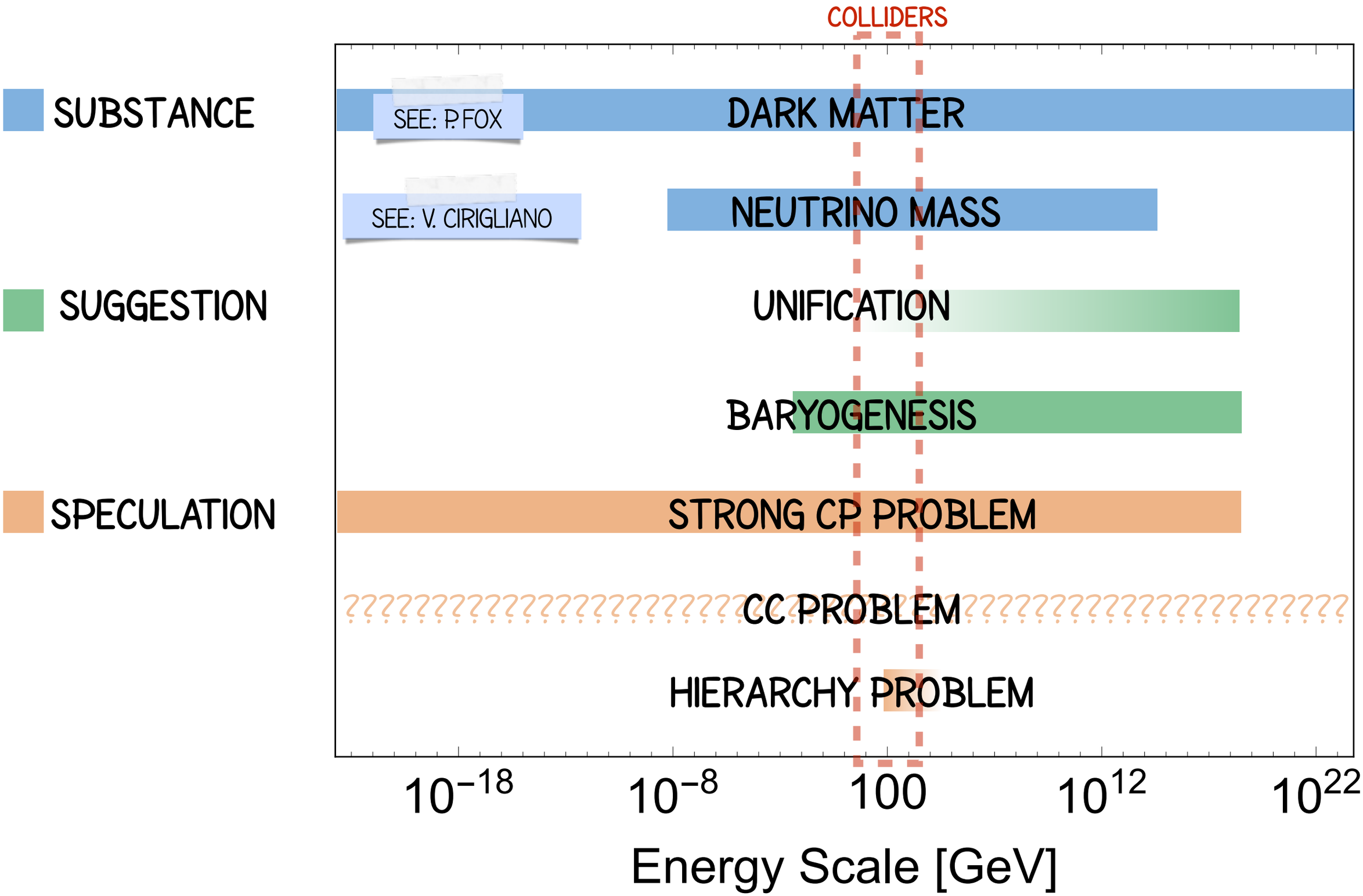
BEYOND THE STANDARD MODEL @COLLIDERS

NATHANIEL CRAIG
UC SANTA BARBARA

SSI 2016: NEW HORIZONS ON THE ENERGY FRONTIER

BEYOND THE STANDARD MODEL



$$\Delta_O = 4$$
$$\text{natural} \sim \mathcal{O}(1)$$

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

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

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

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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

$$|d_n| \lesssim 3\times10^{-26}e\,\text{cm} \Rightarrow \theta_{QCD} \lesssim 10^{-10}$$

APPARENT NUMERICAL TUNING OF 10 ORDERS OF MAGNITUDE!

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

MASSLESS QUARKS?

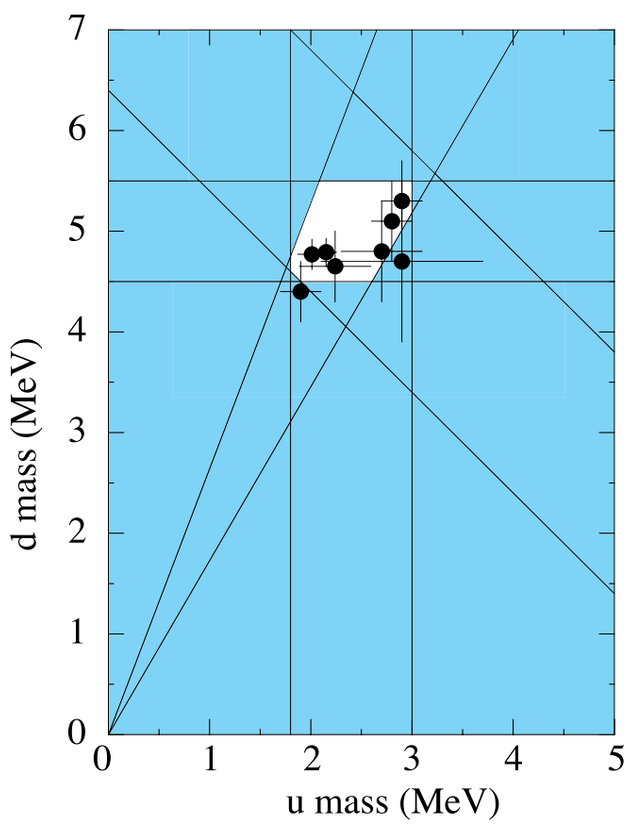
COULD WE SOLVE THE PROBLEM WITHOUT NEW PHYSICS?

UNDER THE REPHASINGS $q \to e^{i\theta} q \qquad \bar{q} \to e^{i\theta} \bar{q}$

MASS TERM PICKS UP PHASE $m \to e^{2i\theta} m$

AND GENERATE A THETA TERM $\delta \mathcal{L} = \frac{\theta}{32\pi^2} G\tilde{G}$ DUE TO AXIAL ANOMALY

CAN USE THIS FREEDOM TO MOVE PHASE BETWEEN QUARK MASS & THETA TERM



NOW IN QCD, HAVE LIGHT QUARK CURRENT MASSES

$$\mathcal{L} \supset m_u \bar{u} u + m_d \bar{d} d$$

IF (SAY) $M_U = 0$, THEN CAN MAKE THETA TERM UNPHYSICAL BY ARBITRARY REPHASING

NO EDM, VIZ. $d_n \sim \frac{e m_u m_d}{(m_u + m_d)\Lambda_{QCD}^2} \theta_{QCD}$

BUT: STRONGLY DISFAVORED BY LATTICE DATA

AXIONS?

