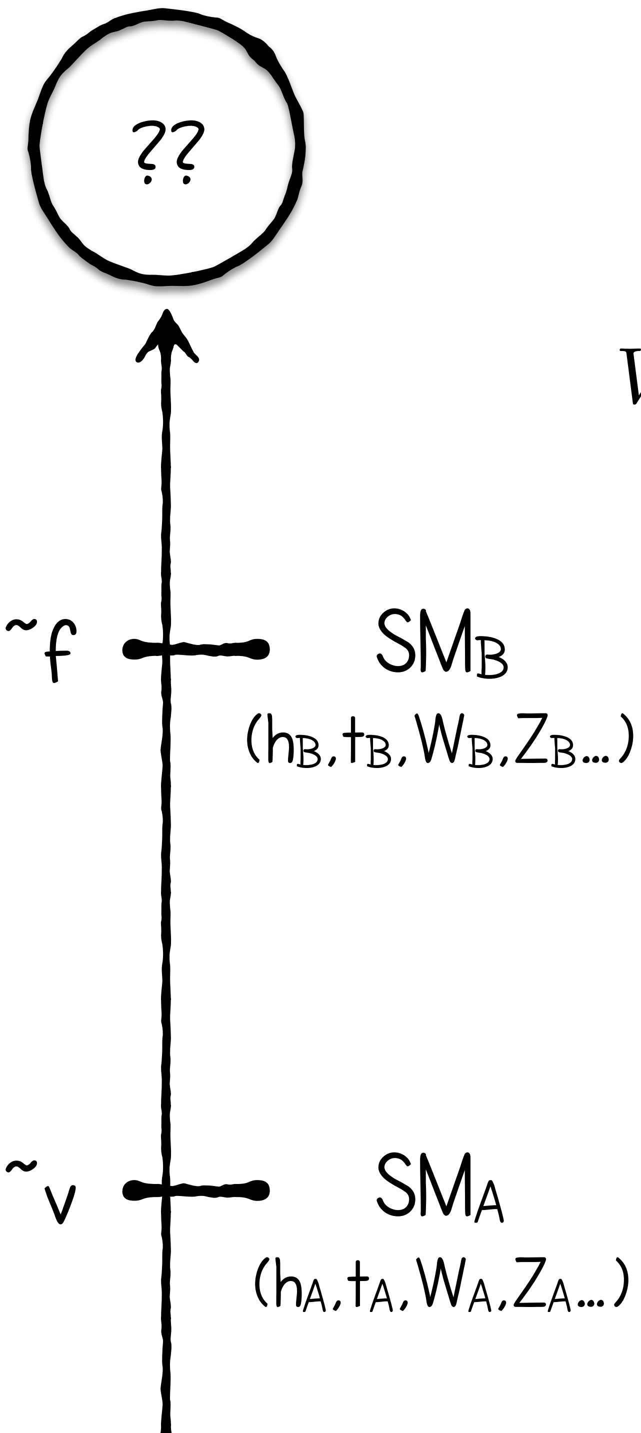
$$V(H) \supset \frac{9}{64\pi^2}\left(g_A^2 \Lambda^2 |H_A|^2 + g_B^2 \Lambda^2 |H_B|^2\right)$$

BUT THESE BECOME SU(4) SYMMETRIC IF $g_A = g_B$ FROM A Z_2

QUADRATIC POTENTIAL HAS ACCIDENTAL SU(4) SYMMETRY.

THE TWIN HIGGS

FULL THEORY: EXTEND Z_2 TO ALL SM MATTER AND COUPLINGS.



$$\boxed{SM_A \times SM_B \times Z_2}$$

$$V(H) \supset \frac{\Lambda^2}{16\pi^2}\left(-6y_t^2 + \frac{9}{4}g^2 + \ldots\right)\left(|H_A|^2 + |H_B|^2\right)$$

$$|\langle H_A \rangle|^2 + |\langle H_B \rangle|^2 = f^2$$

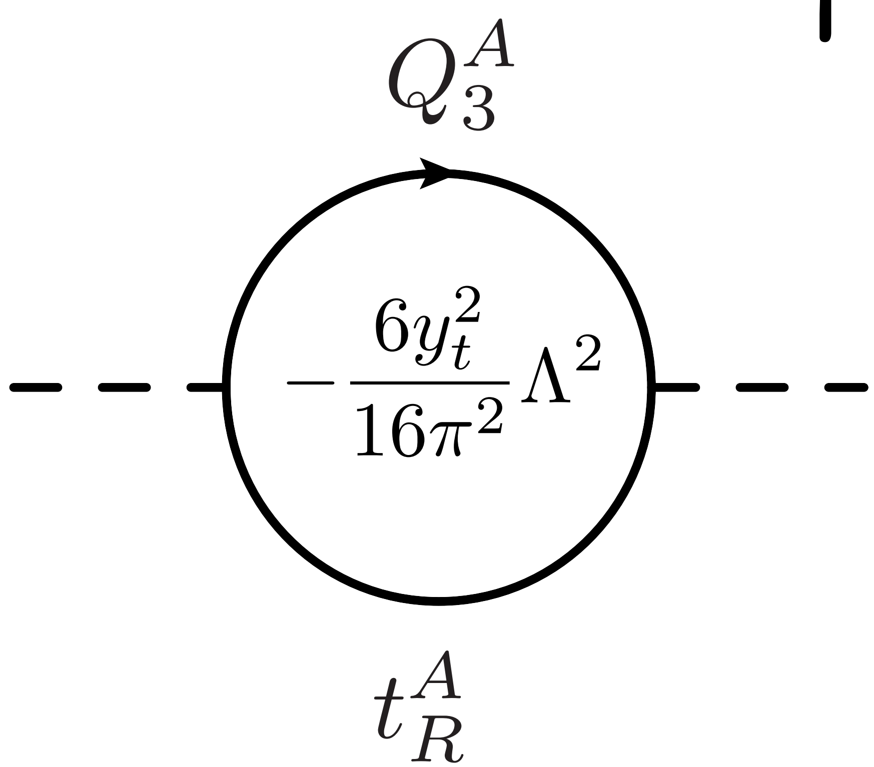
BREAKS "QUADRATIC" SU(4), HIGGSES EWK_A & EWK_B

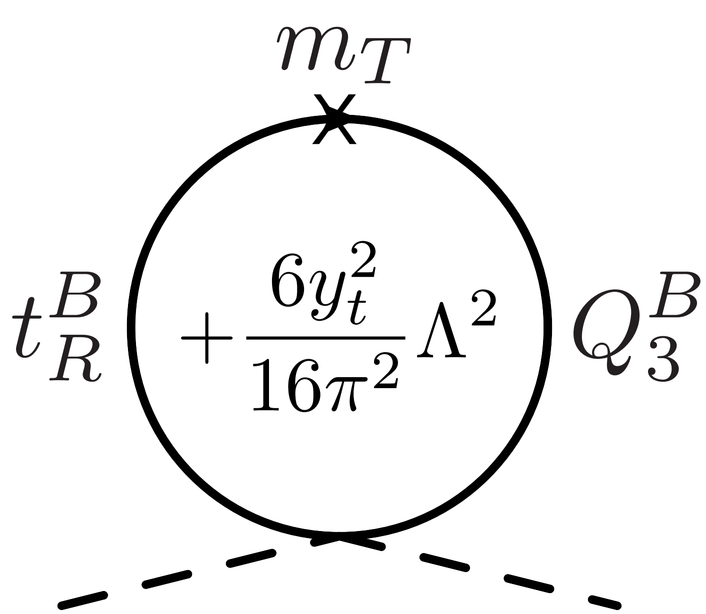
GIVES A RADIAL MODE, A GOLDSTONE MODE, AND EATEN GOLDSTONES.

$V \ll F$ FOR SM-LIKE HIGGS TO BE THE GOLDSTONE

PRIMARY COUPLING BETWEEN SM_A AND SM_B IS VIA HIGGS PORTAL

TWIN HIGGS & THE HIERARCHY PROBLEM





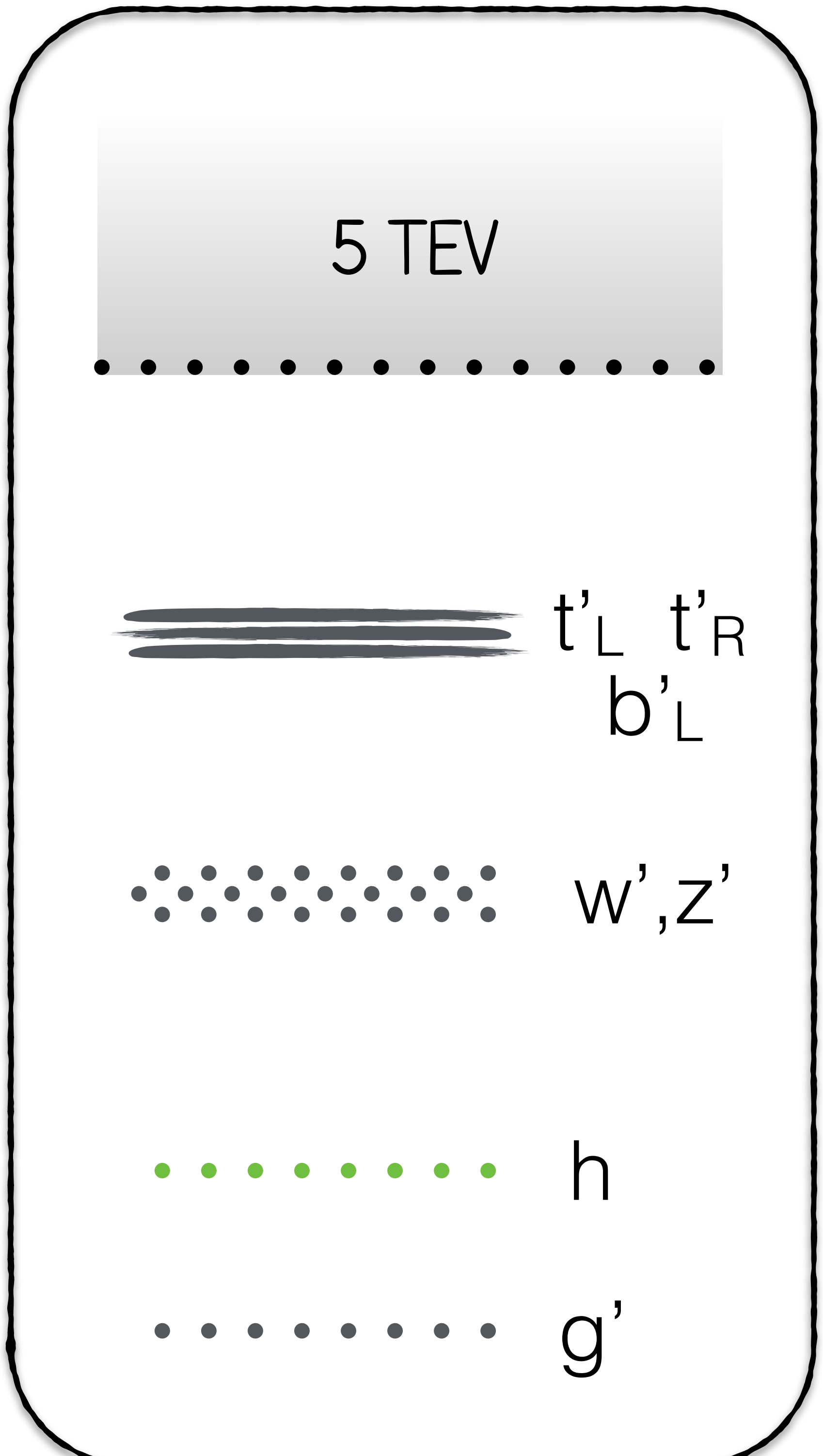
THE TOP PARTNER ACTS AS EXPECTED FROM GLOBAL SYMMETRY PROTECTION, *BUT IS NOT CHARGED UNDER QCD.*

$$\mathcal{L} \supset -y_t t_R^{A\dagger} \tilde{H}_A Q_3^A - y_t t_R^{B\dagger} \tilde{H}_B Q_3^B$$

$$h + \ldots \qquad\qquad f - \frac{h^2}{2f} + \ldots$$

NO DIRECT LIMIT ON TOP PARTNER.

"NEUTRAL" NATURALNESS



SIMPLEST THEORY: EXACT MIRROR COPY OF SM

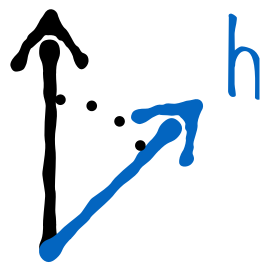
[CHACKO, GOH, HARNIK '05]

BUT THIS IS MORE THAN YOU NEED, AND MIRROR 1ST, 2ND GENS LEAD TO COSMOLOGICAL PROBLEMS

MANY MORE OPTIONS WHERE SYMMETRY IS APPROXIMATE, E.G. A GOOD SYMMETRY FOR HEAVIEST SM PARTICLES.

[NC, KNAPEN, LONGHI '14; GELLER, TELEM '14; NC, KATZ, STRASSLER, SUNDRUM '15; BARBIERI, GRECO, RATTAZZI, WULZER '15; LOW, TESI, WANG '15, NC, KNAPEN, LONGHI, STRASSLER '16]

FINDING A MIRROR



HIGGS STILL A PNGB, TUNING AS IN OTHER GLOBAL SYMMETRIES

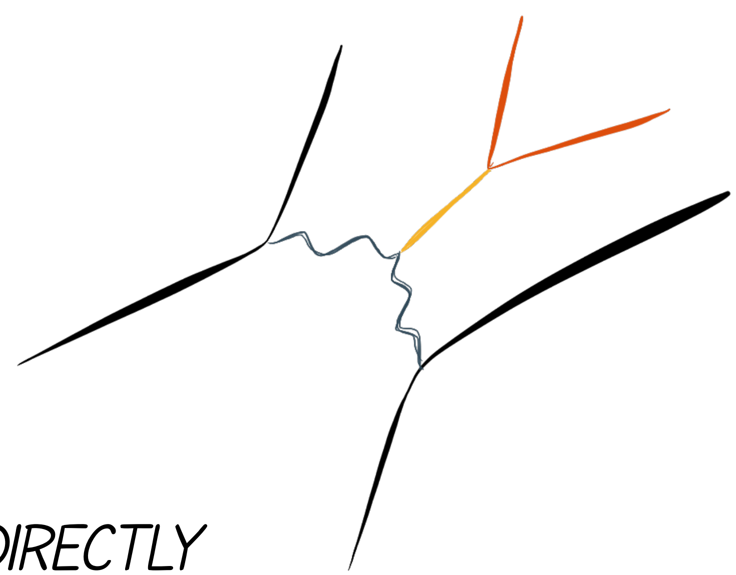
LIMIT $v^2/f^2 < 0.1$

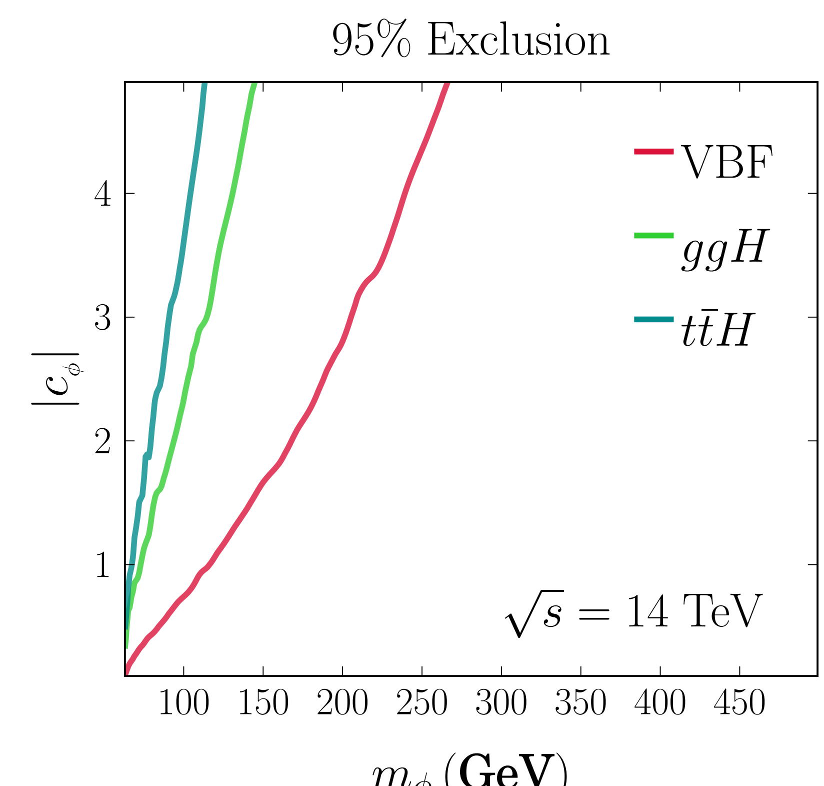
→ **Δ~10 (10% TUNING)**

UNLIKELY TO IMPROVE MUCH IN RUN 2

- PARTNER STATES ARE SM NEUTRAL, COUPLE ONLY TO THE HIGGS. LIGHTER THAN $M_H/2$: MODEST INVISIBLE HIGGS DECAYS.

- HEAVIER THAN $M_H/2$: PRODUCE THROUGH AN OFF-SHELL HIGGS.