DYNAMICALLY ADJUST θ TO ZERO?

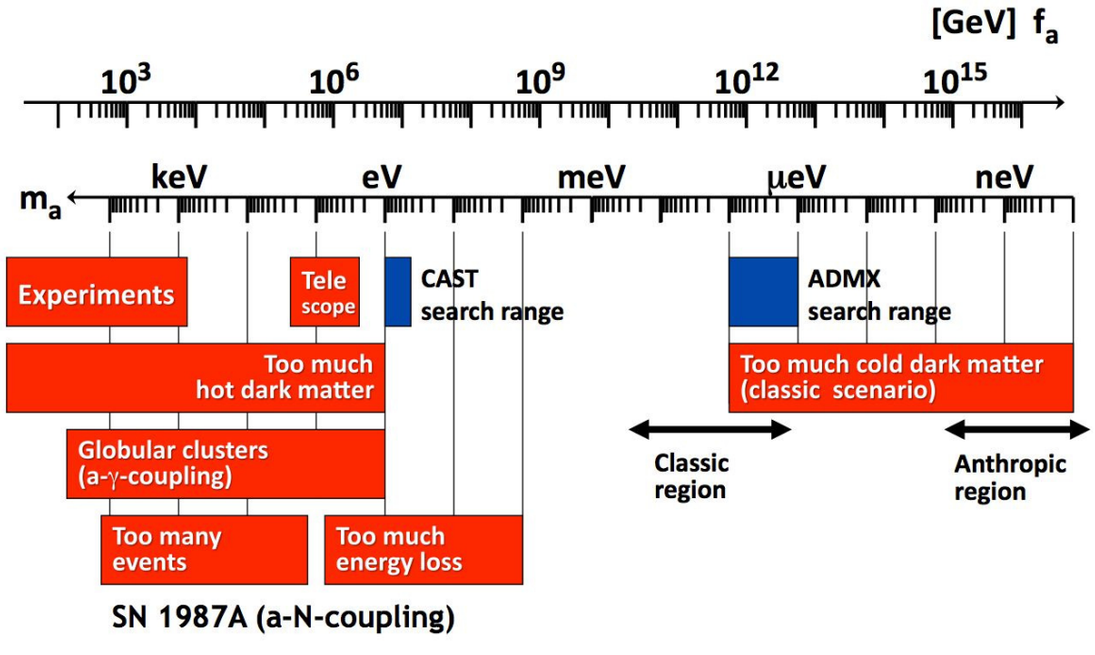
CONSIDER PSEUDOSCALAR a COUPLING TO $G\tilde{G}$

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

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 $\sim \Lambda_{QCD}^2/F$)
COSMOLOGICALLY RELEVANT:
COSMOLOGICAL LIMITS; DARK MATTER?

SPONTANEOUS CPV?

WHAT IF CP (OR P) 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?

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AN ANSWER (ONE OF SEVERAL): 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 NEW PARITY SYMMETRY UNDER WHICH $P: \; SU(2)_L \leftrightarrow SU(2)'_L$

θ ODD UNDER THIS PARITY, SO ZERO IN UV.

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

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]

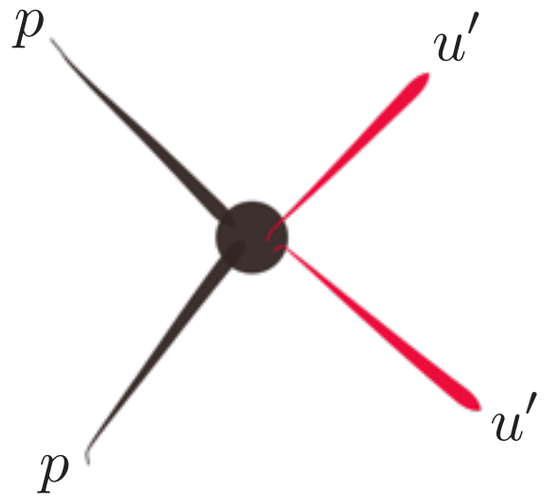
SPONTANEOUS CPV @ LHC

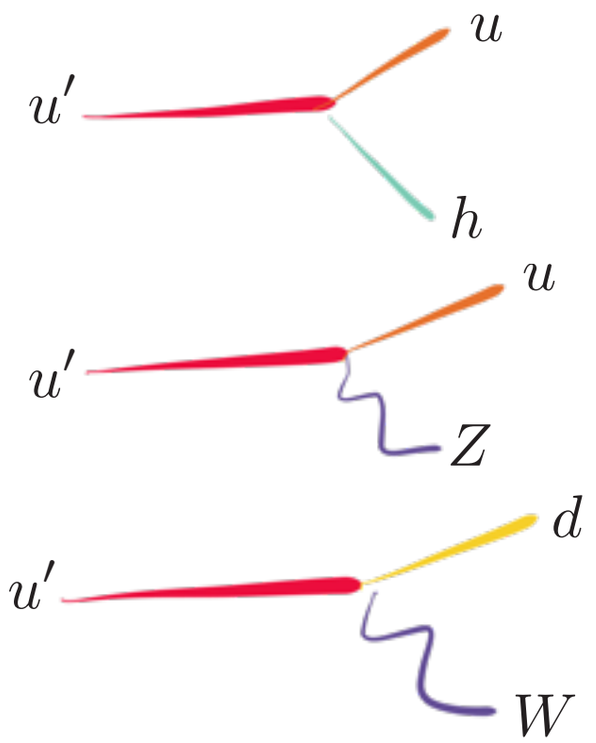
PARITY SOLUTION PREDICTS NEW CHARGED/COLORED FERMIONS <10 TEV W/ SM DECAY MODES

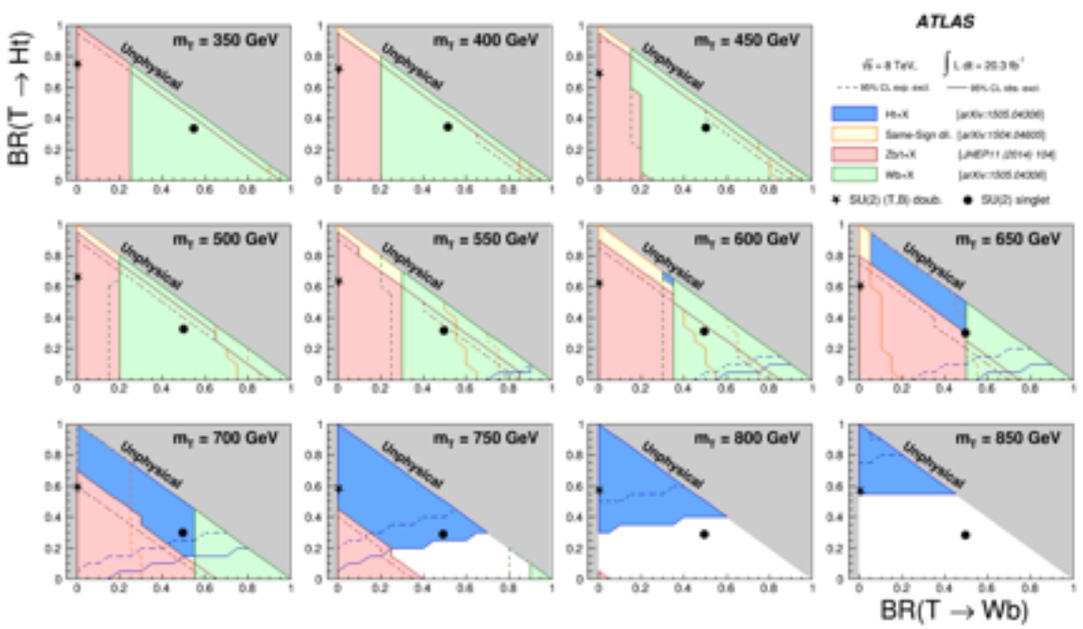
$$u' \to h + u$$

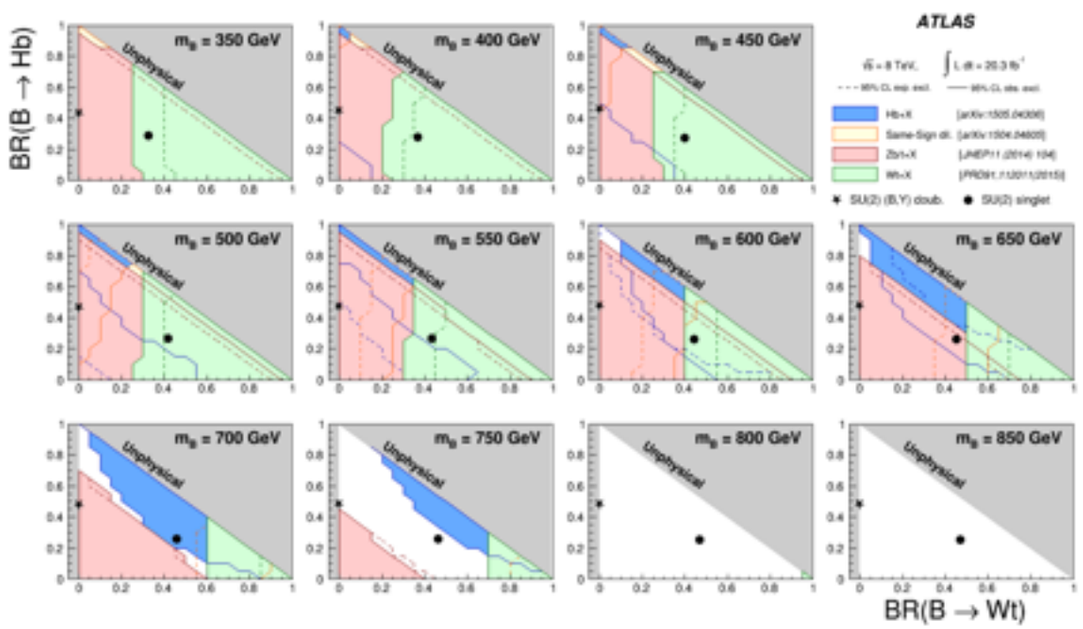
$$u' \to Z + u$$

$$u' \to W + d$$









PART 2: SUGGESTIVE BSM

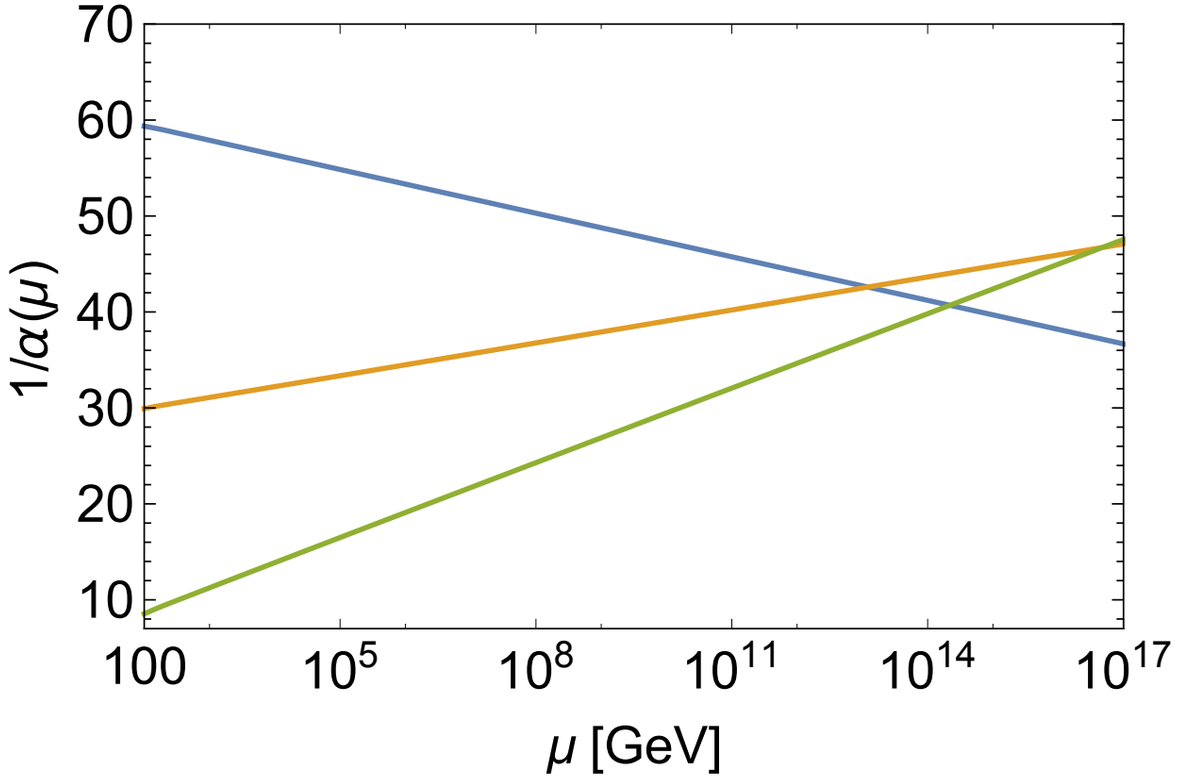
SUGGESTIVE BSM: THERE IS DATA THAT STRONGLY IMPLIES PHYSICS BEYOND THE STANDARD MODEL, BUT COULD BE ACCIDENTAL.

UNIFICATION

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

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

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



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

UNIFICATION

HOW DO THE PIECES FIT TOGETHER?

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

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

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

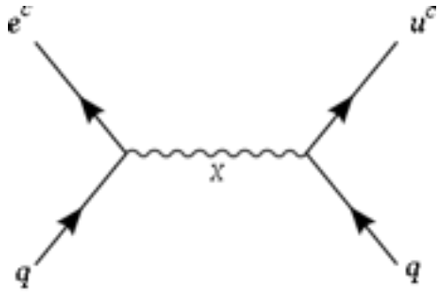
$$\mathbf{10} \to (\mathbf{3},\mathbf{2})_{1/6} \oplus (\bar{\mathbf{3}},\mathbf{1})_{-2/3} \oplus (\mathbf{1},\mathbf{1})_{1} = Q + \bar{u} + \bar{e}$$