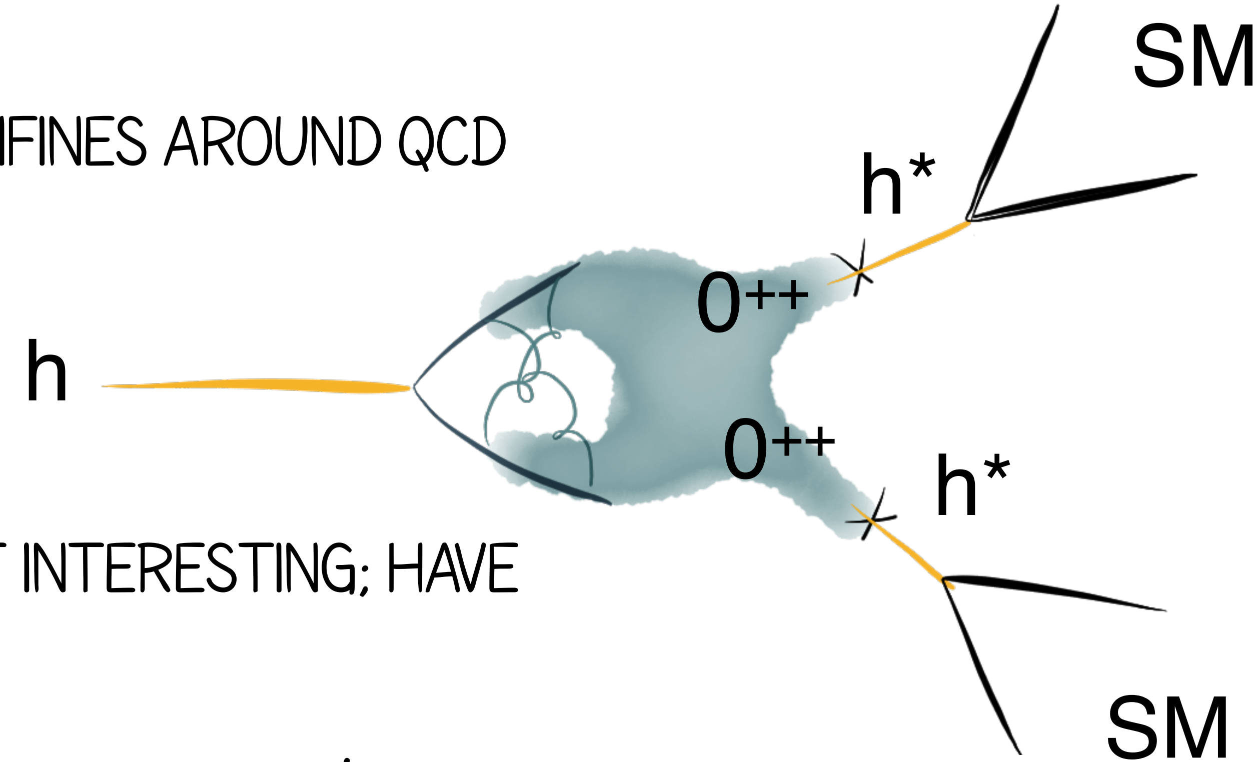


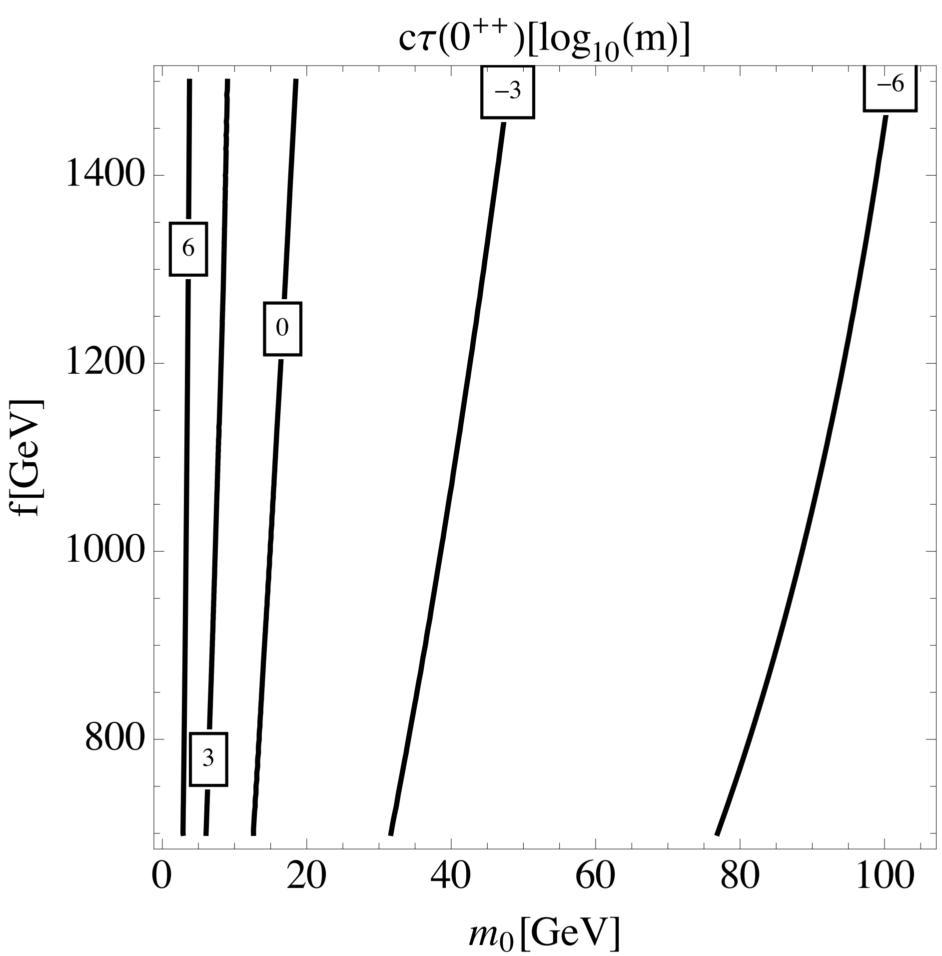
HARD BUT VERY INTERESTING; DIRECTLY PROBE NATURALNESS

[NC, LOU, MCCULLOUGH, THALAPILLIL '14]

EXOTIC HIGGS DECAYS

- TWIN SECTOR MUST HAVE TWIN QCD, CONFINES AROUND QCD SCALE
- HIGGS BOSON COUPLES TO BOUND STATES OF TWIN QCD
- VARIOUS POSSIBILITIES. GLUEBALLS MOST INTERESTING; HAVE SAME QUANTUM # AS HIGGS





$$\mathcal{L} \supset -\frac{\alpha_3'}{6\pi}\frac{v}{f}\frac{h}{f}G'^{a}_{\mu\nu}G'^{\mu\nu}_{a}$$

PRODUCE IN RARE HIGGS DECAYS (BR~10^{-3}-10^{-4})

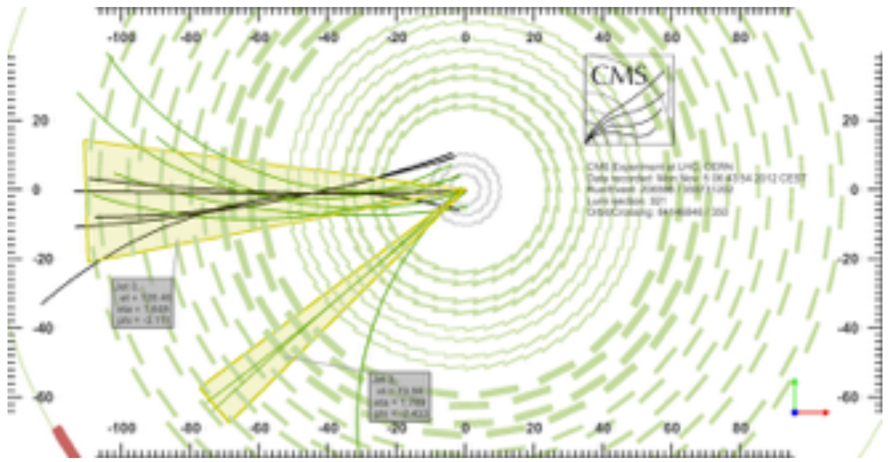
$$gg \to h \to 0^{++} + 0^{++} + \ldots$$

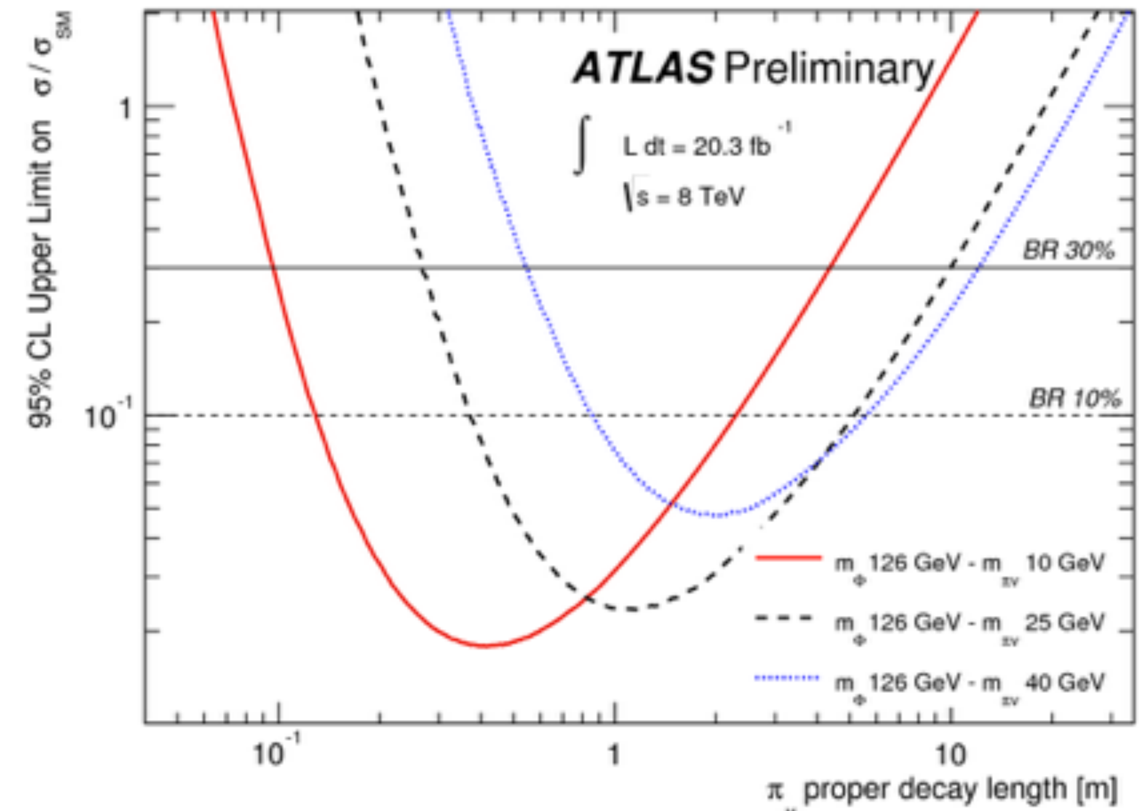
DECAY BACK TO SM VIA HIGGS

$$0^{++} \to h^* \to f\bar{f}$$

LONG-LIVED, DECAY LENGTH IS MACROSCOPIC; LENGTH SCALE ~ LHC DETECTORS

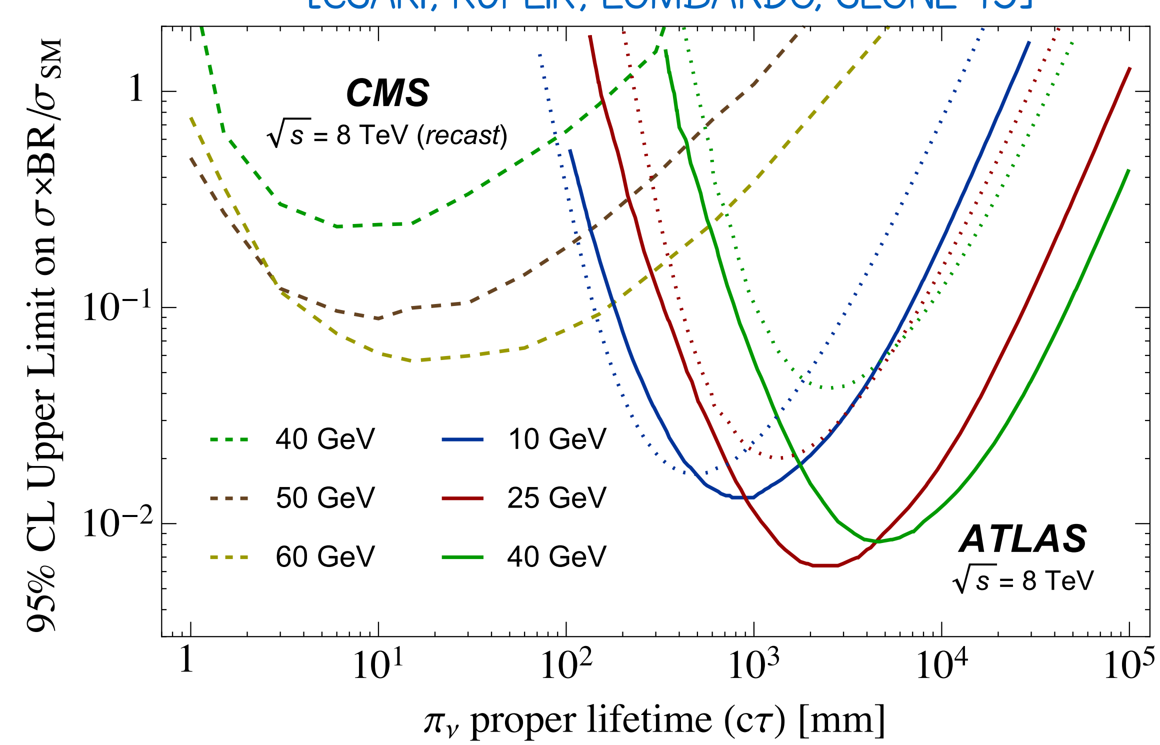
SEARCHING FOR MIRRORS



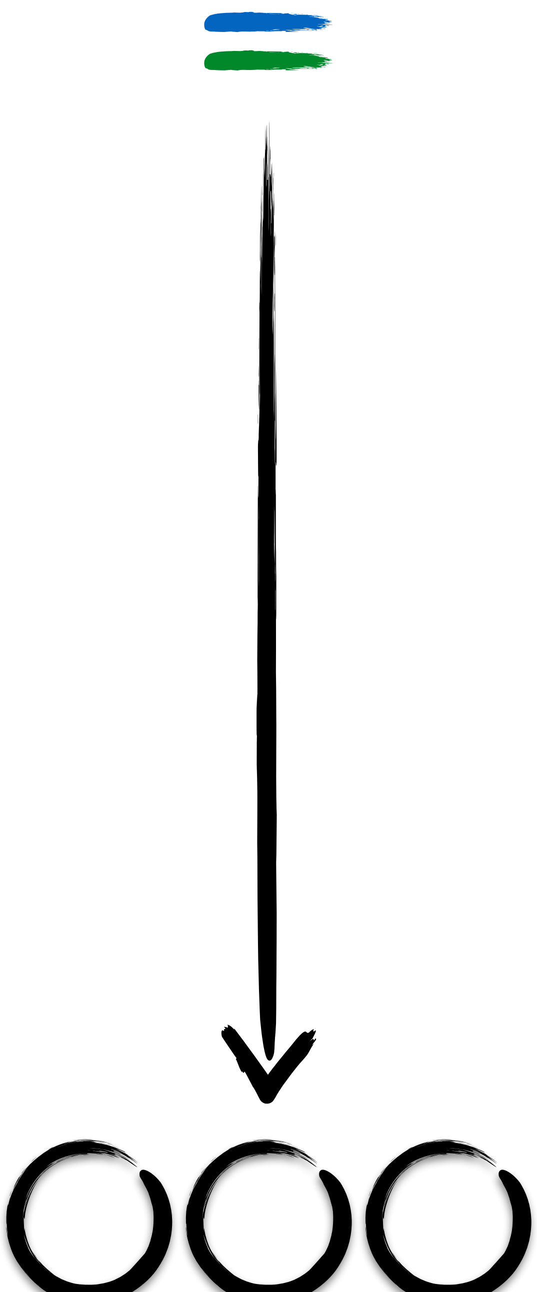


- SIGNAL: DISPLACED DECAYS OF SM HIGGS WITH BR >10^{-3} (σ.BR~20FB @ RUN 1).
- ATLAS: HCAL/ECAL & MUON CHAMBER SEARCHES POWERFUL, SENSITIVE TO DISPLACED HIGGS DECAY.
- CMS: USE INNER TRACKER, SEE VERTEX ON SHORT DECAY LENGTHS. TRIGGER THRESHOLDS TOO HIGH.
- MORE ROOM FOR INNOVATION IN THE DISPLACED DECAY SEARCH PROGRAM...

[CSAKI, KUFLIK, LOMBARDO, SLONE '15]



SELECTING A VACUUM



WE ASSUMED THAT WE ENDED UP IN THE VACUUM WITH THE OBSERVED WEAK SCALE DUE TO SOME ANTHROPIC PRESSURE. CAN WE INSTEAD DO SO DYNAMICALLY?