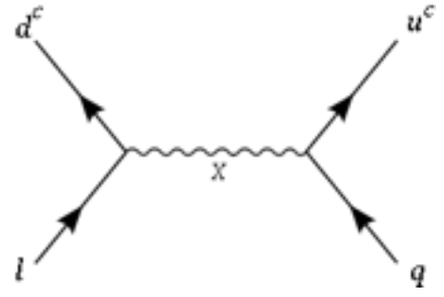
$$\mathbf{24} \to (\mathbf{8},\mathbf{1})_0 + (\mathbf{1},\mathbf{3})_0 + \mathbf{1} + (\mathbf{3},\mathbf{2})_{-5/6} + (\bar{\mathbf{3}},\mathbf{2})_{5/6} = G + W + B + X + \bar{X}$$

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

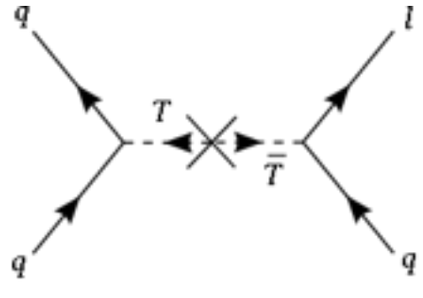
$$\frac{1}{\Lambda^2} QL\bar{u}^\dagger \bar{d}^\dagger$$

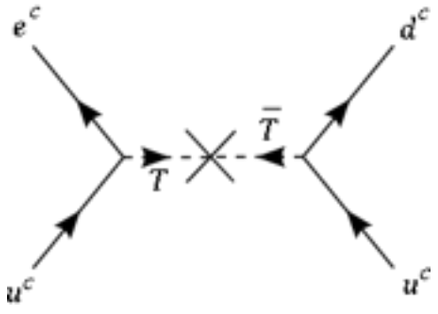
$$\frac{1}{\Lambda^2} QQ\bar{u}^\dagger \bar{e}^\dagger$$

T EXCHANGE GENERATES DIM-6 OPS

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

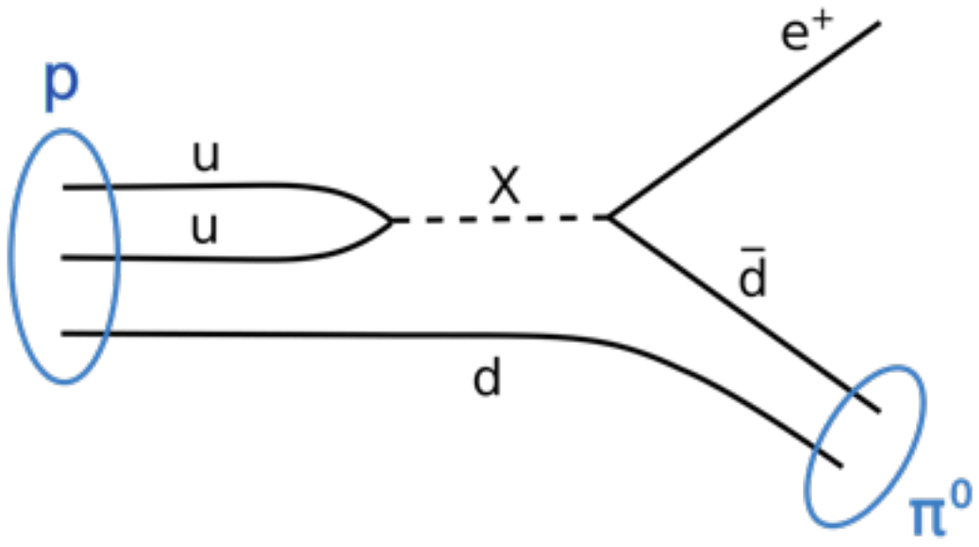
$$\frac{1}{\Lambda^2} QQQL$$





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

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

UNIVERSAL Δb_i ONLY SHIFTS VALUE OF α_{GUT}

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

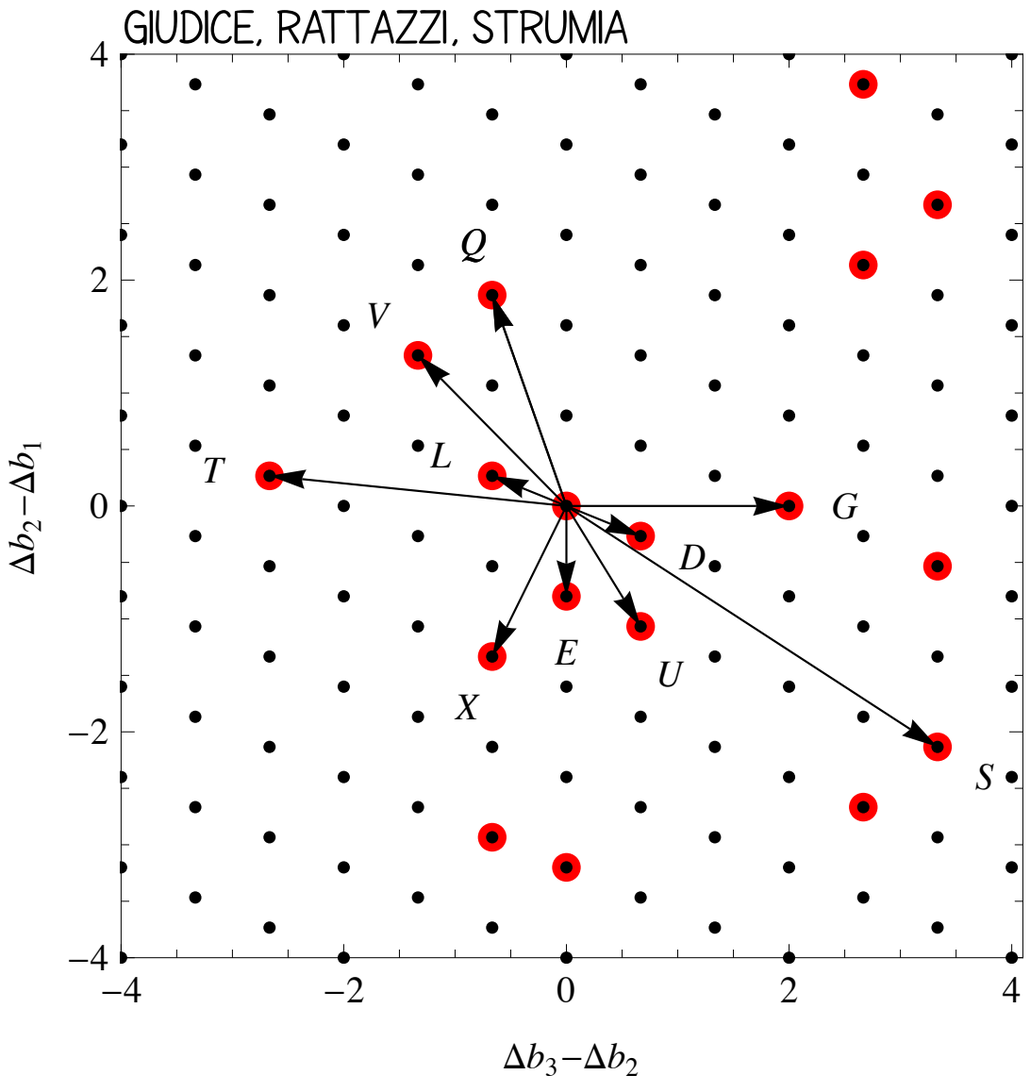
SOME REPRESENTATIONS AND THEIR SHIFTS:

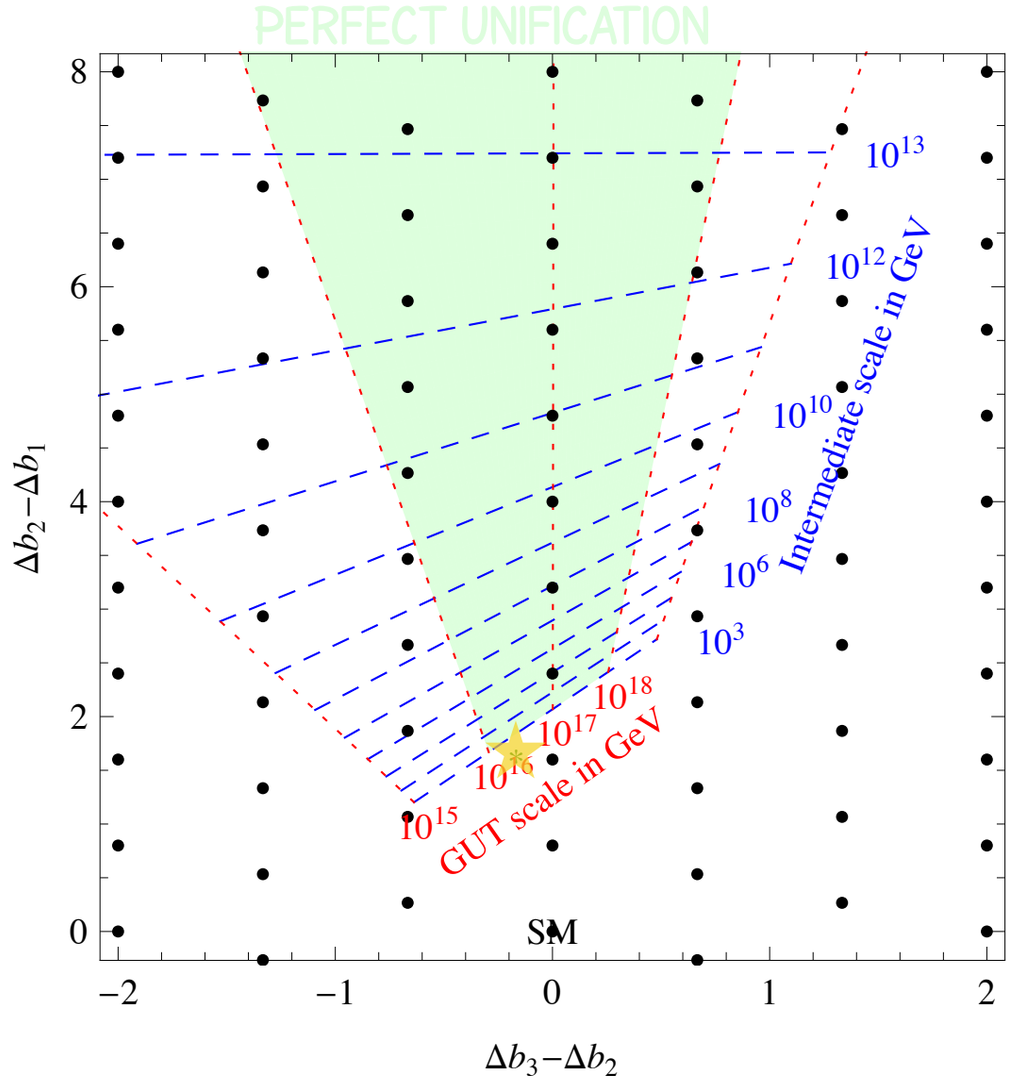
SU(5)	SU(3) ⊗ SU(2) ⊗ U(1)			n_3	$\bar{n}_3$	n_2	z	name	Δb_3	Δb_2	Δb_1
$5 \oplus \bar{5}$	$\bar{3}$	1	$1/3$	0	1	0	0	D	2/3	0	4/15
$5 \oplus \bar{5}$	1	2	$1/2$	0	0	1	0	L	0	2/3	2/5
$10 \oplus \overline{10}$	$\bar{3}$	1	$-2/3$	0	1	0	1	U	2/3	0	16/15
$10 \oplus \overline{10}$	1	1	-1	0	0	0	1	E	0	0	4/5
$10 \oplus \overline{10}$	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.

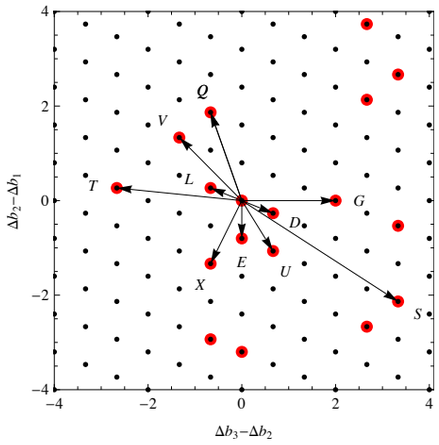
IMPROVING UNIFICATION

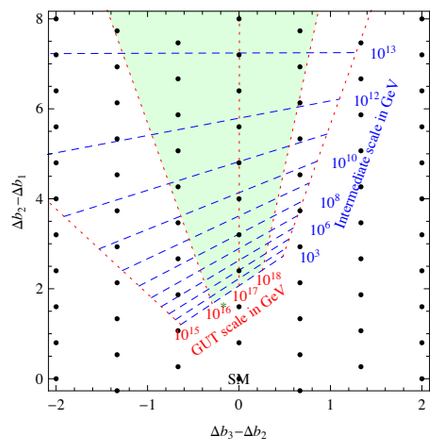




ADDING REPRESENTATIONS IMPROVES UNIFICATION PREDICTION AND RAISES GUT SCALE.
IF REPRESENTATIONS NOT TOO LARGE, NEED SCALE TO BE NEAR WEAK SCALE.

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





UNIFICATION @ LHC

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

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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. → DEEPLY UNSATISFYING, ESSENTIALLY IMPOSSIBLE W/ INFLATION
2. B AND $\overline{\text{B}}$ SPATIALLY SEPARATED. → 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.

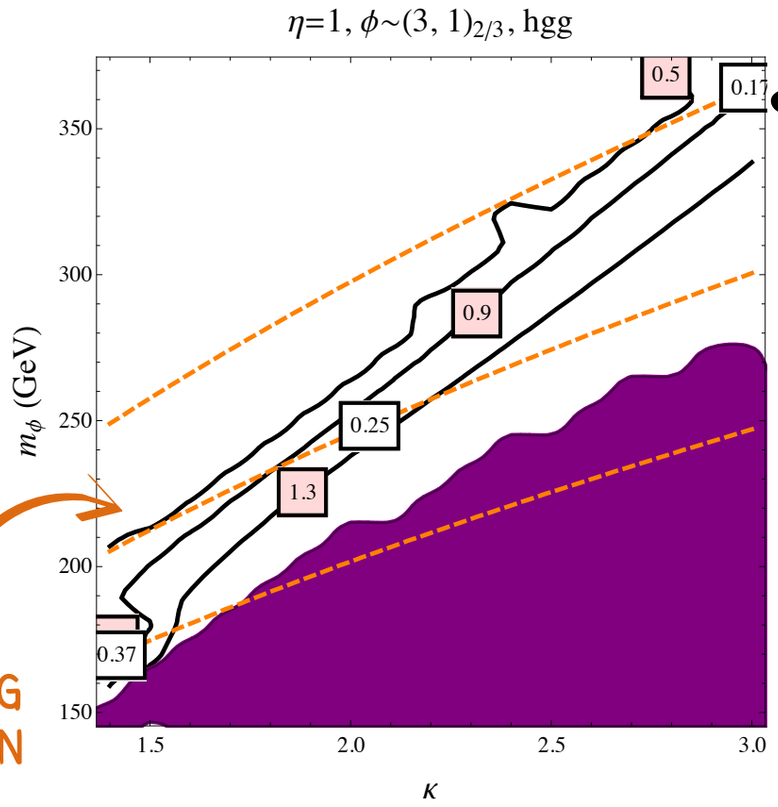
BARYOGENESIS@LHC 1: ELECTROWEAK BARYOGENESIS

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



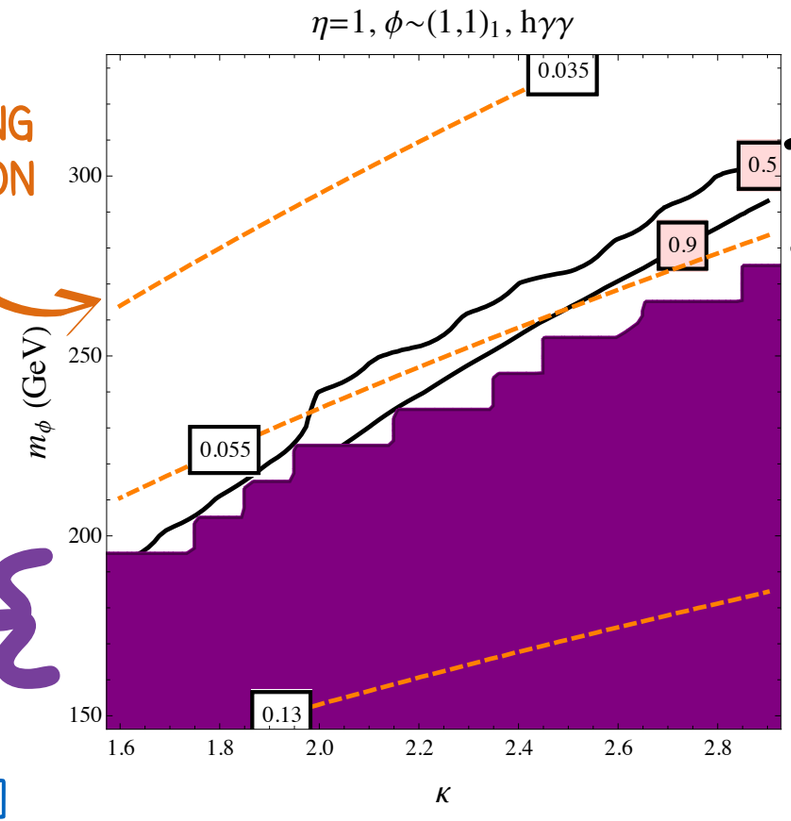
1ST ORDER EWPT

HGG COUPLING DEVIATION

TRANSITION TO WRONG MINIMUM

LOOKS LIKE: RH STAU

HYY COUPLING DEVIATION

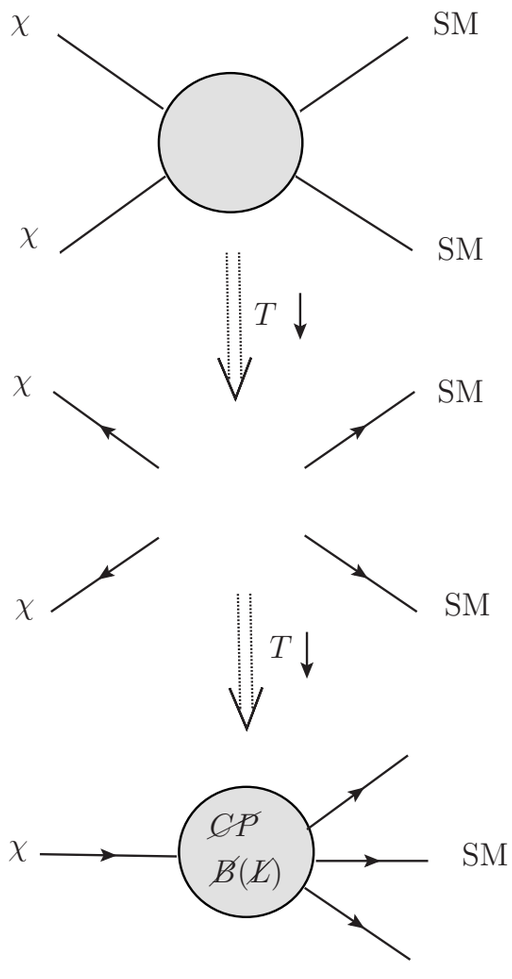


1ST ORDER EWPT

[KATZ, PERELSTEIN]

BARYOGENESIS@LHC 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 #

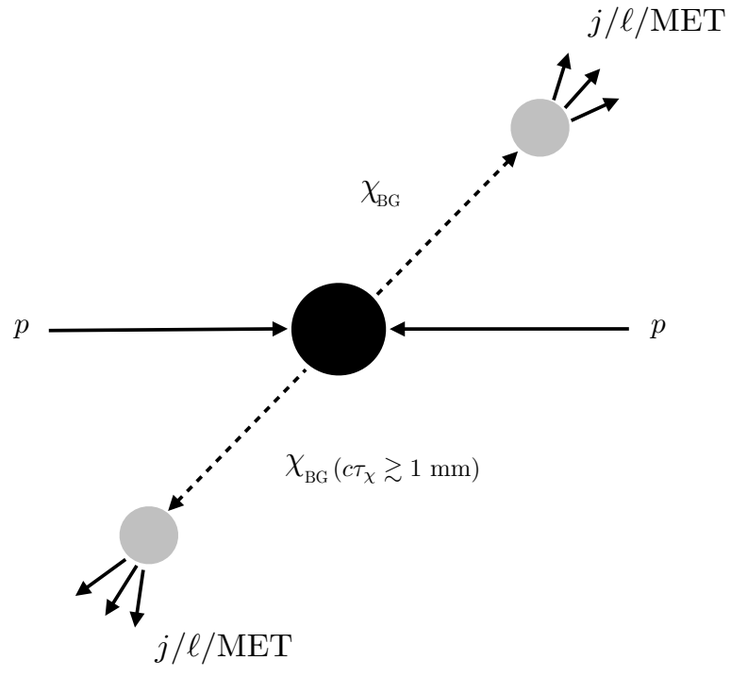


In thermal equilibrium

Thermal freezeout at T_f
$\Rightarrow\ \Omega_\chi^{\tau\to\infty}$

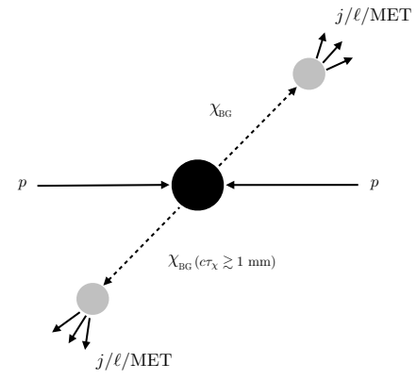
Decay at T_d
$\Rightarrow\ \Omega_{\Delta B} = \epsilon_{CP}\Omega_\chi^{\tau\to\infty}$