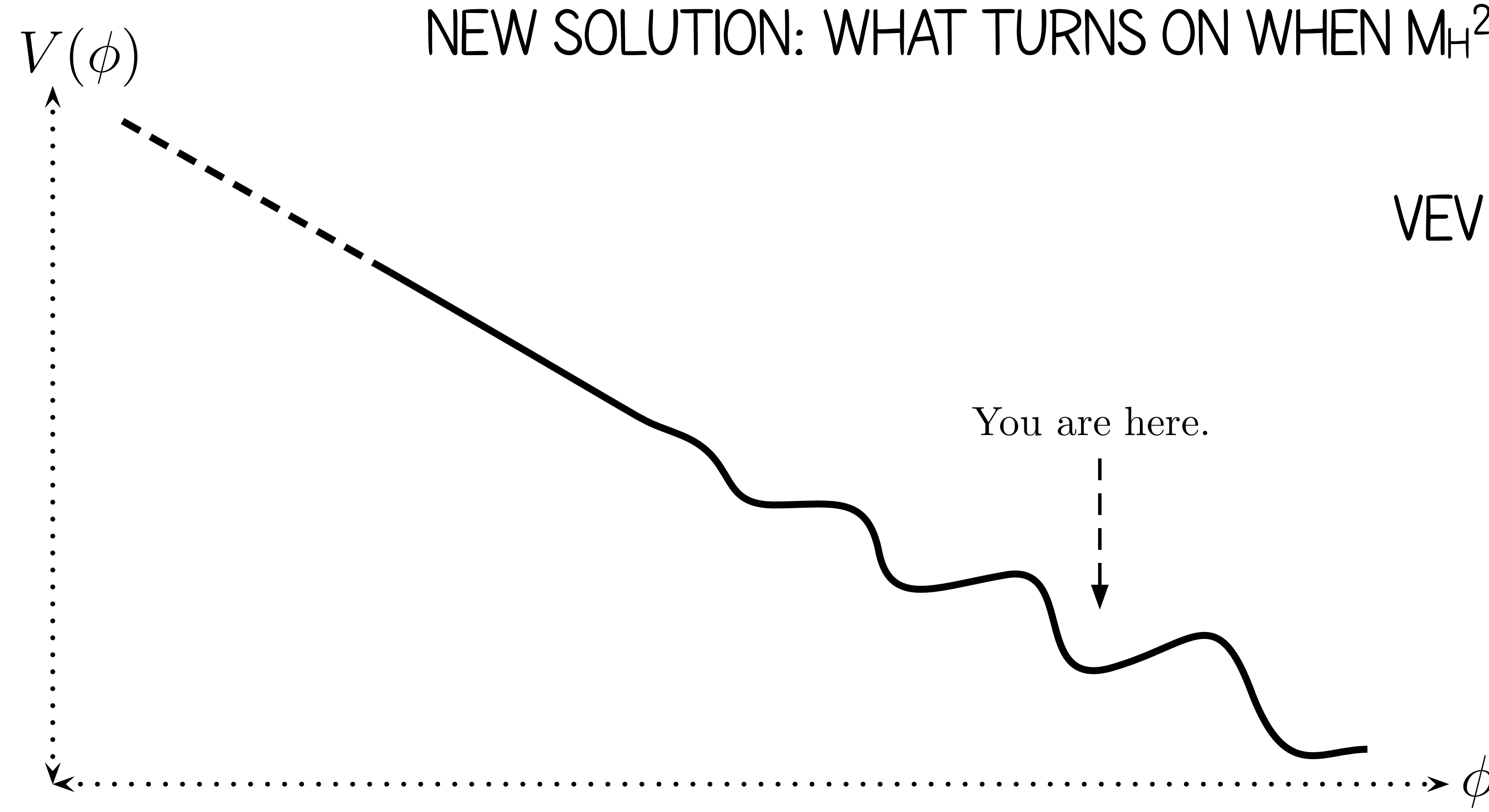
$\Rightarrow$ "RELAXION"

DYNAMICAL SELECTION

WHAT IF THE WEAK SCALE IS SELECTED BY DYNAMICS, NOT SYMMETRIES?

OLD IDEA: COUPLE HIGGS TO FIELD WHOSE MINIMUM SETS $M_H = 0$
OLD PROBLEM: HOW TO MAKE $M_H = 0$ A SPECIAL POINT OF POTENTIAL?

NEW SOLUTION: WHAT TURNS ON WHEN M_H^2 GOES NEGATIVE?



VEV GIVES QUARK MASSES WHICH GIVE AXION POTENTIAL!

"RELAXION"

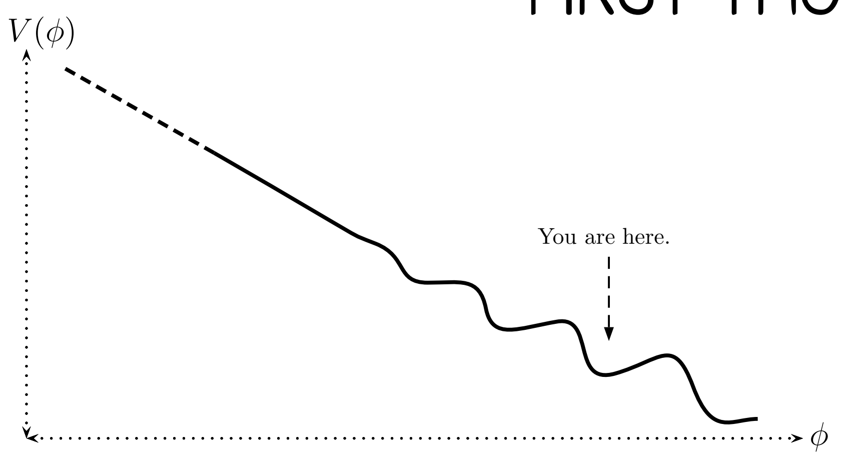
[GRAHAM, KAPLAN, RAJENDRAN '15]

BUT: IMMENSE ENERGY STORED IN EVOLVING FIELD, NEED DISSIPATION.

[GRAHAM, KAPLAN, RAJENDRAN '15]

EX.1: QCD/QCD' RELAXION

FIRST THOUGHT: USE AN AXION COUPLED TO QCD.



$$(-M^2 + g\phi)|H|^2 + V(g\phi) + \frac{1}{32\pi^2}\frac{\phi}{f}\tilde{G}^{\mu\nu}G_{\mu\nu}$$

$$\Rightarrow (-M^2 + g\phi)|H|^2 + V(g\phi) + \Lambda^4 \cos(\phi/f)$$

DISSIPATION: INFLATION! $\ddot{\phi} + 3H\dot{\phi} + V'(\phi) = 0$

REQUIREMENTS: (1) ϕ SCAN OVER ENTIRETY OF ITS RANGE

$$\Delta\phi = (gM^2/H_i^2)N \gtrsim M^2/g \Rightarrow N \gtrsim H_i^2/g^2$$

(2) VACUUM ENERGY DURING INFLATION EXCEEDS CHANGE IN VACUUM ENERGY DUE TO SCANNING

$$H_i > \frac{M^2}{M_{Pl}}$$

(3) BARRIERS FORM THAT ARE SUFFICIENT TO STOP SCANNING

$$H_i < \Lambda_{QCD}$$

QCD RELAXION

(4) CLASSICAL ROLLING BEATS QUANTUM FLUCTUATIONS

$$H_i < V'_\phi / H_i^2 \rightarrow H_i < (gM^2)^{1/3}$$

ADDITIONAL SUBSTANTIAL CONCERNS:

- NON-COMPACT SHIFT SYMMETRY?
- COSMOLOGICAL CONSTANT?

JUST NEED HIGGS + NON-COMPACT AXION + INFLATION W/

- VERY LOW HUBBLE SCALE ($\ll \Lambda_{QCD}$)
- 10 GIGA-YEARS OF INFLATION

CARE REQUIRED TO AVOID TRANSFERRING FINE-TUNING TO INFLATIONARY SECTOR.

IN VACUUM, ϕ IS THE AXION, STOPS
WELL AWAY FROM $\theta = 0 \rightarrow$ GIVES
O(1) CONTRIBUTION TO θ_{QCD}

[GRAHAM, KAPLAN, RAJENDRAN '15]

QCD' RELAXION

FIX: MAKE IT SOMEONE ELSE'S QCD + AXION

Field	$SU(3)_N$	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$
L	$\square$	$-$	$\square$	$-1/2$
L^c	$\overline{\square}$	$-$	$\square$	$+1/2$
N	$\square$	$-$	$-$	0
N^c	$\overline{\square}$	$-$	$-$	0

I.E. AXION OF A DIFFERENT SU(3); NEED TO TIE IN HIGGS VEV

1. NEW QUARKS MUST GET MOST OF MASS FROM HIGGS:

$$\mathcal{L} \supset m_L L L^c + m_N N N^c + y H L N^c + y' H^\dagger L^c N$$

2. MUST CONFINE, BUT WITH LIGHT FLAVOR $\Lambda^4 \simeq 4\pi f_{\pi'}^3 m_N$

DECOUPLE FROM TEV SCALE?

QCD' RELAXION

NOW $$m_N \geq yy'v^2/m_L$$ (SMALLEST SEE-SAW MASS FROM EWSB IF L HEAVY)

BUT ALSO $$\begin{cases} m_N \geq \frac{yy'}{16\pi^2} m_L \log(M/m_L) \\ m_N \geq yy' f_{\pi'}^2/m_L \end{cases}$$

(RADIATIVE DIRAC MASS)

(HIGGS WIGGLES BIGGEST)

THESE BOUNDS IMPLY $$f_{\pi'} < v \text{ and } m_L < \frac{4\pi v}{\sqrt{\log(M/m_L)}}$$

NEW CONFINING PHYSICS NEAR WEAK SCALE!

COUPLES TO HIGGS, ELECTROWEAK BOSONS; HIDDEN VALLEY SIGNATURES.
VARIOUS POSSIBILITIES (N_F=1, PIONS NOT LIGHT)

TO MY KNOWLEDGE, NO SYSTEMATIC STUDY TO DATE.

[HOOK, MARQUES-TAVARES '16]

EX. 2: INTERACTIVE RELAXION

ALTERNATIVE POSSIBILITY: KEEP BUMPS ACROSS ENTIRE POTENTIAL, TURN ON DISSIPATION AT A SPECIAL POINT OF POTENTIAL.

ANOTHER SOURCE OF DISSIPATION: PARTICLE PRODUCTION

CONSIDER AXION-LIKE COUPLINGS TO MASSIVE GAUGE FIELD: $\mathcal{L} \supset -\frac{\phi}{4f} F\tilde{F}$

E.O.M. FOR TRANSVERSE POLARIZATIONS: $\ddot{A}_\pm + \left(k^2 + m_A^2 \pm \frac{k\dot{\phi}}{f}\right) A_\pm = 0$

FOR $\dot{\phi} \approx \text{constant}$ $\quad A_\pm(k) \propto e^{i\omega_\pm t}$ $\quad \omega_\pm^2 = k^2 + m_A^2 \pm \frac{k\dot{\phi}}{f}$

EXPONENTIALLY GROWING SOLUTION FOR $\omega_\pm^2 < 0 \Rightarrow |\dot{\phi}| \gtrsim 2 f m_A$

GROWING MODE DRAINS ENERGY FROM $\dot{\phi}$

EX. 2: INTERACTIVE RELAXION

APPLY TO RELAXION: USE ELECTROWEAK GAUGE FIELDS

INSTEAD OF

$$\frac{\phi}{f} G\tilde{G}$$

+ INFLATION

$\Rightarrow$

USE COUPLING TO EWK GAUGE BOSONS:

$$\frac{\phi}{f}(g^2 W\tilde{W} - g'^2 B\tilde{B}) + \Lambda^4 \cos\frac{\phi}{f'}$$

EXPONENTIAL PRODUCTION OF EWK GAUGE BOSONS
AROUND H~V SLOWS EVOLUTION

IMPORTANT SUBTLETY: CAN'T COUPLE TO PAIRS OF PHOTONS!

FOR DISSIPATION TO BECOME EFFICIENT AT H~V, CAN ONLY COUPLE TO BOSONS ACQUIRING MASS FROM EWSB.

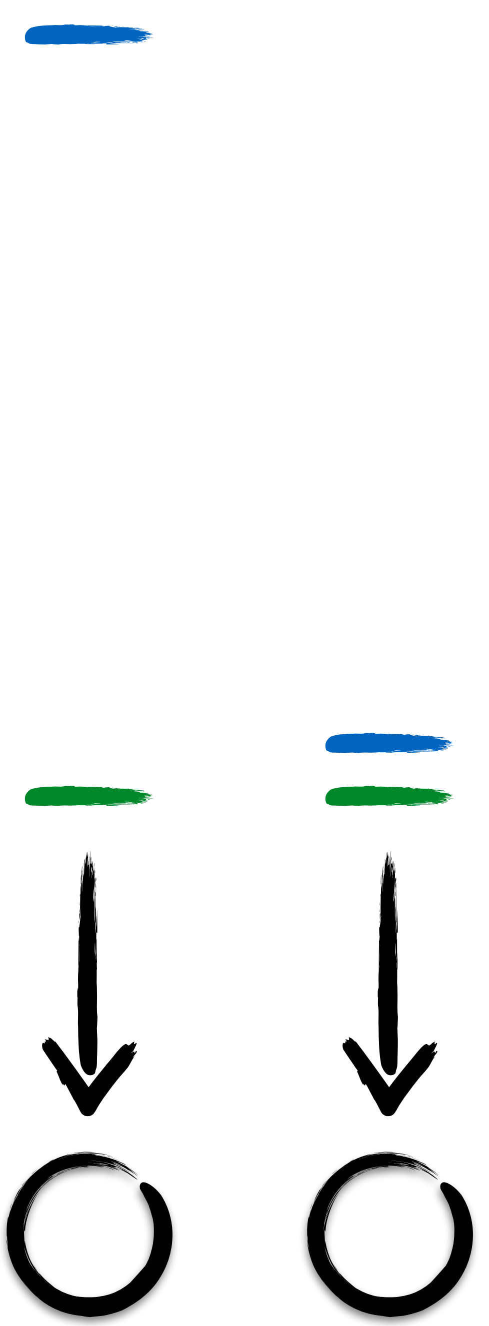
(NOT A TUNING, CAN BE MADE NATURAL WITH SYMMETRIES, E.G., $SU(2)_L \times SU(2)_R$)

$$\mathcal{L} \supset -\frac{1}{4g_L^2} W_L^2 - \frac{1}{4g_R^2} W_R^2 + \frac{\phi}{f}(W_L\tilde{W}_L - W_R\tilde{W}_R)$$

$$\phi \to \phi + \alpha \qquad \theta_L \to \theta_L - \alpha \qquad \theta_R \to \theta_R + \alpha \qquad \Rightarrow \mathcal{L} \propto (\theta_L + \theta_R) F\tilde{F}$$

LOWERING THE CUTOFF

...IN DIVERSE DIMENSIONS

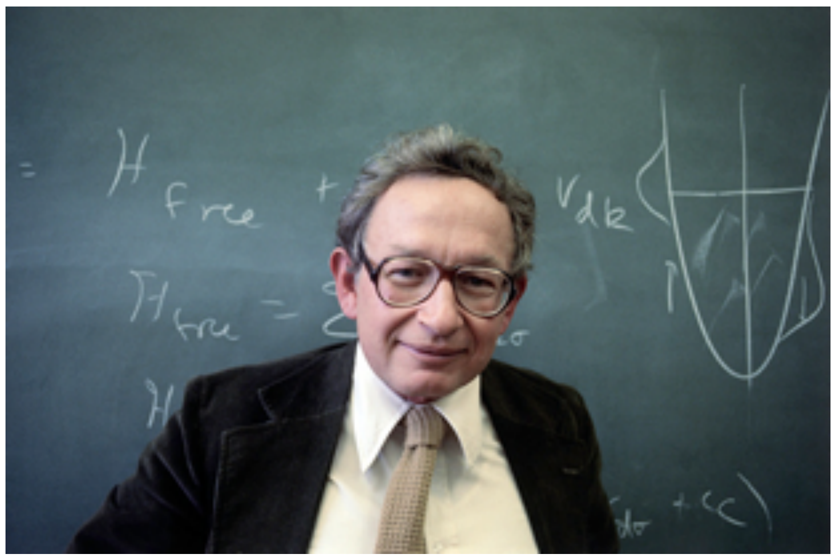


USUALLY ASSUME LOW CUTOFF IS DUE TO E.G. GEOMETRY OF AN EXTRA DIMENSION, GIVING UNIFORM PREDICTION FOR NEW RESONANCES & STRONG LIMITS. CAN WE DO THE SAME THING WITH ORDER INSTEAD OF DISORDER?

$\Rightarrow$ "GRAVITATIONAL ANDERSON LOCALIZATION"

A RANDOM DETOUR

ANDERSON LOCALIZATION



$$H = \sum_i \epsilon_i |i\rangle\langle i| - \sum_{ij} t_{ij} |i\rangle\langle j| + \text{h.c.}$$

IMPURITIES

BOUND STATE ENERGIES

TUNNELING

SIMPLIFY:

$$t_{ij} = t\left(\delta^j_{i+1} + \delta^j_{i-1}\right)$$

NEAREST-NEIGHBOR HOPPING

$$\epsilon_i \in [-W/2, W/2]$$

RANDOM IMPURITIES

TIGHT-BINDING MODEL

$$H = \begin{pmatrix} \epsilon_1 & -t & 0 & \dots & 0 & 0 \\ -t & \epsilon_2 & -t & \dots & 0 & 0 \\ 0 & -t & \epsilon_3 & & & \\ \vdots & \vdots & & \ddots & & \\ 0 & 0 & & & \epsilon_{N-1} & -t \\ 0 & 0 & & & -t & \epsilon_N \end{pmatrix}$$

ANDERSON LOCALIZATION

S.E. FOR ENERGY EIGENSTATES $\psi_E = \sum_i \psi_i |i\rangle$ GIVES (t=-1) $\psi_{i+1} + \psi_{i-1} = (E - \epsilon_i)\psi_i$

ALL EIGENSTATES ARE **LOCALIZED** IN PRESENCE OF DISORDER, $\psi(r) \propto \mathrm{EXP}[-r/L_{loc}]$

BUT LOCALIZATION LENGTHS NOT IDENTICAL

ANALYTIC RESULTS FOR WEAK LOCALIZATION, $\sigma \ll 1$ (FOR $\epsilon_I \in [-W/2, W/2]$, $\sigma^2 = W^2/12$)

STATES FILL A BAND OF $E \in [-2,2]$

(ALLOWED ENERGIES OF BLOCH WAVES FOR $\epsilon_I = 0$)

IN BULK OF BAND, LOCALIZATION LENGTH GIVEN BY THOULESS RESULT

$$L_{loc}^{-1} = \frac{W^2}{96(1 - E^2/4)}$$

ANOMALOUS SCALING NEAR BAND EDGES E =±2

$$L_{loc}^{-1} = \frac{6^{1/3}\sqrt{\pi}}{2\Gamma(1/6)}\sigma^{2/3} \approx 0.13 W^{2/3}$$

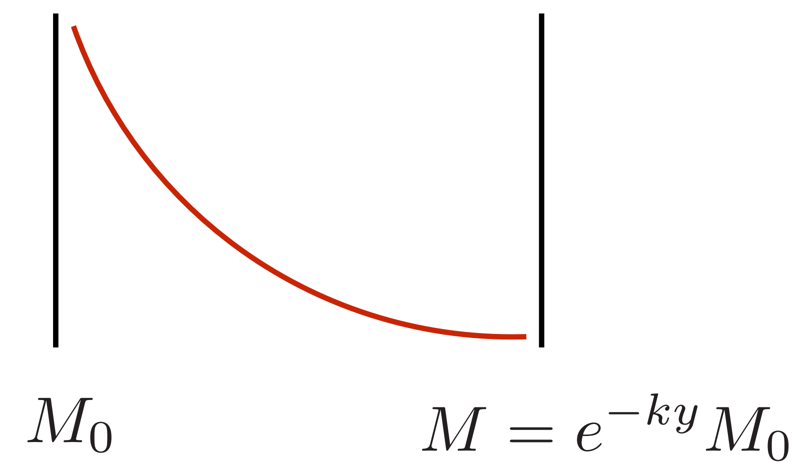
STATES AT BAND EDGES MORE SHARPLY LOCALIZED THAN GENERIC EIGENSTATES AT WEAK DISORDER

THE HIERARCHY PROBLEM?

WHAT YOU'VE BEEN ASKING YOURSELF FOR THE LAST FEW MINUTES...

HOW DOES RS SOLVE HIERARCHY PROBLEM?
CURVATURE LOCALIZES THE GRAVITON ZERO MODE.

→ FIELDS LOCALIZED AT DIFFERENT POINTS IN 5TH DIMENSION SEE DIFFERENT FUNDAMENTAL SCALES

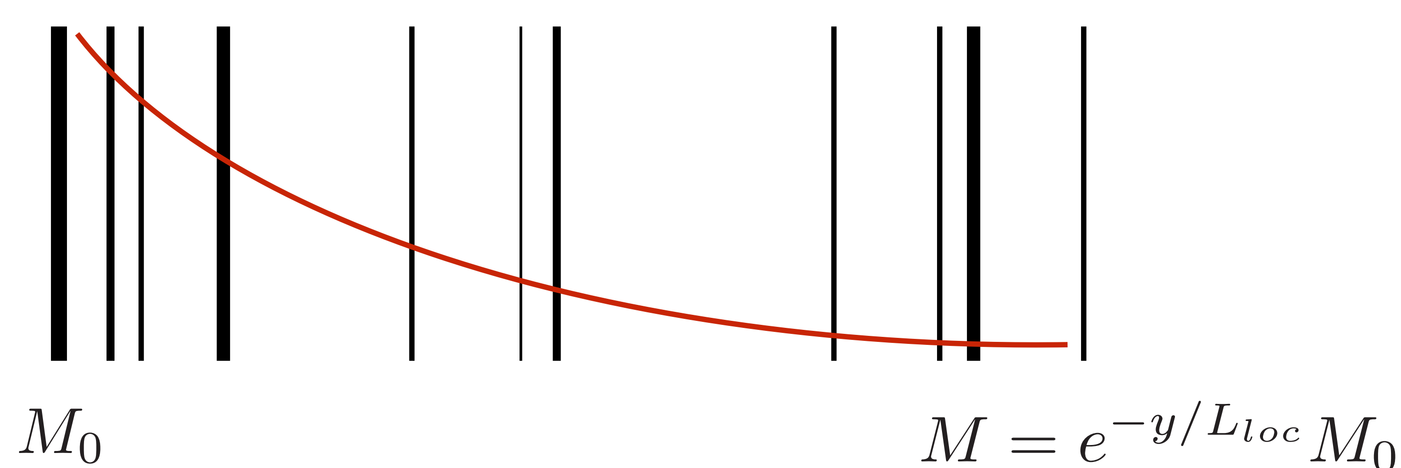


[ROTHSTEIN '12]: *CAN ACHIEVE THE SAME OUTCOME IN A FLAT FIFTH DIMENSION BY LOCALIZING GRAVITON W/ DISORDER*

$$S = -\int d^5x\sqrt{G}(M_\star^3\mathcal{R}) + \sum_{\langle ij\rangle} M_\star^4 V(|X_i - X_j|) - \sum_i \int d^4x\sqrt{g} f_i$$

IN THIS CASE DISORDER = RANDOMLY SPACED & TENSIONED BRANES

THE CHALLENGE: *NAIVE TIGHT-BINDING MODEL DOES NOT REFLECT DIFFEOMORPHISM INVARIANCE*



ON ONE HAND, SPECULATIVE INDICATIONS OF BSM ARE ON, WELL, SPECULATIVE FOOTING!

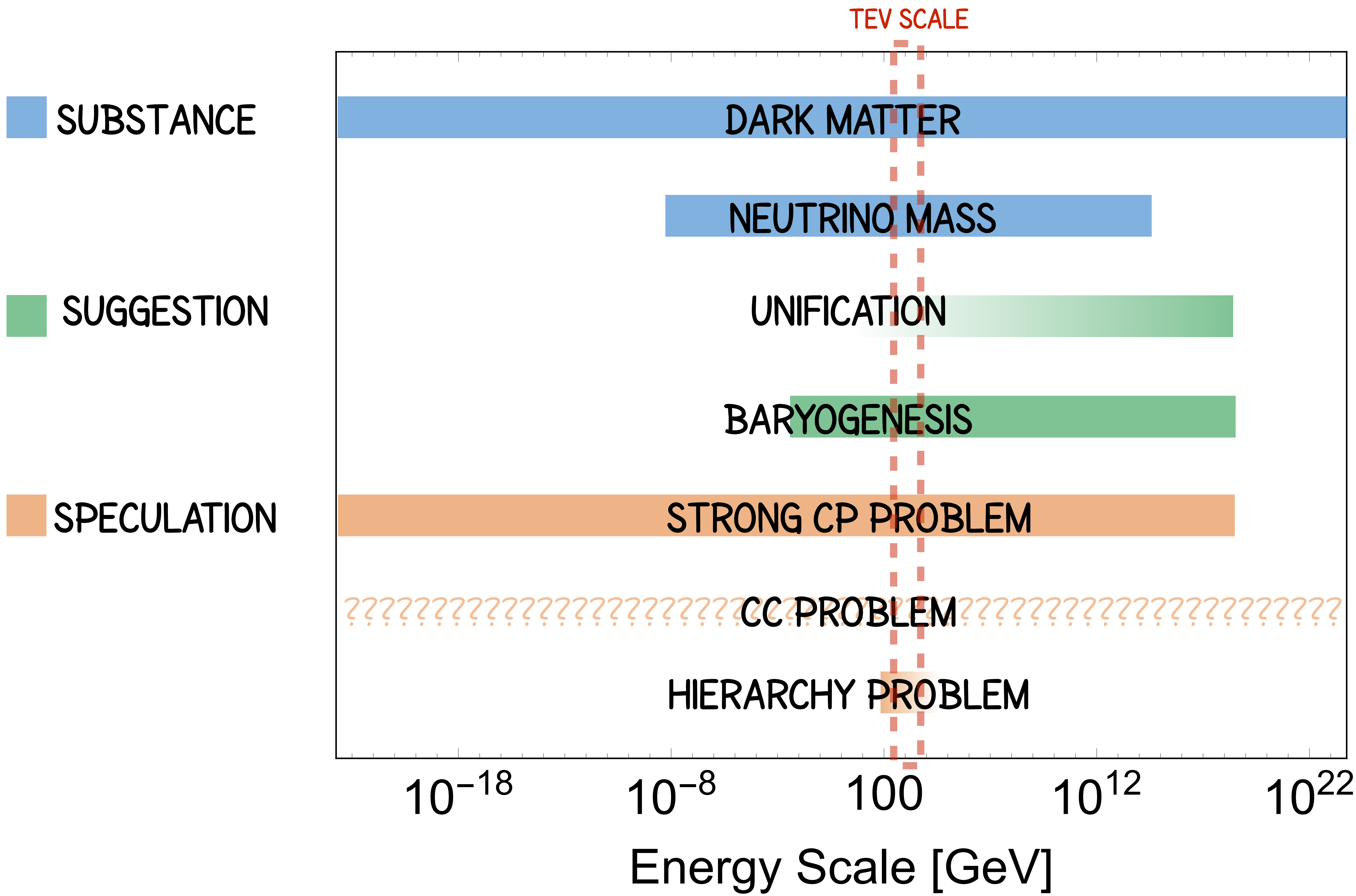
ON THE OTHER HAND, THEY POINT TO DEEP & PROFOUND (RATHER THAN PIECEMEAL) CHANGES TO THE STRUCTURE OF THE SM, WHICH PERHAPS EXPLAINS THEIR APPEAL.

SUCCESSFUL ANSWERS TO THESE SPECULATIVE PROBLEMS OFTEN ALSO FULFILL OTHER INDICATIONS OF BSM PHYSICS (E.G. DARK MATTER, UNIFICATION, & BARYOGENESIS)

CURRENT ERA IS A TIME OF OPPORTUNITY - POPULAR PARADIGMS UNDER STRESS, ROOM FOR INNOVATION.

PART 3: EVERYTHING ELSE

BEYOND THE STANDARD MODEL



$$\boxed{\begin{array}{c}\Delta_O = 4 \\ \text{natural} \sim \mathcal{O}(1)\end{array}}$$

NO SYMMETRY WHEN 0, BUT RADIATIVE CORRECTIONS SMALL/PROPORTIONAL TO VALUE

STRONG CP PROBLEM

IN ADDITION TO GAUGE KINETIC TERMS + MATTER COUPLINGS, QCD ADMITS GENERICALLY O(1) PARITY-ODD COUPLING*

$$\theta_{QCD}\epsilon^{\mu\nu\alpha\beta}G^a_{\mu\nu}G^a_{\alpha\beta}$$

FOLLOWING IT THROUGH THE CHIRAL LAGRANGIAN, LEADS TO COUPLING BETWEEN NEUTRONS AND PHOTONS OF FORM

$$\mathcal{L} = -\frac{id_n}{8}\epsilon_{\mu\nu\alpha\beta}F^{\mu\nu}\bar{N}[\gamma^\alpha,\gamma^\beta]N \quad \text{WHERE} \quad d_n \sim \frac{em_u m_d}{(m_u+m_d)\Lambda^2_{QCD}}\theta_{QCD}$$

THIS IS JUST A CLASSICAL ELECTRIC DIPOLE MOMENT,

$$H_d = -d_n(\bar{N}\sigma N)\cdot\mathbf{E}$$

BUT EXPERIMENTAL BOUND ON NEUTRON EDM GIVES

$$|d_n| \lesssim 3\times 10^{-26}e\,\mathrm{cm} \Rightarrow \theta_{QCD} \lesssim 10^{-10}$$

APPARENT NUMERICAL TUNING OF 10 ORDERS OF MAGNITUDE!

*CAN MOVE IT INTO QUARK MASSES BY REPHASINGS, BUT IT ALWAYS SHOWS UP SOMEWHERE

AXIONS?

DYNAMICALLY ADJUST θ TO ZERO?

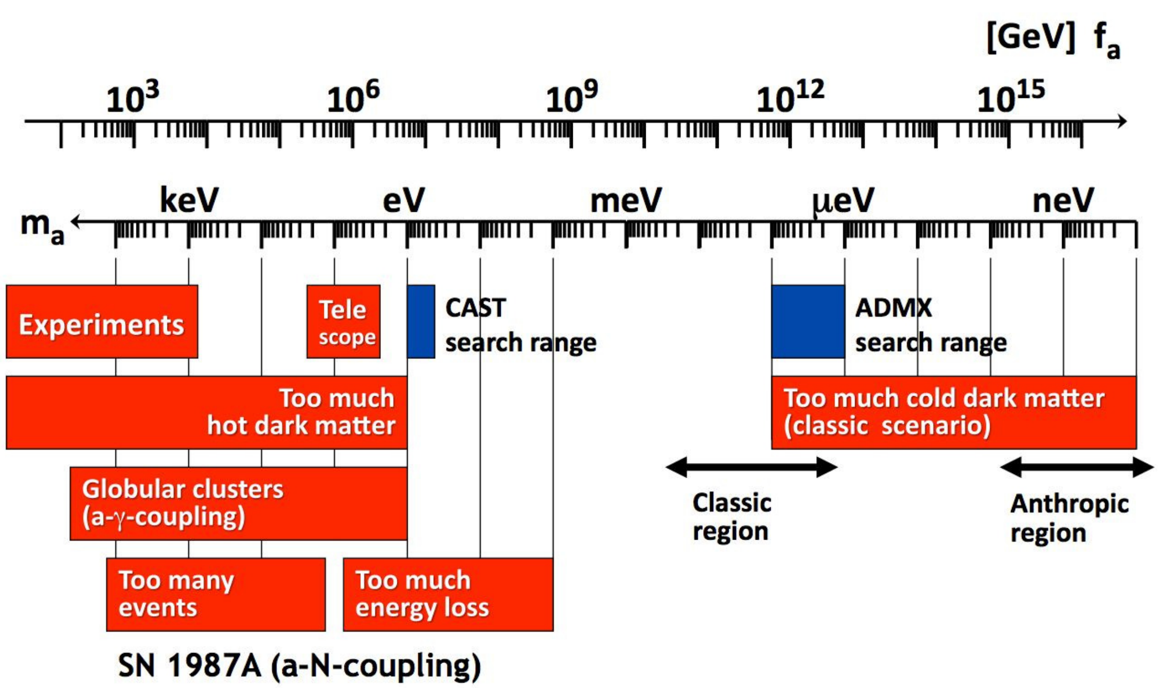
CONSIDER PSEUDOSCALAR a COUPLING TO $G\tilde{G}$

$$\mathcal{L} \supset \frac{1}{2}(\partial_\mu a)^2 + \frac{\theta}{32\pi^2} G\tilde{G} + \frac{a}{f_a}\frac{1}{32\pi^2} G\tilde{G} + \ldots$$

REST OF THEORY HAS SHIFT SYMMETRY $a \to a + \alpha$ FREEDOM TO ARBITRARILY SHIFT θ

IN FACT, QCD VACUUM ENERGY DEPENDS ON θ, $E(\theta) = (m_u + m_d) e^{i\theta} \langle \bar{q} q \rangle$

AXION VEV MINIMIZES QCD VACUUM ENERGY, WITH $\langle a \rangle = \theta f_a \Rightarrow \bar{\theta} = 0$



SEEMS ARBITRARY, BUT COUPLING & SHIFT SYMMETRY FOLLOW DIRECTLY IF AXION IS PNGB OF SPONTANEOUSLY BROKEN U(1)

AXION LIGHT (MASS ~Λ_{QCD}^2/F)
COSMOLOGICALLY RELEVANT:
COSMOLOGICAL LIMITS; DARK MATTER?

SPONTANEOUS CPV?

WHAT IF CP IS A GOOD SYMMETRY OF THE STANDARD MODEL, SPONTANEOUSLY BROKEN IN A CONTROLLED WAY (*BECAUSE CKM*)?

ONE PHYSICAL STRONG CP ANGLE: $\bar{\theta} = \theta_{QYC} - \theta_{QCD}$

WHERE FORMALLY THE QUARK MASS TERM PHASE IS $\theta_{QYC} = \mathrm{ArgDet}[Y_u Y_d]$

THE CHALLENGE:

WHY IS $\theta_{QYC} = \mathrm{ArgDet}[Y_u Y_d]$ SMALL, BUT

THE OBSERVED CKM PHASE

$$\theta_{weak} = \mathrm{ArgDet}[Y_u Y_d - Y_d Y_u]$$

IS BIG?

SOUNDS LIKE IT'S TIME TO BUILD A MODEL...

SPONTANEOUS CPV?

POPULAR CLASS OF SPONTANEOUS CPV SOLUTIONS: **NELSON-BARR**

AN ALTERNATIVE ALONG SIMILAR LINES: SPONTANEOUS PV. [BARR, CHANG, SENJANOVIC '91]

EXTEND SM W/ PARITY

$$SU(3)_c \times SU(2)_L \times U(1)_Y \Rightarrow SU(3)_c \times SU(2)_L \times SU(2)'_L \times U(1)_Y$$

+ EXTRA "MIRROR" COPY OF SM MATTER CHARGED UNDER $SU(2)_L'$

NOW A GENERALIZED PARITY SYMMETRY UNDER WHICH $P: \; SU(2)_L \leftrightarrow SU(2)'_L$

(SENDS SM MATTER INTO MIRROR MATTER)

$\theta \to -\theta$ UNDER THIS PARITY, SO ZERO IN UV IF P IS A GOOD SYMMETRY.

PARITY ALSO REQUIRES $Y_u H Q u + Y'_u H' Q' u' = Y_u H Q u + Y^*_u H' Q' u'$

SO THAT $\mathrm{ArgDet}[Y_u Y_d] + \mathrm{ArgDet}[Y'_u Y'_d] = 0$ BUT CKM PHASE ALLOWED.

SPONTANEOUS CPV?