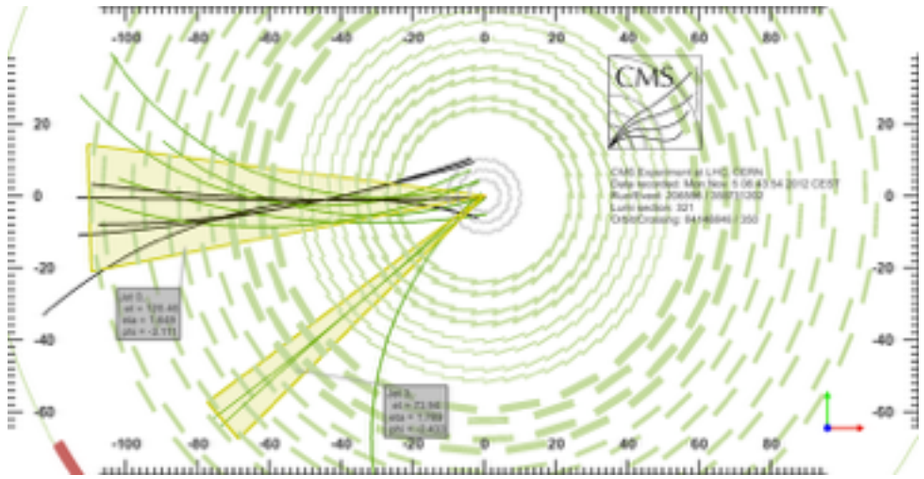
COUPLINGS REQUIRED FOR THESE PROCESSES TO WORK IMPLY PRODUCTION VIA SM AND LONG-LIVED DECAY TO SM.
DISPLACED VERTICES AT COLLIDERS



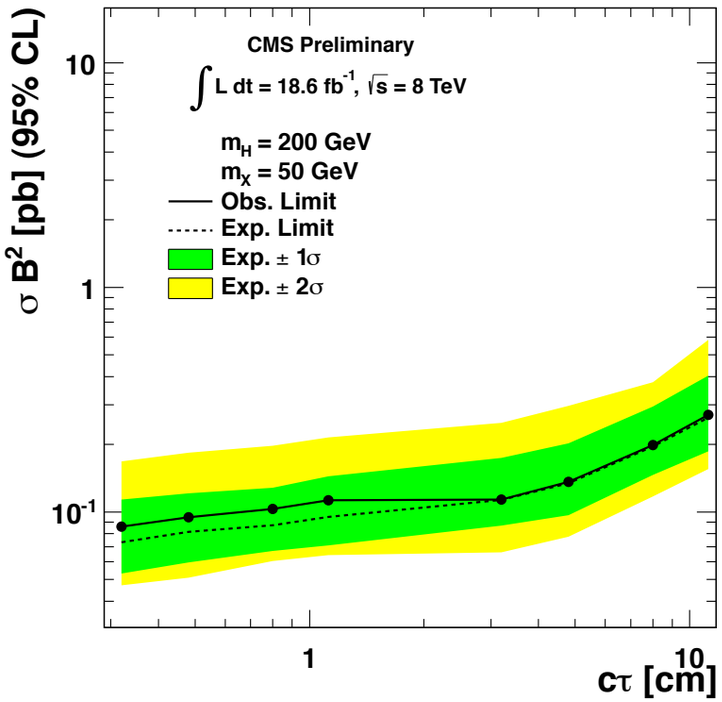
[CUI, RANDALL, SHUVE '11, CUI & SHUVE '14]