BUT: WE DON'T SEE THE MIRROR QUARKS CHARGED UNDER $SU(2)_L'$,
SO MUST SPONTANEOUSLY BREAK $SU(2)_L$ <-> $SU(2)_L'$ PARITY

VIA E.G. A PARITY-ODD FIELD ϕ THAT GETS A VEV AND MAKES $\langle H\rangle \neq \langle H'\rangle$

$$\mathcal{L} \supset g\phi(|H'|^2 - |H|^2) \Rightarrow \langle H'\rangle \sim \langle \phi\rangle \gg \langle H\rangle$$

BUT ϕ VEV CAN'T BE TOO BIG, BECAUSE NOW WE EXPECT OPERATORS LIKE

$$\frac{1}{32\pi^2}\frac{\phi}{M_{Pl}}G\tilde{G}$$

NOT REINTRODUCING STRONG CP PROBLEM BOUNDS

$$\langle \phi\rangle \sim \langle H'\rangle \lesssim 10^{-10} M_{Pl}$$

SO FIRST-GENERATION MIRROR U,D,E FERMIONS SHOULD BE BENEATH 10 TEV!

THESE FERMIONS CARRY BOTH CHARGE AND COLOR.
SYMMETRIES ALLOW MIXING W/ SM FERMIONS:

$$\mathcal{L} \supset -\mu_u u u' - \mu_d d d' - \mu_e e e'$$

MIXING LEADS TO DECAYS SUCH AS E.G.

$$u' \to h + u \qquad u' \to Z + u \qquad u' \to W + d$$

[D'AGNOLO, HOOK '15]

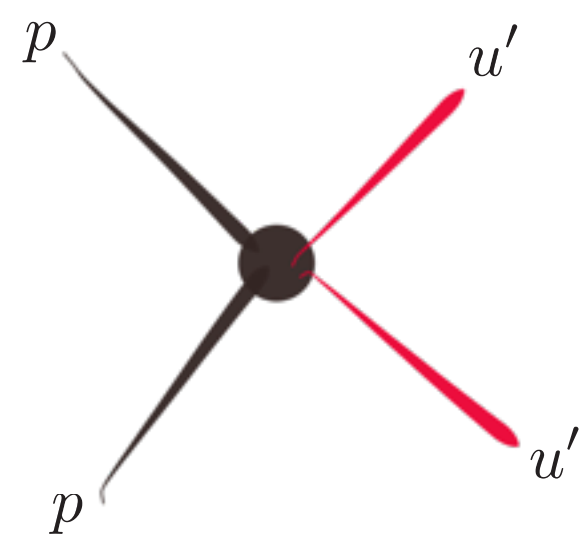
SPONTANEOUS CPV @ LHC

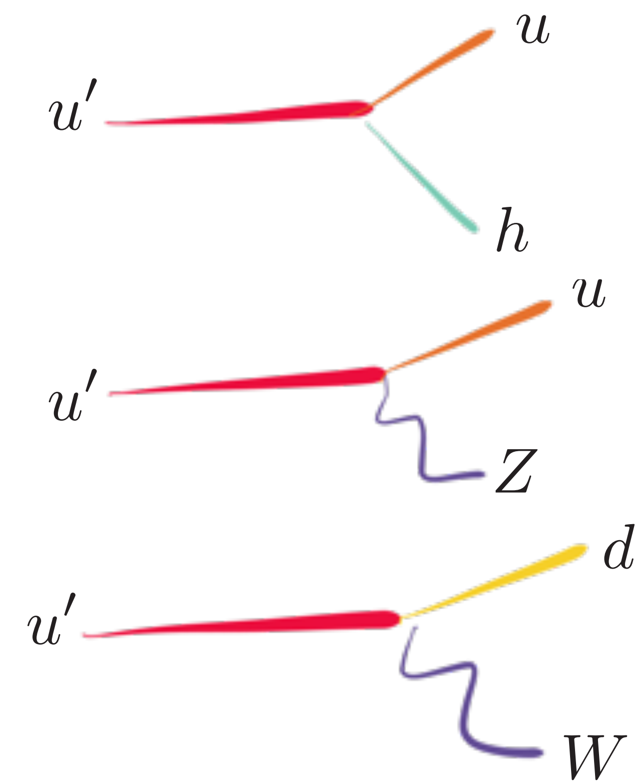
PARITY SOLUTION PREDICTS NEW CHARGED/COLORED FERMIONS <10 TEV W/ SM DECAY MODES

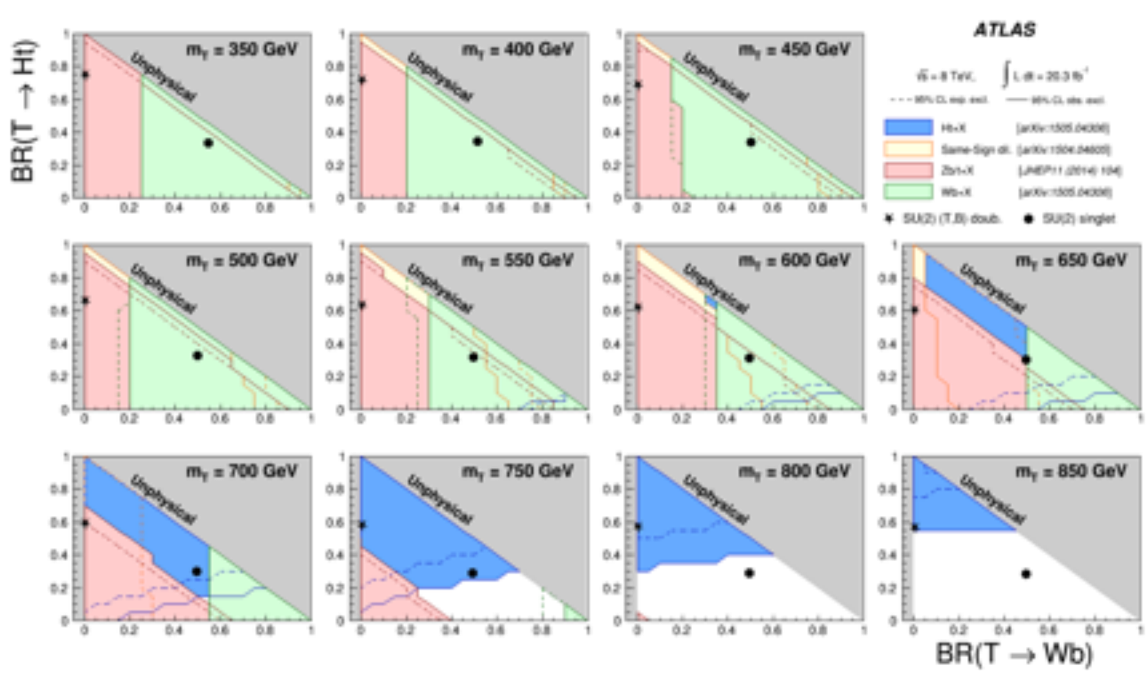
$$u' \to h + u$$

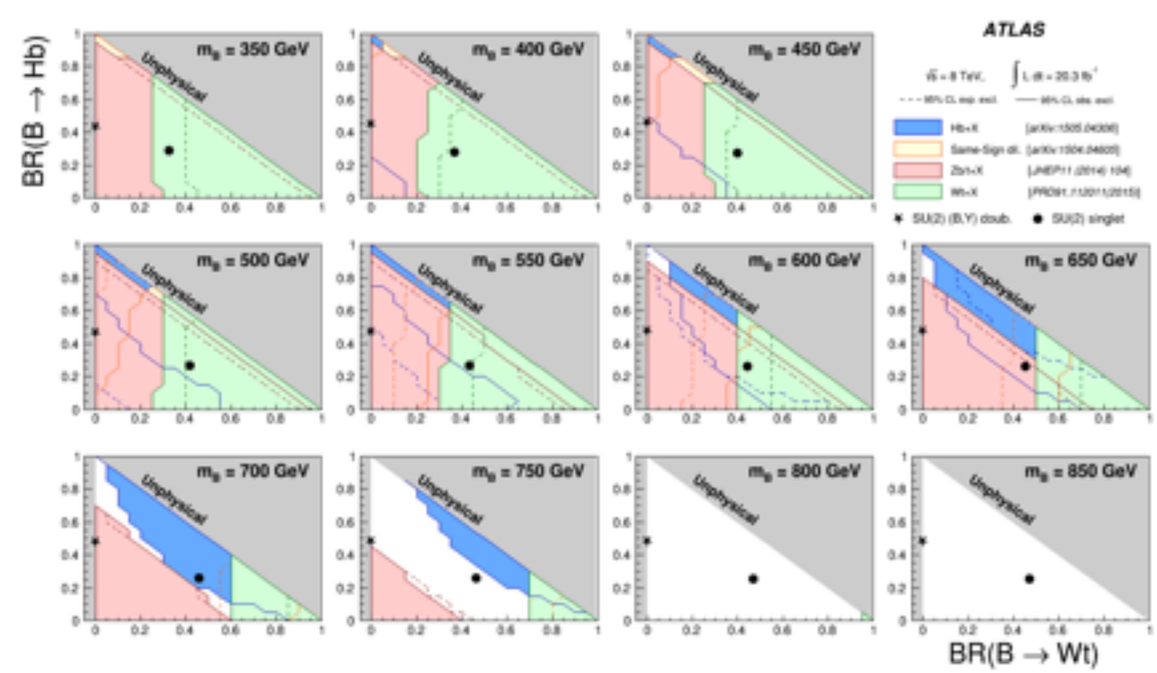
$$u' \to Z + u$$

$$u' \to W + d$$







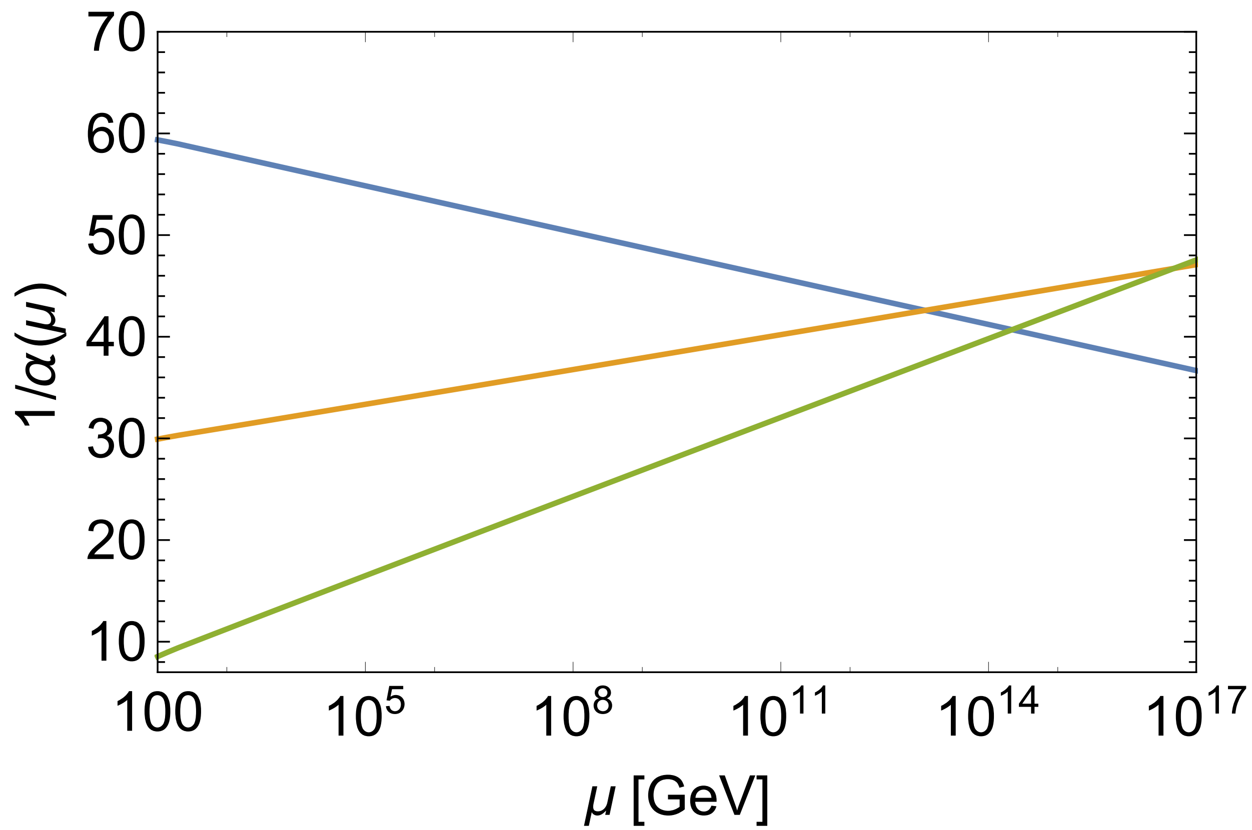


UNIFICATION

GIVEN MEASURED SM GAUGE COUPLINGS AT WEAK SCALE, CAN STUDY EVOLUTION TO HIGHER SCALES WITH RGES.

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

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



SUGGESTIVELY, THE THREE APPEAR TO CROSS (MISSING TRIPLE INTERSECTION BY O(10%)) AROUND 10^{15} GEV.

CONSISTENT WITH UNIFICATION OF SU(3)XSU(2)XU(1) INTO COMMON GAUGE GROUP.

CONVENIENTLY $\quad SO(10) \supset SU(5) \supset SU(3) \times SU(2) \times U(1)$

UNIFICATION

HOW DO THE PIECES FIT TOGETHER?

$$SU(5) \text{ rep} \to (SU(3), SU(2))_{U(1)_Y} \text{ rep} = \text{SM field}$$

$$\mathbf{5} \to (\mathbf{3},\mathbf{1})_{-1/3} \oplus (\mathbf{1},\mathbf{2})_{1/2} = T + H$$

$$\bar{\mathbf{5}} \to (\bar{\mathbf{3}},\mathbf{1})_{1/3} \oplus (\mathbf{1},\mathbf{2})_{-1/2} = \bar{d} + L$$

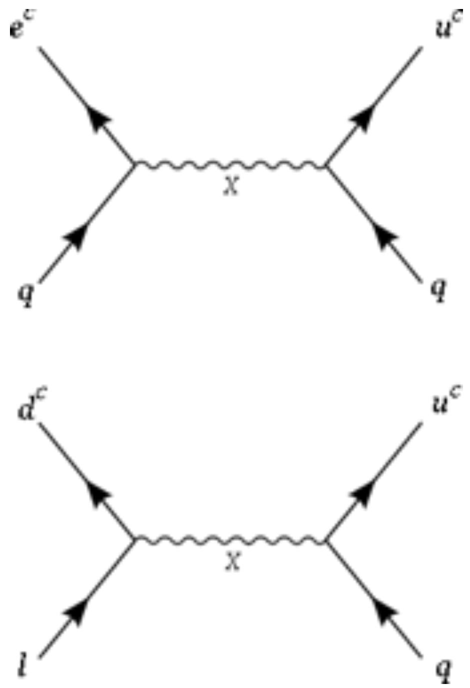
$$\mathbf{10} \to (\mathbf{3},\mathbf{2})_{1/6} \oplus (\bar{\mathbf{3}},\mathbf{1})_{-2/3} \oplus (\mathbf{1},\mathbf{1})_{1} = Q + \bar{u} + \bar{e}$$

$$\mathbf{24} \to (\mathbf{8},\mathbf{1})_0 + (\mathbf{1},\mathbf{3})_0 + \mathbf{1} + (\mathbf{3},\mathbf{2})_{-5/6} + (\bar{\mathbf{3}},\mathbf{2})_{5/6} = G + W + B + X + \bar{X}$$

SM MATTER FITS TIDILY, BUT DEMANDS TRIPLET HIGGS & NEW GAUGE BOSONS.

- BEAUTIFUL IDEA, SIMPLER THEORY IN FAR UV (ORIGINAL "NATURALNESS")
- BUT UNIFICATION OF COUPLINGS IMPERFECT @ 10% LEVEL.
- PREDICTS YUKAWA UNIFICATION, NOT IN GOOD AGREEMENT.
- PREDICTS PROTON DECAY VIA EXCHANGE OF T & X

UNIFICATION



X EXCHANGE GENERATES DIM-6 OPS

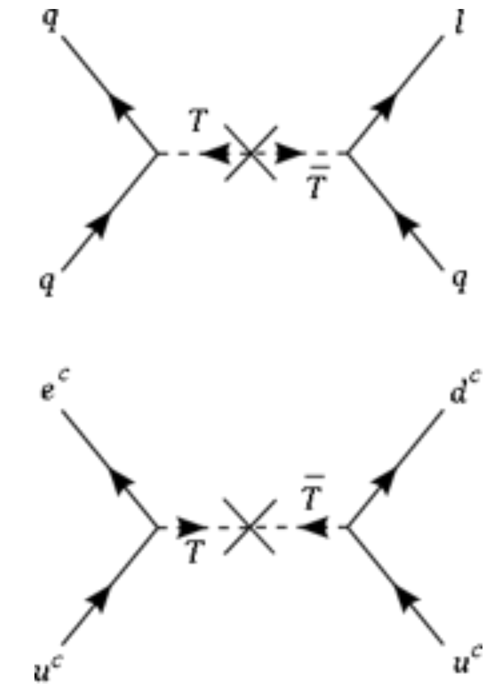
$$\frac{1}{\Lambda^2} Q L \bar{u}^\dagger \bar{d}^\dagger$$

$$\frac{1}{\Lambda^2} Q Q \bar{u}^\dagger \bar{e}^\dagger$$

T EXCHANGE GENERATES DIM-6 OPS

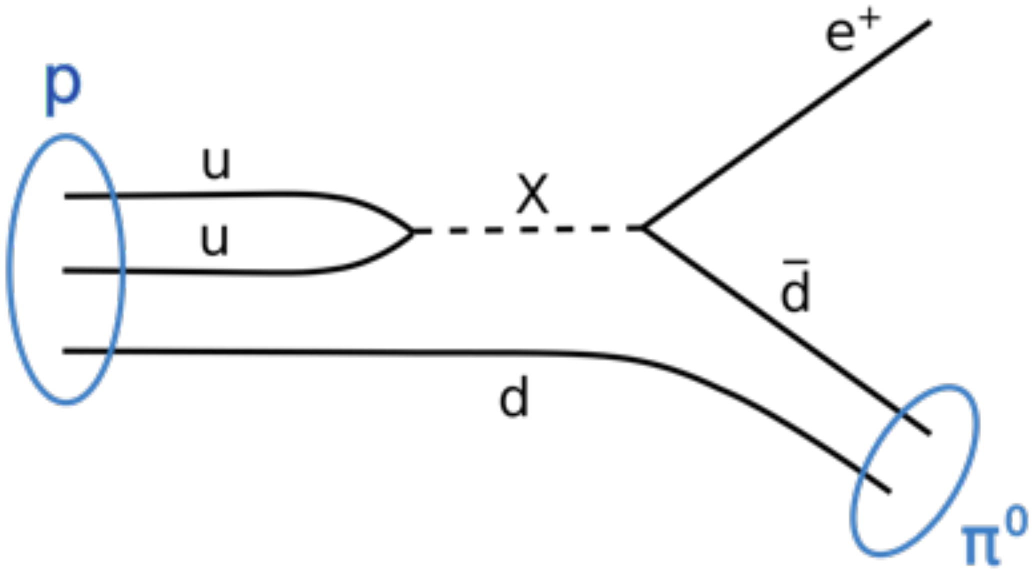
$$\frac{1}{\Lambda^2} \bar{u} \bar{u} \bar{d} \bar{e}$$

$$\frac{1}{\Lambda^2} Q Q Q L$$



WITH $\Lambda \sim M_{GUT} \sim 10^{15}\,\mathrm{GeV}$

GIVES PROTON DECAY VIA E.G.



FOR $M_{GUT}=10^{15}$ GEV, PREDICT LIFETIME

$$\Gamma \sim \frac{m_p^5}{M_{GUT}^4} \sim 10^{29}\ \mathrm{years}$$

EXPERIMENTAL LIMIT (E.G. SUPER-KAMIOKANDE): $\tau > 8 * 10^{33}$ YEARS

VANILLA UNIFICATION EXCLUDED BY DATA.

IMPROVING UNIFICATION

CONSIDER THE EFFECTS OF ADDING NEW FERMIONS* AT SCALE M_Ψ

$$\frac{1}{\alpha_{GUT}} = \frac{1}{\alpha_i(m_Z)} - \frac{b_i^{SM}}{2\pi}\ln\left(\frac{M_{GUT}}{m_Z}\right) - \frac{\Delta b_i}{2\pi}\ln\left(\frac{M_{GUT}}{M_\Psi}\right) + \ldots$$

UNIVERSAL Δb_i ONLY SHIFTS VALUE OF α_{GUT}

DIFFERENCES $\Delta b_i - \Delta b_j$ CHANGE PRECISION OF UNIFICATION & VALUE OF M_{GUT}

SOME REPRESENTATIONS AND THEIR SHIFTS:

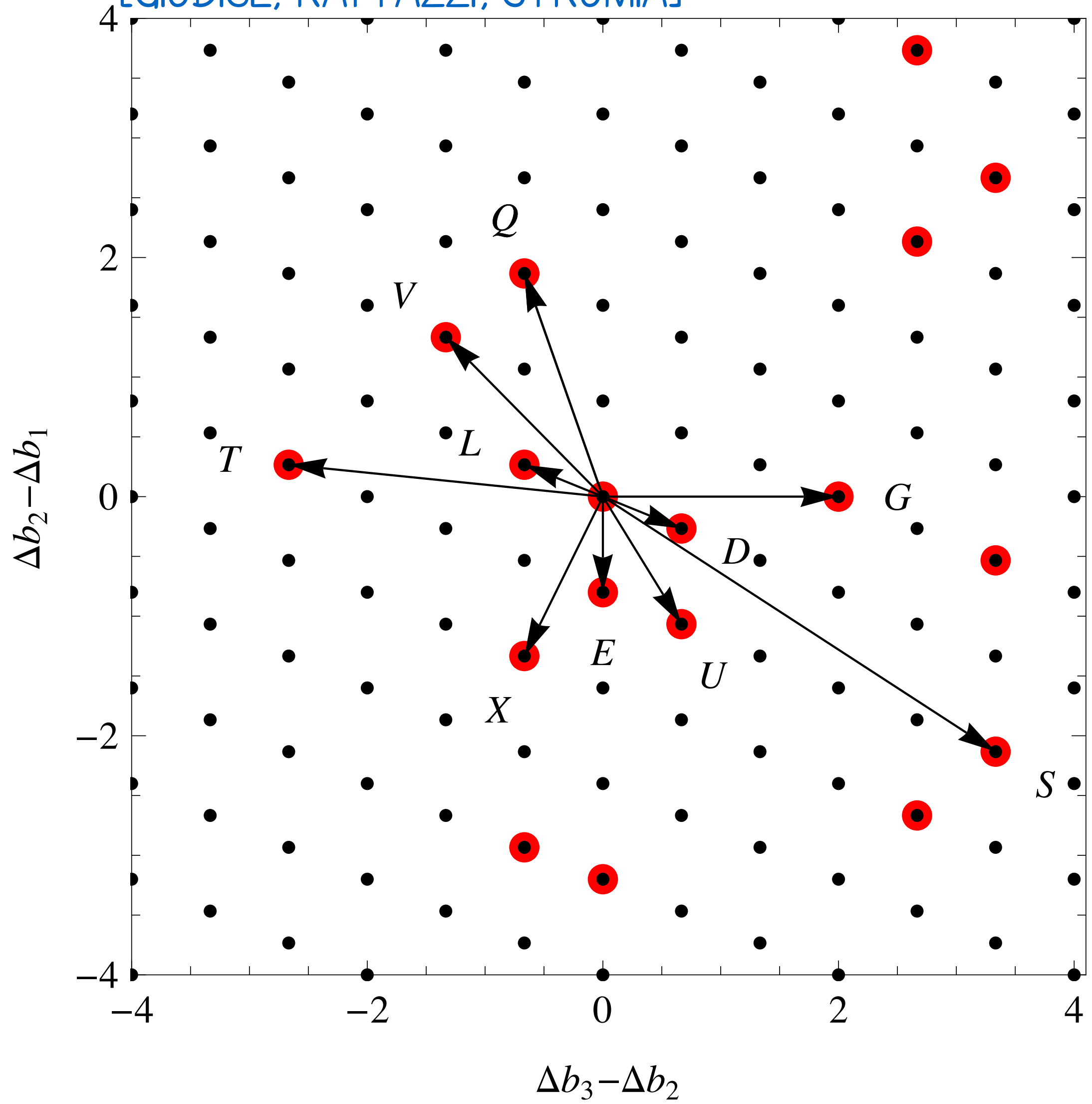
SU(5)	SU(3) ⊗ SU(2) ⊗ U(1)			n_3	$\bar{n}_3$	n_2	z	name	Δb_3	Δb_2	Δb_1
$5 \oplus \bar{5}$	$\bar{3}$	1	$1/3$	0	1	0	0	D	2/3	0	4/15
$5 \oplus \bar{5}$	1	2	$1/2$	0	0	1	0	L	0	2/3	2/5
$10 \oplus \overline{10}$	$\bar{3}$	1	$-2/3$	0	1	0	1	U	2/3	0	16/15
$10 \oplus \overline{10}$	1	1	-1	0	0	0	1	E	0	0	4/5
$10 \oplus \overline{10}$	3	2	$1/6$	1	0	1	0	Q	4/3	2	2/15
$15 \oplus \overline{15}$	3	2	$1/6$	=	=	=	=	Q	=	=	=
$15 \oplus \overline{15}$	1	3	1	0	0	2	0	T	0	8/3	12/5
$15 \oplus \overline{15}$	6	1	$-2/3$	2	0	0	0	S	10/3	0	32/15
24	1	3	0	0	0	2	1	V	0	4/3	0
24	8	1	0	1	1	0	0	G	2	0	0
24	$\bar{3}$	2	$5/6$	0	1	1	0	X	4/3	2	10/3

[GIUDICE, RATTAZZI, STRUMIA]

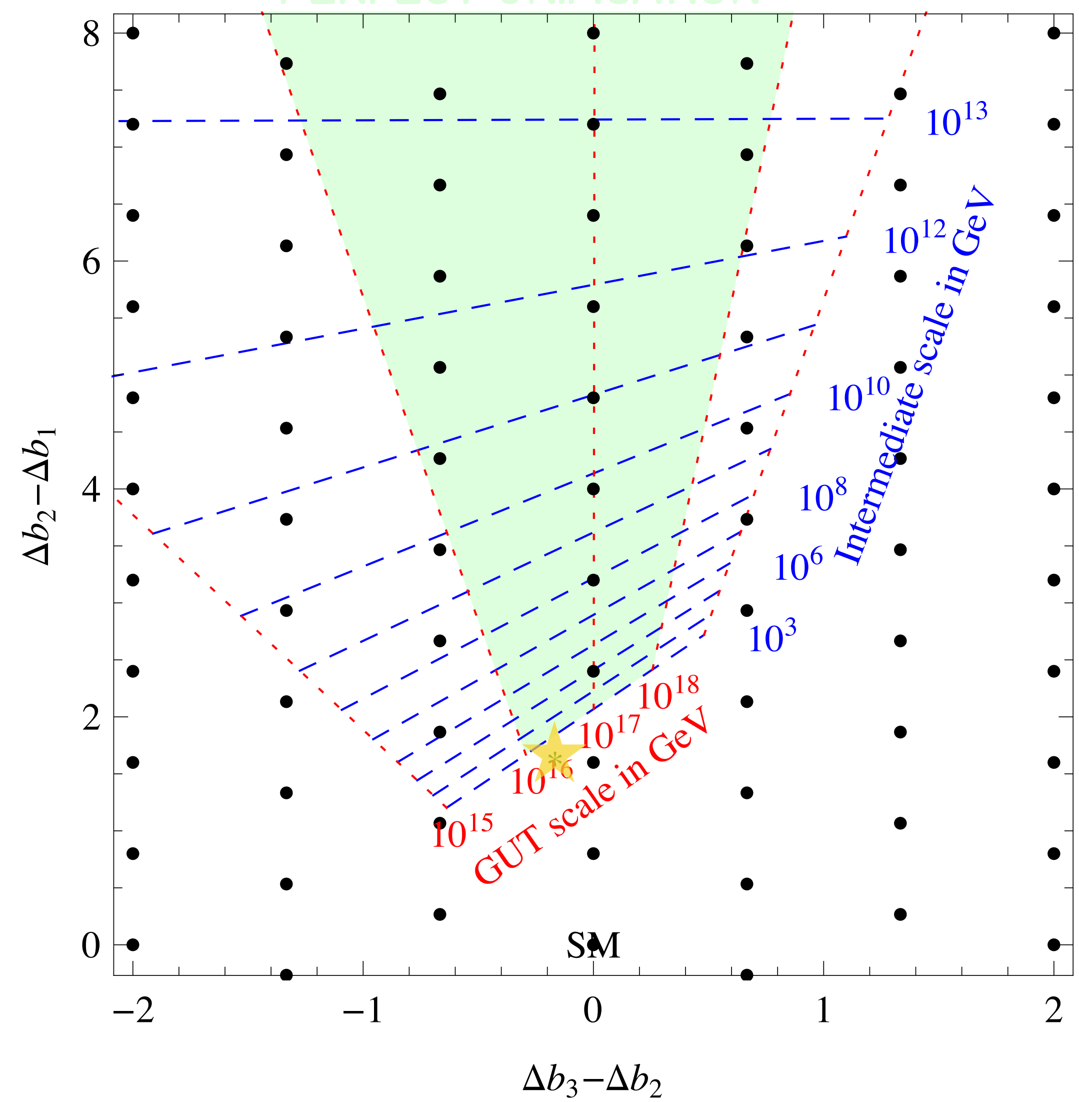
*COULD ADD SCALARS TOO, BUT MAKES MUCH SMALLER CHANGE IN RUNNING.

IMPROVING UNIFICATION

[GIUDICE, RATTAZZI, STRUMIA]

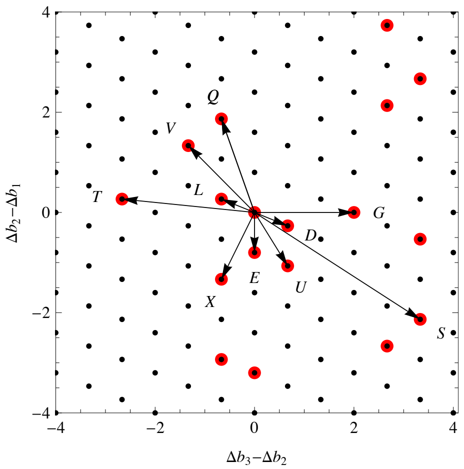


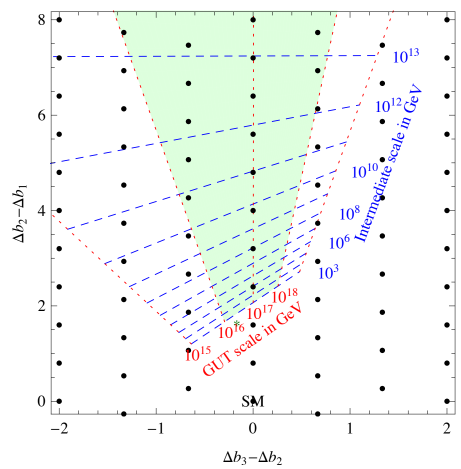
PERFECT UNIFICATION



ADDING REPRESENTATIONS IMPROVES UNIFICATION PREDICTION AND RAISES GUT SCALE.
IF REPRESENTATIONS NOT TOO LARGE, NEED SCALE TO BE NEAR WEAK SCALE.

FOR $M_{GUT}=10^{16}$ GEV, PROTON LIFETIME AT EDGE OF CURRENT LIMITS.





UNIFICATION @ TEV

REPS THAT "HELP" (IMPROVE PRECISION, RAISE SCALE)

SU(5)	SU(3)	$\otimes$ SU(2)	$\otimes$ U(1)	n_3	$\bar{n}_3$	n_2	z	name	Δb_3	Δb_2	Δb_1
$5 \oplus \bar{5}$	$\bar{3}$	1	$1/3$	0	1	0	0	D	2/3	0	4/15
$5 \oplus \bar{5}$	1	2	$1/2$	0	0	1	0	L	0	2/3	2/5
$10 \oplus \overline{10}$	$\bar{3}$	1	$-2/3$	0	1	0	1	U	2/3	0	16/15
$10 \oplus \overline{10}$	1	1	-1	0	0	0	1	E	0	0	4/5
$10 \oplus \overline{10}$	3	2	$1/6$	1	0	1	0	Q	4/3	2	2/15
$15 \oplus \overline{15}$	3	2	$1/6$	=	=	=	=	Q	=	=	=
$15 \oplus \overline{15}$	1	3	1	0	0	2	0	T	0	8/3	12/5
$15 \oplus \overline{15}$	6	1	$-2/3$	2	0	0	0	S	10/3	0	32/15
24	1	3	0	0	0	2	1	V	0	4/3	0
24	8	1	0	1	1	0	0	G	2	0	0
24	$\bar{3}$	2	$5/6$	0	1	1	0	X	4/3	2	10/3

SAME QUANTUM #S AS HIGGSINOS IN SUSY

SAME QUANTUM #S AS VECTOR-LIKE QUARKS IN COMPOSITE HIGGS

TAKEAWAY: SEARCHES FOR HIGGSINOS, VECTOR-LIKE QUARKS CAN BE MOTIVATED BY IMPROVED GAUGE COUPLING UNIFICATION, WHERE THE PRESSURE FOR ACCESSIBLE SCALES COMES NOT FROM NATURALNESS, BUT FROM LOGARITHMIC RUNNING OF COUPLINGS.

BARYOGENESIS

OBSERVE UNIVERSE IS PRIMARILY MADE OF BARYONS, NOT ANTI-BARYONS,

QUANTITATIVELY, $$\eta \equiv \frac{n_B - n_{\bar{B}}}{n_\gamma} \sim 6 \times 10^{-10}$$

IF UNIVERSE STARTED WITH $\eta = 0$ AND BARYONS DECOUPLED LIKE WIMPS,

$$\frac{n_B}{n_\gamma} \simeq \frac{n_{\bar{B}}}{n_\gamma} \simeq \left(\frac{m_p}{T}\right)^{3/2} e^{-m_p/T} \to 10^{-18} \ (T_f \sim 20\,\mathrm{MeV})$$

IN BAD DISAGREEMENT! MORE OR LESS THREE OPTIONS:

1. INITIAL CONDITIONS ARE TUNED. $\longrightarrow$ DEEPLY UNSATISFYING, ESSENTIALLY IMPOSSIBLE W/ INFLATION
2. B AND $\bar{B}$ SPATIALLY SEPARATED. $\longrightarrow$ DISFAVORED BY DATA
3. ASYMMETRY IS DYNAMICAL.

BARYOGENESIS

SAKHAROV CONDITIONS FOR DYNAMICAL BARYON ASYMMETRY:

1. BARYON # VIOLATION (NEED TO GET NET BARYON # FROM B=0)
2. C & CP VIOLATION (OTHERWISE RELATE $B,\bar{B}$-CREATING PROCESSES)
3. DEPARTURE FROM THERMAL EQUILIBRIUM

IN PRINCIPLE POSSIBLE WITHIN SM DURING ELECTROWEAK PHASE TRANSITION:

1. NONPERTURBATIVE ELECTROWEAK CONFIGURATIONS (SPHALERONS)
2. CP VIOLATION FROM CKM + DOMAIN WALL BREAKS C
3. IF PHASE TRANSITION IS STRONGLY FIRST-ORDER

IN PRACTICE, NOT ENOUGH OF ANYTHING: CPV FROM CKM PHASE TOO SMALL, EWPT NOT FIRST ORDER FOR MH=125 GEV.