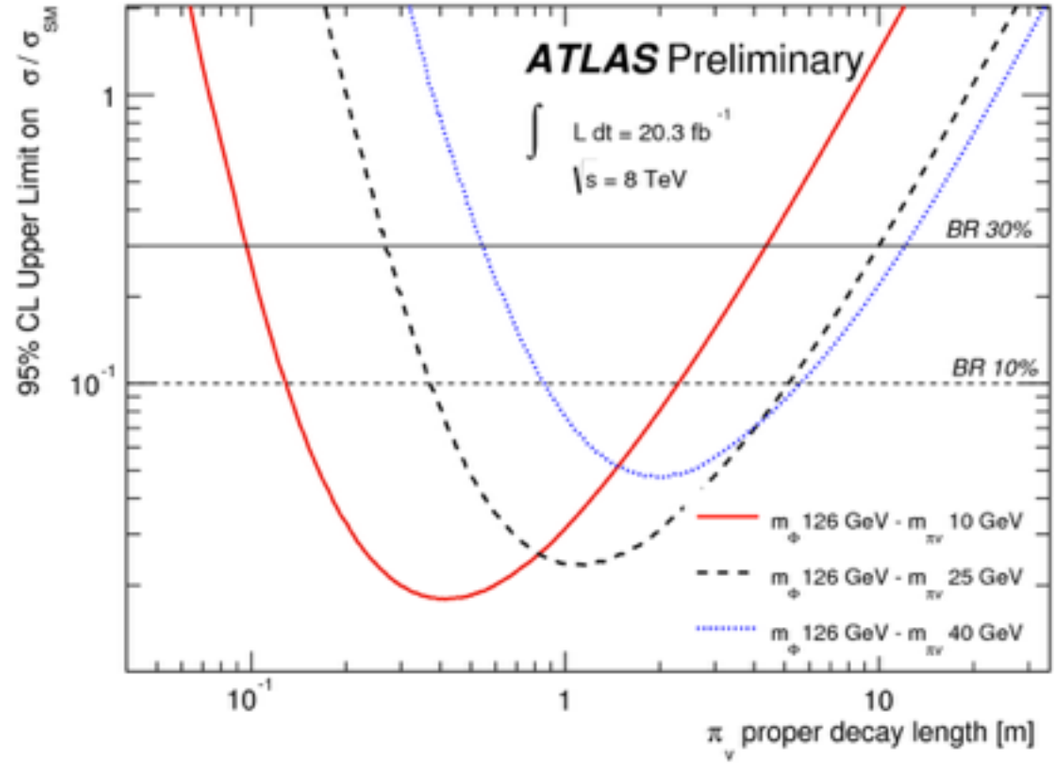
BARYOGENESIS @ LHC





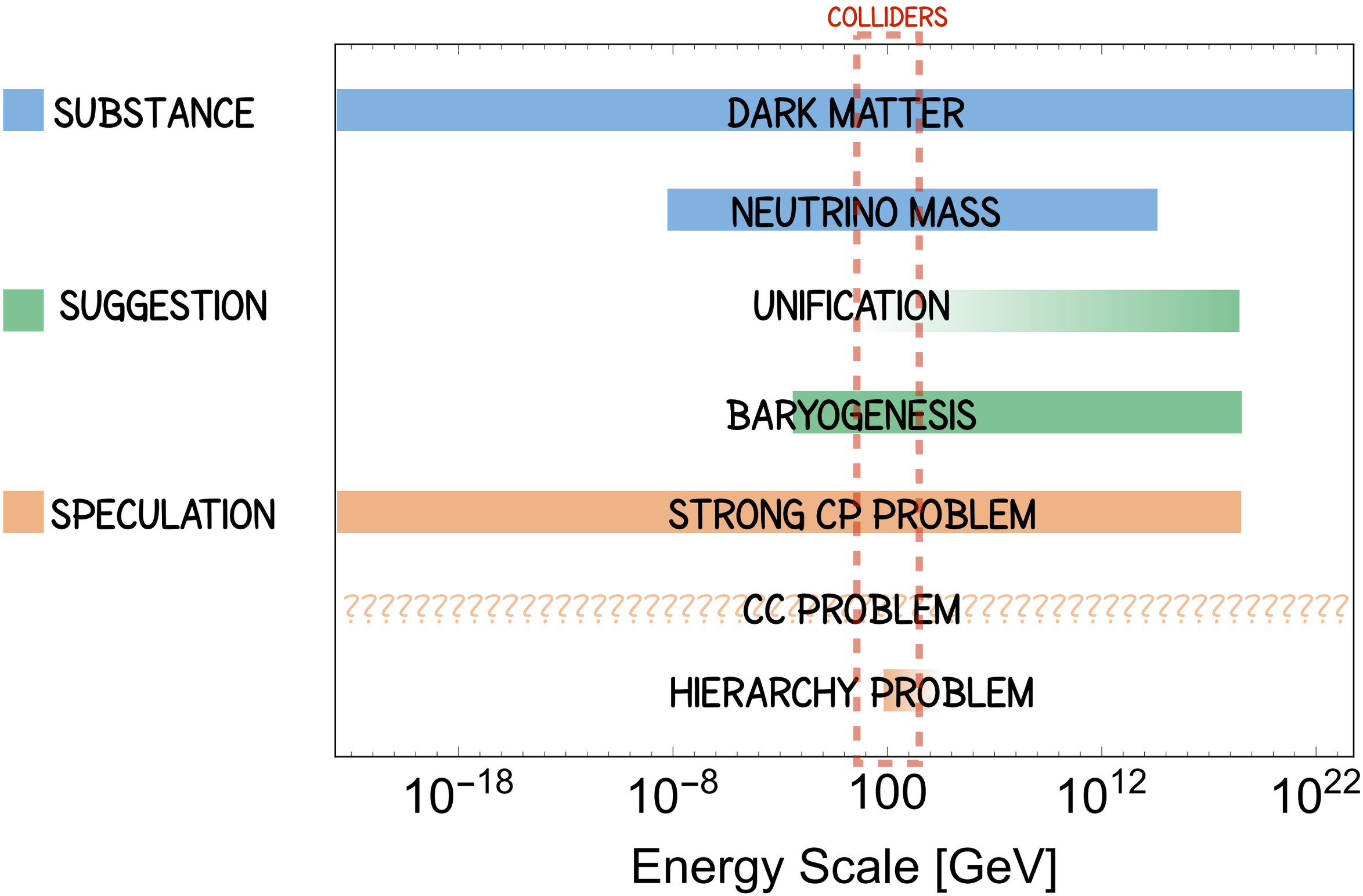
MOTIVATES VARIOUS SEARCHES FOR DISPLACED DECAYS USING, E.G., TRACKER (CMS) OR HCAL/ECAL (ATLAS)





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

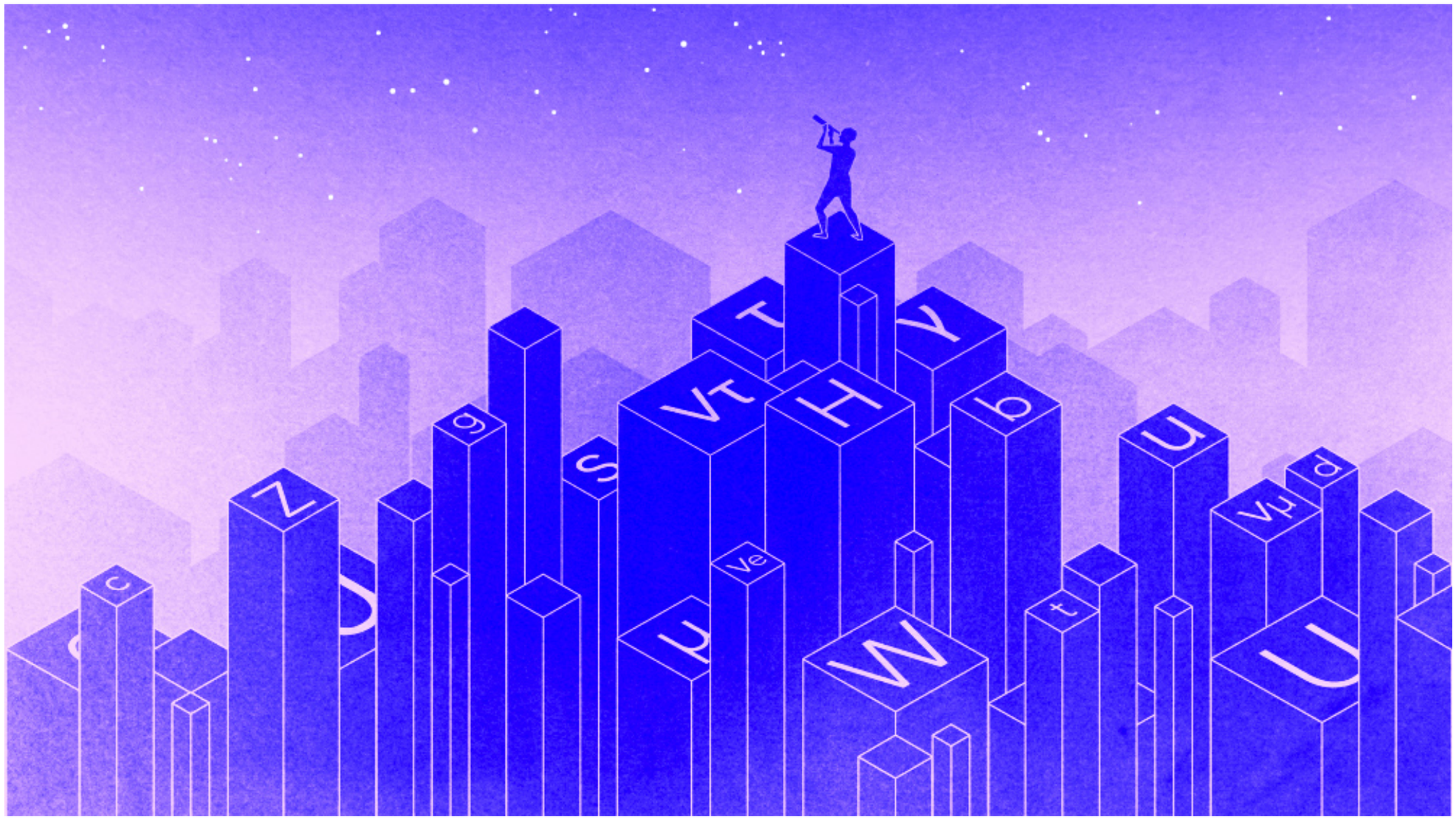
BEYOND THE STANDARD MODEL



QUANTA MAGAZINE illuminating science

What No New Particles Means for Physics

Physicists are confronting their “nightmare scenario.” What does the absence of new particles suggest about how nature works?



Olena Shmahalo/Quanta Magazine

- THE ABSENCE OF EVIDENCE FOR SUPERSYMMETRY JUST MEANS ONE CLASS OF BSM SIGNALS HAS YET TO APPEAR (AND THERE IS A LOT OF ROOM LEFT!).

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

- NEW SOLUTIONS TO THESE PROBLEMS ABOUND, WITH NEW SIGNALS.

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

THANK YOU!