BARYOGENESIS

SOME OPTIONS (NOT EXHAUSTIVE)

ELECTROWEAK BARYOGENESIS

ADD MATTER TO SM TO ALTER HIGGS POTENTIAL, MAKE EWPT STRONGLY 1ST-ORDER

E.G. $\kappa|\Phi|^2|H|^2$

WITH Φ LIGHT AND κ LARGE

POSSIBLE, BUT LEADS TO DEVIATIONS IN HIGGS COUPLINGS (DEPENDING ON QUANTUM # OF Φ) AND HIGGS CUBIC COUPLING; TESTABLE W/ COLLIDER SEARCHES & PRECISION HIGGS MEASUREMENTS.

LEPTOGENESIS

ALREADY EXPECT LEPTON # VIOLATION FROM NEUTRINO MASSES,

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

POSIT TYPE 1 SEESAW (HEAVY RHNS) W/ CPV COUPLINGS FOR CONDITION 2

OUT-OF-EQUILIBRIUM DECAYS OF RHN SATISFY CONDITION 3

ELECTROWEAK SPHALERONS PROCESS LEPTON # VIOLATION INTO BARYON # VIOLATION (CONDITION 1)

AFFLECK-DINE BARYOGENESIS

SCALAR FIELD CARRYING BARYON #, CAN HAVE SMALL CP AND BARYON # VIOLATING COUPLINGS

EFFECTS CAN BE LARGE IF SCALAR HAS LARGE VEV IN EARLY UNIVERSE, THEN OSCILLATES (E.G. FLAT POTENTIAL, INITIALLY PINNED BY HUBBLE FRICTION)

OSCILLATIONS GIVE LARGE EFFECTIVE BARYON # VIOLATION THAT CAN BE TRANSFERRED TO SM FIELDS.

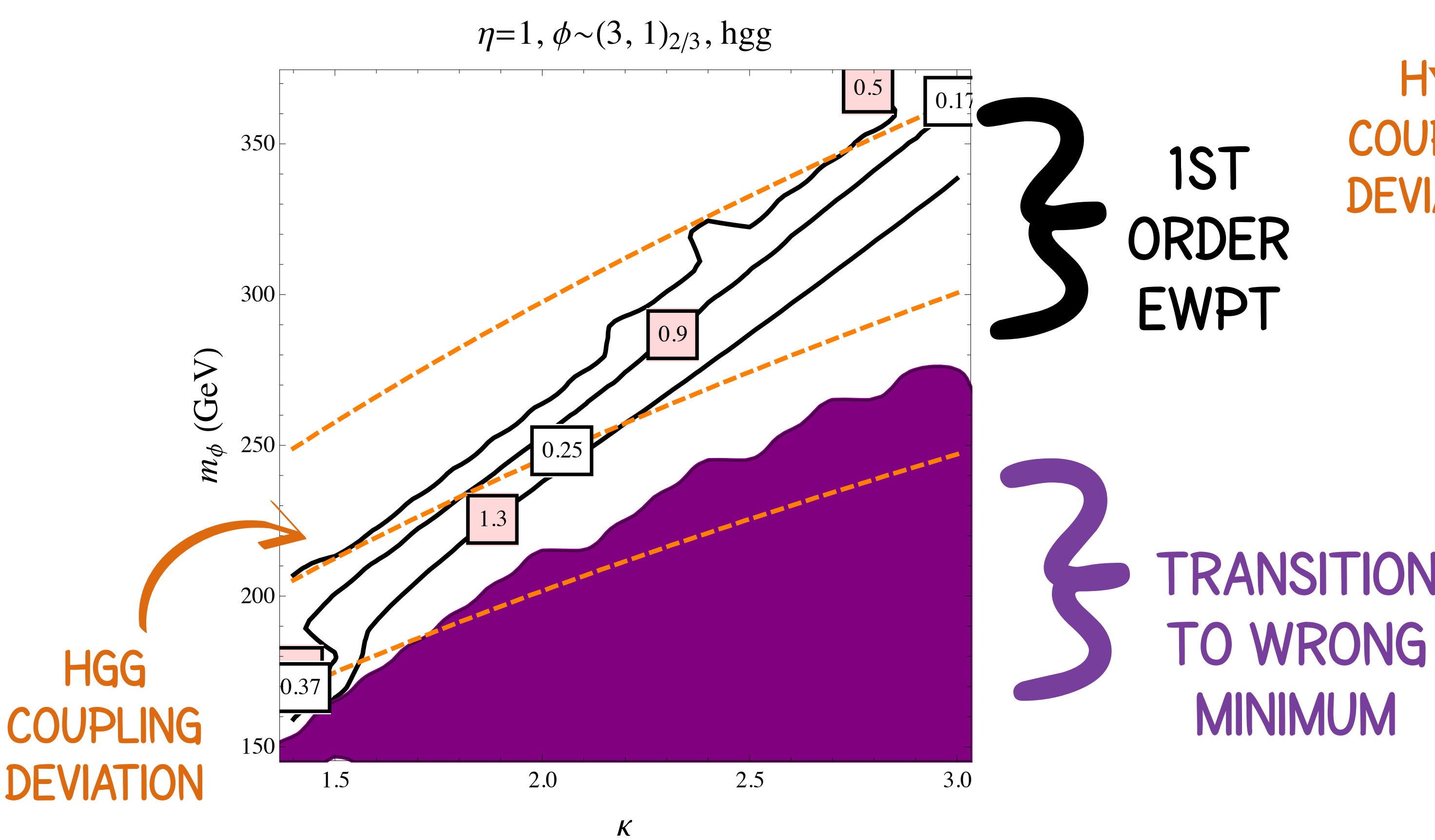
BARYOGENESIS@TEV 1: ELECTROWEAK BARYOGENESIS

ADD MATTER TO SM TO ALTER HIGGS POTENTIAL, MAKE EWPT STRONGLY 1ST-ORDER

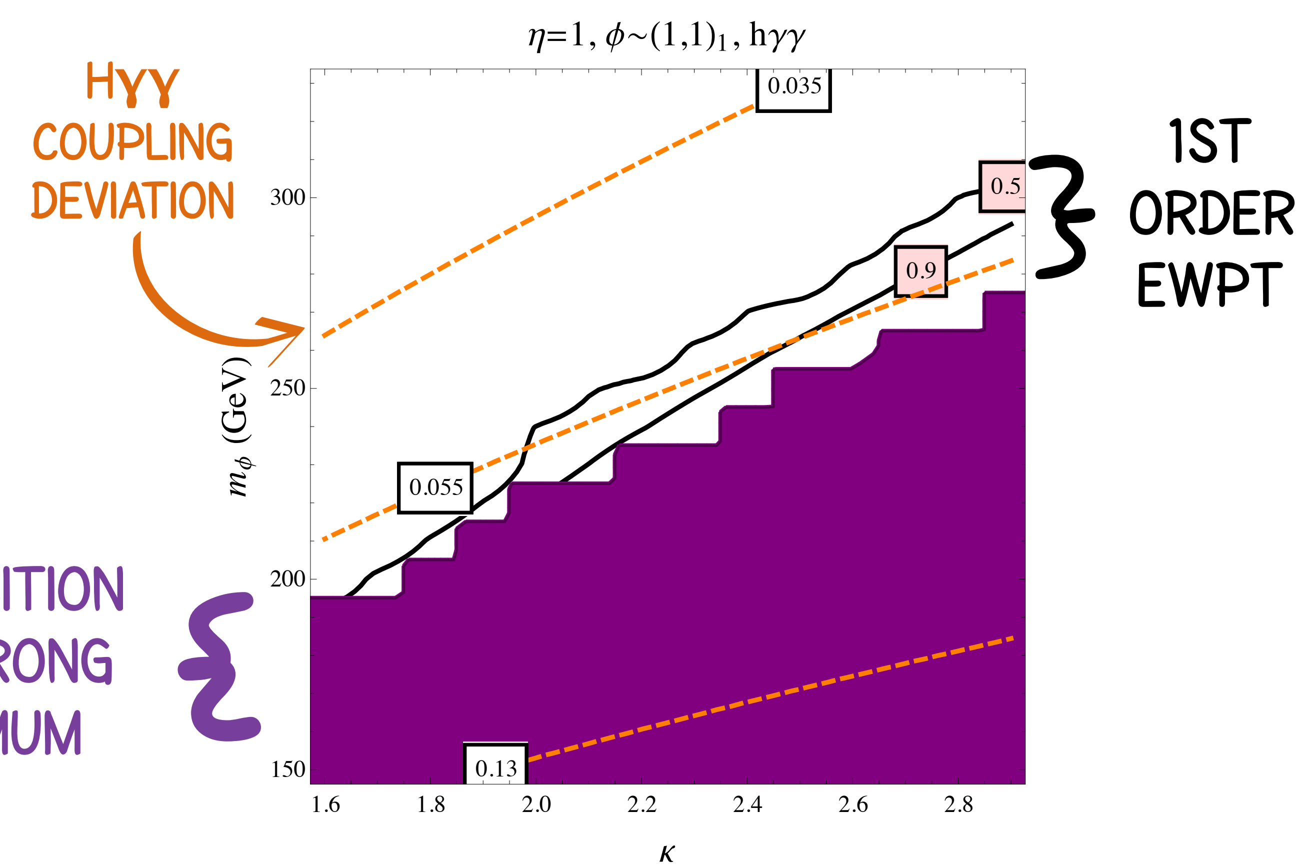
E.G. $\kappa|\Phi|^2|H|^2$ WITH Φ LIGHT AND κ LARGE

IF Φ CHARGED/COLORED, AN EASY GAME: SEARCH VIA DIRECT PRODUCTION AT HADRON COLLIDERS OR LOOK FOR HIGGS COUPLING DEVIATIONS.

LOOKS LIKE: STOP

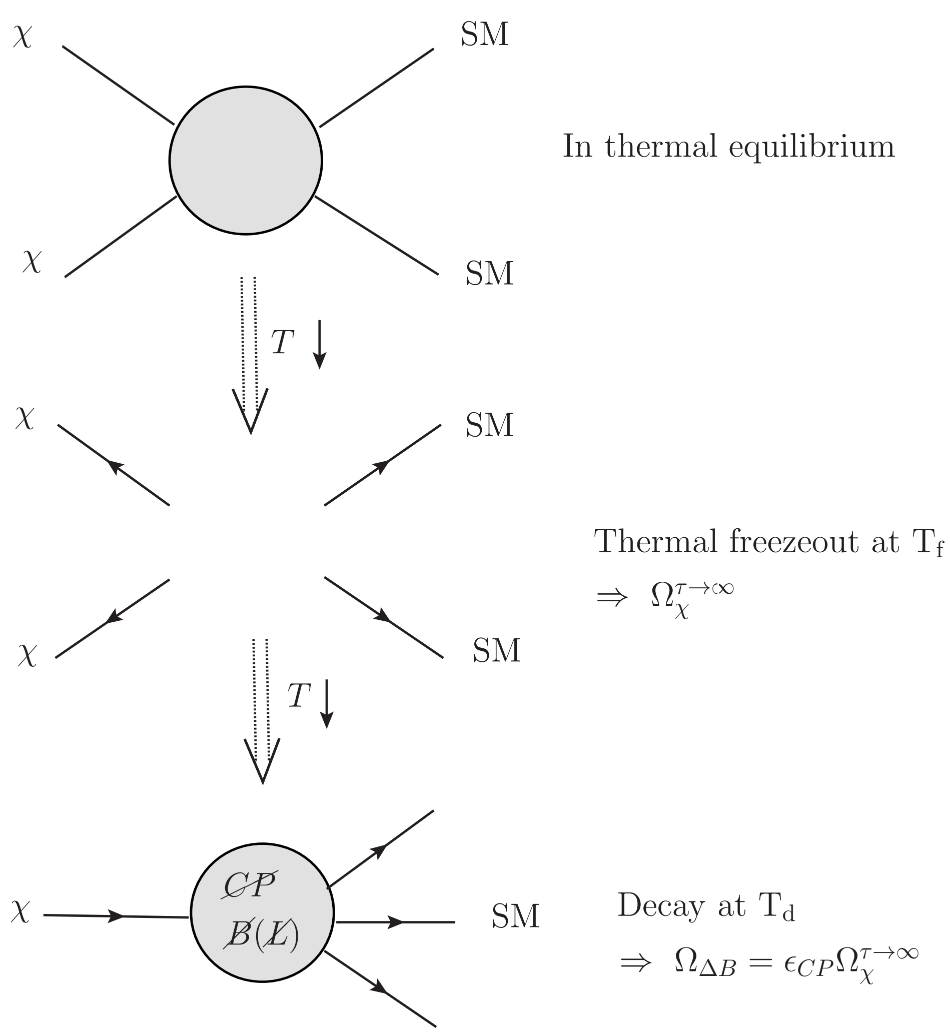


LOOKS LIKE: RH STAU

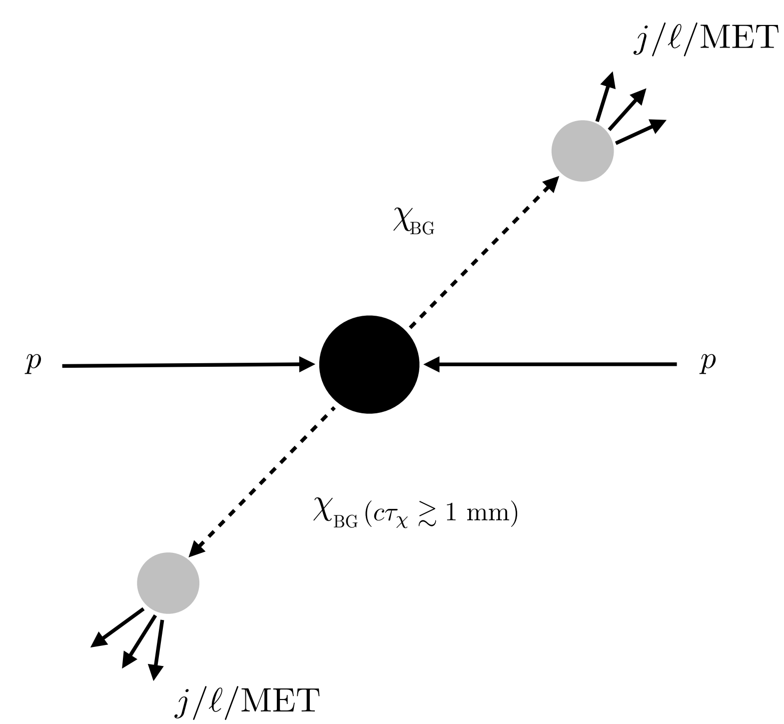


BARYOGENESIS@TEV 2: WIMPY BARYOGENESIS

NEW PARTICLE GETS THERMAL ABUNDANCE FROM FREEZE-OUT, LIKE DARK MATTER
(WIMP MIRACLE → WEAK SCALE COUPLINGS & MASS).
OUT-OF-EQUILIBRIUM DECAYS VIOLATE CP, BARYON/LEPTON #

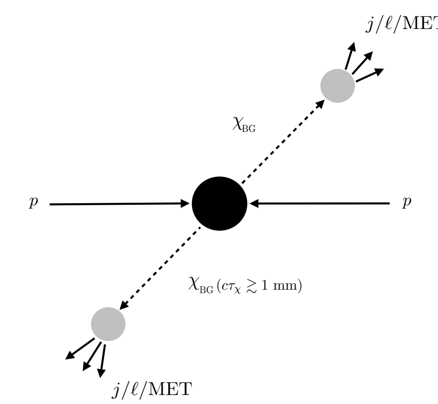


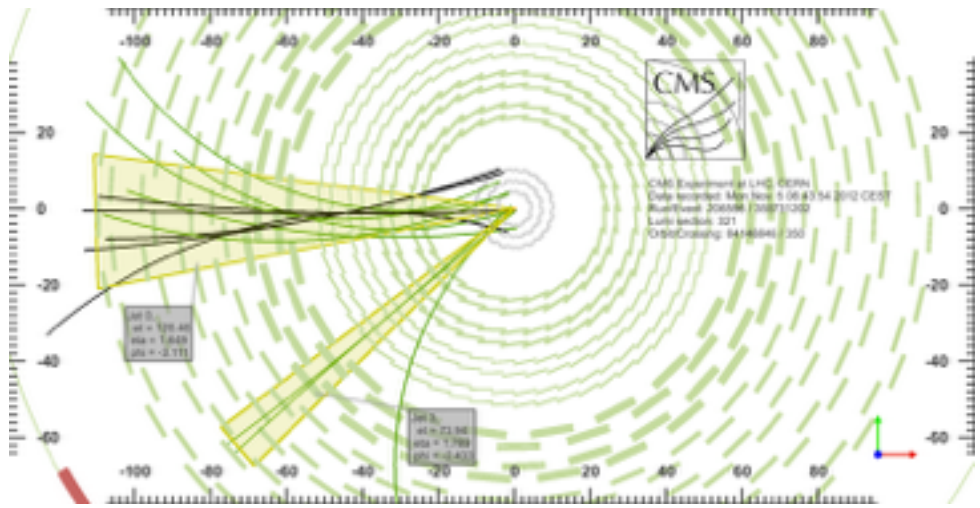
COUPLINGS REQUIRED FOR THESE PROCESSES TO WORK IMPLY PRODUCTION VIA SM AND LONG-LIVED DECAY TO SM.
DISPLACED VERTICES AT COLLIDERS



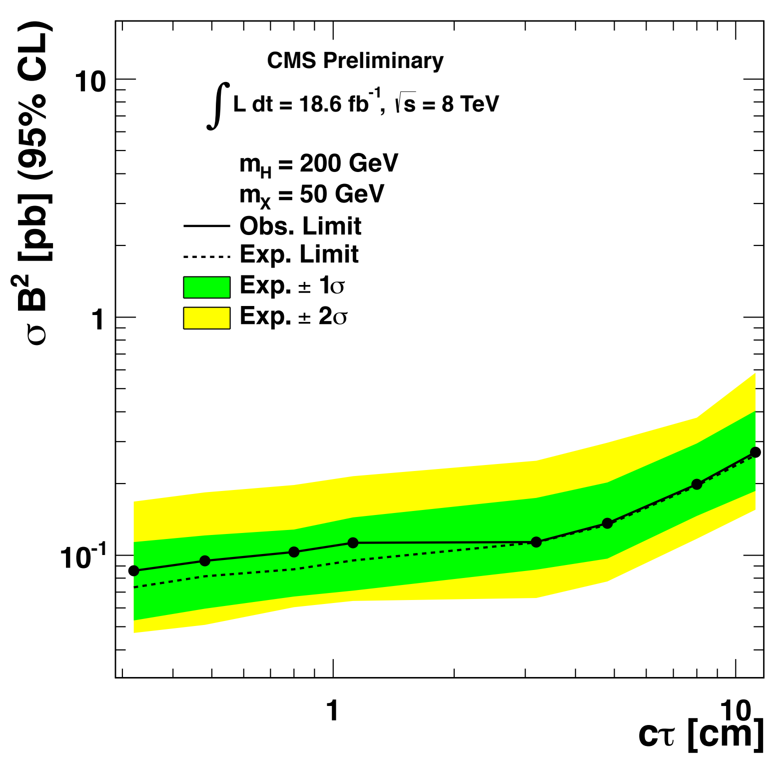
[CUI, RANDALL, SHUVE '11, CUI & SHUVE '14]

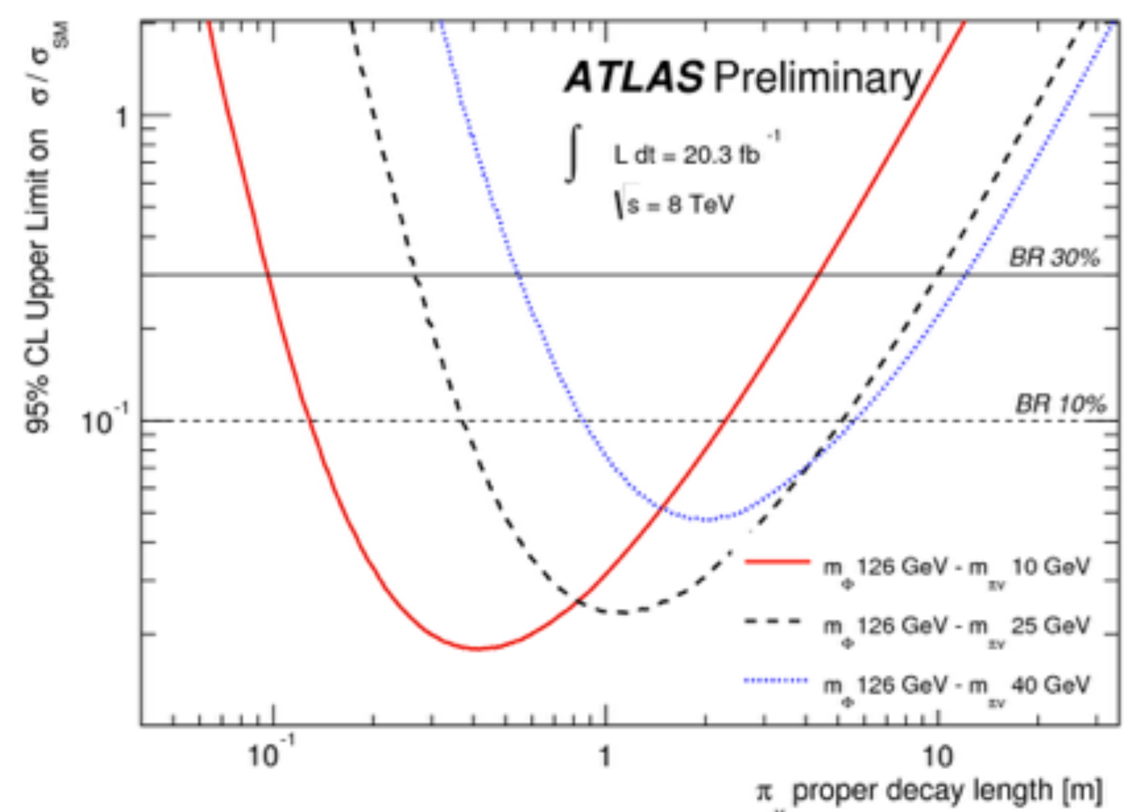
BARYOGENESIS @ LHC





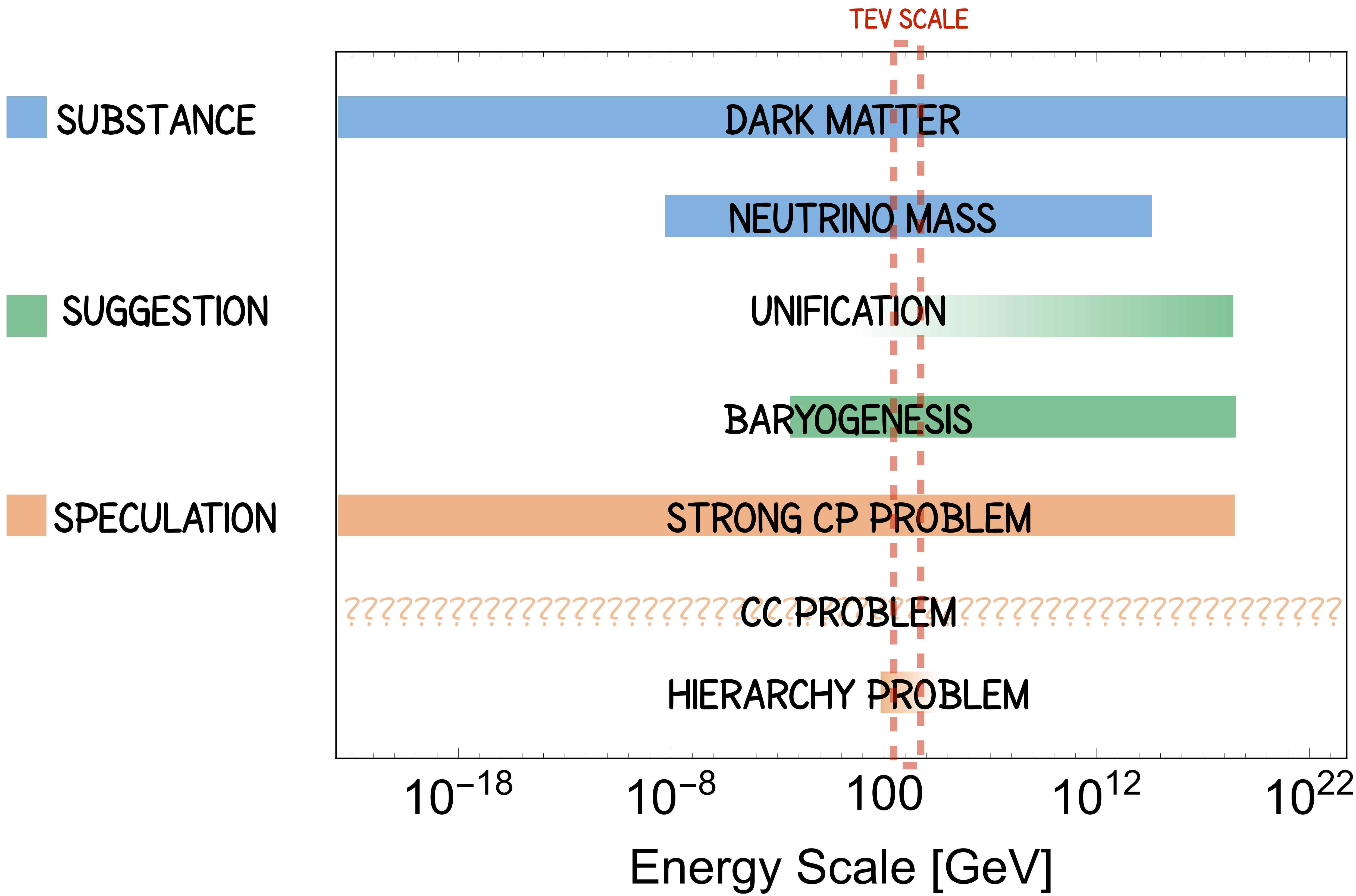
MOTIVATES VARIOUS SEARCHES FOR DISPLACED DECAYS USING, E.G., TRACKER (CMS) OR HCAL/ECAL (ATLAS)





TAKEAWAY: NO GUARANTEE OF ACCESSIBLE NEW PHYSICS, BUT MANY BARYOGESIS MECHANISMS MOTIVATE SIGNALS AT THE WEAK SCALE.

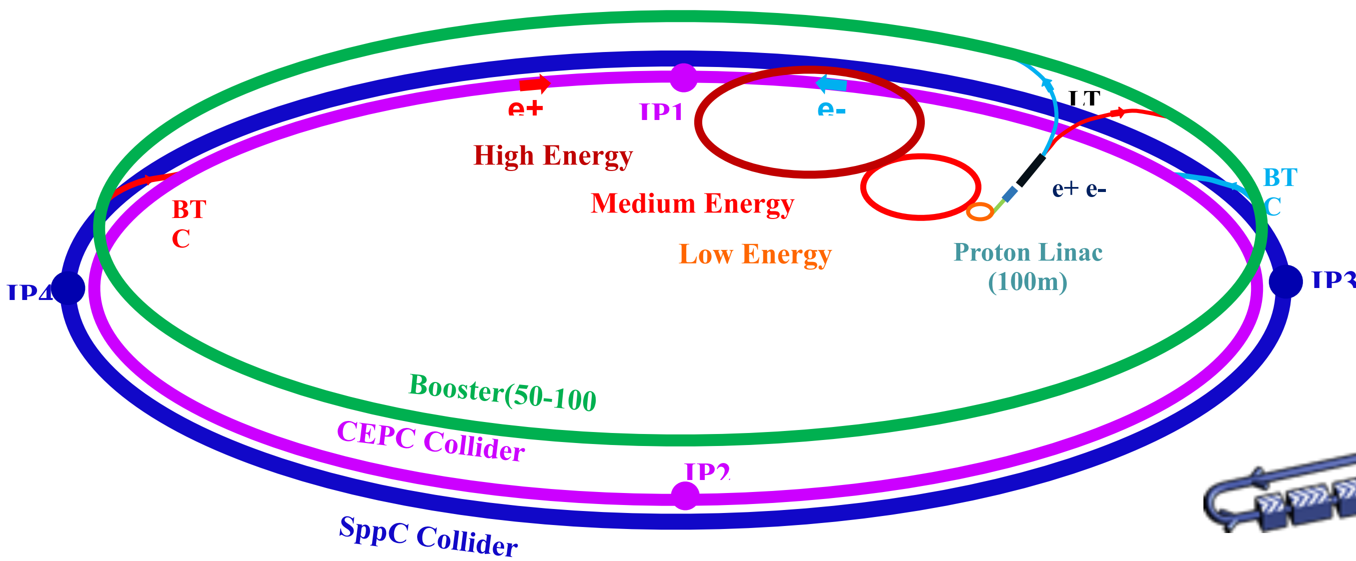
BEYOND THE STANDARD MODEL



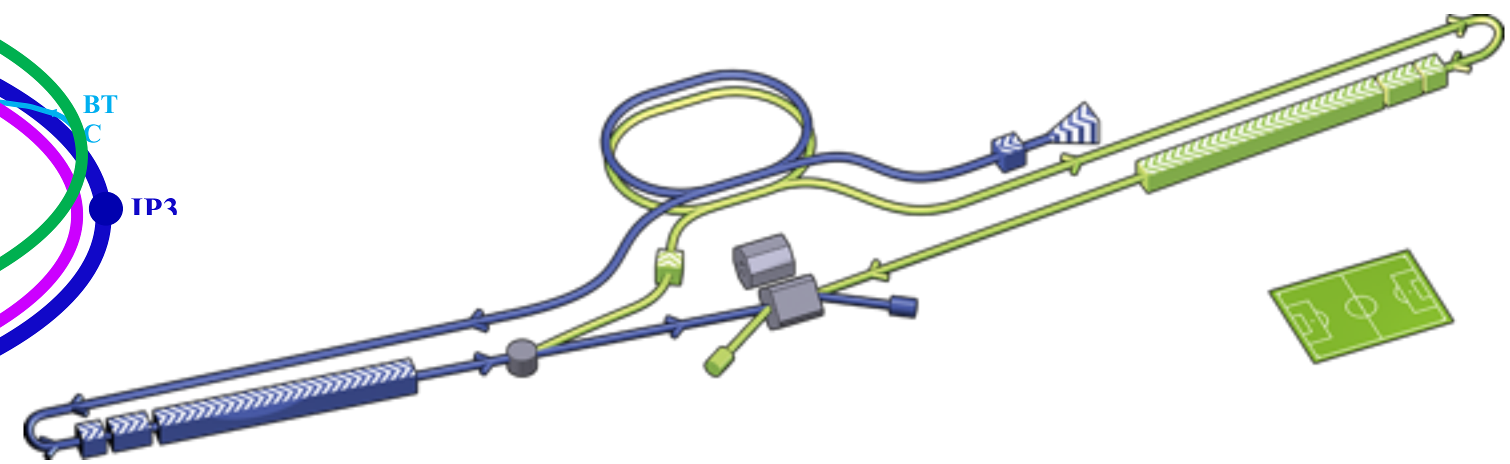
EPILOGUE: LOOKING TO THE FUTURE

LIFE AFTER THE LHC

CEPC (250 GEV), SPPC (50-100 TEV)

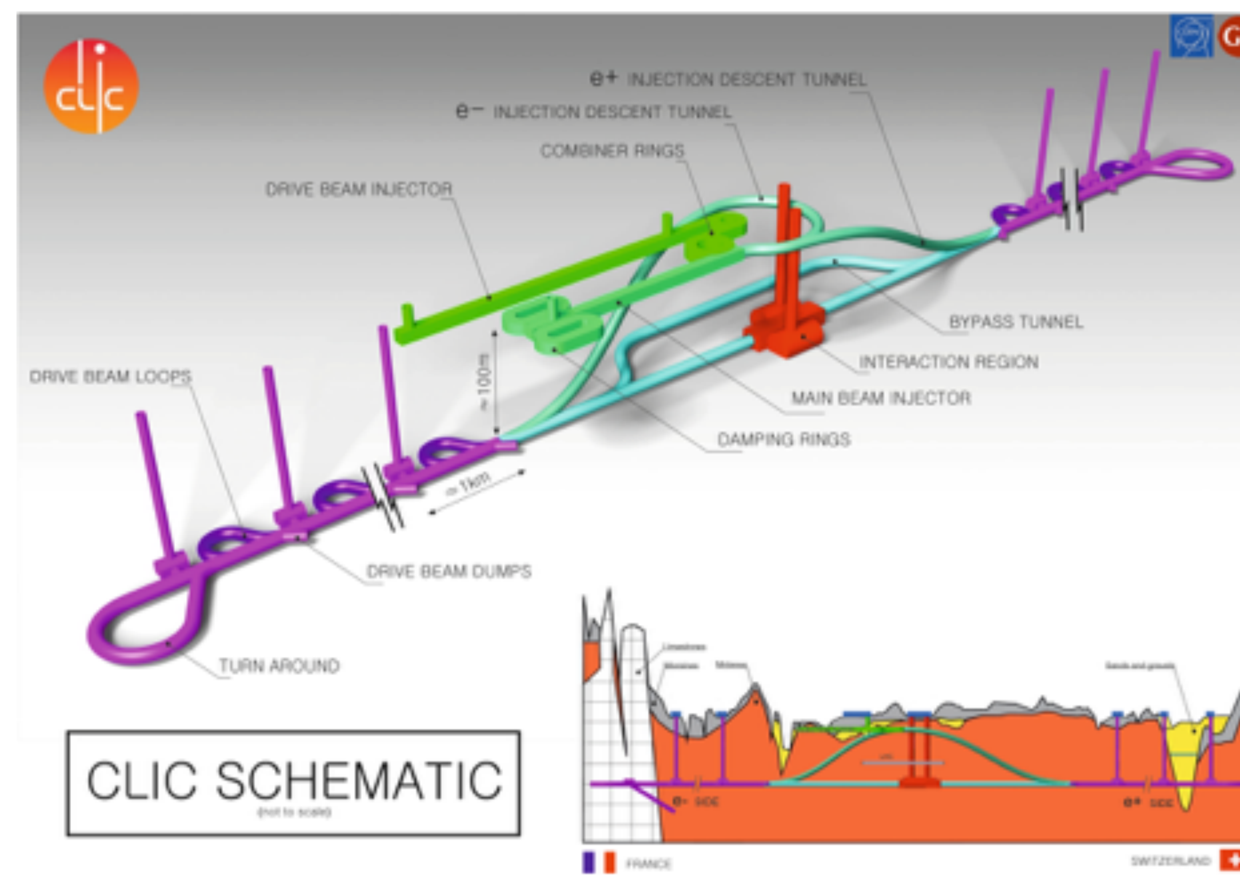


ILC (250 GEV-1 TEV)



CLIC (500 GEV-5 TEV)

FCC-EE (250 GEV), FCC-HH (80-100 TEV)



- THERE IS A *SUPERABUNDANCE* OF MOTIVATION FOR NEW PHYSICS AT THE TEV SCALE, BOTH FROM CONVENTIONAL BSM DRIVERS (**THE HIERARCHY PROBLEM**) AND FROM LESS CONVENTIONAL ONES (**STRONG CP PROBLEM, UNIFICATION, BARYOGENESIS, DARK MATTER, NEUTRINOS,...**).

- POPULAR SOLUTIONS BEING TESTED, BUT NEW SOLUTIONS TO THESE PROBLEMS ABOUND, WITH NEW SIGNALS AT THE TEV SCALE.

- MANY OF THESE SIGNALS ARE ONLY NOW COMING INTO THE REACH OF TEV-SCALE PROBES, AND MAKE INTERESTING GOALS FOR FUTURE COLLIDERS.

THANK YOU!